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Intelligent Command and Control Systems for Satellite Ground Operations

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I. Introduction

The Georgia Tech portion of the Intelligent Control Center project includes several complementary activities. Two major activities entail thesis level research; the other activities are either support activities or preliminary explorations (e.g., task analyses) to support the research. The first research activity is the development of principles for the design of *active* interfaces to support monitoring during real-time supports. It well known that as the operator's task becomes less active, i.e., more monitoring and less active control, there is concern that the operator will be less involved and less able to rapidly identify anomalous or failure situations. The research project to design *active monitoring interfaces* is an attempt to remediate this undesirable side-effect of increasingly automated control systems that still depend ultimately on operator supervision.

The second research activity is the exploration of the use of case-based reasoning as a way to accumulate operator experience and make it available in computational form. This project investigates the use of case-based reasoning technology to accumulate a knowledge base of actual operations experience and, subsequently, to use that experience as aid or advice in an intelligent decision support system. Initially, such a system will monitor real-time operations, forming a knowledge base that reflects the range of nominal operations. As unplanned and/or anomalous events occur the case base grows, in fact it automatically *learns*, broadening its knowledge base to include operations experience accrued in managing these unanticipated events. Such a system uses case-based reasoning technology to build an extensive repository of operations experience, i.e., cases, that over time, can function as the knowledge base for an autonomous system. This project represents one of the first applications of case-based reasoning to real-time decision making and system control. It provides an alternative, and potentially richer, knowledge base than other AI techniques such as rule-based systems. Given the extent of operational experience that comprises the foundation of FOT expertise, a case-based system that can learn from skilled operators is a promising way to encapsulate and capitalize on human experience and subsequently make it available to both other operators and intelligent systems.

Support activities for the two major research thrusts include the following: SAMPEX Operator Function Model, SAMPEX Task Analysis of Anomaly Detection and Correction Processes, TPOCC Simulation/Testbed enhancements, and enhancements to TK+, an object-oriented toolkit for interface design and development.

II. Principles for the Design of Active Monitoring Interfaces (David A. Thurman, M.S. Thesis)

This research is concerned with the design of more effective interfaces for monitoring tasks. It is based on the hypothesis that one of the problems with current monitoring interfaces is that they are too passive. Existing monitoring interfaces do not require sufficient operator interaction to keep the operator engaged in the task of monitoring the system.

This research does not propose, however, to build actions into the interface (in a make-work fashion) simply to keep the operator occupied. Instead, actions should be 'designed' into the interface which convey information to the operator about the state of the system and the tasks that need to be accomplished. In particular, this research explores the use of interface actions to represent the inherent structure of the monitoring task. That is, the interface should visibly represent the required monitoring tasks as actions that operator can take in the interface. In this way, actions available in the interface will correspond to the monitoring tasks that need to be completed by the operator.

The research hypothesis to be tested is that an interface designed in this manner will result in better monitoring performance, resulting in decreased fault detection times, increased fault detection levels, and a better understanding by the operator of the monitoring tasks to be completed.

This hypothesis will be tested by constructing two interfaces. The first interface (conventional interface) will be designed similar to the existing TPOCC interface for SAMPEX. This interface will consist of four subsystem level display pages (ACSOV, WPSEBAT, PDPCUTLM, and TSCTEMPS2), the Master display page, a command line control page, and screens for performing ATS 'loads' and science data 'dumps'. Operator interaction with this interface will be similar to the current SAMPEX/TPOCC interface.

The second interface (interactive monitoring interface) will be designed based on a task analysis of the SAMPEX operators' monitoring task. It will use interface actions (e.g., button presses, menu selections, drag and drop actions, etc.) to provide a representation of the operators' require monitoring tasks. For example, one required monitoring task is to evaluate the state of approximately a dozen critical system parameters. The interactive monitoring interface will facilitate this by providing drag-and-drop capabilities which allow the operator to quickly determine the current state and history of any displayed parameter. The formal thesis proposal for this research is provided in Appendix A.

The interactive monitoring interface (IMI) will consist of the conventional interface with a number of extensions designed to represent the structure of the operator's monitoring task. Using the extended OFM of the SAMPEX on-pass activities, this proof-of-concept interface will provide interface actions which correspond to the monitoring activities which need to be completed by the operator. In particular, the IMI will provide capabilities for monitoring individual telemetry points, identifying and recording critical parameters, monitoring command load and data dump activities, and electronic support for a large number of the record keeping tasks operators are required to perform.

To date, support for monitoring and recording individual/critical telemetry points and anomaly reporting anomaly reporting is completed. Efforts are currently being concentrated on the design and development of the 'command load' and 'science data dump' portions of the interface. While the resulting interface will not support all FOT on-pass activities, telemetry point monitoring, record keeping, command loads, and data dumps are representative of all standard FOT activities.

III. Use of Case-Based Reasoning in an Intelligent Command and Control Center

(Andrew Jay Weiner)

Human-machines systems researchers are interested in human supervisory control of complex systems. One aspect of this research is an interest in how controllers accumulate and store operational knowledge about the system. High operator turnover rates results in a drain of 'corporate memory' from many operational systems. This leads to increased interest in the automated accumulation and storage of operational knowledge. Many approaches to tackling this problem have used techniques borrowed from artificial intelligence research.

One interesting application of AI research in this domain has come from the use of case-based reasoning techniques. In case-based reasoning, the problem solver bases its reasoning on previous cases rather than by the more traditional rule-based approach of generalized knowledge in the form of specific "if-then"-type rules. This technique allows real shortcuts in problem solving by introducing several enhancements to rigid old-style AI techniques. First, previous decisions which have been made can be suggested as solutions to the current situation, so that new reasoning does not have to be done from scratch. Second, the recall of previous cases of failure can serve as a warning of potential failure and allows the system to be flexible in avoiding future failures. Third, the recall of previous cases may allow for patterns to be recognized, allowing for the enhancement of the general knowledge about the system (Kolodner, 1987).

A large body of researchers believe that humans use so-called "case-based" techniques for a large portion of their reasoning processes (see Schank, 1982). In fact, some researchers have gone so far as to suggest that a case-based reasoning system really consists of a human-machine pair working together, rather than just an isolated machine intelligence (Kolodner, 1993). Because case-based reasoning provides a commonsense, intuitive model of problem solving, knowledge acquisition is facilitated in a case-based system. Case-based reasoning is a natural, intuitive process for people. Case-based interactive aiding systems that help a user solve a problem work well. Case-based reasoning systems can provide tools for situation assessment, for adapting retrieved solutions, and for trying out adaptations to old solutions. These tools are important because they facilitate operator problem solving in real-time control systems. When case-based systems are augmented by the experiences of those who use them, they can become an institutional memory for the organization that is using them, allowing personnel to share their experiences.

Two projects were conducted to explore the application of case-based reasoning as a form of 'corporate memory' for the satellite control center. Both explored the possibility that case-based reasoning systems can serve as interactive aids to a satellite controller for the task of resolving spacecraft anomalies. The case-based decision aid for SAMPEX controllers (hereafter referred to as the CBDA) and the Georgia Tech SAMPEX Case-based Anomaly Retrieval System (GT-SCARES) , share a great deal of commonalty in their use of case-based reasoning techniques to deal with a complex and not easily formalizable environment.

GT-SCARES is the more advanced of the two systems in terms of near-term applicability. It is built on the Design-MUSE case-based design aid software developed by the AI group at Georgia Tech. It has remarkable search and cross-referencing capabilities which allow the user to search through and browse the large case library of anomaly reports in any number of ways. Each anomaly is cross-indexed by at least eight different factors which allow the user access to patterns of anomalies which are just not visible when searching through stacks of paper anomaly reports. GT-SCARES has the potential to become the framework for a realistic on-line real-time anomaly database and off-line browser for SAMPEX controllers.

The CBDA is a straw man for a larger and more integrated and autonomous controller and/or decision aid for a satellite ground control system. Its main components are a case-base reasoning system (a much simplified system compared to the one used in

GT-SCARES) in combination with a hand-coded rule-based model of the SAMPEX anomaly resolution and detection procedures. Despite the fact that it's case-based inference system is much less sophisticated than that of GT-SCARES, its use of operator interactivity and its successful explorations into automated acquisition of expert operator knowledge make it potentially much more powerful.

GT-SCARES (Georgia Tech SAMPEX Case-based Anomaly Retrieval System)

Each time a spacecraft anomaly occurs large amounts of information about the situation are recorded in detail by NASA. However, there is currently no way to retrieve the information contained in this historical record. The goal of this project was to create a case-based reasoning (CBR) decision aid system which would recall cases of spacecraft anomalies in order to help a SAMPEX ground controller interpret an anomaly, classify it, and then decide what actions to take in light of the current situation. GT-SCARES aids in the controller's task of resolving anomalies by both giving him/her examples of similar situations and suggesting different courses of action for him to take. Each anomaly report contains all the information about how a controller resolved an anomalous situation in the past. In a sense then, each anomaly report serves as a "case-history" of a spacecraft anomaly. These are the "cases" which give birth to the phrase "case-based reasoning" in this incarnation. We have produced a large case library (consisting of approximately 100 anomalies) based on the SAMPEX anomaly reports recorded by the SAMPEX FOT.

The system works by accessing a large number of anomaly reports which have been cross-indexed by several different classifications. These classifications include: the mnemonics involved, the type of anomaly, the source of the anomaly, etc. To gain access to this information, the controller simply enters all that s/he knows about the current anomalous situation. GT-SCARES then proceeds to match his/her specifications with the cases it contains in its memory, and returns the case (or cases) which best match the reported symptoms. The controller may or may not have complete information about the anomaly. GT-SCARES has the ability to perform partial matching based on any amount of information the operator may possess. If, after looking at the cases which have been retrieved, the controller feels that s/he has gained new insights into the anomaly, s/he then has the option of initiating a new search with this additional information.

CBR allows autonomous systems to deal with domains where tasks are not easily formalizable. CBR supports problem solving in these domains because its reasoning abilities are based on actual experiences within the domain, in addition to any partial formal models which may be available. As a result, CBR systems tend to be more efficient and operate faster in real-time applications than traditional AI systems based on production rules. Appendix C contains a GT-SCARES User's Manual and a brief technical note addressing questions and answers about GT-SCARES.

A Simple Case-Based Decision Aid for SAMPEX Controllers

This project involved the creation of an on-line case-based decision aid to aid SAMPEX command controllers in the process of anomaly resolution. One of the goals of this project was to attempt to utilize the methods of case-based reasoning to capture information about particular anomalies (a facet of the anomaly resolution process which is not readily formalizable), while using more analytical model- and rule-based methods for reasoning about the anomaly identification and resolution process itself (which is much more structured). This system is designed to aid controllers in a complex real-time operational environment. Concurrent to aiding the user the system acts to record operational decisions made by the controller, thus facilitating the storage of this information for retrieval by other operators at a later date, and thus automating the process of accumulating expert operator knowledge in the system.

As stated before, case-based systems rely on knowledge of previous occurrences of a situation (or cases) to form the basis of their problem solving capabilities. Model- and rule-based systems use generalized knowledge about the operation and dynamics of the system (usually coded in the form of production rules) to reason about the environment. This project also utilized a level of interactivity with the user to skirt some of the more difficult problems inherent to knowledge acquisition in expert systems. Operational knowledge is acquired from user responses to queries based on a normative anomaly resolution model. This model was based on the SAMPEX Anomaly Detection and Resolution flowcharts supplied by the SAMPEX FOT (these are included in their entirety in Appendix B). The steps taken in the decision process are stored to facilitate explanation of when the system later presents cases as solutions to the user. A normative model describes how the controllers *should* do things (the realm of rules and models), while a descriptive model describes how things are actually done (the realm of cases). The cases in this system are similar to the anomaly reports currently used by the operators of SAMPEX.

An operator initiates the operation of the CBDA by entering a description of an anomaly. The CBDA software then searches its memory for a previous anomaly which most closely matches the description of the anomaly entered by the operator. When it finds a match it returns the name of the anomaly resolution procedure which must be initiated to resolve the anomaly. The program also returns a trace of the steps which resulted in this decision.

If no match is found, or if the operator rejects the particular remedy suggested by the CBDA, the software will prompt the user for the information it needs to step through an anomaly resolution decision tree. This tree acts as the formal model of solution generation in the system and is again based on the Anomaly Detection and Resolution flow charts produced by the SAMPEX FOT. The interaction with the user will take the form of questions which the user will answer with a Yes or No. Once a conclusion is reached the system will inform the user of the proper steps to carry out to resolve the anomaly, again based on the flowchart-based anomaly resolution model. The system will store the steps taken to resolve the anomaly as part of its case memory. Thus the system, guided by the user, will be able to learn new cases and add them to its memory.

Prospects for Future Research

The long-term goal of the research project which resulted in the development of the SAMPEX CBDA and GT-SCARES is the development of a case-based reasoning system for real-time command and control operations. These research projects have given the Georgia Tech ICC team a thorough introduction into the potential gains and pitfalls from using a case-based system in a real-time mission operations environment. These issues will be catalogued in detail in a future report, but the advantages of case-based systems over rule- and model-based systems (as spelled out previously in this report) should be obvious.

The intimate knowledge of the workings of the spacecraft possessed by the original members of the FOT, who have worked with the spacecraft through development, integration and test, and launch and early orbit (LEO), is unsurpassed. A case-based command and control system would have the advantage of being able to utilize and integrate the expertise possessed by these personnel. The case-based system could take on many of the responsibilities of the FOT after the initial LEO period of spacecraft operations. It is our hypothesis (still under study) that most major spacecraft anomalies occur or are identified during the first few months of a mission. The knowledge gained during this critical period (in the form of anomaly reports and operator knowledge) would form the primary knowledge base of the case-based system. The system would not be designed to act completely autonomously but would perform many of the tedious and routine monitoring operations currently performed by humans. The system's authority would be prescriptively limited to boundaries set by the FOT. Rather than reasoning independently about unexpected occurrences, the system would contact members of the "mission cluster" (as distinct from the current "mission specific") FOT for help, similarly to how human controllers currently operate when they are confronted by an unexpected anomaly.

In conclusion, it is our belief that case-based reasoning techniques have an important role to play in the achievement of the goals of the ICC project. In conjunction with a reasoning module based on a normative model of spacecraft operations (perhaps based on the SAMPEX OFM), we believe that a case-based reasoner has the potential to form the robust core of a future ICC.

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IV. SAMPEX Task Analysis: An Extended Operator Function Model (David A. Thurman)

An extended Operator Function Model was used to conduct a task analysis of the SAMPEX Flight Operations Team activities (see Appendix D). While the task analysis encompasses all of the Flight Operations Team's activities, the above research focuses primarily on the tasks during the on-pass phase of operator activities, and specifically on those activities related to monitoring system performance.

The traditional Operator Function Model was extended for this task to include a representation of information flow between operator tasks. This information has been invaluable in the design of the interactive monitoring interface.

One of the problems often found in control system interfaces is their requirement that operator's read a piece of information from one portion of the interface and record it in another portion of the interface. This practice is time-consuming for the operator, risks potential problems due to errors in transferring information, and results in

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potential problems due to errors in transferring information, and results in operators who feel like they are little more than glorified clerks. One of the goals of the proposed design methodology for interactive monitoring interfaces is to identify instances when information required in one task is available from another task and facilitate automatic or (at least) interface-supported (e.g., through drag and drop) transfer of that information in the interface.

The extended OFM is currently being revised to include comments made by Leo McConville (GSFC). Leo has been extremely helpful in reviewing the OFM and helping accurately analyze the FOT's tasks. Current revisions are primarily targeted at the monitoring tasks associated with the on-pass phase of operator activities.

V. SAMPEX Task Analyses of Anomaly Detection and Correction Processes

(Michael Albers, John G. Morris, Andrew Jay Weiner)

Appendix E contains two analyses of SAMPEX anomaly detection and correction (Albers, 1993; Morris & Weiner, 1994). These analyses are intended to provide an understanding of how often and what happens when unanticipated events and anomalies occur. They investigates what happen when the unexpected happens during real-time operations--who can respond, how and when. The studies address events that occur post launch and early orbit (LEO) , i.e., examination of those events that are considered to have occurred during the SAMPEX nominal operations phase. The SAMPEX Anomaly Detection and Correction Task Analysis investigates what happen when the unexpected happens during real-time operations--who can respond, how and when.

This study are being carried out in coordination with the SAMPEX OFM, particularly with respect to the issue of non-preplanned activities. Recall, the OFM will include comment on what actions are pre-planned (always, usually, sometime), opportunistic (i.e., planned and executed on the fly without inclusion in the pass plan). In the latter case we will attempt to document the types of opportunistic activities undertaken and the personnel who formulate and execute them (e.g., lead analyst, spacecraft engineer).

VI. ICC/ TPOCC Simulation/Testbed
(David A. Thurman)

Rose Chu and Patty Jones developed a object-oriented, discrete event simulation of the MSOCC environment as part of their Ph.D. dissertation research. That simulation was given to NASA along with Rose's GT-VITA tutoring system for use in their FOT training program. Doug Lankenau (GSFC) made a number of changes to the MSOCC simulation in order to support tutoring in a TPOCC environment and for the sake of program efficiency. Unfortunately, some of the changes made for program efficiency (with regards to VITA's use of the simulation) made the simulation unusable for other projects. It is anticipated that this simulation will be used by other ICC research teams (e.g. Jones, UIUC).

The last six months have seen a near-complete rewrite of the TPOCC simulation in order to make it usable by a number of projects within CHMSR. Currently, Dave Thurman, Andy Weiner, and Mike Albers all plan to use the current simulation for their research projects. Modifications to the simulation include:

- cleaning up the communication between ground component objects (workstation, FEP, LTS, CTS, NASCOM, Ground Station). The simulation now provides a clean, two-way transport of commands and data (analogous to forward and return links) and a standard convention for transmitting/receiving data from the spacecraft and transmitting/receiving commands from the operator.

- removal of extraneous objects not suited to the simulation of the TPOCC/SAMPEX environment. This was a simple change and the simulation is easily reconfigurable in the future to simulate other spacecraft (e.g., FAST, WIND/POLAR) environments.

- incorporation of recorded SAMPEX pass information to increase the fidelity of the simulation. Dustin Aldridge (GSFC) provided us with files of recorded SAMPEX data from approximately a dozen passes. These files contain data from the major subsystems, recorded at five or ten second intervals during actual passes. The simulation has been modified to read those files and pass that data to the interface along with the simulated data. This effort has resulted in increasing the number of subsystem parameters available from the simulation from approximately 20 to more than 200 subsystem parameters. This effort required modifying the scenario configuration portion of the simulation as well as the Attitude Control and Power Subsystem components.

- incorporation of SAMPEX-like Solid State Recorder and SEDS Software Manager objects for simulation of activities related to those components.

Conventional Interface

The conventional interface (CI) is designed to mimic the current TPOCC interface used by the SAMPEX Flight Operations Team. While it is not quite as robust as the SAMPEX/TPOCC console interface, it does contain four subsystem display pages (ACSOV, PDPCUTLM, WPSEBAT, TSCTEMPS2), the Master page, ATS command load (table operations) and science data dump (recorder operations) pages, and a command line interface similar to the SAMPEX/TPOCC interface. Not included in this SAMPEX/TPOCC interface are some of the less often used pages.

The display pages, however, are exact copies of the SAMPEX/TPOCC display pages, with the exception of some page header information related to the packet/frame format of the data received from the spacecraft. Since our TPOCC simulation does not include the CCSDS packet format (which SAMPEX uses for data transmissions), it does not make sense (nor is it possible) to provide this information in the interfaces. It is possible that Andy Weiner will add this capability to the simulation, and will then need to modify the display pages to provide this information. This should be relatively easy as the display pages are easily reconfigured.

VII. TK+: An Object-Oriented Toolkit for Interface Design and Development (David A. Thurman)

TK+ is an object-oriented, interface development toolkit that provides for the development of Motif interfaces by building simple hierarchies of C++ objects. TK+ provides standard interface objects (buttons, labels, menus, lists, etc.), manager objects (grids, canvases, etc.), and supporting I/O functionality (input handlers). The I/O functionality allows a TK+-based interface to communicate with another program, e.g., a discrete event simulation.

TK+ is based on X11R5 and Motif 1.2.2. At some point in the future, it will be upgraded to X11R6 and Motif 2.0. TK+ is currently being used by several students for their research projects and will continue to be used for both instructional and research purposes. Version 1.2 (the current public release) provides the standard interface objects and functionality mentioned above. Version 1.3 is a special release created to support an internal CHMSR research project.

Version 1.4 is the current development version which provides drag-n-drop support for TK+ interface objects. Drag-and-drop is standard in Motif 1.2, and the additions to TK+ v1.4 support the standard drag-and-drop functionality as well as providing additional support for the interface objects in TK+. These extensions provide for defining the drag capabilities of a TK+ interface object (beyond the standard Motif drag-and-drop functionality) and adding drop handlers to any TK+ interface object. The drag capabilities of an object define the functionality to be invoked when the user 'drags' an object (presses mouse button 2 and moves the cursor on the screen). A drop handler defines the functionality to be invoked when an object is dropped in a drop site. This functionality is critical to Dave Thurman's research in interactive monitoring interfaces.

TK+ is being used for interface development tasks on a number of NASA research projects. Currently, Dave Thurman, Andy Weiner, Mike Albers, Jennifer Ockerman and John Morris are all either using or planning to use TK+ for developing the proof-of-concept systems. A copy of the TK+ User's Guide for version 1.2 is provided in Appendix F. An improved user's guide for version 1.4 explaining new functionality and including pictures of the various interface objects supported by TK+ is under development.

The following appendices are available from Christine M. Mitchell

Appendix A

Improving Operator Effectiveness in Monitoring Complex Systems: A Methodology for the Design of Interactive Monitoring Interfaces, David A. Thurman, M.S. Thesis Proposal, Center for Human-Machine Systems Research, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Appendix B

A Simple Case-Based Decision Aid for SAMPEX Controllers, Andrew Jay Weiner, Center for Human-Machine Systems Research, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Appendix C

GT-SCARES User's Manual and Questions and Answers about GT-SCARES, a brief technical note, Andrew Jay Weiner, Center for Human-Machine Systems Research, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Appendix D

SAMPEX Task Analysis: An Extended Operator Function Model, David A. Thurman. Center for Human-Machine Systems Research, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Appendix E

SAMPEX Task Analyses of Anomaly Detection and Correction Processes (Albers, 1993; Morris and Weiner, 1994, in process). Center for Human-Machine Systems Research, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Appendix F

TK+ An Object-Oriented Toolkit for Interface Development (in C++ and OSF Motif), David A. Thurman and Uday Sreekanth. Center for Human-Machine Systems Research, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, GA 300332-0205.