COMBINED SYSTEMS

A System of Systems Architecture

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Abstract: Combined Systems is aimed at exploring distributed decision support systems in open, complex chaotic environments. On a general scale, Combined is all about decision-making: observing the environment, making decisions and effectuating these to manage the current situation. Crisis management is a typical domain in which Combined-type systems can prove their value. For this reason the Combined project uses crisis management as primary case-domain. In this paper we highlight the key technologies that are subject of the Combined research, and we describe them in the light of crisis management.

1. INTRODUCTION

The Combined Systems project is a joint effort of industry, research institutes and universities on technologies for intelligent information systems. In general, the Combined project is all about decision making: observing the environment, making decisions and effectuating these to manage the situation.

Combined Systems is actually a class of systems that have a variety of applications. Crisis management is a typical domain, in which Combined-type systems can prove their value. For this reason this domain is used within the project for research, analysis, prototyping and proof-of-concept purposes. The acronym of Combined Systems (Chaotic Open world Multi-agent Based Intelligent NEtworked Decision support Systems) makes clear that these types of systems have some specific characteristics.

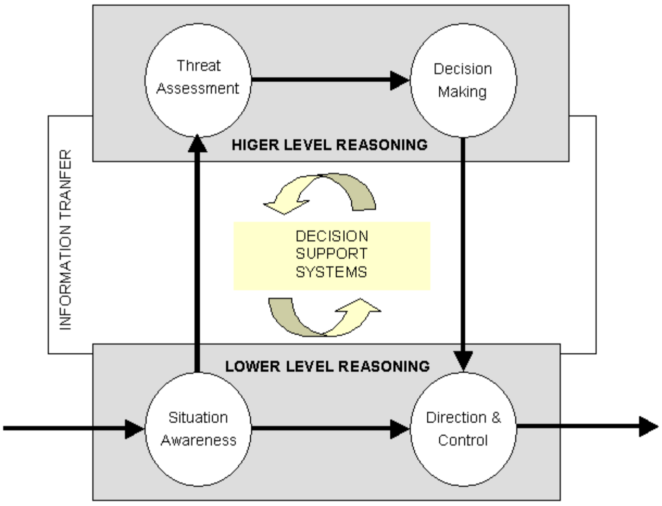
First, we consider systems that operate in a complex chaotic world, which is characterized by continuously changing environments and events caused by unexpected autonomous causes. To control such an environment and to take appropriate actions is a far from trivial problem.

Second, we require decision support systems to be open. This means that humans, sensors, actuators and other computational resources can join or leave the system (at run-time or design-time), depending on the operational requirements at hand.

Thirdly, Combined Systems are networks of heterogeneous distributed systems. Various subsystems interact and cooperate with each other to achieve a common goal. We view intelligent agents as the enabling technology to realize interoperability, communication, interaction and coordination. Agents will provide various services by unlatching and fusing data and functionality of heterogeneous (legacy) systems. Even more, layers of agents will help to rapidly reorganize and reconfigure the system as the situation changes. For background reading on agent systems, we refer to [Knapik 1998], [Weiss 1999] and [Wooldridge 2002].

Finally, Combined Systems support a decision making process. Decision making processes have been modeled in a variety of forms. For the Combined prototype we consider a generic Command and Control (C2) process model that contains four functions:

- *Situation Awareness (SA):* builds and maintains the actual situational overview using (pre-processed) sensor data and additional sources of information,



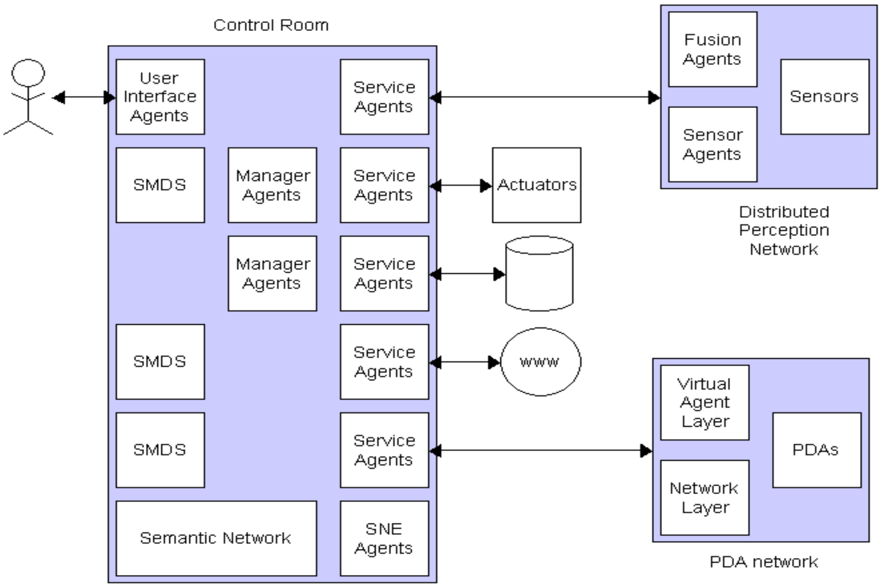
- *Threat Assessment (TA)* interpreting the current situation from a tactical point of view,
- *Decision-making (DM)* plans missions and counter-actions and
- *Direction and Control (DC)* takes care of actually deploying the actions.

The processes (SA and DC) represent tasks that are fairly low in complexity: they represent *skill- and rule-based* tasks (Rasmussen, 1986). The two processes (TA and DM) are higher-order processes that rely more on knowledge and reasoning, and may be regarded as being more *knowledge-based* level tasks. The above figure depicts the C2 control loop. In general, Combined Systems need to capable to perform all of these tasks at some level of abstraction. The core technologies that are explored play an important role in achieving this aim.

This paper stresses the logical and functional architecture of the Combined Systems crisis management prototype rather than the technical or infrastructural architecture. The outline is as follows. In Section 2 the high-level architecture of a Combined-type system is discussed. By means of a case scenario Section 3 illustrates how a Combined System is supposed to operates in a crisis. This paper is concluded by a brief overview of the main research challenges of the project. For a further introduction to the research strategy and topics see our contribution on the Combined Point of View [Burghardt 2004].

2. SYSTEM OF SYSTEMS

Within the Combined project we envision mission-critical systems that can operate in truly open environments. A Combined system is not a single entity, but a network of distributed systems that interact and cooperate with each other in order to achieve a common goal. Besides system qualities such as timing guarantees, robustness, fail-safety and graceful degradation, a Combined system should possess the ability to dynamically configure itself to meet the current operational requirements. This means that for a relatively small decision support task (e.g. crisis management), the network that constitutes the system is also relatively simple. Should the situation escalate, the system will scale up e.g. by incorporating new resources in the network, both intra- and extra-organizational. In this way, a *system of systems* is created.



A Combined system is composed of a number of system segments that – on a high level – correspond to functions of the C2 loop described in Section 1. First, a “Distributed Control Room” segment is composed of a network of systems that support the knowledge level tasks of the TA and DM functions. One can think of crisis management command centers, or military command and control facilities. Second, in a Combined System the SA function is performed by a network of cooperating sensors or “Distributed Perception Network”. Finally, tasks associated with the DC function are performed by a network of mobile devices (i.e. Personal Digital Assistants) which enables humans to receive instructions or get an operational overview of the situation, tailored to their specific task. These segments are discussed in detail in de following subsections. The above figure illustrates the interrelations and main components of the segments.

2.1 Distributed Control Room

In the “Distributed Control Room” (DCR) segment we envision decision support systems that do not offer a rigid, fixed set of functions. Instead a system consists of numerous specialized intelligent agents, called *Service Agents* that can perform specific calculations, gather and fuse information from various sources and address resources at the operational level. There is little or no pre-defined application logic. Depending on the current needs for information (as stated by subsystems or humans), the service agents are organized “on-the-fly” into an ad-hoc application that has the sole purpose of resolving the information need at hand. For background reading on such self-managing systems see [Hannebauer 2002].

Each service agent has a service description that specifies the agent’s capabilities, interfaces and constraints. Based upon these descriptions *Self-Managing Distributed Systems (SMDS) Agents* construct an execution plan and contract the appropriate service agents. Furthermore, other types of SMDS Agents monitor the execution of the plan and intervene when necessary.

In large systems, consisting of many Service Agents, it might not be desirable to let the SMDS Agents perform all the planning. Service Agents can be clustered by domain and are then controlled by *Manager Agents*. The Manager Agents are within the span of control of the SMDS Agents and take high-level instructions. Next, Manager Agents perform the detailed planning and delegate subtasks to the underlying Service Agents. The research to delegation strategies between agents is inspired by human organizations as described in [Aart 2004].

Systems operating in real-world environments need capabilities that can deal with, and adhere to the complex semantic nature of information and knowledge in real-life. To this end, the Combined project explores the use of *semantic network technology* to provide a flexible and dynamic infrastructure upon which information and knowledge can be represented. Initial ideas on semantic networks were based on a biological metaphor of information storage [Quinlan 1968], [Anderson 1973]. Later these ideas were extended further: semantic networks were seen as a knowledge representation paradigm [Findler 1973], [Lehman 1992], [Sowa 1991, 2000]. Currently, the concept of semantic networks is adapted in the semantic web community [Berners-Lee 2001].

For research purposes a prototype called the *Semantic Network Engine (SNE)* is used within Combined. This engine facilitates the representation and storage of concepts and their relations. A concept is represented as a node, and is connected to other concepts by relations. Both relations and nodes have descriptive attributes. The semantic meaning of a concept is now given by its context, i.e. the network itself. The SNE offers flexibility since no *a priori* domain knowledge is needed to construct an information model, as is the case with common (relational) databases. Within the DCR special SNE Agents provide services on top of the semantic network, like information retrieval, storage, information housekeeping and automated knowledge discovery. Whereas SMDS provides flexibility at the control level, the SNE yields open systems at the information and knowledge level.

Agents in a Combined System communicate with other agents and with human users of the system. The latter type of communication is dealt with by User Interface Agents. When agents provide intelligent services to users, they need to know what the user wants or needs, and which goals the user is trying to achieve. This holds especially for agents that act (partly) autonomously. Symbiosis between humans and agents by means of mixed initiative systems [Horvitz 1999] is a key topic of interest within the Combined Systems project. In mixed initiative systems, initiative can be taken either by the user or by the agents. For an agent to take the correct initiative at the right time requires good user modeling, user monitoring and context awareness. One of the Combined prototypes in this area addresses the problem of establishing shared organizational awareness in complex disaster response organizations [Oomes 2004].

2.2 Distributed Perception Networks

For the operator in a control room it is required that he receives quick and up-to-date information about the crisis at hand. The Combined project intends to create sensor systems that aid in interpreting and presenting their own information. In this way, an operator has better situational awareness and consequently is better apt to respond to the information he receives. Within Combined we envision *Distributed Perception Networks (DPN)* in which sensors are connected in a network, cooperate with each other to perform a sensing task and interpret their data. The difference between a distributed sensor system and just a number of sensors sharing the same goal is the aspect of information extraction through communication between the sensors.

The sensors are self-managing, in a similar way as the Service Agents described in the previous subsection. Depending on the characteristics of the sensing task, a network of cooperating sensors is created on the fly. Each sensor is represented by a Sensor Agent that provides a software interface to device, e.g. for sensor control, access to sensor data or status information. Also, Sensor Agents contain knowledge on the specific capabilities of the sensor. The sensing tasks stated at the level of the Distributed Control Room are interpreted by Fusion Agents and mapped to the capabilities of the available sensors. After the network of sensors is set-up, the Fusion Agents are responsible for merging and interpreting the sensor data.

DPNs offer a number of advantages. Firstly, the data is filtered because observations of individual sensors are compared with observation of others. Using an appropriate probability calculation method, the reliability of the presented data can be increased. Secondly, a sensor system can interpret its own data by making an assessment of the semantic value hidden in their data. The sensors are “task-aware”, meaning that the sensors have an explicit description of the way sensory data should be interpreted. Depending on the task, this description can be altered. For background reading on networks of collaborating sensors we refer to [Xiang 2002].

2.3 PDA networks

Individuals or teams (police officers, fire brigade, medical personnel, and so forth) in the field do not have a complete overview of the crisis at hand. This lack of overview may effect their decisions and actions in a counterproductive way. Alternatively, the field level is able to provide detailed information on the local situation to higher organizational levels. In turn, the tactical and strategic level should be able to access and interpret this information, in order to make well-considered decision at a higher level.

The key to bridging the information gap between the operational and the tactical / strategic level (alternatively: the DC and DM/TA functions) is information sharing and filtering. The Combined project explores whether Personal Digital Assistants (PDAs) like mobile phones, Palm, PocketPC or Zaurus devices can be applied to achieve this. Individuals in the field are equipped with such a PDA that can communicate with other PDAs in the vicinity. Together the PDAs form an ad-hoc network. Users can enter their own observations to the PDA, like the position of victims, or a description of the current situation at particular location (e.g. smoke, emergency exits, traffic congestion). This information is entered in a special iconic language called Crisis Language, developed within Combined. Reversibly, the PDAs inform the users on the overall situation of the crisis.

Information is distributed and shared with other PDAs in a robust peer-to-peer network [Oram 2001]. To avoid a single point of failure there is no central computer that stores all information. Consequently, the network must be robust for the fact that PDAs are not always available. In that case there should be no loss of information. Since it is not feasible that each PDA contains *all* the shared information, special coding mechanisms are researched which allow each PDA to only store a subset of the shared information. The remaining information can be reconstructed from the information that is available in the remaining PDAs in the network. The basis of this research is formed by the work of Richardson and Urbanke [Richardson 2003] and the DISCUS project [Sandeep 1999].

Finally, not only do we need to balance the load over the network [Schoonderwoerd 1996], also we have to prevent that individuals are overloaded with information. Therefore special filtering mechanisms are applied. Each organizational level receives the right information on the right level of detail.

3. CRISIS MANAGEMENT CASE

For demonstration and prototyping purposes, a common case scenario is defined within the Combined project. This scenario is situated in the Rotterdam harbor. A tanker collides with a ship causing an explosion and the release of a toxic chemical. The south-west wind directs a first toxic cloud directly, and a second toxic cloud indirectly over the Rotterdam Harbor area. Among other areas, the Erasmus University building and the highway are threatened. A crisis command center is located in the World Port Center (WPC). Various (mobile) sensors like gas-detectors and cameras are operational in the harbor area.

The toxic clouds will spread over the area and cause multiple casualties. People will panic when they see the gas cloud and see the first casualties in their environment. They will start fleeing and calling the emergency services (“112”). Buildings, like the Erasmus University, need to be evacuated. There will be a severe strain on the hospitals. Traffic, public transport, waterway and telephone infrastructure will be under severe pressure. The chemicals that are leaking into the river are polluting the water.

This scenario is sufficiently rich for Combined research, proof-of-concept, prototyping and demonstration purposes. The case scenario is used to analyze and assess the system qualities of the various Combined System segments described in the previous section. Next we describe, for the sake of illustration, a possible role of the Combined system segments within this case.

One can imagine that a control room segment will be operational in the WPC. Here the various emergency calls are collected in a semantic network, even as sensor readings from gas-detectors and cameras. SNE Agents continuously monitor for emergency situations. In case of an alert, the appropriate emergency response plan will be retrieved.

SMDS agents will then try to resolve the information needs that arise from the emergency response plan. For instance: in case of a chemical incident, it has to be determined whether or not a certain area has to be evacuated. For this, SMDS generates a plan to first consult Service Agents that are able to classify the gas (toxic, non-toxic) based on the observations (“112” calls and sensor readings), and second to consult Service Agents that can predict the spread of the gas cloud (using weather forecasts and dispersion models).

In case the Erasmus building needs to be evacuated, alerts are sent to people’s mobile devices (e.g. SMS messages). In a more advanced setting, the PDAs of the people in the building form an ad-hoc network. Thereby, people share information on the evacuation and inform each other on escape routes.

4. DISCUSSION

In this paper we discussed the logical architecture of a Combined System. In this architecture communications and sharing of information is a key subject. However, it must be stressed that the project is not about developing middleware. Being a system of systems, a Combined system is inherently hybrid (i.e. agent systems, non-agent systems, humans; different technology, design and organizational structures). This means connectivity has to be realized between subsystems that all use different, but existing communication and middleware technology. Layers of intelligent agents will be responsible for unlatching (legacy) subsystems and providing coordination and connectivity services, and thereby create an abstraction of the underlying communication mechanisms.

A specific goal of the Combined project is to contribute to the challenges defined by the agent systems community. The AgentLink network of excellence has defined a roadmap, which sketches the short-term, mid-term and long-term goals of agent based computing [Luck 1999]. The key research aims of Combined are inspired by this roadmap:

1. Design and implementation of agent systems that operate in open environments.
2. Semantic description of information, to improve interoperability.
3. Mechanisms for agent systems to adapt to changes in the environment.
4. Dynamic, self organizing, agent organizations.
5. Inclusion of human and artificial (agent and non-agent) participants in multi-agent systems.
6. Increase user confidence and trust.
7. Quality of agent software (to the level of industrial standards).

By the end of 2004 the project will deliver an architectural baseline for Combined Systems. This baseline is supported by a number of initial prototypes. In the next 2 years the baseline will be refined, keeping the AgentLink challenges in mind.

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