Partnership for Research Excellence and Transition (PRET) in Human System Interaction:

Human Centric Design Environments for Command and Control Systems: The C2 Wind Tunnel

Year 1 Progress Report

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TEAM MEMBERS:

**Vanderbilt:** J. Sztipanovits (PI), G. Balogh, G. Biswas and G. Karsai
**UC Berkeley:** C. Tomlin (Lead and co-PI), K. Goldberg, S. Sastry and P. Varaiya
**GMU:** Alex Levis (Lead and co-PI) and Abbas Zaidi

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1. Objectives

Our goal is to develop a design environment for mixed-initiative C2 systems, using key ingredients of control and decision theory, model based design, human centered systems design, and robotics, with the following research objectives:

1. Develop adaptive modeling, model validation, and design techniques for mixed initiative teams of distributed decision makers.
2. Develop adaptive models and algorithms for groups and organizations in urban environments.
3. Develop modeling and system integration technology for constructing and executing empirical studies in human system interaction paradigms in dynamic C2 architectures.

Our proposed approach to achieving these objectives will develop the theoretical and technical foundations of an integrated design and rapid prototyping environment for the model-based design of architectures, human and system interfaces and command and control software components for testing and evaluating multiple candidate solutions. Our deliverables will include the models, algorithms, prototype software, interfaces, and metrics for evaluation of the C2 designs.

2. Status of the Effort

We have developed basic components of the project along the three objectives. Towards Objective 1, we are developing an adaptive modeling and algorithmic framework that allows mixed initiative teams formed by automated agents and humans to collaboratively share control over one or more remote UAVs. Motivation for the research was provided by the specific needs of search and rescue and military reconnaissance. Towards Objective 2, a Vignette, involving a future Combined Air and Space Operations Center (CAOC) and air assets such as Unmanned Air Vehicles and F/A-22 strike assets prosecuting Time Sensitive Targets in a net centric environment has been formulated. A CPN model of the decision making organization of the Vignette has been developed that includes decision making organization, Unmanned Air Vehicles (the platform, the sensors, and the controller), and networks. We have developed spreading activation network (SA-NET) structures that work as components of the human organizational structure modeled as Colored Petri Nets (CPNs) and model the plan sequences that human decision makers would generate to execute different mission scenarios. Towards Objective 3, we have developed a model-based approach to the prototyping and integration of C2 Systems, where C2 system architectures could be evaluated in a simulated environment. The integration approach uses the DoD High-Level Architecture (HLA) framework for the communication and time synchronization between system components and an object-oriented middleware (ICE) for data exchange. We have developed interfaces to specific modeling tools and simulators, including: CPN Tools (used to model and simulate organizations and decision making processes), Simulink/Stateflow (used to model and simulate flight vehicle dynamics), Omnet++ (used to model and simulate local area, wide area, and wireless networks), and other, small-scale custom simulation tools. We have build demonstrations that illustrate how these packages could be configured from a common set of models, integration code generated, and simulation experiments executed.
3. Accomplishments and New Findings

3.1 Adaptive modeling, model validation, and design techniques for mixed initiative teams of distributed decision makers (Tomlin, Goldberg, Sastry, Varaiya - UCB)

For search and rescue and military reconnaissance, we are developing an algorithmic framework that allows automated agents and humans to collaboratively share control over one or more remote UAVs. We optimize search in a geometric region with constraints: which frames should the camera capture? Note that these frames are not required to be a subset of the user-requested frames, but are in fact derived from them with the intention of satisfying multiple users at the same time. Once a set of tasks is identified, in which order should the camera proceed to accomplish these tasks?

Over the course of the last few months, we have developed geometric algorithms to answer these two questions independently. We modeled the second problem as a variant of the Traveling Salesman Problem that relaxes the constraint that all nodes be included in the tour and associates a priority with each node. The question then becomes to find a tour of shortest length but maximum weight.

In addition, we have designed a framework for "information-theoretic search", in which groups of UAVs acting as mobile sensors autonomously coordinate to maximize a measure of information about the environment. The mobile sensors can share information to coordinate their motions with respect to each other, yet they act in a decentralized way. We are currently exploring the aspects of noisy information, limited communication bandwidths, as well as the effects of incorporating humans as additional "sensors" in the system.

One of the key challenges in our project is the mixed initiative aspect: understanding how humans and automation should share authority over complex command and control systems. Through the multiple vehicle "hen-chicks" framework that we've built up on this project, we have approached this problem by formulating an optimization problem in which humans and automation can collaboratively attempt to maximize a measure of information about the system.

In one case, we construct an optimization problem that seeks to find the smallest set of frames that maximizes the sum of all users' individual satisfaction. Using a known polynomial-time algorithm for the case of identifying a single satisfaction-maximizing frame, we give a greedy solution as follows:

1. We run the single frame selection (SFS) algorithm to find the single optimal frame \(C^*\), which has a corresponding cumulative satisfaction \(S^*\).
2. For each requested frame that overlaps with \(C^*\), we decrement the utility constant by a factor of 1 minus its satisfaction with \(C^*\), or the level of dissatisfaction the frame has with the candidate.
3. We then re-run the SFS algorithm to find the second-best candidate frame, and continue this procedure until some pre-specified maximum number of frames have been generated, or until the amount of cumulative satisfaction gained falls below some threshold.
4. When the algorithm terminates, we are left with a set of candidate frames, each with a priority according to their cumulative satisfaction level.

We have posted a graphical demonstration of the algorithm at the following site:
http://www.ocf.berkeley.edu/~ebitton/mfs/mfsapplet.html

A brief description of the program is the following:

When "new instance" is selected, a set of ten frame requests is randomly generated, and the initial priority of each frame is uniformly distributed from 0 to 1. The level of transparency of each frame directly reflects its priority (or satisfaction) level, so the more transparent the frame, the more it has been satisfied. We use the single frame selection algorithm to pick the next optimal frame, and we then reduce the priority level of each request that it satisfied by a factor of its ‘dissatisfaction', or 1 minus its satisfaction.

In a second case, we are designing an optimization problem in which a group of mobile vehicles make measurements, using on board cameras and magnetic field sensors, of a potential target location, trying to maximize an information theoretic cost representing the possible distributions of target location. We have designed algorithms for solving these optimization problems suboptimally, using approximations that allow the algorithms to run in real time.

3.2 Adaptive models and algorithms for groups and organizations in urban environments. (Levis, Wagenhals, Zaidi – GMU, Biswas – VU)

A vignette has been developed and is being implemented in the C2 Wind Tunnel. The vignette consists of 13 steps, each having an operational description and technical implementation. Steps 9 thru 13 involve organizational decision making. An excerpt from the Vignette is shown in Figure 1. The full Vignette is available on the project wiki: (https://wiki.isis.vanderbilt.edu/c2w/index.php/Main_Page). The organization conducts Battle Damage Assessment to determine whether a re-strike is necessary. The re-strike targeting solution is determined, the decision to re-strike is made, the re-strike order is given, the re-strike occurs, and BDA to determine the results of the re-strike is accomplished. Data Flow Models have been developed to capture the organizational interactions of the COD, DTC, SODO, etc in com-

Figure 1: Excerpt from the Vignette.
pliance with AFI 13-1 AOC, Volume 3. The Data Flow Models include their activities, e.g., combat assessment, targeting and weaponeering. These models formed the basis for the development of an executable organization model using CAESAR III which is a software suite of applications for design, simulation and evaluation of organizations. The model is implemented in the software application called CPNTools. An objectives hierarchy has been constructed to support the development of a Spreading Activation Network that will capture the organizational decision making. The vignette has been revised resulting in a sub-vignette for creating a simple proof of concept demonstration of the distributed test-bed. It includes a federation of the CPN decision making organization, a simulation of an Unmanned Air Vehicle (the platform, the sensors, and the controller), a simulation of the target environment, and a simulation of the network over which all communications will pass.

An example for the organization model using CEASAR III is shown in Figure 2.

An important component of decision making for command and control in theaters of urban operation is the ability for quick assimilation of data and information as it becomes available, combining this with knowledge and other situational information, and then deriving plans (i.e., action sequences) that take into account scheduling constraints and resource availability in the context of assigned goals for recon and attack missions. In year 1 of the project, we have developed spreading activation network (SA-NET) structures that work as components of the human organizational structure modeled as Colored Petri Nets (CPNs) and model the plan sequences that human decision makers would generate to execute different mission scenarios.

An example scenario, where the DTC chief makes decisions for damage assessment that involves the use of traditional (e.g., UAVs) and nontraditional (e.g., F-22 aircraft) ISR assets is illustrated below.
The DTC chief is tasked with three damage assessment tasks, labeled X, Y, and Z, with the highest priority to task X, then task Y, and task Z. The DTC chief reviews the assets available, and using the SA-NET structure assigns damage assessment for target X (which is of type A) to the F-22, and the damage assessment of target Y to a UAV formation, which delaying the damage assessment for target Z because of the lack of available resources. If conditions change, e.g., the priority of target Z increases above Y, or say other analysis shows target Y is no longer a threat, the SA-NET mechanism can replan and redeploy assets to the highest priority goals.

The SA-NET planning program has been implemented in C++ for year 1. The interfaces to the CPN structure have been defined, and we are integrating the SA-NET planner with the CPN-human centered decision making structures. In year 2, we will focus on developing more complex decision making structures, and extend the SA-NET planning approach to different components of the human organizational structure, e.g., the ISR module.

### 3.3 Modeling and system integration technology for the C2 Wind Tunnel (Balogh, Kar-sai, Sztipanovits – VU)

We have developed a model-based approach to the prototyping and integration of C2 Systems, where C2 system architectures could be evaluated in a simulated environment. The integration approach uses the DoD High-Level Architecture (HLA) framework for the communication and time synchronization between system components and an object-oriented middleware (ICE) for data exchange. We have developed interfaces to specific modeling tools and simulators, including: CPN Tools (used to model and simulate organizations and decision making processes), Simulink/Stateflow (used to model and simulate flight vehicle dynamics), Omnet++ (used to model and simulate local area, wide area, and wireless networks), 3-D modeling packages and other, small-scale custom simulation tools (see Figure 4). The implemented HLA interfaces enable to build large distributed, heterogeneous simulations. We have selected high quality, public domain package to allow the use of the evolving C2 Win Tunnel configuration for research groups. We have build demonstrations that illustrate how these packages could be configured from a common set of models, integration code generated, and simulation experiments executed.
Integration of heterogeneous simulators with HLA-s RTI requires the development of a control interface between the internal schedulers and the RTI time control mechanisms. We have developed a solution that has also well-defined links to the modeling environments, so model-level integration is also supported. Figure 5 below captures the details of the CPN simulator interface to the HLA RTI. Similar interfaces have been implemented for Simulink and OmNET.

Figure 5: CPN – HLA Interface
While the CPN, OmNET, Simulink and 3D geometry components in the HLA framework provide a quite rich infrastructure for complex C2 studies, we continue progressing toward the implementation of our C2 Wind Tunnel vision as shown in Figure 6. We will integrate in the architecture HLA Proxies for “real components” running on our Emulab Platform and we will also expend the basic reusable component library.

A unique design goal for the C2 Wind Tunnel is model-based simulation integration. This goal recognizes the fact that integrating heterogeneous simulation engines into a unified framework (HLA) is only one part (arguably the smaller part) of the challenges. We address the full model-based integration of simulations by developing a modeling overlay for the heterogeneous simulation platform using components of VU’s Model-Integrated Computing (MIC) tool suite.

Figure 7 shows low-level elements of the emerging modeling environment. The primary focus of our future effort will be the development of the different modeling layers, model transformation and generation tools and simulation instrumentation tools.

The emerging Model Integrated Simulation Environment (MISLE) of the C2 Wind Tunnel will be demonstrated in June 2007.
4. Personnel Supported

Vanderbilt:

1. Prof. Janos Sztipanovits (PI)
2. Prof. Gabor Karsai
3. Prof. Gautam Biswas
4. Gyorgy Balogh

Associated but not supported:

1. Himansu Neema
2. Peter Humke

Berkeley:

1. Prof. Claire Tomlin,
2. Prof. Ken Goldberg,
3. Prof. Shankar Sastry,
4. Prof. Pravin Varaiya,  
5. Ephrat Bitton,  
6. Maryam Kamgarpour

**GMU**
1. Prof. Alexander H. Levis  
2. Prof. Abbas K. Zaidi  
3. Prof. Lee W. Wagenhals  
4. Ashraf AbuSharekh (PhD)

Associated but not supported:
1. Prof. Peter Pachowicz  
2. LTC Stewart Liles, USA (PhD student)  
3. John Pham

5. **Publications**


6. Interactions/Transitions

6.1 Participation/presentations at meetings, conferences, seminars

2. J. Sztipanovits and T. Bapty attended the Software and Systems Test Track (SSTT) mid-term review at AFRL-IF, Rome NY on November 2, 2006. The C2 Wind Tunnel design was used as a discussion reference point.
3. J. Sztipanovits attended the C2 Experimentation Workshop, 13-14 November 2006 Air Force Research Laboratory/Human Effectiveness Directorate (AFRL/HE), Wright Patterson AFB, OH
4. A technical interchange meeting was held at George Mason University on December 15, 2006 with researchers from Vanderbilt University. Initial progress on the grant and plans for future tasks were developed.
5. J. Sztipanovits, T. Bapty and G. Balogh demonstrated the C2 Wind Tunnel initial capabilities at the SSTT final report in Arlington, VA on January 19, 2007. The C2 Wind Tunnel design and early demonstration version was used as illustration for the SSTT concept for OSD and industry participants.
6. Researchers from George Mason University visited Vanderbilt University on March 28-29, 2007 and participated in tool demonstrations and developed techniques for creating the interfaces between the simulations needed to create the initial C2 Wind Tunnel capability.
7. Goldberg, GRASP Robotics Lab, Univ of Pennsylvania, Phila, PA, Nov 06
8. Goldberg, CITRIS Distinguished Lecture Series, UC Berkeley, CA, Nov 06
9. Goldberg, American Association for the Advancement of Science (AAAS), Annual Meeting, SF, Feb 07
10. Goldberg, NASA Ames Research, Mt View, CA, Apr 07
11. Goldberg, IEEE International Conference on Robotics and Automation (ICRA), Keynote, Rome, Italy, Apr 07 (Goldberg)
12. Tomlin, NASA Ames Research Center, November 2006 (Invited by the Director of Aeronautics and the Chief Scientist to give a talk to the entire Center.
13. Tomlin, IEEE Conference on Decision and Control (CDC), December 2006

6.2 Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories. Provide factual information about the subject matter, institutions, locations, dates, and names(s) of principal individuals involved

1. Shankar Sastry was a member of the AF Scientific Advisory Board (9/03-9/06) responsible for reviews of information technology programs in the Air Force.
2. Profs. Alexender H. Levis and Janos Sztipanovits serve as member of the AF Scientific Advisory Board.
4. J. Sztipanovits and A. Ledeczi (VU-ISIS) started discussions on the use of model-based methods in C2 design with Dan Fayette, AFRL-IF. Preliminary agreement was formed on developing a training for AFRL-IF personnel on the use of the MIC tool suite of VU.

5. Continuation of this interaction will be VU participation (Ted Bapty) at the first Integrated C2 workshops scheduled to be held at the Georgia Tech Research Institute (GRTI) on 12-13 June 2007.

6. Professors Alexander H. Levis and Lee Wagenhals participated in a workshop at Maxwell AFB (Air War College) on 8-9 March 2007. The title of the workshop was Adversary Behavioral Modeling: Available Tools and Applications for the Warfighter. GMU presented and demonstrated the CAESAR III tool suite that is part of the C2 Wind Tunnel.

6.3 Technology Assists, Transitions, and Transfers.

1. The integration framework being developed in this project will be used to build the simulation environment for a new project at Vanderbilt, titled: Model-Based Software Technologies Targeting Interoperability for Systems of Systems, sponsored the US Army Research Labs. That project develops a modeling and experimentation environment for studying Service-Oriented Architectures on Mobile Ad-hoc Networks.

6.4 New discoveries, inventions, or patent disclosures.

None.

6.5 Honors and Awards

1. Stewart Liles Meritorious Service Medal, US Army
2. Abbas K. Zaidi Promotion to Research Professor
3. Alexander H. Levis IEEE Life Fellow
5. Claire Tomlin MacArthur Foundation Fellowship, 2006
6. Claire Tomlin Okawa Foundation Award, 2006