Situation-Aware Multi-Agent System for Disaster Relief Operations Management

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ABSTRACT

Natural and human-made disasters create unparalleled challenges to Disaster Situation Management (DSM). One of the major weaknesses of the current DSM solutions is the lack of comprehensive understanding of the overall disaster operational situation, and very often making decisions based on a single event. Such weakness is clearly exhibited by the solutions based on the widely used Belief-Desire-Intention (BDI) models for building the Muiti-Agent Systems (MAS). In this work we present the adaptation of the AESOP situation management architecture to address the requirements of disaster relief operations. In particular, we extend the existing BDI model with the capability of situation awareness. We describe how the key functions of event collection, situation identification, and situation assessment are implemented in MAS architecture suitable to the characteristics of large-scale disaster recovery. We present the details of a BDI agent in this architecture including a skeleton ontology, and the distributed service architecture of the AESOP platform.

Keywords

Disaster relief operations, situation management, multi-agent systems, BDI agent model

INTRODUCTION

Natural and human-made disasters create unparalleled challenges to the response, relief and recovery operations. Disaster Situation Management (DSM) is a complex multi-dimensional process involving a large number of inter-operating entities (teams of humans and systems) and is affected by various social, medical, geographical, psychological, political, and technological factors. From the information technology viewpoint the DSM processes can be hindered by lack of adequate, comprehensive and timely information; the presense of conflicting goals, policies, and priorities; lack of effective coordination between different rescue operations augmented with inability of many units to act autonomously. Consequently there are important research issues to improve the current methods and algorithms of DSM.

To a large extent the conventional DSM practice is characterized by a large number of heterogeneous loosely connected or isolated systems, including databases, event monitoring and dispatch systems, public or private voice and data communication systems (over fixed or wireless lines), and public emergency announcement systems. During the last decade significant progress was made in the development and deployment of integrated disaster information monitoring systems, including weather, earthquake, fire, chemical, radiological and biological activity monitoring systems. Experimental computer supported cooperative work (CSCW) systems were developed for planning the routes and dispatching the emergency medical, fire, and police vehicles. The introduction of GPS and GIS added significant functionality to the disaster monitoring and emergency team dispatching systems. In recent years the progress in miniature low-powered sensors and sensor networks, unmanned aerial vehicles (UAVs), geo-spatial information systems, wireless broadband communications, and new emerging solutions of cognitive information processing, situation management, distributed computing, and agent-technologies are opening opportunities for new solutions for DSM.

Previously we described a case study of urban transportation threat monitoring using situation management (Buford, 2005). In the post-incident recovery phase, the situation manager uses the situation models and event data captured during the preventive and deployment phases to help operations staff to characterize the scope of incident, deploy evacuation resources, communicate to the public, control and contain the perimeter, manage recovery and cleanup, and collect forensics.

The Multi-Agent Systems (MAS) (Wooldridge, 2002) approach has proven to be an effective solution to solve the disaster situation management tasks due to the distributed organizational framework, the use of the behavioral principles of mobile intelligent agents, and natural fit to model the teaming of both the human and system entities.

The need to model the intelligent acts of perception of the operational environment, goal-directed behavior, and reasoning about the environment, prompted the MAS community to use the well-known conceptual architecture of Belief-Desire-Intention (BDI) agents (Bratman, 1987; Rao and Georgeff, 1995). Since its inspection, BDI model has experienced several functional advancements and software implementations, however recent attention to large-scale disaster relief operations, homeland security tasks, and management of asymmteric network-centric battlespaces have revealed the weakness of the current BDI model, namely the weakness to cope with the fast moving, unpredictable and complex operational situations. The major reason for this weakness in the BDI model is two-fold: (a) a relatively simple reactive paradigm "Event-Plan", and (b) lack of synergy between the stages of reactive and deliberative reasoning.

In this work we propose to extend the BDI model with the capability of situation awareness, particularly, we propose the paradigm "Event-Situation-Plan", where plans are activated not as a response to a single event, but they are generated based on recognized dynamic situations. This dynamic situation recognition process is carried out by two synergistic tasks, event correlation (reactive component) and analogy-based reasoning (deliberative) component.

We can refer to several recent approaches and experimental systems, which use the elements of situation awareness, and which experiment with the tasks of disaster management and medical emergency situation management, including using the methods of high-level data fusion and situation analysis for crisis and disaster operations management (Llinas, 2002; Scott and Regova, 2004), knowledge-driven evacuation operation management (Smirnov et al, 2005), and urban transportation threat monitoring (Buford, 2005).

The rest of the paper is organized as follows. The next section describes an overall model for DSM applied to medical relief operations. We then decompose the DSM model into a multi-agent system. The following two sections describe the agent model using the Belief-Desire-Intention paradigm and a medical relief ontology for the BDI agents respectively. We then describe a realization of the MAS architecture in the AESOP situation management platform.

A DSM SCENARIO: MANAGING POST-DISASTER MEDICAL RELIEF OPERATIONS

Medical Relief Operation Scenario

A critical element of disaster recovery is medical relief to provide treatment and support to those injured due to the disaster or whose previously sustained conditions or vulnerability (e.g., elderly or displaced patients) place them in medical jeopardy due to the disaster. Medical relief operations include field mobile ambulatory aid, evacuation processes, emergency hospital operations coordination, and logistics support for medical supplies and equipment.

The scale of the disaster determines the number of jurisdictions and relief organizations participating, the extent of use of extra-regional medical teams, and the overall complexity of the coordination and communication. In the case of recovery involving international teams, language and equipment differences compound the communication problem. The scope of the disaster may frequently make local medical facilities inoperative, and it may place relief teams in hardship conditions or at risk due to infrastructure damage and unknown conditions, limited food and water supplies, societal breakdown, and lack of law enforcement support.

At the information level, there is a significant distribution of data across teams of people, systems, information sources, and environments, and the ongoing data collection and changing state makes the overall picture very dynamic. Further, there is a strong benefit to the overall effort if different teams can share relevant information. For example, in order to perform effective provisioning of field medical services, the mobile ambulatory teams need to develop a common inderstanding of the medical situation on the ground, share road and access information, and coordinate medical relief and evacuation operations.

Specific tasks that need to be supported in an automated DSM system include:

- Overall planning of the medical recovery effort including sizing, personnel, equipment and supply requisition
- Dispatching, scheduling, and routing of mobile ambulatory and other emergency vehicles
- Evacuation of victims
- Prioritization of relief operations
- Maintenance and well-being of relief personnel
- Resource allocation
- Coordination and communication between medical teams and to other relief operations

With these considerations, we next describe a high-level closed-loop system (Figure 1) in which situation-awareness is used to address these issues and requirements.

DSM – Forward Path

The DSM (Figure 1) constructs a real-time constantly refreshed Situation Model from which relief operations can be planned and updated. The Situation Model contains a knowledge-level view of the disaster from the medical relief perspective, using an ontology specifically designed for that domain. The model is created and updated by a constant flow of events and reports collected from the operational space. These events include both human intelligence and signal intelligence. Because of the large amount of raw data being collected, the event stream needs to be processed and correlated to produce "situational events", i.e., events at the domain level. This reduction and inference step is performed by an information correlation stage. We describe later in the paper how the information correlation function and the situation assessment function can be distributed in a Multi-Agent System (MAS) architecture.

Integrated with the real-time Situation Model are decision support systems (DSS) for medical relief operations. The DSS rely on the Situation Model and operations staff oversight to manage the scheduling, dispatching, routing, deployment, coordination and reporting tasks. A chain of distributed communication and control systems leads from the DSS to the medical personnel in the field to direct the execution of these tasks.

Medical relief organizations have the responsibility and expertise to prepare for disaster recovery in many different scenarios, which includes defining goals and policies, enforcing legal and regulatory requirements, and specifying deployment plans. These goals, policies, requirements and plans are incorporated into the DSM knowledge base and are used by the situation awareness function and DSS to ensure plans, actions, and priorities are formed consistently.

Although it is an important problem in DSM, the issues of how situation assessment reflects on knowledge and events about the state of its own data collection infrastructure, as might be impacted in a disaster, is not discussed in this paper. Further, the situation assessment function is assumed to use techniques for reasoning with incomplete information characteristic of this type of environment. These techniques permit incomplete and possibly inconsistent situations with different probabilities and event support to be maintained and changed as new information arrives.

DMS - Reverse Path

The DSM (Figure 1) adapts to requests and feedback from medical relief personnel and DSS, as indicated in the reverse path. These requests can lead to refinement of the Situation Model, meta-level guidance to the information correlation function, and a focus on specific sensor data.

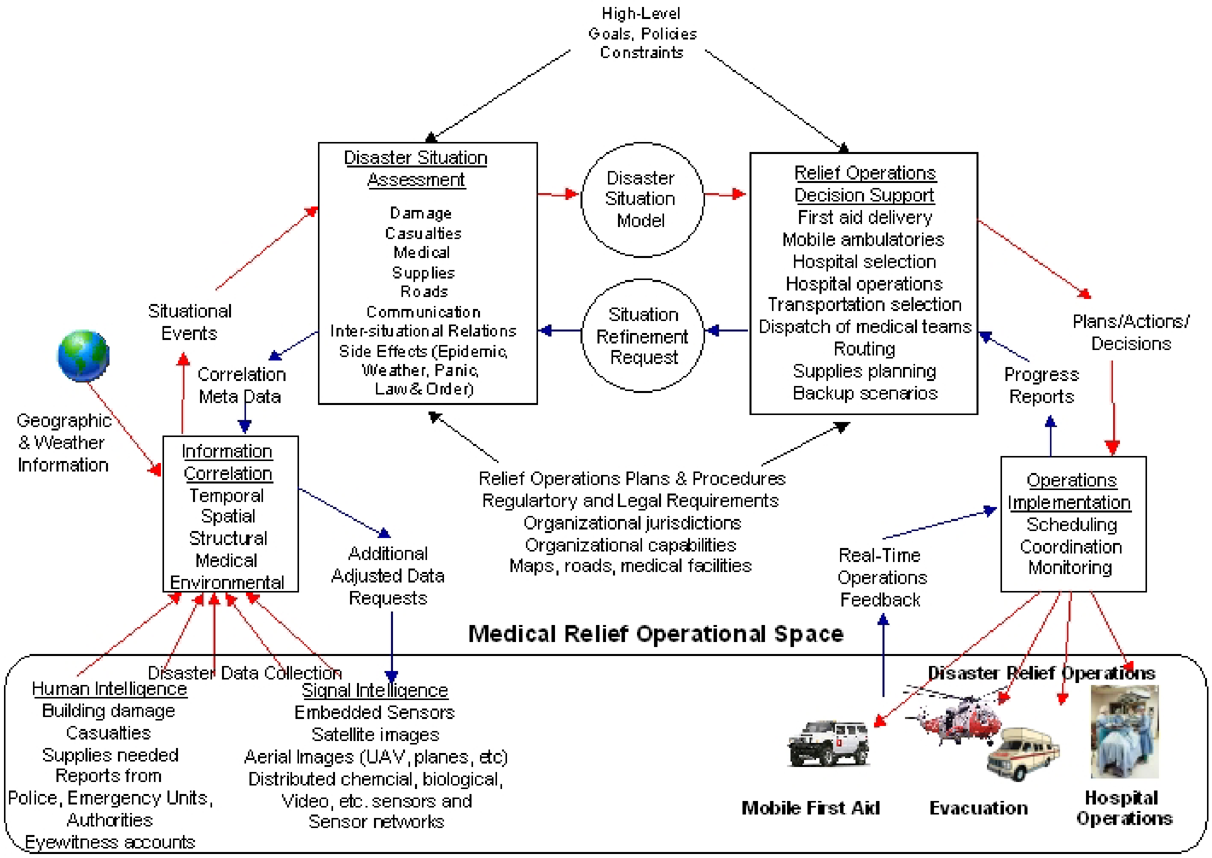

Figure 1 Closed-Loop Post-Disaster Medical Relief Operations Management using DSM

MULTI-AGENT SYSTEMS APPROACH TO DSM

Basic Principles of the Approach

In this section we outline several basic principles that were used in order to develop our MAS approach to DSM.

General Situation Control Loop

We see situation management as a closed-loop process (Figure 2), where primary information is sensed and collected from the managed operations space (the World), then analyzed, aggregated, and correlated in order to provide all required inputs for the situation recognition process. During the next step the reasoning processes are performed to select predefined plans or automatically generate them from the specifications embedded in the situations. It is assumed that all the mentioned steps are performed by agents of the MAS. Finally the actions are performed to effect the World. As the World gets effected, new information about the World is sensed and the proccess is repeated. Having such iterative control loop cycle is an important element of our approach.

Distribution and Specialization of Agents

The distribution and specialization of agents is not a new concept in MAS, howecver the DSM environment creates an interesting subtask, namely mapping the physical agents (vehicles, robots, human teams, etc.) into the abstract framework of MAS. This task involves several enginering considerations, including energy consumption, relative autonomy of physical agents, information sharing, security, etc.

Agent Teams and Control

The natural structure of the DSM operations prompts the MAS organization, where distributed agent teams (communities) having peer-to-peer decentralized internal communication among the agents, are controlled externally by a higher-level control agent (see Figure 2)

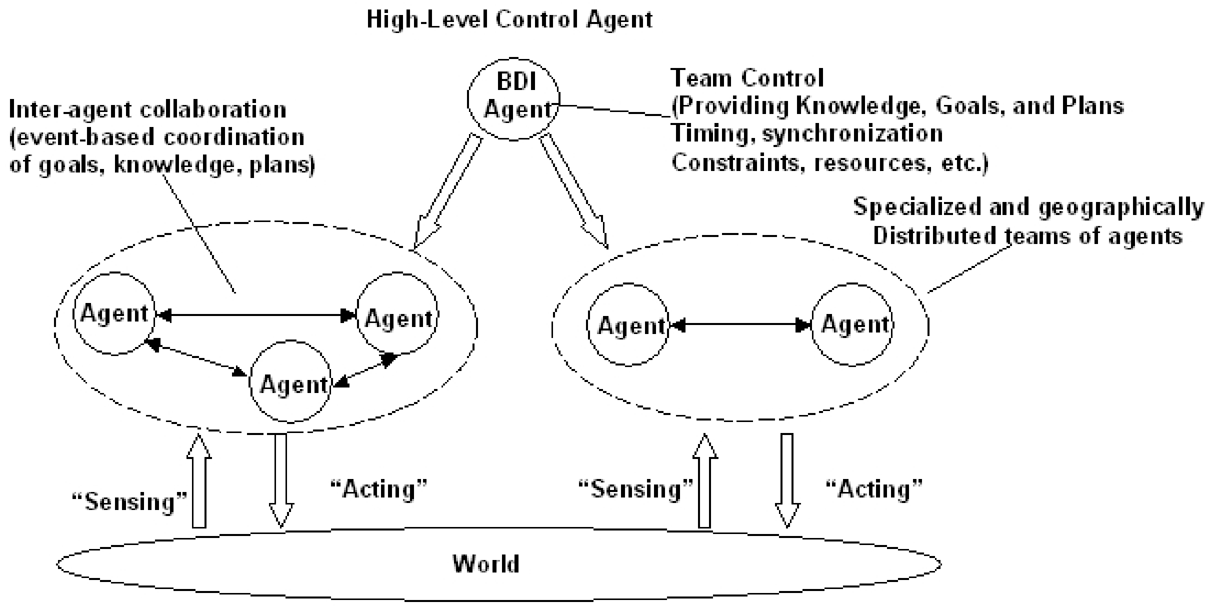

Figure 2. MAS approach for DSM control

Situation-Aware BDI Agents

One of the major contributions of this paper is the introduction of the concept of the situation-aware BDI agent, where the paradigm of classical plan invocation by a single event (Wooldridge, 2002) is replaced by an enhanced model, where plans are invoked by situations. This situation recognition process is carried out by two synergistic tasks, event correlation (reactive component) and analogy-based reasoning (deliberative) component.

As it was illustrated on Figure 1, the DSM domain is characterized by undertaking the actions that in most cases require simultaneous analysis of multiple events. The introduction of the paradigm of plan invocation by a situation has specific importance to the DSM domain, since it allows to proceed with the plans not on a basis of a single event, but taking account the patterns of multiple events. Such event patterns will be recognized due to the use of the methods of event correlation.

Abstract BDI Agent Architrcture

The Belief-Desire-Intension (BDI) model was conceived as a realtively simple rational model of human cognition (Bratman, 1987). It operates with three main mental attitudes: beliefs, desires and intentions, assuming that human cognitive behaviour is motivated by achieving desires (goals) via intentions providing the truthfulness of the beliefs.

As applied to agents, the BDI model got concrete interpretation and first order logic based formalization in (Rao and Georgeff, 1995). Among many BDI agent models, the dMARS formalism serves as a well-recognized reference model for BDI agents (d'Inverno, Luck, Georgeff, Kinny, and Wooldridge, 2004). Since we use the dMARS framework as a starting point to our approach on situation-aware BDI asgents, we will informally sketch the basic notions of dMARS. A BDI agent is built upon the notions of beliefs, desires, events, plans and intensions.

Beliefs are the knowledge about the World that the agent posesses and believes to be true. Beliefs could be specifications of the World entities, their attributes, relations between entities, and states of the entities, relations. In many cases, the agent's beliefs include the knowledge about other agents as well models of itself. Desires are agent's motivations for actions.

Plans are operational specifications for an agent to act. An agent's plan is invoked by a trigger event (acquisition of a new belief, removal of a belief, receipt of a message, acquisition of a new goal). When invoking a plan, an agent tests whether the plan invocation pre-conditions are met, and tests run-time conditions during the plan execution. The actions in the plan are organized into an action control structure, which in dMARS is a tree-like action flow. Actions could be external ones, essentially procedure calls or method invocations; or internal ones of adding and removing of beliefs. Abstract plans are stored in the agent's plan library. During agent operations certain abstract plans are selected from the library and instantiated depending on variable bindings, substitutions and unifications.

An agent's intention is understood as a sequence of instantiated plans that an agent is commited to execute. Always while responding to a triggering external event, an agent is invoking a plan from the plan library, instantiating it and pushing into a newly created stack of intentions. Contrary to that, when agent reponds to an internal triggering event, i.e., an event created by an internal action of some previous plan instance, then the new plan instance is pushed into the stack of the previous plan that caused the invocation of the new plan instance. An abstract architecture of BDI agent is presented on Figure 3

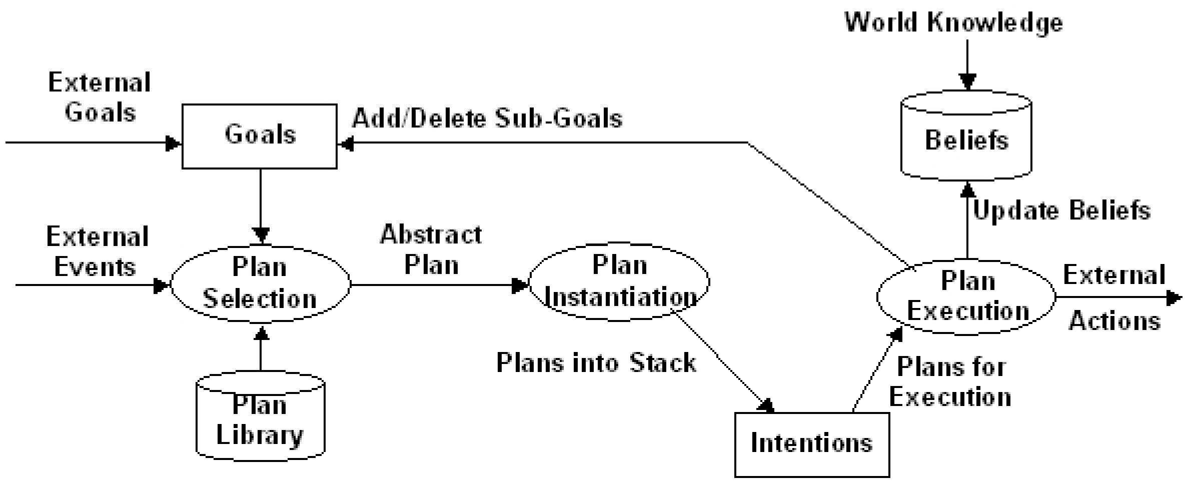

Figure 3. Abstract BDI Architecture (Motivated by dMAS Specification (d'Inverno, Luck et al, 2004)) Situation-Aware BDI Agent

Abstract Architecture

The current BDI models have quite simple plan invocation model, where either the plan is triggered by a single event or by a single goal. Preference between these two invocation methods leads to event or goal-directed planning of actions. While the single goal directed planning satisfies in most cases the majority of the applications needs, the single event directed planning does not. In the majority of cases of military disaster operations planning, battlefield management, and security applications, decisions are made not on the basis of a single event, but rather correlating multiple events into a complex event and mapping it to a situation happening in the operational space. The central piece of our approach to extending the capabilities of the BDI agent is the introduction of situation awareness. According to the proposed approach, a plan will be invoked by a situation, rather by a single event (Figure 4).

The external events received by the BDI agent and the events generated by the agent itself while executing the plans are correlated into compound high-level events called synthetic events. The real-time event correlation process (Jakobson, Buford, and Lewis, 2004) takes into account temporal, causal, spatial, and other domain-specific relations between the multiple events as well constraints existing between the information sources producing the events. The event correlation process could be an iterative multi-stage process, where some synthetic events could be used for building more complex synthetic events.

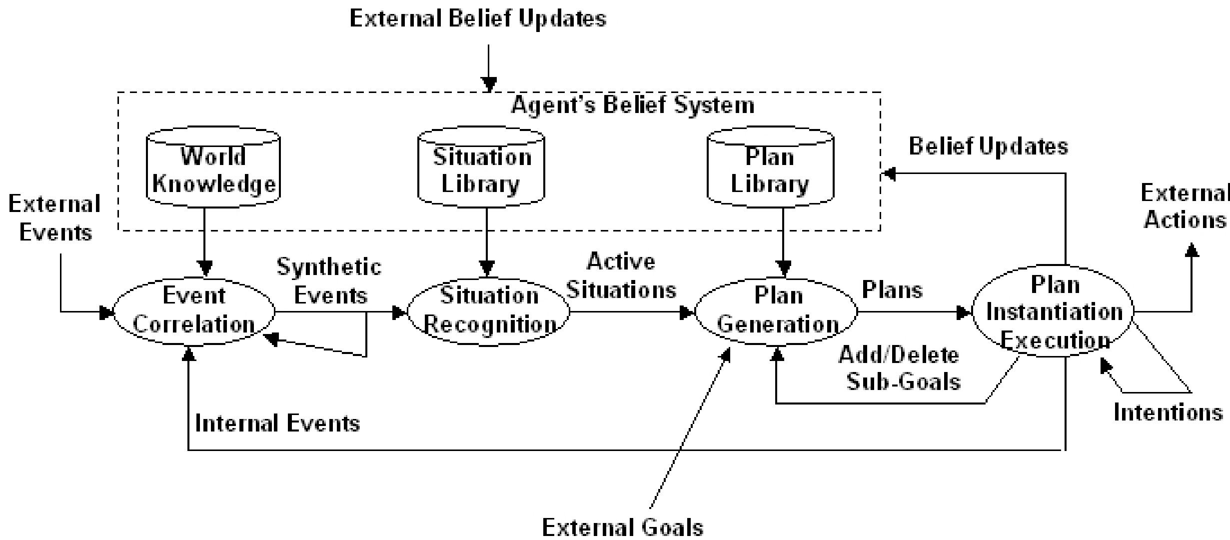

Figure 4. Situation Aware BDI Agent

The synthetic events serve as a basis for recognizing situations taking place in the world. They are used in the triggering patterns of abstract situations while invoking them from the Situations Library. The multiple invoked situations are instantiated and are combined into an overall situational model of the world.

The situations contain either references to the plans that will be invoked by triggering conditions specified in the situations, or contain specifications for reasoning and generating plans. The steps of plan instantiation and execution are similar to those performed in the dMAS BDI model.

Event Correlation Process in BDI Agents

Event correlation is considered to be one of the key technologies in recognizing complex multi-source events. We are using event correlation as a major tool leading to situation recognition. As it will be showed later, the importance of the event correlation process influenced us to introduce a special type of event correlation agent.

The task of event correlation can be defined as a conceptual interpretation procedure in the sense that a new meaning is assigned to a set of events that happen within a predefined time interval (Jakobson and Weissman, 1995). The conceptual interpretation procedure could stretch from a trivial task of event filtering to perception of complex situational patterns occurring in the World. The act of recognition of a new situation by the correlation procedure could be formally handled as a synthetic event, and as such, it is a subject for further correlation.

The process of building correlations from correlations allows the formation of a complex fabric of multiple inter-connected correlation processes, suitable for the paradigm of integrated distributed cognition and collective behavior that is proposed in this project. In the "correlation fabric" we will consider several basic connections between correlation processes as shown on Figure 5. Intermixing between different correlation connections creates a flexible and scalable environment for complex situation modeling and awareness solutions.

While recognizing situations happening in the DSM World, the event/situation correlation process should take account of a variety of different conditions and relations occurring between the static, dynamic and mobile entities of the World. In order to match the complexity and richness of the World from the event/situation correlation perspective, we will introduce the following dimensions to the correlation process:

- Spatial Dimension – geo-spatial, topological and structural relations;
- Temporal Dimension – temporal relations, time-dependent evolution and life-cycle of the entities;
- Conceptual Dimension – concept, concept classes, and concept ontologies;
- Computational Dimension – event filtering, suppression, escalation, and counting, and callable functions;

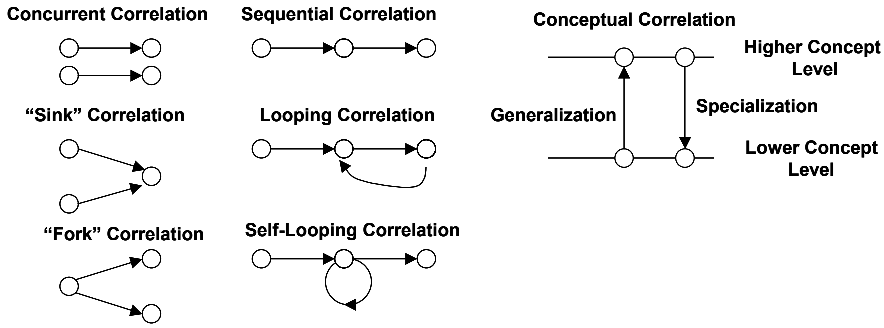

Figure 5. Interconnection Types Between Different Correlation Processes

- Domain Dimension – entities, relations (including causal and action-oriented relations), constraints, policies, first principles, etc., specific to the domain;
- Logical Dimension – Predicate calculus expressions over the terms formed from the statements using the elements of the previous dimensions.

The temporal model-based event correlation technology used in this work has been developed and implemented for managing complex telecommunication networks. More about the details of the technology could be found in (Jakobson and Weissman, 1995).

Situation Recognition and Prediction

Our approach to DSM situation recognition and prediction is to use a specific model of analogy-based reasoning called case-based reasoning (CBR), where a case is a template for some generic situation (Lewis, 1995; Pavón, Corchado, and Castillo, 2004). The formation of the library of standard case templates for representing the typical generic situations allows (a) construction of specific DSM models by selecting the appropriate case templates, (b) modifying and instantiating the selected cases with concrete parameter values, and (c) combining the instantiated cases into overall case representation of the situation. The CBR research community has developed effective solutions for tasks (a)-(c). Further, the CBR approach allows learning from experience and adapting more-or-less standard situations to accommodate the nuances of current situations.

ONTOLOGIES FOR BDI AGENTS

Situation management is a knowledge intensive process and central to this process is situation knowledge representation, i.e. how to effectively and efficiently describe entities, relations, situations, goals, and reasoning processes related to situation modeling and reasoning. One of the most effective tools for handling knowledge is Ontology. Informally, ontology is a set of concepts which define the domain entities and relations between them. Ontology can be expressed using text, graphs, structured data, or tables. Formally, ontology is often expressed using languages based on first (or higher) order predicate calculus, so that detailed, accurate, consistent, sound, and meaningful distinctions can be made among the entities, properties, and relations. The roots of ontology as a knowledge representation method can be found in semantic networks as well as in frame representation languages.

The Semantic Web community with the development of the Web Ontology Language (OWL) has made significant progress in formal ontology specification. OWL has been used with moderate success for describing situations, however the lack of explicit declarations for describing the dynamic components of situation management (events, situations, time, temporal relations, situation transitions, etc.) limits the expressiveness of OWL. Recent extensions to OWL have expanded its rule-based reasoning capabilities (SWRL – the Semantic Web Rule Language).

One can find three major components in ontology: (a) Ontology vocabulary - the set of terms of the modeled domain; (b) The structure of the ontology - statements formed by terms and relations between them; and (c) Rules for semantic interpretation of the statements. Ontologies have multiple dimensions, depending on different application domains, as well the level of abstraction of the concepts that the ontology represents. Regarding those dimensions, the following types of ontologies can be defined:

- Core ontologies – definitions of general concepts that have a wide scope of validity and usually represent the basic concepts and the first principles of the domain. Usually, core ontologies represent theoretical or abstract concepts like entity, relation, attribute, time, goal, list, set, etc.
- Domain ontologies – ontologies describing the concepts of a particular application domain, medical ontology, transportation ontology, etc. Domain ontologies might form complex multi-level hierarchies of component ontologies, e.g. medical ontology, clinical ontology, internal medicine ontology, cardiology ontology, etc.
- Situation ontologies – ontologies which describe typical time-dependent states of the entities and relations between them, e.g. road condition ontology, infrastructure damage situation ontology.
- Problem-solving ontologies – ontologies describing different problem solving methods and algorithms

Depending on the particular situation management context, other, more specific ontologies could be defined, e.g. goal ontologies, action ontologies, and process ontologies could be introduced.

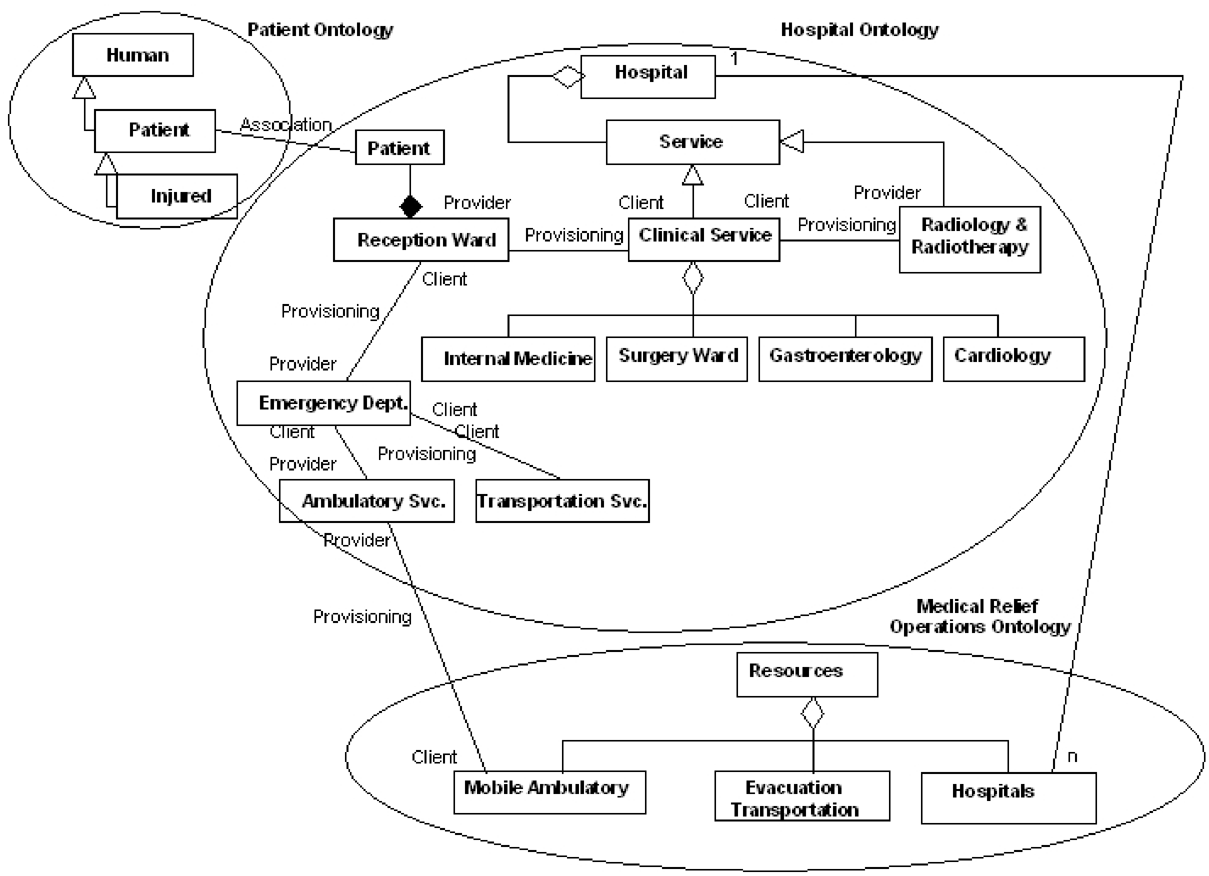

Figure 6. Sample ontology (fragment) for medical relief operations

DISTRIBUTED AESOP PLATFORM FOR IMPLEMENTING DSM SYSTEM

Instantiation of the Abstract Agent Model into MAS

The abstract architecture of the situation aware BDI agent describes the conceptual level of the processes occurring in the BDI agents. In a concrete embodiment of the abstract features of the BDI agents in the MAS framework, one can see a mapping of those abstract features into concrete functions of the agents in MAS. In our approach the abstract features of the BDI agents are mapped into the following categories of agents:

- Agents-Specialists (event correlation, situation awareness, plan generation, etc. agents)
- Perception and Information Access Agents
- Interface Agents
- Belief System Management Agents

An important task of the system design is representation of the physical DSM agents (vehicles, teams of humans, hospitals, etc) in the MAS framework, i. e. mapping from the physical agent level onto MAS agent level. We are not going to discuss this issue in detail, since it is out of the scope of this paper.

AESOP: Distributed Service Architectre Based MAS Implementation

The foundation for implementation of the DSM system is distributed AESOP (Assistance with Events, Situations, and Operations) service architecture (see Fig. 7). AESOP identifies several classes of agents as discussed in the previous section, except with specific customization, which reflects the idiosynchracies of the DSM domain. These agent classes are: Disaster Information Access Agents, Relief Teams Communication/Interface Agents, DSM Agents-Specialists and DSM Belief Management Agents. Each agent is actually an embodiment of a service within AESOP. The use of standard services (agents) with well-defined functionality and standard inter-component communication protocols allows the building of open, scalable, and customizable systems. The encapsulation of the idiosyncrasies of components and the use of functions of addition, replication, and replacement of services provides an effective environment for developing multi-paradigm, fault-tolerant, and high-performance systems.

The Disaster Information Access Agents, Relief Teams Communication/Interface Agents and DSM Agents-Specialists are inter-connected via fast event transfer channel, while the agents-specialist are getting the required knowledge and data from the DSM Belief Management Agents via online data and knowledge transfer channel. AESOP uses Core System Services such as Naming, Directory, Time, Subscription, and Logging services, which are used as the major services to build the DSM services.

Different instances of the services can be used as long as they satisfy overall functional and semantic constraints. For performance or functional reasons, multiple processes of the same service could be launched. For example, a hierarchy of Event Correlation Services could be created. This hierarchy could be used to implement a multilevel event correlation paradigm, e.g., to implement local and global correlation functions.

The Event Notification Service enables event-passing interfaces between distributed objects—the producers and consumers of events. The interfaces are mediated via event channels that allow decoupling of producers and consumers in the sense that they possess no knowledge about each other. The CORBA standard for the Notification Service, OMG's COSNotification Service, defines several important features of the Notification Service, including asynchrony, event subscription, multicast event routing, event filtering, quality of service, and structured events. The output of one channel can be chained to the inputs of another channel to create event notification chains, for example from Sensor network management Agent to Event Correlation Agent, then to Situation Awareness Agents, to Relief Planning Agent and finally, to Human Interface Agent. Each of the agents in a notification chain may cache events, take actions, perform some transformation on the events, and forward them along the chain.

Extendable Markup Language (XML) is used for transporting data and knowledge between distributed components. XML represents arbitrary semantics as strings. While distributed systems define their framework in the CORBA Interface Definition Language (IDL), they will define much of the data semantics in XML. This approach allows components of the system to be decoupled in order to support a consistent knowledge and data transport mechanism.

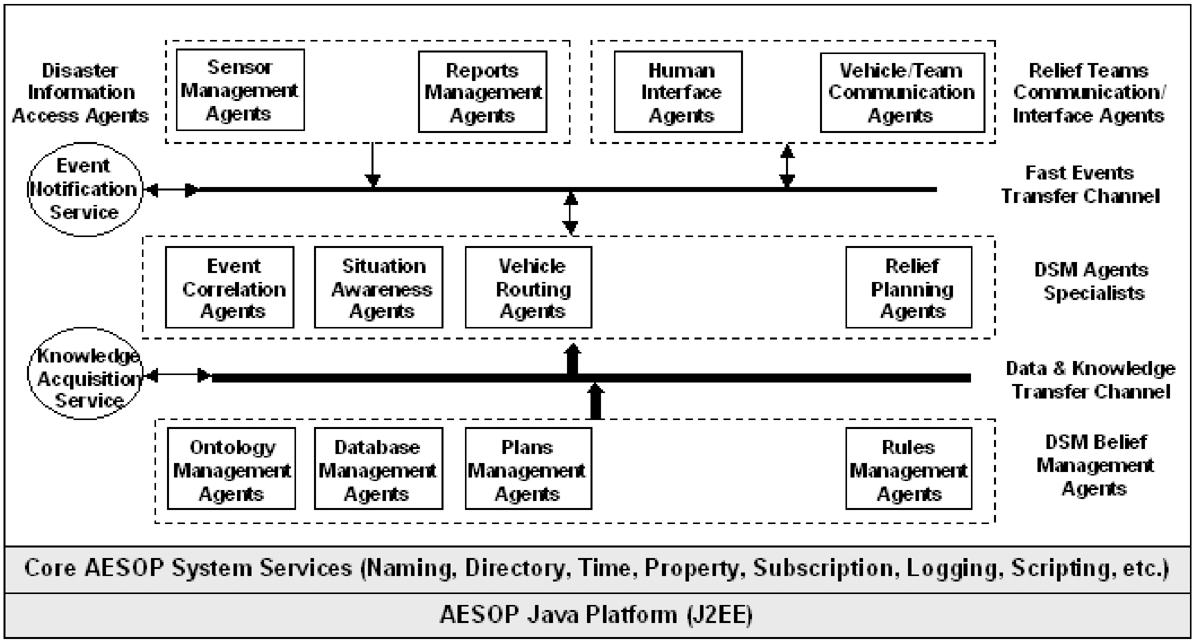

Figure 7. Distributed AESOP Platform for DSM

CONCLUSION

In this paper we described an MAS approach to DSM. The central part of our approach is the introduction of the concept and model of situation awareness into the environment of BDI agent based MAS. The DSM is very demanding and challenging domain from the viewpoint of IT solutions, and is complicated by several social, political, organizational and other non-IT aspects. From the research described in this paper but also from the results of many other research and development projects, it is obvious that despite the achieved results, many issues of comprehensive, effective and secure DSM need yet to be solved, including many advancements of the MAS models discussed in this paper. We will refer to some of them: optimal mapping from the physical infrastructure of DSM agents (vehicles, robots, human teams, etc. into the abstract framework of MAS; advancement of the agent capabilities to recognize complex situations reflecting temporal, causal, spatial, and other domain specific relations; exploration of MAS with self-adaptation, learning, and situation prediction capabilities; and deeper understanding the rules, policies, and behavioral constraints among the agents.

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