

An Overview of the Multiagent Systems Engineering Methodology

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Abstract. To solve complex problems, agents work cooperatively with other agents in heterogeneous environments. We are interested in coordinating the local behavior of individual agents to provide an appropriate system-level behavior. The use of intelligent agents provides an even greater amount of flexibility to the ability and configuration of the system itself. With these new intricacies, software development is becoming increasingly difficult. Therefore, it is critical that our processes for building the inherently complex distributed software that must run in this environment be adequate for the task. This paper introduces a methodology for designing these systems of interacting agents.

1. Introduction

The advent of multiagent systems has brought together many disciplines in an effort to build distributed, intelligent, and robust applications. They have given us a new way to look at distributed systems and provided a path to more robust intelligent applications. However, many of our traditional ways of thinking about and designing software do not fit the multiagent paradigm. Over the past few years, there have been several attempts at creating tools and methodologies for building such systems. Unfortunately, many of the tools focused on specific agent architectures [1, 12] or have not gone to the necessary level of detail to adequately support complex system development [8, 24]. In our research, we have been developing both a complete-lifecycle methodology and a complimentary environment for analyzing, designing, and developing heterogeneous multiagent systems. The methodology we are developing is Multiagent Systems Engineering (MaSE).

Constructing multiagent systems is difficult. They have all the problems of traditional distributed, concurrent systems, plus the additional difficulties that arise from flexibility requirements and sophisticated interactions. Sycara states in [21] that there are two technical hurdles to the extensive use of multiagent systems. First, there is a lack of a proven methodology enabling designers to clearly structure applications as multiagent systems. Second, there are no general case industrial-strength toolkits that are flexible enough to specify the numerous characteristics of agents.

This paper addresses the first technical hurdle by proposing a methodology for the design of multiagent systems. The focus is on the construction of a multiagent system

through an entire software development lifecycle from problem description to implementation. Research into multiagent system methodologies, for the most part, has focused more on high-level descriptions and concepts than on an actual design methodology. Other design paradigms - object-oriented systems in particular - do exist as general-case solutions, but these are neither tuned for, nor particularly useful in creating a system that is intended to take full advantage of agent capabilities. Object-oriented design has achieved some maturity and provides a stable foundation upon which to build. However, object-oriented methodologies are not directly applicable to agent systems - typical agents are significantly more complex in both design and behavior than objects.

1.1 Scope

Because of assumptions made to simplify the research, MaSE has a few limitations. First, we assume that the system being created is closed and that all external interfaces are encapsulated by an agent that participates in the system communication protocols. Second, the methodology does not consider dynamic systems where agents can be created, destroyed, or moved during execution. Third, inter-agent conversations are assumed to be one-to-one, as opposed to multicast. However, substituting a series of point-to-point messages can be used to fulfill the requirement for multicast. Finally, it is assumed that the systems designed with MaSE would not be very large; the target is ten or less software agent classes. This is not a hard constraint, but simply indicates that no verification or validation of larger systems was done and that no thought was given to the potential problems of such systems.

Work is ongoing at the Air Force Institute of Technology (AFIT) to extend this methodology in these and other areas. Both the problems of dynamic systems and multicast conversations appear to be relatively straightforward extensions using predefined *move* activities and special multicast conversations. While not designed for open systems, MaSE can also be used to design agents that operate in an open environment as long as there are appropriately define protocols for the agent to use.

1.2 Related Work

There have been several proposed methodologies for analyzing, designing, and building multiagent systems [8]. The majority of these are based on existing object-oriented or knowledge-based methodologies. In fact, the syntax of many of the models was taken from the Unified Modeling Language even though the methodology itself is dissimilar to most object-oriented approaches.

Actually, MaSE builds upon the work of many agent-based approaches; it takes many ideas and combines them into a complete, end-to-end methodology. For instance, work on goals and roles by Kendall [11] influenced the initial MaSE analysis steps while the mapping of roles to agent classes builds off the concepts presented by Kinny, Georgeff, and Rao [12]. Only the Gaia approach [24] attempts to encompass the entire life cycle, although the authors admit to its shortcomings. The main advantage of MaSE over previous methodologies is its scope and completeness.

2. Multiagent Systems Engineering Methodology

The Multiagent System Engineering (MaSE) methodology, takes an initial system specification, and produces a set of formal design documents in a graphically based style. The primary focus of MaSE is to guide a designer through the software lifecycle from a prose specification to an implemented agent system. MaSE is independent of a particular multiagent system architecture, agent architecture, programming language, or message-passing system. A system designed in MaSE could be implemented in several different ways from the same design. MaSE also offers the ability to track changes throughout the process. Every design object can be traced forward or backward through the different phases of the methodology and their corresponding constructs. MaSE is described in more detail in [4, 22]. An overview of the methodology and models is shown in Figure 1.

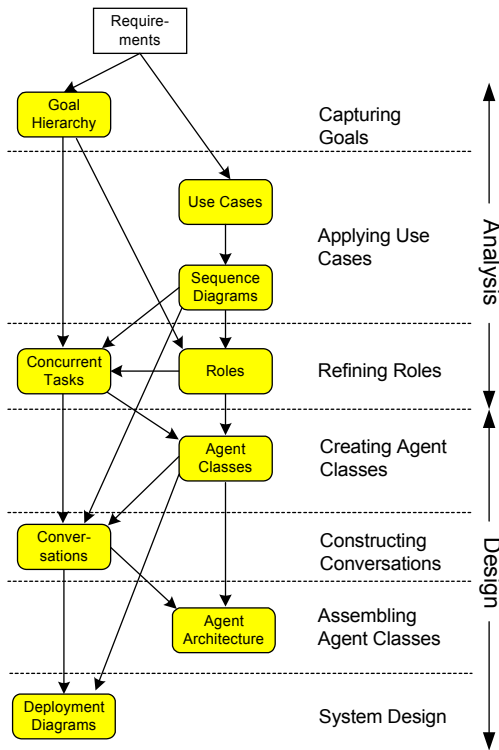


Fig. 1. The MaSE Methodology

The general operation of MaSE follows the progression of steps shown in Figure 1, with outputs from one section becoming inputs for the next. The methodology is iterative across all phases with the intent that successive "passes" will add detail to the models described later. The gray boxes denote models used within the methodology

and the phases are listed down the right side of the figure. The arrows indicate how the models influence each other.

2.1 Capturing Goals

The first phase in MaSE is Capturing Goals, which takes the initial system specification and transforms it into a structured set of system goals as shown in a Goal Hierarchy Diagram (Figure 2). This phase of MaSE is drawn in a large part from analysis patterns in [11]. In the MaSE methodology, a goal is always defined as a system-level objective. Lower-level constructs may inherit or be responsible for goals, but goals always have a system-level context.

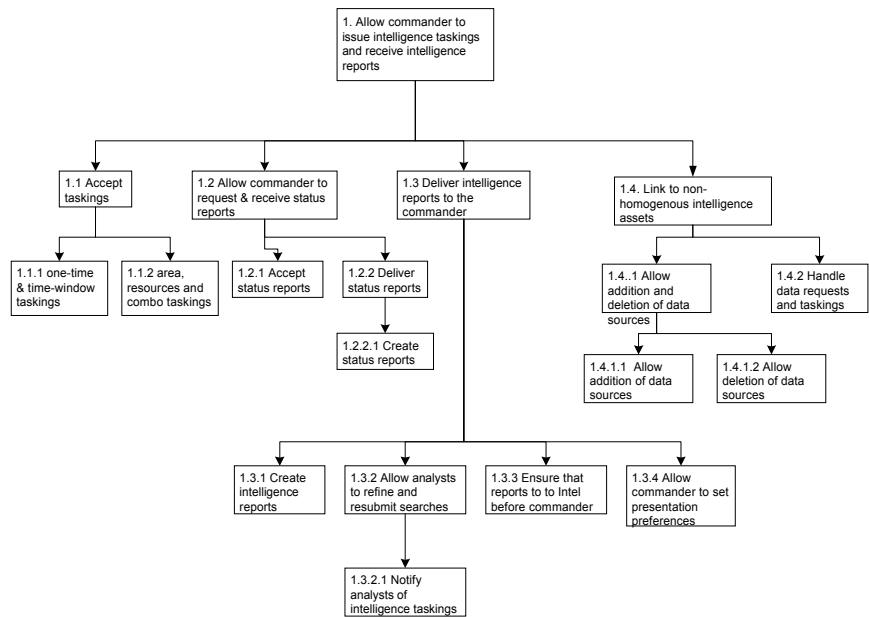


Fig. 2. Goal Hierarchy Diagram

There are two parts of the Capturing Goals phase: identifying and structuring goals. The goals are identified by distilling the essence of the set of requirements. These requirements may include detailed technical documents, user stories, or formalized government specifications. Once these goals have been captured and explicitly stated, they are less likely to change than the detailed steps and activities involved in accomplishing them.

The goals are then analyzed and structured into a form that can be passed on and used in the design phases of the MaSE methodology. In a Goal Hierarchy Diagram, goals are organized by importance. The main sequences of interaction and subordinate details must be distinguishable from one another. Each level of the

hierarchy contains goals that are roughly equal in scope and all sub-goals relate functionally to their parent.

2.2 Applying Use Cases

It is the conversations between agents that are the real backbone of a multiagent system, as they enable the distributed operation that is the strength of agent technology. The second phase of MaSE looks down the road toward constructing these conversations and creates use cases to ease this difficulty.

The Applying Use Cases phase captures use cases from the initial system requirements and restructures them as a Sequence Diagram (Figure 3). A sequence diagram depicts a sequence of messages between multiple agent roles.

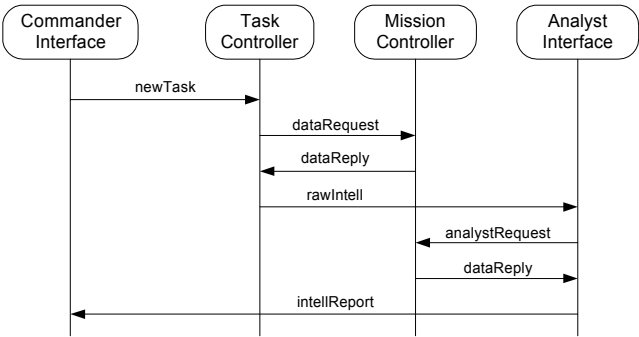


Fig. 3. Sequence Diagram

First, use cases are drawn from the system requirements. Use cases are narrative descriptions of a sequence of events that define desired system behavior. They are examples of how the user (or the requirements document editor) thinks the system should behave in a given case.

A Sequence Diagram is used to determine the minimum set of messages that must be passed between roles. If a message is passed between two roles, then there must be a corresponding communication path between them. A communication path between roles played by separate agent classes means that a conversation must exist between the two agent classes to pass the message. The agent class playing the role that initiated the communication becomes the initiator of that conversation, while the receiving agent class becomes the responder. Typically, we create at least one sequence from a use case. If there are several possible scenarios, multiple Sequence Diagrams are created.

2.3 Refining Roles

The third step of MaSE is to transform the structured goals of the Goal Hierarchy Diagram into a form more useful for constructing multiagent systems: roles. Roles

are the building blocks used to define agent's classes and capture system goals during the design phase. We guarantee that system goals are accounted for by ensuring that every goal is associated with a role and that every role is played by an agent class.

A role is an abstract description of an entity's expected function and encapsulates the system goals that it has been assigned the responsibility of fulfilling. Roles are created to do something. They are similar to the notion of an actor in a play or an office within an organization. Roles are described in detail in [10,12,24].

The general case transformation of goals to roles is one-to-one; each goal maps to a role. However, there are many exceptional situations where it is useful to combine goals. Similar or related goals may be combined into single roles for the sake of convenience or efficiency. Goals that share a high degree of cohesion as described in [16] can be combined into a single role.

Some goals imply distributed roles. Any mention of separate machines or other distribution requires one role for each "side" of the distributed relationship. Interfacing with an external source is the same. One role must interface with the source while another may be required to bridge the gap back to the system. This is also true for any database, file interface, or user interface in the system. A user interface implies a role by itself and should be separate from other roles as if it were a separate data source.

Role definitions are captured in a traditional Role Model [10] as shown in Figure 4. MaSE also allows a more complete version of a Role Model, as shown in Figure 5, which includes information on interactions between role tasks. However, the traditional version of the Role Model is more useful at the outset of the role definition process before tasks have been defined, as well as later in the analysis to provide a high-level view of the system. In the traditional Role Model, lines between roles denote possible communications paths between roles. These paths are derived from the Sequence Diagrams developed in the previous step.

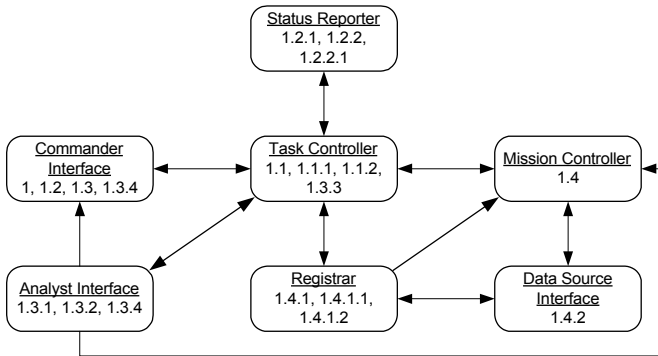


Fig. 4. Traditional Role Model

In MaSE, roles are typically documented in a more detailed version of a Role Model as shown in Figure 5. First, the goals associated with each role are listed under the role name. It also shows the set of tasks associated with each role, which are used

to define the role's behavior. Roles are denoted by rectangles, while the role tasks are denoted by ovals attached to the role. Tasks are simply identified in the MaSE Role Model. The detailed description of a task's definition is provided in the next section. Lines between tasks denote communications protocols that occur between the tasks. The arrows denote the initiator/responder relationship of the protocol with the arrow pointing from the initiator to the responder. Solid lines indicate peer-to-peer communications, which are generally implemented as external communications protocols. External protocols involve message passing between roles that may become actual messages if their roles end up being implemented in separate agents. Dashed lines denote communication between concurrent tasks within the same role. A line is dashed if it will only occur within the same instance of the role in the final system. Roles may not share or duplicate tasks. Sharing of tasks is a sign of improper role decomposition. Shared tasks should be placed in a separate role, which can be combined into various agent classes in the Design phase.

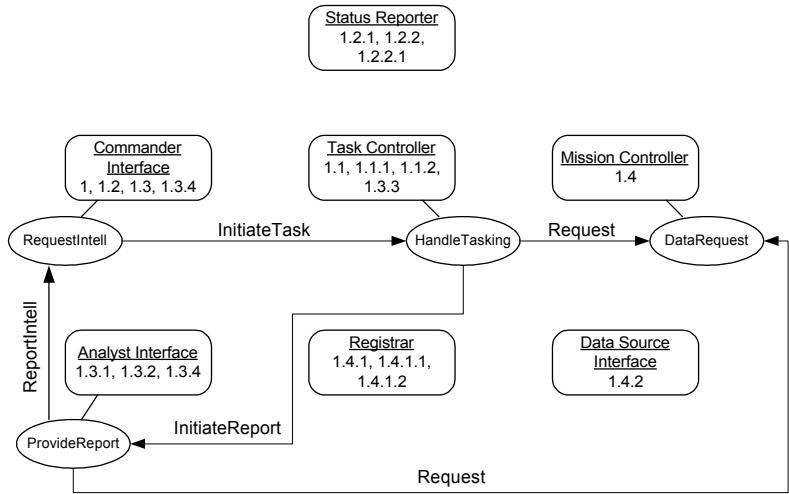


Fig. 5. MaSE Role Model

After roles are created, tasks are associated with each role. Every goal associated with a role can have a task that details how the goal is accomplished. This must be done after role creation since tasks communicate with tasks in other roles. A MaSE task, which captures a bidder's behavior in a Contract Net Protocol, is shown in Figure 6. A task is a structured set of communications and activities, depicted as a state diagram.

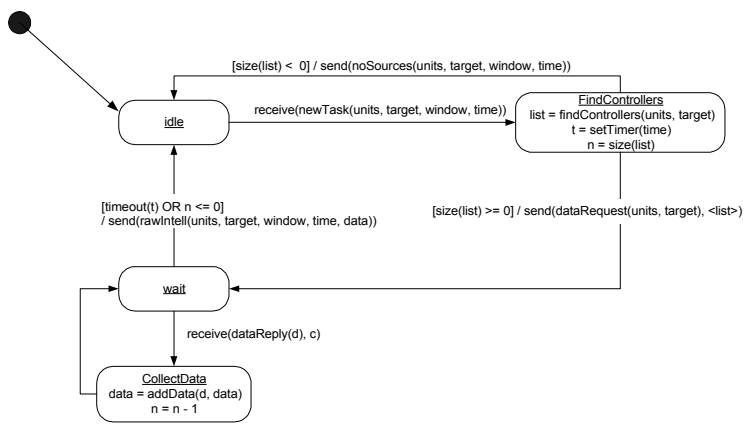


Fig. 6. MaSE Task

2.4 Creating Agent Classes

In the Creating Agent Classes phase of the MaSE methodology, the agent classes are identified from component roles. The product of this phase is an Agent Class Diagram, shown in Figure 7, which depicts agent classes and the conversations between them. The boxes in the figure are the agent classes, containing the class name and its assigned roles. Lines with arrows denote conversations and point from the initiator of the conversation to the responder, with the name of the conversation written either over or next to the arrow.

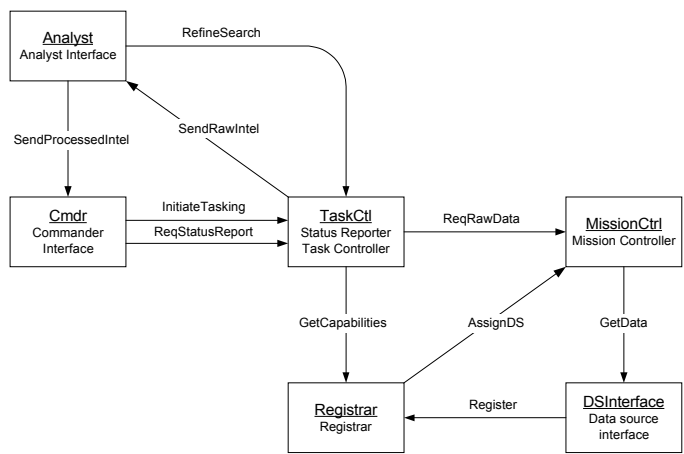


Fig. 7. Agent Class Diagram

During this phase of MaSE, agent classes consist of two components: roles and conversations. In a later MaSE phase, internal details are added to agent classes. The conversations of an agent class are those that it participates in, either as an initiator or responder.

The primary difference between the Agent Class Diagram and similar object diagrams is the semantics of the relationships between agent classes. In Agent Class Diagrams, these relationships define conversations that are held between agent classes. In fact, the primary purpose of this phase is to identify the agent classes that "anchor" each side of a conversation.

Just as before, when mapping goals to roles, there is generally a one-to-one mapping between roles and agent classes. However, the designer may combine multiple roles in a single agent class or map a single role to multiple agent classes. Since agents inherit the communication paths between roles, any paths between two roles become a conversation between their respective classes. As such, it is desirable, where possible, to combine two roles that share a high volume of message traffic. When determining which roles to combine, size and frequency of communications are important, not just the number of communication paths.

2.5 Constructing Conversations

Constructing Conversations is the next phase of MaSE. It is closely linked with the phase that follows it, Assembling Agents. As will be discussed later, it is often beneficial to alternate between the two phases. A MaSE conversation defines a coordination protocol between two agents. Specifically, a conversation consists of two Communication Class Diagrams, one each for the initiator and responder. A Communication Class Diagram is a pair of finite state machines that define the conversation states of the two participant agent classes. The *initiator* side of a conversation is shown in Figure 8 with its associated *responder* side shown in Figure 9. The initiator begins the conversation by sending the first message.

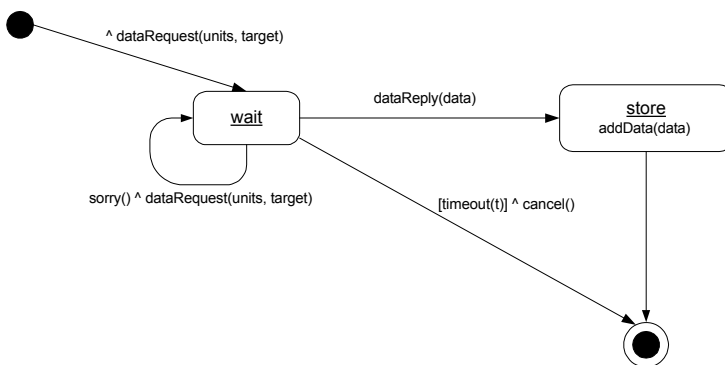


Fig. 8. Initiator Communication Class Diagram

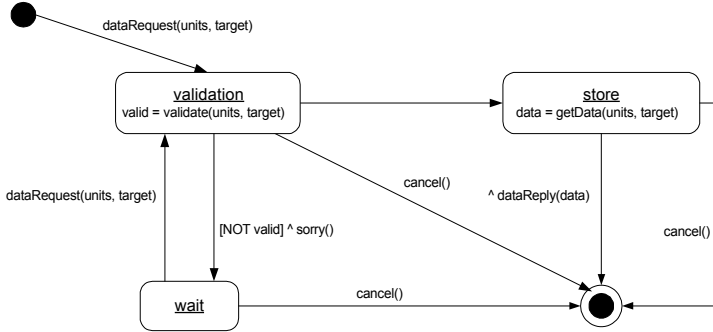


Fig. 9. Responder Communication Class Diagram

When an agent receives a message, it compares it to its active conversations. Upon a match, the agent transitions the appropriate conversation to a new state and performs any required activities from either the transition or the new state. Otherwise, the agent compares the message to all possible conversations that it may participate in with the agent that sent the message, and begins a new conversation if the message matches a transition from the start state. Any activities in a conversation, which may occur in a state or on a transition, are mapped to methods in the corresponding agent classes. The syntax of a transition follows conventional UML notation as shown below, and described in [3].

`rec-mess(args1) [cond] /activity^trans-mess(args2)`

While the operation of a conversation is relatively simple, its design can be quite complicated. Conversations are defined at a high level. Specifically, the initiator and responder agent classes are specified for each conversation in the system. The problems encountered in this phase deal with building the finite state automata that define the operation and protocol of conversations.

Conversations must support and be consistent with all sequence diagrams derived earlier. They may also incorporate states from tasks. Some tasks, in fact, operate entirely over single conversations and can be designed directly. In general though, conversations are built by first adding all possible states and transitions that can be derived from the Sequence Diagrams and tasks. At this point, much of the conversation often exists. For the rest of the conversation design, it is a matter of adding states and transitions as necessary to convey the required messages and provide robust operation. Automatic verification of conversation correctness is addressed by Lacey in [13].

2.6 Assembling Agent Classes

In this phase of MaSE, the internals of agent classes are created. Work by Robinson [18] describes the details of assembling agents from a component-based architecture. He defines five different architectural style templates: Belief-Desire-Intention (BDI),

reactive, planning, knowledge based, and a user-defined architecture. Each architecture template has a specific set of components. For example, a reactive architecture includes a Controller, MessageInterface, RuleContainer, and Effectors.

A designer can either define components from scratch or use pre-existing components. Furthermore, components may have sub-architectures containing components. Components are joined with either inner- or outer-agent connectors. Inner-agent connectors (thin arrows) define visibility between components while outer-agent connectors (thick dashed arrows) define connections with external resources such as other agents, sensors and effectors, databases, and data stores. Internal component behavior may be represented by formal operation definitions as well as state-diagrams that represent events passed between components. An example of a component-based architecture is shown in Figure 10.

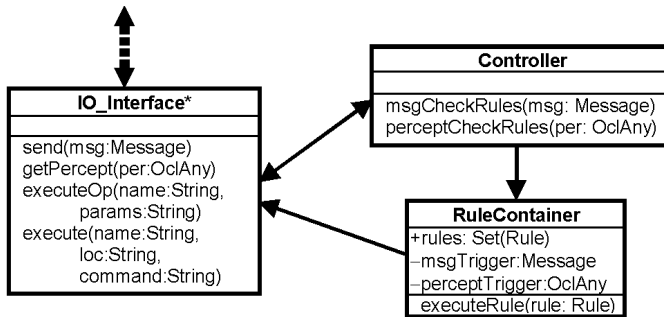


Fig. 10. Generic Reactive Agent Class Architecture

2.7 Constructing Conversations versus Assembling Agent Classes

As discussed in their respective sections, constructing conversations and agent class assembly are closely related activities. In practice, it is useful to alternate between these phases while staying within one functional area of the design. The question of which to do first is answered best by the style of conversations the system uses. In particular, is the system communication-heavy? Are the communications relatively complex? The designer should design conversations first if the system consists of many simple conversations, or if the initial context of the system includes many use cases. It is generally better to define the agents first if there are complex conversations, or if many of the agent classes are being reused.

2.8 System Design

The final phase of the MaSE methodology takes the agent classes and instantiates them as actual agents. It uses a Deployment Diagram to show the numbers, types, and locations of agents within a system. System design is actually the simplest phase

of MaSE, as most of the work was done in previous steps. The idea of instantiating agents from agent classes is the same as instantiating objects from object classes in object-oriented programming.

Deployment Diagrams are used to define a system based on agent classes defined in the previous phases of MaSE. Deployment Diagrams define system parameters such as the actual number, types, and locations of the agents within the system. Figure 11 shows an example Deployment Diagram. The three dimensional boxes are agents, and the connecting lines represent conversations between agents. The agents are named either after their agent class, or in the form of "designator: class" if there are multiple instances of a class. A dashed-line box indicates that agents are housed on the same physical platform.

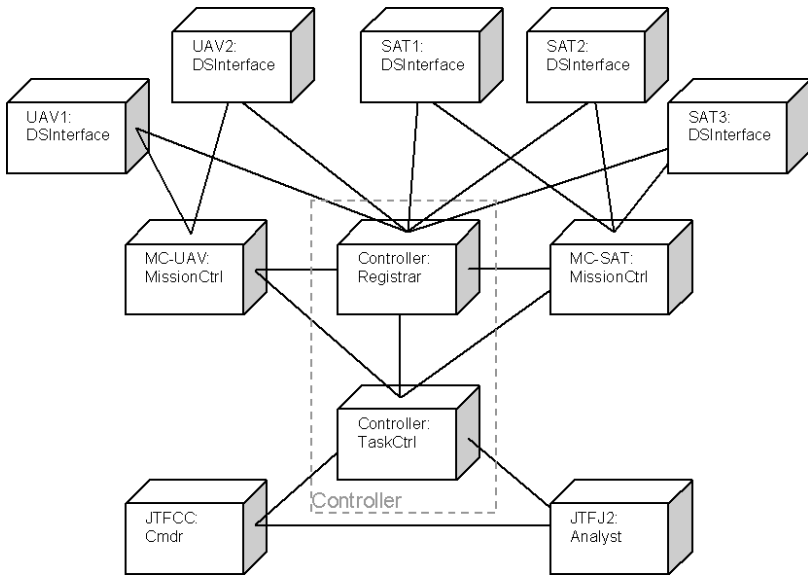


Fig. 11. MaSE Deployment Diagram

A system must be arranged in a Deployment Diagram before it can be implemented in code. This is due to the differences between agents and agent classes. An agent requires information such as a hostname or address to participate in a multiagent system. A Deployment Diagram also offers another opportunity for the designer to tune the system. Agents can be arranged among various machine configurations to take advantage of the available processing power of network bandwidth.

A final element to consider is automatic code generation. The MaSE methodology is concerned with actually engineering agent systems. As such, all of the steps of the methodology work toward that end. It is our vision that code generation be a largely automatic process. Code generation is not a part of MaSE at this time, but is assumed to happen just after this phase.

3. Contributions

MaSE guides a multiagent system designer through the entire software development lifecycle, beginning from a textual system representation and proceeding in a structured manner toward a working implementation. MaSE combines several pre-existing models into a single structured methodology. Most of the models used within the methodology have therefore been already justified and validated within the realm of agents and multiagent systems. A sequence of guided transformations connects the elements of this strong foundation together into a clear high-level picture of how a designer should go about creating a multiagent system.

In conjunction with the MaSE methodology, we have developed a tool, called agentTool, to support the development of multiagent systems using MaSE [5]. The agentTool system currently supports the entire lifecycle from the Goal Hierarchy diagram down to code generation. Developing the methodology and tool together allowed us to focus the methodology toward automation. Focusing on automation forced us to define an unambiguous semantics for the models as well as the relationships between the models. Using MaSE and agentTool we have shown that you can develop a multiagent systems development methodology, along with an automated toolset, that supports multiple types of agent architectures, languages, and communications frameworks.

4. MaSE Applications

MaSE has been successfully applied in numerous graduate-level projects as well as several research projects. The Multi-Agent Distributed Goal Satisfaction project [20] is a collaborative effort between AFIT, the University of Connecticut, and Wright State University where MaSE is being used to design the collaborative agent framework to integrate different constraint satisfaction and planning systems. The Agent-Based Mixed-Initiative Collaboration project [2] is also using MaSE to design a multiagent system focused on distributed human and machine planning. MaSE has been used successfully to design an agent-based heterogeneous database integration system [14] as well as a multi-agent approach to a biologically based computer virus immune system [7].

5. Acknowledgements

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Security for Mobile Agents

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Abstract. In view of the proliferation and expansion of wide-area open networks such as the intranets and extra-nets, agent technology is attracting greater attention. However, as yet there is well-established and widely used method of developing safe and secure agent systems. In this paper, we propose a methodology that supports the step-by-step development of mobile agent systems while ensuring consideration of security issues. This approach results in a robust infrastructure for practical system development, and by supporting calculation of various costs allows efficiency and security tradeoffs to be objectively evaluated.

1 Introduction

In view of the mounting use of computer networks such as the intranets and extra-nets between organizations, and the expansion of such networks, the software that supports these networks is becoming increasingly important. It is this context that the concept of mobile agents is attracting attention. However, mobile agents suffer from insufficiencies respecting developmental methodology and security. Until these problems are solved, widespread adoption of agents is unlikely. In particular, this is because it is difficult to build practical large-scale systems in the absence of rigorous developmental methodologies.

In this paper, we propose a methodology that supports the step-by-step development of mobile agent systems while ensuring consideration of security issues. The methodology revolves around the use of patterns that take these issues into account.

Our methodology has the following features. Firstly, it is a concrete development method with security concerns fully integrated. Secondly, we can easily construct a suitable computation model by examining the patterns and their costs. The pattern approach was originally conceived as an aid to object-oriented software development. In this paper we apply the same concept to the development of agent systems. This results in a robust infrastructure for practical system development, and by supporting calculation of various costs allows efficiency and security tradeoffs to be objectively evaluated. Such tradeoffs and methodologies are important because the system that concerns the security by ad-hoc method may be too slow and have security hole.

In addition, software for intranets/extra-nets recently should be adopted dynamical changes safely and quickly, when the structure of organization changes for innovation.

Our methodology allows us such changes because it uses not only structure of agents but also organization and control information of hardware.

Previous work has included proposals for safety and security techniques for mobile agent systems [8]. However, these proposals did not incorporate a concrete methodology, and focused on only parts of the overall system rather than taking the necessary holistic approach. This state of affairs is reflected in the absence of any general guidelines for mobile agent systems. Tahara [43] proposed mobile agent patterns. Other approaches have also been proposed, but without the integration of security and safety issues. Additionally the absence of objective cost guidelines was a problematic omission. We have developed more abstract patterns in order to avoid the domain-specificity of other work.

The contribution of this work can be viewed from a variety of different perspectives. From the software engineering point of view, (1) our work provides a basis for CASE and IDE tool design, (2) agent migration necessity can be discussed formally, and (3) security can be maintained while integrating legacy applications. From the system management perspective, it provides a mechanism for evaluating the system in terms of efficiency and security.

The paper is structured as follows. Section 2 provides the overview of our methodology. Details of our methodology are described in section 3 to 5. Section 3 describes the models used in the methodology. Section 4 describes the patterns. Section 5 describes the process. In section 6, we evaluate the methodology by using an example and discusses the methodology. Section 7 describes related work and some final remarks are provided in Section 8.

2 Summary of the Development Process

The process is summarized in Figure 1. The round rectangles denote the sub-processes, the solid rectangles denote the products, and the dotted rectangles denote the patterns presented in this paper. In the process, we use 3 kinds of information: agent structure model for application information, system requirements model for hardware information and access model and confidentiality model for organization information. The method consists of migration decision phase and security decision phase, and in each phase we use patterns: basic patterns and secure patterns respectively.

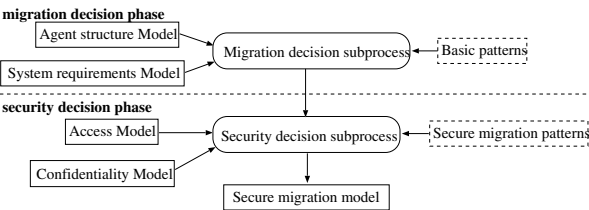


Fig. 1. Summary of process

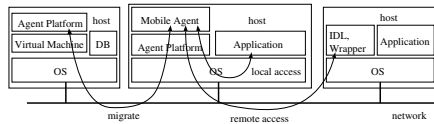


Fig. 2. Mobile Agent Architecture

Mobile Agent Architecture that we use to develop a system is shown in Figure 2. In a system, mobile agents can access applications and databases in other hosts through the agent platform and the wrappers. In addition, an agent consists of some objects or subroutines. In our methodology, we only consider the security for a mobile agent against attacks from others.

3 Models

3.1 Agents Structure Model

This model expresses data flow of agents and the following information.

Amount of data are indicated beside each arrow.

Computing hosts where the computation is performed and the data are stored are indicated at the top left-hand corner of each node.

If any hosts in the system are allowed to perform the computation, “*” is indicated instead of host names.

Initial computation host name : is indicated in the double-lined box and an arrow is drawn from the box to the computation performed first.

Computation time : is indicated in the circle at the bottom left-hand corner of each node.

Code size is indicated after the computation time and “/”.

The computation time and the amount of data are set at their average or typical value. Figure 3 shows an example of an agent structure model. This example represents that Data store is a database on hostA, and operation is performed on hostA or hostB.

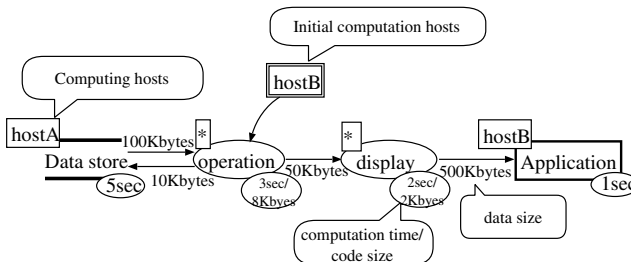


Fig. 3. Agent Structure Model

The times indicated at the bottom right-hand corner of the data stores denote the times from when inputs such as SQL are given until the resulting data are taken. Figure 3, for

example, represents that 10K bytes input is needed in order to get 100 Kbytes data from the data store and it takes 5 seconds to get the outputs from the inputs.

3.2 System Requirements Model

This model includes the information on the resource constraint on the hosts and the network: the longest stay time of agent and network transfer speed. The reason we consider stay time is for load balancing of a host.

Figure 4 shows an example of a system requirements model. The figure illustrates that an agent cannot stay for more than 10 seconds in hostA. It also indicates that the transfer speed between hostA and hostB is 30 Kbytes/sec at the worst point.

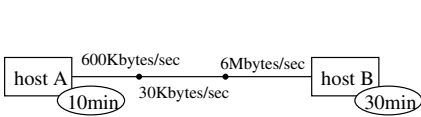


Fig. 4. Example of System Requirements Model

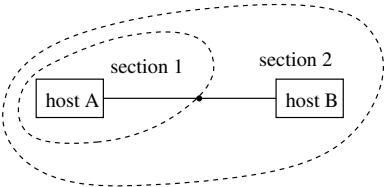


Fig. 5. Control model

3.3 Control Model

This model represents which organization accesses the network and hosts. Figure 5 shows an example of a control model. This example represents that the member of section 1 can access to host A, host B and the network between connected to host A, and the member of section 2 can access to the host B and the network connected to host B.

We assume that person who does not belong to the controlling organizations cannot access to the network and the hosts of the organizations.

3.4 Confidentiality Model

This model represents to which organizations the data handled by the service can be opened. Figure 6 shows an example of a confidentiality model. This figure indicates that the Data store's input and output data can be opened to only section 1 and the input and output of display can be opened to section 1 and section 2.

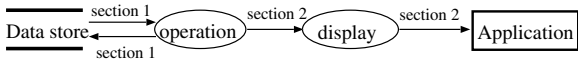


Fig. 6. Example of Confidentiality Model

4 Patterns

4.1 Basic Migration Patterns

Migration patterns that do not consider security are composed of the following basic migration patterns shown in Figure 7. Pb1 and Pb2 are the computation patterns and represent typical situations of computation of mobile agents. Pb3, Pb4 and Pb5 are coupling patterns and represent typical situations of migration of mobile agents between the hosts.

For each computation process, a computation pattern and several coupling patterns are composed and a migration pattern is established.

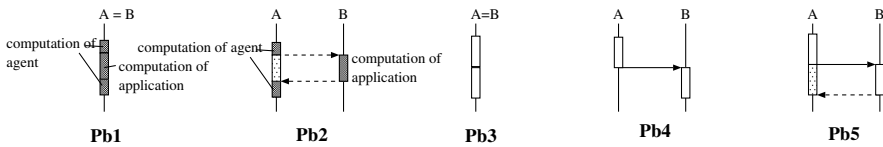


Fig. 7. Basic Migration Patterns

The vertical lines denote hosts and time flows from the top to the bottom. The black rectangles represent that computation is actually performed, and the gray rectangles represent that computation is not performed while the hosts are blocked by computation of some other hosts. The dotted horizontal lines denote communication by the message and the solid lines denote the migrations of mobile agents. The white rectangles denote computation other than the computation in question and are not parts of the patterns.

The following are detail of the patterns.

- Pb1** is applied if the host performing the computation and the host that has the actors and the data stores related to the computation coincide.
- Pb2** is applied if the host performing the computation interacts by exchanging messages with the host that has the actors and the data stores related to the computation.
- Pb3** is applied if the host performing the computation in question and the host performing the next computation coincide. The mobile agent does not migrate.
- Pb4** is applied if the host performing the computation in question and the host performing the next computation differ and the mobile agent migrates totally.
- Pb5** is applied if the host performing the computation in question and the host performing the next computation differ, the mobile agent migrate partially or totally to the latter host and the original mobile agent is blocked until the remote computation is completed. At least, only the data and the codes necessary to the remote computation migrate and only the results are returned to the original host.

Which pattern of Pb1 or Pb2 is applied can be automatically determined by assignment of the host performing each computation.

4.2 Secure Migration Patterns

The secure migration patterns are the enhanced basic migration patterns considering encryption/decryption time for preventing data leak and signature generation/checking for preventing tampering.

The situations in which security should be considered are classified into 12 categories according to risk of the network on the way to the host for the next computation, risk of the host for the next computation and the basic migration patterns with such dangers.

Figure 8 shows the secure migration patterns. In this figure, Pse1, Pse2, Pse3, and Pse4 are the computation pattern Pb2 enhanced with security techniques, Pse5, Pse6, Pse7, and Pse8 are the migration pattern Pb4 enhanced with security techniques and Pse9, Pse10, Pse11, and Pse12 are the migration pattern Pb5 enhanced with security techniques. The black rectangles in these patterns denote the extra time for increasing the system security.

In general, the countermeasures listed in the following table are used as the ways of increasing the system security.

Insecure part	Kind of attack	Countermeasure
Network	Wiretapping	Encryption
Network	Tampering	Signature
Host	Masquerading	Authenticating

Considering these issues, the patterns here add encryption, signature and authentication costs to the basic migration patterns. In detail, the encryption costs are included in Pse3, Pse4, Pse7, Pse8, Pse11 and Pse12 in which the network is insecure and the authentication costs are included in Pse2, Pse4, Pse6, Pse8, Pse10 and Pse12 in which a host is insecure. In this paper, all the data flowing in the network are given signatures even in Pse1, Pse2, Pse5, Pse6, Pse9 and Pse10 in which the network is secure because we assume that there is the danger of tampering even if the network is secure.

The following patterns are representative ones.

Pse1 is applied to Pb2 if the host A, B and the network between them are secure. In this pattern, the host A sends its data with the signature of the host itself in order to avoid tampering over the network. First, the hosts should exchange their public keys to handle their signatures. Then the hosts sign their data using their secret keys and verify the data using the corresponding public keys. In this pattern, as indicated by the black boxes in the figure, more time is required for the key generation, the key delivery, signing and the signature verification than in the case of Pb2.

Pse7 is applied to Pb4 if the network to the destination host is insecure. In this pattern, the data should be encrypted before the migration so that more time is required for it than in the case of Pb4.

Pse12 is applied to Pb5 if the destination host and the network to it are insecure. In this pattern, it is necessary to authenticate the destination agent platform on the host B, to encrypt the agent before the migration and its result.

As mentioned previously, among the patterns in Figure 8, we have no ways to avoid wiretapping by the destination host in Pse6, Pse8, Pse10 and Pse12 in the case that the destination host is not secure. Therefore, it may be necessary to change the computation assignment or the managers of the hosts so that these patterns are not needed.

4.3 Migration Model

The migration model consists of combinations of the patterns explained so far. The difference between the patterns and the migration models is that the computation time is

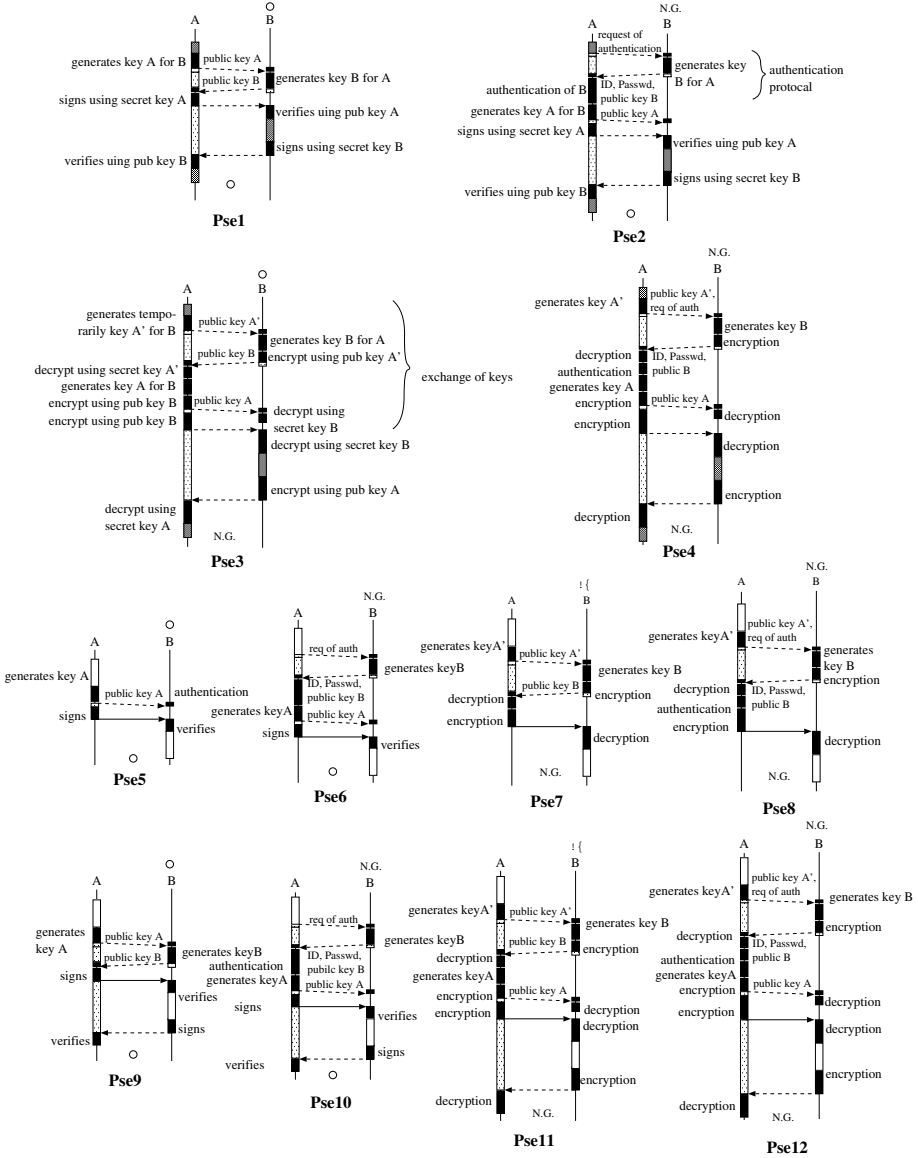


Fig. 8. Secure Migration Patterns

the actual one or not, and that the time of the data transfer over the network is considered or not.

Figure 9 shows an example of a migration model. In this example, the four computation processes are executed in the patterns Pb1, Pb2, Pb1 and Pb1, respectively, and the processes are combined by the patterns Pb4, Pb5 and Pb4.

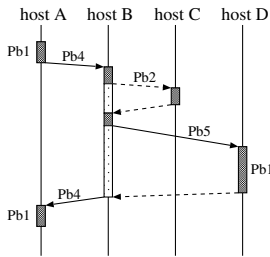


Fig. 9. Example of Migration Model

5 Development Process

5.1 Migration Decision Phase

This phase is summarized as follows. First, the computation in agents are assigned to the hosts. After that, the basic migration model is constructed by selecting appropriate migration patterns.

Figure 10 shows some basic migration models derived for the example.

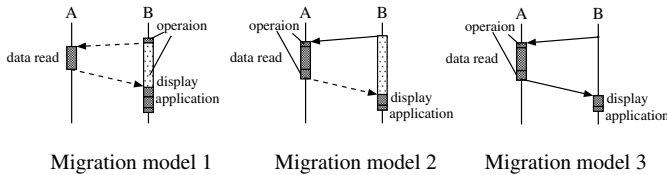


Fig. 10. Derived Basic Migration Model

5.2 Security Decision Phase

In this phase, we apply secure migration patterns to the migration model constructed by previous phase by using an access model and a confidentiality model.

In this paper, we define the security policy as follows. That is network is insecure when data which is sent through network is not open to the organization by which the network can be accessed, and a host is insecure when data which is used in the host is