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INTELLIGENT SYSTEMS FOR CONTROL

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ABSTRACT This keynote presentation covers the subject of intelligent systems development for monitoring and control in various NASA space applications. Similar intelligent systems technology also has applications in terrestrial commercial applications. Discussion will be given of the general approach of intelligent systems and description given of intelligent systems under prototype development for possible use in Space Shuttle Upgrade, in the Experimental Crew Return Vehicle, and in free-flying space robotic cameras to provide autonomy to these spacecraft with flexible human intervention, if desired or needed. Development of intelligent system monitoring and control for regenerative life support subsystems such as NASA's human rated Bio-PLEX test facility is also described. A video showing two recent world's firsts in real-time vision-guided robotic arm and hand grasping of tumbling and translating complex shaped objects in micro-gravity will also be shown.

1. INTRODUCTION

All developed nations are currently feeling a quality and productivity improvement imperative. In the U.S. the private sector has taken the lead and set an example for others to follow. The purpose of this paper is to describe a new approach to achieving quality and productivity improvements in NASA human space missions: use of adjustable autonomy intelligent systems for monitoring and control. Similar intelligent systems technology also has applications in terrestrial commercial applications such as nuclear power (where I was educated in nuclear engineering) and service robotics (where I will discuss some uses).

Rather than new technology, this is current technology waiting for new development to make it useful in new applications. The previous euphoria and let-down that occurred with artificial intelligence (AI) are understood. Despite possible cynicism, there are now sound reasons based on the real progress in capabilities and understanding in AI to again give serious consideration to intelligent system applications. A focus on monitoring and control is presented.

NASA human space mission (Space Shuttle) operations are centrally monitored and controlled under the supervision of trained operators(astronauts, flight controllers). Operations are of impressively complex systems that are challenging to understand and operate correctly. The task of the operators is one of continuous, real-time monitoring and control, with feedback. The job can be difficult partly because the engineered system is tightly coupled and depends on complex interactions. Complex interactions are those of unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible. Deciding on the correct control action during a crisis can be difficult; a bad decision can be disastrous. A key cognitive skill is the formation of a mental model of the engineered system that fits the current facts and enables the operators to correctly predict the system behavior and predict the effect of possible control actions.

The operations job is difficult partly because the operators must make timely decisions using information that is incomplete and uncertain. Making the information more complete by providing new sensors is not a solution since cognitive overload is already a problem in emergencies involving complex systems and spacecraft sensors imply added mass (added cost of launch and added cost of extra fuel to achieve all mission maneuvers), power, and cabling. Providing more time to make a decision is not a reasonable alternative. Providing more operators to share the workload, and more expertise to handle unusual situations, can help up to a point where timely integration of information becomes an issue, but is too costly, in general. It is here that intelligent systems for monitoring and control can make a major difference as "intelligent associates," aiding the decision making or being given control.

These intelligent systems can handle the thousands of signals in real-time to detect anomalies instantaneously. They can diagnose a fault in the presence of multiple faults even with intermittent or noisy indications through examining hypotheses consistent with the data. They can do these things while simultaneously assisting in other operator tasks such as achieving the desired operating conditions and predicting the effects of proposed control actions.

Improvements to existing operations systems are suggested by analyzing accidents involving complex systems. Perrow[1] has analyzed the records of many accidents and offers the following lessons:

- The systems that have the highest potential for catastrophic failure are those in which interactions are complex and coupling is tight. Human space missions are in this category.
- The computerization (old technology) of process/plant control "does not encourage broader comprehension of the system — a key requirement for intervening in unexpected interactions."
- In many accidents caused by human error, the operator "built perfectly reasonable mental models of the world, which worked almost all the time, but occasionally turn out to be almost an inversion of what really exists."

Another lesson is that we need better aids for operating complex systems.

These aids must help operators to understand the system, its modes and configurations, and to form correct mental models when abnormal situations arise. The aids must do this not by offering more raw data, but by analyzing and interpreting the available data and by giving expert advice.

An overview of the argument presented in this paper is:

- The essence of automation is the application of knowledge to the restructuring of the productive process around the better use of knowledge.
- Intelligent systems offer the means to apply more knowledge and reasoning in more flexible and effective ways than conventional automation approaches to provide more robust performance, adjustable autonomy, and greater transparency of operation to humans.

"The essence of automation is not machinery; it is the application of knowledge in rethinking of the productive process and its restructuring around information."[2]

Table 1. Criteria for When to Automate Functions

Automate:

With consideration of operators acceptance
To avoid perceptual saturation
To reduce concurrent tasks
Tasks on compressed timelines
To avoid human bandwidth limitations
Routine tasks
Memorization tasks
Sequential and timed tasks
Monitoring tasks
Time consuming, boring, or unmotivating tasks
Complex logical or mathematical tasks
Complex tasks that must be performed rapidly
To enhance system reliability
Safety endangering tasks
Emergency-prevention devices

An important part of the knowledge to apply in rethinking of the productive process is given in Table 1 about when it is best to automate.

Note these are largely human factors criteria. Before describing the benefits of using intelligent systems, both their definition and advantages over conventional automation are presented.

2. WHAT ARE INTELLIGENT SYSTEMS

Intelligence is the ability to acquire and apply knowledge and skills to achieve state goals in the face of variations, difficulties, and complexities imposed by a dynamic environment having significant unpredictability. The essence of intelligent systems is that they are capable of collecting and applying knowledge of a situation gained at execution time and correlating it with other knowledge to take effective actions in achieving goals. Intelligent systems are composed of sensors for sensing the "world," effectors for acting on the world, and computer hardware and software systems for connecting the sensors and effectors in which a part of the processing is symbolic(non-numeric) enabling practical reasoning and thus behavior which in humans we call intelligent. Examples of AI capabilities in intelligent systems are: knowledge based systems, expert systems, natural language understanding systems, robotic visual perception systems, intelligent control and planning systems, qualitative and model-based reasoning systems, and human supervised autonomous robots.

Intelligent systems can be of four basic kinds: non-mobile, non-manipulative systems such as monitoring and control systems; non-mobile, manipulative systems such as robot arms fixed in place at the shoulder; mobile, non-manipulative systems such as inspection robots; and, mobile, manipulative systems such as mobile service robots with arms and end-effectors. These are usually connected to information systems such as Computer Aided Engineering (CAE) from which knowledge can be obtained about hardware and software configurations and processes.

Expert systems are sophisticated computer programs that manipulate knowledge to solve problems efficiently and effectively in a narrow problem area[3]. An expert system provides high-level expertise to aid in problem solving. The expertise (knowledge) is explicit and accessible. Expert systems have broad acceptance generally, with several thousand operational expert systems now in use in the U.S.

Recently, however, very useful intelligent systems have been developed consisting of layered architectures possessing the combined capabilities of "multi-agent" planning and scheduling; reactive continuous activity, tight sense-act loops often called "situated skills"; "conditional execution" and sequencing of these skills by various operating procedures; execution self-monitoring of the plans, schedules, operations procedures, and skills; fault detection, isolation, and recovery reasoning including practical model-based diagnosis; "cognizant failure" capabilities to be self-aware that the system is failing at a task and taking appropriate action; and, adjustable autonomy in which shared and traded control with humans is enabled by design features including situational awareness displays providing insight to the human about the state of the system hardware and software with context-sensitive advice about successful operational procedures.

3. WHY INTELLIGENT SYSTEMS

It is important to understand the advantages intelligent systems have over conventional automation. Table 2 lists some advantages.

Table 2. Advantages of Intelligent Systems Over Conventional Automation

Intelligent Systems:

Provide greater flexibility in dealing with uncertainty in advance or with ill-structured situations

- rational decisions despite incomplete information
- dynamic environments require reactive ability
- task demands a thorough analysis of a complex set of conditions where a typical performer seems not to perceive or remember all the essentials
- allows designs where information is more complete

Are better able to earn human trust through being safer, more capable, reliable, transparent, and leading to a better role split with humans
- roles adjustable without reprogramming during operations
- machines as people amplifiers, reducing cognitive overload
- humans for cognitive and perceptive and supervision

Provide capability of being better understood
- ask permission, explain why and how

Can be used to solve exponentially hard problems in reasonably short times through use of knowledge

Provide better ways to apply more knowledge since knowledge bases/models are part of the system

Provide more likely path to systems that learn from experience

These advantages derive directly from symbolic computation and knowledge engineering techniques which are different in concept than conventional approaches to automation.

4. INTELLIGENT SYSTEMS BRING BENEFITS

The benefits of using intelligent systems in both human space missions and terrestrial commercial applications are improved and increased safety, reliability, and productivity. These benefits are derived from applying more knowledge and reasoning in more flexible and appropriate ways than conventional automation approaches to provide more robust performance, greater choice of interaction modes with operators, and greater transparency of operation and of transitions between human and intelligent system control modes. These are achieved through amplification of human capabilities.

Safety is improved because intelligent systems provide greater robustness by aiding with perceptual overload through interpretation, by aiding with concurrent tasks through parallel processing, by aiding with tasks on compressed timelines by meeting real-time needs, by helping to avoid human bandwidth limitations by integrating and interpreting, and by detecting, but not creating or ignoring, unsafe states. Safety is also improved because intelligent systems encourage broader comprehension of the engineered system by the operators when properly designed.

Reliability is improved through providing better end-to-end functionally in the face of degraded capability, better fault tolerance and redundancy management, and more accurate and rapid diagnosis of anomalies.

Productivity is improved by reduced operations cost and improved availability.

5. AN INTELLIGENT SYSTEM ARCHITECTURE

JSC has developed an autonomous control architecture that separates the general intelligent system problem into three interacting layers or tiers of software (and thus is known as 3T):

- o A set of subsystem hardware specific situated skills that represent the architecture's connection with the world. The term situated skills is intended to denote a capability that, if placed in the proper context, will achieve or maintain a particular state in the world. For example, guidance and navigation. The skills are maintained by a skill manager.
- o A conditional sequencing capability that can differentially activate several situated skills in order to direct changes in the state of the world and accomplish specific tasks. In each phase of operation, the skills of the reactive skill level are connected to function as a collection of networked state machines. We are using the Reactive-Action Packages (RAPs) system developed by James Firby at the University of Chicago for this portion of the architecture.
- o A deliberative planning capability which reasons in depth about goals, resources, and

timing constraints. We are using a state-based non-linear hierarchical planner known as AP developed by Chris Elsaesser at MITRE.

AP is a multi-agent planner which can reason about metric time for scheduling, provide estimates of the probability of success of the plan, monitor the execution of its plans, and replan accordingly. Plans are constructed in terms of RAPs, meaning minimal commitment at planning time to how a plan will be carried out, since RAPs invoke different situated skills depending on the situation at the time of execution and each skill is also flexible in reacting to the situation as sensed.

The architecture works as follows: the deliberative tier takes a high-level goal, decomposes it into a set of sub-goals, and syntheses these into a partially ordered list of operators that correspond to one or more RAPs in the conditional sequencing tier. The sequencing tier interpreter decomposes the selected RAP into other RAPs and finally activates a specific set of skills in the lowest sense-act tier. Also activated are a set of event monitors in the skill tier which notify the conditional sequencing tier of the occurrence of certain world conditions. The activated skills will move the state of the world in a direction that should cause the desired events. The sequencing tier will terminate the actions, or replace them with new actions when the monitoring events are triggered, when a time-out occurs, or when a new message is received from the deliberative tier indicating a change in plan (generally due to a change in the unpredictable, dynamic world or a change in goal from the human).

5.1 3T Enhanced with MBR beyond Malfunction Procedures

When an engineered system such as a spacecraft has been analyzed for failure modes and effects such that the conditions for each failure provide a signature and procedures have been devised for operating the system under degraded performance for each failure signature, 3T has a mechanism in its conditional sequencing tier to implement these signatures and conditional malfunction procedures. However, there is still a need to employ further reasoning processes in the software to deal with situations not covered by the failure modes and effects analysis and malfunction procedures. Just such a capability is provided by model based reasoning, where a model of the system is employed to hypothesize about failures and to "explain" the anomalous data coming from the system. We are in the process of enhancing 3T with a model based reasoning capability.

5.2 3T Enhanced with Adjustable Autonomy

Further enhancement of 3T was necessitated by the need for human supervision by exception of otherwise autonomous systems. This is the case in all human space exploration missions. The capabilities being added to 3T are (1) a method of shared and traded control between the intelligent system and the human operators, (2) a situated awareness capability that (a) enables the human to obtain insight into the state of the world and the state of the system prior to and during all transitions in control authority, and (b) enables the system to maintain insight into the state of the world and the state of the system during human operations, and (3) a proactive context-sensitive advice capability providing operating options and recommendations to the operator. These capabilities enable adjustable autonomy for the intelligent system architecture.

6. INTELLIGENT SYSTEMS IN NASA SPACE MISSIONS

We describe several applications of our intelligent system architecture including adjustable autonomy.

6.1 Space Shuttle Upgrades

NASA will be operating the Space Shuttle through at least 2015. As a result of that decision, a number of Shuttle subsystems should be upgraded for obsolescence, safety, and cost reasons. The Orbiter Upgrade project was initiated to develop a strategy and an implementation plan.

As subsystems are identified for upgrades, the re-design of these subsystems should be performed with a crew-centered focus. Crew-centered focus is defined as giving the crew user of the system control over and improved situational awareness insight into the current, past (insight only), and possible future operations of the system whenever the user chooses. The user can select automatic operation including automated fault detection, isolation, and recovery (FDIR), or the user can operate the subsystem completely manually with available information. This capability would be provided through the use of improved displays and controls, and flexible, adaptable automation technologies, as well as intelligent systems which can be developed to greatly simplify configuration and operation of subsystems for a given mission phase or task. These intelligent systems can also take information from the subsystem, interpret that data to detect faults within the subsystem, and assist the user in dealing with the fault. This assistance could range from a "monitor and suggest options" standpoint to a more autonomous "here is what I did to solve the problem," provided on demand, all with the same software. Intelligent systems can collect data on the health of the subsystem to support failure trends analysis and other systems management tasks. This can greatly reduce the ground manpower required to support on-orbit operations, as well as pre-flight and post-flight checkout.

The Advanced Orbiter Cockpit project is being focused on evaluating Orbiter operations concepts, and specifically dealing with the subsystems selected for upgrading. Addition of intelligent systems drives changes in subsystem design, as well as displays and controls related to that subsystem. In the evaluation of the displays and controls, it is important to use intelligent system monitoring and control and a simulation of the subsystem to drive the displays. The user will make better suggestions through interaction with intelligent system monitoring and control and a simulation, thus seeing the effects of that interaction on the displays. A realistic simulation of the subsystem is also required for intelligent systems to be able to interpret the status of the subsystem and provide feedback to the user and/or take actions on the user's behalf. It is important for the simulation to have fault insertion capability to test the intelligent systems' ability to provide advice or take action on different failure scenarios. The intelligent systems should be able to provide several levels of autonomy based on requirements for a given scenario. All of these elements are needed to ensure a crew-centered focus in the redesign effort.

To facilitate the design process, a test bed is being developed which can provide the capability to model the cockpit displays and controls, the 3T-based intelligent system software, and the modified or re-designed subsystem models. This test bed must provide a realistic simulation of the new vehicle design. The development of operations concepts for how this vehicle should look and perform will be done in a "concurrent engineering" manner where the users of the system will be working with the designers of the system (D&C, subsystems, intelligent systems) as well as human factors personnel. Once a concept/design has been developed and evaluated, a decision process can take place to implement that design as part of the Orbiter Upgrade activity.

The first subsystem being used as a forerunner in the Orbiter Upgrade evaluations is the Payload Deployment and Retrieval System, essentially consisting of the Remote Manipulator System (RMS). The RMS Assistant project is using 3T enhanced with MBR and adjustable autonomy to evaluate against ground simulations prior to attempting a Shuttle detailed test objective evaluation in space.

A second subsystem being used to develop a prototype intelligent system is the Orbital Maneuvering System (OMS). The OMS is also being re-engineered to use non-toxic propellant and a simplified design which can reduce ground operations costs and achieve safer operations.

6.2 Experimental Crew Return Vehicle (X-35)

The experimental crew return vehicle project, being led by JSC, is developing a prototype vehicle to test and demonstrate technologies needed for building a low-cost operational spacecraft that will rapidly return Space Station crew to the earth in an emergency situation. An operational vehicle will be completely autonomous in case of crew inability to the fly the vehicle (due to illness or injury, lack of recent training, etc.). Early prototype software for fault detection, isolation, and recovery has used the 3T intelligent system architecture.

6.3 Monitoring and Control of Advanced Life Support Systems

Advanced Life Support Systems (ALSS) which supply food, water, and oxygen to humans on long duration missions in space by bioregenerative or physico-chemical recycling of air, water, and solids need to be not only self-sustaining with nearly no re-supply from Earth, but also self-sustaining with nearly no crew or ground control time required for operation or maintenance, so that crew time can be devoted to the science and technology products of the mission. It is to meet this minimum crew and ground control time requirement that we are developing intelligent monitoring and control systems to replace most crew cognitive demands for operations. But there is an even more important reason for intelligent monitoring and control of ALSSs. The only known closed (to mass flows) life support system for humans is the Earth's biosphere. The attempt to build a self-sustaining life support system for space can be characterized as attempting to replace the large-scale processes and large reservoirs of Earth with small-scale processes, small reservoirs, and an external intelligent monitoring and control system which can take dynamics into account. Such systems have been called Controlled Ecological Life Support Systems, or CELSS, when bioregenerative processes including crops have been employed.

Our goal is to supply the intelligent monitoring and control system to support the NASA Bio-PLEX 120-day human test with 4 crew in 2000, using the current and on-going Early Human Test Initiative (EHTI) Phase I, II, and III tests to learn how to adapt and integrate intelligent system technologies into Advanced Life Support Systems to provide robust capabilities that meet the requirements.

Our approach is to adapt and integrate our multi-agent 3T intelligent systems architecture. The ability to use models of the dynamics of ALSSs to provide reasoning support to the AP planner about the futurity of current operating decisions is part of our approach and is under study.

In 1995, we adapted 3T to operate with a physical life support chamber for EHTI Phase I, consisting of a wheat crop linked to a human through an airlock. There are ten subsystems to be monitored and controlled along with a simulation of a robot, called Traybot, which we are designing to move plant trays in and out of the chamber to support harvesting and planting. We divided the systems into five "agents" : climate (thermal, dew-point, lighting), gases (O_2-CO_2 exchange), fluids (flow of hydroponics through the growing areas), nutrients (control of the pH, dissolved O_2 and conductivity of the hydroponics), and the Traybot.

Finally, we have developed AP plan operators which will determine the planting cycles of various crops to support gas exchange as well as dietary requirements of the crew, set up long term profiles of the life support system agents, and assign the use of the Traybot system.

After the planner sets up the monitoring and control schedules the software monitors over 200 sensor channels to generate climate control settings, hydroponics solution changes, valves and pump settings for flow control, and commands for the gas injectors and scrubbers to adjust the O_2 / CO_2 concentrations. Our successful demonstration was for monitor-only mode with control recommendations that shadowed the test control operators and control system. Simultaneously, Traybot is commanded to various tray locations to retrieve and replace plant trays in support of the current harvest or planting operation. The Traybot skill manager developed for this demonstration will be able to operate on the physical robot hardware when it is completed in 1997.

This broad form of monitoring and control of both subsystem processes and mechanization is possible due to the inherent multi-agent nature of the 3T architecture. As we have discussed, our planner is inherently a multi-agent system. RAPs puts no limits on which agent can carry out a task, but we needed to be able to send enabling and disabling messages to the right agent at the right time. So we extended the interface of the RAPs to the skills to allow the first bound variable of each skill to be an agent name. This allows the communication mechanism to send and receive messages to and from the appropriate agent.

This was by far the largest application of 3T thus far. Though the planning level is not much more involved than for the EVA Helper/Retriever space robot program [below], there are 40 RAPs and 67 skills for the five agents. The system is capable of running continuously, with our longest test being 36 hours. This puts us on schedule to support the Bio-PLEX human tests in 2000.

6.4 Autonomous EVA Robotic Camera (AERCam)

The AERCam II - Associate robot uses the 3T architecture and is planned to achieve autonomous free-flying dual video camera inspection of spacecraft such as the Space Shuttle and the International Space Station in 1998. AERCam I - Sprint is a teleoperated robot for early demonstration in 1997 on the Shuttle of the value of camera views not otherwise available.

6.5 EVA Helper/Retriever

This voice-controlled, free-flying space robot project demonstrated two world's firsts on the NASA Reduced Gravity KC-135 aircraft. In February of 1994, the world's first real-time autonomous robotic vision-guided tracking and dexterous grasping of free floating symmetric objects was demonstrated. In early 1996, a second world's first was demonstrated: real-time autonomous robotic vision-guided tracking and dexterous grasping of two non-symmetric, complex shaped objects whose orientation must be measured in real-time as well as their position. The demonstrated capabilities were essentially 3T situated skills needed by any free-flying robot to attach itself to a spacecraft.

7. SUMMARY

In attempting to describe intelligent systems in human space missions, a focus on monitoring and control in operations in human space missions was used to present several attractive characteristics and a persuasive rationale.

A summary of the rationale presented in this paper is as follows:

- Knowledge is power and proper use of knowledge is powerful.
- The essence of automation is the application of knowledge to restructuring the productive process around the use of knowledge. A list of criteria for when to automate functions was given.
- Intelligent systems are a powerful form of automation, a form of applied artificial intelligence.

  Definitions and advantages of intelligent systems were given.
- Intelligent systems offer the means to apply more knowledge and reasoning in more flexible and appropriate ways than conventional automation approaches to provide safer, more robust performance, greater choice of interaction modes with operators, and greater transparency of operation.
- A number of intelligent systems in human space missions were briefly presented, each based on the same intelligent system architecture with recently achieved adjustable autonomy. Requirements and issues were given.
- Space mission operations involve systems which are tightly coupled and depend on complex interactions, which makes use of adjustable autonomy intelligent systems a quality improvement approach.

The benefits of improved safety, reliability, and productivity are derived from achieving adjustable autonomy and greater robustness, flexibility, and transparency by using intelligent systems.

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