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EXPERT SYSTEM FOR ON-BOARD SATELLITE SCHEDULING & CONTROL

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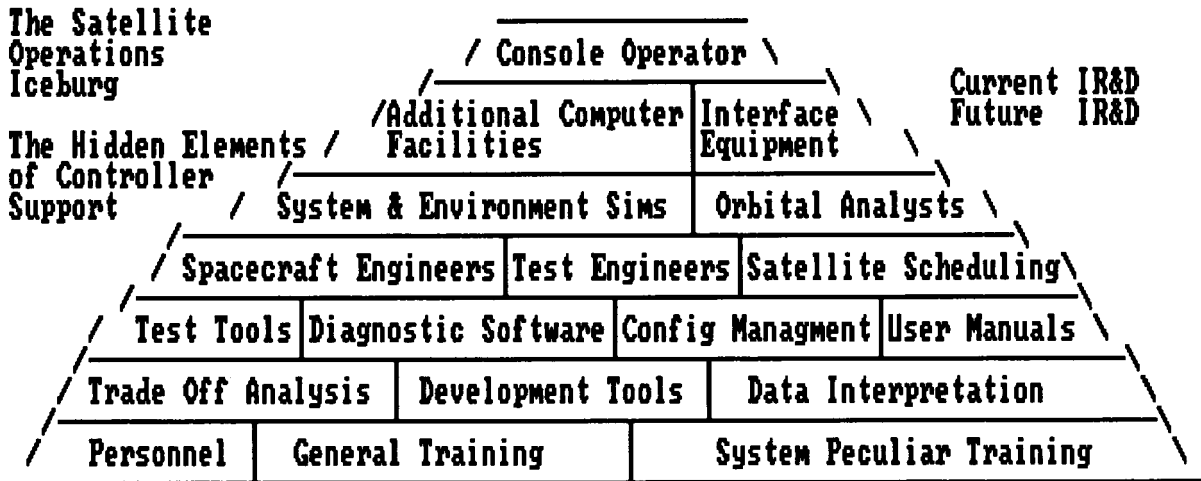
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ABSTRACT

This paper describes an Expert System which Rockwell Satellite & Space Electronics Division (S&SED) is developing to dynamically schedule the allocation of on board satellite resources and activities. This expert system is the Satellite Controller. The resources it will schedule include power, propellant and recording tape. The activities controlled include scheduling satellite functions such as sensor checkout and operation. The scheduling of these resources and activities is presently a labor intensive and time consuming ground operations task. Developing a schedule requires extensive knowledge of the system and subsystem operations, operational constraints, and satellite design and configuration. This scheduling process requires highly trained experts anywhere from several hours to several weeks to accomplish. The process is done through "brute force" -that is examining cryptic mnemonic data "off line" to interpret the "health and status" of the satellite. Then schedules are formulated either as the result of practical operator experience or heuristics - that is "rules of thumb. Orbital operations must become more productive in the future to reduce life cycle costs and decrease dependance on ground control. This reduction is required to increase autonomy and survivability of future systems. The design of future satellites require that the scheduling function be transferred from ground to on board systems.

INTRODUCTION

Most satellite operations are accomplished by sending software commands via communications from ground control centers to the satellite. These commands monitor and control satellite "health and status" and uplink new schedules to control the satellite utilities and mission. The present method of managing these resources is through interpretation of digital satellite data, manually creating new schedules, then uplinking them to the satellite. This method, often referred to as the "software screwdriver," will dominate satellite operations until launch availabilities/capacities increase and launch costs are drastically reduced. Software techniques developed to manage these resources will supplement eventual on-orbit repair and replenishment schemes.



Operational costs will be lowered by reducing the facilities and personnel needed to operate a satellite. Currently an average of eight console operators are needed to support each satellite, each backed up by an army of personnel and tools. RADC estimates that satellite autonomy could reduce the number of console operators per satellite from eight to one. This reduction is especially significant when applied to programs such as SDI where the total number of satellites will be far more than any other program to date.

Press <any key> to continue, F10 to skip to demo.

Figure 1. The satellite operations iceberg

Even using the software screwdriver, operating and maintaining a satellite in orbit is a large, expensive, and complex task which requires many people, diverse skills, and coordination of various contractor and government organizations. Air Force studies indicate that an average of 8 controllers are required to operate and maintain 1 satellite. However, this figure is just the "tip of the iceberg". Backing up these controllers are "back room support" personnel such as orbital analysts, computer operators, programmers, systems engineers and so forth. This support easily expands into 200-300 people per satellite system (see Figure 1).

If we were to scale this present mode of support to the expected number of satellites for future space operations, the costs would be prohibitively high. We can no longer afford to control future spacecraft missions in the manner that we support such highly successful programs such as Viking and Voyager. Studies indicate that the satellite operations costs will rise dramatically if we continue these present methods. These increasing cost trends clearly indicate a need to simplify and automate the maintenance of satellites through an improved ground command and control environment. Ignoring these trends will severely limit NASA's ability to afford the acquisition, deployment and control of future space programs. Therefore, reducing ground command and control costs is a way to make more money available to develop future space programs.

The present method of analyzing and fixing problems, changing mission tasks on the ground, and sending commands back to the satellite must be changed. A loss of communication from the control centers due to war, terrorism or natural disaster would leave the satellite in a position where its mission might be degraded or unattainable. The design of future satellites require that the scheduling function be transferred from ground to on-board systems to increase autonomy, survivability, adaptability and reduce costs and response time.

TRADITIONAL APPROACHES TO SATELLITE CONTROL

Approaches to improve control satellites traditionally concentrate on automating computational and data reduction tasks, and developing better displays. However, these efforts alone will not solve the satellite Operational and Maintenance (O&M) problem. The solution is not trivial because significant engineering judgement and reasoning are required to operate the satellite and resolve anomalies. Satellite operation is complex because of the limited amount of on-board resources available such as electrical power. This situation is further complicated by multimission satellites which must share these resources among a variety of sensors. Sharing resources requires consideration of multiple constraints dependent on the sequencing of operations and availability of resources.

The management and planning of missions is presently accomplished by manually or automatically translating, sorting, and analyzing large amounts of digital data and displaying trends. A typical satellite console display contains only cryptic alphanumeric data that the operator must decipher. Some satellite operations centers then transmit this data to other computers for off-line analysis to display trend and graphical data. However, trend analysis is insufficient to accurately predict and correct all satellite anomalies. Such analysis cannot predict multidimensional, constraint-based anomalies or develop potential solutions to correct the anomalies.

INNOVATIVE ROCKWELL APPROACH

Rockwell Satellite & Space Electronics Division (S&SED) is developing an Expert System to dynamically schedule the allocation of on-board satellite resources and activities. This expert system is the Satellite Controller. The controller is a continuation of prior Rockwell on-board satellite intelligence research concepts. These concepts included not only the controller but also other "intelligent agents," such as the satellite planner, and subsystem specialist. The primary function of the planner is to generate a plan for fulfilling the objectives of a satellite or a group of mission related payloads. The subsystem specialist is responsible for the operational availability of its associated subsystem. The controller coordinates the generation of an agenda for executing selected missions of a satellite or

group of mission related payloads. The controller is being prototyped to substantiate the concept of increasing on-board satellite autonomy. This concept also provides insights to simplify the task of the present satellite operations ground controller and the personnel who support ground control. This simplification reduces vast amounts of cryptic satellite data to create more intelligible operator displays.

The expert system of the satellite controller develops feasible strategies to manage the satellite resources and activities. These strategies are based on heuristics or "rules of thumb" currently used by ground satellite operations specialists. These heuristics are being incorporated into the reasoning algorithms of the Rockwell expert system. Rockwell will transition the ground expert system into future satellite designs once they have been proven and tested in the ground control environment.

The Rockwell approach is based on examining current design and operations of several satellite systems which it is currently designing, producing or operating. These systems include the various navigation and surveillance satellites. Our approach starts with a functional examination of the objectives needed to operate and maintain a satellite in the most cost effective manner. The Rockwell concept concentrates on presenting knowledge or formulating advice instead of displaying only raw information to an on-board controller. This knowledge is the result of known constraints, an operational model of the satellite systems, and the judgement developed by experts. Today this knowledge is created by the previously mentioned "back room support" personnel. The Rockwell approach is to reduce and display digital data in a manner which simplifies operator understanding. This approach will result in real time satellite control and analysis which can be implemented within the spacecraft systems to increase autonomy.

The innovative Rockwell approach described in this paper and demonstrated on a personal computer in this conference covers several facets. These facets include the Satellite Controller Concept, the Enhanced User Interface, the Knowledge Base, the Satellite Controller Description and Operation, and Mission Planning. This later facet will be illustrated to the user by leading him through a scenario handled by the Rockwell Satellite Controller.

RAPID PROTOTYPING

Rockwell developed a low risk, high confidence approach to the controller design through rapid prototyping. Rapid prototyping is a technique which one models the visual interface and operation, but not complete functionality of the desired product. The controller's perspective was obtained through dialogue and feedback from current Air Force satellite operations personnel. This perspective emphasized simplification of the user interface and reduction in the number of operational personnel. We used this information and rapid prototyping to encapsulate the satellite controller actions. The result was deemed by rep-

representatives of the Air Force to accurately reflect the visual cues a satellite controller would like to see. Designing this perspective allows us to simplify ground control mechanisms and functions and understand the processes required to design more autonomy into satellites. The prototype is designed so that it can be readily changed to reflect enhancements to the controller's perspective and true operation of the system without extensive re-coding.

THE SATELLITE CONTROLLER CONCEPT

Controlling satellites is a labor intensive and time consuming ground operations task. Developing a schedule requires extensive knowledge of the system and subsystem operations, operational constraints, and satellite design and configuration. This development process requires highly trained experts anywhere from several hours to several weeks to accomplish. The process is done through "brute force" - that is, examining cryptic mnemonic data "off line" to interpret the "health and status" of the satellite. Then schedules are formulated either as the result of practical operator experience or heuristics - that is "rules of thumb." Rockwell is developing the Controller to improve orbital operations productivity, reduce life cycle costs, and decrease dependence on ground control.

The Rockwell Satellite Controller is an expert system which controls, coordinates, and manages the activities of various subsystem specialists. Subsystem specialists control and manage their respective subsystems such as the propulsion, power, attitude control, or communication subsystem. The coordination is achieved through an agenda or common area that either the controller or the subsystem specialists can access. Requests or statuses of actions are posted on the agenda. This information is used by the controller in creating an initial schedule and in coordinating its execution. This IR&D project has concentrated on developing the satellite controller and simulating the activities performed by the subsystem specialists. Also, this IR&D project has begun to determine the division of knowledge between the controller and the subsystem specialists. The controller is knowledgeable of the information necessary to make global decisions that may affect the subsystem specialists, whereas the subsystem specialists are knowledgeable of the information specific to their respective subsystem.

SCHEDULING LOGIC

The scheduling logic was developed in parallel with the prototype user interface using CLIPS, a C-based expert system building tool developed by NASA. Controlling this process involves an inference mechanism known as forward chaining. Forward chaining is an inductive mechanism which uses facts and rules to "reason" toward a solution. This mechanism examines the premises of rules to see whether or not they are true given the

information on hand. If so, then the conclusions are added to the list of facts known to be true and the system examines the rules again. The satellite controller uses this process through the information in the knowledge base, concerning interpretive rules and information about the design and operation of the satellite systems.

ENHANCED USER INTERFACE

The prototype of a user interface concentrates on displaying relevant knowledge - i.e. "digested information," meaningful to the operator. This interface can replace digital data from several operator terminals with a single screen displaying English language phrases which do not require deciphering. Therefore, the operator is presented with the phrase "sensor 1 slewed 5 degrees" instead of the normal digital data that must be interpreted. This process is more than a simple transformation. It actually involves parsing or interpreting inferred information from the inputs of several systems aboard the satellite.

The controller interface generates four key groups of data during its execution: agenda information, satellite controller actions, subsystem health and activity status, and task schedule timelines. The user interface was developed to demonstrate understanding of an on-board design approach, portray a potential ground station controller's workstation, and provide user control of the expert system simulation.

The English phrases are displayed in one of two windows of the Satellite Controller. The main screen is divided up into a SATellite CONTroller (SATCON) window, an Agenda window, Subsystem Icons and a MENU. The SATCON window displays the actions of the controller as it creates a schedule. The Agenda window shows REQUESTS for action from either a subsystem or the controller. The Agenda window also shows the current STATUS of the various subsystems of the satellite. These windows can be activated by a macro key on the terminal which toggles between the two activities. Both windows can be scrolled to display an audit trail of activities that have occurred on the satellite. The display has icons on the right side of the screen which activate other macros to allow the operator to "EXAMINE" the schedule, a "HELP" key, and others. In addition, the satellite subsystems are displayed in icons across the bottom of the screen. The individual subsystem icons are activated whenever activity is occurring which affects that subsystem. This activation assists the operator in visualizing subsystem status (see Figure 2).

The enhanced user interface of the satellite controller replaces the digital display mnemonics of current systems. More importantly it consolidates information of several satellite operators and support personnel into one display. The experience gained from this design will be used to define the data flows for the eventual on-board controller.

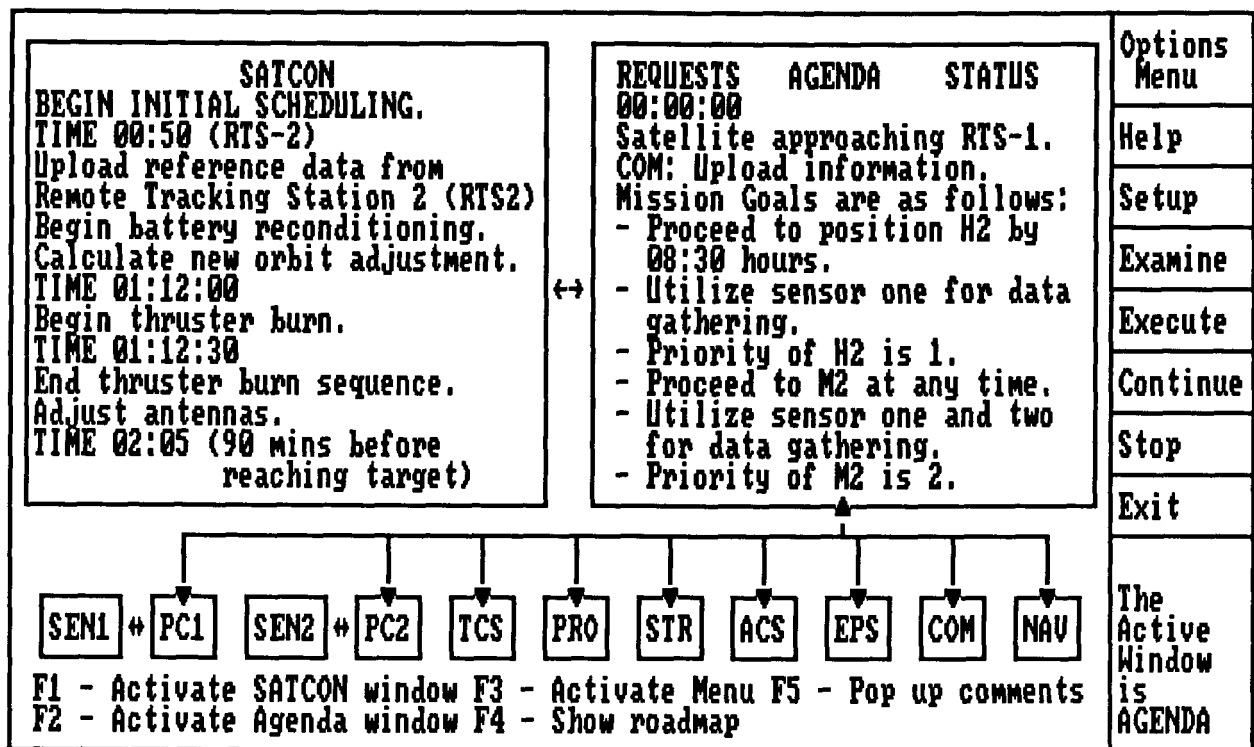


Figure 2. The Satellite Controller User Interface

A real user interface to visualize the controller's perspective was coded in Turbo C to be used by the scheduler. This scheduler, plus the user interface and the knowledge base, provides the platform for the Satellite Controller expert system development.

KNOWLEDGE BASE

Construction of a knowledge base is a complex process which involves an intimate knowledge of the subsystems, their relationships, constraints/rules and operating parameters. Initially, the Rockwell knowledge base is purely rule based. Eventually we will organize this knowledge base into frames which is a knowledge representation scheme that associates an object with a collection of features (e.g. facts, rules, defaults, and active values). This knowledge representation facilitates the development of model based reasoning schemes. Model based reasoning can create dynamic schedules based on a system representation rather than pure rule based system. The advantages of a model based system is that it can infer an "unknown" situation not specifically stored in the knowledge base.

The contrast between a rule based and model based automobile diagnostic system illustrates this point. A rule based system can accurately diagnose a condition directly attributable to a procedure or checklist which is already in the knowledge base. For example, such a system can isolate a failed voltage regulator if the car will not start. However, if an unpredicted event such as a meteor fell on the engine the night before, the rule based expert system would not accurately diagnose the problem. However, a model based system contains not only rules but the description on "how" the system should operate. This description includes hierarchical or complex relationships among the systems and message passing. This description actually forms a "model" on how the system works. This model based reasoning would then determine that there is major damage to the engine compartment or some subsystem(s) instead of developing a false diagnosis. This information is more useful and accurate than that developed by a rule based system because it can make inferences on dynamically changing situations.

MISSION PLANNING

As a premise to scheduling activities and resources, the expert system performs mission planning. A mission scenario was created to validate these concepts. Initially the planning would be developed and tested a ground control workstation. Rockwell plans is investigating the use their Mission Operations Support Center to construct and test a satellite controller on its Global Positioning System. The ultimate goal is to develop the technology to design this expert system to operate on-board future satellites.

A mission consists of a goal or objective, a start time, a duration, and a priority. The present Rockwell expert system is modeled after a surveillance satellite. A typical mission might be to view a ground location at a prespecified time. A mission is made up of multiple tasks that must be completed in order to satisfy a mission. For a viewing mission, typical tasks that must be scheduled would include operating a sensor, preparing a sensor for operation, shutting down a sensor, and downloading data to a remote tracking station when recorders are full following a mission. General station keeping tasks must also be scheduled such as orbit adjustments, uploading current reference updates when over a remote tracking station, or momentum dumps.

Given multiple, conflicting missions, the expert system will try to schedule as many missions as possible. Currently, priority is the only constraint used to determine which missions will be scheduled first and which missions cannot be scheduled at all. The satellite moves on a path over the earth called a ground track and can move or slew itself several degrees in the plus or minus direction in order to view a location. Therefore, it would be possible to view two locations when on the same ground track by slewing the sensor. It could also move to another ground track to view a location, but this will require resources such as propulsion in order to make the move. In the future, the expert system will incorporate the reasoning to determine how to satisfy as many missions as possible by

traveling on a ground track where multiple locations could be viewed at once while minimizing the amount of resources used.

CONSTRAINT BASED TASK SCHEDULING

Constraint based reasoning is used to assist in the mission planning function. Given several mission goals, the expert system will determine what tasks must be accomplished in order to satisfy a mission goal. It will determine when to schedule these tasks based on constraints. Typical constraints include temporal constraints such as prepare for sensor operation must be done before sensor operation or shutdown sensor must be done after sensor operation (see Figure 3). Other constraints include scheduling a download data task after all recorders are full. This can be calculated by summing the durations of sensor operation tasks. Or if it has been over 90 minutes since gyro heaters have been turned on then schedule a 90 minute prepare for sensor operation task in order to allocate enough time to run the gyro heaters before a sensor operation task begins. Tasks are made up of subtasks. For example, a sensor preparation task is made up of tasks to power up the payload and initialize it, turn a recorder to standby, turn the payload electronics to standby, and perform enhanced attitude adjustment. Enhanced attitude adjustment includes turning on the gyro heaters, enabling the GN2 thrusters, enabling the rate gyros, and maintaining attitude. Scheduling is performed at the task level if possible, otherwise scheduling can be done at any subsequent task level below.

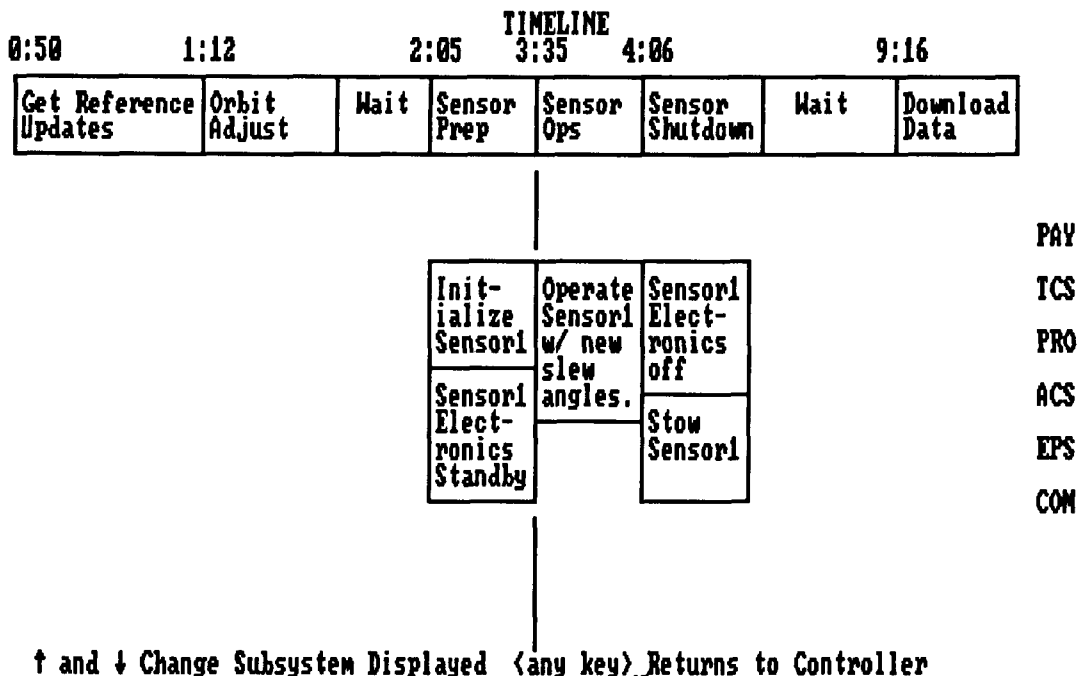


Figure 3. The Satellite Controller display for a sample sensor payload schedule

RESOURCE MANAGEMENT

Included in scheduling of tasks and subtasks is scheduling of the on-board resources which enable the task to be completed. Currently, the system will determine if a task can or cannot be scheduled based on available resources. In the future, it will be able to reason about when would be the best time to perform a task based on the resources the task will use. For example, it is better to perform a task on the current ground track, rather than move to another ground track because less propulsion will be used. Currently, three resources are managed: power, propellant, and recording tape. Power is a resource that stays at a fixed level and is reduced or increased when a task is performed or completed. All tasks use power and a minimum amount of power is always used for station keeping. Propellant starts at a given level and is used as tasks are performed but it is never replenished. Recording tape is used during a sensor operation and is completely used when all recorders are completely full of data. Recorders are replenished when all data has been dumped to the ground when over a remote tracking station.

These are just a few resources that must be considered when designing the Satellite Controller. Future research will concentrate on expanding the controller functionality to handle other missions. This research will be integrated with other Rockwell projects with reliability, fault detection and diagnosis.

SUMMARY

The Rockwell Satellite Controller project is using Artificial Intelligence technology to develop a concept to reduce future space operational costs and increase effectiveness in controlling satellites. The initial objectives of the Rockwell project are to schedule on-board satellite resources and activities. In the process, Rockwell is developing techniques which can simplify operations and improve the productivity of ground controllers. The Rockwell approach of investigation is based on examining system operations and gaining feedback from satellite operators. This feedback was used to construct the prototype demonstrated in this conference on a personal computer.

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BIOGRAPHY

John Barry is currently the Program Development Manager for Research & Technology at Rockwell's Satellite & Space Electronics Division in Seal Beach, California. Prior to joining Rockwell he was an Air Force Officer for 20 years serving the USAF Space Division and Rome Air Development Center. He has a B.S. Degree in Math and Physics, from LeMoyne College, an M.S. Systems Management from the University of Southern California, and M.S. in Logistics Management from the Air Force Institute of Technology and an M.S. in Computer Science from Northrop University. Mr. Barry is an adjunct professor in the graduate program at Northrop University in the Computer Science Department. He is also a Senior Member of the Society of Logistics Engineers.

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