Supporting the Coalition Agents eXperiment (CoAX) through the Technology Integration Experiment (TIE) Process

Ranjeev Mittu, Frank Segaria
Suleyman Guleyupoglu
Naval Research Laboratory
4555 Overlook Avenue
Washington, DC 20375
{mittu, fsegaria, suleyman}@ait.nrl.navy.mil

K. Suzanne Barber and Tom Graser
Lab for Intelligent Processes and Systems
Electrical and Computer Engineering
University of Texas at Austin
Austin, TX 78712
{barber, graser}@mail.utexas.edu

Robert Ross
University of Maryland
A.V. Williams Building
College Park, MD 20742
robross@cs.umd.edu

Track: Coalition Interoperability

Supporting the Coalition Agents eXperiment (CoAX) through the Technology Integration Experiment (TIE) Process

Ranjeev Mittu, Frank Segaria
Suleyman Guleyupoglu
Naval Research Laboratory
4555 Overlook Avenue
Washington, DC 20375
{mittu, fsegaria, suleyman}@ait.nrl.navy.mil

K. Suzanne Barber and Tom Graser
Lab for Intelligent Processes and Systems
Electrical and Computer Engineering
University of Texas at Austin
Austin, TX 78712
{barber, graser}@mail.utexas.edu

Robert Ross
University of Maryland
A.V. Williams Building
College Park, MD 20742
robross@cs.umd.edu

ABSTRACT

The CoAX demonstration was an international effort between the Defense Advanced Research Projects Agency (DARPA), Defense Science Technology Office (DSTO), Defense Scientific Technical Laboratory (DSTL), and The Technical Cooperation Program (TTCP). The CoAX participants included the Department of Defense (DoD) laboratories, industry and academia that were brought together with the purpose of showcasing the power of software agents to rapidly construct and maintain a coalition Command and Control Structure. The CoAX was conducted through numerous Technology Integration Experiments (TIEs). The purpose of the TIEs was to pair up participants in the demonstration in order to leverage the synergistic effects of software agent technology being developed by each participant. The Naval Research Laboratory (NRL), University of Maryland (UMD) and University of Texas (UTEX) participated in a TIE which demonstrated the integration of the NRL Global Command and Control System Maritime (GCCS-M) surrogate with the Interactive Maryland Platform for Agents Collaborating Together (IMPACT) system and UTEX's Adaptive Agent Organization and Information-Trust-Evaluation agents. This paper will describe the CoAX 30-month experiment and the TIE that was conducted between NRL, UMD, and UTEX to support the experiment. We will conclude with a brief summary and areas for future investigation.

Keywords: Coalition Operations, Software Agents

1 Introduction to Coalition Operations

Military coalitions are complex organizations that, in many cases, must be rapidly created and effectively managed as the battlefield dynamics change. Issues such as information security, interoperability between data and systems across geopolitical boundaries, lack of information, and labor-intensive approaches to data collection are a few examples of barriers that must be overcome in order for the coalition to be successful in meeting its objectives. Systems generally exist in stovepipe form, particularly across coalition boundaries, and it is very difficult for them to exchange meaningful data.

The U.S. Navy's vision of FORCENET is to integrate networks of sensors, weapons, systems and platforms together in order to multiply force power. If this is to become a reality, the integration must be easily accomplished in spite of the barriers that exist in current stovepipe systems. Software agents are being increasingly examined as a potential technology to overcome some of the barriers in making FORCENET a reality, particularly for a coalition command and control environment.

Agent aided information retrieval and decision support has attracted the attention of the agent research community for several years. The concept of large ensembles of semi-autonomous, intelligent agents working together is emerging as an important model for building the next generation of sophisticated software applications. This model is especially appropriate for effectively exploiting the increasing availability of diverse, heterogeneous, and distributed on-line information sources, and as a framework for building large, complex, and robust distributed information processing systems. The development of enabling infrastructure for mobile computing and interoperability among programs residing at distant sites, and new generations of distributed operating systems, will continue to make the construction of systems based on this model much easier. Software agents represent a new paradigm in distributed computing. The notion of autonomous software entities able to work autonomously, or in cooperation with each other, to perform tasks in satisfying their objectives represents a powerful concept. Thus, software agents have been deployed in many commercial, academic, and military domains. In the following sections, we will describe the CoAX 30-month experiment and explain the TIE interaction between NRL, UMD, and UTEX to support the experiment.

2 Multi-Agents Systems Support for Coalition Agents Experimentation (CoAX)

The Defense Advanced Research Projects Agency (DARPA) has sponsored the Control of Agent Based Systems (CoABS) program [8], one of their largest programs investigating the use of software agents to support military command and control. The culminating event of the CoABS program was the CoAX 30-month demonstration [9], an international collaborative effort between DARPA, DSTO, DSTL, and TTCP. In addition, DoD laboratories, universities, and industry provided software agent research and technology in order to demonstrate that multi-agent systems are an effective mechanism in fostering coalition interoperability. The scenario chosen for CoAX was based on operational concepts developed by TTCP describing the fictional country of Binni shown in Figure 1. In the scenario two fictional countries, Agadez and Gao, are in dispute over Binni due to the geopolitical and economic development of this country. From an operational point of view, a coalition is formed to bring peace to the region (and the coalition systems are integrated through software agents).

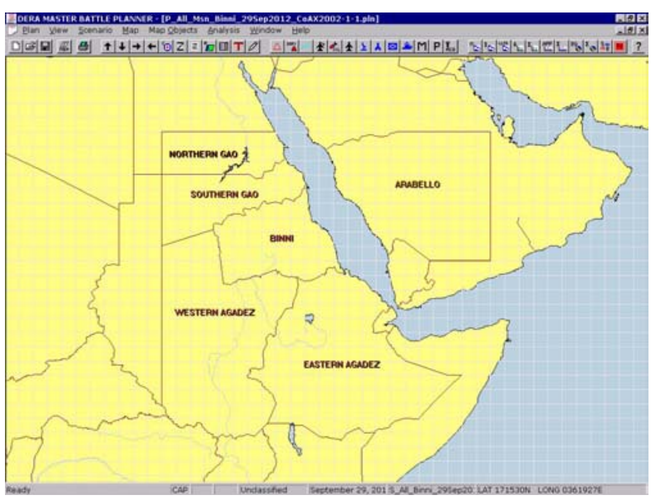

Figure 1: The fictional countries used in the CoAX demonstration

Each of the software agents (approximately 70 in the experiment, representing various functional capabilities of the coalition) was incorporated within military domains, for example, the maritime component command in Figure 2. Each domain had associated with it policies to limit the behavior of the agents according to their role in the domain. The interoperability of the agents was enhanced through the use of ontologies, which provided semantic meaning to the information that was exchanged by the agents, and the CoABS agent grid [8] provided the infrastructure to allow the agents to register and lookup other agents as well as providing other functions. The CoABS agent grid is currently being utilized in joint experimentation programs such as the Navy Expeditionary Sensor Grid Enabling Experiments (the EEE demonstrates the utility of flexibly and dynamically integrating naval sensors and C2 systems via the agent grid), the Air Force Joint Battle InfoSphere and several Army programs.

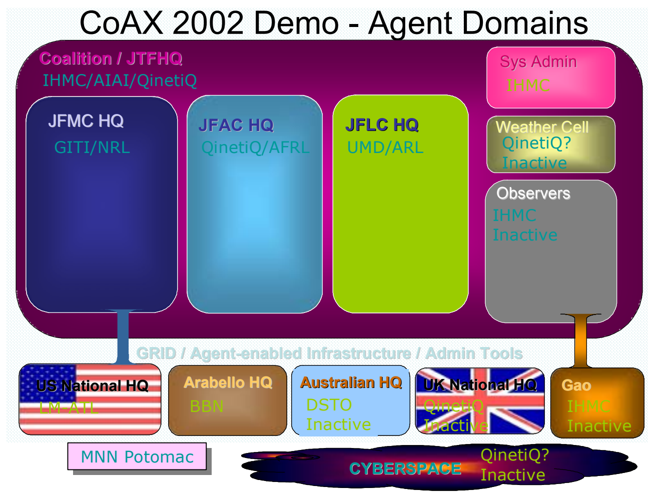

Figure 2: The military domains associated with the CoAX demonstration

The CoAX demonstration was conducted through Technology Integration Experiments (TIEs). The purpose of each TIE was to pair up certain groups based on the synergistic nature of the technology solutions provided by each of these participants in support of the Binni Scenario. In this scenario both Agadez and Gao are in dispute over Binni, with Agadez becoming increasingly desperate over the territory. Because of this desperation, they launch a submarine-based missile strike against an Australian ship in the Red Sea. This strike injures many on board and damages critical capabilities on the ship, including the Magnetic Anomaly Detection systems (MAD detectors). As the coalition becomes aware of the strike and subsequent damage, mobile medical monitoring agents are dispatched to the ship to collect injury reports contained in medical databases. From these reports, agents are able to work cooperatively to schedule the evacuation of those critically injured. A neutral country on the eastern coast of the Red Sea, Arabello, agrees to offer its ASW (Anti-Submarine Warfare) capabilities to help track down and neutralize the Agadez submarines. These ASW capabilities are rapidly integrated via agents with the coalition systems already in place, and expeditiously begin to provide contact reports on possible positions of the Agadez submarines.

We will now describe the TIE interaction between NRL, UMD and UTEX in support of Binni.

3 CoAX TIE between NRL, UMD and UTEX

The purpose of the TIE collaboration between UMD (via their IMPACT system), NRL (through their Global Command and Control System Maritime - GCCS-M - surrogate), and UTEX (through their Adaptive Agent Organization and Information-Trust-Evaluation agents) was to demonstrate the capability of tracking and predicting the location of enemy submarines via agents. With regard to Figure 3, the UTEX Adaptive Agent Organization (AAO) integrated appropriate ASW capabilities from Arabello and the "Information-Trust-Evaluator" (ITE) agents assigned confidence values to the ASW reports. Once these confidence values were assigned, NRL database agents communicated with the ITE agents to pull and store the reports in the simulated Track Database Manager (TDBM) server for eventual display in the GCCS-M "surrogate" map view. Users of the surrogate map view could then query the UMD prediction agents to forecast the state of the Agadez submarines at some future time. This flow of information is noted by the circled numbers in Figure 3. The circled numbers represented as "0" at the top indicate agents that communicate simulation data to the rest of the agents as well as the fact that all the agents were required to register with the KAoS domain policy service, all prior to any other agent interaction taking place.

In the following sections, we will describe the UTEX Adaptive Agent Organization and ITE agent, the NRL GCCS-M agent-enabled surrogate and the UMD-predict agent.

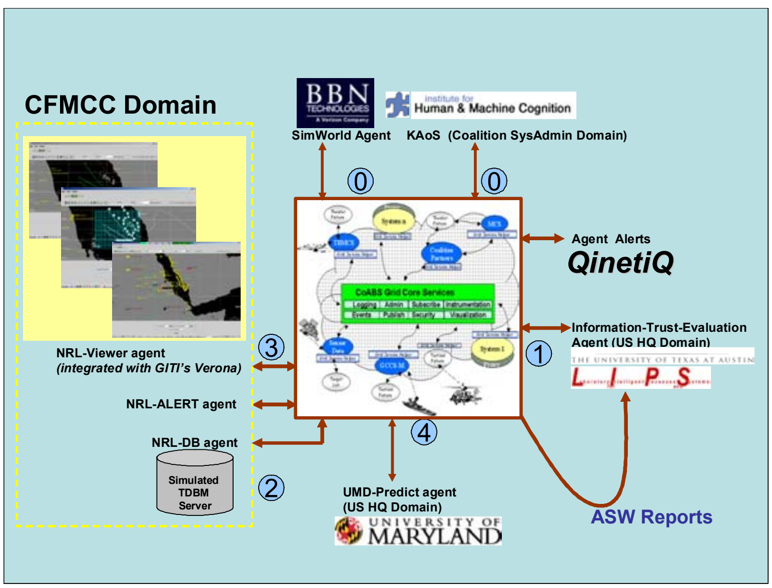

Figure 3: Several TIE components for CoAX

3.1 *University of Texas Adaptive Agent Organization and Information-Trust-Evaluator Agents*

The Adaptive Agent Organization (AAO) is designed to support the configuration of a coalition organization and is well suited to respond to the current situational picture and mission. As this scenario demonstrates, factors affecting mission operations are constantly in flux (e.g. available assets and capabilities, mission plans, threats, deadlines) and knowledge about these factors and the situational picture is inherently uncertain. Therefore, the coalition must dynamically adapt in order to respond to those changes. The process of configuring coalition organizations involves (i) searching for potential partners, (ii) evaluating those partners and the resources they offer, (iii) selecting one or more partners, (iv) determining the "best" distribution of decision-making control and execution obligations among selected partners working to solve a given problem, and (v) negotiating for and instantiating the proposed organization [2].

3.1.1 *AAO Interaction in the CoAX Scenario*

The AAO service resides with the Coalition Force Commander (CFC) domain. The CFC leverages the AAO technology when evaluating potential partners to assist in monitoring the position of the Agadez submarine in the Red Sea. The CFC invokes the AAO service through the IX Process Panels [9], and receives an HTML report describing the recommended organization (example shown in Figure 4). The following describes the steps performed by AAO in the context of the CoAX scenario:

1) *Identify ASW sensor resources with maximum utility:* The AAO service prioritizes potential members based on the utility of their respective ASW sensors for the task of monitoring the Agadez submarine. Supplied with a pool of potential members possessing ASW capabilities, the AAO evaluation highlights the value provided by Arabello, a country known to have extensive ASW sensor resources. In calculating utility, considerations include (i) cost of using the sensor resource (e.g., communication cost), (ii) benefit to achieving the goal (i.e., degree to which the quality of goal solution will increase by leveraging the resource), and (iii) sensor reliability. Figure 4 depicts the list of sensors under consideration, sorted in descending sequence by utility.

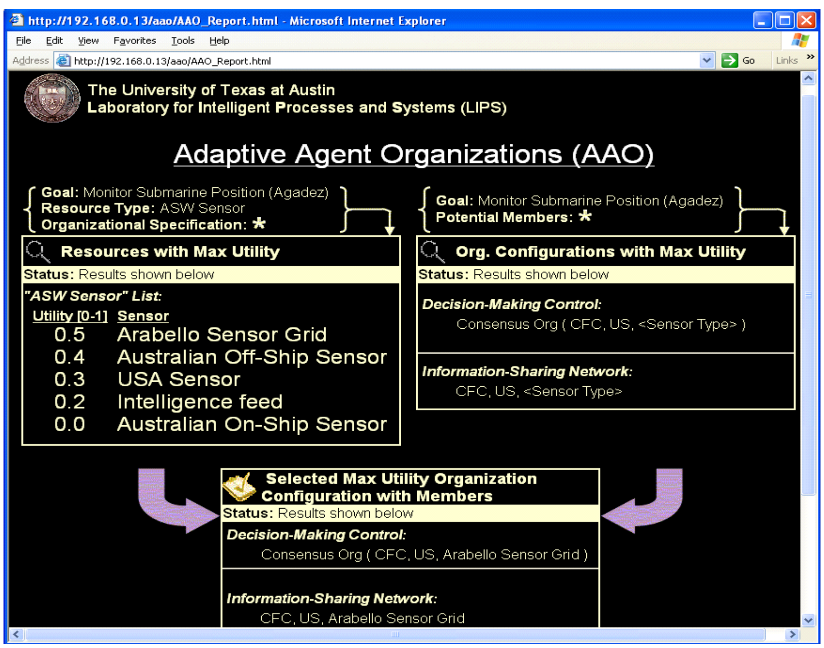

Figure 4: Report generated by UTEX's Adaptive Agent Organizations (AAO) in the Coax scenario

2) *Determine the best organization configuration among coalition members:* In addressing the goal to monitor the position of the Agadez submarine, coalition members may collaborate on a number of dimensions. As shown in Figure 4, AAO recommended organizations for two such dimensions: (i) *decision-making control* – which members should participate in

planning for the submarine monitoring goal and (ii) *information-sharing network* – which members should have access to information about the submarine's position once the monitoring task begins. For both decision-making control and information sharing organizations, AAO recommends collaboration between the CFC, US Headquarter (HQ) domain, and whatever coalition member is eventually selected to offer the needed sensor resources (identified as placeholder "<Sensor Type>" in Figure 4). Furthermore, AAO recommended that the collaborators in the decision-making control organization establish a peer-to-peer *consensus* relationship. Such a relationship is in contrast to arrangements where agents plan independently or receive tasks from a single, designated planner.

3) *Recommend a set of organization configurations with designated members:* AAO combined the results from steps 1 and 2, resulting in decision-making and information-sharing organizations that include the CFC, US-HQ, and the Arabello Sensor Grid.

4) *Form the recommended organizations:* AAO enables the negotiation necessary among participants in the proposed organizations. Assuming successful negotiation, the recommended decision-making and information-sharing organizations are formed and remain intact until the goal has been achieved.

3.1.2 *Information Trust Evaluator (ITE)*

Formulating a single, accurate situational picture requires the coalescing and analysis of information received from multiple sources. An inherent consideration in the coalescing process is assessing the credibility of each piece of information received and the trustworthiness of the sources providing that information. Since perfect sources of information rarely exist for constructing a situational picture, coalition members must coalesce knowledge obtained from multiple sources/sensors and must form some notion of how dependable those sources are. UTEX's Information Trust Evaluator (ITE) service helps decision makers construct rational beliefs about facts asserted by multiple sources based on trust in those sources and the information they provide [3].

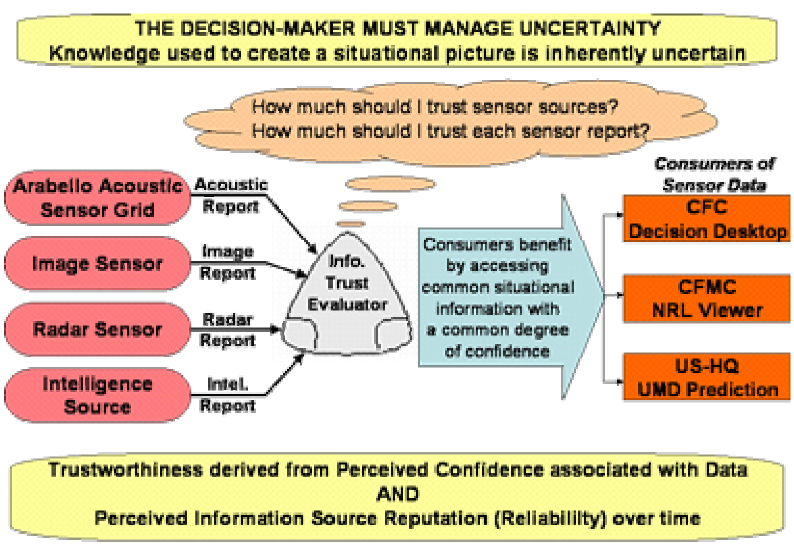

Figure 5: Role of UTEX's Information Trust Evaluator (ITE) in the CoAX scenario

In the CoAX scenario, the US HQ is tasked with monitoring the Agadez submarine in the Red Sea and providing a clear picture of its movements to CFC and Coalition Forces Maritime Component Command (CFMCC) operations. The US HQ uses the ITE to help coalesce sensor feeds from multiple sources including Arabello, US and Australia. Specific sensors considered by the ITE in the CoAX scenario include (i) an Arabello sonar sensor grid on the Red Sea floor, (ii) an Australian image sensor, (iii) a US radar sensor, and (iv) a US-controlled intelligence source (see Figure 5).

ITE enables this process by creating a "net belief" of the submarine's position for each time stamp reported. Each net belief is created from a collection of related sensor reports where each report is qualified by an associated confidence level assigned by the respective source and the source's current "reputation." Source reputations are initialized based on characteristics such as reliability and accuracy; as information is received over time, reputations are revised to reflect actual reliability and accuracy experienced by the ITE (based on the error associated with the source's sensor report, where error is defined as the magnitude of deviation from the coalesced value). By maintaining reputation, the ITE is better able to isolate deceptive or faulty sources to minimize their impact on the decision-making process.

The resulting stream of net beliefs becomes the input to subsequent path prediction analysis performed by the UMD agents and is displayed on the CFC and CFMCC (i.e., GCCS-M "surrogate") viewers. The ITE agents allow these information consumers to focus on analysis and visualization without the need for extensive mechanisms to coalesce data and manage reputations.

3.2 *NRL GCCS-M "Surrogate" Map View*

The NRL participated under the military domain of Coalition Forces Maritime Component Command (CFMCC - a major component of CoAX), and interfaced a GCCS-M surrogate to the agent grid. The interface demonstrated the manner in which software agents would integrate information into a Navy command and control system. Furthermore, the purpose of the demonstration was to show how commanders could interact with such an agent-enabled system to make decisions based on the future state of the Agadez threats. The surrogate GCCS-M system was a COTS product called the eXtensible Information System (XIS) [10]. The XIS was chosen for its similar "look and feel" to GCCS-M, and is planned as a future segment within the Defense Information Infrastructure (DII) Common Operating Environment (COE). The DII COE is the architecture in which the GCCS-M is embedded within.

Interacting with the GCCS-M surrogate and map view, a user (representing a CFMCC staff member) could trigger an NRL display agent to communicate with the IMPACT agent for a prediction on the future location of the Agadez submarine tracks (that are continually received from the ITE agents and stored in the TDBM server).

In the demonstration, the user was able to draw a rectangular region of interest in which a prediction is requested. In the left image of Figure 6, one can see a rectangular region and an icon representing the current location of the Agadez submarine. This information was communicated by the NRL display agent to an IMPACT agent, which returned a two-dimensional probability distribution for the requested region. For each position within this region, the distribution specifies the probability that the submarine will be located at that position during a user-designated time in the future. The distribution is shown in the right image of Figure 6. In this image, a heat color scale is used to display the results such that the higher probabilities are shown in a lighter shade of red. One can also note that underneath the map view there are several dialogue windows prompting the user for input. The set of inputs include *cell latitude length*, *cell longitude length* and *forecast time.* The *cell latitude length* and *cell longitude length* represent the size of the sub-cells within the region and the *forecast time* represents the time in the future in which the user is interested in a prediction.

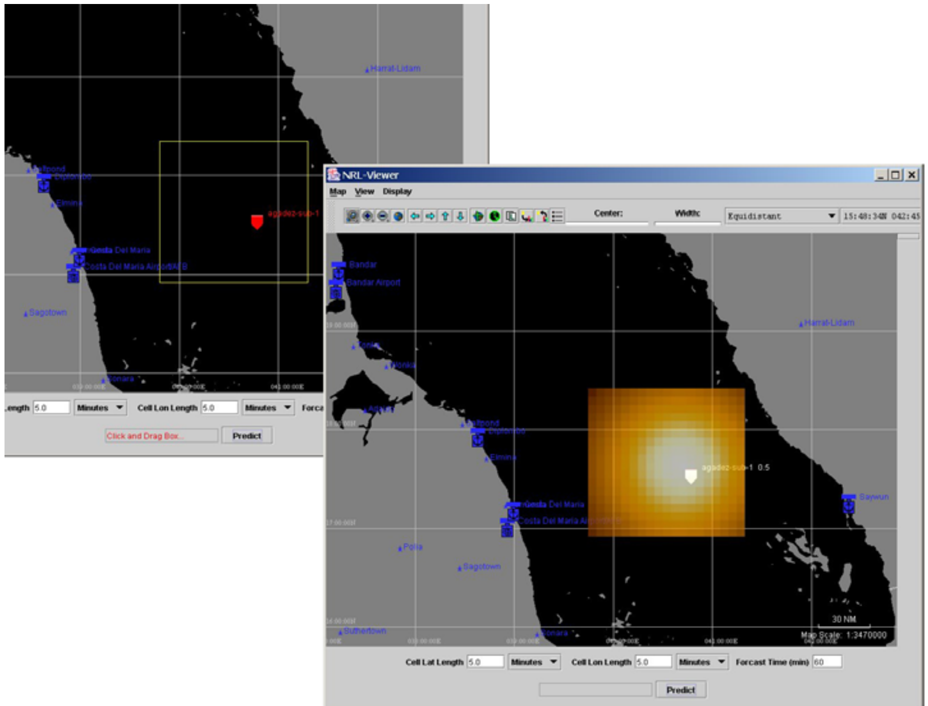

Figure 6: Prediction region that is sent to the UMD-Predict agent (left) and the results returned by the UMD-Predict agent (right)

3.3 *Description of the UMD-Predict Agent*

The probability distribution described in the previous section was generated by the UMD-Predict agent. This agent was developed in IMPACT, the Interactive Maryland Platform for Agents Collaborating Together [1, 6, 7]. IMPACT's powerful libraries made it easy to interpret messages from the CoABS agent grid and to efficiently manipulate the times, positions, velocities, confidence values, probabilities, etc. contained in these messages in order to derive reasonable predictions.

There is a large variety of models that can be used to generate predictions. Some of these models infer future states based on past observations, for example, by fitting a curve through the positions of an Agadez submarine that were reported by UTEX's ITE agent. Other models may create forecasts based on the present situation without considering the past. For example, based on the asset locations and priorities specified by a QinetiQ-Intel agent (another agent on the grid providing intelligence reports), one of these models may predict that an Agadez submarine will head toward the closest high-priority asset, regardless of how the sub arrived at its present location. Even if we restrict our attention to models based on curve fitting for the parametric equations X=f(t) and Y=g(t), we can still derive a large number of mutually inconsistent estimates. For example, predictions based on choosing the best fitting line will not, in general, coincide with predictions based on choosing the best fitting parabola. The UMD-Predict agent considered models based on linear, quadratic, cubic, and periodic (sine wave) regression. Also, to help prevent overfitting of the data, the agent supports models that consider only the *n* most recent observations whose confidence value exceeds a threshold *c*. For example, model m_1 may determine f(*t*) and g(*t*) via linear regression over all past observations while model m_2 may determine f(*t*) via linear regression and g(*t*) via quadratic regression over the last five reports that came from sources with a reliability of at least 90%. Furthermore, the design of UMD-Predict makes it easy to incorporate new models.

There are many ways to combine a set of models into a single, unified model *M*. For simplicity, the UMD-Predict agent determined *M* by using weighted averages where, based on several factors such as user-definable parameters and the sum of the squared residuals, each model *m* was assigned a weight $p(m) \geq 0$ such that $\sum_m p(m) = 1$. The unified model *M* can be represented by a set of probability matrices where each matrix is associated with a time interval. This set of matrices can be concisely stored in a probabilistic temporal relation [4]. Note that the results returned by UMD-Predict are obtained by modifying *M*. For example, if the sub cannot reach (*x*, *y*) by time *t* or if the elevation at (*x*, *y*) is too high for the sub, then the probability assigned to (*x*, *y*, *t*) must be zero. Furthermore, the values in each matrix where smoothed.

To summarize, UMD-Predict is an agent that benefits from IMPACT's ability to efficiently handle multimedia data such as sensor reports. Its forecasts are obtained by generating a large number of prediction models, combining their estimates into one unified model, transforming this model (e.g., by considering terrain and routing information), and then filtering the results (e.g., by constraining the output to the requested time instant and bounding box). For CoAX, the results were visualized by the GCCS-M surrogate.

4. Summary

Effectively conducting military operations requires accurate situation assessment and the ability to quickly adjust and execute plans to respond to the current situational picture. In today's geopolitical climate, coalition operations are often the preferred means for responding to international conflicts. Given the collaborative nature of coalition operations and the ability of software agents to function autonomously as well as in a coordinated fashion, agent-based systems have been promoted as an innovative technology for enabling military personnel to respond efficiently to the changing situational picture and leverage the resources offered by coalition members.

The CoAX demonstrated the value of AAO for dynamically integrating a new coalition member possessing a submarine sensor grid to replace the loss of ASW sensing capabilities associated with a damaged ship. Once integrated, the new sensor grid became one in a series of information sources providing ASW contact reports to help assess the situational picture. Since some degree of uncertainty is associated with each report received, military personnel must consider trustworthiness when assessing the situation and devising an appropriate response. In the CoAX scenario, ITE helped decision makers determine the trustworthiness associated with the contact reports received and the sources providing those reports by maintaining source "reputations" and generating a "net report" for each reporting period reflecting individual report certainties and respective source reputations.

The TIE also showed how these reports could be easily integrated via agents into coalition systems such as the GCCS-M surrogate, and how a user was able to interact with the surrogate map view to trigger the NRL-display agent to query the agent within IMPACT for a prediction of the future state of the Agadez submarines. The TIE between the these three organizations was a critical component in the CoAX experiment that demonstrated how their respective systems could be easily integrated via agents and used to end the simulated regional conflict between two disputing countries in a timely fashion.

The CoAX demonstration successfully showed how software agent technology could be used to integrate (sometimes incompatible) systems together, the utility of policy and domain management facilities to bound agent behavior and facilitate selective sharing of information, and how the ease of composing the agent systems together lead to adaptive responses to changes and unexpected events.

5. Future Work

Building upon the CoAX experiment, UTEX researchers are exploring techniques to (i) more accurately calculate the utility of potential members; (ii) ensure scalability when choosing from many possible organization configurations; and (iii) guarantee reliability in the face of possible communication and processing errors. The UTEX researchers focusing on ITE are investigating more advanced reputation representations as well as mechanisms for managing a hybrid of discrete and continuous information.

The NRL is currently examining the integration of the actual GCCS-M system with the ITEM (Integrated Theatre Engagement Model) simulation via the CoABS grid [5]. The purpose of this integration is to develop and utilize software agents to decompose planning information and efficiently monitor those plans within ITEM. This work is being sponsored by the Defense Modeling and Simulation Office (DMSO). The hypothesis is that agents integrated with both GCCS-M and ITEM will improve the generation of courses of action (COA) and analysis since these agents will help the user to understand the important cause/effect relationships within the plans via simulation.

Acknowledgements

The authors wish to thank DARPA who provided funds for NRL participation, Army Research Laboratory, who funded The University of Texas at Austin, and The University of Maryland in part through contract DAAL-0197K0135 and the CTA on Advanced Decision architectures and Army Research Office (ARO) contract DAAD190010484.

Research sponsored by the Army Research Laboratory was accomplished under Cooperative Agreement Number DAAD19-02-2-0008. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

References

[1] K. Arisha, T. Eiter, S. Kraus, F. Ozcan, R. Ross, and V. S. Subrahmanian. "IMPACT: A Platform for Collaborating Agents". *IEEE Intelligent Systems*, 14(2):64-72, 1999.

[2] Barber, K. S. and C. E. Martin. "Dynamic Adaptive Autonomy in Multi-Agent Systems: Representation and Justification," International Journal of Pattern Recognition and Artificial Intelligence (IJPRAI), Special Issue on Intelligent Agent Technology, World Scientific Publishing Company, Vol. 15, No. 3, pp.405-433, 2001.

[3] Barber, K.S., J. Kim. "Soft Security: Isolating Unreliable Agents from Society," 1st International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2002), 5th Workshop on Deception, Fraud and Trust in Agent Societies, pg 8-17, July 15-19, 2002, Bologna, Italy.

[4] A. Dekhtyar, R. Ross, and V. S. Subrahmanian. "Probabilistic Temporal Databases, I: Algebra". *ACM Transactions on Database Systems*, 26(1):41-95, 2001.

[5] R. Mittu, Z. Furness, and R. Emami. "Agent Mediated Interface Between Command Control Communications Computers and Intelligence (C4I) Systems and Simulation". *Proceedings of the 2003 Spring Simulation Interoperability Workshop (SIW)*, April 2003.

[6] T.J. Rogers, R. Ross, and V. S. Subrahmanian. "IMPACT: A System for Building Agent Applications". *Journal of Intelligent Information Systems*, 14(2-3):95-113, 2000.

[7] V. S. Subrahmanian, P. A. Bonatti, J. Dix, T. Eiter, S. Kraus, F. Ozcan, and R. Ross. *Heterogeneous Agent Systems*. MIT Press, 2000.

[8] http://coabs.globalinfotek.com

[9] http://www.aiai.ed.ac.uk/project/coax

[10] http://www.polexis.com