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**SUPERVISORY CONTROL STATE DIAGRAMS TO
DEPICT AUTONOMOUS ACTIVITY**

Michael Patzek

George Bearden

Allen Rowe

Warfighter Interface Division

Supervisory Control & Cognition Branch

Wright-Patterson AFB OH 45433-7511

Clayton Rothwell

InfoSciTex Corporation

Benjamin Ausdenmoore

Ball Aerospace

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**AIR FORCE RESEARCH LABORATORY
711 HUMAN PERFORMANCE WING,
HUMAN EFFECTIVENESS DIRECTORATE,
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE**

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//signed//

Allen J. Rowe, Work Unit Manager
Supervisory Control and Cognition Branch

//signed//

Gregory J. Barbato, Chief
Supervisory Control and Cognition Branch
Warfighter Interface Division
Human Effectiveness Directorate
711 Human Performance Wing
Air Force Research Laboratory

//signed//

William E. Russell, Acting Chief
Warfighter Interface Division
Human Effectiveness Directorate
711 Human Performance Wing
Air Force Research Laboratory

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14. ABSTRACT A recent report on a vision for Air Force science and technology emphasized shifting “from control to autonomy,” with a goal of developing autonomous systems that have significantly increased decision making capabilities, requiring little to no human input (Technology Horizons, 2010 p. 42). For future unmanned aerial vehicle (UAV) systems, the operator’s central responsibility conceivably shifts from teleoperation to monitoring machines’ autonomous activities. Yet research has shown that high levels of automation are negatively related to operator’s situation awareness and knowledge of system intent, which can lead to poor decisions and inappropriate responses or actions by the operator.					
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PREFACE

The Air Force Research Laboratory's (AFRL's) Value of Information in Collaborative Systems (VICS) initiative is developing technology to enable collaborative control of a flexibly autonomous system. The objective of this research is to investigate the effects differing communication levels and automation display concepts have on supervisory control of multiple UAVs, (711 HPW/RHCI), Work Unit 53290901, Supervisory Presentation for Research, Information Integration & Testing (SPRINT).

1.0 SUMMARY

As capabilities of autonomous systems expand, traditional geospatial information displays used for supervisory control will likely need to be augmented with more explicit information on higher-order autonomous activities, such as goal-directed task selection, situation assessment, decision-making, and planning. We present a supervisory control interface for higher-order autonomy based on finite state machine diagrams called Layered Pattern Recognizable Interfaces for State Machines (L-PRISM). L-PRISM is a hierarchically arranged set of nested state diagrams coupled with a temporal control and payload viewer. The mission goals and tasks are at the top-most layer and sub-tasks and states at lower layers, providing varying levels of information abstraction. Task diagrams use unique layouts to facilitate pattern recognition, which is anticipated to improve the operator's situation assessment. Furthermore, system behaviors can be viewed in real time or retrospectively evaluated. This paper will describe the L-PRISM concept and plans for examining its effect on supervisory control performance.

2.0 INTRODUCTION

The Air Force Research Laboratory's (AFRL's) Value of Information in Collaborative Systems (VICS) initiative is developing technology to enable collaborative control of a flexibly autonomous system. The system is characterized as being composable and fractionated (United States Air Force Chief Scientist, 2010) where heterogeneous members, both human warfighters and unmanned systems, within the system can assemble and combine their respective capabilities and strengths to achieve mission objectives. The heterogeneous components, under varied communication conditions, can coordinate with each other and have the latitude to perform decentralized planning and decision-making as the situation dictates. The goal is to enable agile and adaptive mission management and control for a team comprised of unmanned aerial vehicles (UAVs), unattended ground sensors (UGS), dismounted warfighters with mobile control stations, and an operator located in a central control station. With UAVs equipped and authorized to re-plan and act without human input and under complex, uncertain conditions, a significant technical challenge being addressed is enabling effective supervisory control of the autonomous system. Specifically, the challenge is developing methods for a human operator to sufficiently monitor, inspect, and manipulate the UAVs' activities, which include goal-directed task selection, situation assessment, decision-making, planning, and actions.

Much of the past emphasis in developing multi-UAV supervisory control interface technology has been on effectively portraying the geo-spatial (e.g., a tactical situation map) and vehicle status (e.g., flight parameters, navigation mode, fuel level) information. The associated displays (see example of multi-UAV control station in Figure 1) have transitioned well for many supervisory control concepts as these have typically been applications where the mission planning and management was done with the operator's direct and near-continuous involvement (Feitshans, Rowe, Davis, Holland, & Berger, 2008; Patzek et al., 2009). However, as future,

more autonomous systems assess situations and create their (re-)plans with little or no human involvement, the information typically contained in the tactical situation map and system status displays will not be adequate for the operator to fully understand what the vehicles are doing and why in every case. This, combined with periodic (versus continuous) updates on vehicle locations, status and plans, may lead to significant operator uncertainty and errors in supervisory judgment.



Figure 1. AFRL’s Vigilant Spirit Control Station: An Example of a Multi-UAV Control Station. A) Tactical Situation Map, B) Vehicle Summary Information, C) Vehicle Management Panel, and D) Sensor Management.

Given well-known human-automation interaction shortcomings (e.g., mode confusion, vigilance decrement, lack of appropriate feedback, automation complacency, and bias) and foreseeing supervisory control challenges with a dynamic multi-vehicle autonomous system, we are investigating supervisory control interface concepts to display higher-order mission management and control information pertaining to the vehicles’ progress towards mission goals, tasks, and the underlying rationale for plan changes during mission execution. The goals, tasks, and rationale are intended to provide a window into the vehicle’s perception and assessment of the situation. In addition to providing more detailed information concerning the information processing and behavior of the autonomous system, there is a challenge to present the information in a manner that affords quick and accurate assessment of the multi-vehicle system. With this in mind, our goal is to design concepts that can support the use of symbols and patterns in an attempt to support “at a glance” recognition of complex activities.

We examined design visualization techniques used to illustrate and represent complex, multi-state systems and processes with the idea that perhaps these methods could be made dynamic and animated to represent real-time (and/or past) activities. Diagram and graph methods such as flowcharts, binary decision trees, goal graphs, finite state machine diagrams, and petri nets were assessed for their potential application for an intuitive dynamic display of the autonomous system. Finite state machine diagrams were selected given their efficiency to display multiple systems traversing multiple tasks and states, and the ability to nest states (Harel, 1987) within tasks to represent rules, constraints and overall mission decision logic. Furthermore, the arcs or directional lines between states represent the conditions that must be met by the systems to be able to move from one state into the next, which supports the notion of providing the operator the

rationale for autonomous mission, task, and state changes. Another reason for choosing finite state machine diagrams as the basis for the interface was that they can be formed in a manner to produce unique layouts or patterns, supporting the goal to develop an interface that fosters efficient recognition of the activities. Finally, a form of a state diagram user interface has been demonstrated for robot mission planning and representing robot tasks (MacKenzie, Arkin, & Cameron, 1997; Endo, MacKenzie, & Arkin, 2004).

Currently, we are developing hierarchical pattern-oriented state diagram concepts to represent the autonomous activities. In addition, a control timeline and payload viewer are also being developed to navigate and inspect the past events and associated details, including images, videos, audio recordings, and text messages. The layered finite state machine diagrams combined with a control timeline and payload inspection display, collectively referred to as Layered Pattern Recognizable Interfaces for State Machines (L-PRISM), will be integrated with the multi-UAV control station's tactical situation map and system status information to assist the operator to not only be aware of vehicles' locations and planned routes but also their mission goals, associated tasks, and states to achieve the mission goals. The remainder of this paper will describe the L-PRISM concept and plans for its testing and evaluation.

3.0 THE L-PRISM CONCEPT

The L-PRISM concept, shown in Figure 2, is composed of three display components: A) the State Diagram, B) the Timeline and C) the Payload Viewer. The State Diagram uses the conventions of finite state machine diagrams to represent the autonomous system activity to the operator in real time. The State Diagram depicts the autonomy through the state nodes and transition arcs of the diagram. State nodes are display elements that represent autonomous tasks, showing what the vehicle is doing. The transition arcs represent the specific criteria for changing tasks, showing why the vehicle may move to a new task. Figure 2 shows the diagram for the "Monitor" task, which has five sub-task or state nodes: Patrol, Isolate, Capture, Deliver, and Response. When a task change occurs, the transition arc is animated with the vehicle color to emphasize the task change and help mitigate change blindness (see Simons, 2000, for a review).

Expanding on the conventions of finite state machine diagrams, multiple vehicles can be displayed in one diagram to accommodate multi-UAV monitoring and control. The State Diagram simultaneously shows the state of each UAV in the mission through vehicle icons. Vehicle icons depict the vehicle type, identify the vehicle by its call sign and unique color, and provide a time-on-task clock. The UAV's call sign and unique color are consistent throughout the rest of the control station and support visual momentum when transitioning between different displays. The time-on-task clock shows how long the vehicle has been working in a specific task. If a vehicle's task changes, its icon moves to a new task. The autonomous system can only make task and sub-task changes that follow the transition arcs. For example, in the Monitor task, Patrol can only lead to Isolate. The operator, however, is able to reassign vehicles to any task or sub-task regardless of transition arcs by dragging and dropping the UAV symbol into the desired task (i.e., direct manipulation). For tasks that have no transition arcs, such as the middle task in Figure 2's State Diagram, task changes can only be made by operators. In general, vehicle

control within L-PRISM has the flexibility to support different levels of automation (e.g., management by exception, management by consent, operator directed), as long as there is adequate communication with the particular vehicle(s).

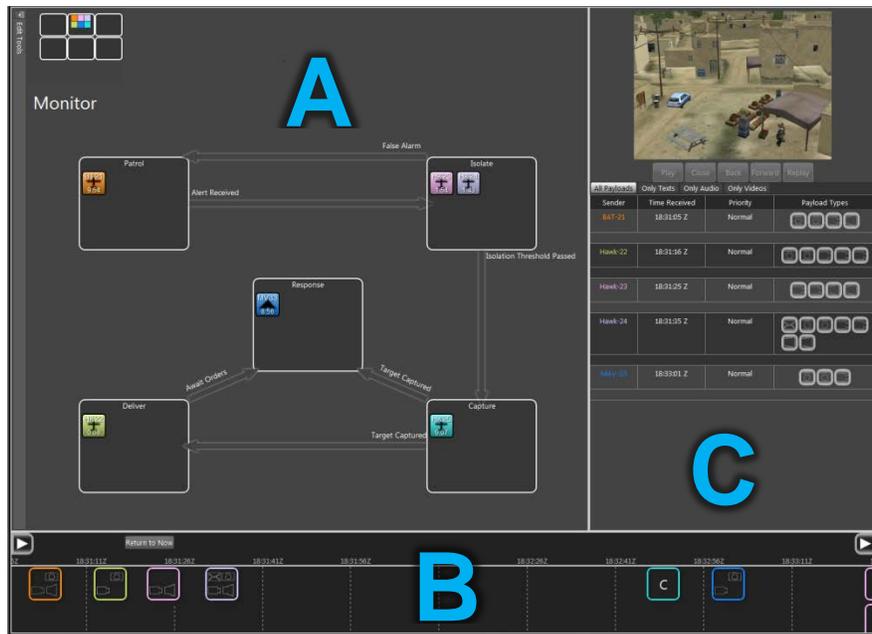


Figure 2. L-PRISM and its three components: A) the State Diagram, B) the Timeline, and C) the Payload Viewer.

Another expansion on the conventions of finite state machine diagrams is in how L-PRISM uses a layered arrangement of nested state diagrams to provide representation of autonomous tasks at varying levels of abstraction. L-PRISM’s State Diagram is currently made up of three levels or layers: the Mission Layer, the Task Layer, and the Sub-Task Layer (Figure 3). These levels of abstraction are expected to enhance understanding and management of autonomous activities in part by displaying connections between actions, plans, and goals. The Monitor task diagram (described above and shown in Figure 2) is an example of a Task Layer that shows sub-task components making up the monitoring mission task. At a more abstract level, the State Diagram shows the Mission Layer (see Figure 3) where each mission task (e.g., Monitor, Surveillance, Overwatch) contains its sub-tasks. Active tasks and sub-tasks are identified with UAV icons shown in them. Additional details concerning the tasks and the UAVs performing the tasks can be found by viewing the associated Task Layer. To maintain overall system awareness when accessing a Task or Sub-Task layer, a small higher level state diagram is portrayed in the top left corner of the display. It shows the UAVs’ mission task assignments and also functions as method to navigate back to a higher layer. Across all levels, each state machine has a uniquely patterned layout to redundantly code the individual tasks, attempting to facilitate “at a glance” recognition. The Monitor task layer can be identified by its unique “X” layout, which is viewable at abstract and detailed levels.

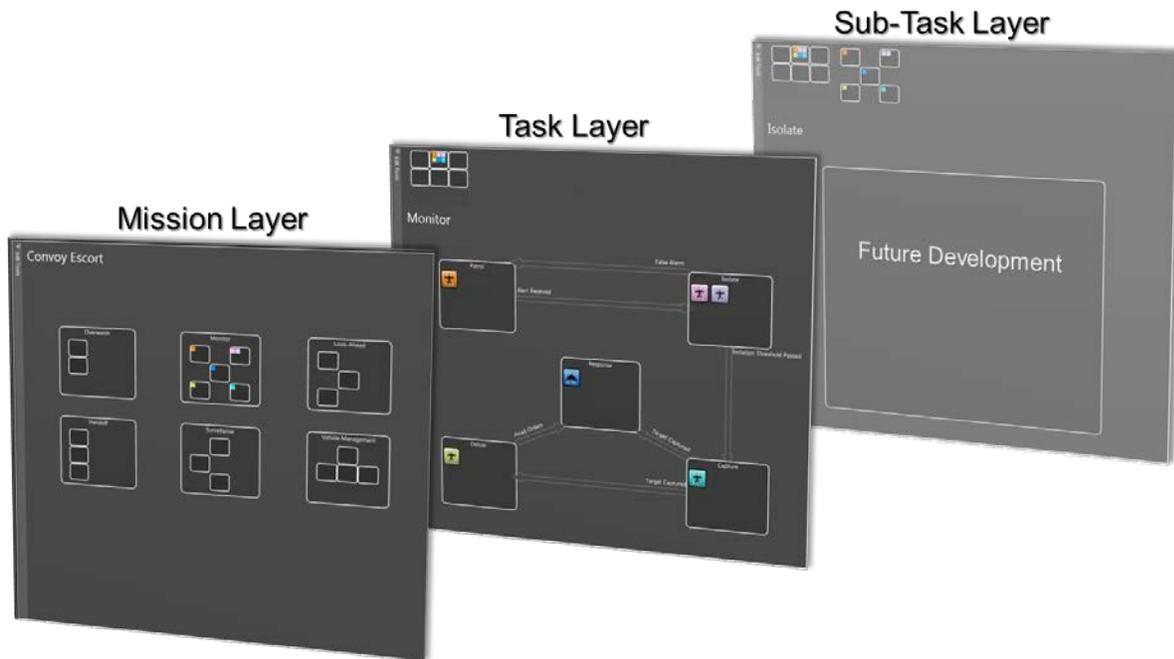


Figure 3. L-PRISM’s layers of nested state diagrams showing varying levels of abstraction. The unique patterns of state diagrams are persevered across different layers. At the Task and Sub-Task layer, a small high-level view is presented to maintain some overall system awareness.

Lastly, the State Diagram can be used to build or edit any layer (Mission, Task, or Sub-Task). When in “Edit mode,” a tool bar appears that allows new state nodes and new transition arcs to be added to the task diagram. Additionally, all the current state nodes and transition arcs can be moved or deleted. Any changes are snapped to a grid, to facilitate the layout of new patterns. Every node and transition arc has a label that can be edited as well.

The Timeline (see Figure 2) presents information on significant mission events and provides controls to retrospectively review that information across the control station. An event is represented by a colored tile containing a letter or icon that depicts a vehicle task change or payload delivery. Colors match the vehicle color that is used throughout the control station, and icons show the type of payloads. When used as a controller, the time selected on the Timeline updates the State Diagram, the Payload Viewer, tactical situation map and vehicle summary displays with the corresponding information at that time. Operators can proceed forward or backward in time to investigate the tasks and actions of the vehicles and rationale behind those actions using controls for temporal navigation: zoom the time scale in and out, scroll forward and back, step serially through events, and return to current time. This retrospective functionality is in contrast to many timeline applications, which represent what is planned or scheduled to happen. This retrospective was designed to gain better situation awareness of past activities and help in supervisory control of the overall system given challenges associated with periodic communication conditions (e.g., decentralized control). For a vehicle that regained communication with the control station after being out of communication for a period of time, all

of its activities will populate the Timeline and are distinguished from other entries by a dashed border. In addition to the retrospective functionality, we plan to expand the timeline to include a view of autonomous system's scheduled tasks and develop a means to contrast the plan with present and past activities. Finally, the Timeline is integrated with the Payload Viewer, such that selection of a payload event on the Timeline will highlight and display that payload in the Payload Viewer.

The Payload Viewer (see Figure 2) displays a sortable list of mission-relevant data referred to as payloads. Typical payloads are images or videos from UAV sensors, but could be operator-generated images or videos as well. Additionally, all operators (i.e., dismounted warfighters with mobile control stations and the stationary central control station) can create and send text messages or "voice note" audio recordings as payloads. Because many of the payloads are an asynchronous form of communication between the system components, the list of payloads was designed to be roughly analogous to email. Each line entry in the list corresponds to a single message that can have multiple payloads attached. The messages and individual payloads show who created the message, what time it was created, the payload type icon, and the message priority. The list of payloads allows sorting and filtering, so that operators can quickly find any payload. When selected, payloads are displayed in the top window with the appropriate controls (e.g., a video payload uses video playback controls).

4.0 FUTURE PLANS

The L-PRISM concept has evolved into a functional design and plans are underway for an empirical study to assess the effect L-PRISM has on an operator's supervisory control performance. The plan is to conduct a set of complex, multi-vehicle mission simulations using AFRL's Vigilant Spirit Control Station with and without L-PRISM. The mission context will be reconnaissance, surveillance, and target acquisition related to finding a suspect vehicle within a large road network, referred to as "road monitoring". The UAVs will be operating, for the most part, in a decentralized control manner where they will patrol and isolate the location of the suspect vehicle in collaboration with the unattended ground sensors and dismounted warfighters. L-PRISM will depict the vehicles' tasks and task changes to display the adaptive autonomous systems. The emphasis will be on assessing L-PRISM's impact on the operator's situation awareness and the ability to detect an anomaly or fault (e.g., an incorrect task or action). Mental workload and confidence ratings will also be compared across the conditions.

Two additional independent variables are being considered for the first or perhaps a subsequent study. The first would vary communication between the heterogeneous system members from continuous, real-time communication to periodic. In past evaluations under continuous communication, operators would, on occasion, attempt to infer the automation activities from the tactical situation map. We are interested in examining if the L-PRISM information changes the reliance on the map for assessing the vehicles' tasks and how the communication level affects the operator's behavior. The second variable of interest is the reliability of the autonomous planning and actions and its effect on the use of L-PRISM information given the operator's understanding of the reliability and resulting trust levels. Here the hypothesis is that the L-

PRISM display would be relied on more for autonomous systems prone to more situation assessment and planning mistakes as L-PRISM provides a more detailed medium to inspect the higher-order activities.

As part of the VICS initiative, the Vigilant Spirit Control Station and L-PRISM design will be integrated with decentralized control algorithms for a multi-UAV flight test to demonstrate the road monitoring mission task. The plan is to place unattended ground sensors along a large road network and have the UAVs collect information from them and locate vehicles detected by the UGSs or dismounted warfighters. The L-PRISM information will be available to both the central control station and the mobile control stations used by the dismounted warfighters. L-PRISM is expected to provide critical information to understand the complex conditions and activities associated with this composable and fractionated autonomous system.

5.0 SUMMARY

In summary, L-PRISM is an evolving supervisory control display concept to enable an operator to quickly gain situation awareness and effective oversight of adaptive autonomy and the associated systems: their mission goals, tasks, states, and the underlying rationale for adaptive plans and actions. L-PRISM shows promise for providing many of the desired attributes and features for displaying information on a highly autonomous multi-vehicle system. It supports scaling of the team size, the heterogeneous systems and capabilities, assorted mission tasks and embedded states, both real-time and periodic communication conditions, the patterns for recognizing the tasks, states and overall situation, and can and will be integrated within an existing multi-vehicle supervisory control station.

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