SYSTEMS AUTONOMY

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NASA Ames Research Center

TECHNOLOGY FOR FUTURE NASA MISSIONS

AN AIAA/OAST CONFERENCE
ON CSTI AND PATHFINDER

12-13 SEPTEMBER, 1988
WASHINGTON D.C.
SYSTEMS AUTONOMY PROGRAM

MARS EXPLORATION

ENABLING TECHNOLOGIES FOR THE NATIONAL SPACE CHALLENGES

THE EVOLUTION OF MACHINES THAT THINK

- LOWERS MISSION OPERATIONS COSTS
- INCREASES PRODUCTIVITY
- RENDERS HIGHER QUALITY DECISIONS
- MAINTAINS TECHNOLOGICAL LEADERSHIP

LUNAR OUTPOST

PERMANENT PRESENCE IN SPACE

TRANSPORTATION
END-TO-END SYSTEMS INTEGRATION OF HUMANS, INTELLIGENT SYSTEMS, AND FACILITIES
SYSTEMS AUTONOMY PROGRAM
WHY INTELLIGENT AUTONOMOUS SYSTEMS

REDUCE MISSION OPERATIONS COSTS

• AUTOMATE LABOR INTENSIVE OPERATIONS

INCREASE MISSION PRODUCTIVITY

• AUTOMATE ROUTINE ONBOARD HOUSEKEEPING FUNCTIONS

INCREASE MISSION SUCCESS PROBABILITY

• AUTOMATE REAL-TIME CONTINGENCY REPLANNING
DESCRIPTION OF INTELLIGENT AUTONOMOUS SYSTEMS

CHARACTERISTICS

KNOWLEDGE-BASED SYSTEMS
• DYNAMIC WORLD KNOWLEDGE ACQUISITION, UNDERSTANDING, AND EXECUTION OF COMMAND FUNCTIONS
• RELIABLE DECISIONS IN UNCERTAIN ENVIRONMENTS
• LEARNING ABILITY
• ALLOWS "GRACEFUL" RETURN TO HUMAN CONTROL

CAPABILITIES

GOAL-DRIVEN BEHAVIOR
• COMMUNICATE AT HIGH LEVELS WITH HUMANS AND OTHER MACHINES

"COLLABORATIVE" HUMAN-MACHINE INTERACTIONS
• RECOGNIZE AND RESOLVE COMMAND ERRORS

SELF-MAINTENANCE
• OPERATE AUTONOMOUSLY FOR EXTENDED PERIODS OF TIME
SYSTEMS AUTONOMY PROGRAM
HOW DO WE GET THERE - PROGRAM ELEMENTS

ONGOING CORE TECHNOLOGY
- PLANNING AND REASONING
- OPERATOR INTERFACE
- SYSTEMS ARCHITECTURE

PERIODIC DEMONSTRATIONS
- LONG TERM EVOLVING TESTBED
- SHORT TERM SPECIFIC DOMAIN DEMOS

SHUTTLE
MISSION CONTROL
SHUTTLE LAUNCH DIAGNOSTICS
SPACE STATION
IN SPACE CONSTRUCTION
TECHNOLOGY FOCUS
RESEARCH PRODUCTS
SYSTEMS AUTONOMY PROGRAM

TECHNICAL CHALLENGES

- **REAL-TIME** KNOWLEDGE-BASED SYSTEMS

- **DYNAMIC** KNOWLEDGE ACQUISITION AND UNDERSTANDING

- **ROBUST** PLANNING AND REASONING

- **COOPERATING** KNOWLEDGE-BASED SYSTEMS

- **VALIDATION** METHODOLOGIES
SYSTEMS AUTONOMY PROGRAM - TECHNOLOGICAL CHALLENGES

A. WHERE WE ARE TODAY

REAL-TIME KNOWLEDGE-BASED SYSTEMS
- NO PARALLEL SYMBOLIC-NUMERIC PROCESSORS
- SLOW SPECIAL-PURPOSE HARDWARE (1 GBYTE MEM, 5 MIPS)
- PROTOTYPING S/W SHELLS (ART, KEE, KNOWLEDGECRAFT)
- DIAGNOSIS AND PLANNING DECISIONS IN 1-10 MINUTES

DYNAMIC KNOWLEDGE-ACQUISITION & UNDERSTANDING
- NO AUTOMATED EXPANSION OF K-B
- SMALL STATIC PRE-PROGRAMMED K-B
- DEC "XCON" LARGEST (5000 RULES, 2000 COMPONENTS)

ROBUST PLANNING AND REASONING
- HEURISTIC RULES ONLY, NO CAUSAL MODELS
- PRE-MISSION PLANNING (NO REAL-TIME REPLANNING)
- DIAGNOSIS OF ONLY ANTICIPATED SINGLE FAULTS
- "FRAGILE" NARROW DOMAINS (RAPID BREAKDOWN AT K-B LIMITS)

COOPERATING KNOWLEDGE-BASED SYSTEMS
- SINGLE STANDALONE DOMAIN SPECIFIC SYSTEMS
- HUMAN INTERACTION ONLY, NO INTELLIGENT SYSTEMS INTERACTION

VALIDATION METHODOLOGIES
- CONVENTIONAL TECHNIQUES FOR ALGORITHMIC SYSTEMS
AUTOMATED SYSTEMS FOR IN-FLIGHT MISSION OPERATIONS
EVOLUTION OF AUTOMATION TECHNOLOGY

NASA AMES RESEARCH CENTER
OAST-SPONSORED RESEARCH
SYSTEMS AUTONOMY PROGRAM DEMONSTRATION
SYSTEMS AUTONOMY DEMONSTRATION PROJECT (SADP)

OBJECTIVES
DEMONSTRATE TECHNOLOGY FEASIBILITY OF INTELLIGENT AUTONOMOUS SYSTEMS FOR SPACE STATION THROUGH TESTBED DEMONSTRATIONS

- 1988: SINGLE SUBSYSTEM (THERMAL)
- 1990: TWO COOPERATING SUBSYSTEMS (THERMAL/POWER)
- 1993: HIERARCHICAL CONTROL OF SEVERAL SUBSYSTEMS
- 1996: DISTRIBUTED CONTROL OF MULTIPLE SUBSYSTEMS

PARTICIPANTS AND FACILITIES

PARTICIPANTS
- AMES RESEARCH CENTER
- JOHNSON SPACE CENTER
- LEWIS RESEARCH CENTER
- MARSHALL SPACE FLIGHT CENTER
- INDUSTRY

FACILITIES
- ARC INTELLIGENT SYSTEMS LABORATORY
- JSC INTELLIGENT SYSTEMS LABORATORY
- JSC THERMAL TEST BED
- LeRC POWER TEST BED

SCHEDULE

<table>
<thead>
<tr>
<th>TCS</th>
<th>TCS/Power</th>
<th>Hierarchical Multiple Sys.</th>
<th>Distributed Multiple Sys.</th>
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<td>87</td>
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1988 DEMONSTRATION SYSTEMS AUTONOMY DEMONSTRATION PROJECT
SPACE STATION THERMAL CONTROL SYSTEM (TEXSYS)

OBJECTIVES
IMPLEMENTATION OF AI TECHNOLOGY INTO THE REAL-TIME DYNAMIC ENVIRONMENT OF A COMPLEX ELECTRICAL-MECHANICAL SPACE STATION SYSTEM - THE THERMAL CONTROL SYSTEM.

- REAL-TIME CONTROL
- FAULT DIAGNOSIS AND CORRECTION
- TREND ANALYSIS FOR INCIPIENT FAILURE PREVENTION
- INTELLIGENT HUMAN INTERFACE
- CAUSAL MODELLING
- VALIDATION TECHNIQUES

PARTICIPANTS AND FACILITIES

PARTICIPANTS
- AMES RESEARCH CENTER
- JOHNSON SPACE CENTER
- INDUSTRY: LEMSCO, ROCKWELL INTERNATIONAL, GEOCONTROL SYSTEMS, STERLING SOFTWARE

FACILITIES
- ARC INTELLIGENT SYSTEMS LABORATORY
- JSC INTELLIGENT SYSTEMS LABORATORY
- JSC THERMAL TEST BED

SCHEDULE

Development
Requirements Definition
Design Definition
Integration V & V
TCS Demonstration
Power System Interfaces
TCS/Power Demonstration
Analysis, Reporting
### SYSTEM AUTonomy DEMOnstration PROJECT

**TCS FUNCTIONAL CAPABILITIES**

#### PROTOTYPE OBJECTIVES

<table>
<thead>
<tr>
<th>PROTOTYPE OBJECTIVES</th>
<th>DEMO 1/87</th>
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<tbody>
<tr>
<td>CAUSAL MODELS/SIMULATION</td>
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<tr>
<td>LIMITED FAULT DIAGNOSIS</td>
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#### DEMONSTRATION OBJECTIVES

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<thead>
<tr>
<th>DEMONSTRATION OBJECTIVES</th>
<th>1 6/87</th>
<th>2 9/87</th>
<th>3 12/87</th>
<th>4 2/88</th>
<th>5 5/88</th>
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<tbody>
<tr>
<td>NOMINAL REAL-TIME CONTROL</td>
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<tr>
<td>FAULT DIAGNOSIS AND CORRECTION</td>
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<td>TREND ANALYSIS</td>
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<td>INTELLIGENT INTERFACE</td>
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<td>DESIGN ASSISTANCE</td>
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<td>TRAINING ASSISTANCE</td>
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#### KNOWLEDGE BASE EXPANSION

INTELLIGENT INTERFACE

TRAINING ASSISTANCE

© HL/AIAA 98-88 (LAH)
SYSTEMS AUTONOMY PROGRAM - TECHNOLOGICAL CHALLENGES

B. WHERE WE NEED TO GO

REAL-TIME KNOWLEDGE-BASED SYSTEMS
- PARALLEL SYMBOLIC-NUMERIC PROCESSORS (100 GBYTES, 500 MIPS)
- NEURAL NETWORKS (BRAIN CELL EMULATION)
- LAYERED TRANSPARENT SW
- DIAGNOSIS AND PLANNING IN MILLISECONDS

DYNAMIC KNOWLEDGE ACQUISITION & UNDERSTANDING
- AUTOMATED K-B EXPANSION IN REAL-TIME (LEARNING)
- LARGE DYNAMIC DISTRIBUTED K-B

ROBUST PLANNING AND REASONING
- COMBINED HEURISTIC RULES AND CAUSAL MODELS
- REAL-TIME CONTINGENCY REPLANNING
- DIAGNOSIS OF UNANTICIPATED FAULTS
- SPECIFIC DOMAINS ON BROAD GENERIC K-B (GRACEFUL DEGRADATION)

COOPERATING KNOWLEDGE-BASED SYSTEMS
- HIERARCHICAL AND DISTRIBUTED SYSTEMS
- HUMAN AND INTELLIGENT SYSTEMS INTERACTION

VALIDATION METHODOLOGIES
- METHODOLOGY FOR EVALUATING DECISION QUALITY
- FORMAL THEORETICAL FOUNDATION
Architecture of an Autonomous Intelligent System

- Operator Interface
- Displays
- Controls
- Simulator
- Monitor
- KNOWLEDGE BASE:
  - Dynamic World Model
  - CAD/CAM Data Base
  - System Configuration
  - Heuristic Rules
- Perceptor
- Effector
- Sensing & Perception
- Internal Observables
- External Observables
- State Changes
- State Observables
- Manipulators & Control Mechanization

System Architecture & Integration

- Task Planning & Execution
- Operator Interface
- Task Description
- Execution Status
- World State
- Nominal World State Changes
- Direct World State Updates
- Inferred World State Updates
- Anomalies
- Replan Order
- Nominal Plan
- Commands
### SYSTEMS AUTONOMY DEMONSTRATION PROJECT

**Technology Demonstration - Evolutionary Sequence**

<table>
<thead>
<tr>
<th>1988</th>
<th>1990</th>
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<tbody>
<tr>
<td>Automated Control Of Single Subsystem (&quot;Intelligent Aide&quot;)</td>
<td>Automated Control of Multiple Subsystems (&quot;Intelligent Apprentice&quot;)</td>
</tr>
<tr>
<td>Thermal Control System</td>
<td>Thermal Control System and Power System</td>
</tr>
<tr>
<td>- Monitor/real-time control of a single subsystem</td>
<td>- Coordinated control of multiple subsystems</td>
</tr>
<tr>
<td>- Goal and causal explanation displays</td>
<td>- Operator aids for unanticipated failures</td>
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<tr>
<td>- Rule-based simulation</td>
<td>- Model-based simulation</td>
</tr>
<tr>
<td>- Fault recognition/warning/limited diagnosis</td>
<td>- Fault diagnosis for anticipated failures</td>
</tr>
<tr>
<td>- Resource management</td>
<td>- Real-time planning/replanning</td>
</tr>
<tr>
<td>- Reasoning assuming standard procedures</td>
<td>- Reasoning about nonstandard procedures</td>
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<th>1993</th>
<th>1996</th>
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<tr>
<td>Hierarchical Control of Multiple Subsystems (&quot;Intelligent Assistant&quot;)</td>
<td>Distributed Control Of Multiple Subsystems (&quot;Intelligent Associate&quot;)</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td>- Multiple subsystem control: ground and space</td>
<td>- Autonomous cooperative controllers</td>
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<tr>
<td>- Task-oriented dialogue &amp; human error tolerance</td>
<td>- Goal-driven natural language interface</td>
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<tr>
<td>- Fault recovery from unanticipated failures</td>
<td>- Fault prediction and trend analysis</td>
</tr>
<tr>
<td>- Planning under uncertainty</td>
<td>- Automated real-time planning/replanning</td>
</tr>
<tr>
<td>- Reasoning about emergency procedures</td>
<td>- Reasoning/learning, supervision of on-board systems</td>
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AUTONOMOUS SYSTEMS FOR ADVANCED LAUNCH SYSTEMS (ALS)
UNMANNED LAUNCH VEHICLES

NASA AMES RESEARCH CENTER
OAST/AF-SPONSORED RESEARCH
AI Research Issues

- MACHINE LEARNING
- COOPERATING KNOWLEDGE-BASED SYSTEMS
- REAL-TIME ADVANCED PLANNING AND SCHEDULING METHODOLOGIES
- MANAGEMENT OF UNCERTAINTY
- AUTOMATED DESIGN KNOWLEDGE CAPTURE
- VALIDATION OF KNOWLEDGE-BASED SYSTEMS
MACHINE LEARNING

PREDICTIONS:

BAD

BETTER

GOOD

REMEMBER SEARCH MISTAKES

MODEL REFINEMENT

BEFORE

AFTER

SCHEDULING HEURISTICS

Technicians are in great demand

Histogram Pane
DESIGN KNOWLEDGE LOST WHEN DESIGNER LEAVES:

BUT WHY
IS THIS APERTURE
2.7 mm?

CONSERVATION OF DESIGN KNOWLEDGE

WHY DID THEY CHOOSE SILVER INSTEAD OF STEEL?

ELECTRONIC NOTEBOOK

HUMAN USE:

PROCESS CONTROL
DIAGNOSIS
REPAIR
DESIGN

"(DRIVEN-BY $OBJECT MOTOR-3977)"

AUTOMATED USE:

DESIGN KNOWLEDGE FROM "LIFECYCLE"

DOMAIN KNOWLEDGE

PHYSICAL LAWS
Knowledge Intensive
- Strong prior theory
- One (or few) examples
- Verification by proof
- Learned concept must be useful

Knowledge Weak
- Weak prior model
- Many examples required
- Cannot prove theory
- Learned concept reflects intrinsic structure

Machine Learning

EBG

Discovery Learning

Model Discovery

Markov Models

Classification Models

Series Prediction

Supervised

Unsupervised
The spectra show two closely related IRAS classes with peaks at 9.7 and 10.0 microns. This discrimination was achieved by considering all channels of each spectrum. AutoClass currently has no model of spectral continuity. The same results would be found if the channels were randomly reordered. The galactic location data, not used in the classification, tends to confirm that the classification represents real differences in the sources.
Evolution of Advanced Architectures for Real-time, On-board Teraflop Systems

- **Function**: RT Image Processing, Knowledge Understanding & Control, Deep Reasoning
- **Technology Status**: Applied R&D, Development, Basic Research
- **Technology Forecast**: Late 1990s, Current, Early 2000s
- **Examples**: KBS-controlled Photonic Processor, SVMS (6-Processor System), Neural Networks, Fuzzy Logic Controllers
Computer Architecture Research Issues
(Numeric/Symbolic Multiprocessor Systems)

- OPERATING SYSTEMS FOR REAL-TIME MULTIPROCESSING SYSTEMS IN A HETEROGENEOUS ENVIRONMENT
- VALIDATED COMPILERS AND TRANSLATORS FOR AN ADA-BASED MULTIPROCESSING ENVIRONMENT
- DATABASE MANAGEMENT FOR LARGE DISTRIBUTED DATABASES GREATER THAN 10GB
- AUTOMATED LOAD SCHEDULING FOR MULTIPROCESSORS
- REAL-TIME FAULT TOLERANCE AND RECONFIGURATION
- RADIATION HARDINESS WITH MINIMUM PERFORMANCE COMPROMISES
  - PROCESS TECHNOLOGY
  - VLSI/VHSIC TRADEOFFS
  - EFFICIENT COMPILERS AND INSTRUCTION SET ARCHITECTURES
SPACEBORNE VHSIC MULTIPROCESSOR SYSTEM (SVMS)
NASA/AF/DARPA COLLABORATION

**PROCESS**

VHSIC TECHNOLOGY

- 0.5μ TARGET
- 1.25μ BACKUP
- RAD-HARD CMOS
- 10^5 RADS RADIATION RESISTANCE
- NO SINGLE EVENT UPSETS

**SYSTEM CHARACTERISTICS**

- PARALLEL ARCHITECTURE
  - 40-BIT SYMBOLIC PROCESSORS
  - 32-BIT NUMERIC PROCESSORS
- FAULT-TOLERANCE/AUTOMATED RECONFIGURATION
- OPTICAL INTERCONNECTS
- 25 MIPS SUSTAINED UNIPROCESSOR PERFORMANCE (40 MIPS TARGET)
- MINIMUM OF 100 MIPS OVERALL SYSTEM PERFORMANCE
- DBMS FOR 10G BYTE MEMORY MANAGEMENT

**POTENTIAL SPACE & AERONAUTICS APPLICATIONS**
PHOTONIC PROCESSOR FOR REAL-TIME IMAGE UNDERSTANDING

OBJECTIVES

- REAL-TIME PHOTONIC PROCESSORS & TECHNIQUES for Terrain Analysis Tasks
- SYSTEM CONTROL & INTEGRATION OF EMBEDDED PHOTONIC PROCESSORS with Integrated Numeric/Symbolic Multiprocessor Systems
- TECHNOLOGY FEASIBILITY DEMONSTRATIONS Focused on Planetary Rovers & Space Vehicles

BENEFITS

- Real-time, High Performance Parallel Processing for Image Processing & Understanding
- Fault Tolerance
- Low Power, Weight, and Size

POTENTIAL APPLICATIONS

- Autonomous Landing
- Sample Acquisition and Analysis
- Sample Return

NASA Ames Research Center
CASS-SPONSORED RESEARCH
Knowledge-Based Systems

The tasks involved with an image-understanding-system can be divided into three layers as shown. The problem is to find a synergistic balance between all layers so that as knowledge of the image accrues, the reliability of the interpretation, recognition, and enhancement increases, while the amount of required computation decreases. Methodologies of organizing a knowledge-base of object and using a rule-based system to effectively search the knowledge-base and directing the computations of photonic processors are being developed. The majority of the domain specific knowledge for a task will reside in the interpretative level making the photonic processor a general purpose computing tool.
Neural Networks

Hopfield

Bidirectional Associative Memory

Counter Propagation

Self-Organizing Maps

Neocognitron

Backward-Error Propagation

Rumelhart

There are many models in the real world that cannot be represented by a two-layer system such as the Hopfield model. For example, there exist one-dimensional systems that cannot be approximated by the Hopfield model. These systems are not represented by the Hopfield model.

Rumelhart

Adaptive Resonance Theory

There are many models in the real world that cannot be represented by a two-layer system such as the Hopfield model. For example, there exist one-dimensional systems that cannot be approximated by the Hopfield model. These systems are not represented by the Hopfield model.

Rumelhart

Grossberg

Carpenter and Grossberg have developed their Adaptive Resonance Theory, which is designed to model the brain. They have designed a network that is trained without supervision. The network consists of a set of input and output neurons. The input layer is trained to match the input pattern. The output layer is trained to match the output pattern. The network is trained to match the input pattern and the output pattern. The network is trained to match the input pattern and the output pattern.

Rumelhart

Kohonen

One important organizing principle of sensory pathways in the brain is that the placement of neurons is orderly and often reflects some physical characteristics of the afferent stimulus being sensed. For example, each level of the auditory pathways has a characteristic place in the auditory pathway, with some cells being interaural and others being interaural.

Rumelhart

Fukushima

The model is a hierarchical multi-layered network consisting of a cascade of many layers of simplified neurons. It has a hierarchical structure and hierarchic connections between layers. The forward signal propagates the function of pattern recognition, while the backward signal propagates the function of adaptive attention and associative recall. The forward and backward signals interact with each other at every stage of the hierarchical sequence.
America's Future in Space