Multi-agent Infrastructure Assisting Navigation for First Responders

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ABSTRACT

Navigating multiple first responders to multiple destinations avoiding moving obstacles poses a set of challenges for navigation researchers. When first responders are performing their tasks, new data about the moving obstacles and new tasks might arrive, which create needs for re-planning of routes and re-allocation of tasks. To be able to do so, they need a path planner that is capable of processing large volumes of spatio-temporal data from different resources, and able to generate routes as quickly as possible. In this paper, we propose a multi-agent infrastructure for navigating multiple responders to multiple locations avoiding moving obstacles. To our knowledge, this type of navigation has not yet been addressed in the literature. We design and develop a set of software agents according to their roles in emergency response, which assists emergency actors in data collection, data processing, route generation, and task allocation. We also use an auction-based approach to allow the agent system to allocate different target locations to the responders. We apply our system to a real road network and show some preliminary results.

Categories and Subject Descriptors

H.4.2 [**Information Systems Applications**]: Metrics—*Decision support*; I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*Multiagent systems*; C.0 [**Computer Systems Organization**]: General—*System architectures*

General Terms

Design, Performance

Keywords

Multi-agent system, Navigation, First responders

1. INTRODUCTION

In this paper, we concentrate on navigation cases that one or multiple moving objects have to be navigated to many static destinations, avoiding many moving obstacles. It has practical application in disaster management when disasters (e.g. fire, plume) occur and emergency response groups are sent to multiple places to search and rescue people [1]. To perform their tasks, the groups have to consider dynamic environments as well as the locations of the other groups. Therefore the coordination and communication between the groups is very important. We use hazard simulation models (e.g., fire model [2], plume model [3]) to capture dynamics of the hazards and to make predictions about the obstacles produced during disasters. However, as the sensor measurements change over time, the predictions provided by the hazard models using the sensor information may also change rapidly, resulting in vast amounts of dynamic information. Moreover, when responders are on their way to perform their tasks, new tasks might arrive. In such cases, re-allocation of tasks and/or re-planning of routes have to be performed. To deal with these changes, a navigation system is needed, which can process large volumes of updated data obtained from the hazard simulation models and can quickly generate new routes.

In this study we apply agent technology to aid emergency navigation. A set of software agents with specific functions is designed to assist the routing process to avoid moving obstacles. Agent technology has been widely used in many applications, such as location based services [4, 5], information provision [6], data exchange and processing [7], and vehicle routing problems [8, 9, 10]. Recently there is a growing interest in application of agent technology in GIScience [11]. Various types of agents are being developed to study interactions and behaviours between entities in a spatial environment as well as to support spatial data handling, distributed problem solving, or data interoperability. Here we design Software Geospatial Agents [11] that assist people in managing geographic information.

Path planning to avoid moving obstacles has the following features that make agent technology a proper tool to solve this problem. First, the path planning problem can be decomposed into a number of sub-problems, such as localization, collection and processing of data about moving obstacles, route generation, visualization and guidance, etc. These sub-problems can be distributed amongst a group of agents in such a way that each agent focuses on an individual local problem. Second, the data about moving obstacles come from different hazard simulations and have different structures and formats. Various types of agents with

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domain-specific knowledge can be developed to handle the hazard simulation output data, and integrated into the system according to real applications needs. Third, because the environment affected by disasters changes rapidly, the agents can act autonomously on behalf of GIS specialists to collect the spatio-temporal information of the environment, and can adequately respond to the environmental changes.

In our navigation system, we develop a set of software agents to deal with spatio-temporal information produced during disasters, to generate obstacle avoidance paths, and to dynamically assign tasks (i.e., target locations) to multiple responders. Here we try to shorten the total time taken to visit all the target locations. We are not much interested in obtaining the optimal solutions, because the optimal solution requires extensive computations and is sensitive to environmental changes. We try to give a method that is simple and robust, combining existing algorithms to give a feasible solution in the fastest possible time. This is indeed important for emergency response because there is no time to wait for hours calculations.

The remainder of the paper is organized as follows. The next section analyses the related works mentioning the routing among moving obstacles and task allocation. Section 3 further explains the proposed multi-agent system. Section 4 describes the implementation of the proposed system. Section 5 shows the results of a case study in its application to a real road network. In Section 6, we present some preliminary experimental results. Finally, Section 7 gives the conclusions and some future work.

2. RELATED WORK

The emergency navigation problem we consider consists of two aspects: routing among moving obstacles and task allocation. Here we give a brief overview of prior work on these two aspects.

2.1 Routing Among Moving Obstacles

Natural disasters can create all sorts of moving obstacles (e.g. floods, plumes, fires), which makes parts of the road network inaccessible for certain periods of time. In robotics, routing among moving obstacles has been considerably investigated. [12] introduces the concept of safe intervals to compress search space and to generate collision free paths in dynamic environments with moving obstacles. [13] presents an online-based method to address the problem of multi-robot pursuing a moving target amidst both dynamic and static obstacles. The proposed method first generates a set of collision-free paths and divides possible directions into several parts, from which a near-optimal path to the target is selected for the robot to follow. [14] proposes a roadmap based approach to find a trajectory for a robot in a scene with both static and dynamic obstacles. It uses two-level strategy: first to find local trajectories on single edges of the roadmap and then to find a global trajectory in the entire roadmap. However, most of the previous research in robotics focuses on the routing within free space, which doesn't consider constrained movement on a network. In [1], we study the routing problem taking into account both the network and dynamic obstacles. We also extend the A* algorithm to solve the shortest path problem by incorporating dynamic blocks caused by moving obstacles [15]. This extended algorithm is used generate routes from a single source to a single destination, when multiple responders and multiple destinations are involved.

2.2 Task Allocation

The task allocation problem arises when a number of tasks have to be assigned to a team and have to be accomplished by the members. It has been thoroughly studied in robotics [16]. The considered tasks are simply locations that should be visited by the robots, so the task allocation problem for robots is essentially the path planning problem. Due to situations changes and robot failures, the tasks need to be re-allocated, which can be considered as a dynamic task allocation problem. Auction-based approaches have been proposed for coordinating multiple robots by [17, 18] and are being recently applied to dynamic allocation problems. [19] presents an auction-based method which allows rebidding on the un-accomplished tasks, addressing robustness issues caused by unexpected events. [20] evaluates the effects of different auction schemes on the optimality of the dynamic task allocation results. Because of its efficiency in multi-agent coordination [16], in this study we apply an auction-based approach to allocate tasks to rescue vehicles and focus on the ability of the multi-agent system to adapt to changing conditions of the road network.

3. THE PROPOSED MULTI-AGENT SYSTEM

In this section, we propose our multi-agent infrastructure for navigating multiple responders avoiding moving obstacles. The proposed infrastructure is compliant with the model formalising emergency response processes and actors.

3.1 Formalization of The Processes in Emergency Response

In the Netherlands, emergency response procedures have been well defined and formally modelled [21]. The disaster is managed by *Processes* involving several *actors* that perform certain *tasks*. There are 25 types of *processes* defined for four *sectors*: police, fire brigade, municipality, and medical care (see figure 1). Because fire brigade is one of the primary responders in the Netherlands, we take fire fighting as an example to illustrate the workflow of fire brigade. In the case of big fires, server *processes* will be activated. The call centre receives the emergency call, registers the incident, and informs the responsive fire brigade units to fight fires and to do measurement and observations. A special Regional Operational Team (ROT) is formed to lead management of the emergency and to coordinate actions. The officer on duty and the fire brigade trucks leader move to the location of the fire incident. On the way to the fire they examine the needed information, such as vulnerable objects in the area, the locations of fire hydrants, etc., and request the optimal route to the destination. They also report to the ROT. The above process can be enhanced with agents that assist emergency actors in handling the needed information for routing in the case of fire.

3.2 The System Architecture

Following the above procedures defined for emergency response, we introduce our multi-agent system assisting navigation in emergency response. It is composed of five types of agents (see figure 2): Hazard Agent, Network Monitoring Agent, Task Monitoring Agent, Task Allocation Agent, Vehicle Agent. Each agent is developed to support the tasks performed by emergency actors. The Task Monitor-

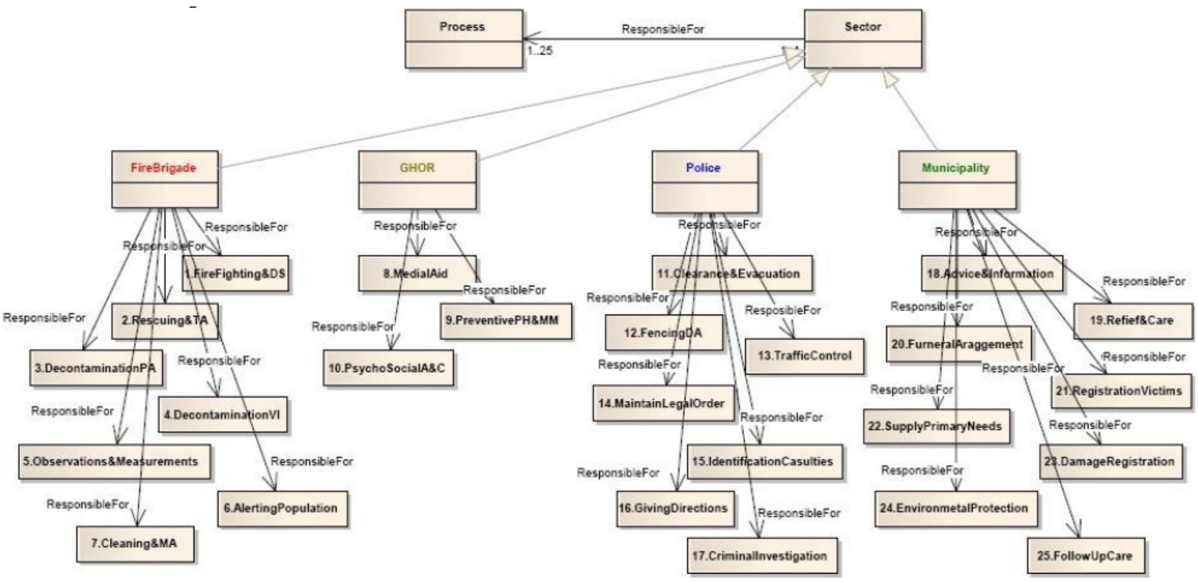

Figure 1: *Processes* defined for emergency response *sectors* in the Netherlands (from [21])

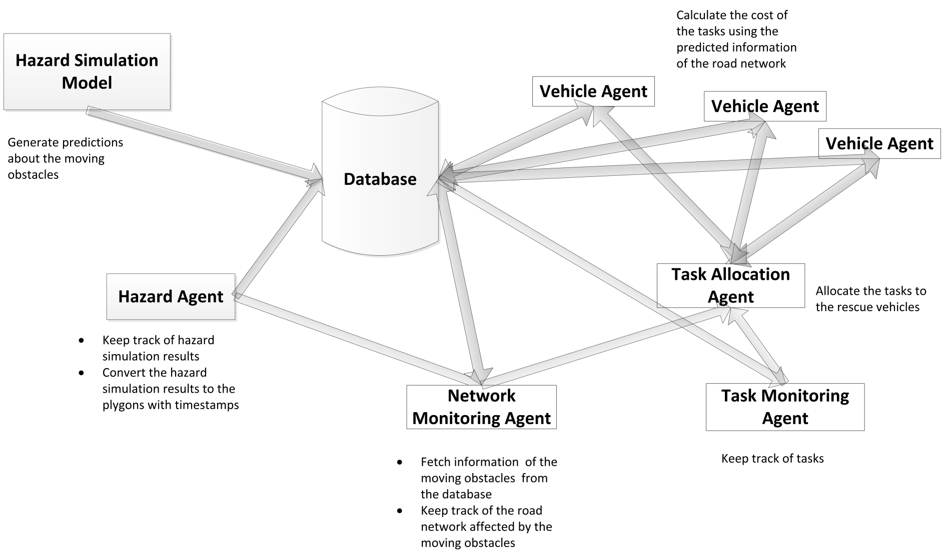

Figure 2: The architecture of the proposed multi-agent system

ing Agent helps the Call Centre to collect tasks. The Task Allocation Agent corresponds to the ROT, coordinating activities of other actors. The Vehicle Agent is developed to assist the response units (e.g., the fire brigade vehicles) in the routing. Because the first responders are usually not GIS specialists or hazard simulation experts, two types of agents are added into the system: the Hazard Agent, which deals with the hazard simulation data, and the Network Monitoring Agent, which handles the spatio-temporal information of the network. Since we focus on allocation issues and especially on efficient allocation calculations, we make the following simplifications:
(1). The execution time of tasks is neglected.
(2). The communication network between agents is always available.
(3). All rescue vehicles are equal and have the same moving speed.

3.3 Hazard Agent

The Hazard Agent provides the data about obstacles with a timestamp and updates the database. In our system, the obstacles during disasters are represented as one or more moving polygons crossing a certain road network (see figure 3). These moving obstacles block some roads for certain periods of time. This agent can be extended to different types of hazard agents with specific knowledge to handle the output data from different hazard simulations. Here the Hazard Agent is manly used to test our proposed system.

3.4 Network Monitoring Agent

The Network Monitoring Agent is responsible for both processing predicted disaster information and collecting spatio-temporal information of the road network. It retrieves the polygons, which represent obstacles, from the database. Then an intersection operation between the obstacle polygons and the road network is performed to determine all the affected roads and the time periods they are not accessible.

(a) T=t_1 (b) T=t_2

Figure 3: Snapshot of a moving obstacle at different time instances ($t_1 < t_2$)

3.5 Task Monitoring Agent

The Task Monitoring Agent collects all available tasks and updates them into the database according to the data model designed for emergency response [22]. Because the task ordering has an influence on the allocation results, we order the tasks based on their priorities. The priorities are associated and dependent on the processes. The tasks with higher priorities are passed first to the Task Allocation Agent for auction to guarantee that they are accomplished first. The tasks associated with the same process are ordered based on the First In First Out (FIFO) strategy.

3.6 Task Allocation Agent

The Task Allocation Agent is responsible for coordination of all rescue vehicles. A dynamic allocation strategy is applied for this agent to allocate all available tasks to the Vehicle Agents. In the system, we use the sequential single-item (SSI) auction scheme for dynamic task allocation. During auctions, the Task Allocation Agent first makes an announcement to all vehicle agents notifying them about a new task. Then the Vehicle Agents calculate the cost of completing the new task and decide for themselves whether they should bid for the task. Finally the Task Allocation Agent collects the bids and selects the Vehicle Agent with the lowest cost to carry out the new task. Because we focus on the dynamic task allocation considering dynamic information about the road network, i.e., dynamically allocate tasks according to the predictions of disasters, all previously assigned but unaccomplished tasks should be auctioned again. The allocation process is restarted when new predictions about obstacles arrive.

3.7 Vehicle Agent

The Vehicle Agent corresponds to a single rescue vehicle and is characterized by a set of attributes (i.e., position, current speed, maximal speed ,and type of vehicles) and performs certain actions (i.e., moving, waiting, and bidding). During auctions, it estimates the cost of carrying out the potential tasks and sends the bid to the Task Allocation Agent. Here the estimated cost is the completion time of the new task. It is calculated by the routing algorithm presented in [15], based on the path planning from the last assigned task with its completion time to the new task.

4. IMPLEMENTATION

We have implemented the proposed multi-agent system for emergency navigation by using Java Agent DEvelopment framework (JADE) [23]. JADE (http://jade.tilab.com) is a free, open source software. It is developed by TILAB (Telecom Italia LABoratories), in compliance with the FIPA specifications with respect to the platform architecture as well as the communication infrastructure. JADE has been successfully used in many academic and industrial communities. To make the multi-agent capable of handling the spatial data, we use JADE as underlying agent infrastructure and combine it with another agent-based toolkit, Mason [24, 25], to enhance the JADE agents with GIS functionalities. This combination allows agents not only to perform spatial data process and analysis using the utility methods provided by Mason, but also to communicate and collaborate with each other using the services provided by JADE. We select OpenStreetMap (www.openstreetmap.org) as a data source to extract the street network. The developed multi-agent system is connected with a geo-database, PostGIS (http://postgis.refractions.net) that supports storage of the spatio-temporal data produced during disasters. We also develop an exporter to generate files that can be read by other applications, such as web-application, android application.

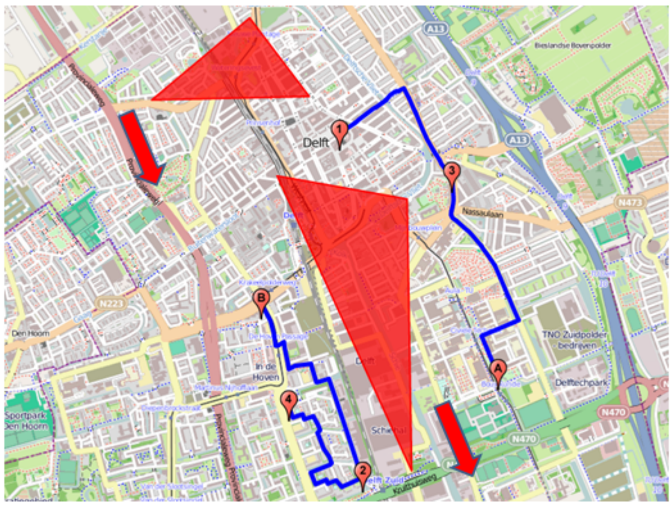

Figure 4: Snapshot of calculated routes (in blue) for two vehicles avoiding two moving obstacles (in Red)

5. CASE STUDY

We have applied our multi-agent system to the city road network of Delft, using artificial disaster datasets. The network is composed of 1586 edges and 1780 nodes. We study the case that two first responders have to be routed to multiple destinations avoiding moving obstacles. The considered scenario is that a chemical plant explosion takes place in the northern part of the city and results in several moving contaminant plumes. Two different processes are activated, which involve four tasks that should be allocated to two fire

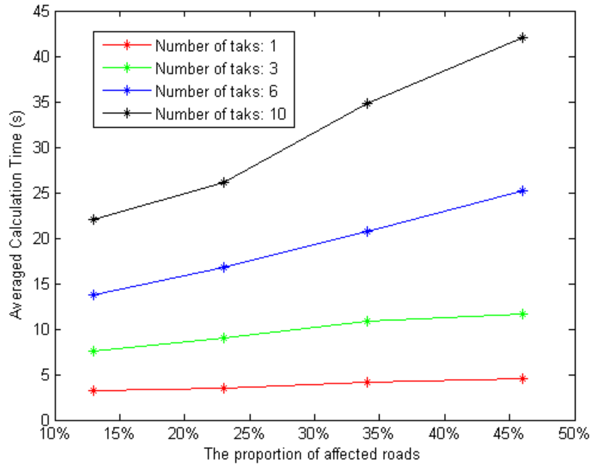

Figure 5: A comparison of calculation time

brigade vehicles. Each task is associated with a location and consists of a set of operations that should be performed at that location. *Rescuing Process*={*task2*}, *Measurements and Observations Process*={*task1, task3, task4*}. Here we assume that *Rescuing Process* has a higher priority than *Measurements and Observations Process*.

Figure 4 shows the results of the assigned tasks and the generated routes for the two vehicles. As we can see, although the *task4* is closer to the starting location of *VehicleB*, *task2* is accomplished prior to *task4*. Because the tasks are ordered by their priorities, the Task Monitoring Agent (i.e., the Call Centre) passes *task2* first to the Task Allocation Agent for auction to guarantee that it will be accomplished first. The other tasks are allocated to the vehicles with the lowest travel time cost, which ensures the efficiency of the whole group.

6. TEST

Because the calculation capability of navigation systems is important for emergency response, we did a set of experiments with different environment configurations to evaluate some factors on the performance of our system. Each experiment was repeated five times with different number of tasks and different impacts of moving obstacles on the network. In each run, we randomly selected destinations for different vehicles to avoid bias effects caused by target locations. We used the proportion of affected roads to indicate the impact of moving obstacles on the road network. Four datasets of moving obstacles were generated to vary the impacts on the road network. We compared the allocation time with the different experimental setups and averaged the results over five runs.

Figure 5 shows the results of our experiments. From the figure, we can see that the allocation process become slower as we increase the number of tasks. The figure also indicates that increased affected roads in the network leads to a higher allocation time. This is because the affected roads introduce more possibilities in the search space, which results in more calculation time for the extended shortest path algorithm [15] to explore.

7. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a multi-agent infrastructure to support navigation for multiple first responders to multiple destinations avoiding moving obstacles. Five types of agents are designed and developed in the proposed multi-agent infrastructure to assist the emergency actors, collect spatio-temporal information of road network, and perform route planning and task allocation. We integrate the extended shortest path algorithm to generate routes avoiding moving obstacles, and the auction-based approach to assign the target locations to the rescue vehicles. This integration allows the rescue vehicles to dynamically adjust their routes and destinations as soon as new predictions of the obstacles and new tasks arrive, which is a way to adapt to dynamic situations.

Compared to other multi-agent systems developed for vehicle routing problems, our multi-agent infrastructure for emergency navigation has the following advantages: (1) follows the emergency procedures defined for the emergency actors, (2) supports incorporation of the user profile into the routing process, and (3) supports integration of different hazard simulation models to provide information about moving obstacles. Despite these advantages, the current system has some limitations that should be addressed in further developments. First, the tasks considered in the paper are simply locations visited by the rescue vehicles. The execution time of the tasks is neglected. Because we plan paths using the predicted information of the network, the temporal aspect is very important. Adding duration of tasks and considering it into the routing process will make the system even more realistic. Second, currently the routes are calculated in an automatic way, but the results may not meet the responders' requirements. In some situations, the responders want to interact with the agents and influence calculation results. The system should be equipped with adjustable autonomy techniques to allow human and machine interactions. Third, the performance of the multi-agent system relies on the availabilities of the communication network and the cooperating agents. The failure of any of them could make the proposed system incapable of allocating tasks. Taking the failure situations into account will make the system more robust to unexpected changes

In future work, we will apply the system to aid navigation in various types of natural disasters, using different hazard simulation models (e.g., fire model [2], plume model [3]). More types of agent will be designed and integrated into the system to handle heterogeneous data from these models. Furthermore, we will investigate the routing among non-clear boundary obstacles. In some situations, the obstacles produced during disasters are not homogeneous, e.g. the toxic gas has variable concentration or the inundation depth vary in the flooded area. These obstacles are usually also dynamic, i.e. their shape and characteristics change with the time. Adding user profiles into the routing process is needed to identify conditions under which the responder can go through these obstacles. A spatio-temporal data model should be also defined to support the representation of the non-clear boundary obstacles and their influence on the road network.

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