ELECTRONIC NEURAL NETWORKS

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ELECTRONIC NEURAL NETWORKS
JET PROPULSION LABORATORY

BACKGROUND

- NEURAL NETWORKS OFFER A TOTALLY NEW APPROACH TO INFORMATION PROCESSING THAT IS ROBUST, FAULT-TOLERANT, AND FAST.

- MODELS OF NEURAL NETWORKS ARE BASED ON HIGHLY PARALLEL AND DISTRIBUTIVE ARCHITECTURES.

- JPL IS DEVELOPING ELECTRONIC IMPLEMENTATIONS OF ARTIFICIAL NEURAL NETWORKS TO EXPLOIT THEIR EMERGENT PROPERTIES FOR "INTELLIGENT" KNOWLEDGE ENGINEERING APPLICATIONS.

- IN AN ELECTRONIC EMBODIMENT, "NEURONS" ARE REPRESENTED BY THRESHOLD AMPLIFIERS, AND "SYNAPSES" BY RESISTORS. INFORMATION IS STORED IN THE VARYING STRENGTHS OF SYNAPTIC CONNECTIONS.

- ELECTRONIC IMPLEMENTATIONS OF APPLICATION - SPECIFIC HIGH SPEED NEUROPROCESSORS FOR:
  - ASSOCIATIVE RECONSTRUCTION
  - CARTOGRAPHIC ANALYSIS
  - RESOURCE ALLOCATION
  - GLOBAL OPTIMIZATION
  - AUTONOMOUS CONTROL
INTRODUCTION

• ARTIFICIAL NEURAL NETWORKS:

• MASSIVELY PARALLEL ARCHITECTURES INSPIRED
  BY THE NATURE'S APPROACH TO INTELLIGENT
  INFORMATION PROCESSING

• KEY QUESTIONS:

• WHAT GOOD ARE THEY?

• CAN THEY DO SOMETHING UNIQUE FOR SPACE
  STATION?

• WHEN WILL THEY DELIVER?
NUMBERS!

- A HUMAN BRAIN HAS OVER $10^{14}$ NEURONS AND $10^{10}$ SYNAPSES.
- HARDWARE IMPLEMENTATIONS TODAY ARE AT ABOUT $10^3$ NEURONS AND $10^5$ SYNAPSES.

BUT
- THE BRAIN IS NOT FULLY CONNECTED!
- THE CURRENT ARTIFICIAL NEURAL NETWORKS ARE ALREADY PROVING THEMSELVES EXTREMELY USEFUL.
- NEURAL NETWORKS ARE NOT GENERAL PURPOSE COMPUTERS. THEY ARE SPECIAL-PURPOSE HIGH PERFORMANCE CO-PROCESSORS.
NEURAL NETWORK

BASIC COMPONENTS:  

- NEURONS
- SYNAPSES

ELECTRONIC IMPLEMENTATION:

INPUT  NEURON  OUTPUT
ELECTRONIC NEURAL NETWORKS
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NEURAL NETWORK ARCHITECTURES

\[ \dot{C}_i \frac{du_i}{dt} = \sum T_{ij} V_j - \frac{u_i}{R_i} + I_i \]

FEEDBACK NETWORK

FEEDFORWARD, LAYERED
ELECTRONIC IMPLEMENTATIONS

JPL's approach has been:

- To develop neural net "building blocks" for modular hardware
- To verify design of neurocircuits in simulation
- To tailor "neuroprocessors" for selected applications

Technologies:

- **VLSI:** CMOS, bipolar, and EEPROM (floating gate)
- **Thin Film:** Amorphous semiconductors, electrochromic materials, and chemical microswitches
- **Hybrid:** VLSI/Thin Film, single/multi-chip, wafer-level integration
VLSI/THIN FILM HYBRID HARDWARE FOR NEUROCOMPUTING

1024 CAPACITOR-REFRESH, ANALOG SYNAPSE CHIP

32 x 32 BINARY SYNAPSE CHIP

A NEURO-PROCESSOR

A NEURAL-DIGITAL HYBRID COMPUTER SYSTEM

17-NEURON ARRAY CHIP

HIGH DENSITY, THIN FILM SYNAPTIC ARRAY
ELECTRONIC NEURAL NETWORKS

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CASCADABLE, PROGRAMMABLE, 32 x 32 SYNAPTIC CMOS CHIP

- A BUILDING BLOCK FOR VLSI NEURAL NET HARDWARE
- PROVIDES OVER $10^9$ ANALOG OPERATIONS/SEC
- POTENTIAL APPLICATIONS:
  - MULTI SENSOR DATA FUSION
  - ASSOCIATIVE RECONSTRUCTION
  - PATTERN RECOGNITION
COMPUTATION WITH ANALOG PARALLEL PROCESSING

- NEURAL NETWORK ARCHITECTURES
  - ASSOCIATIVE MEMORY
  - AUTONOMOUS CONTROL
  - GLOBAL OPTIMIZATION
  - CARTOGRAPHIC ANALYSIS

- CELLULAR ARRAY PROCESSORS
  - PATH PLANNING
  - RESOURCE ALLOCATION

- CUSTOM THIN FILM MICRODEVICES
  - HIGH-DENSITY INTERCONNECTIONS
  - NON-VOLATILE ANALOG MEMORIES
FEATURES OF NEUROPROCESSORS

- APPLICATION-SPECIFIC ARCHITECTURES
- FINE-GRAN, MASSIVELY PARALLEL, ANALOG, ASYNCHRONOUS PROCESSING
- EXTREMELY HIGH SPEED: TERRA-OPS RANGE
- INHERENT FAULT-TOLERANCE
- UNIQUE CAPABILITIES TO "LEARN" FROM EXPERIENCE AND SELF-ORGANIZE
- TRULY ENABLING NATURE, COMPLEMENTING THE ABILITIES OF HIGH SPEED DIGITAL MACHINES
APPLICATIONS OF NEUROPROCESSORS

- AUTOMATION AND ROBOTICS
- ON-BOARD, REAL-TIME, GLOBAL OPTIMIZATION
  - ALLOCATION AND MANAGEMENT OF RESOURCES
- AUTONOMOUS, SCHEDULING, SEQUENCING, AND EVENT-DRIVEN MISSION REPLANNING
- SCIENCE DATA ANALYSIS AND MANAGEMENT
  - PATTERN RECOGNITION, CLASSIFICATION
  - MODELING OF LARGE SYSTEMS
  - CODING, DECODING, ASSOCIATIVE RECONSTRUCTION FROM CORRUPT DATA
Neural network classification results. Each color denotes a particular decision or classification for a pixel. e.g., green = "GO", yellow = "GO SLOW", orange = "GO VERY SLOW", and red = "NO GO". 
NEURAL NETWORK HARDWARE FOR TERRAIN TRAFFICABILITY DETERMINATION
A DEDICATED PROCESSOR FOR PATH PLANNING

- MASSIVELY PARALLEL, ANALOG, ASYNCHRONOUS PROCESSING

- ACCEPTABLE SOLUTION IN REAL TIME, THAN THE BEST SOLUTION AFTER A LONG TIME

- ORDERS OF MAGNITUDE SPEED IMPROVEMENT, PARTICULARLY FOR "WHAT IF" EXPERIMENTS

PATH COMPUTATION
HARDWARE DETAIL FOR SIGNAL SORTER AND MAP SEPARATES APPLICATIONS

I/O BUS

DOWNLOAD INTERFACE

MUX INPUT NEURON
64-CH

32 x 32 SYNAPSE CHIP

32 x 32 SYNAPSE CHIP

32 x 32 SYNAPSE CHIP

32 x 32 SYNAPSE CHIP

32 x 32 SYNAPSE CHIP

32 NEURON CHIP

DOWNLOAD INTERFACE

A/D BOARD

SIGNAL SORTER 128-1024 INPUT UNITS

MAP SEPARATES 64-256 INPUT UNITS
JPL NEURAL NETWORK SYSTEM INTERFACE

DATA RATE: 1 MByte/sec

DIRECT INPUT

DIRECT OUTPUT

SCSI CONTROLLER
HOST COMPUTER

SCSI CONTROLLER
DOWNLOAD INTERFACE
FOR PROGRAMMING INPUT VALUES

ANALOG INPUTS

NEURAL NETWORK SUBSYSTEM

DOWNLOAD INTERFACES
FOR PROGRAMMING WEIGHTS

I/O BUS (DIGITAL)

A/D CONVERTER
ELECTRONIC NEURAL NETWORKS
RAPID HARDWARE PROTOTYPING OF NEURAL PROCESSORS FOR "REAL" PROBLEMS

THE PROBLEMS

• MAP KNOWLEDGE BASE APPLICATIONS REQUIRING LARGE AMOUNTS OF DATA AND HIGH SPEED PROCESSING

• CROSS-COUNTRY MOBILITY DETERMINATION: A MULTIDIMENSIONAL EUCLIDEAN DISTANCE MINIMIZATION PROBLEM

• GENERATION OF MAP SEPARATES: AN IMAGE SEGMENTATION PROBLEM

• DETERMINATION OF "BEST" PATH: A ROUTING PROBLEM

THE SOLUTION

• DEDICATED NEUROPROCESSORS IMPLEMENTING NEURAL ALGORITHMS FOR SOLVING THESE PROBLEMS

• THESE NEUROPROCESSORS WILL BE INTERFACED WITH A PORTABLE ASAS WORK STATION (PAWS) FOR USER EVALUATION AT THE CENTER FOR SIGNALS WARFARE (CSW)
NEURAL NETS FOR ROBOTIC CONTROL

Layered, feed-forward nets with abilities to 'learn' from 'experience'.

- Learning algorithm: Error back propagation
- 'Knowledge' is accumulated in the analog synaptic weights
ERROR BACKPROPAGATION ALGORITHM FOR LEARNING

RANDOMIZE SYNAPTIC WEIGHTS

TRAINING SET

FEED INPUT

FORWARD PASS

COMPAR E OUTPUT WITH DESIRED TARGET

GENERATE ERROR VECTOR

IS LEARNING COMPLETE? YES NO

ERROR < TOLERANCE

STORE WEIGHTS

Δwij = ηδjσj
RESOURCE ALLOCATION MATRIX
## Resource Allocation Processor Simulation

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### Diagrams:
- Diagram 1: Two sections with black squares scattered across.
- Diagram 2: A single section with black squares similar to Diagram 1.
GLOBAL OPTIMIZATION NEUROPROCESSOR

- RESOURCE ALLOCATION
- DYNAMIC ASSIGNMENT
- MESSAGE ROUTING
- TARGET-WEAPON PAIRING
- LOAD BALANCING
- MULTI-TARGET TRACKING
- SEQUENCING / SCHEDULING
- REAL TIME, ADAPTIVE MISSION RE-PLANNING

- NEUROPROCESSING APPROACH OFFERS OVER 4 ORDERS OF MAGNITUDE SPEED ENHANCEMENT OVER THE CONVENTIONAL COMPUTING TECHNIQUES.

- ARBITRARY MULTIPLE TO MULTIPLE ASSIGNMENTS ARE POSSIBLE, WHICH ARE NOT EASILY ACCOMPLISHED BY CONVENTIONAL TECHNIQUES.
ELECTRONIC NEURAL NETWORKS

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PROGRAMMABLE, NONVOLATILE, HIGH-DENSITY, THIN FILM SYNAPTIC ARRAY FOR INFORMATION STORAGE

- POTENTIAL FOR HIGH DENSITY APPROACHING $10^9$ BITS/CM$^2$
- FAULT-TOLERANCE
- ASSOCIATIVE, CONTENT-ADDRESSABLE RECALL
- NO MOVING PARTS
- STORAGE IN "PASSIVE," RAD-HARD INTERCONNECTIONS
ELECTRICALLY PROGRAMMABLE
READ ONLY THIN-FILM SYNAPTIC ARRAY

A 62 x 62 SYNAPSE TEST ARRAY WITH
4-\(\mu\)m FEATURE SIZE

a-Si:H MICROSWITCH
AND RESISTOR SANDWICHED
BETWEEN METAL ELECTRODES
CONCLUSIONS

• THE FIELD OF NEUROPROCESSING HAS SIGNIFICANTLY ADVANCED IN RECENT YEARS. INVESTMENTS OF DOD AND NASA ARE RESULTING IN THE DEVELOPMENT OF APPLICATION-SPECIFIC, HIGH PERFORMANCE, MODULAR NEUROPROCESSORS.

• SUCH NEUROPROCESSORS OFFER TOTALLY NEW CAPABILITIES, COMPUTATIONAL BREAKTHROUGHS, AND ORDERS OF MAGNITUDE PERFORMANCE ENHANCEMENT WHERE CONVENTIONAL PROCESSING METHODS CHOKE.

• DOD IS MOVING AHEAD IN THE DIRECTION OF HARDWARE PROTOTYPING OF DEPLOYABLE NEUROPROCESSORS FOR COMPLEX PROBLEMS IN BATTLEFIELD MANAGEMENT AND TACTICAL FUSION OF INTELLIGENCE, ETC.

• TIME IS RIGHT FOR NASA TO TAKE ADVANTAGE OF THIS POWERFUL TECHNOLOGY. TAILORED NEUROPROCESSORS WILL BE IDEALLY SUITED TO SATISFY NASA'S UNIQUE AND GROWING DEMANDS IN COMPUTATION AND DATA MANAGEMENT WITH THE EVOLUTIONARY DEVELOPMENT OF SPACE STATION.