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Integrating mobile agent technology with multi-agent systems for distributed traffic detection and management systems

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ABSTRACT

Agent technology is rapidly emerging as a powerful computing paradigm to cope with the complexity in dynamic distributed systems, such as traffic control and management systems. However, while a number of agent-based traffic control and management systems have been proposed and the multi-agent systems have been studied, to the best of our knowledge, the mobile agent technology has not been applied to this field. In this paper, we propose to integrate mobile agent technology with multi-agent systems to enhance the ability of the traffic management systems to deal with the uncertainty in a dynamic environment. In particular, we have developed an IEEE FIPA compliant mobile agent system called Mobile-C and designed an agent-based real-time traffic detection and management system (ABRTTDMS). The system based on Mobile-C takes advantages of both stationary agents and mobile agents. The use of mobile agents allows ABRTTDMS dynamically deploying new control algorithms and operations to respond unforeseen events and conditions. Mobility also reduces incident response time and data transmission over the network. The simulation of using mobile agents for dynamic algorithm and operation deployment demonstrates that mobile agent approach offers great flexibility in managing dynamics in complex systems.

1. Introduction

Over the last decade, agent technology has shown great potential for solving problems in large scale distributed systems. The reason for the growing success of multi-agent technology in this area is that the inherent distribution allows for a natural decomposition of the system into multiple agents that interact with each other to achieve a desired global goal (Hernandez et al., 2002). The multi-agent technology can significantly enhance the design and analysis of problem domains under following three conditions (Adler and Blue, 2002): (1) The problem domain is geographically distributed. (2) The sub-systems exist in a dynamic environment. (3) Sub-systems need to interact with each other more flexibly. The domain of traffic and transportation systems is well suited for an agent-based approach because of its geographically distributed and dynamic changing nature (Jennings et al., 1998). Our literature research shows that the techniques and methods resulted from the field of agent and multi-agent systems have been applied to many aspects of road traffic control and management, including modeling and simulation (Dia, 2002; Hidas, 2005; Chabrol et al., 2006), dynamic routing and congestion management (Adler and Blue, 2002; Logi and Ritchie, 2002; Adler et al., 2005), intelligent traffic management (Hernandez et al., 2002; Garcia-Serrano et al., 2003), and urban traffic signal control (Roozemond, 2001; Choy et al., 2003; Chen et al., 2005).

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Although the agent technology has contributed to the advancement of traffic management, the design, implementation, and application of agent-based approaches in this area are still immature and need to be further studied. In this paper, we address three issues: ability to handle uncertainty, interoperability, and extensibility of agent-based distributed traffic management systems. First, the reported agent-based applications in roadway traffic management focus on developing multi-agent systems (MASs) that consist of multiple distributed stationary agents. The use of multi-agent systems provides a clear added value of high degree of autonomy and co-operability to conventional systems. However, MASs have a limited ability to deal with uncertainty in dynamic environments. To overcome this weakness, we propose to integrate mobile agent technology with multi-agent systems to enhance the flexibility and adaptability of large scale traffic management systems. Different from stationary agents, mobile agents are able to migrate from one node in a network to other nodes and to be executed on any nodes in the network. Mobile agents can be created dynamically at runtime and dispatched to destination systems to perform tasks with most updated code and algorithms. Mobility provides great opportunities to address challenges in traffic control and management systems, such as quick incident diagnosis, dynamic system configuration, deploying new algorithms or operations dynamically, taking unanticipated actions, and reducing data transmission over a network.

Second, most existing agent-based traffic management systems are lack of taking consideration of the interoperability between agent systems at the agent platform level. The interoperability is critically needed in making decisions based on information across systems, organizational and jurisdictional boundaries. To tackle interoperability issue, IEEE FIPA (Foundation for Intelligent Physical Agents), a consortium of companies, government agencies, and schools, has been working on producing software standards for heterogeneous and interacting agents and agent-based systems. The goal of FIPA standards is to guarantee the interoperability between agents by coordinating different aspects of systems, including system architecture, agent communication, agent management, and agent message transportation.

Third, less attention has been paid on the openness and scalability design of systems, which is important for system extension.

To address aforementioned issues, we have developed a mobile agent system called Mobile-C (Chen, 2005; Chen and Cheng, 2005; Chen et al., 2006), which integrate mobile agent technology with multi-agent systems for distributed traffic detection and management. Mobile-C is an IEEE FIPA compliant mobile agent system and supports both stationary agents and mobile agents. Building on Mobile-C, the agent-based traffic detection and management system (ABRTTDMS), takes advantages of both stationary agents and mobile agents. Compliance with IEEE FIPA standards ensures the interoperability of ABRTTDMS. The architecture of ABRTTDMS is open and able to integrate new detection systems by wrapping them to sub-agent systems. The integration of data from heterogeneous detection systems will help operations become more efficient by enabling a more comprehensive view of the system.

The remainder of the article is organized as follows: Section 2 introduces the background of agent applications in traffic control and management systems. Section 3 describes an FIPA compliant agent system for supporting both stationary agents and mobile agents. Section 4 presents an agent-based traffic detection and management system based on Mobile-C agent system. Section 5 shows how to use mobile agents to achieve dynamic algorithm and operation deployment. Finally, conclusions are drawn in Section 6.

2. Background

Traffic control and management systems can be characterized as highly distributed and dynamic changing systems. Agent technology is a promising approach to solve problems in this domain. A distributed vehicle monitoring test-bed presented in Durfee (1988) is an early example of distributed problem-solving network. Recently, a number of agent-based applications related to traffic control and management in different modes of transportation, including road (Hernandez et al., 2002; Logi and Ritchie, 2002; Adler et al., 2005), railway (Bel and van Stokkum, 1999; Blum and Eskandarian, 2002; Proenca and Oliveira, 2004), and air transportation (Glover and Lygeros, 2004; Li et al., 2005), have been reported. This section examines agent applications in road traffic control and management systems.

Adler and Blue (2002) and Adler et al. (2005) proposed an agent-based approach for vehicle route choice and capacity allocation. The proposed framework, Cooperative Traffic Management and Route Guidance System (CTMRGS), extends the ITS National Architecture Market Package ATIS6 by adding a middleware layer that is comprised of agents and agent negotiation protocols. Agents in the system represent travelers (Agent-IRANS), information service providers (Agent-ISP), and system operators (Agent-TMC), respectively. A principled negotiation is used to guide interactions between Agent-IRANS and Agent-ISP to make route choice and capacity allocation satisfying the objectives of both drivers and system operators. Logi and Ritchie (2002) investigated the inter-jurisdictional traffic congestion management on freeway and surface street (arterial) networks. Their system is composed of two interacting real-time decision support agents, a freeway agent and an arterial agent, for analysis of congestion and generation of suitable responses. The freeway agent supports incident management operations for a freeway sub-network, and the arterial agent supports operation for the adjacent arterial network. Both agents interact with a human operator at their local Traffic Operation Center (TOC) and generate suitable local control plans. The system provides a dialog facility through a distributed user interface to allow operators at different TOCs to agree on the selection of a global solution.

Garcia-Serrano et al. (2003) and Tomas and Garcia (2005) designed two multi-agent systems for road traffic management. In Garcia-Serranos' work, several TRACK-R agents, each is responsible for a geographical area, have been designed to provide traffic routes recommendation for humans or other agents. Tomas et al. proposed a multi-agent system to help traffic operators to determine the best traffic strategies for dealing with non urban road meteorological incidents. Agents in these two systems were implemented using JADE (Java Agent DEvelopment Framework).

Hernandez et al. (2002) studied and compared two agent-based architectures for intelligent traffic management in an urban traffic network. Their experience showed that the decentralized architecture has advantages in synchronization, reusability, and scalability. However, the complexity of decentralized systems is increased. Choy et al. (2003) presented a hierarchical multi-agent system for real-time traffic signal control in urban traffic networks. The system consists of three types of agents, intersection controller agents (ICA), zone controller agents (ZCA), and regional controller agents (RCA). A ZCA controls several pre-assigned ICAs, and one RCA controls all of the ZCAs. The implementation of agents is based on neural network and fuzzy logic theories.

In summary, most existing agent-based traffic management applications are based on multi-agent systems. These systems consist of multiple functional stationary agents that are intelligent and cooperative. The coordination between agents is achieved through certain type of protocols. The agent system architectures include simply interacting agents, centralized hierarchical architecture, and decentralized architecture. However, to the best of our knowledge, there are not in-depth studies of mobile agents for applications in traffic control and management systems. Another issue related to the agent applications in traffic control and management systems is lack of compliance with agent standards. Most systems are proprietary and hard to interoperate with other agent systems.

We have proposed using mobile agents for the ITS (Intelligent Transportation System) applications in the article (Chen et al., 2004). This paper presents the research results of the integration of mobile agents with multi-agent systems for applications in traffic detection and management systems based on the previously proposed concepts.

3. A FIPA compliant agent system

The operation of agents is supported and managed by distributed software platforms known as agent systems. The name of multi-agent systems usually refers to systems that support stationary agents and mobile agent systems refer to systems that support mobile agents. Mobile agent systems provide mechanisms for agent management, agent communication, and agent directory maintenance. In addition, mobile agent systems need additional mechanisms to support the mobile agent migration and execution. In a mobile agent system, agencies are the major building blocks and reside in each node of a networked system, in which agents reside and execute. To facilitate the interoperation of agents and agent systems across heterogeneous agent platforms, agencies designed to comply with agent standards are highly desirable.

Mobile-C (Chen, 2005; Chen and Cheng, 2005; Chen et al., 2006) is an IEEE FIPA compliant agent system supporting both mobile and stationary C/C++ agents. The IEEE FIPA standard is one of the major international agent standards, which guarantees the interoperability between agents. Mobile-C is compliant with the FIPA standards at both agent-level and platform-level. At the agent-level, the conformance includes agent communication language (ACL), message exchange interaction protocols, communicative acts, and content language representations. At the platform-level, Mobile-C provides an agent management system to manage the life cycle of the agents, agent communication channel to allow agent communication over the network, and directory facilitator to serve as yellow page services. Since FIPA mainly addresses the interoperability between stationary agents (SA), Mobile-C extends FIPA specifications to support mobile agents. An embeddable C/C++ interpreter–Ch (Cheng, 1993; Cheng, 2006) has been integrated into the system as a mobile agent execution engine. The architecture of agencies in Mobile-C is shown in Fig. 1.

The core of an agency provides local service for agents and proxies to access remote agencies. The main components of an agency and their functionalities can be summarized as follows:

- *Agent Management System (AMS):* The AMS manages the life cycle of agents in the system. It controls creation, registration, retirement, migration, and persistence of agents. AMS maintains a directory of Agent Identifiers (AID). Each agent must register with an AMS in order to get a valid AID.
- *Agent Communication Channel (ACC):* The ACC routes messages between local and remote agents and realizes messages using an agent communication language (ACL).
- *Agent Security Manager (ASM):* The ASM is responsible for maintaining security policies for platform and infrastructure.
- *Directory Facilitator (DF):* The DF serves yellow page services. Agents in the system can register their services with DF to provide to the community. They can also look up required services with DF.
- *Agent Execution Engine (AEE):* The AEE serves as the execution environment for the mobile agents. Mobile agents must reside inside an engine to execute. The AEE has to be platform independent in order to support a mobile agent executing in a heterogeneous network.

For the regulation of mobile agent migration, a mobile agent mobility protocol has been developed to specify the procedure of mobile agent migration. Mobile agent migration is achieved through ACL messages in Mobile-C. The data state and code of a mobile agent are packed into an ACL message and transmitted to a remote host through agent communication channel. Each mobile agent runs in its own execution engine, which is embedded into the system in a separate thread. The use of multiple threads for multiple mobile agents is much more efficient than multi-process approach because the start-up and termination of multi-processes and the expensive inter-process communication are avoided.

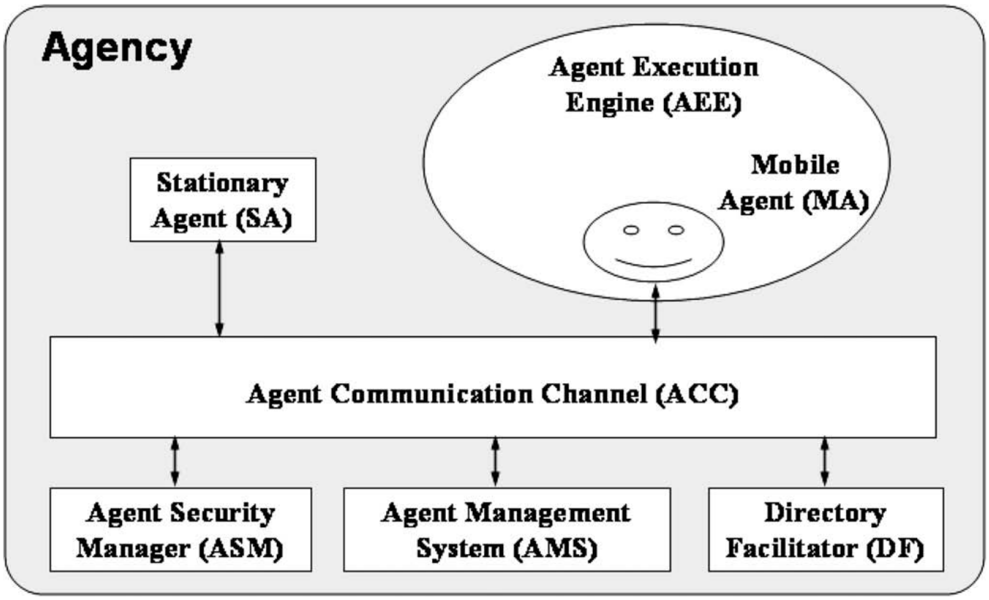

Fig. 1. The architecture of agencies in Mobile-C.

4. An agent-based traffic detection and management system

4.1. System overview

The architecture of proposed agent-based traffic detection and management system (ABRTTDMS) has multiple levels as shown in Fig. 2. The lowest level is composed of various detectors to detect traffic parameters. The useful information for the traffic management is travel time, vehicle speed, incident verification, and traffic volume (Palen, 1997). Currently, the technologies used for detecting these parameters are magnetic loop detectors (Ostland et al., 1997; Sun and Ritchie, 1999) and video monitoring systems (MacCarley, 1997; Malik and Russell, 1997). A new laser-based detection system (Cheng et al., 2001; Wang et al., 2003) developed by the Integration Engineering Lab at UC Davis can also detect the speeds and length of vehicles on the highway. ABRTTDMS can integrate different detectors, such as laser detectors, loop detectors, video cameras, and new detectors into one system by wrapping them into agent-based sub-systems as shown in Fig. 2. The lowest level also contains agencies for different detectors. Stationary agents, laser detector (LRD) agents, loop detector (LPD) agents, and video camera detector (VCD) agents, are used to process the outputs of the corresponding detectors and provide the desired intelligence. A traffic detection execution system (TDES) agent coordinates all of the LRD agents, LPD agents, and VCD agents in a sub-network and communicates with other TDES agents and an upper level transportation management center (TMC) agent. The TMC agent delegates tasks to the lower level agents and analyzes the information from these agents. It can also dispatch mobile agents to lower level agencies to fulfill unforeseen tasks.

4.2. Stationary agents

4.2.1. LRD agents or LPD agents

The tasks of LRD agents or LPD agents can be summarized as follows:

- Process real-time data from laser detectors or loop detectors.
- Realize vehicle re-identification, estimate travel time and density on a freeway segment; detect incidents.
- Improve detection algorithms and selects proper algorithms dynamically.
- Track real-time traffic conditions and alert predefined events to TMC operators.

4.2.2. VCD agents

The functions of VCD agents are to control different cameras to verify incidents. The incident detection of LRD agents or LPD agents is usually based on checking whether the link travel time is in a reasonable time window. The LRD agents or LPD agents cannot give the incident location or other detailed incident information. VCD agents are designed to provide the necessary incident information when the incident occurs. For example, the VCD agents can control different cameras to photograph the scene of the incident and analyze video streams to obtain the requested information.

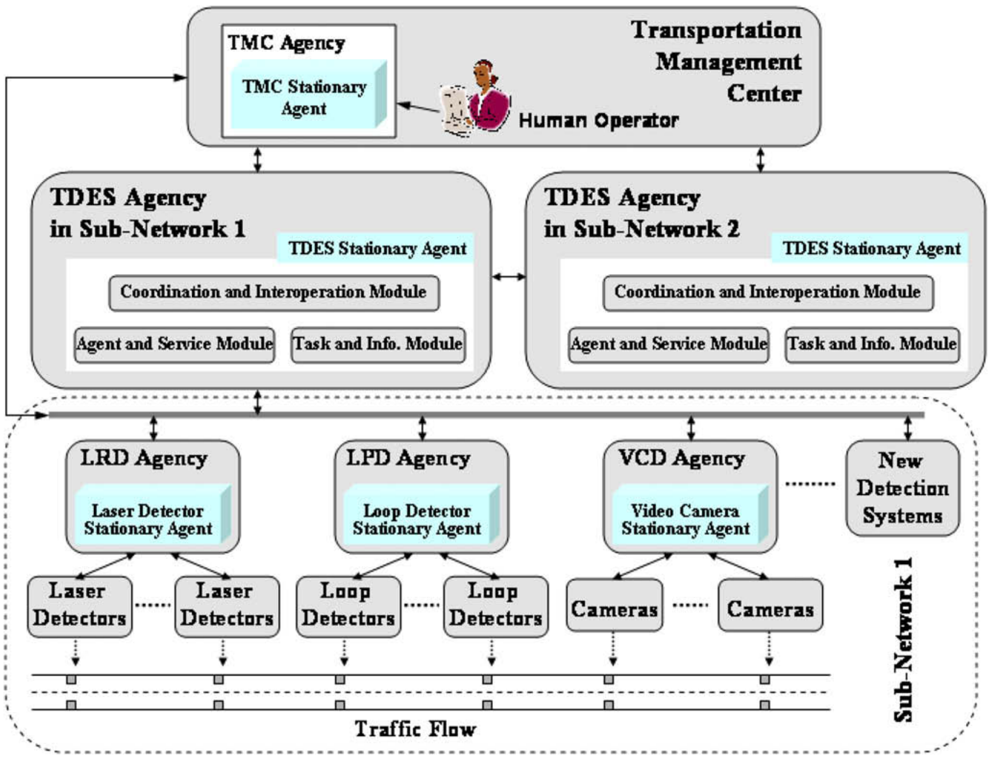

Fig. 2. The system architecture of ABRTTDMS.

4.2.3. TDES agents

A TDES agent is a coordinator of lower level agents in a sub-network. All of the lower level agents register themselves and their services with a TDES agent. A TDES agent has the knowledge of geographical distribution of lower level agents and their capabilities. The tasks of TDES agents are as follows:

- Serve as agent name server and maintain the available services of agents in a sub-network.
- Dynamically group lower level agents into a cluster according to the task assigned and coordinate these agents to accomplish the task.
- Decompose tasks assigned by the TMC to sub-tasks. Plan, schedule, and track these sub-tasks.
- Integrate the information from lower level agents and report to the TMC agent.
- Interoperate with other TDES agents to solve inter-network problems.

4.2.4. The TMC agent

The TMC agent is designed to perform following tasks:

- Interface with the personnel at the TMC to accept human commands.
- Generate tasks dynamically and assign these tasks to lower level agents.
- Analyze the information from lower level agents and generate reports or control proposals to the personnel at the TMC.
- Create mobile agents and dispatch them to different agencies.

4.3. Mobile agents

The purpose of introducing mobile agents into ABRTTDMS is to increase the flexibility and the ability of the system to deal with the uncertainty in a dynamic environment. A stationary agent executes only on the system where it begins execution, and the code of stationary agents, including control algorithms and provided services, cannot be changed during execution. On the other hand, a mobile agent is not bound to the system where it begins execution. It has the unique ability to transport itself from one system in a network to another. The ability to travel allows a mobile agent to move to a system that contains an object with which the agent wants to interact and then to take advantage of being in the same host or network as the object. Since mobile agents can be generated dynamically during the execution, new software components (control algorithms or operations) can be deployed as mobile agents and be executed on any sub-systems in a network. Mobile agent technology has been increasingly studied and its strength, such as reduce network load, overcome network latency, support disconnected operation, work in heterogeneous environments, able to deploy new software components dynamically, has been identified by several researches (Lange and Oshima, 1999; Gray et al., 2002).

The strength of mobile agents has great value for the application in traffic management systems. A traffic information system is usually distributed, and the integration of data from distributed detection stations takes a long time. If a mobile agent can migrate to detection stations near incident scene and process data locally, it will significantly reduce the delay of incident response. Using mobile agents also helps to achieve the cooperation between distributed roadway electronics and moving vehicles, which is one of the US DOT's major ITS efforts. The communication of moving vehicles with roadside information infrastructure relies on expensive or fragile wireless network connections. Tasks requiring a continuous connection between a moving vehicle and a traffic information network are probably not economically or technically feasible. To solve this problem, tasks can be encapsulated as mobile agents and be dispatched to the roadside network or moving vehicles. After being dispatched, the mobile agents become independent of the system that created them and can continue their tasks even if the connection to the source system goes down. The moving vehicle can reconnect at a later time to collect or send the results from mobile agents. More importantly, mobile agents can enhance the ability of traffic management system to handle uncertainty introduced in a dynamic environment. New services, operations, or control algorithms can be implemented as mobile agents. These software components can be dynamically installed on remote machines as they were part of the remote machines' pre-installed components. The simulation of mobile agents for dynamic algorithm and operation deployment is presented in Section 5.

4.4. System control architecture

Heragu et al. (2002) classify common control architectures of agent-based systems into hierarchical, heterarchical, and hybrid. Generally, the hierarchical approach decomposes the overall system into small sub-systems that have weak interaction with each other. On the other hand, the heterarchical approach is a completely decentralized approach and focuses on interactions between sub-systems. The lack of predictability and global perspective are major drawbacks of heterarchical frameworks. Hybrid approach combines the features of hierarchical and heterarchical approaches. Hybrid control architecture takes the advantage of hierarchical and heterarchical architectures. However, the static hybrid control architecture is still insufficient for a system that needs to dynamically group different agents for different tasks. We employ the concept of the partial dynamic hierarchical control architecture (Brennan et al., 1997). This concept organizes multiple agents dynamically based on task decomposition. To achieve dynamic organization, a number of heterogeneous agents are dynamically grouped into virtual clusters as needed. The control architecture of our system is shown in Fig. 3. Our system's hierarchy has three layers. The highest-layer agent is the TMC agent, TDES agents sit at the middle layer, and LRD agents, LPD agents, and VCD agents are at the lowest layer. Under certain scenarios, a number of heterogeneous lowest layer agents are dynamically grouped and interact with each other to perform a task. A TDES agent coordinates these agents in a sub-network. The TMC agent can assign tasks to either TDES agents or to the lowest agents directly.

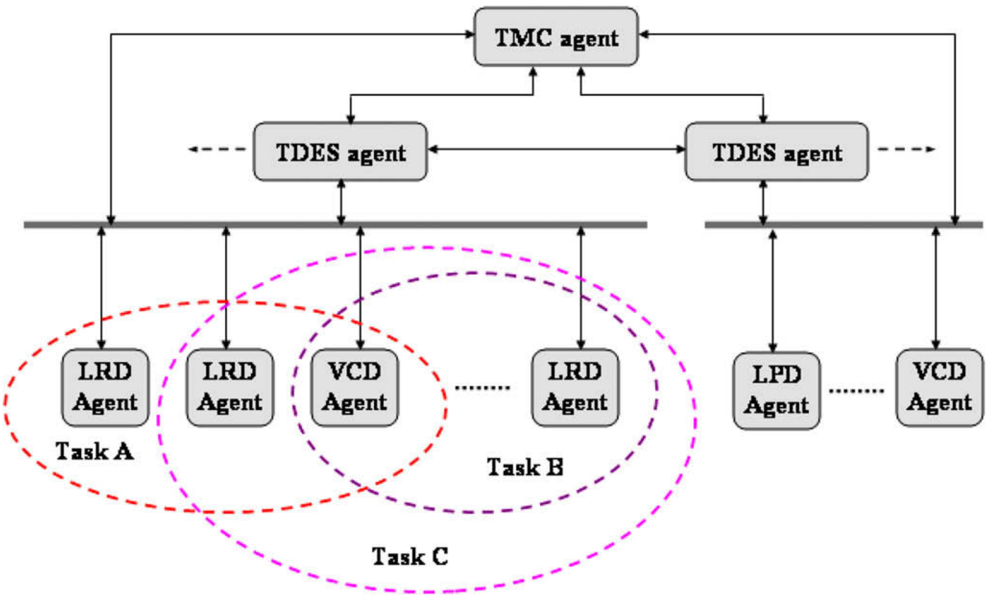

Fig. 3. Dynamic grouping multiple agents to virtual clusters for different tasks.

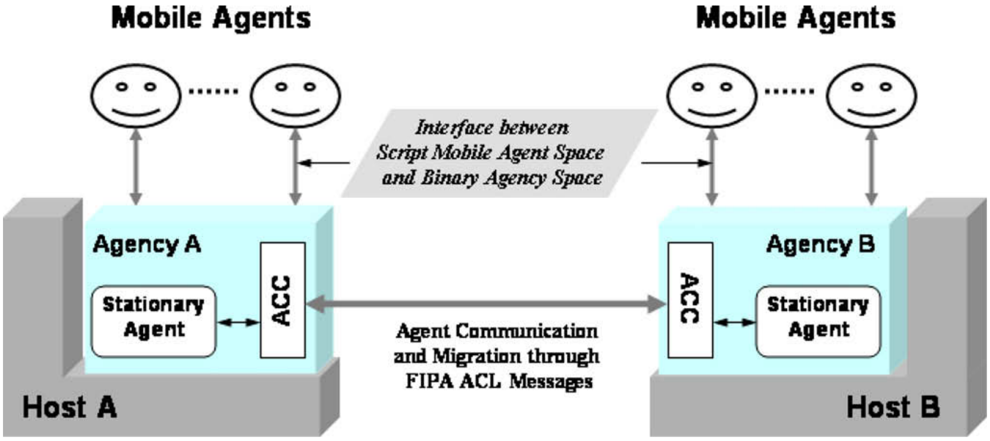

Fig. 4. Agent communication and migration.

4.5. Agent communication and migration

Agents in FIPA compliant agent systems communicate by exchanging messages which are expressed in FIPA agent communication language (ACL). FIPA ACL is a high-level language with a precise syntax and semantics allowing agents to communicate. In Mobile-C, agent communication is achieved through ACC built on top of TCP/IP socket connections as shown in Fig. 4. The transport protocol uses HTTP. Messages are sent asynchronously to a recipient agent identified by its global unique identifier. Messages are expressed in FIPA ACL and encoded in XML. The local agent to agent platform information exchange is achieved by Ch SDK and Embedded Ch (http://www.softintegration.com/), an interface between agent platform space (binary C/C++ space) and interpreter space (Ch space).

Mobile agent migration is also achieved through ACL mobile agent messages, which convey mobile agents as the content of a message. Mobile agent migration based on ACL messages is simple and effective for agent migration in FIPA compliant systems because these systems have mandatory mechanisms for message transmission and processing.

5. Simulation of mobile agents for dynamic algorithm and operation deployment

This section presents the simulation of mobile agents for dynamic algorithm and operation deployment. Fig. 5 shows the configuration of the simulation. The simulation system consists of a laser-based highway detection system and two networked computers, one acts as laser detector agency and the other acts as a higher level agency. The laser-based highway detection system shown in Fig. 6 was developed in the Integration Engineering Lab at UC Davis sponsored by Caltrans (Cheng et al., 2001, 2005; Wang et al., 2003). The laser-based detection system is designed to detect the delineation and speeds of moving vehicles on the highway. The detection system consists of two laser/sensor pairs. Each pair has a laser module and a spatially offset sensor. The detector is positioned above the plane of detection (the road surface). The laser module utilizes line-generating optics to generate a laser beam and projects it to the road surface where objects are detected. The sensor

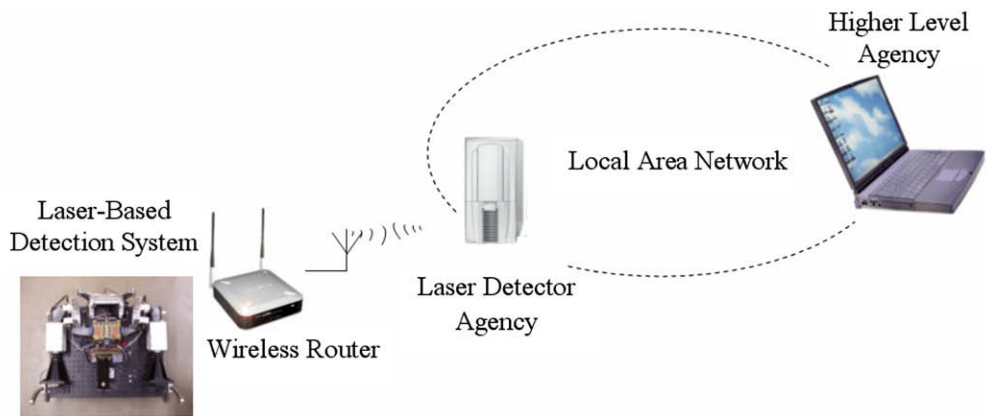

Fig. 5. The configuration of simulating mobile agents for dynamic algorithm deployment.

Fig. 6. A laser-based highway detection system.

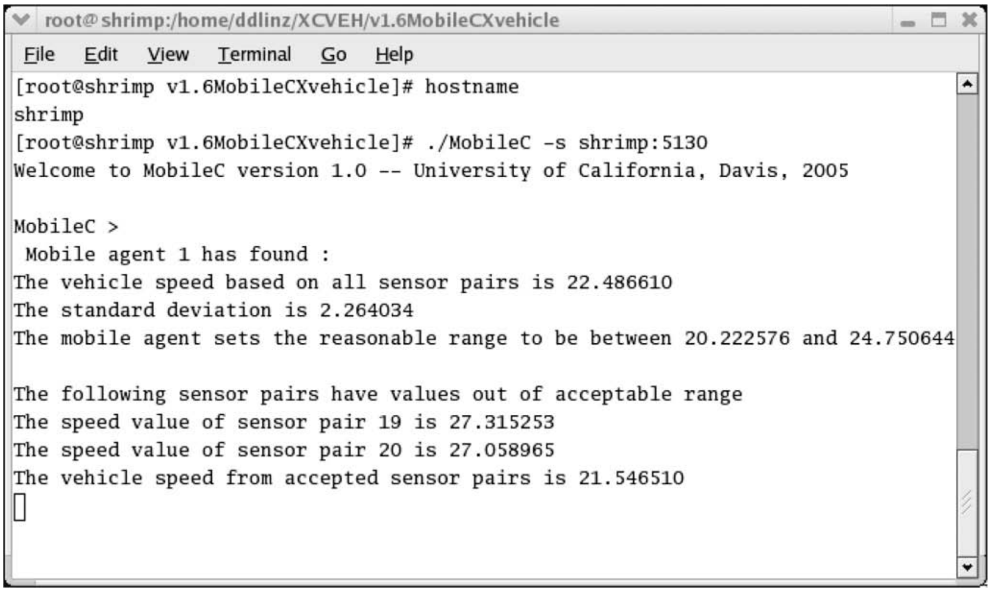

Fig. 7. The mobile agent outputs in LRD agency.

consists of sensor optics and an avalanche photodiode (APD) array with 24 elements. The offset sensor receives the reflected laser light emitted from its laser module counterpart. The sensor output signals are processed by the signal pre-processing circuitry to generate reliable digital signals. A Rabbit 3200 microprocessor reads these digital signals, packs them into TCP packages, and sends these TCP packages to a remote LRD agency through a wireless Ethernet connection. The stationary LRD agent in the LRD agency processes real-time vehicle data and does necessary calculation for the speed, acceleration, and the length of detected vehicles. Since each sensor array has 24 elements, the vehicle speed is the average speed of 24 speeds measured by 24 sensor pairs. The raw data are also saved to data files for further processing or off-line playback.

In this simulation, a mobile agent is dispatched by a higher level agency to the LRD agency. The task of the mobile agent is to check the detection results from 24 sensor pairs and use new algorithm to replace the local vehicle speed calculation algorithm if there are sensor pairs whose values are out of a reasonable range. When the mobile agent reaches LRD agency, it communicates with the stationary LRD agent and reads the real-time detection data. After that, the mobile agent dynamically sets a checking range according to the standard deviation of vehicle speeds based on the entire 24 sensor pairs and uses

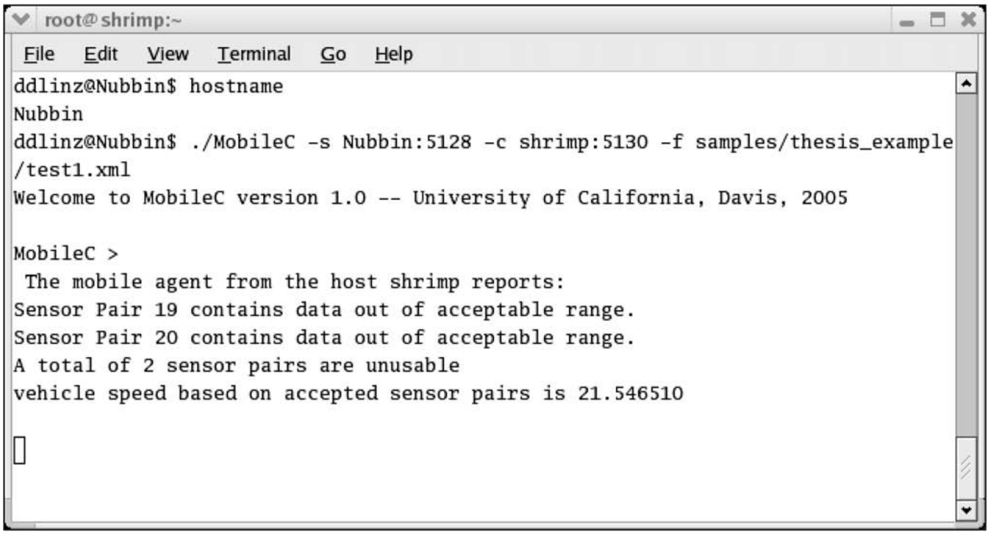

Fig. 8. The information sent back by the mobile agent.

this range to check each sensor pair. The sensor pairs that are out of this range are checked and will not be used to calculate the final vehicle speed. Fig. 7 shows the execution results of the mobile agent in LRD agency. The estimated vehicle speed based on 24 sensor channels is $v1 = 22.486610$ mph. The standard deviation of 24 speeds is std = 2.264034. The mobile agent sets the lower and upper boundary of the acceptable range to be $v1 - \text{std}$ and $v1 + \text{std}$, respectively, and uses only sensor pairs that are within this range to calculate the final vehicle velocity of 21.546510 mph. The mobile agent also sends the names of bad sensor pairs and the new vehicle speed back to the higher level home agency as shown in Fig. 8.

6. Conclusions

This paper reports our research on integrating mobile agent technology with multi-agent systems for distributed traffic detection and management. An IEEE FIPA compliant mobile agent system called Mobile-C has been developed. Based on Mobile-C, the ABRTTDMS has following advantages:

- It supports both stationary agents and mobile agents. Mobile agents enhance the ability of a traffic management system to deal with the uncertainty in a dynamic environment.
- ABRTTDMS is designed to be compliant with IEEE FIPA standards both at agent-level and agent platform level. Compliance with IEEE FIPA standards ensures the interoperability of ABRTTDMS.
- ABRTTDMS integrates multiple detection systems, which enables traffic operators to have a comprehensive view of a traffic system. The open architecture of ABRTTDMS allows new detection systems to be easily added by wrapping them into sub-agent systems.

Using mobile agents for dynamic algorithm and operation deployment has been simulated through a laser-based vehicle detection system, laser detector agency, and a higher level agency. The simulation results showed that mobile agents provide an effective way for dynamic software component deployment.

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