An Organization-Based Adaptive Information System for Battlefield Situational Analysis

Eric Matson Scott DeLoach
Multi-agent and Cooperative Robotics Laboratory
Department of Computing and Information Sciences, Kansas State University
234 Nichols Hall, Manhattan, Kansas 66506, USA
{matson, sdeloach}@cis.ksu.edu

Abstract – *On the field of battle, it is crucial to retrieve a continual flow of information necessary to achieve information superiority. Sensors used to provide the information streams can be lost due to dangerous conditions. In this paper, we show how the combination of Adaptive Information Systems and organizational models create a flexible agent system capable of overcoming sensor incapacitation or loss within a battlefield scenario.*

1. INTRODUCTION

The goal of a battlefield information system is to provide the commander both tactical and strategic intelligence during a conflict situation. To accomplish this goal, various types of sensors are used to detect events and objects of interest. This sensor data can then be combined, or fused, with other sensor data to provide a commander with a much clearer, more complete picture of the battlefield. Due to the nature of war, there is also a high probability that a percentage of these sensors will become disabled during the battle. However, when these sensors are lost or destroyed, the information produced by those sensors is still needed; the information must still be provided to the battlefield commander.

To provide the required information, the battlefield information system must satisfy two requirements simultaneously: (1) overcome the loss of sensors and sensor data, and (2) provide continuous information flow. To accomplish both requirements, the battlefield information system must be capable of detecting sensor failures and adapting it's processing to continue to provide the required information in a timely manner. Thus, the battlefield information system must be adaptive.

An *Adaptive Information System* (AIS) can modify its processing algorithms or the sources of its sensor input to produce the information at various levels of efficiency and effectiveness. In general, an AIS selects the best available data and fuses it in an attempt to answer queries from AIS users.

In this paper, we present our approach to building adaptive information systems, as applied to the area of battlefield information systems. Specifically, we combine multi-agent systems with an organizational theoretic approach in the hopes of providing highly adaptive, efficient information systems. Central to our research is our *organizational model*, which captures the structure used by a team of agents to answer specific information queries. The organizational model also provides the knowledge the team must have to adapt to sensor loss and new user queries. In reviewing other AIS models, there has been work in the area of AIS [1], some even containing the the notion of organization [2]. Others have approached AIS from an intentional Multi-agent System (MAS) approach [3]. While these approaches are functional AIS systems, they lack the ability to reorganize and adapt if required due to environmental effects. We seek to prove that our approach yields benefits with the addition of the organization model and the ability to self reorganize and adapt to the necessary requirements of the surrounding environment.

To show the efficacy of our organizational model, we have developed a battlefield simulation using the Battle of Khafji scenario from the 1991 Gulf War [4,5]. To answer queries, we have developed an organization-based AIS. The goal of our research is to show that adaptive multi-agent organizations, which have the ability to reorganize as needed, based on organizational knowledge, can accomplish their goalsw more effectively and consistently than statically defined systems.

We begin this paper by presenting our organizational model in Section 2 and how we used it to implement a battlefield AIS in Section 3. Finally, we discuss our results in Section 4 and further work in Section 5.

2. AGENT ORGANIZATION MODEL

Our agent organization model [6] captures the essence of the organization used by a team of agents to satisfy its goals [7, 8]. The organization model (O) is comprised of a structural model, state model and a transition function.

$$\mathbf{O = (O_{structure}, O_{state}, O_{transition})}$$

The organization model elements are utilized in the instantiation of an organization through the processes of initial organization or reorganization. These processes will arrive at one of three outcomes.

Organization Structure

The *Structural Organization* ($O_{structure}$) is comprised of Goals, Roles, Rules/laws, Relationships, Ontology, Capabilities and Agents. Figure 1 shows the Static Organizational Model structure.

A *goal* is used to identify critical aspects of system requirements. Therefore, an analyst should specify goals as abstractly as possible without losing the essence of the requirement. For example, “listen to sensor” is a goal. How to listen to a specific sensor is a requirement that may change with time or between various operating systems and is not a goal. There are two levels of goals within this model: critical and non-critical. Critical goals are the set of all goals on the critical dependency path from start to finish of the global organization goal. Non-critical goals are not on the critical dependency path from start to completion.

A *role* describes an entity that performs some function within the system. Roles are analogous to roles played by actors in a play or by members of a typical company structure and have specific capabilities and relationships defined in order to meet the overall company goal.

An *agent* is equivalent to an actor with a set of specific capabilities. Agents coordinate with each other via conversations and act proactively to accomplish individual and system-wide goals. Within an organization, agents play roles required by the goals.

Capabilities are the abilities inherent within a particular agent. Computational capabilities are the set of algorithms that provide the robot basic functional intelligence.

Relationships are dynamically allocated, cohesive links that exist from role-to-role and agent-to-agent during the active organization lifespan.

We introduce the notion of *laws* into the organization, which operationalize norms, sanctions/rewards, and their relationship. Laws should also conform to organizational values. Laws constrain an organization with such notions as how many agents can play in a specific role or in the definition of goal dependency graphs.

The word ontology was taken from philosophy where it represents the study of the nature of being. Much debate exists on the exact definition of ontology when used for knowledge engineering or artificial intelligence. The most common definitions state that an ontology is a specification of a conceptualization or that an ontology is the shared understanding of some domain of interest. This research uses the latter definition, specifically, that ontologies define classes, functions, object constants, and axioms to constrain meaning of some type of world view of a given domain. [9]

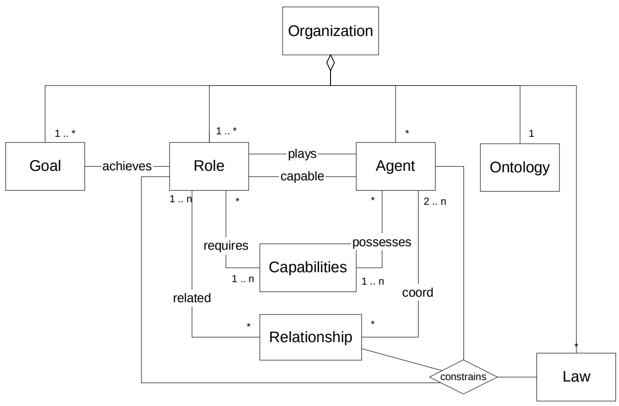

Figure 1. Organizational model

Organization State

The second element of the Organization Model is its state. The *Organizational State* (O_{state}) is an instance of the organizational structure at a point in time. As the Organization Model is a template, the state is an instance of the model. In an instance of an organization state, each of the elements will be bound to a set of values that represent the organization attributes. An organization will possess at least one goal, one role to accomplish the goal, and one agent to play the role where the agent will possess capabilities required by the role. Not every organization state element is required to be populated by an instance variable for creation of a valid organization. The constraints and laws of an organization will govern the requirements on a specific state. An example of a simple organization will have the following tuples:

<*organization, monitor*>
<*goal, monitor infrared sensor data*>
<*role, sensor monitor*>
<*agent, sensor agent*>
<*capability, {sensor monitor, feedback generation}*>

Organization Transition

The *Organization Transition Function* ($O_{transistion}$) defines the ability of the organization to reorganize from an instance state to the next instance state over the organization life span. From the initial organization, through its termination, the organization may transition its state model numerous times.

Organization Process

The initial step in organizing an AIS is to use the existing information production goals to establish the organizational roles required to produce the appropriate information. At the same time, the team of agents making up the AIS must assess their individual and collective capabilities to determine whether they can fulfill the required roles [10]. If the required roles can be filled, then the capabilities exist to satisfy the information production goals and the team assigns the necessary roles to agents (effectively defining the state of the team's organization). Once the assignments are made, the team may initiate action to satisfy the team information production goals.

$$\mathbf{O}_{\mathbf{state(0)}} \rightarrow \mathbf{O}_{\mathbf{state(1)}}$$

Reorganization Process

The reorganization process follows the same basic steps as the organization process; however, it differs in the point of initiation. Reorganization is initiated by a trigger event, such as sensor loss, during the execution of an already existing organization. When such an event occurs, the team must determine if it still has the capabilities to satisfy team information production goals or whether it must reorganize to do so.

$$\mathbf{O}_{\mathbf{state(n)}} \rightarrow \mathbf{O}_{\mathbf{state(n+1)}}$$

Organizational Outcomes

The outcomes of the organization and reorganization processes are equivalent. The three available outcomes are goal satisfaction, goal relaxation or goal abandonment. *Goal satisfaction* indicates that the capabilities exist within the remaining team to accomplish all critical and non-critical goals. *Goal relaxation* indicate that capabilities exist within the remaining team to meet all critical goals, but some or all non-critical goals may not be met and will have to be "relaxed". *Goal abandonment* means the remaining member's capabilities do not allow the organization to continue because not all critical goals can be satisfied and success is not achievable.

3. IMPLEMENTATION

In general, the battlefield contains many human as well as sensor based data sources. The fusion of data from these sources provides the foundation for the information gathered and analyzed from the field of battle.

Our current research explores an organization-based AIS implementation that results in a cooperative agent team with no defined leaders, no subordinate role assignments, and no hierarchical structure. In this model, air and ground sensors are monitored to evaluate enemy force deployment and movement intelligence. Each type of sensor has the capability to track and return a single, specific data stream. An example of a sample AIS is shown in Figure 2.

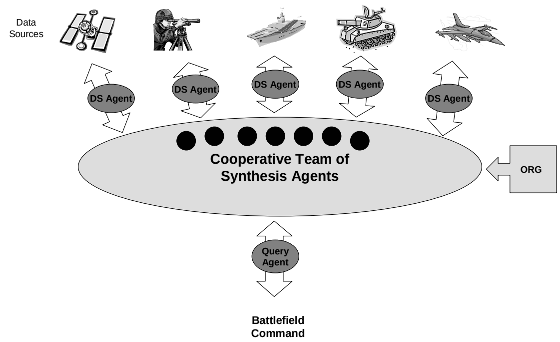

Figure 2: AIS Overview

We have defined three agent types for the implementation. Each fills a role in the situational analysis of the battlefield simulation scenarios. The three agent types are:

- **Data Sensor Agent**: The *Data Sensor Agent* (DS) provides the interface between the hardware sensor and the Synthesis Agents. Our current research utilizes multiple air and ground based sensors. Each of the hardware sensors will require a DS to monitor its data and communicate to the organization.
- **Synthesis Agent**: Each *Synthesis Agent* (SA) has a defined set of inherent capabilities that allow it to work with a set of DS's. Its function is to fuse data

from various sensor types to formulate answers to requests for information of the Query Agent.

- **Query Agent**: The *Query Agent* (QA) translates, manages and communicates the present query to the active team of Synthesis Agents. The queries have two forms: transient or persistent. A *transient* query is executed once and has a definite start and end. A *persistent* query is executed periodically for an indefinite period of time.

Our current implementation allows for the team to self organize and work to satisfy a set of goals, which are defined by queries from the user. Once the team organizes, if it successfully satisfies its goals with no sensor loss, there would be no reason to reorganize. However, if the team detects a sensor loss, the team must assess the impact based on the current goals and team organization; reorganization occurs if the team can no longer satisfy its goals with the current organization. During the reorganization process, the team will come to one of three decision states:

- *Capabilities exist within the remaining team to provide all required streams of data.*
- *Capabilities exist within the remaining team to meet all critical goals, but some or all non-critical goals may not be met and will have to be "relaxed".*
- *The remaining member's capabilities do not allow the organization to continue because not all critical goals can be satisfied and success is not achievable*.

The organization will consist of the collection of all Data Sensor Agents, Synthesis Agents and the Query Agent required for accomplishing the goal of resolving the query.

The implementation of our organization-based AIS model is developed using Java giving the AIS the ability to operate on all required platforms. The full *Static Organization Model* has been implemented with the exception of *ontology* for this research.

Queries

When a query is executed to provide battlefield intelligence, the query will *de facto* be the goal of the organization formed to satisfy the query. Our organization-based AIS will utilize two types of queries differing on their temporal constraints. T*ransient* queries are singly executed with definite start and end points. P*ersistent* queries are executed over an indefinite period of time with a definite start point but no stop point, at least defined at initiation.

When a query is launched there is no assurance the resources required to execute the query will be available for the duration. This applies to *Transient* queries but more so to *Persistent* queries because of the time required to complete execution. A *Persistent* query may execute and report information over a long time, heightening the probability that sensors will be destroyed or incapacitated that are being used in the information gathering to satisfy the information goals of the query. If a sensor is damaged, the current organization may be required to re-evaluate its global capability to satisfy the query requirements. If the requirements are not being met, a re-organization will be triggered to re-instantiate the static organizational model into a new instance that will meet the query goal requirements.

Queries will be created using a English (natural) language type syntax with keywords. The query will be parsed and evaluated by the QA assigned by the organization. Examples of these queries are:

- *Show all tanks within sector 5.*
- *Show all ground troops, vehicles, helicopters and airplanes within the field of battle.*

Once the QA has parsed the query, goals will be created and passed to SA's assigned to the organization who possess the capabilities that satisfy the particular goals.

Example Scenarios

In this section, we define valid implementation test scenarios our system will evaluate and provide unified information streams to aid in the evaluation of battlefield scenarios.

In Figure 3, we show the example of a simple transient query resulting in the generation of an organization to meet the goal of answering the query. In this scenario,

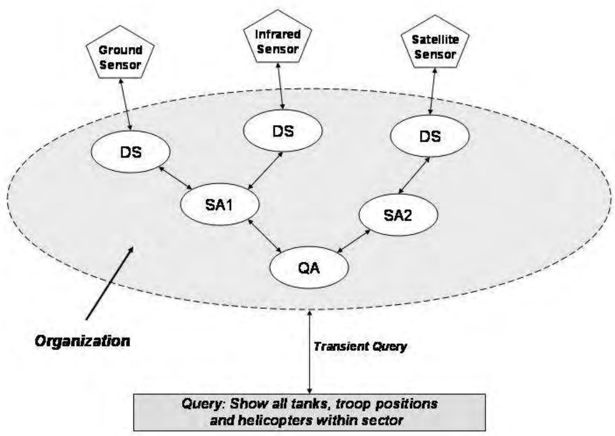

Figure 3: Transient Query Organization

the organization-based AIS will answer the query, "*Show all tanks, troop positions and helicopters within sector"*. There are three sensors required to answer this query. The ground sensor will detect the presence of troops, the infrared sensor will detect all tanks within the sector and a satellite sensor will detect all helicopters within the sector. Since this is a transient query the data from each sensor will create a instantaneous snapshot of the current battlefield sector.

There is a DS to monitor and interact with each of the three physical sensors. The data streams produced from each will be forwarded to the SA which is capable of interpreting the information and passing it to the Query Agent. SA1 has the capability to interpret and synthesize data from both the Ground Sensor DS and the Infrared Sensor DS. SA2 has the capability to interpret the data from the Satellite Sensor DS.

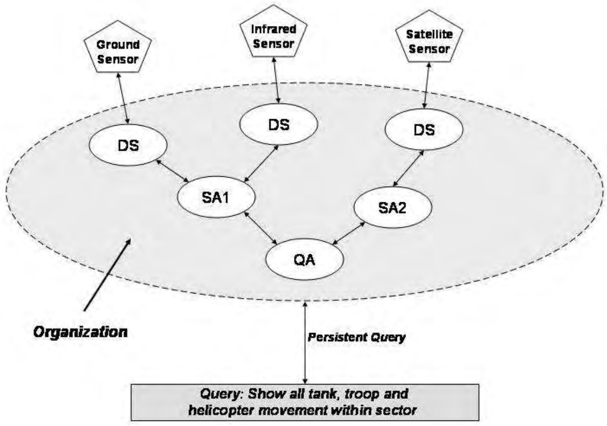

Figure 4: Persistent Query Organization

Figure 4 describes the initial organization set up to answer the persistent query, "*Show all tank, troop and helicopter movement within sector"*. In this case, the organization is similar to the initial transient scenario in Figure 4. The organization requires the capabilities of 3 sensors and 3 DS agents to interpret the raw data. SA1 again possesses the capability to accept data from ground and infrared sensors and synthesize it for return to the QA. SA2 accepts and passes data from the satellite via the DS agent. The difference is this query is persistent with no end time and will continue to monitor the battlefield.

In the case that a sensor is lost or incapacitated, the organization will consider if re-organization is warranted. The loss of an agent within the organization will also trigger an evaluation to determine if re-organization is required. In the Persistent Query Organization scenario shown in Figure 4, the loss of any sensor will trigger a re-organization and re-allocation of resources. The change from $\mathbf{O}_{\mathbf{state(current)}} \rightarrow \mathbf{O}_{\mathbf{state(current+1)}}$ will result in relationship changes as well as changes to elements of the organization state.

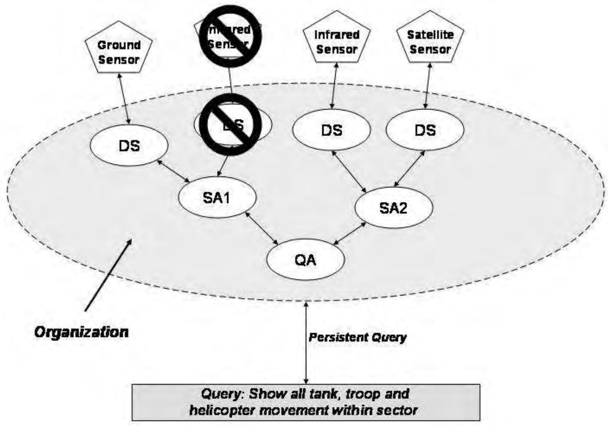

Figure 5: Persistent Query Post Re-organization

Figure 5 describes the organization set up to answer the persistent query, "*Show all tank, troop and helicopter movement within sector"*, after the initial organization has been replaced because of a loss of the infrared sensor to monitor the tank data stream in the battlefield scenario. The loss of a sensor and the attached DS triggers requires switching to another infrared sensor unit and allocating another DS to interpret the sensor's data. In the process or reorganization, the capability evaluation determines SA2 now has a higher capability to synthesize data from the satellite sensor and also the infrared.

Because of the potential duration of a persistent query and the conditions under which the sensors are subjected to, it is possible that the organization may be transitioned many times over the course of a single query. The ability to continually evaluate the organization and reason about its viability is central to the nature of our organization-based MAS.

4. CONCLUSIONS

In this paper, we show how the combination of AIS and organizational models creates a flexible agent system capable of overcoming sensor incapacitation or loss within a battlefield scenario. Sensor loss is overcome by a re-organization of the available sensors and agents to compensate for the lost organization member.

Our initial results show the ability to complete the processes of organization and reorganization within the structure of AIS. The current implementation allows the organization to monitor itself and reorganize in the event of the loss of a team member agent or sensor. Furthermore, the organization uses the reorganization decision states to determine how best to satisfy its goals.

An advantage of a multi-agent system using the organization theoretic model is its extensibility. There are no numerical limits to the number of agents, roles or goals integrated and included in an organization.

In our evaluation, 100,000 organization scenarios were executed to determine the success ratio of the ability of an instantiated organization to overcome the loss of a sensor. Sensors were simulated using random number generating sequences that determine operational ability. When a sensor would go off-line, a re-organization was triggered and a new organization formed. All cases were successful in the ability to successfully re-organize. Our success is tempered by viewing this as a simulated exercise, where new software-based sensors can be automatically generated. In a true field study, new hardware-based sensors must be available for a level of success anywhere near the simulated exercise. This will not be the case in a true battlefield scenario, where resources are surely limited.

5. Further Work

This work is part of a larger effort to more fully define the usefulness of an organizational theoretic approach to building a multi-agent system. In the near future, we plan to add new sensor types and thus assign more, different types of agent capabilities. This will allow us to more fully evaluate the scalability of the organizational model and the effectiveness of our organizational reasoning techniques.

Another goal is to investigate the use of effectiveness and efficiency as reorganization triggers. In a battlefield, information system effectiveness and efficiency generally refer to timeliness and confidence levels. If an organization has become inefficient, below a defined threshold, then the team can trigger a reorganization to improve efficiency. A similar stimulus and response relationship would exist for organizational effectiveness.

Finally, we plan to apply our organization theoretic approach to areas other than information systems. In particular, we are considering cooperative robotics, which has direct applicability to the control of uninhabited military vehicles.

6. Acknowledgements

This research is supported by a grant from the Air Force Office of Scientific Research (AFOSR) under grant number F49620-02-1-0427.

7. References

[1] S. Garlatti, S. Iksal, et al., *Adaptive On-line Information System*, Information System, Analysis and Synthesis, (ISAS'99), Orlando, Florida. 1050-1057, 1999.

[2] K. Ragab, T. Ono, N. Kaji, K. Mori. *Autonomous Decentralized Community Concept and Architecture for a Complex Adaptive Information System.* The Ninth IEEE Workshop on Future Trends of Distributed Computing Systems (FTDCS'03). San Juan, Puerto Rico, May 28 - 30, 2003.

[3] A. Cardon, F. Lesage. *Toward Adaptive Information Systems: Considering Concern and Intentionality.* Eleventh Workshop on Knowledge Acquisition, Modeling and Management (KAW'98). Banff, Alberta, Canada. April 18 -23, 1998

[4] R. Grant. "*The Epic Little Battle of Khafji*," Air Force Magazine: Journal of the Air Force Association. Volume 81, No. 2, February 1998.

[5] J.B. Rochelle. *The Battle of Khafji: Implications for Air Power*. Graduate Thesis, School of Advanced Airpower Studies, Air University, Maxwell Air Force Base, Alabama, 1997.

[6] E. Matson, S. DeLoach. "*Organizational Model for Cooperative and Sustaining Robotic Ecologies*," *Proceedings of the Robosphere 2002 Workshop*, NASA Ames Research Center, Moffett Field, California, November 14-15, 2002.

[7] P. Cohen, and H. Levesque. *Teamwork*. Special Issue on Cognitive Science and Artificial Intelligence, 1991, pp. 487-512.

[8] M. Tambe, W. Zhang. *Towards Flexible Teamwork in Persistant Teams.* Second International Conference on Multi-Agent Systems, 1996.

[9] J. DiLeo, T. Jacobs, S. DeLoach. *Integrating Ontologies into Multiagent Systems Engineering*, Fourth International Conference on Agent-Oriented Information Systems (AIOS-2002), 15-16 July, 2002, Bologna, Italy.

[10] E. Matson, S. DeLoach. *Using Dynamic Capability Evaluation to Organize a Team of Cooperative, Autonomous Robots*, Proceedings of the 2003 International Conference on Artificial Intelligence (IC-AI '03), Las Vegas, Nevada, June 23-26, 2003.