Outdoor Evacuation Experiment Augmented by Massively Multiagent Simulation

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Abstract

The spread of mobile terminals like cellular phones and PDAs, and positioning systems like GPS, will realize a ubiquitous environment for city-dwellers. Ubiquitous/pervasive computing systems in the public space often interact with anonymous users. A large-scale evacuation navigation system, which is an example of socially embedded system, is selected as a target application in this research.

Any socially embedded system must be verified from the macro standpoint and the micro standpoint. The former is concerned with how efficient all citizens use system. The latter addresses how a citizen uses the system. Verification will be accurate only when the human subjects feel as if their environment is populated with an adequate number of participants. But it is quite difficult to conduct an experiment with a large number of human subjects. We build an environment for verifying a evacuation navigation system with a small number of human subjects.

The goal of this paper is to augment a real world experiments with multiagent simulation for testing socially embedded systems. An augmented environment for outdoor experiment consists of multiagent simulations, GPS-capable cellular phones and observation monitor. We conduct proving test and confirm that the environment can create a situation in which human subjects feel like they are participating with a large number of humans.

Augmented experiment enhances a real world experiment with multiagent simulation. The augmented experiment system lets human subjects perceive the results of the simulation performed in the virtual space concurrently with the real-world experiment. The human subjects are made to feel that they are participating with many other humans. This approach yields data comparable to that by performing real-world tests with a great many human subjects. In addition, comparing the movements of the human sub-

jects with those of the agents can enable us to refine the user models of the agents.

The following three issues are solved in order to augment real-world experiment with multiagent simulation for testing socially embedded system.

1. *Platform for massively multiagent simulation*

   Augmented experiments require the massively multiagent simulation for producing virtual users of a target system. Making a massively multiagent system work properly is difficult if only single agent is designed. Therefore, it becomes important to control agents by describing interaction protocols predicting agent interaction in a top-down scenario. In this research theme, we describe the architecture of a system that uses protocol descriptions to control hundreds of thousands of agents in order to realize a mega-scale multiagent simulation platform for executing simulation of city-scale crowds. We implement a system that based on proposed architecture and evaluate it.

   The system has three features. The one is separation of protocol design and agent development. The architecture realizes the separation of protocol design and agent development, which enables the experts of different domains to cooperatively and efficiently develop large-scale multiagent simulation system. The second is dynamic switching of protocols. By separating protocol processing system and agent internal models, experimenters can easily switch protocols according to the changing situations while running the simulation. The third is scalability. By implementing both protocol processing system and agent internal models in a large-scale agent server, scalability of the system is improved.

2. *Analysis of pedestrian navigation using cellular phones*

   To examine a design implication of the navigation system, it is necessary to investigate the information requirements of pedestrians when they use a navigation system. However, a developing navigation system cannot analyze with log data in a practical operation because the system has not installed yet. We conduct experiment with small groups of human subjects and analyze of the navigation system from the point of view of one user. We investigate the communication between them by conversation analysis method. In the navigation experiments in which a pedestrian reads a map on a GPS-capable cellular phone is guided by a distant navigator. We also examine the information required by pedestrians using the navigation system. The result indicates that pedestrians require information about the current location, the current direction and a proper route to a destination. We find that pedestrians and navigators often use maps as a basis of verbal navigation through navigator's knowledge with voice conversation. We also find that in the cases where pedestrians do not understand the surrounding environment, navigation sometimes fails due to the lack of communication basis.

3. *Augmentation of experiment in evacuation navigation*

   In this research, we built a framework of augmented experiment in evacuation guide system. We built the environment that show a virtual crowd to human subjects based on GPS-capable mobile phones and agent technology.

   The key point of the augmented experiment is how to provide the human subjects with a sufficient level of reality. The method of displaying virtual city for human subjects and the communication media between an experimenter and human subjects becomes crucial.

   We conducted evacuation navigation experiments in real space augmented by a large scale multiagent simulation, ensuring the feasibility and usefulness of augmented experiments. The interview of experiment shows that the augmented experiment successfully affects route selection of the participants.

The results of this research indicate that the environment of augmented experiment has feasibility and usefulness for analyzing the evacuation navigation system.

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Chapter 1

Introduction

1.1 Objectives

The spread of mobile terminals like cellular phones and PDAs, and positioning systems like GPS (global positioning system), will realize a ubiquitous environment for city-dwellers. Ubiquitous/pervasive computing systems in the public space often interact with anonymous users. A city-wide evacuation navigation system, for example, is a socially embedded system where a large number of users interact with each other.

Any socially embedded system must be verified from the macro standpoint and the micro standpoint. The former is concerned with whether all citizens can take action efficiently. The latter addresses how a citizen uses the system. Verification will be accurate only when the human subjects feel as if their environment is populated with an adequate number of participants. Unfortunately, real-world experiments with many people are too expensive and rather dangerous.

In this thesis, we realized a novel experimental environment that multiagent technology is applied to analyze a large-scale evacuation navigation system. The goal of this thesis is to augment a real world experiments with multiagent simulation for testing socially embedded systems.

A city-wide navigation system is selected as a target system for analysis. We build an experimental environment which consists of multiagent simulation and real world experiment. An experiment of evacuation navigation is conduct for ensuring the usefulness of the environment.

1.2 Approach

The Augmented Experiment was proposed to test large-scale ubiquitous computing systems [Ishida 07]. A real-world experiment with a small number of human subjects is enhanced by a large-scale multiagent simulation.

Figure 1.1 illustrates how an augmented experiment for a city-wide navigation system is realized. Virtual city information and real world information are mixed in the experiment. The augmented experiment for the navigation system proceeds as follows.

- A multiagent simulation is executed with user agents in a virtual space. The virtual space for multiagent simulation represent real world. Simultaneously, a real world experiment is conducted with human subjects.

- A user agent in the simulation sends its location to a navigation system, who wants navigation instructions, and receives a navigation map. The user agent determines his behavior considering the instructions and his situation in the virtual space.

- The human subject, on the other hand, sends his location to the navigation system and his position is projected into the virtual space. Avatars to represent human subjects are created corresponding of their location gathered by sensors. The navigation system sends navigation instructions and the status of the virtual space including positions of other evacuees to the subject. Human subjects feel as if they are participating together with a large number of humans.

- A monitor for the experimenter visualizes the experiment in real space enhanced by simulations in virtual space. The experimenter feels as if the experiment has adequate number of participants. The concept of observation monitor is based on transcendent communication. Transcendent communication is a new monitoring interface, where a visually simulated public space provides a more flexible view than regular surveillance systems [Nakanishi 04b].

The augmented experiment system lets human subjects perceive the results of the simulation performed in the virtual space concurrently with the

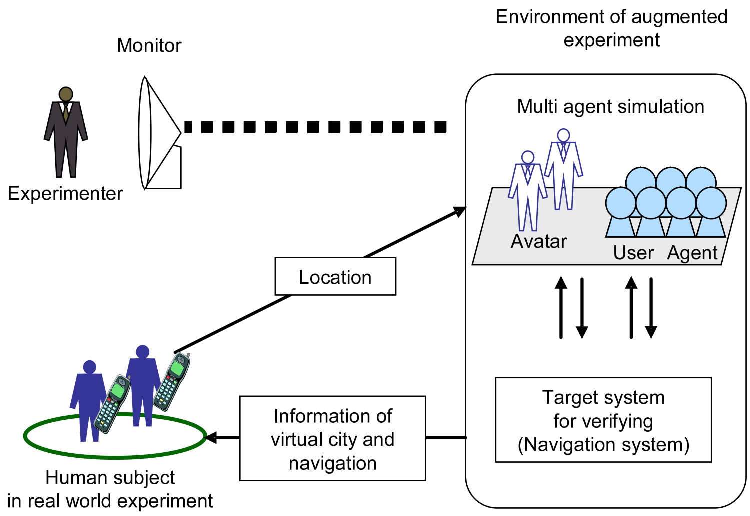


Figure 1.1: Augmented experiment for navigation system

real-world experiment. The human subjects are made to feel that they are participating with many other humans. This approach yields data comparable to that by performing real-world tests with a great many human subjects.

In addition, comparing the movements of the human subjects with those of the agents can enable us to refine the user models implemented into the agents. Even though the models can only capture a part of the variations possible in human behavior, the models is useful in educating people or testing system. A precise model which is acquired from the augmented experiments can reproduce more accurate multiagent simulations.

Participatory simulations are another method that allows the actions of human subjects in a virtual space to be extracted [Drogoul 02, Guyot 05]. Participatory simulations have been already studied intensively for modeling human societies. However, multiagent simulations cannot produce the reality of the actual application environment because the simulations conducted on a virtual space.

In a participatory simulation, some agents are replaced by human-controlled avatars. A participatory simulation is performed in virtual space, and the avatars are controlled by human subjects sitting in front of their computers. Participatory simulations are useful but it is sometimes fails to provide enough reality for testing of ubiquitous/pervasive computing environments. Because, the simulation is not conducted in the real world where the users act but in a virtual space. Reproducing user behaviors and environments in everyday life is difficult. Therefore real world experiments are often required to understand how users really respond to socially embedded systems.

In the case of a pedestrian navigation system, for example, it is essential to observe how individual users employ their navigation system in real space. In ubiquitous/pervasive computing, experiments with a large number of human subjects are required, but their costs become quite expensive.

The concept of augmented experiment is employed in this thesis. Augmented experiments provide the environment which can enhance experiment where just a small number of human participate with large scale multiagent simulations.

1.3 Issues

In this thesis, a large-scale evacuation guide system is treated as a good test of the augmented experiment approach. The precise specification is written in Chapter 4. In this system, guide agents, each of which is assigned to an evacuee in disaster areas, get locations of evacuees from their GPS-capable cellular phones. An agent is instructed on a direction of evacuation by a commander in a control center. The agent retrieve shelters around the user, and select a destination according to the ordered direction and distance between the user and each shelter.

The following three issues are solved to realize an experimental environment which augments an evacuation experiment with multiagent simulation. The relation of the three issues are showed in Figure 1.2

- **Platform for Massively Multiagent Simulation**
  Making a massively multiagent system work properly is difficult if only single agent is designed. Therefore, it becomes important to control agents by describing interaction protocols predicting agent interaction in a top-down scenario. In this thesis, "Protocol" refers to the interactions permitted between agents and the external world (other

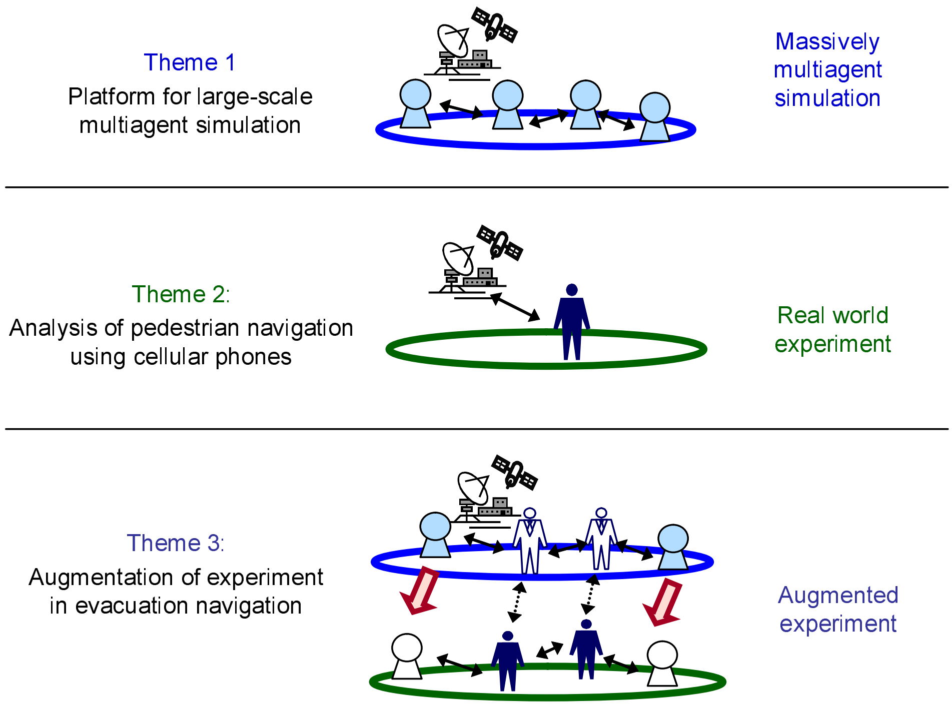


Figure 1.2: Structure of research theme

agents and the environment). We describe the construction of a system that uses protocol descriptions to control hundreds of thousands of agents in order to realize a mega-scale agent simulation about city-scale crowds.

To realize a massively multiagent system platform, we address the following three issues.

– *Separation of protocol design and agent development*
  In developing a mega-scale navigation system, experts of the intended domain (*e.g.* traffic or protection against disasters) will design the agent interaction protocols while computer experts will develop the agent system. If the agent platform forces the agent system developers to integrate agent internal models with protocol descriptions, the former must be significantly re-

vised, which is very expensive, if the protocol descriptions are changed. This shows that any truly practical development environment must separate protocol descriptions from the agent internal models.

  - *Dynamic protocol switching*
    In a simulation of large-scale social systems, each agent faces a variety of situations. A single protocol description to deal with all such situations may become large and complex. Instead, our architecture allows experimenters to dynamically switch protocol descriptions given to agents corresponding to the changing situations.
  - *Scalability*
    Most of existing protocol processing systems and agent systems are not designed with the management of a large number of agents in mind. To manage large-scale social simulations, systems have to control a large number of agents that model human behaviors. We achieve the scalability by applying large-scale agent server which is recently developed and works on event driven object models.

- **Analysis of Pedestrian Navigation using Cellular Phones**
  Some people may not be able to reach their destination even if they use navigation systems which provide guide maps according to the users' location. People who are not good at reading maps should ask others for help.

  A developing navigation system cannot analyze with log data which are results of practical operation because the system has not installed yet. We conduct experiment with small groups of human subjects and analyze of the navigation system from the point of view of one user. The human subjects participate in evacuation drill as using the navigation system. To demonstrate requirements of the guiding system, we address the following two issues.

  - *Analysis of information required by pedestrian*
    To examine a design implication of the guiding system, it is nec-

essary to investigate the information requirements of pedestrians when they use a navigation map.

  – *Analysis of communication between pedestrian and navigator*
    A pedestrian cannot be always guided into a proper route by a distant navigator. Investigation of failure cases is needed in order to examine the limitation of remote navigation. We analyze the communication between the pedestrian and the navigator using conversation analysis.

- **Augmented Experiment by Massively Multiagent Simulation**
  In developing such evacuation guide systems as socially embedded systems, it is necessary to estimate the user behavior in a crowd and the crowd behavior. However, it is difficult to perform tests on such a system given the large number of human subjects. We address the following two issues.

  – *Seamless connections between virtual and real spaces*
    The key point of the augmented experiment is how to provide the human subjects with a sufficient level of reality. To confirm the subjects naturally feels in real space. The method of displaying virtual city for human subjects and the communication media between an experimenter and human subjects becomes crucial. In this research, we built a framework of augmented experiment in evacuation guide system. We built the environment that show a virtual crowd to human subjects based on GPS-capable mobile phones and agent technology.

  – *Confirm feasibility and effectiveness in real world example*
    We conducted evacuation navigation experiments in real space augmented by a large scale multiagent simulation, ensuring the feasibility and usefulness of augmented experiments. The augmented experiment uses the proposed environment and let participants in a small experiment feel in a crowd.

1.4 Thesis Outline

This thesis consists of seven chapters, including this chapter as the introduction.

Chapter 2 is dedicated to introduce the background of this thesis and describe about execution process of multiagent simulation and usage of multiagent simulation. First, we will see construction process of social simulation and construction process with varied domain expert. Second, we will see usages of multiagent simulation in the field of artificial intelligence, sociology and traffic engineering and so on.

Chapter 3 describes a massively multiagent platform based on scenario description. This platform manages virtual user agents for augmented experiment. The proposed architecture has three features: separation of protocol design and agent development, dynamic protocol switching, and scalability.

Chapter 4 introduces the target system of the augmented experiment. We build large-scale personal evacuation system based on multiagent system as a typical example of socially embedded system. The navigation system is a multiagent system that assigns one guide agent to each human. In this system, an agent can provide personalized navigation instructions considering the human's characteristics, city-supplied evacuation targets, and the surrounding environment.

Chapter 5 describes analysis of the navigation system showed in the preceding chapter. The navigation system cannot analyze with log data which is result of practical operation because the system has not installed yet. We conduct experiment with small groups of human subjects and analyze of the navigation system from the point of view of one user. We examine the information requirements of pedestrians who use a navigation system with think aloud method. We also analyze the communication between the pedestrian and the navigator using conversation analysis. Conversation analysis is a methodology for studying social interaction.

Chapter 6 describes augmentation of experiment in evacuation navigation. Tow issues are shown. The one is how to realize seamless connections between virtual and real space. The second is to confirm the feasibility and usefulness of augmented experiments and to determine their future issues. We conduct an outdoor evacuation experiment augmented by a large scale multiagent simulation

Chapter 7 discusses about other experimental methodologies and concludes the thesis summarizing the result obtained through this research. We also address the prospect of the future research.

Chapter 2

Background

Conventional simulations are mostly based on top-down approach. The subjects of simulation are modeled from the macro standpoint and expressed in governing equations. However, such conventional simulations are inadequate to include interactions in modeling. On the other hand, multiagent simulations used in augmented experiment are bottom-up approach. The subjects of simulation are modeled from micro standpoint. An entity in the focused environment is modeled as an agent. Therefore multiagent simulations are adequate to include interactions in modeling. Agents are described as actors who could perceive environment through their sensor and act to environment with their actuator.

Many studies on multiagent simulation have been done in not only artificial intelligence but various fields, for example, politics, economics, marketing, traffic engineering, disaster management, and so on.

The following sections show execution process of multiagent simulation including those platform and applications of multiagent simulation.

2.1 Construction of Multiagent Simulation

2.1.1 Construction Process of Multiagent Simulation

Gilbert *et. al* summarized construction process of social simulation as five steps; 1) observation of target, 2) design of agent model, 3) execution of simulation, 4) verification, 5) validation [Gilbert 99]. Related works are introduced along these steps.

1. *Observation of target*
   The target is observed for modeling, and acquiring parameters and initial conditions as refer to literatures and theories of the target.

   Participatory technology has been used for getting precise models of humans as described in Section 2.2.1. Sempé *et al.* [Sempé 05] proposed how to acquire information that could explain a subject's behavior through dialogue with the subject's own agent during participatory simulations.

2. *Design of agent model*
   Conceptual model of agents are designed based on hypotheses. Generally, the model includes many complicated hypotheses when the purpose of the simulation is prediction, while the model includes simple hypotheses when the purpose is understanding the target system.

   The key technology to implement multiagent simulation is agent modeling. This is because collective phenomena emerge from the local behaviors of many agents; that is, the simulation result depends on each agent's micro-level behavior. But it is difficult to translating conceptual models into computational models.

   Agent models have been mostly constructed founded on KISS (Keep it Simple, Stupid) principle. For example, Balmer *et al.* execute simple traffic simulation uses simple driving model for reproducing traffic congestion of Switzerland [Balmer 04]. Izumi *et al.* examined the conditions under which evolutionary algorithms are appropriate for artificial market models [Izumi 04]. When factors which should be focused on are clear, KISS principle works well. But, if the factors are not clear, the KISS principle tends to have risk of over abstraction [Li 06].

   "Keep it Descriptive Stupid" (KIDS) are suggested as a new approach [Edmonds 04]. The KIDS approach requires simulation model that relates to the focused phenomena in the most natural way as possible. This approach is complete opposite of KISS approach. Edmonds *et al.* also points out importance of expert opinion for agent modeling.

The conceptual model constructed in previous step is transformed to a computer program before executing simulation.

3. *Execution of simulation*
   The experimenter executes simulation and records the results as setting various models and parameters.

   Sanchez *et al.* said methodology for simulation execution [Sanchez 06]. He point that the experimenters tend to execute simulation in a range which they are focused on. Such execution processes are not effective. Moreover the results lead to an erroneous conclusion.

4. *Verification*
   The simulation program is checked whether the simulation actually executed what is expected. We have to debug the simulator carefully using a set of test data which can easily expect the simulation result.

   Law *et al.* presents techniques for constructing valid and reliable simulation models [Law 06]. They discussed importance of a definitive problem formulation, discussions with domain experts, development of a written assumptions document, use of sensitivity analysis to determine important model factors, and comparison of model and system output data for an existing system. Their discussion is consistent with this simulation process as mentioned in [Gilbert 99].

5. *Validation*
   Experimenter validate whether the simulation can reproduce the phenomena in the observation. Validation of the simulation result is difficult when we predict future situation. We compare the output of the simulation with data gathered from real world. It is also necessary to check sensitivity of the model for parameter settings and initial conditions such as sensitivity analysis.

   In [Poile 06], Poile *et al.* claim the importance of the interpretation of simulation results. Results of multiagent simulation often validate with statistical method such as t-test, analysis of variance and so on. He point out the risk of abusing statistical analysis without a second thought. Edmonds *et al.* also note simple statistical measure is not suitable for multiagent simulations because it cannot describe structure consists of agents and their interactions [Edmonds 06].

Multiagent simulations have been applied various field. But, these researches verified their simulation programs and the results by each evaluation method. That is the reason why well-understood analysis has not defined yet. General criteria evaluating simulation results are required for applying multiagent simulations to various fields.

It is necessary to involve domain expert in construction process of multiagent simulation because their opinions are important for modeling target phenomena [Law 06], [Edmonds 04].

Dragoul *et al.* proposed construction process of multiagent simulation collaborating with thematician, modeler, computer scientist [Drogoul 02]. The design process consists of the three roles. In their proposed process, different three actors who will interact to produce a multiagent simulation as follow.

1. *Thematician*
   Thematicians defines a domain model and an intention of a simulation process. They describe theories and assumptions which define a set of rules or knowledge associated with the target domain. the parameters and initial conditions to the multiagent simulation are also provided by them. In other wards, the thematician formalizes micro knowledge into a domain model.

2. *Modeler*
   Modelers define a design model. The design models consist of formal refinement of domain model which defined by the thematicians. Its properties are extracted from concepts of target system; behavioral model, interactions, communications, type of environment and so on. The modeler translates domain knowledge described by the thematician into computational model which can be implemented by a computer scientist.

3. *Computer scientist*
   Computer scientists define operation models which can be calculated on a computer. They translate design model defined by the modelers

into computational agents and implement them in simulation environments. They are also due to provide a agent model that could allow for a discussion with the modelers.

The design process with scenario description language *Q* and interaction pattern card also evaluates as a construction process of multiagent simulation with varied domain expert [Ishida 02]. In the process, domain expert and system developer could develop a multiagent simulation concurrently because of common vocabulary defined by *Q* language [Murakami 03].

2.1.2 Platform for Multiagent Simulation

Implementing multiagent simulation system is hard task because it requires concurrent programming, GUI programming and large-scale calculations of the system developer. There are general-purpose multiagent simulation platform which decrease the development cost.

Swarm[1] is a platform for multiagent simulation including conceptual frameworks for designing and software which implement the frameworks. The main target of this platform is artificial life.

RePast[2] is a software framework for building multiagent simulations with Java language. It consists of useful class libraries, for example, a library for creating agent model, for running simulation, for displaying log data with 2D and 3D graphics, and for collecting log data of multiagent simulation.

CORMAS[3] is a multiagent simulation platform which is used to prove and to get better understanding the complex interactions between natural and social dynamics [Bousquet 98].

NetLogo[4] is a multiagent modeling platform [Sklar 07]. The user of NetLogo can model complex systems with thousands of interacting agents, and investigate the relation between the micro-level rules and the macro level emergent patterns. Agents on NetLogo are represented moving entities or stationary cells as in a cellular automaton.

[1] `http://www.swarm.org/`
[2] `http://repast.sourceforge.net/`
[3] `http://cormas.cirad.fr/`
[4] `http://ccl.northwestern.edu/netlogo/`

MASON[5] [Luke 03] is a fast discrete-event multiagent simulation library. The main focus of this simulation library is the foundation for large-scale multiagent simulations. MASON contains both a model library and an optional suite of visualization tools in 2D and 3D.

FreeWalk[6] [Nakanishi 04a] is a platform where human participants and autonomous characters can socially interact with one another in a virtual city space. The FreeWalk include 3D chat, multi-user training, and visual simulations. FreeWalk has used for reproducing real environments such as Kyoto city and Kyoto railway station and so on. Many users and many agents can interact with each other in FreeWalk so that it provides an environment of participatory simulation. Agent scenarios which describes how to interact with environment and other agents by Q Language[7] can control agents on the FreeWalk [Ishida 02].

There are multiagent platforms specialized to a particular domain, for example, traffic flow, rescue navigation and artificial market.

MATSim[8] [Balmer 04] provides a toolbox to create large-scale multi-agent based traffic simulations. MATSim provide a toolbox for demand-modeling, agent-based mobility-simulation (traffic flow simulation). MATSim consists of two layers; mental layer and physical layer. Agent on MATSim decides the route which achieves a task in the mental layer and decides how to drive on the route in the physical layer.

RoboCup Rescue[9] [Kitano 99, Takahashi 00] is a citywide rescue simulation platform. The platform simulates a city disasters and rescue planning after that. The simulation evaluates rescue strategies of firefighters who put out fire concertedly in complex environmental changes such as earth quake and fire diffusion.

U-Mart[10] is a set of artificial market software. It provides economists and computer scientists with an artificial market,and a multiagent simulation system of a financial market. The U-Mart consists of network-based and stand-alone artificial market, API and a wrapper program for development.

[5] `http://cs.gmu.edu/~eclab/projects/mason/`
[6] `http://www.ai.soc.i.kyoto-u.ac.jp/freewalk/`
[7] `http://www.ai.soc.i.kyoto-u.ac.jp/Q/`
[8] `http://www.matsim.org/`
[9] `http://www.robocuprescue.org/`
[10] `http://www.u-mart.org/html/`

Many users and many agents can participate in the market and interact with each other.

We also use agent servers for platforms of multiagent simulation. The multiagent system model is the effective model to design complex systems [Jennings 01]. Recently, massively multiagent systems are researched in order to develop applications which provide users with personalized services in ubiquitous environments [Sashima 04]. They research various methods to manage many agents efficiently [Rana 00, Helsinger 03].

There has been some research on large-scale multiagent platforms, for example, MACE3J [Gasser 02]. MACE3J is a Java-based multiagent simulation platform. This platform demonstrates a significant degree of scalability. Because the platform can run on multiprocessor workstations and in large multiprocessor cluster environments.

Caribbean[11] is also an agent server. It is developed to construct web applications providing users with services based on their personalities [Yamamoto 99, Yamamoto 01]. One agent is created as an event driven object on the Caribbean. An agent object has user's personal data. Caribbean has two features to realize scalability. The first is integration of data and method. An agent acts in single thread because the agent has not only data bat also method. The second is control of threads with high efficiency. The number of threads which a system can manage concurrently is limited. The thread scheduler of Caribbean assigns threads to only agents who become to activate. An agent implemented on event driven objects only consumes thread only if the agent needs to act.

2.2 Applications of Multiagent Simulation

2.2.1 Model Extraction

Multiagent simulation yields artificial societies that virtually reproduce human societies. Multiagent simulation seemed as an excellent tool for analyzing the real world. The key technology to conduct multiagent simulation is agent modeling.

For getting more precise models of humans and extracting human be-

[11] `http://www.alphaworks.ibm.com/tech/caribbean/`

havior, conventional methodology which stakeholders participate in a model construction process is RPG (Role Playing Game) such as board game and card game. But RPGs have faults; a lack of reality and a difficulty of complex experiment. These days, participatory simulations which stakeholders participate in simulation are proposed. Participatory simulations are applied for various domains, for example, evacuation simulation, market simulation, and negotiation simulation and so on.

In [Guyot 05], Guyot *et al.* design participatory simulations as multi-agent simulation with a domain model, a design model and an operation model. They conducted participatory simulation about coffee producers. They observed the emergence of specialized roles which were not included in the initial model.

Guyot *et al.* also aim to design interaction models by observing the emergence of power-relations and coalitions during participatory simulations [Guyot 06]. Observing the behavior of human players, the authors noticed the apparition of power relations between players. This paper also advocates the use of agent based participatory simulations to test and validate features of interaction protocols.

Murakami *et al.* aimed to extract human model of evacuation in the basement [Murakami 05]. They conduct participatory simulation and acquire a operation histories of avatar which controlled by participants on the simulation. This research proposed modeling process which extract each human subject's model from their each log data. Using these observation data and the domain knowledge including known operation rules, they generate an explanation for each behavior. Hypothetical reasoning is also applied to modeling, which offers consistent selection of hypotheses, to the generation of explanations.

INRETS's ARCHISIM projects also conducts participatory simulation for modeling driving behavior with a 3D driving simulator [Espie 99]. They claimed that using driving simulator particularly interesting for studying risky situations and road situations involving elements which do not yet exist.

2.2.2 Prediction and System Design

Multiagent simulations are used for reproducing virtual users so that system developers design and verify developing systems. The maturation of ubiquitous computing technology, it has become feasible to design new system to improve our urban life. Multiagent simulations are widely used to verify such systems.

Yamashita *et al.* proposed new car navigation system which shares information of route choices and verifies the system with multiagent simulation [Yamashita 05]. Noda *et al.* tested feasibility of demand bus system [Noda 04]. Dresner *et al.* proposed new traffic signal control system and confirm the efficiency by a multiagent simulation [Dresner 05]. The results of multiagent simulation are reliable if the user agent models for verifying each system are correct. But it is difficult to predict a complete user model for developing system.

To verify working system in the real world, there are some researches aimed at improving reproducibility of multiagent simulation with real time data [Fujimoto 06].

Hunter *et al.* study to create an accurate estimate of the changing state of transportation systems [Hunter 06]. They examine how well the simulation using real-time roadway data, which is aggregated at various update intervals; per one minute and per one hour and so on, reflects the real world transportation system.

Blikstein *et al.* also try to include real-world information into simulations using various sensors [Blikstein 06]. They demonstrate an integrated environment consist of the three fields; a software-based multiagent modeling platform on the computer, a participatory simulation environment equipped user interface for controlling avatar, and robots which can act as physical agents in the real world.

In artificial market simulation researches, daily market data is used for assuring reproducibility of the market [Hoffmann 06].

2.2.3 Interpretation of Social Phenomena

Multiagent simulations attract not only computer scientist but also various domain experts (*e.g.* [Dessalles 07, Kurahashi 05]) because they can model objects of analysis without costs of abstraction. Many social simulation researches also have been conducted in computer science (*e.g.* [Moyaux 04, Shinoda 07]).

Note that some multiagent simulations are not implemented as multiagent system where the agents have no autonomy, reactivity, and sociality. They only use concept of multiagent simulation.

Schillo *et al.* compare simulations founded on the concept of computer scientist and that of sociologist [Schillo 01]. They discuss about micro and macro terminology in sociology and distributed artificial intelligence. Similarities and differences in these viewpoints are described.

They apply the sociological notion of the micro and macro terminology for a discussion about the agent simulations in distributed artificial intelligence research. They aimed to transfer of sociologically founded concepts to agent-based social simulation. They discuss following four points.

1. *Mechanism design is macro level design*
   Mechanism design is belong to macro level in distributed artificial intelligence community. Mechanism design is coordination of actions of individuals to achieve global or some group social benefit. However, sociologists would not agree that mechanism design is macro level design, unless there is structure or dynamics in the system that goes beyond the single interaction.

2. *Macro level behavior is emergent behavior*
   Result that is not defined preliminarily is called emergent behavior. However, all unexpected behavior in macro level is not emergent behavior.

3. *Value aggregation is an analysis of macro phenomena*
   In current distributed artificial intelligence research, the macro perspective means to values which are aggregated from the individuals focus on numerical parameters like score, speed, number of communication acts, voting results and so on. On the other hand, sociological approach on the macro level focuses on more complex structures or dynamics.

4. *Populations of artificial agents are artificial societies*
   A multiagent simulation tends to include intention of the simulation

designer, which are many assumptions about human behavior, the user's goals, and desires. Thus observed phenomena in the multiagent simulation would not only be caused by artificial actors, but also by the intentions of the simulation designer. In this sense, sociologist would not consider that population of artificial agents is artificial society.

Chapter 3

Platform for Large-Scale Multiagent Simulation

Augmented experiments required the massively multiagent simulation for producing virtual users of a targeting system. This chapter describes a massively multiagent platform based on scenario description in order to realize a mega-scale agent simulation about city-scale crowds [Nakajima 06].

3.1 Introduction

In developing as evacuation navigation system and car navigation system such socially embedded systems, it is necessary to estimate the influence and the movement of its users and to get feedback. However, it is difficult to perform tests on such a system given the large number of human subjects involved and its scale, which matches that of a major city. One possible solution is proposed herein, the augmented experiment; it combines a massively multiagent simulation with a small-scale experiment performed with human subjects.

Making a massively multiagent system work properly is difficult if only single agent is designed. Therefore, it becomes important to control agents by describing interaction protocols predicting agent interaction in a top-down scenario. In this thesis, "Protocol" refers to the interactions permitted between agents and the external world (other agents and the environment).

In this chapter, we describe the construction of a system that uses protocol descriptions to control hundreds of thousands of agents in order to realize a massively multiagent platform targeting simulation of city-scale crowds.

To realize a massively multiagent simulation platform, we address the following three issues.

- **Separation of protocol design and agent development**
  In developing a large-scale multiagent simulation system, experts of the intended domain (*e.g.* traffic or protection against disasters) will design the agent interaction protocols while computer experts will develop the agent system. If the agent platform forces the agent system developers to integrate agent internal models with protocol descriptions, the former must be significantly revised, which is very expensive, if the protocol descriptions are changed. This shows that any truly practical development environment must separate protocol descriptions from the agent internal models.

- **Dynamic protocol switching**
  In large-scale social simulations, each agent faces a variety of situations. A single protocol description to deal with all such situations may become large and complex. Instead, our architecture allows experimenters to dynamically switch protocol descriptions given to agents corresponding to the changing situations.

- **Scalability**
  Most of existing protocol processing systems and agent systems are not designed with the management of a large number of agents in mind. To manage large-scale social simulations, systems have to control a large number of agents that model human behaviors. We achieve the scalability by applying large-scale agent server which is recently developed and works on event driven object models.

Section 3.2 explains the architecture we adopted for our platform and clarifies our approach to the realization of the massively multiagent platform. In Sections 3.3 and 3.4, we describe the implementation of a platform consisting of the scenario description language *Q* and the large-scale multiagent server Caribbean with *Q* scenario translator. In Section 3.5, we describe the evaluation of the platform.

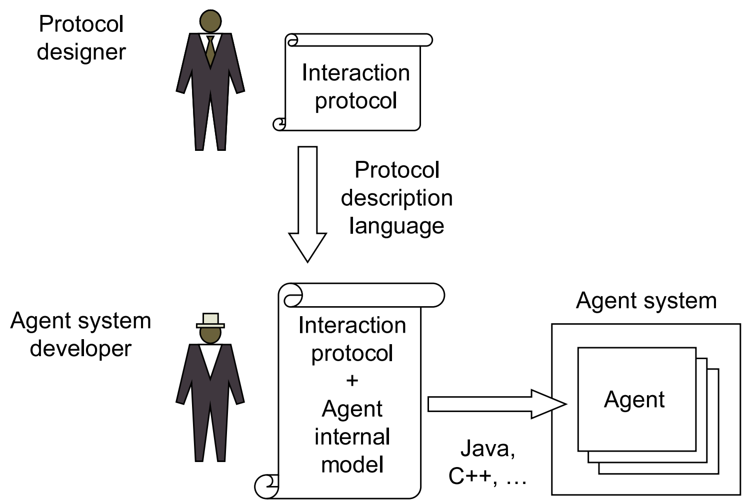


Figure 3.1: Both protocol and internal model are implemented in each agent

3.2 Architecture

There are two possible types for the mechanism to control agents by giving designed protocols. One of them is the one shown in Figure 3.1, where protocol description and agent internal model are implemented together into an agent. The other is shown in Figure 3.2, where an external protocol processing system controls agent internal model.

In the approach shown in Figure 3.1, the developer of the agent system implements an agent by integrating the protocol description, which is given in an inexcusable language such as AgentUML [Odell 00], and the agent internal model. In this method where both the protocol description and the agent internal model are implemented in a single agent, the agent implementer has to absorb the knowledge of domain experts first, and then reflects their ideas to agent implementation, which is not efficient. Also, it is hard to switch the protocol according to the changing situations during the operation.

In contrast, the approach shown in Figure 3.2, the protocol description is given in an executable protocol description language, and an external protocol interpreter interprets it and controls the agent internal model. In this

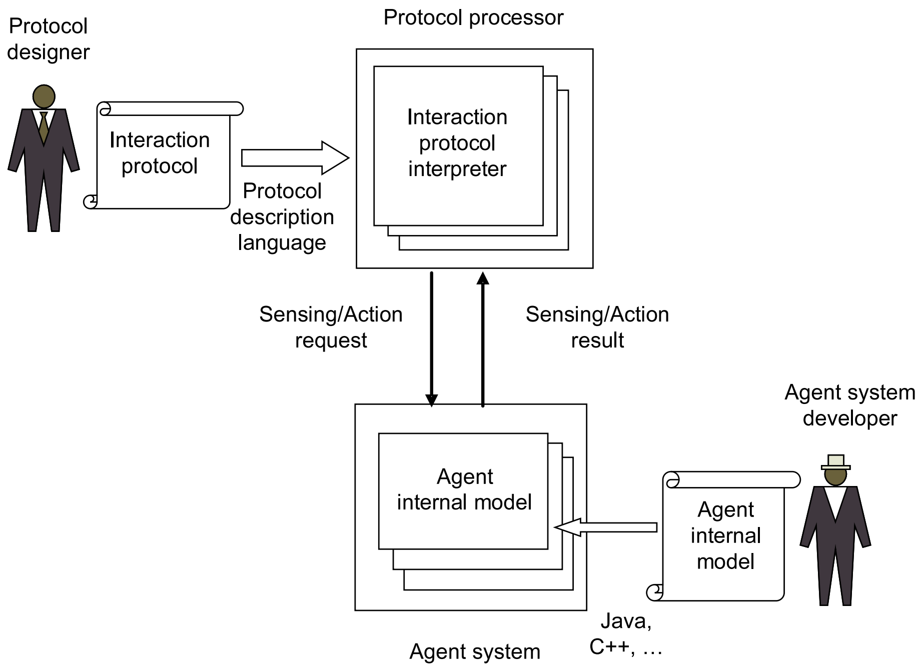


Figure 3.2: External protocol interpreter controls agent system

approach, domain experts can directly design protocols without considering the internal implementation of agents. Thus, domain experts and agent implementers can independently develop a multiagent system.

In this research, we propose an architecture shown in Figure 3.3 that extends the one given Figure 3.2 by implementing both protocol interpreters and agent internal models on a large-scale agent server to achieve scalability. A large-scale agent server can manage hundred-thousands of agents by keeping agents as objects and by allocating threads to those objects appropriately. As an example of such large-scale agent servers, we describe Caribbean [Yamamoto 01] in the following section.

Since the protocol description and the agent development are separated in this approach as in Figure 3.3, protocol designers can change protocols without knowing the detail of agent implementation. The protocol interpreter requests the execution of sensing and actions in the protocol given

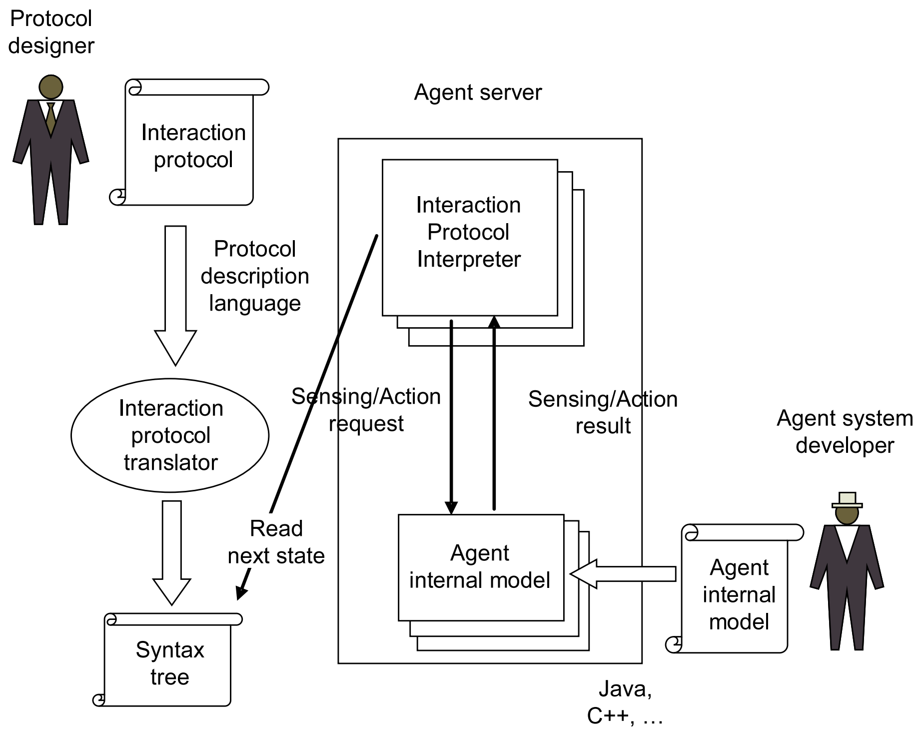


Figure 3.3: Protocol interpreter on agent system controls agent

to agents and receives the result, which enables the dynamic switching of protocols given to agents.

Our architecture is aimed at realizing the separation of the protocol design and agent the development, which enables the experts of different domains to cooperatively and efficiently develop large-scale multiagent system. Our technique removes the communication bottleneck shown in Figure 3.2. Furthermore, we achieve separation of protocol design and agent development because we let protocol interpreters send only sensing event/action requests to agent internal models and receive the results of these requests from the models.

There has been some research on large-scale multiagent platforms, for example, MACE3J [Gasser 02] and RoboCup Rescue [Takahashi 00].

MACE3J has distributed architecture so that it accrues scalability. But, agent internal models do not separate from protocol descriptions in this platform unlike with proposed architecture. RoboCup Rescue is a specialized simulator for wide area disaster simulation. On the other hand, proposed architecture be aimed at general multiagent system. This architecture realizes development environment which separate protocol descriptions from the agent internal models for multiple domain expert.

3.3 Fundamental Technology

We have combined a scenario description language and a large-scale agent server to build a platform for large-scale multiagent system. We describe the two technologies precisely below.

3.3.1 Scenario Description Language *Q*

Q is an interaction design language that describes how an agent should behave and interact with its environment including humans and other agents. For details see [Ishida 02]. In modeling human actions, it has been shown that the *Q* approach, describing the interaction protocol as a scenario, is more effective than alternative agent description methods that simply describe the appearance of a human being [Murakami 03, Murakami 05]. They view interaction models as behavioral guidelines of human users playing with socially embedded systems; users keep autonomy within the given guidelines.

To control agents, this architecture separates agent models from interaction models: the former covers the beliefs, desires, intentions, and emotions of human users, and the latter covers protocols, methods, rules, or laws that guide users when interacting with the socially embedded systems.

The features of the *Q* are summarized as follows.

- *Cues and Actions*
  An event that triggers interaction is called a cue. Cues are used to request agents to observe their environment. A cue has no impact on the external world. Cues keep waiting for the event specified until the observation is completed successfully. Actions, on the other hand, are

used to request agents to change their environment. Cue descriptions begin with “?” while action descriptions begin with “!”.

- *Scenarios*
  Guarded commands are introduced for the case wherein we need to observe multiple cues in parallel. A guarded command combines cues and actions. After one of the cues becomes true, the corresponding action is performed. A scenario is used for describing state transitions, where each state is defined as a guarded command.

- *Agents and Avatars*
  Agents, avatars and a crowd of agents can be defined. An agent is defined by a scenario that specifies what the agent is to do. Avatars are controlled by humans so they do not need any scenario. However, avatars can have scenarios if it is necessary to constrain their behavior. In addition, a tool called Interaction Pattern Card (IPC) is introduced into *Q* to support scenario descriptions. Even computer novices can easily describe scenarios using this tool.

Following steps, which refers to the process of [Murakami 03] are defined as creating multiagent simulation process for the proposed platform.

- *Step1: Defining a vocabulary*
  In the first step, cues and actions in the target domain are defined. The scenario writer describes scenarios and a system developer implements the vocabulary into simulator.

- *Step2: Describing scenarios*
  In the second step, scenario writer describe the scenarios required for the simulation by analyzing target system.

- *Step3: Extracting interaction patterns*
  In the third step, scenario writer extract interaction patterns and pool interaction pattern with IPC card.

- *Step4: Execute simulation*
  In the last step, the scenario writer conducts simulation.

3.3.2 Agent Server Caribbean

Caribbean is a large-scale agent server implemented in Java language.

Caribbean manages agents as objects. There are two types of objects in Caribbean, *service objects* and *event driven objects*. Objects in Caribbean communicate with each other using Caribbean messaging facility. Service objects can be run at any time and are used for implementing such modules as databases with common information which are frequently accessed. In contrast, event driven objects runs only when they receive messages from other objects. Caribbean scheduler allocates threads to event driven objects based on messages. Usual modules in a system on Caribbean are implemented as this type of objects.

Caribbean limits the number of objects in the memory and controls the consumption of the memory, by swapping objects between the memories the auxiliary store. When the number of objects on memory exceeds a limit, Caribbean moves the objects that are not processing messages to the auxiliary store. When objects in the auxiliary store receive messages from other objects, Caribbean swaps them into the memory to process the messages. By performing these swapping efficiently, Caribbean manages a large number of agents that cannot be stored in the system memory at once.

3.4 Implementation

3.4.1 Structure of Caribbean/*Q*

We build a scalable multiagent platform that realizes the separation of protocol design and agent development and the dynamic switching of scenarios by applying the proposed architecture. We developed a large-scale multiagent platform, Caribbean/*Q*, by combining scenario description language *Q* and large-scale agent server Caribbean based of the proposed architecture. Figure 3.4 depicts the outline of the system. A *Q* scenario describes an interaction protocol between an agent and the outer world.

The conventional interpreter of *Q* language is implemented in Scheme and the interpreter is attached agent system externally. It supposed that the interpreter is not scalable due to interprocess communication as mentioned in Figure 3.2 . New *Q* interpreter is required which can take advantage of the

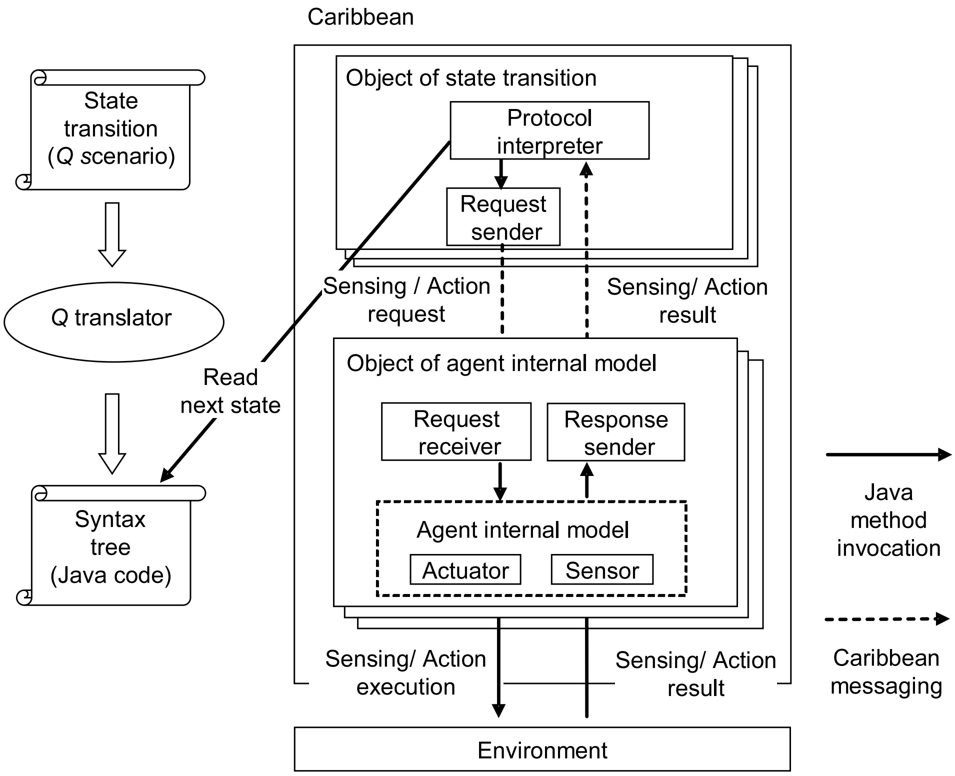


Figure 3.4: Overview of Caribbean/*Q*

scalability of Caribbean. Our approach is implementing scenario interpreter on agent server as described in Figure 3.3.

In order to execute *Q* scenarios on Caribbean, we build *Q* translator which exchange *Q* scenarios into a syntax tree object in Java. A scenario interpreter on Caribbean executes the converted syntax tree stepwise. Conventional interpreter uses interprocess communication among a agent internal model and a scenario, while the scenario interpreter on Caribbean uses messaging in the same application on JVM (java virtual machine) among of them. Thus, the proposed architecture is able to maintain the scalability of Caribbean.

3.4.2 Scenario Execution

Protocol interpreters and agent internal models are implemented as event driven Caribbean objects. An example of translating *Q* scenario into a syntax tree with *Q* translator is shown in Figure 3.5. Caribbean/*Q* executes the syntax tree as follows.

Step 1 One state transition object is generated for each agent internal model object. Message exchange starts between the state transition object and the agent internal model object, when the multiagent system requires a state transition object to start a scenario.

Step 2 An agent internal model object invokes a method of the state machine to get an execution request. The state machine object parses a syntax tree describing its scenario expressed by *QScenarioNode*. The state transition object moves to first *QSceneNode*.

QScenarioNode consists of *QSceneNodes*. A *QSceneNode* represents a state of *Q* scenario and it includes *QGuardNode* or *QCueHandlerNode*.

Step 3 The state machine parses the tree and returns an execution request to the agent. The state machine reads an executable node such as *QGuardNode* or *QCueNode*, it returns a sensing request of them. The request includes a name of the command and values of arguments.

QGuardNode shows a guarded command which is the parallel sensing of cue. *QGuardNode* has *QCueHandlerNodes* as child node.

A *QCueHandlerNode* consists of *QCueNode* and *QSequenceNode*. When a *cue* indicated by a *QCueNode* is observed, the corresponding sequence described by *QSequenceNode* is executed.

Step 4 The agent internal model executes its method according to the content of the received sensing request indicated by *QCueNode* and the agent observes the environment. When the *cue* is a passive *cue*, which means the agent has to wait until the event notification message is delivered, the agent sets a cueing flag and waits for the message.

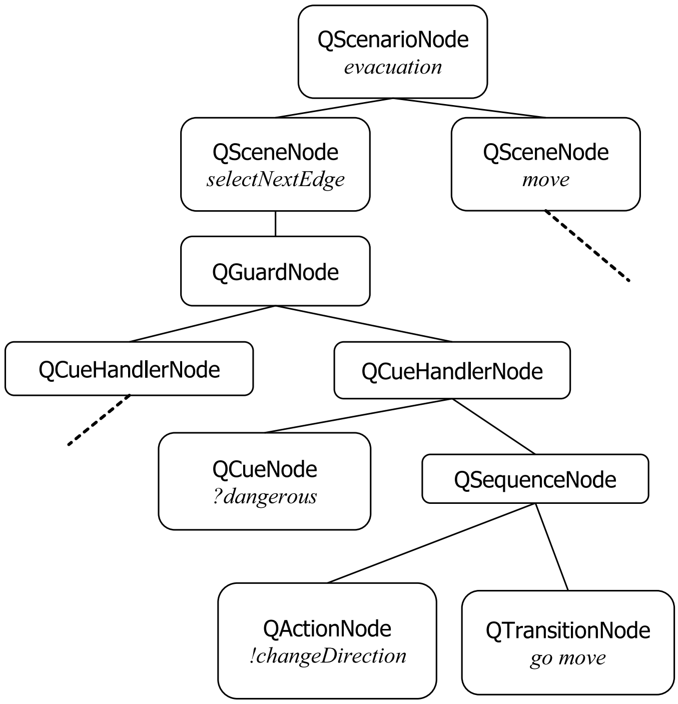


Figure 3.5: Translate *Q* scenario into syntax tree with *Q* translator

When the *cue* is active *cue*, which means the agent finishes observation immediately by checking the environment, the agent executes the method to observe and gets the result.

QCueNode has a command name of sensing environment and arguments of the command.

Step 5 The agent internal model returns the result of sensing to the state transition machine object.

Step 6 The state machine sends an action sequence included *QSequenceNode* according to observed *cue*.

QSequenceNode consists of an action sequence expressed as *QActionNodes* and a next state to transition indicated by *QTransitionNode*.

Step 7 The agent internal model object executes the actions described by *QActionNodes* and return the results.

QActionNode has a command name of effecting environment and arguments of the command.

Step 8 The state machine reads a transition node described by *QTransitionNode* and the state transits to the next state indicated by *QSceneNode*. The process goes back to Step 3.

QTransitionNode expressed a scene to transit next.

In summary, this system carries out a *Q* scenario by repeating the following process. At first, a state transition object sends an execution request (cues/actions) to an agent internal model agent as a Caribbean message. Next, the agent internal model object observes the cue from the environment (or performs the action on the environment) and notifies the result to the state transition object as a Caribbean message. Finally, the informed state transition object reads the syntax tree converted by *Q* translator and changes to the next state.

State transition objects have only two operations. One is sending a request message (cues/actions) to an agent internal model object. The other is receiving a completion message from the agent internal model object. In other words, an agent system developer can freely describe agent internal model agents within the constraints of sending and receiving Caribbean messages.

An agent internal model object that receives a request message from a state transition object is forced to reply with a Caribbean message upon completion of the cue observation or action execution. After this, these objects which have been in a condition to wait for the result don't get busy till receive the notification message. This improves the scalability of the system because it is not necessary to assign a thread to idle objects.

3.5 Evaluation

In this section, by comparing Caribbean/*Q* and an implementation where the original *Q* system is externally attached to control Caribbean, we validate the improvement in scalability. The computer used in the following experiment has Xeon 3.06GHz dual core processors and 4GB memory, which is enough to keep all the Caribbean objects on memory.

The performance of Caribbean/*Q* system is also evaluated. We compare the performance of the original Caribbean system and that of the Caribbean/*Q* system to evaluate the trade off between the two merits of Caribbean/*Q* (the separation of protocol description and agent development, and the dynamic switching of protocols) and system performance.

3.5.1 Trade off between Caribbean and Caribbean/*Q*

We examine the trade-off between scenario description and performance with comparing processing time of Caribbean and that of Caribbean/*Q*.

Original Caribbean requires implementing data and method which belong to an agent on one event driven object as for achieving high performance processing and scalability. On the other hand, Caribbean/*Q* characterized by our proposed architecture separate between protocol description and agent model in order to parallel development and protocol dynamic switching. There is a trade-off between the two benefits and message increasing.

An agent on original Caribbean requires to one messaging for the agent perform one action. While an agent on Caribbean/*Q* requires to four messaging to act because it sends message of sensing request, sensing result, action request, and action result.

P which is ration of the time for processing one action by Caribbean and Caribbean/*Q* is expressed the following equation.

$$P = \frac{4m+s+a}{m+s+a} = \frac{4+\frac{s+a}{m}}{1+\frac{s+a}{m}} \tag{3.1}$$

In the equation 3.1, m means average processing time of Caribbean message, s means that of sensing and a means that of action.

```
(defscenario scenario ()
  (scene1
    ((?receive) (!send) (go scene1))))
```

Table 3.1: Scenario for evaluation

3.5.2 Performance in Simple Case

For evaluation from other view, to test the performance that Caribbean/*Q* allocates scenarios to agents, the simple scenarios showed on Table 3.1 with simple cues and actions are used. In complex scenarios, the number of states and the number of parallel observed cues increases. The increase in the number of states does not affect the throughput, since a state transition corresponds to a single edge in the syntax tree. The increase in the number of parallel observed cues does not affect the performance either, since it only increases the number of patterns that shows the names of cues returned from agent internal model objects.

Figure 3.6 is shown the system structures for evaluation. (a) is ordinal Caribbean, (b) is existing *Q* interpreter and Caribbean, and (c) is Caribbean/*Q*. In this experiment, action counters are used to confirm that all the agents execute an action before they go to the next states, in order to guarantee that each agent executes the uniform number of cues and actions and to avoid situations where only a small set of agents run.

The chart in Figure 3.7 shows the relationship between the number of agents and the processing time for the each agent to execute one action.

The management of more than thousand agents failed in the implementation where the original *Q* interpreter is just attached externally to the original Caribbean system as shown in Figure 3.7.

In contrast, Caribbean/*Q* successfully managed 1,000,000 agents. The increase in the number of agents does not affect the time to process an action, which means the time to process the whole system is proportional only to the cues and the actions executed.

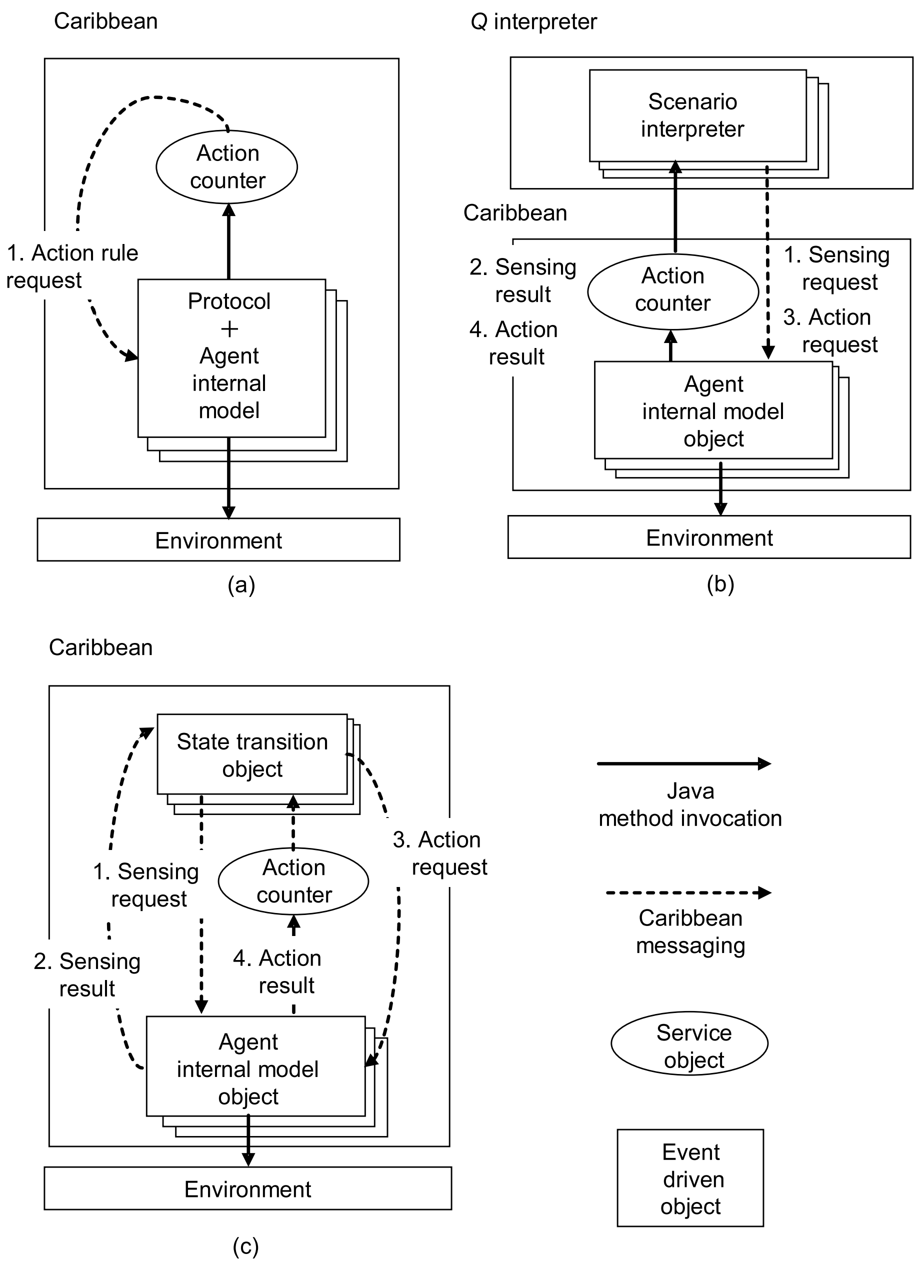


Figure 3.6: System structure for evaluation

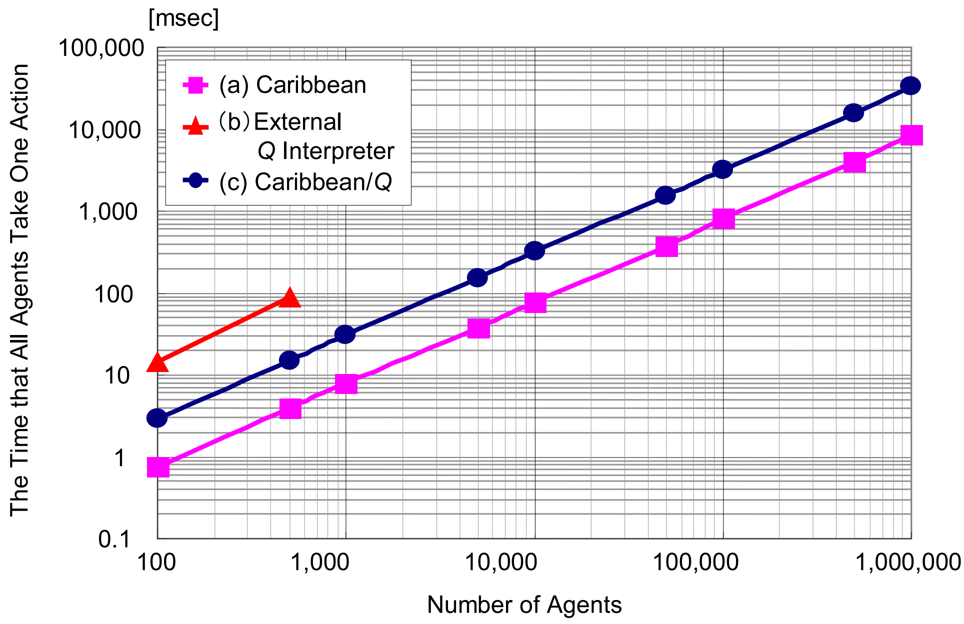


Figure 3.7: Evaluation of performance of Caribbean/*Q*

Figure 3.7 shows Caribbean/*Q* spend fourfold time than that of Caribbean. Because a agent of Caribbean requires one messaging to perform one action while Caribbean/*Q* needs four messaging to act because it send message of sensing request, sensing result, action request and action result. The original Caribbean system requires that the data and the functions of an agent are implemented to a single event driven object. In contrast, the implementation of an agent in Caribbean/*Q* is divided into two objects, a state machine object and an agent internal model object, to separate protocol description and agent internal model and to switch protocols dynamically. This demonstrates that there is a trade-off between the two merits in developing multiagent systems and the performance. This result agrees with the equation in previous section.

$s+a$ in the example scenario is smaller than that of a multiagent simulation, because sensing and actions are quite simpler than that of a multiagent simulation. In a multiagent simulation which produces virtual users, $s+a$ become bigger than example scenario and the overhead of message become

```
(defscenario evacuation ()
 (wait ((?notifiedStart) (go evacuate))
       ((?instructed) (go instructed)))
 (instructed ((?straggle) (!changeDirection) (go wait))
             (otherwise (go wait)))
 (evacuate ((?dangerous) (!changeDirection) (go move))
           ((?backShelter) (!changeDirection) (go move))
           (otherwise (go move)))
 (move ((?arriveShelter) (!finishEvacuation))
       ((?finishMove) (!finishMove) (go wait))
       ((?endEdge) (go select))
       (otherwise (!move) (go move)))
 (select ((?nearDamage) (!avoidDamage) (go move))
         ((?nearShelter) (!approachShelter) (go move))
         ((?directed) (!followDirection) (go move))
         (otherwise (!randomSelect) (go move))))
```

Figure 3.8: Scenario for an evacuation agent

smaller than fourfold.

3.5.3 Performance in Practical Case

We examine the performance of Caribbean/*Q* in a practical case. We produced a virtual large-scale evacuation simulation for confirming the effectiveness of Caribbean/*Q*. In the simulation, users agent of a navigation system evacuate in a virtual disaster city. The agents are controlled by the scenario which is shown in Figure 3.8.

About Ten thousands of simulation agents on the multiagent platform can perform one action per one second in this simulation. Processing time of action and sensing ($s+a$) is about $4m$ in the simulation and the performance ratio (P) become about 1.37.

In this prototype, evacuee agents are given a simple uniform scenario. In future works, more complex evacuation simulation is provided by giving more variety of scenarios. Such scenarios will include ones that reflect social roles, such as firemen and police, individual contexts, such as injury, and so on.

3.6 Conclusion

We have proposed architecture for large-scale multiagent platform. We implemented a system that based on this architecture, evaluated it, and gave a sample application.

The problems we tackled in this work is as follows.

- **Separation of protocol design and agent development**
  The one is separation of protocol design and agent development. The architecture realizes the separation of protocol design and agent development, which enables the experts of different domains to cooperatively and efficiently develop large-scale multiagent simulation system.

- **Dynamic switching of protocols**
  The second is dynamic switching of protocols. By separating protocol processing system and agent internal models, experimenters can easily switch protocols according to the changing situations while running the simulation.

- **Scalability**
  The third is scalability. To execute large-scale social simulations such as evacuees on the metropolis, simulation platforms have to control a large number of agents that model human behaviors. By implementing both protocol processing system and agent internal models in a large-scale agent server, scalability of the system is improved.

The result of experiments shows that the Caribbean/*Q* system successfully manages 1,000,000 agents. However, to build more practical system, the speeding up is still necessary. To achieve it, technologies to distribute among multiple computers and to perform parallel are necessary. Besides the issue, we plan to study visualization methods of large-scale simulation system.

In this chapter, we build the massively multiagent simulation platform. This platform is used for producing virtual users of a socially embedded system in augmented experiment.

Chapter 4

Large-Scale Evacuation Navigation System

The purpose of this thesis is testing socially embedded system as evacuation navigation system with augmented experiment which can mix human subjects and software agents. We introduce a large-scale evacuation navigation system as the target of the augmented experiment [Nakajima 08].

4.1 Introduction

The ubiquitous environment extends which includes mobile terminals like cellular phones and PDAs, and positioning systems like GPS. Using this environment, we can build a large-scale navigation system (mega-scale navigation system) like traffic control or evacuation navigation for any particular city. Current systems simply broadcast the same instructions over a large area, but what is needed is a system that can provide individualized instructions to each person. Our approach is to build a multiagent system that assigns one guide agent to each human. In this system, an agent can provide personalized navigation instructions considering the human's characteristics, city-supplied evacuation targets, and the surrounding environment.

The system commander assigns an evacuation destination and evacuation direction through the control interface. The commander issues high level instructions to the guide agents using a map and the guide agents as-

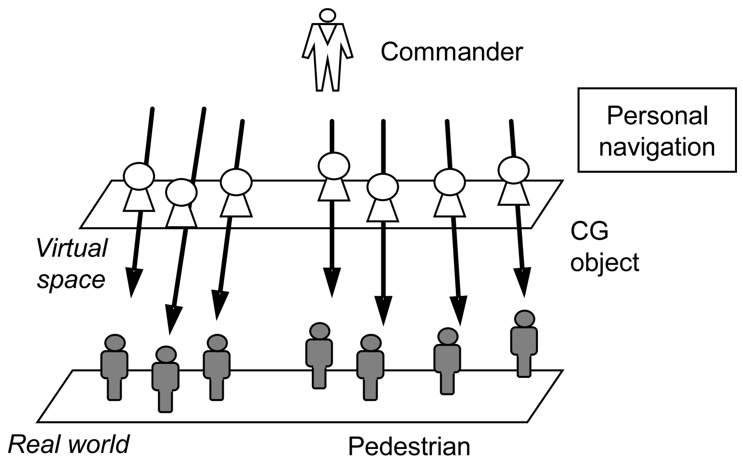


Figure 4.1: Personal navigation based on transcendent communication

signed to the evacuees on a one-to-one basis provide individual navigation instructions. Guide agents give information to evacuees via GPS-capable cellular phones.

4.2 Personal Navigation based on Transcendent Communication and Guide Agents

Transcendent communication is proposed as the method for navigation in public spaces [Nakanishi 04b]. In transcendent communication, the distribution of evacuees in the real space is reproduced on the virtual space as CG object of human figures that mirror the positions of evacuees; the positions of the subjects are acquired by sensors (Figure 4.1). Commander can grasp the users' behavior via bird-eyes view and sends navigation to each user with voice message or e-mail. Transcendent interface enables the commander to recognize wide area information and to create personal communication channel to each user. Experiments in the Kyoto station demonstrate the effectiveness of transcendent communication [Ito 06, Ito 07].

Current navigation systems simply broadcast the same instructions over

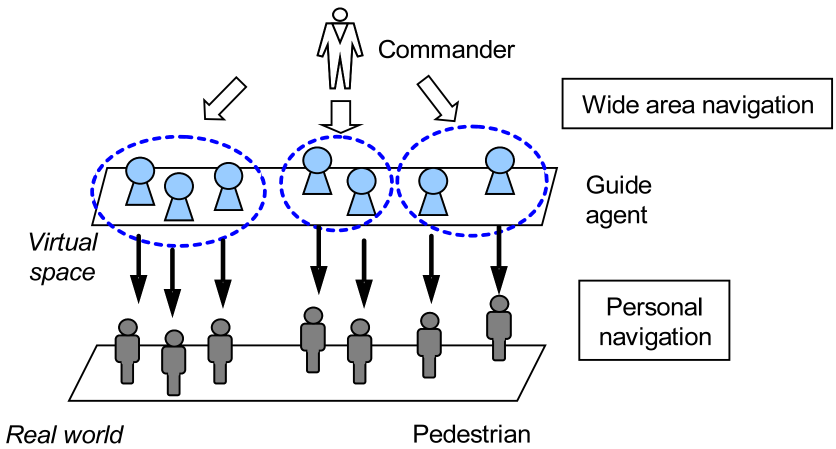


Figure 4.2: Personal navigation based on transcendent communication and guide agents

a large area, the required function is to provide individualized instructions to each user. But it is difficult for a commander to guide a large number of users personally. This navigation system is based on multiagent system which assigns one guide agent to each user. In the system, the human commander gives rough instructions to guide agents. A guide agent can create individualized navigation instructions depending on each owner's surrounding circumstance (Figure 4.2).

The control interface has a function to provide just the direction to the shelter to many evacuees at the same time. In order to provide the instructions, the commander specifies the group of guide agents corresponding with evacuees in the real world with drawing a rectangle, and points out the direction to agents within the rectangle. After obtaining the rough instruction from the commander, guide agents calculate a route to a shelter from their assigned evacuee's position consider for their surrounding environments and their personal properties.

We extend the transcendent communication for realizing the approach which uses personal guide agents. We replaced the CG objects, which are only used for reproducing locations of evacuees, with guide agents and let them support the navigator.

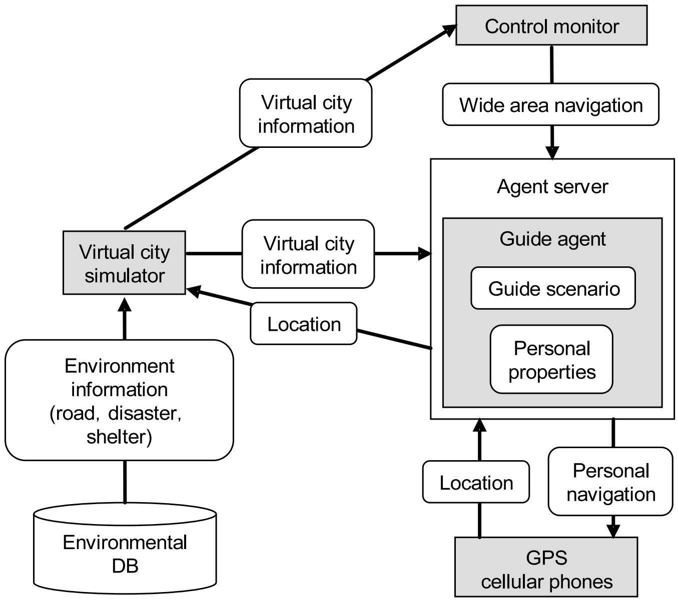


Figure 4.3: Architecture of large-scale personal navigation system

4.3 Implementation

We produced a large-scale evacuation navigation system to use a target of augmented experiment. The navigation system featuring transcendent communication is implemented founded on a massively multiagent platform and GPS-capable cellular phones. The architecture of the navigation system is displayed on Figure 4.3.

In a guidance system which uses ubiquitous information infrastructure on a city, the system can acquire information of each individual user in real time. However, the quantity of the information becomes enormous. There occurs a problem that a human who controls system cannot handle all the information. In the navigation system, a commander gives rough navigation to agents and the agents give precise navigation to each person.

4.3.1 Navigation Process with Navigator and Guide Agents

In a large scale disaster, the commander should not be trying to provide detailed instructions to each evacuee. The solution for the commander is to group evacuees in certain areas and to send rough instructions to the guide agents as shown in Figure 4.4. However, such rough instructions can't provide enough information to the evacuees. Therefore, the guide agents acquire the rough instructions from the commander and send personalized navigation to their users by interpreting it as shown in the figure.

A guide agent sends a surrounding map centered on the user's location upon receiving location information from the user's GPS-capable cellular phone. The map shows locations of dangerous sites such as fires, shelters to evacuate to, and the direction of destination. The user can send his location and get a new map whenever he wants to.

The commander tells the guide agents the direction to be taken to evacuate through the control interface. The interface provides a complete map of the disaster area so that the commander can discern the current locations of all evacuees. The commander can also assign evacuation sites, set places of shelters, and record the information about dangers such as fires.

This system places geographical information of the disaster area into the virtual space by accessing a database holding numerical maps (1/25000) issued by the Geographical Survey Institute[1]. Evacuation guides and disaster situations that are entered through the control interface are recorded in this database at regular intervals.

Figure 4.4 shows a sample navigation process for guiding evacuee to a shelter. A commander guides evacuees as following process.

1. The commander selects wide area with drawing a rectangle and issues high level instruction with drawing a arrow.

2. The guide agents get the instruction from the commander and generate personal navigation map around the corresponding evacuees considering their properties.

[1] `http://www.gsi.go.jp/kiban/`

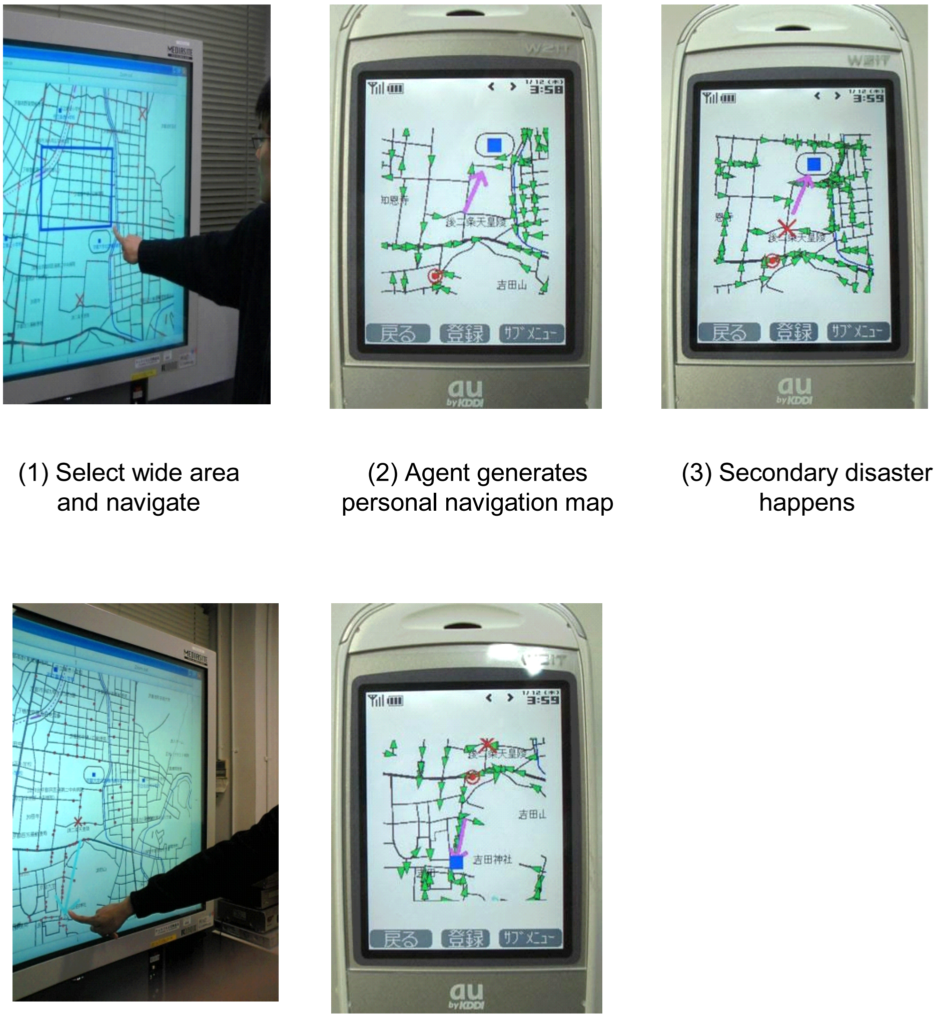
3. When a secondary disaster happens, the guide agent sends the information to the evacuee with drawing an x-mark. The commander changes the evacuation policy and navigates to another shelter.

4. The guide agent recalculates the path to the changed shelter after receiving the instruction from the commander.

4.3.2 Control Interface

The commander instructs the guide agents the direction to evacuate through the control interface. In the interface, the map of a wide area is displayed so that the commander views the current locations of evacuees. The commander can also assign evacuation sites, set places of shelters, and record the information about dangers such as fires.

On control interface, the distribution of people in the real space is reproduced on the virtual space with human figures based on positions of people acquired with sensors. The state of the virtual space is displayed on the monitor of the control center, so that the commander can widely grasp how people move in the real world through the virtual space of the bird-eye view. In addition, the commander can instruct particular people by handling human figures on the screen. The system can notify the people who register their phone numbers or e-mail addresses preliminarily. Due to this transcendent interface, it is possible to grasp situations of all people with global view and provide local navigation with consideration of global coordination.



(1) Select wide area and navigate

(2) Agent generates personal navigation map

(3) Secondary disaster happens

(4) Change destination

(5) Agent recalculates destination

Figure 4.4: Navigation process by a commander and guide agents

4.3.3 Guide Agents

Guide agents provide individual navigation instructions to each evacuee using information of the evacuee's position, navigation targets set by the commander, and the environmental situation. They get information of dangerous sites and shelters from the environment database. These functions are implemented as functions of guide agents.

The guide agents of this system are implemented as extensions of the event-driven object of Caribbean/*Q*. The behavior of the agents is given as the *Q* scenario. *Q* scenarios are described as finite state machine which is combination of cue (sensing) and action. The functions of navigation are defined as actions described in Table 4.1 and the triggers of action are defined as cues showed in Table 4.2. The guide agents navigate each users considering the *Q* scenario.

The navigation scenario assigned the guide agents as follows.

- A guide agent sends a navigation map according to a user's location when it receives location information from a user's GPS capable mobile phone. On this map, locations of dangerous areas such as fires, locations of shelter to evacuate to, and a direction to the nearest shelter are displayed. Users send their location and get a new map whenever they need.

- Guide agents retrieve shelters around the user and choose a destination considering for the distance and the situation of users. For example, the guide agent navigates to a nearest hospital when the user is wounded or the guide agent lead to nearest shelter when the user is well-being.

- Guide agents share access information with agents of family which is preliminarily registered. The agent who receives information from other family's agent notifies the corresponding user of the access information about his family.

Table 4.1: *Actions* of guide agent

Action Name	Description
!responseEvacuationMap	Send a map to a user as a response to a user's request with a location
!notifyAccess	Notify agents of family of a user's access
!sendFamilyMap	Notify a user of a family access with a map
!sendFamilyText	Notify a user of a family access with text
!sendEvacuationMap	Send a map with location of damage to a user
!sendMessage	Send a message from the control center to a user
!sendNavigationMap	Send a map with new destination to a user
!finishNavigation	Finish an navigation

Table 4.2: *Cues* of guide agent

Cue Name	Description
?requestPosition	Observe a request with location information from a user
?notifiedAccess	Observe an access notification message from a family agent
?notifiedDamage	Observe a damage notification message
?notifiedShelter	Observe a shelter addition message
?notifiedDirection	Observe a direction instruction message
?notifiedMessage	Observe a text message from the control center
?nearDamage	Check if a damage area is on the route
?nearFamily	Check if a family is near
?changeDirection	Check if it is necessary to change a destination
?arriveShelter	Check if a user has arrived at a shelter

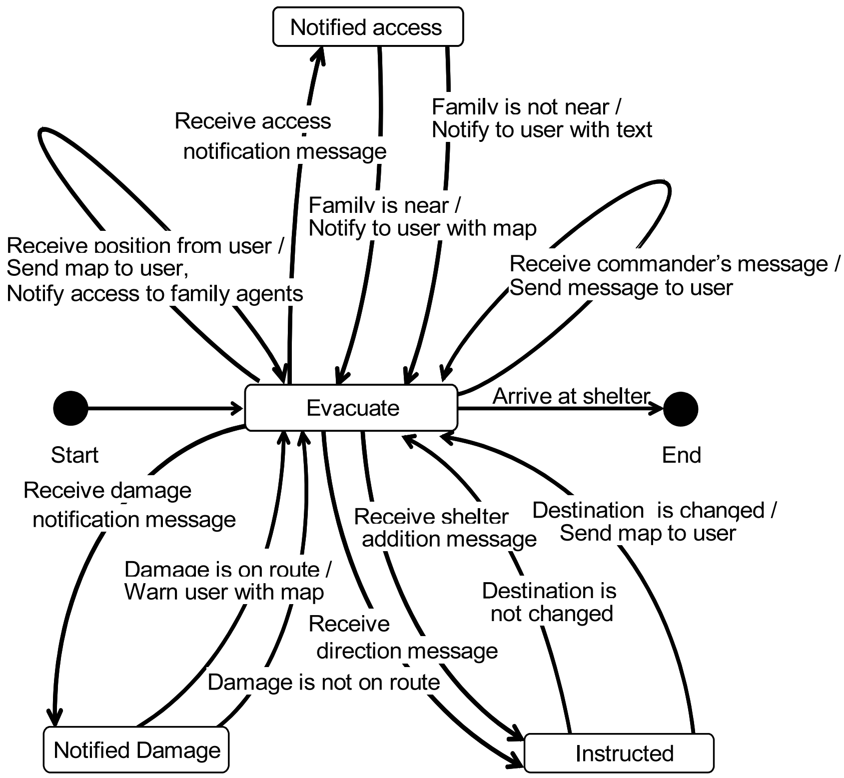


Figure 4.5: Example of navigation scenario for family man

- A guide agent alerts its user with a map which includes the location of the damage when new disaster information is registered. If the path becomes dangerous, the agent recalculates to safer path to shelters

An evacuation navigation scenario for people having family is shown in Figure 4.5 as an example. When the agent is informed that the family members of the handling user accesses the navigation system (Notified Access), and the family members are near the user (?nearFamily), the agent calculates nearest shelter from all the family members and sends navigation map (!sendFamilyMap).

4.4 Conclusion

We implemented a city-wide evacuation guide system using GPS-capable cellular phones based on massively multiagent system. The system has two features; First, the scalability to use for the evacuation in the metropolis, second, the utilization of multiagent to decompose and individualize the rough indication. An agent is instructed on a direction of evacuation by the control center. The agent retrieves shelters around the user, and selects a destination according to the ordered direction and distance between the user and each shelter. If a destination is changed by instructions, the agent notifies the user.

The purpose of this thesis is testing such socially embedded system as this system. It is hard to conduct an experiment that a large number of people actually evacuate in Kyoto city. Our approach is augmented experiment which can mix human subjects and software agents in the real world experiment in order to virtually simulate evacuation under the large scale disaster. The experiment is described in Chapter 6.

Chapter 5

Analysis of Pedestrian Navigation using Cellular Phones

The target system for augmented experiment is introduced in the previous chapter. The navigation system cannot analyze with log data which is result of practical operation because the system has not installed yet. We conduct experiment with small groups of human subjects and analyze of the navigation system from the point of view of one user [Nakajima 09].

5.1 Introduction

Traveling in an unfamiliar city is a daily task for ordinary people. For instance, they look for meeting spots or shops in unfamiliar cities. These days, more and more pedestrians use cellular phones as information sources for route guidance. Pedestrians use cellular phones in two ways as information sources. One is displaying a map showing the current location, and the other is consulting with a distant navigator via voice conversations.

Due to the popularity of and improvement in sensor devices and network devices, environments that support ubiquitous computing are spreading. In such environments, it is possible to provide personal navigation that suits the properties, the location and the context of each user [Koyanagi 04]. We built evacuation navigation system based on multiagent server, which assigns one guide agent to each human. In this system, an agent can provide a personalized navigation map considering the current location and the surrounding environment [Ishida 04].

Some people may not be able to reach their destination even if they use such navigation systems. People who are not good at reading maps should ask others for help. We conduct experiments where pedestrians take part in evacuation drill with the evacuation navigation system. To demonstrate requirements of the guide agent, we address the following two issues.

- **Analysis of information required by pedestrian**
  To examine a design implication of the guide agent, it is necessary to investigate the information requirements of pedestrians when they use a navigation map.

- **Analysis of communication between pedestrian and navigator**
  A pedestrian cannot be always guided into a proper route by a distant navigator. Investigation of failure cases is needed in order to examine the limitation of remote navigation. We analyze the communication between the pedestrian and the navigator using conversation analysis. Conversation analysis is a methodology for studying social interaction. It was principally developed by Harvey Sacks and Emanuel Schegloff [Sacks 74].

Section 5.2 shows the overview of focused system. Section 5.3 shows and discusses the experiment about support information for traversing. Section 5.4 shows and discusses the experiment for observing communication between a pedestrian and a navigator. Section 5.5 shows the design implication of guide agents founded on the result of the experiments.

5.2 Large-Scale Evacuation Navigation System

We produced a large-scale evacuation guide system based on large scale agent platform and GPS-capable cellular phones. Figure 5.1 depicts system architecture of pedestrian navigation system [Nakajima 08]. In a navigation system which uses ubiquitous information infrastructure on a city, the system can acquire information of each individual user in real time. However, quantity of the information becomes enormous. There occurs a problem that

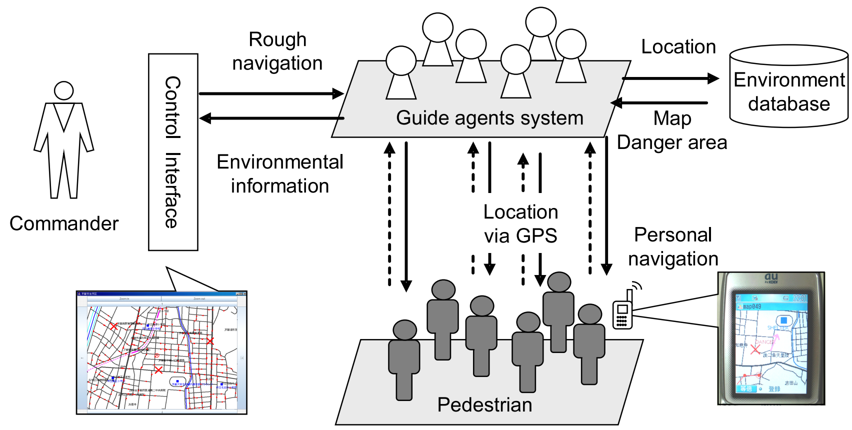


Figure 5.1: Large-scale evacuation guide system with guide agents

a human who controls system cannot handle all the information. Our approach is that a human gives rough navigation to agents and the agents give precise navigation to each person. This system aims at realizing a mega-scale navigation using GPS-capable cellular phones.

The control interface is implemented based on transcendent communication architecture. Transcendent communication is proposed as the method for navigation in public spaces [Nakanishi 04b]. In transcendent communication, the distribution of evacuees in the real space is reproduced on the virtual space as human figures that mirror the positions of evacuees; the positions of the subjects are acquired by sensors. The system commander assigns evacuation destinations and evacuation directions through the control interface shown in Figure 5.1. The commander issues high level instructions to the guide agents using a map.

The guide agents that assigned to evacuees on a one-to-one basis provide individual navigation maps via GPS-capable cellular phones. An agent is instructed on a direction of evacuation by the control center. The agent retrieves shelters around the user, and selects a destination according to the ordered direction and distance between the user and each shelter. The agent also obtains the surrounding environmental data from a database. Then, the agent sends the personalized navigation map showing a destination, the direction, impassible point, the current location and the movement history

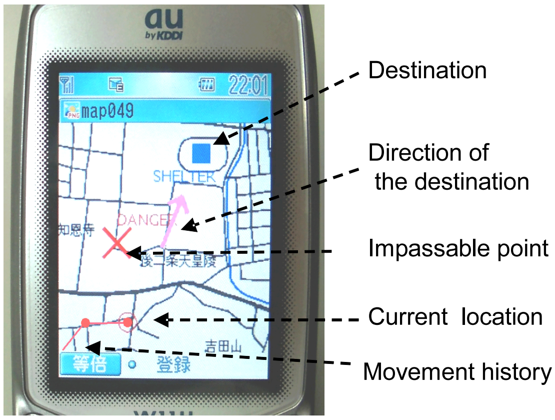


Figure 5.2: Navigation map on cellular phone

as indicated on Figure 5.2.

5.3 Analysis of Support Information for Traveling

We conduct two navigation experiments in which pedestrians evacuate with the large-scale evacuation navigation system. These experiments have two purposes. One is to investigate the information required by pedestrians, and the other is to analyze communication between the pedestrian and the remote navigator. May *et al.* already examined information requirements in an experiment of navigation based on turn-by-turn strategy [May 03]. However the human subjects did not take along a map showing the current location in the research.

5.3.1 Overview of Experiment

The main function of the guide agents is sending support information for approaching to goal. Providing navigation map based on the current location of a user is typical method in these days. Therefore, in following experiment, we analyze what kind of information is required by a pedestrians who

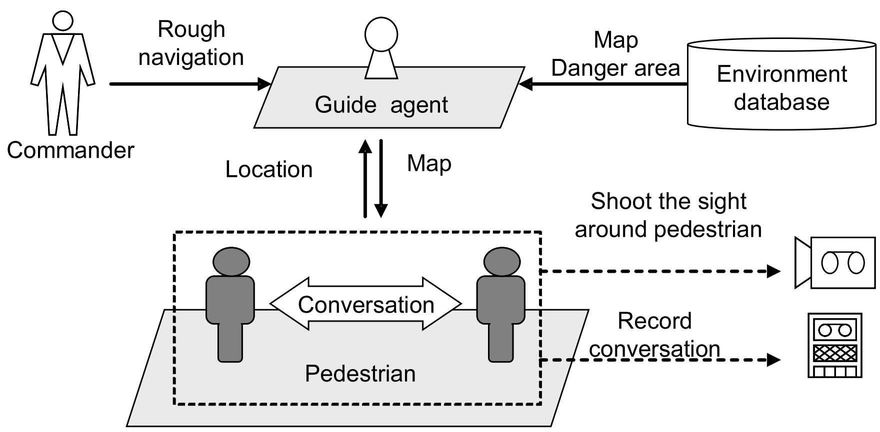


Figure 5.3: Experiment 1: observation of conversation between pedestrians

traveling in a city.

We conducted experiment for observation of conversation between pedestrians. The pedestrians used navigation system which provided a map as Figure 5.2. In the first experiment, we let human subjects to use system in pairs and instructed them to talk to each other (Figure 5.3, Figure 5.4). We refer to this experiment as *Experiment 1*.

In Experiment 1, pairs of pedestrians left start points and headed for destination points. They consulted a map showing the current location on a cellular phone and talked to each other on their travel. In Experiment 1, pedestrians were expected to discuss any questions and problems with the partner.

5.3.2 Scenario of Experiment

We assumed the scenario that a huge earthquake struck around Kyoto University and dwellers escaped to shelters using navigation system through GPS-capable cellular phones. We chose an evacuation drill as scenario for the reason that pedestrians must choose their route carefully and more depended on the system than usual. We preliminarily set disaster points and subsequently added secondary disaster points during the experiment in order to make route selection difficult and to make pedestrians behave carefully.

Figure 5.4: Subjects participating for experiment with think aloud method

The direct distance from a start to a destination in the experiment was about 1.5 km. Figure5.5 shows a course of Experiment 1. A red circle shows a start point and a blue rectangle shows a goal point. The x-marks indicate there are impassible points.

The number of human subjects participated as pedestrians were four. All of them were students and unfamiliar with the testing area. Additionally, they had no experience using the evacuation navigation system. In Experiment 1, the pedestrians performed the task in pairs so that we gathered two groups of data.

Pedestrians were expected to be aware of the necessity to select routes carefully and to be encouraged to voice what they were thinking in these experiments. To ensure it, we gave the instructions below to the human subjects in the experiments; “This is an evacuation drill. Pedestrians are expected to act carefully and to commit themselves to reach shelters in safety”, “Disaster points are impassable so that pedestrians must avoid them”.

Figure 5.5: A area of Experiment 1

5.3.3 Setting of Experiment

We analyzed the information requirements with *think aloud method* [Ericsson 80] which was to observe what human subjects behave and thought. The method has actually been applied to experiments in navigation systems. In the method, an experimenter instructs human subjects to think aloud while performing tasks. The experimenter observes the human subjects' behavior and thinking at the same time. The experimenter can combine human subjects' behavior with their feelings about the system which they have in mind.

Think aloud method has been used in many experiments on system evaluation such as usability testing. In the meanwhile, there is also a problem that it is too unnatural for the subjects to voice what they are thinking continuously. In such outdoor experiment, the subjects are to perform already complicated tasks. They have to use the system and pay attention to the environment around, in addition to thinking aloud. Thus, it becomes difficult letting the subject to voice what they are thinking. In this experiment, we let the subjects talk with each other while using the system instead of thinking

A: ((The corner to turn is)) here? What do you think about that?
B: Further, isn't it further? Because it is still
A: What? But it ((= map)) has not reloaded yet.
B: I see.

Table 5.1: Conversation about current location

aloud, so that we could observe what they were thinking properly.

In Experiment 1, a cameraman followed a pair of pedestrians and shot their behaviors with a video camera. We recorded speeches of the pedestrians with attached microphones and transmitted them to the video camera by Bluetooth audio transmitters.

In order to analyze the relation between the conversation and the behavior, we needed to gather actions, speeches and eye sights of human subjects. Following three data were collected; 1) recordings of the conversations between pedestrians, 2) video pictures of the behavior of pedestrians, 3) video pictures of the sight pedestrians have seen. The two speeches are recorded separately on the two audio channels of the camera. We collected the two pedestrians' behaviors and speeches at the same time.

5.3.4 Result of Experiment

Conversations about questions, confirmations and trouble were extracted from pedestrians' speeches and transcribed. These transcripts were categorized according to pedestrian's intentions or pedestrian's demands. The result showed that the pedestrians required information about the current location, the current direction and a proper route to a destination. The information was used to confirm and trust a route as well as decide it. The information required by pedestrians are categorized into the following three types.

We describe the details about the three kinds of information with the transcripts that actually observed in the experiment. In the following transcripts, a phrase bracketed by '(())' means a supplement by us.

- *Current location*

A: So, ((should we read the map)) in this direction? ((Should we go)) in this way? B: This way. A: Is this OK? B: eh? A: ((We should read this map)) in this direction, don't you? Yes, yes, because we are walking this way now. B: This way, this way, it's bad to read the map as it is. A: Yes, it is.

Table 5.2: Conversation about current direction

A: Which route? This one? B: How about downside? ((See the road heading southward)) this way? A: I agree. Because the danger zone exists over there, this way is better.

Table 5.3: Conversation about route selection

In Table 5.1 case, pedestrians could not have the confidence in correspondence between a map and the real world. Such cases were frequently observed when pedestrians could not recognize the corner that they had decided to turn as reading a map in advance.

- *Current direction*
  In Table 5.2 case, pedestrians could not understand a map properly because of losing sense of direction. Sense of direction was important for understanding maps.

- *Proper route toward destination*
  In Table 5.3 case, pedestrians were not only aware of the current location and the current direction but also read the map properly. However they had no concrete idea which route was optimal.

5.4 Analysis of Communication between Pedestrian and Navigator

In the second experiment, pedestrians used the navigation system and consulted with distant navigators via voice conversations (Figure 5.6). We instructed pedestrians to talk to navigators anytime they had a question. We call this experiment as *Experiment 2*.

In Experiment 2, a cameraman followed a pedestrian and shot his behavior with a video camera as in the case of Experiment 1. Maps provided to pedestrians and navigation screens were recorded by DV video recorder. Conversations between the pedestrian and the navigator were also recorded with call-recording microphone. After the experiments, the graphic data was synchronized with the voice data.

In Experiment 2, the pedestrians performed the task alone so that we gathered four groups of data.

5.4.1 Overview of Experiment

Pedestrians traveling on a city use three information resource [N.Shingaki 98]. The first is "support information" like a map provided by navigation system. The second is "surrounding environment" such as roads, rivers, buildings and so on. The last is "other person", for example, a remote navigator who is familiar with target areas. Therefore, a pedestrian who cannot approach to goal watching "surrounding environment" and "support information" would rely on "other person" who is far from the pedestrian.

In the following experiment, we analyzed communication between pedestrians and navigators with conversation analysis [Sacks 74] for improving guide agent to provide navigation information as "other person".

In Experiment 2, pedestrians had two cellular phones so that they could consult with a distant navigator with reading a navigation map. When they had any questions or any troubles, they could consult the navigator to solve it. In Experiment 2, pedestrians were expected to ask a navigator any questions and problems they had. The navigator was familiar with the test area and had practiced remote guidance for pedestrians.

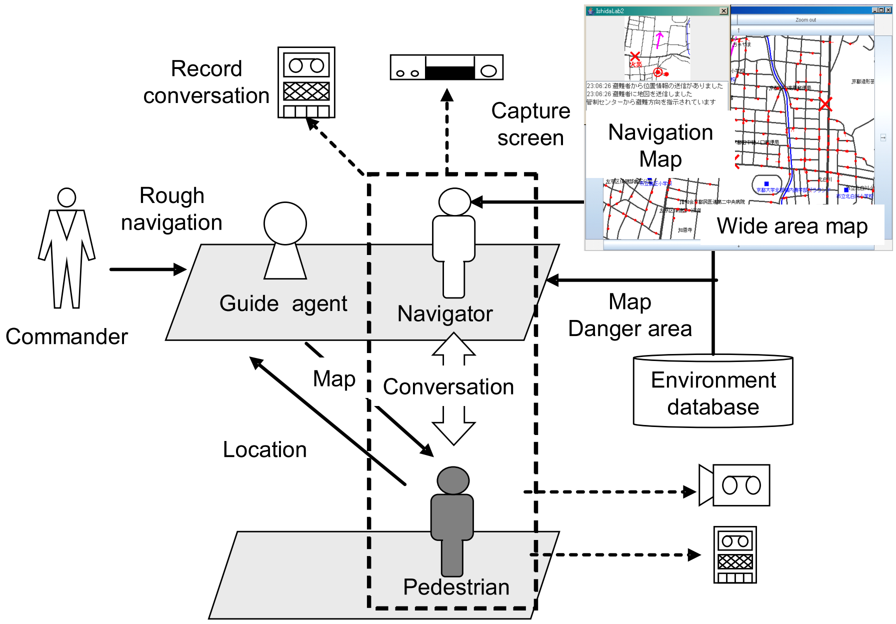


Figure 5.6: Experiment 2: observation of conversation between pedestrian and navigator

5.4.2 Setting of Experiment

In Experiment 2, the task of a navigator was to answer questions from a pedestrian. The navigator was expected to make the maximum efforts to answer any questions from a pedestrian. The navigator should use information on the navigation system sufficiently. An information screen for a navigator is shown in Figure 5.6. A navigator could view environmental information about the target area, the current locations of pedestrians, and a map provided to a pedestrian. Considering those information, the navigator guided the pedestrian via voice conversation. The navigator answered the questions consulting a screen of the navigation system.

Experimenters who were familiar with the experimental area acted as navigators. Additionally they had practiced guiding pedestrians beforehand. They guided pedestrians one-on-one in the experiment. A navigator must not speak to a pedestrian voluntarily. The purpose of the experiment was to

1 P: Did I pass over the corner to turn?
2 N: Let [me see::
3 P: [I should turn slightly behind, [right?
4 N: [Yes, at the previous cross point
5 N: [Do you remember?
6 P: ((Stop walking)) [Oh::,
7 P: ((Pedestrian turn back)) crossing, oh, cross point?
8 (0.8)
9 N: Yes. Ah, just now, (0.5) well, (1.9) just,
10 N: (0.8) Let see:, now, can you see a cross point now?
11 P: ((Look around)) now, cross point, ((see backward))
12 N: Narrow road, [I suppose.
13 P: [No, I can't. Eh, should I turn back?
14 (0.6)
15 N: Well, [Yes, [Turn back.
16 P: [Ah, [Oh,
17 P: Did I pass over (.) long?
18 N: Yes, that's right.

Table 5.4: Navigation based on pedestrian's movement history

analyze how a pedestrian extract helpful information from a remote navigator.

5.4.3 Result of Experiment

In this section, we analyzed the interaction between pedestrians and navigators in Experiment 2 in the term of the communication basis.

We describe the details about the conversations with the transcripts that actually observed in the experiment. In the following transcripts, 'P:' means an utterance of a pedestrian and 'N:' means an utterance of a navigator. Number in parentheses indicates elapsed time in silence by tenth of seconds and a dot in parentheses indicates a tiny gap within or between utterances. A phrase bracketed by '()' means unclear speech. A phrase bracketed by '(())' means a supplement by us. The plural sentences started with '[' means that

1 P: Does this bold black line mean this big (.) street?
2 N: Yes.
3 (3.3)
4 P: ((turn right)) We:[ll,
5 N: [If you go straight,
6 (0.4)
7 P: Yes.
8 N: Well, fire [disaster, you will face the fire disaster,
9 P: [Do you mean fire disaster?
10 P: I see.
11 N: Go, (.) slightly leftward.
12 P: OK.

Table 5.5: Navigation based on navigation maps

they are started at the same time. ':' shows sounds are stretched or drawn out (number of : indicates the length of stretching). ',' means continuing intonation. '?' means rising intonation and '.' means closing or stopping intonation.

Table 5.4 shows a success case of verbal navigation, in which a pedestrian communicated a navigator based on a movement history. The pedestrian wondered if she had passed the corner to turn by mistake. She confirmed with the navigator whether she had passed the corner (see line 1). The navigator answered yes and tried to navigate the pedestrian to a proper route in the response (line 4 or later). In this successful case, the navigator attempted to guide the pedestrian with the words such as "slightly behind" and "previous cross point". These instructions were based on the pedestrian's movement history. The instructions helped the pedestrian to recognize the proper route despite lack of direction sense.

Table 5.5 shows a transcript of information sharing based on a navigation map. First, the pedestrian asked the question "Does this bold black line mean this big street?" (see line 1). This question implied that the pedestrian believed to read the same map as the navigators. The navigator said "Go slightly leftward" (line 11) for guiding the pedestrian. The word "leftward" did not indicate "left side of the body (=eastward)" but "left side of the map

1 ((Pedestrian stops just after departure and ask the route to navigator))
2 P: Now, which direction ((to go))? (0.5)
Should I turn at first, leaving the park?
3 (1.6)
4 N: Well:, Can you see a road (.) heading southward straight?
5 P: ((Starts walking)) Southward, ((look around)) ((turn back))
6 P: Well, maybe.
7 (0.6)
8 N: Well, hard to fi:nd?
9 P: Yes. I can't grasp the direction.
10 (0.4)
11 N: Well.
12 (0.9)
13 P: Oh, now (.) I start walking randomly.

Table 5.6: Failure case of navigation caused by obscurity of pedestrian's situation

(=westward)" in this conversation. In a word, he meant that the pedestrian had to go westward in the instruction. The pedestrian properly interpreted this confusing instruction and started heading westward without hesitation. It appears that they used the map as common basis. Such a instruction was typical case when a pedestrian used maps and voice conversations.

As previously mentioned, navigations based on a movement history occurred several times in Experiment 2. A navigation based on a movement history sometimes failed due to the difficulty of understanding the pedestrian's situation. On the other hand, a navigation based on a navigation map often succeeded because they could use the map as a concrete common basis. Misconceptions were not likely to occur as long as a pedestrian can read maps properly.

A navigator tried to guide a pedestrian, but the navigator sometimes could not guide him to a proper route. Hereinafter, we discuss failure cases of verbal navigation and analyze why they failed to communicate.

Table 5.6 shows an example of failed navigation caused by a navigator who could not recognize a situation of a pedestrian. In Table 5.6, the pedestrian asked the navigator about route selection (see line 2). In the case, the navigator could not understand the pedestrian's situation and failed to navigate the pedestrian (line 4-11). The map on a cellular phone showed an instruction to go southward but the pedestrian lost sense of direction and wrongly started going eastward as saying "I start walking randomly" (line 13). The conversation was started with the request for route guidance but the navigator could not meet the pedestrian's demand. The navigation failed due to the difficulty for the navigator to check the pedestrian's situation in the case.

A map on a cellular phone was reloaded every one minute. Location measurement and a server access took about 15 seconds on the navigation system. Consequently, the map was updated every 75 seconds. Additionally, location measurement via GPS sometimes had a gap between the current location shown on the map and the current location in the real world. Resolving the gap, the navigator was required to ask some questions to the pedestrian about the pedestrian's situation at first. However, when the pedestrian was lost and asked the navigator for guidance, it was difficult for the navigator to get correct information from the pedestrian. The failure cases were considered to be caused by the lack of common basis between the pedestrian and the navigator.

5.5 Design Implication of Guide Agent

We demonstrated that the kinds of information required by pedestrian were the current location, the current direction and a proper route toward a destination.

Pedestrians could not be convinced their location even if they could get their current location via GPS. Because GPS system had little measurement error and the navigation system delayed of about 75 seconds for updating a navigation map. Real time updating of the navigation map is needed.

Pedestrians also could not be convinced their current direction. Guide agents can calculate their current direction based on the movement histories. However, it is difficult for the guide agents to calculate the current direction from the movement history when they just leave a start point or turn a corner. The navigation system can capture precise direction of a pedestrian easily with cellular phone equipped electronic compasses.

In addition, pedestrians wondered which route they should select. Because there were plural courses that could arrive at a destination. For supporting route selection, guide agents should be equipped a function to show a route which is suited to user preferences (*e.g.* movement distance or a number of turns).

As the results described in Section 5.4.3, pedestrians got lost when they could not understand where they were and which direction they walked to. The navigators supported to let the pedestrians recognize correspondence between maps and their current location using their movement history and navigation maps.

Thus, guide agents should provide pedestrians who are not good at reading map with the message for bring moving histories and navigation map up in their consciousness. As a result, the pedestrians become conscious of the current situation and they can approach the goal more smoothly.

5.6 Conclusion

The approach of target system for analysis is to build a multiagent system that assigns one guide agent to each human for providing personal navigation. This research attempts to demonstrate a design implication of the guide agent. The problems we tackled in this work are as follows.

- **Analysis of information required by pedestrian**
  We examined the information required by pedestrians using the navigation system. The result indicated that pedestrians required information about the current location, the current direction and a proper route to a destination.

- **Analysis of communication between pedestrian and navigator**
  In the navigation experiments where a pedestrian using a map on a GPS-capable cellular phone was guided by a distant navigator, we investigated the communication among of them by conversation analysis method. Movement histories and navigation maps were used as communication basis in successful cases. When a pedestrian did not

understand a map and the surrounding environment adequately, navigation sometimes failed due to lack of communication basis.

In this research, we analyzed the information required by pedestrians and the limitation of remote navigation using maps and voice conversations. Future works include determining how to reflect the result of this experiment to the implementation of guide agents. Another future direction is to design of agent system like social coordination service [Yamashita 05] which could provide adequate navigation for groups.

Chapter 6

Augmentation of Experiment in Evacuation Navigation

In previous chapter, analysis by small group experiments is described. This chapter shows an augmented experiment for the evacuation guide system described in Chapter 4. At first, we see how to realize seamless connections between virtual and real space. Secondly, To confirm the feasibility and usefulness of augmented experiments and to determine their future issues, we conducted an outdoor evacuation experiment augmented by a large-scale multiagent simulation [Nakajima 07].

6.1 Introduction

Due to the popularity of and improvement in mobile phones, environments that support ubiquitous computing are spreading. In traditional information services, the user accesses the services desired via a terminal fixed in a room. However, in the ubiquitous environment, each user has his/her own portable device and accesses the services desired from any location via the wireless network. Because each person has his/her own device such as a mobile phone, it is possible to show different information to each user. In addition, GPS (Global Positioning System) and RFID (Radio Frequency Identification) tags enable devices to get information of the location and the situation of the user. In such an environment, it is possible to provide services that suit the properties, the purpose, the location and the context of each user. Navigation in public spaces is one such service [Jin 02, Koyanagi 04].

To understand the behavior of such social systems, it is desirable to perform confirmation experiments with a large number of human subjects. Unfortunately, cost and safety concerns preclude such experiments from being performed on a realistic scale. The solution is the augmented experiment approach; multiagent simulations are combined with small-scale experiments in the real world [Ishida 07].

Any large-scale evacuation guide system must be verified from the macro standpoint and the micro standpoint. The former is concerned with whether all citizens can take refuge efficiently. The latter addresses how a citizen uses the system. Verification will be accurate only when the human subjects feel as if their environment is populated with an adequate number of participants. Our goal is to devise a process for verifying city-wide navigation systems. In this research, we confirm that the combination of multiagent simulation and GPS-capable cellular phones can create a situation in which human subjects feel like they are participating with a large number of humans.

- **Seamless connections between virtual and real spaces**
  The difficulty with augmented experiments is to provide the human subjects with a sufficient level of reality. To guide human subjects in a timely fashion, the subjects must receive the result of the simulation on a virtual city through the communication channels.

- **Confirm feasibility and usefulness in real world example**
  To confirm the feasibility and usefulness of augmented experiments and to determine their future issues, we conduct outdoor evacuation experiments in real space enhanced by a large scale multiagent simulation.

Section 6.2 introduces our large-scale evacuation guide system for augmented experiments. Section 6.3 describes our approach which multiagent simulation enhanced a real world experiment and Section 6.4 how to realize the augmented environment. In Section 6.5, we explain the setting of the augmented experiment for evacuation navigation and its results.

6.2 Large-Scale Evacuation Navigation System

We produced a large-scale evacuation guide system as a good test of the augmented experiment approach.

The precise specification is written in Chapter 4 and Chapter 5. Figure 5.1 shows the overview of the system. In this system, guide agents, each of which is assigned to an evacuee in disaster areas, get locations of evacuees from their GPS-capable cellular phones. A commander gets aggregated information, and then points out evacuation destinations, which are typically shelters, and the direction for evacuation through the control interface. The commander gives rough instructions to guide agents. Each guide agent provides individualized navigation instructions, *i.e.*, evacuation route. An evacuee gets instructions on his/her GPS-capable cellular phones.

After obtaining the rough instruction from the commander, guide agents create a route to a shelter from their assigned evacuee's position, then provide the route as the individualized navigation instructions to each evacuee using information of the evacuee's position, navigation targets set by the commander, and the environmental situation. An evacuee moves, referencing to the map sent by his/her guide agent. The map centered on the evacuee's location shows the place of dangerous spots, shelters, and the direction to the shelter indicated by the commander. An evacuee can see the position/direction of movement of other evacuees on the map, so that he/she can grasp the situation of others.

6.3 Methodology for Analyzing Socially Embed System

A city-wide evacuation guide system is a large-scale social information service where a large number of users interact with each other. Test of the system requires analyzing the movement of crowds and the usability of the system. These analyses need human subjects who feel as if they are participating together with a large number of humans. Unfortunately, real-world experiments with many people are too expensive and rather dangerous.

The augmented experiment was proposed method to test large-scale ubiquitous computing systems [Ishida 07]. A real-world experiment with

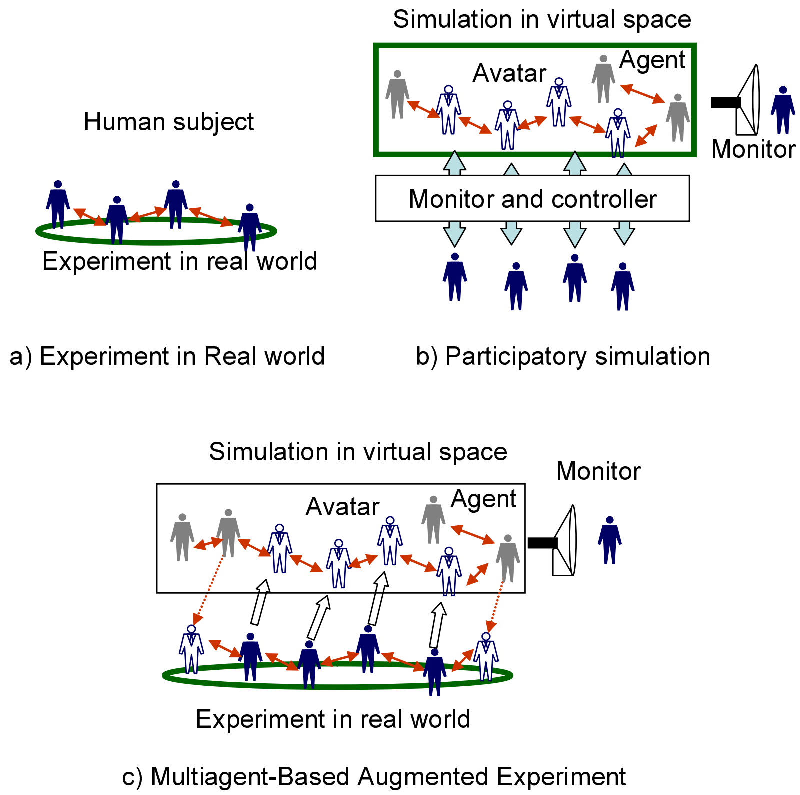


Figure 6.1: Compare augmented experiment and participatory simulation

a small number of human subjects is enhanced by a large-scale multiagent simulation. Figure 6.1 (a) shows the real world experiment with only human subjects. Figure 6.1 (c) shows augmented experiment which is enhanced by multiagent simulation. The main constituent of augment experiment is real world experiment.

Figure 6.1 (c) illustrates how an augmented experiment for a city-wide navigation systems is realized. The augmented experiment system lets human subjects perceive the results of the simulation performed in the virtual space concurrently with the real-world experiment. The human subjects are made to feel that they are participating with many other humans. This approach yields data comparable to that by performing real-world tests with a great many human subjects. In addition, comparing the movements of the human subjects with those of the agents can enable us to refine the user models of the agents.

The augmented experiment for the navigation systems proceeds as follows. The human subject sends his location to the navigation systems and the subject's position is projected into the virtual space. The guide agent for the subject sends navigation instructions and the status of the virtual space including positions of other evacuees to the subject. The real-world experiment and the simulation in a virtual space are executed concurrently.

A user agent pretends to a human subject in a simple term. A user agent in the simulation sends its location to a guide agent and receives navigation instructions. The user agent determines his behavior considering the instructions and his surrounding situation in the virtual space.

Participatory simulations are another method that allows the actions of human subjects in a virtual space to be extracted [Guyot 05]. Figure 6.1 (b) shows that participatory simulation includes the decision making of human subjects. The main constituent of the participatory simulation is simulation on a computer.

In a participatory simulation, some agents are replaced by human-controlled avatars. A participatory simulation is performed in virtual space, and the avatars are controlled by human subjects sitting in front of their computers. Participatory simulations are particularly useful, but sometimes fail to give valid results. To understand how users really respond to socially embedded systems, real world experiments are often required.

Participatory simulation is a kind of simulation. It means human subjects in the real world enter a simulation via avatar. On the other hand, augmented experiment is a kind of experiment. It means user agents on a computer enter an experiment conducted in the real world through a portable device.

6.3.1 Importation of Real World Information

A virtual city simulation is executed on massively multiagent simulation for producing virtual user of the evacuation navigation system. Virtual user models of the target system are predicted and implemented on the agent.

Human subject are desired to interact with others without distinction between virtual users and human subjects in an environment of augmented experiment. The Commander also desired to interact with the participants without distinction between virtual users and human subjects.

The environment of augmented experiment reproduces human subject's behavior based on the information gathered by sensor for the reason that the multiagent simulation of virtual users require to import the human subject information.

The current state of the virtual space is displayed as a birds-eye view on the monitor of the control center, so that the commander can grasp how evacuees are moving in the real world. In addition, the commander can instruct individual evacuees by clicking on the human figures on the screen. The system passes the instructions to the appropriate evacuees via their registered phone numbers or e-mail addresses. The use of transcendent communication, make it possible to grasp the situations of all evacuees while providing local navigation instructions as needed.

By running multiagent simulations, the commander can develop and optimize evacuation instructions as if he were interacting with a large number of human subjects. The commander views the virtual space via transcendent interface, and treats real evacuees and virtual evacuees in the same way. The situation augmented by virtual refugees provides the commander with the environment of navigation training.

6.3.2 Exportation of Virtual City Information

Each guide agent navigates its user with consideration of the user's surrounding environment via GPS-capable cellular phone. The positions and movements of other evacuees and evacuee agents are shown on the navigation map. In this way, human subjects can feel as if they are participating with a large number of humans.

We could use head mounted displays and capture the face directions of the subject. The agents are displayed so as to overlay the real-world view. But the cost should be too expensive to test a developing system. Using head mounted display is also dangerous because it reduces the visibility of human subject who participate in the augmented experiment conducted in outdoor.

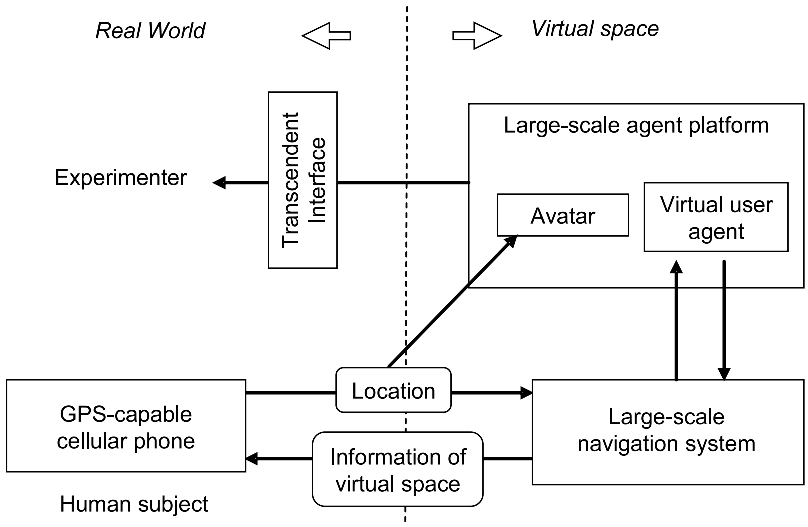


Figure 6.2: Structure of analysis environment for socially embeded system

6.4 Implementation of Environment for Analyze Socially Embed System

The difficulty with augmented experiments is to provide the human subjects with a sufficient level of reality and to realize seamless connections between virtual and real spaces.

The structure of analysis environment for the evacuation navigation system are displayed in Figure 6.2. The environment of augmented experiment is implemented with the concept described in section 6.3.

6.4.1 Production of Evacuee Agent

We build a multiagent simulator for producing the virtual users of the evacuation navigation system. Caribbean/*Q* are used as the multiagent platform which described in Chapter 3.

The features of Caribbean/*Q* are agent management based on scenario description and scalability enough to control hundreds thousands of agents. The positions and movements of other evacuees are provided to the human

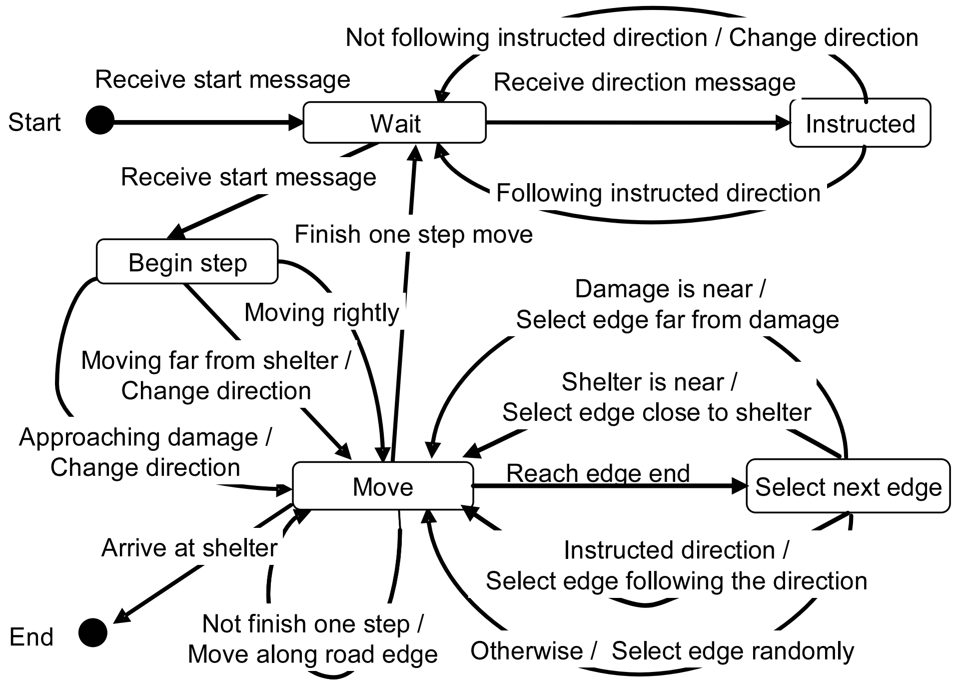


Figure 6.3: Scenario of evacuee agents

subjects through their navigation maps. The positions of the human subjects are captured by GPS and plotted in the virtual space. Evacuee agents determine their behavior after consideration of this data.

Evacuee agents behave as navigated users and act in the virtual space according to their scenario. An evacuee agent requests its guide agent to send a navigation map and uses the map in determining his movements. The scenario of an evacuee agent is shown in Figure 6.3. *actions* and *cues* used by evacuee agents are shown in Tabel 6.1 and 6.2.

Table 6.1: *Actions* of evacuee agent

Action Name	Description
!changeDirection	Change a direction to head toward
!move	Move along a road segment
!avoidDamage	Select a next road intersection avoiding a damage area
!approachShelter	Select a road intersection close to a shelter
!followDirection	Select a road intersection following a given direction
!randomSelect	Select a road intersection randomly
!finishEvacuation	Finish an evacuation

Table 6.2: *Cues* of evacuee agent

Cue Name	Description
?notifiedStart	Observe a message which triggers a step
?instructed	Observe a direction instruction message
?dangerous	Check if the current direction is approaching damage
?backShelter	Check if the current direction is heading far away from a shelter
?finishMove	Check if a move distance has amounted to a threshold
?straggle	Check if a current direction is against a given direction
?endEdge	Check if an agent has reached a road intersection
?nearDamage	Check if a damage area is near
?nearShelter	Check if a shelter is near
?directed	Check if an agent is instructed on a direction
?arriveShelter	Check if an agent arrives at a shelter

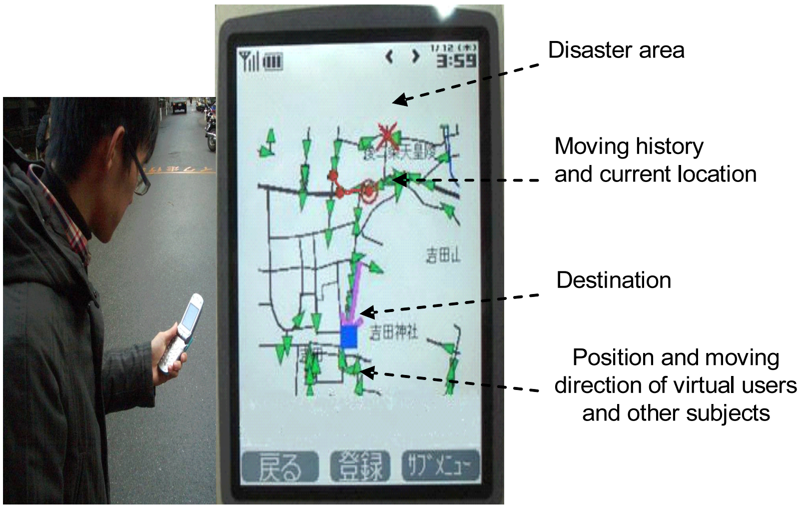


Figure 6.4: Evacuee in augmented experiment and GPS-capable cellular phone

The virtual user agents walk on roads in the virtual city. The road data is extracted from numerical maps (1/25000) issued by the Geographical Survey Institute. The road network in the virtual city consists of intersections (nodes) and segments (links). Virtual user agents evacuates along the roads taking account of shelters, dangerous area sites and the given direction.

One cycle of an evacuee agent is as follows. First, the evacuee agent decides his goal. The agent checks if the current heading direction has become incorrect due to the emergence of dangerous sites or the disappearance of shelters. If the heading direction should be changed, the agent turns to new direction. Next, the agent starts to move along a road segment. If it reaches an intersection, it selects the next intersection and moves along the segment to the intersection. When it selects the next intersection, it obeys rules such as, not to approach dangerous sites, to select an intersection close to a shelter, and to follow the direction set by the control center.

In this experiment, all guide agents are controlled with the same scenario. However, by creating various scenarios, it is possible to develop a simulation system that navigates users in various scenes or with different properties and goals.

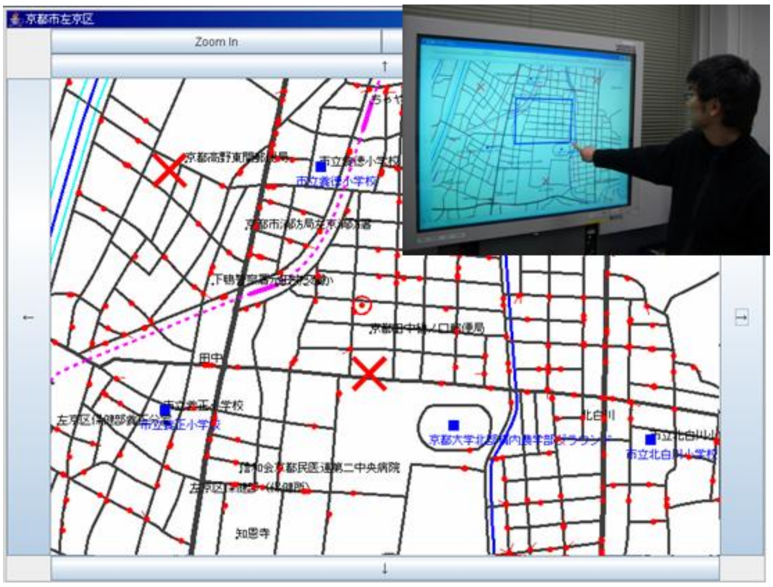


Figure 6.5: Monitor overlapping real world and virtual city

6.4.2 Connection between Real World and Virtual City

We selected a GPS-capable cellular phone as a transfer device of information about virtual city to a human subject. Mobile phones send the location of each human subject for reproducing their position in virtual city on the computer. The locations which are gathered via GPS is displayed as avatars in the virtual city (Figure 6.5).

Human subject feel as if their environment is populated with an adequate number of participants in the augmented experiment. The data flow between real world and virtual city is described as follows and Figure 6.6.

1. A GPS-capable cellular phones send the location information of each human subject to corresponding guide agents via GPS.

2. Guide agent receives the location information and update position of avatar on the virtual city. The locations of the evacuee agents and those of the human subjects are aggregated on the virtual city.

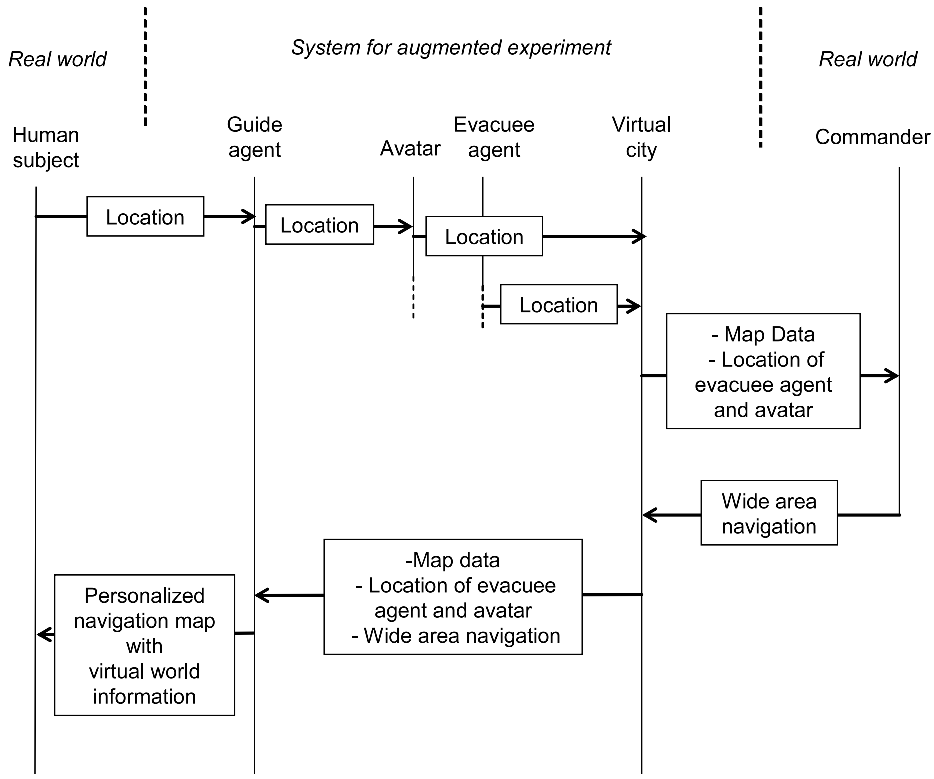


Figure 6.6: Data flow between real world and virtual city

3. Guide agents extract the map information and the location information from the virtual city and create a map which is displayed the navigation information including the position and moving direction of virtual users and other human subjects. The guide agent sends the map to the corresponding human subject.

4. The human subjects decide a route to goal considering the map.

The experimenter requires to observe whole users' behavior and to interact with them so as to analyze characteristic of the crowd. Therefore, the observation monitor is required to enables the experimenter to interact participants without distinguishing between human subjects in the real world and evacuee agents in the virtual city. The observation monitor is implemented founded on the concept of transcendent interface as shown in Figure 6.5. The interface displays virtual city information including real world information with birds-eyed view [Nakanishi 04b]. The experimenter can manage participants regardless of whether they are humans or agents with the monitor.

6.5 Experiment

We develop an environment of augmented experiment for the evacuation navigation system and practically conduct an augmented experiment. This experiment is conducted in order to confirm how human subjects responded to the simulated crowd. The experiment aims to confirm the feasibility and usefulness of augmented experiments and to determine their future issues.

6.5.1 Setting of Experiment

The experiment was conducted around Kyoto University. The area had a side length of 4 km. About 10 human subjects (13 in the first phase, 10 in the second phase) and 3,000 simulation agents were evacuated together. Five shelters were dispersed throughout the area in advance.

The system was accessed via web browsers of mobile phones. Each mobile phone determined its location with GPS and sent it to the system every minute automatically. In addition, human subjects could send their location manually whenever they needed a new map. Upon receiving location information, a guide agent would send a map that showed dangerous sites, shelters, and the direction to be followed its user. Additionally, the map showed the position and moving direction of virtual users and other human subjects.

Human subjects answered questionnaires and interview for estimating effect of augmented experiment.

The experiment proceeded as follows. When a disaster warning was issued for the area around Kyoto University, the commander started the evacuation guide. The commander grasped the disaster scene through the transcendence interface and selected groups of agents, and gave them rough directions for safe shelter or evacuation. The guide agents received the location information from the GPS-capable cellular phones and sent navigation maps to the users. When a secondary disaster occurred, it was displayed to the commander. The commander changed the navigation instructions the evacuees impacted by the secondary disaster. The commander could also provide personal navigation instructions to evacuees via e-mail.

6.5.2 Task for Subjects

The tasks of human subjects were to arrive at a shelter using the evacuation navigation system with each GPS-capable cellular phone. Human subjects started separate points and approached to indicated shelters. They could get navigation information by hand or by automatically updating every one minutes.

Before the experiment, the human subjects were told that virtual refugees participated in the experiment. They were given no instructions about responding to them such as following them or avoiding them.

One person played the role of the commander. He viewed the virtual space displayed on the monitor in the control room, and instructed both guide agents and evacuee agents. When the human subjects happened to go away from the area of experiment, the commander sent personal navigation manually.

Guide agent created the map to the nearest shelter and replans the route when secondary disasters happened or the commander issued a different instruction.

6.5.3 Questionnaire

All of human subjects answered questionnaires consisted of 6 questions about the evacuation navigation system (2 questions about reliability, 2 questions about usability and 2 questions about ease of use), and 6 questions about the augmented experiment (3 questions about effect of the virtual refugees, 3 questions about the whole experiment) and 5 dummy question. 22 human subjects answered the questionnaire without one parson who had trouble in the experiment. Questions about augmented experiments are explained below.

	Displaying virtual users	Not displaying virtual users	Unaffected	Percentage of affect
When could you evacuate smoothly ?	9	4	9	13/22= 59%
When could you evacuate calmly?	4	9	9	13/22= 59%
Which evacuation do you feel reality?	7	1	14	8/22= 36%

Table 6.3: Questionnaire about effect of displaying virtual evacuees

We asked 3 questions about smoothness, calmness and reality comparing the case where virtual users were displayed and the case where virtual users were not displayed, for examining the effect of the virtual refugees. All questions are rated on a scale of one to nine. The results are shown in Table 6.3.

You see that virtual refugees affect about 60 percent of human subjects in view of smoothness and calmness, and also affect about 40 percent of human subjects in view of reality.

Human subjects were asked "Have you evacuate smoothly in this experiment?" as for smoothness. The average score is 6.0 and standard division is 2.3. They were asked "Have you evacuate calmly in this experiment?" as for calmness. The average score is 7.0 and the standard division is 1.8. They were also asked "Do you feel reality as evacuation in the experiment?" as for reality. The average score is 3.3 and the standard division is 1.7.

6.5.4 Interview

Our purpose is to discern if human subjects would participate in the navigation experiment as if they are in the midst of a large crowd. In this experiment, each navigation map showed the directions to shelters, locations of dangerous sites, and the positions and movements of evacuee agents.

Interviewer:
What kind of criteria did you have for deciding a route to goal?
Subject A:
I selected clear road and the shortest path as possible. In the first experiment, are they virtual refugees? I chose the course where no virtual refugees were walking.
(Interviewer: Could you tell me exactly what clear road is?)
Big road, basically.
Subject B:
I selected clear road and... , contrary to what he said, I chose the course where refugees were walking because I guessed the road is good.
Subject C:
Well, first of all, I selected likely the shortest path and avoided disaster areas indicated with red x-mark. In the first experiment, I avoided crowded road where displaying virtual refugee because it seems congested.
Subject D:
I also selected route considering what subject C said. Additionally, I chose the roads where I have ever taken in my daily life
Subject E:
What subject C and D said is similar to me, I selected the shortest path, the straight course which I didn't need to turn for approaching goal because of not losing way. I was also aware of congestion of virtual refugees. I would follow them if those have been the real human. But in the experiment, I avoided crowded big roads and go through free narrow ways.

Table 6.4: Interview about decision making for route choice at evacuation

After the experiment, five human subjects were asked "Have you evacuate smoothly in this experiment?", "How do you feel about the navigation information?" and "What kind of criteria did you have for route choice?". We explained about route choice which demonstrates the effect of augmented experiment.

All of them said that they had formed their evacuation plans after considering the virtual refugees. Human subject A, C and D answered that they avoided virtual refugees. On the contrary, human subject B answered that he followed virtual refugees. Human subject E answered that he took different decision making in the case of normal experiment and in the case of augmented experiment.

This shows that the notification of the virtual evacuees, which was even a simple graphic representation, could influence human behavior. In the experiment, the subjects were made aware of the presence of the virtual evacuee agents via the maps displayed on their mobile phones.

6.5.5 Discussion

Another purpose of augmented experiment is observing behavior of whole crowd with a monitor featuring transcendent interface. In this case, if the virtual user agents on the computer do not have enough reproducibility of evacuees, it makes no sense to analyze the behavior of whole agents.

The human subjects in the navigation experiment decided to go through route with taking surrounding evacuees into consideration as we confirmed in interview. But the implemented agent did not equip a route choice methodology which is taking account of surrounding evacuees. Therefore, the behavior of agent crowd is different from that of human crowd. But it is difficult to presume the user model of a developing system. It is necessary to devise method to refine the models of evacuee agents from interviews and questionnaires which are acquired in augmented experiment.

Detailed behavior of human subjects can be collected from small real-world experiments and participatory simulations. In small real-world experiments, the behavior of human subjects can be recorded by cameras easily. In participatory simulations, behavior can be reproduced from the histories of avatars on a computer. But the data recorded in augmented experiment are sparse since the human subjects are dispersed widely across the test area.

The data that could be captured in the augmented experiment of evacuation was limited to just the time and the location where each subject requested a new map. This was supplemented by replies to questionnaires and interviews performed after the experiment. New methodologies which can extract user model from such limited data are needed for refining a multiagent simulation.

6.6 Conclusion

To develop a navigation system for humans with mobile terminals, it is necessary to test the system with a large number of human subjects. However, any experiment in the real world with many human is too expensive and rather dangerous. Thus we took the augmented experiment approach which uses a multiagent simulation to expand a real-world experiment with a few subjects.

We produced a city-wide evacuation guide system with GPS-capable cellular phones. In this system, each user receives updated maps and instructions from his/her own guide agent. We subjected this system to an augmented experiment.

In the augmented experiment, positions and movements of simulated users were shown on the navigation maps sent to each subject. Interviews of the human subjects confirmed that the system successfully gave the impression to the human subjects that they were participating with a large number of users. The results of this experiment give some indication of the possibility of using augmented experiments to refine city-wide navigation systems. We address two issues as below.

- **Design environment of augmented experiment with massively multiagent simulation**
  In this research, we built a framework of augmented experiment in evacuation guide system. We implement the environment that shows a virtual crowd to human subjects based on GPS-capable mobile phones and multiagent simulation.

- **Confirm feasibility and usefulness in real world example**
  To confirm the feasibility and usefulness of augmented experiments

and to determine their future issues, we conducted an outdoor evacuation experiment augmented by a large scale multiagent simulation. We carried out an augmented experiment using the proposed system and let participants of a small experiment feel in a crowd. The interview of experiment shows that the augmented experiment successfully affected route selection of the participants.

Chapter 7

Conclusion

7.1 Discussion

In this section, we compare augmented experiment and other methods from the point of view of environments and participants. Figure 7.1 shows relation between experimental methods.

Horizontal axis of the figure indicates types of participant. The far left shows all participants of experiment are humans and the other side shows all the participants are artificial software on a computer or hardware in the real world. The middle of the horizontal axis means that human subjects and artificial subjects participate in the experiment together.

Vertical axis of the figure shows where experiments are conducted. The top indicates in real world and the bottom means in virtual world. Experiment in the real world is a typical case of the top area and simulation on a computer is a typical case of the bottom area.

A simulation using the platform of Chapter 3 corresponds to a simulation in virtual world with artificial subjects. The advantages of this method are scalability and repeatability. Increasing number of virtual user agents is easier than increasing that of human subjects. The running cost of executing simulation is quite low. How to acquire correct agent model is a key issue.

The experiment of Chapter 5 corresponds to an experiment in the real world with human subjects. The advantage of this method is observing human behavior in practical case. The execution cost of the experiment is low if the number of the participants is small, but the experiment cannot

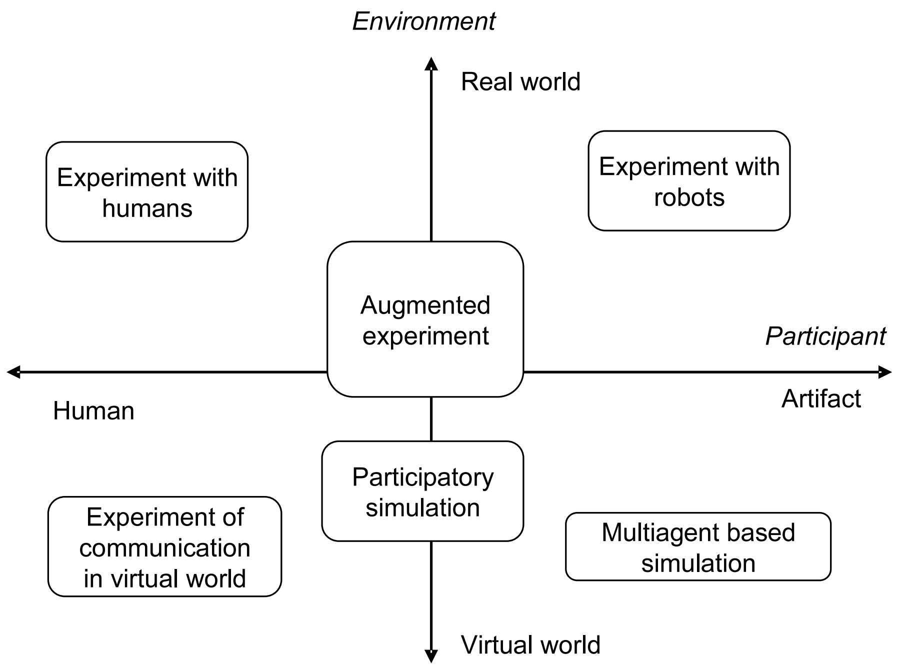


Figure 7.1: Relation between experimental methods: horizontal axis shows what types of subjects participate in experiment and vertical axis shows where experiments are conducted

examine the human behavior in the crowd. A large-scale experiment can investigate the human behavior in the crowd but the cost is quite expensive.

The augmented experiment of Chapter 6 corresponds to an experiment in the real world with human subjects and multiagent simulation. The advantages of this method are observing human behavior in the crowd and practical case. The augmented experiment showed in previous chapter use cellular phones as devices for displaying behavior of virtual agents. If robots are used for display device, the position of augmented experiment shift to right in Figure7.1. If an augmented environment uses head mounted displays for device displaying virtual world, which is a mixed reality environment, the augmented experiment is characterized by the center of the figure.

Most difference between participatory simulation and augmented experiment is the environment of experiment. Participatory simulation can generate any situation which an experimenter needs because the simulation is executed on a computer. Therefore, participatory simulation suits for experiments which exclude physicality of human subjects and cannot execute in real world such as dangerous experiment and completely controlled experiment. On the other hand, augmented experiment suits for experiment to analyze how individual users employ a developing system in the practical case.

7.2 Contributions

The purpose of this thesis is devising a new experimental environment for supporting development of socially embedded system. We assumed an evacuation navigation system as an example of socially embedded system. Testing such socially embedded system requires analyzing the movement of crowds and the usability of the system. These analyses need human subjects who feel as if they are participating together with a large number of humans. The approach of this thesis is to augment a real-world experiment with a multiagent simulation.

We develop large-scale evacuation navigation system that can provide individualized instructions to each person as a target system to augmented experiment. The navigation system assigns one guide agent to each human. In this system, an agent can provide personalized navigation instructions considering the human's characteristics, city-supplied evacuation targets, and the surrounding environment.

The following three issues are solved to realize an experimental environment which augments an evacuation experiment with multiagent simulation.

1. **Platform for Massively Multiagent Simulation**

   The first theme is proposing architecture for large-scale multiagent platform. To develop a large-scale social simulation, it is necessary for specialists of application domains and of computation systems to cooperate with each other. In such simulations, there is variety of situations that each agent faces. Also, the scalability is one of the primary requisites to reproduce phenomena in a city where hundreds of thousands of people live. As a solution to these problems, we propose architecture for multiagent simulation platforms where the execution of simulation scenario and the implementation of agents are explicitly separated. Caribbean/*Q* was implemented based on the proposed architecture, and evaluated with simple scenario and disaster simulation scenario.

The problems which we tackled in this work are as follows.

- *Separation of protocol design and agent development*
  The architecture realizes the separation of protocol design and agent development, which enables the experts of different domains to cooperatively and efficiently develop large-scale multiagent simulation system.
- *Dynamic switching of protocols*
  By separating protocol processing system and agent internal models, experimenters can easily switch protocols according to the changing situations while running the simulation.
- *Scalability*
  By implementing both protocol processing system and agent internal models in a large-scale agent server, scalability of the system is improved. The result of evaluation experiments shows that the Caribbean/*Q* system successfully manages 1,000,000 agents.

2. **Analysis of Pedestrian Navigation using Cellular Phones**

   The second theme is analysis of evacuation navigation system with small group.

   This research attempts to investigate a design implication of the guide agent on the large-scale evacuation navigation system with a small experiment. In navigation experiments where a pedestrian using a map on a GPS-capable cellular phone was guided by a distant navigator, we investigated the communication between them by conversation analysis method. The problems we tackled in this work are as follows.

- *Analysis of information required by pedestrian*
  We examine the information required by pedestrians using the navigation system. The result indicates that pedestrians require information about the current location, the current direction and a proper route to a destination.
- *Analysis of communication between pedestrian and navigator*
  We find that pedestrians and navigators often use maps as a basis of verbal navigation. We also show that in the cases where pedestrians did not understand surrounding environment adequately, remote navigation sometimes fails due to the lack of basis.

3. **Augmentation of Experiment in Evacuation Navigation**

   The third theme is augmentation of experiment in outdoor evacuation navigation.

   To develop a navigation system for humans with mobile terminals, it is necessary to test the system with a large number of human subjects. However, any experiment in the real world with many human is too expensive and rather dangerous. Thus we took the augmented experiment approach which uses a multiagent simulation to expand a real-world experiment with a few subjects.

   We produced a city-wide evacuation guide system with GPS-capable cellular phones. We subjected this system to an augmented experiment.

   The problems which we tackled in this work are as follows.

   - *Design environment of augmented experiment with massively multiagent simulation*
     In developing a large-scale navigation system, it is necessary to estimate the user behavior in a crowd and the crowd behavior. However, it is difficult to perform tests on such a system given the large number of human subjects. We built a framework of augmented experiment in evacuation guide system. The environment shows a virtual crowd to human subjects using GPS-capable mobile phones and multiagent simulation.

- *Confirm feasibility and usefulness in real world example*
  To confirm the feasibility and usefulness of augmented experiments and to determine their future issues, we conducted an outdoor evacuation experiment augmented by a large scale multiagent simulation. We conducted an augmented experiment using the proposed environment and let participants of a small experiment feel in a crowd. The interview of experiment indicates that the augmented experiment successfully affects route selection of the participants.

Our goal is to devise a novel experimental environment for verifying city-wide navigation systems. In this research, we confirm that the combination of multiagent simulation and GPS-capable cellular phones can create a situation in which human subjects feel like they are participating with a large number of humans. It demonstrates feasibility and usefulness of the environment of augmented experiment.

7.3 Future Directions

We conclude this thesis with the list of possible future directions of augmented experiment. When these research themes are solved, augmented experiment become more effective tool for analyzing the socially embedded system.

- *Refine agent model extract from log data of augmented experiment*
  Simple agent based on KISS (Keep it simple, stupid) principle is highly-popularized for social simulation because the sociologist expect to explain what is a factor to affect the objective environment. On the other hand, more precise agent models are required when system developer want to analyze the movement produced by new system's users. Because the system developer wants to reveal relations between each person's decision making and the simulation results.

  In the interview of the augmented experiment about evacuation navigation, it shows that each person has different route choice strategy. To extract such diverse user models, the agent behavior must exhibit distinct personalities in multiagent simulations. It is important to invent modeling methodology to extract personal decision models from the subjects' action history in augmented experiments. This is different from inductive approaches to acquire a general user model from all subjects' log data.

- *Experiment for studying effect of multiagent simulation in augmented experiment*
  It is necessary that more precise analysis about the effect of multiagent simulation in augmented experiment. We conduct three type experiments in order to examine the effect of displaying the result of multiagent simulation.

  The first type of experiment intends to reveal the difference between virtual users and human subjects. We conduct experiments changing ratio of agents to human subjects.

  The second type of experiment is aimed at demonstrating the effect of devices displaying virtual city information to human subjects. Cellular phones are used in the evacuation navigation experiment as mentioned in Chapter 6, we conduct augmented experiment with other display device such as head mount display.

  The third type of experiment is aimed at making known the effect of accuracy of the virtual user's model to human subjects. We compare the effect of virtual refugees founded on an original agent model and that of an agent model refined by log data of augmented experiments.

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4. Hironori Shiina, **Yuu Nakajima**, Hirofumi Yamaki, and Toru Ishida, "Development of Mega-Scale Navigation Based on Multiagent Simulation", in *IPSJ SIG technical reports*, MBL32-UBI7, pp. 255-262, 2005 (In Japanese).

Award

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