Autonomous and Intelligent Systems: Futures

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Potentially Disruptive Technologies

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Introduction/Outline

- "Senior Staff Scientist for Premature Technology"

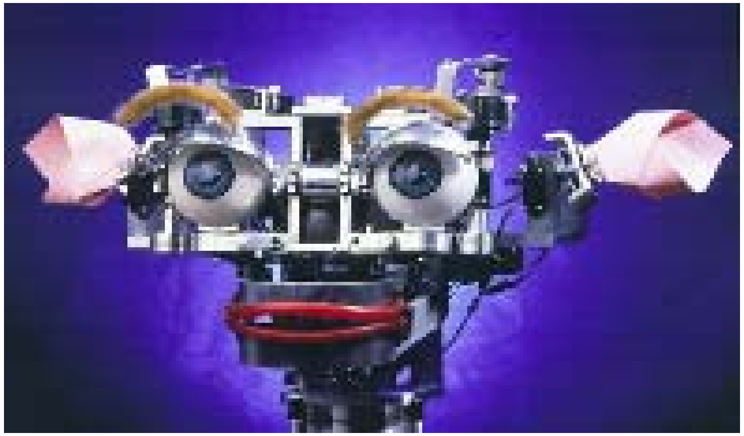
- My Current Programs
  - Where I am coming from

- Observations, Opinions, and Predictions
  - This is not Official DARPA Position
  - This is not Unofficial DARPA Position
  - This is not even necessarily My Position

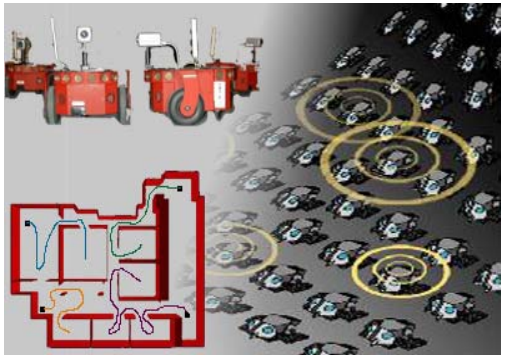
IPTO Robotic Software Programs

Mobile Autonomous Robot Software

Machine learning and perception for effective navigation in diverse real-world environments and effective interaction with humans



Software for Distributed Robotics



Coordinated behaviors and effective user interfaces for large numbers of small robots

MARS Technical Approach

Intervention

User interfaces structured so that humans can assist robots when needed

Interaction

Natural information exchange between robots and humans -- as teammates, bystanders, supervisors, and operators

Perception

Sensor-based algorithms to sense, interpret, and "understand" salient environmental features

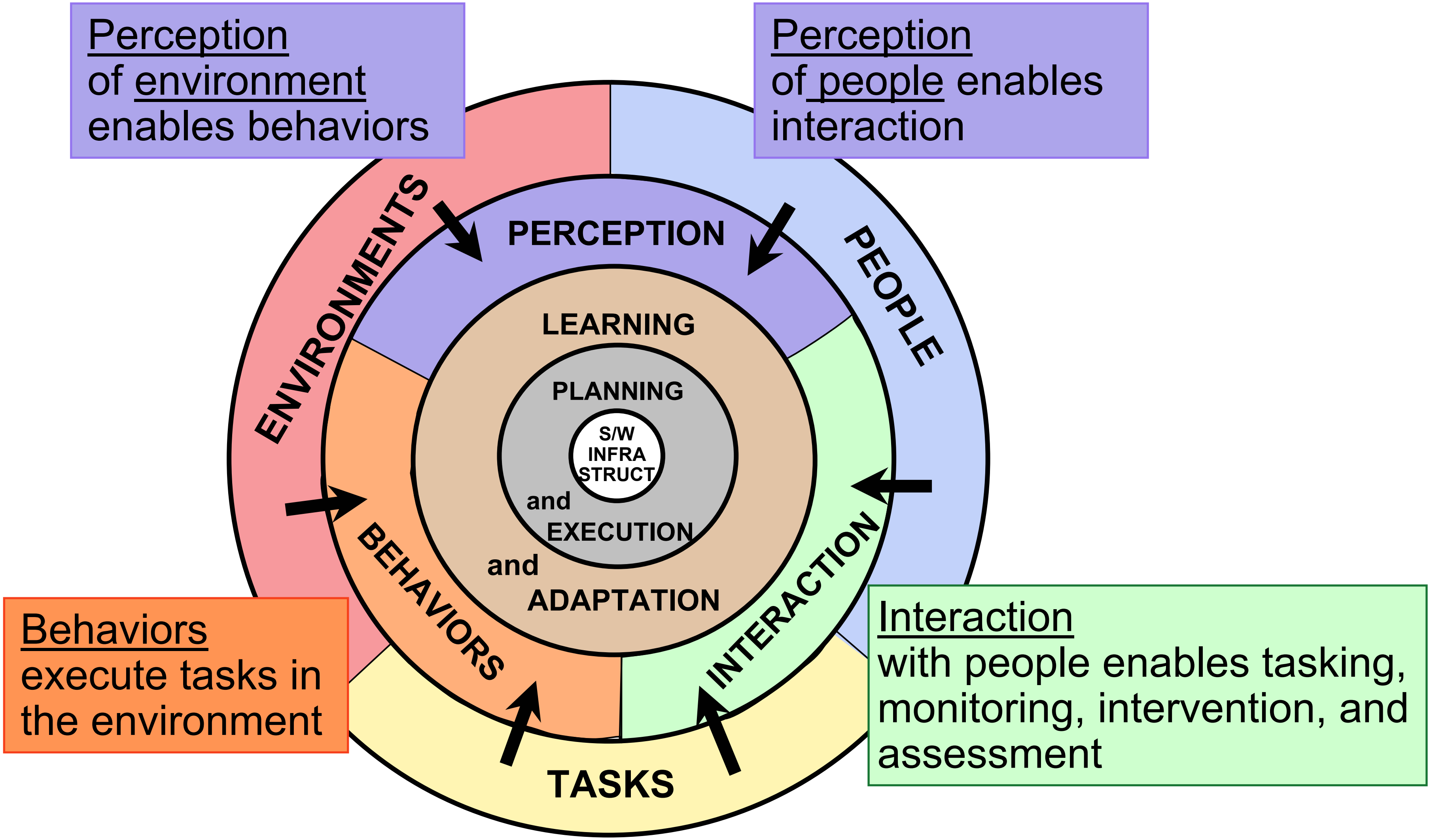
Learning and Adaptation

Techniques to acquire knowledge through reinforcement, supervised, or imitative learning

Behaviors and Architecture

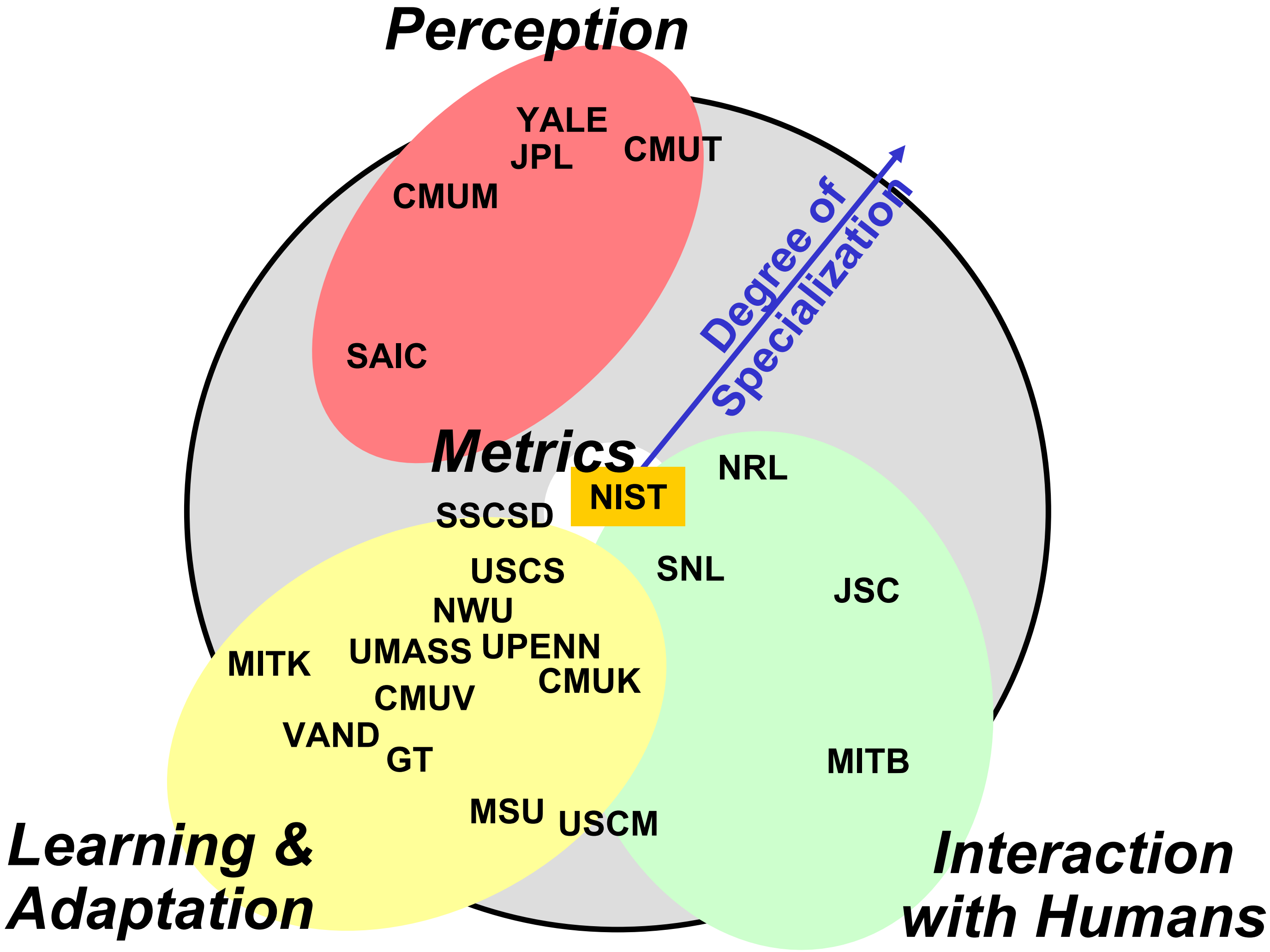
Software components and structures to perform robot tasking

A Robot's "Intelligence" is Embodied, Situated, and Taskable



Initial MARS Efforts & Technical Focus Areas

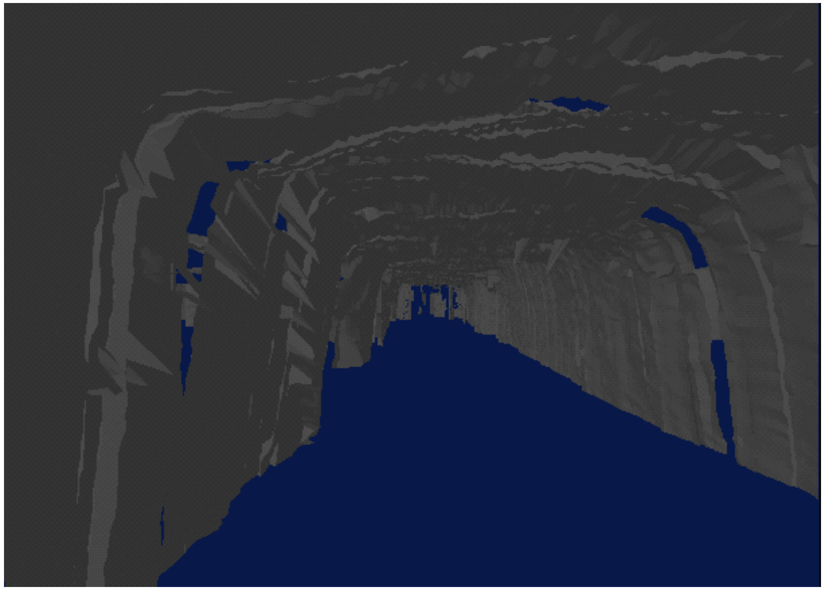
Performers
CMU (Manuela Veloso)
CMU (Hans Moravec)
CMU (Pradeep Khosla)
CMU (Sebastian Thrun)
Georgia Tech (Ron Arkin)
MIT (Rod Brooks)
MIT (Leslie Kaelbling)
Michigan State (John Weng)
NASA Johnson(Bob Savely)
NASA JPL (Larry Matthies)
NIST (Jim Albus)
Northwestern (Ian Horswill)
NRL (Alan Schultz)
Sandia (Hamilton Link)
SAIC (Matt Morganthaler)
SSC-SD (Hoa Nguyen)
U Mass (Rod Grupen)
U Penn (Vijay Kumar)
USC (Gaurav Sukhatme)
USC (Maja Mataric)
Vanderbilt (Kaz Kawamura)
Yale (Paul Hudak)



Period of Performance: FY99 – FY03

Perception

- Mapping Complex Indoor/Outdoor Environments
  - Faster, more accurate, larger scale
- Dynamic Environments
  - Detection, Tracking, Modeling



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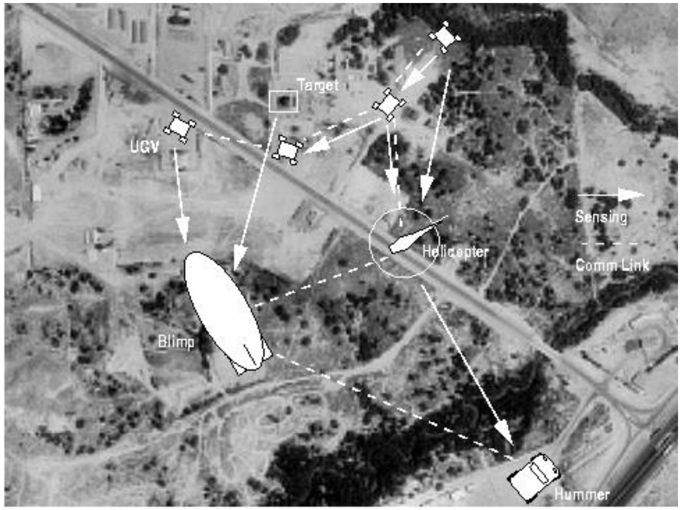
MARS Vision 2020 from Technologies to Capabilities

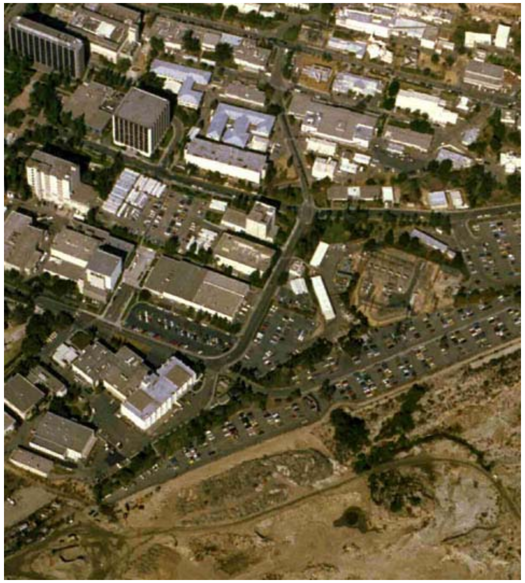
Driving

Humanoid

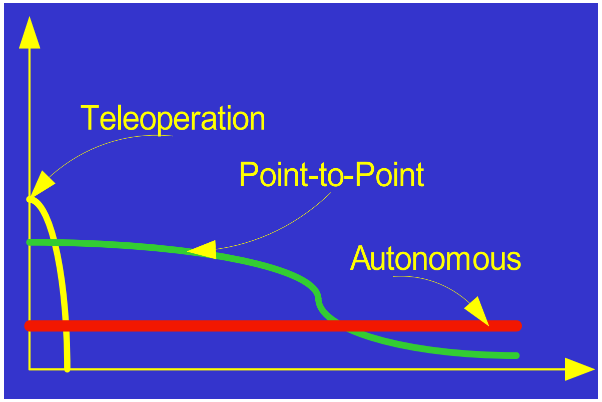
Teams



Urban



Interaction



Robo-Boat

BAA 02-15 Awards

Period of Performance: FY02 – FY04

Multiple Modalities of Human-Robot Interaction

- **Psycho-spatial Relationships**

Human Role	Human's POV	Psycho-spatial Relationship
Commander	god's-eye	remote
Peer	bystander	beside the robot
Teleoperator	robot's-eye	become the robot: "telepresence"
Developer, maintainer	homunculus	inside the robot

- **Authority Relationships (needs more columns…)**

Authority Relationship	Function	Context required
Supervisor	Commands "what"	Tactical situation
Operator	Commands "how"	Detailed perception
Peer	Cross-cueing	Shared environment, functions
Bystander	Interacts	Shares environment

- **Responsibility Relationships**

Monitor	Alarms, alerts, high bandwidth data stream (?)
Maintainer	Diagnostic and maintenance tools

We've been at this for a while…

12 Electronic Engineering Times - Monday, January 30, 1984

DOD Targets 3 Projects For AI, Supercomputer Uses

By Chappell Brown

BOSTON — Lynn Conway, assistant director of strategic computing for the Department of Defense, outlined a broad-based program here last week to apply artificial intelligence and supercomputer technology to military systems.

Congress has approved $50 million in funding in fiscal 1984 for an initial project that targets development of three military artificial intelligence systems by technology and applications "communities," Conway said.

Projects Described

Conway, speaking at a VLSI conference at the Massachusetts Institute of Technology, said the systems to be developed initially include an autonomous land vehicle, a personalized adviser for jet pilots and an aircraft battle-management system.

Though Conway did not go into details about each project, in the past the Defense Department has said that the military would like a land vehicle that could roam a battlefield and detect enemy troops or equipment. The jet pilot's "adviser" will be an expert system giving instantaneous advice to jet pilots during flight, and a computerized battle management system would coordinate attacks from an aircraft carrier.

Military Applications

Conway said development of these systems would provide the basis of a "strategic computing" program that would develop technology of "unprecedented capabilities."

The program will focus on military applications that require machine intelligence and will draw on recent advances in computer vision, speech, and expert system technology.

Expert systems are a branch of artificial intelligence research that use databases derived from the experience of human experts to draw inferences in novel situations.

Conway used an incident in the Falklands war as an example, illustrating the use of this kind of system in a battle.

Falklands Incident Cited

British ships were using a computer-controlled radar system as a defense against Argentine aircraft. Although the system was highly advanced, the Argentinian pilots found a ploy that would confuse the system—they would fly in a tight pattern, appearing as a single object to the radar, and then quickly disperse.

This unexpected maneuver confounded the computer-controlled system. The experts needed to reprogram the system were all back in Britain.

What was required was an instantaneous expert at the scene, or, even better, a system that was more adaptable to novel situations, Conway said.

There are three broad technological goals of the strategic computing program: to provide the United States with a broad-based machine intelligence capability, demonstrate applications important to defense and provide technological spinoffs.

A fundamental theme of the project will be the interaction of advanced areas of research. For example, advanced VLSI architectures need to be combined with the kind of software and systems work being undertaken by artificial intelligence researchers. At this time, research groups such as these are not coordinated, Conway pointed out.

Applications 'Pull'

In Conway's view, specific programs—such as developing an autonomous land vehicle—impel this kind of cooperation; she spoke of applications providing the "pull" needed to create machine intelligence.

Although DARPA (Defense Advanced Research Projects Agency) will manage the project, approximatly 10 "computer technology communities" will be created to develop the required technology and another five to 10 "applications communities" will work on implementation. Each community will involve 100 professionals from private, academic and government areas.

A high degree of interactivity will be crucial to the project, and networks and interactive workstations will be heavily used. Conway used the phrase "an online window into activities."

Although the need for secrecy on defense projects might work against this open communications network, Conway replied that only the specific applications communities would be operating under classified information restrictions. The basic technology development program would be open.

The plan calls for $50 million in 1984, $96 million in 1985 and $150 in 1986.

Japanese Reveal VLSI Thrusts

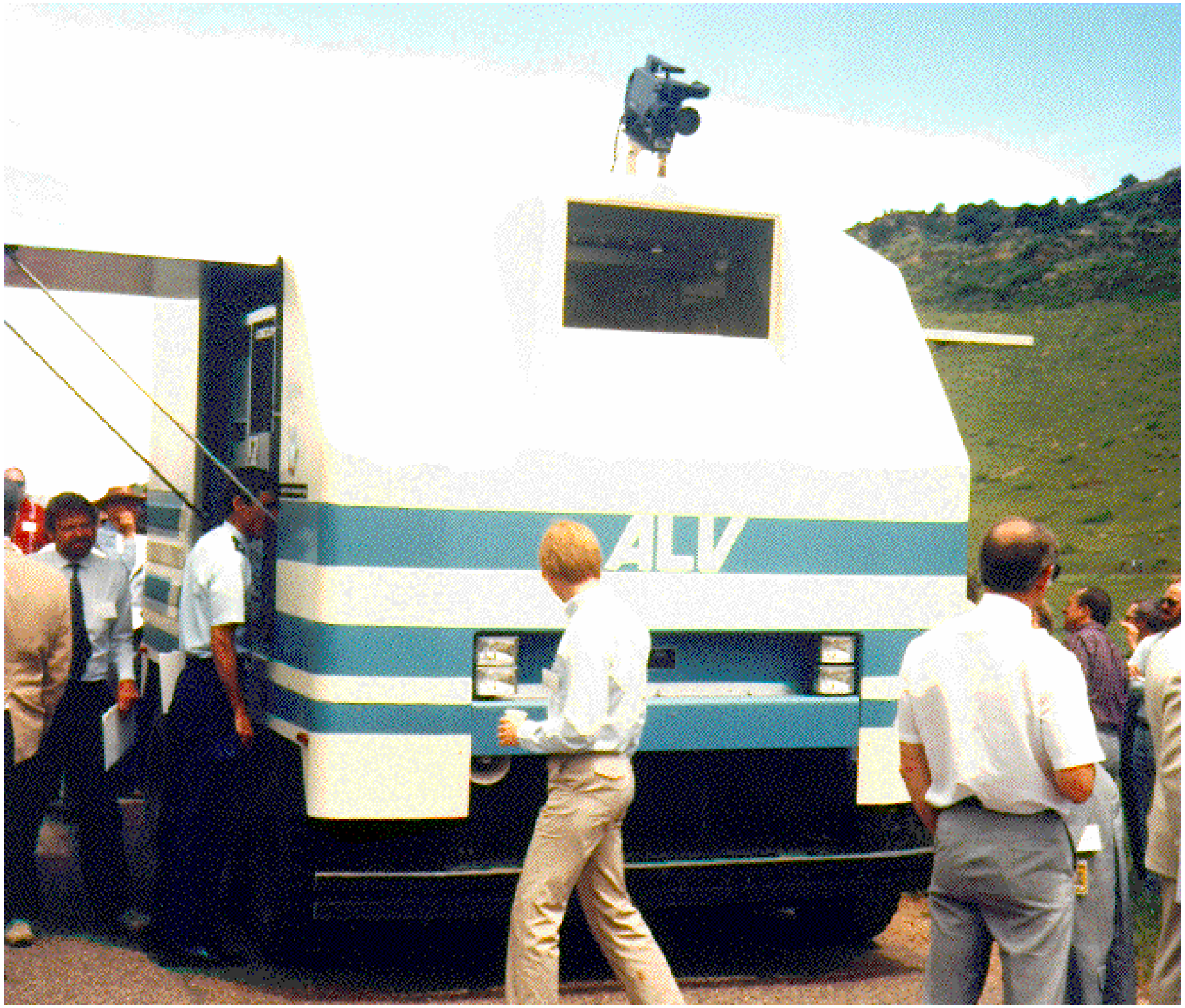
By Chappell Brown

which are still laboratory curi-

Apple: Mac Won't Repeat Lisa Mistakes

Announcement of DARPA ALV program, January 1984

Autonomous Land Vehicle (ALV)



The Downside Risk: A Cynic's View

GOAL

To explore the possibilities and implications of a proposed innovative behavior/control/navigation architecture/system

APPROACH

To implement a physical robot to serve as a testbed and demonstration platform

WHAT IS LEARNED

- Alkaline batteries are good
- Rechargeable batteries work best when actually recharged
- Connectors and cables are failure prone
- Sensors are "unreliable“
- Whatever monitoring tools were implemented in the systems aren't good enough to tell what's "broken" when “it doesn't work”
- A cut-up cardboard box can keep the sun off a monitor screen
- You never have enough batteries for your digital camera
- On demo day, all robots use the same RF frequency

Alan Alda's comments from "Natural Born Robots"

- "…but while I was there it was barely able to lurch to its feet."
  - re Case Western Reserve giant pneumatic cockroach
- "And so a sinking robot pike joins the stubborn robot cockroach in demonstrating just how hard it is to copy mother nature."
  - after MIT's "Robo-pike" developed a leaky "head-gasket"
- "I'm beginning to wonder if I'm some sort of robot jinx."
  - after a motor failed on MIT's "Spring Flamingo"
  - from Scientific American Frontiers: Natural Born Robots (show 1002), on PBS, 2 November 1999

General Lessons Learned From MDARS-I (3)

Expect the unexpected!

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Software for Distributed Robotics

DARPA

The SDR Program is developing coordinated behaviors and effective user interfaces to enable useful systems of thousands of small robots.

Because large numbers of robots provide

- **Spatial diversity**
- **Redundancy**
- **Expendability**

SDR is developing the required

- **Coordinated behaviors**
- **Inter-robot communications**
- **User tasking, monitoring, intervention, and assessment**

In order to use small robots that are

- **Lightweight**
- **Easy to transport**
- **Fit into small spaces**

SDR software must work even with extremely limited

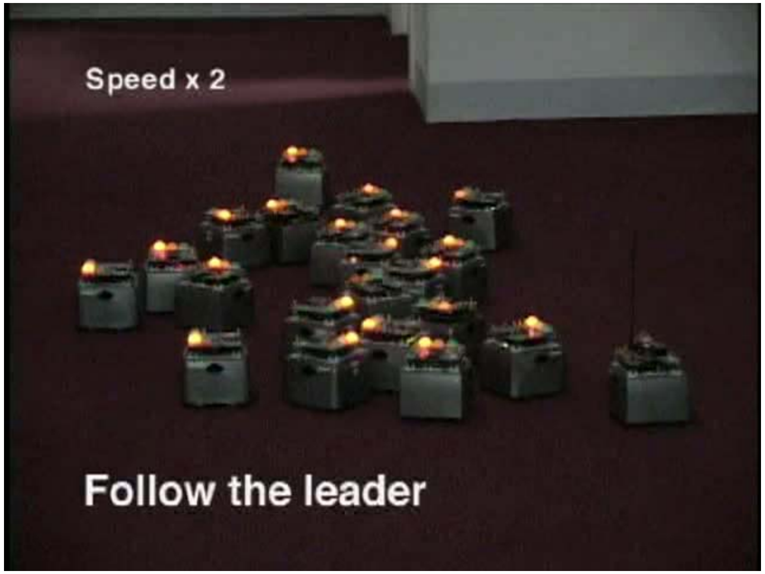
- **Processing**
- **Power**
- **Communications**
- **Sensing**
- **Strength**

SDR Technical Thrust Areas

- ***Coordinated Behaviors***
  - Explicit sensor-based behavior and model-based control
  - Distributed (emergent) control techniques (*e.g.*, analogous to potential field theory in mechanics)

- ***Inter-robot Communications***
  - Lightweight energy-conserving networking protocols
  - "Pheromone" communication strategies
- ***Computational architecture***
  - Distributed processing
  - Proxy (off-board) processing
  - Hybrid (shared or hierarchical) processing
- ***Human-robot Interface***
  - Explicit symbolic interface
  - Implicit embedded or stigmergic interface
- ***Lab & Field Experiments***
  - Control/Communications
  - Human-robot interaction
  - Technology transitions

Examples of Group Behaviors



- Distributed algorithm behavior library of primitive, individual, and group behaviors
- Implicit communications using virtual pheromones and exchanging data packets
- Debugging using standard and embedded techniques. Hands-off operation: HIVE and the Robot Ecology
- MTO DR Deployer project collaboration for low-cost platform development. Demonstrated scalability from 12-robot to 120-robot swarms, 30 robots at DARPATech

SDR Evolutionary Path

	Baseline	FY 00 - 01	FY 02 - 03	Goal State
Group Size	< 10	10 - 20	100 +	1000 +
Robot Platforms	• COTS & custom research robots	• Adapted COTS research robots	• MTO Distributed Robotics designs	• Integrated microrobots
Applications	• Simple search • Sentry	• Plume tracing • HAZMAT localization • Mapping	• Distributed interior surveillance	• Covert distributed interior surveillance
Behaviors	• Discrete • Cooperative	• Physics-based • Task level integration • Market-based control	• Mission level integration • Self monitoring	• Self maintaining • Hands-off
Comms	• Standard RF • Fixed network • Standard protocols	• IR & acoustic pheromones • Ad hoc dynamic networks • Energy conserving protocols	• Robot-network partnership	• Free space optical • Networked microrobots
Human-Robot Interface	• Explicit tasking	• Augmented reality displays • PDA-based control	• Colony level control (HIVE)	• Robots as “pixels”

SDR Technology Efforts and Performers (BAA 99-20: FY00 – FY02)

Performer	Project Title	Thrust Areas
IRobot (IS Robotics)	Software for Disposable Robot Swarms	Communications (implicit) Architecture
BBN Technologies	Energy-Conservation Network Protocols for Small-Scale Robots	Communications (explicit)
Carnegie Mellon University	Cognitive Colonization: A New Paradigm for Distributed Robotics	Behaviors (explicit) Architecture
HRL Laboratories	Pheromone Robotics	Human Robot Interface Communications (implicit)
U Mass, Amherst	Software, Programming, and Run-Time Coordination for Distributed Robotics	Behaviors
Sandia National Labs	Analysis and Control Software for Distributed Cooperative Systems	Behaviors (implicit & explicit)
INEEL	Command and Control Architectures for Autonomous Micro-Robotic Forces and Human Interface Concepts for Autonomous Distributed Control	Behaviors (implicit) Human Robot Interaction
UC Berkeley	Networked Mobile Micro Robots	Integrated Microrobot Communications (explicit)

Distributed Interior Surveillance (BAA 02-14: FY02 - FY03)

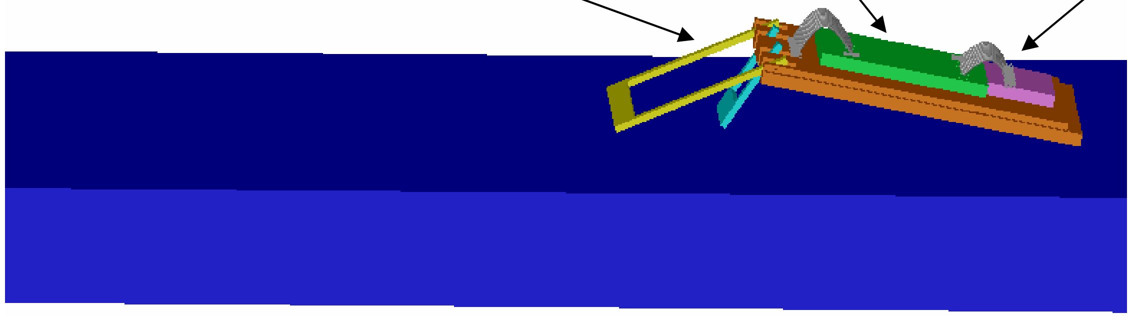
- **Situation**
  - An object of value is believed to be located within a large, single-story, previously unexplored building
  - Opposing forces may or may not be present in the vicinity
  - Apart from possible opposing force intruders, no humans or other moving entities are present
- **Task**
  - Deploy a 100-robot system to map the building and locate the object of value
  - Protect object by detecting, tracking, and reporting the position of any intruders who may enter the space
  - Operate for a period of at least 24 hours
- **Assumptions/Ground Rules**
  - Robots are permitted to return to the base station for manual recharging
  - The demonstration may incorporate multiple types of physical robots
  - Fixed baseline performance will be established for the protect phase by using manually deployed fixed sensors

Integrated Microrobot

Solar cells, 30 V drivers (in-house custom process)

CMOS 1V controller (in-house design, National Semiconductor process)

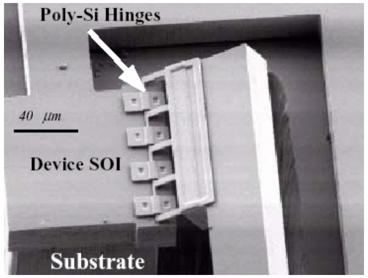
Legs, motors, hinges (in-house custom process)

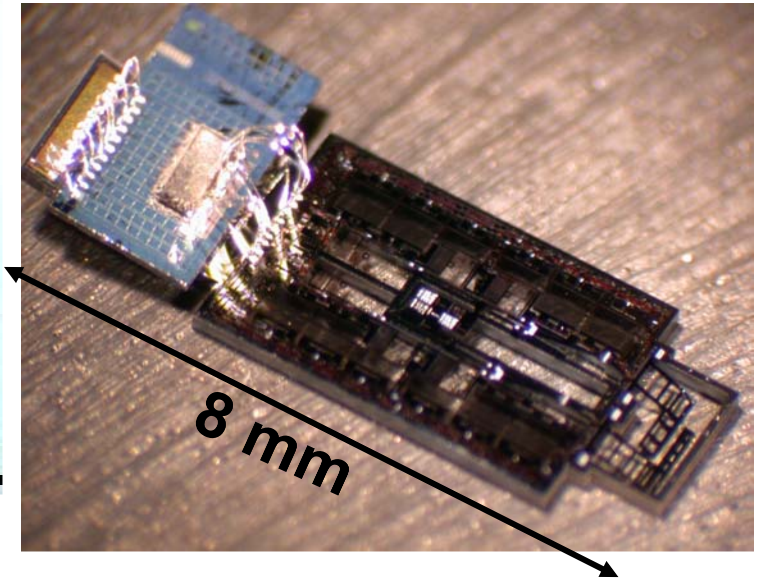


- Fabrication of 8 mm long autonomous micro-robot
- UC Berkeley – Kris Pister and Anita Flynn (“Gnat Robots”)
- Solar-powered three-chip hybrid
- Adding MEMS-based on-chip mobility to Smart-Dust/SensIT “mote”

A thousand half-gram robots in a pound!

Microrobot Fabrication



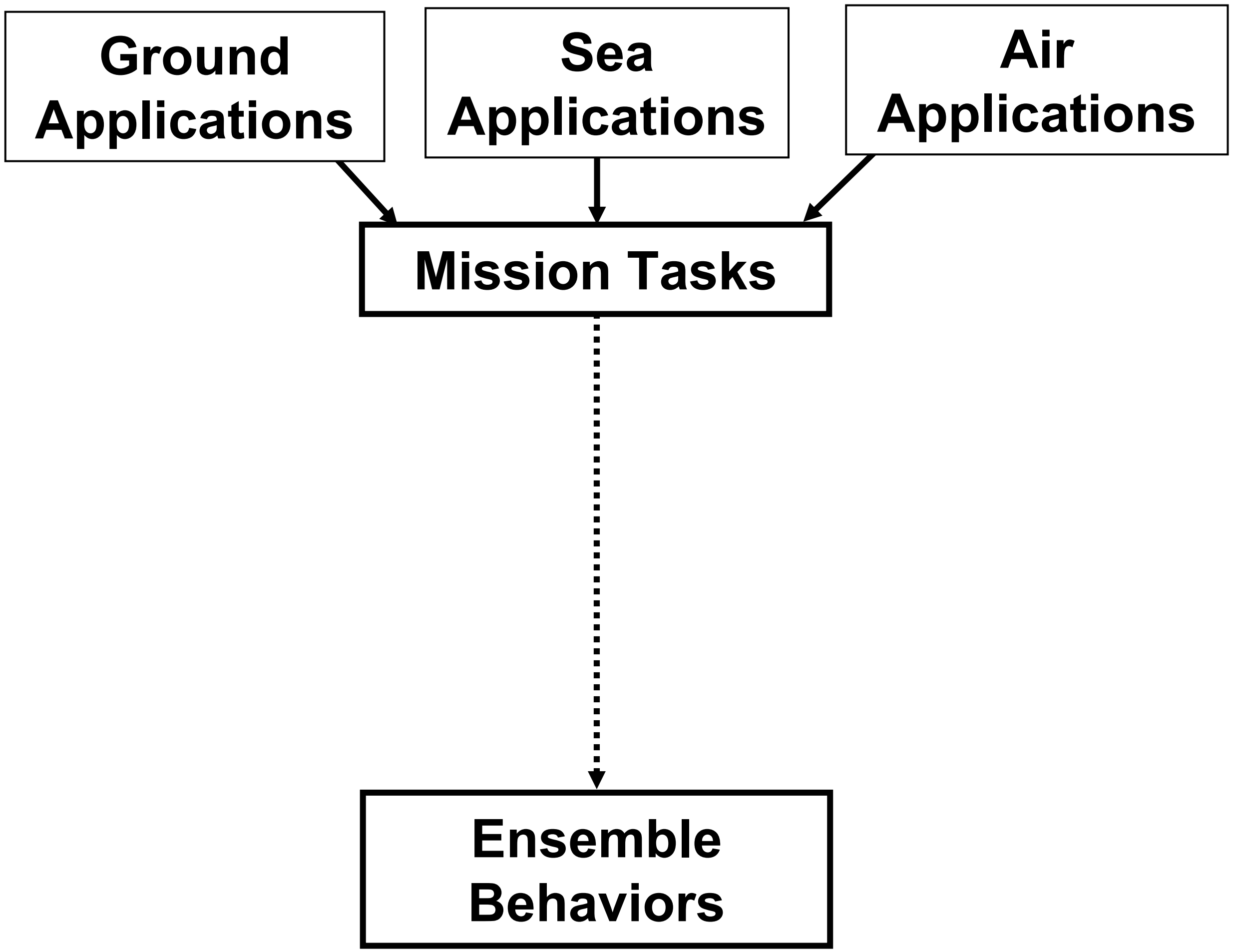


- 150-200 robots per 4” wafer
- Current chip yield: MEMS 65%, CMOS, solar 100%
- Current assembly yield 25%
- Target total yield 80% = 120-160 bots/wafer

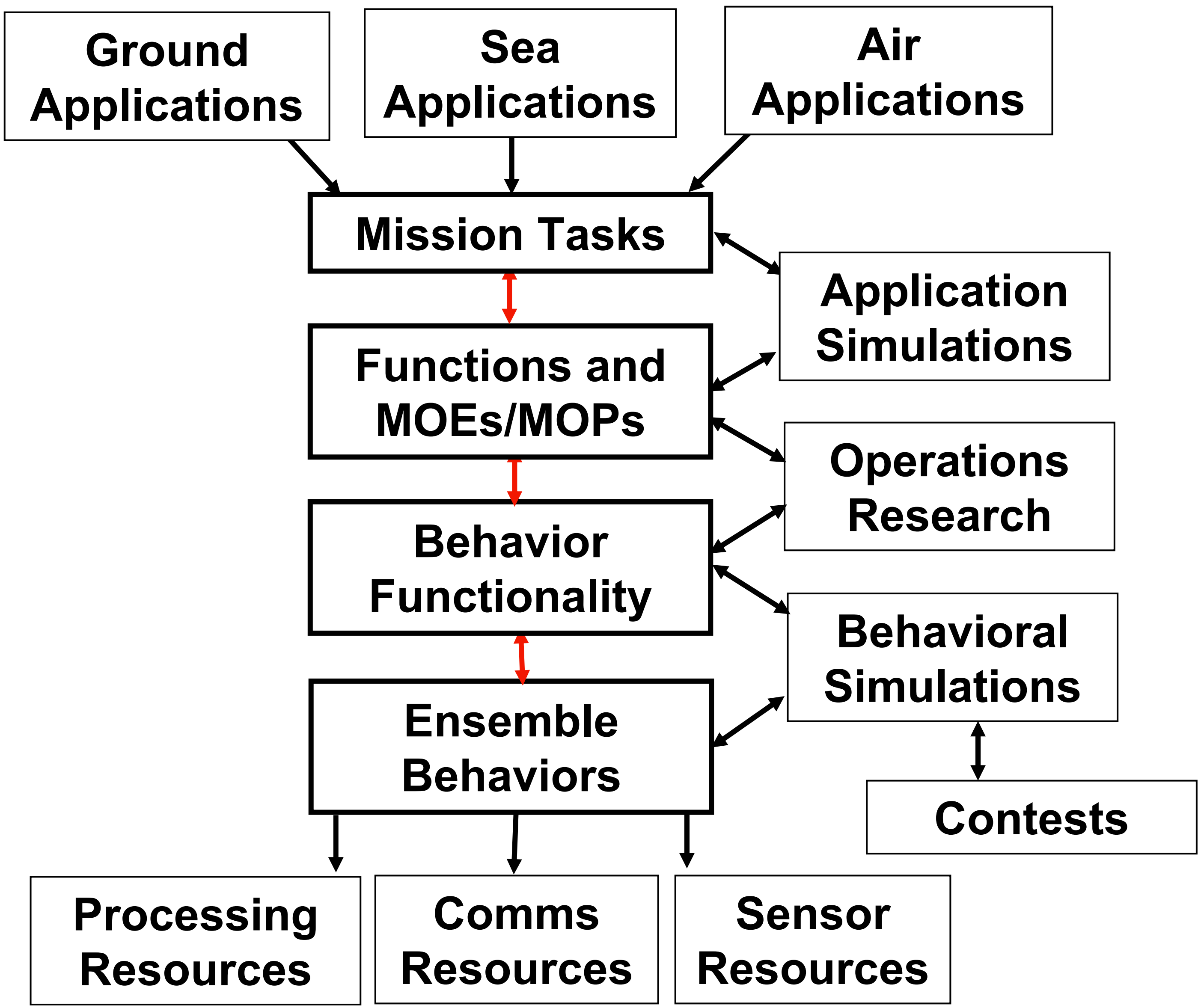
Irrelevant Algorithm Syndrome

- Generally manifested as simulation (or "toy" demo) totally decoupled from reality
- Case 1: "Fantastical" sensors
  - Group foraging algorithm using sensor that reliably provides the distance and direction to the "nearest food item"
  - Formation algorithm using sensor that reliably provides the distance and direction to the farthest member of the group
- Case 2: Unrealistically precise sensors
  - Perfect landmark detection, identification, tracking
- Exception -- a new sensor that provides a truly revolutionary capability
  - Sick laser rangefinder that "cut the Gordian knot" for indoor mapping

Mission Level Integration



Mission Level Integration



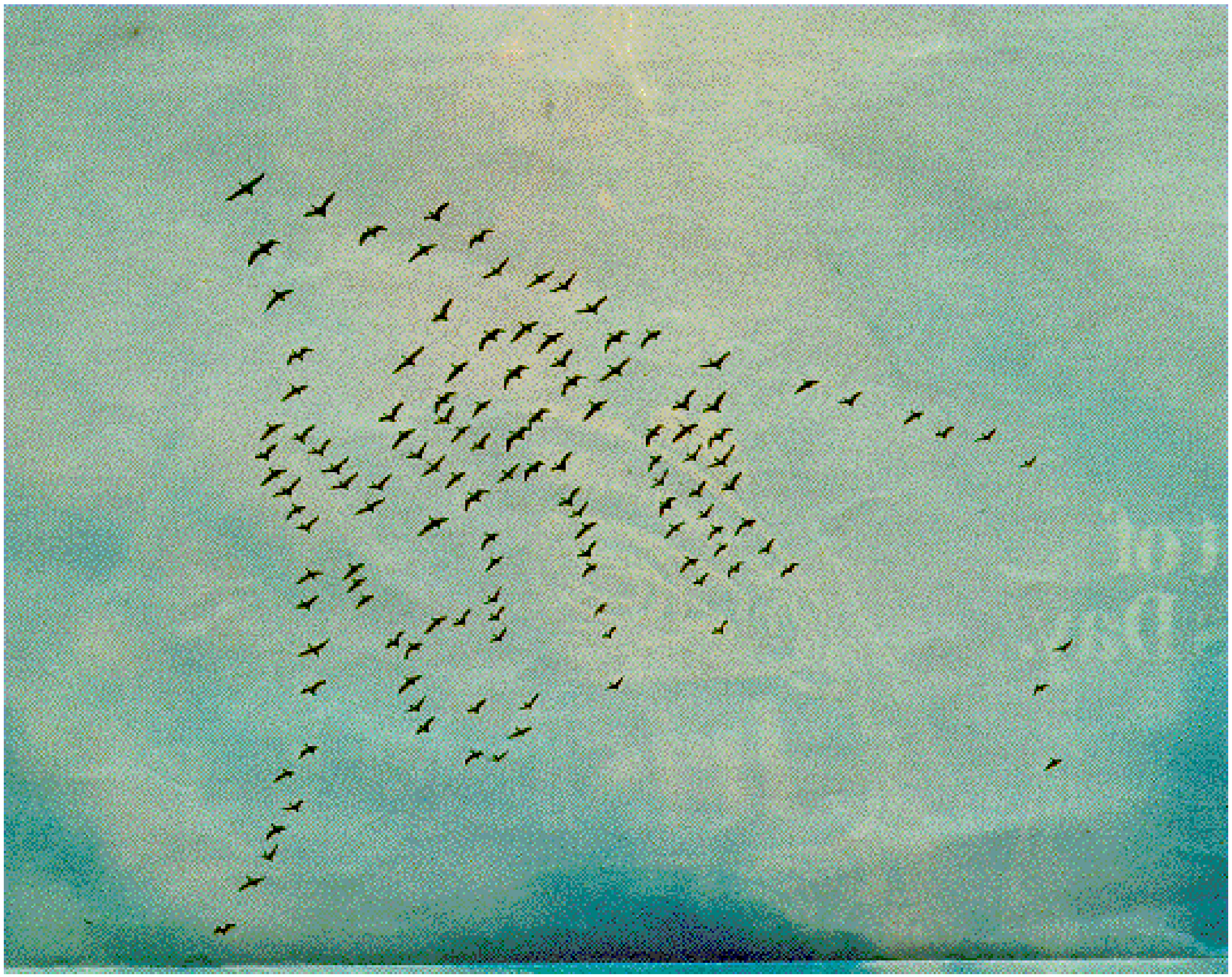
Biologically Inspired Systems

- A biological system is evolved, and does just what it does. It is not necessarily the "existence proof" for something "similar" that would be "useful"
  - Lacks a well defined "control interface" to modulate system goals
  - Implemented as opportunistic collection of special cases
  - Implementation layering is imperfect
- Implication: opportunities for exploitation of biological approaches have well defined limits
  - Effectiveness and efficiency: automobiles have wheels, not legs, airplanes don't flap their wings like birds
  - Physical evolution generally too expensive in terms of time and resources

Systems Existence Criteria

- **Existence Criteria for Natural Systems**
  - Physiological: capable of coherent functioning to sustain life until reproduction
  - Ontogenetic: capable of developing from an embryo
  - Phylogenetic: genotype derivable from that of pre-existing progenitors by natural "genetic algorithms“
  - Ecological: able to survive and reproduce in the environment in which it is situated
- **Existence Criteria for Artificial Systems (by analogy)**
  - Functional: able to perform its function, whatever that may be
  - Manufacturable: by some available processes
  - Designable: imaginable by designers working in their cultural context
  - Marketable: perceived to serve some purpose well enough, when compared to competing approaches, to warrant its design, manufacture, and purchase

“Now that’s flying first class”



"Whither Speech Recognition?"

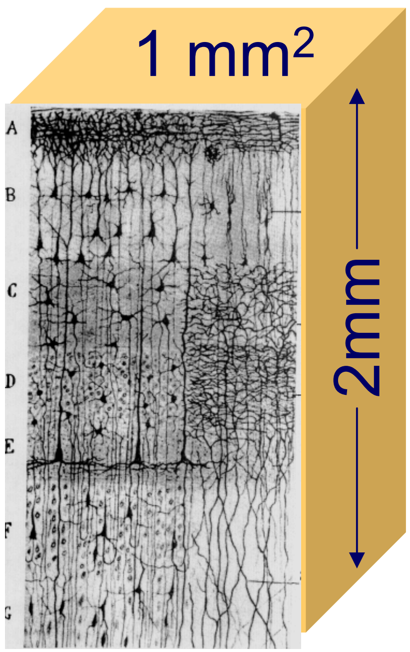
J. R. Pierce, Bell Labs, Letter to the Editor of Journal of Acoustical Society of America, 1969:

- "Most recognizers behave, not like scientists, but like mad inventors or untrustworthy engineers. The typical recognizer gets it into his head that he can solve "the problem". The basis for this is either individual inspiration (the "mad inventor" source of knowledge) or acceptance of untested rules, schemes, or information (the untrustworthy engineer approach)…
- "The typical recognizer… builds or programs an elaborate system that either does very little or flops in an obscure way. A lot of money and time are spent. No simple, clear, sure knowledge is gained. The work has been an experience, not an experiment."
- JASA Volume 46, Number 4 (Part 2) 1969, pp 1049-1051.

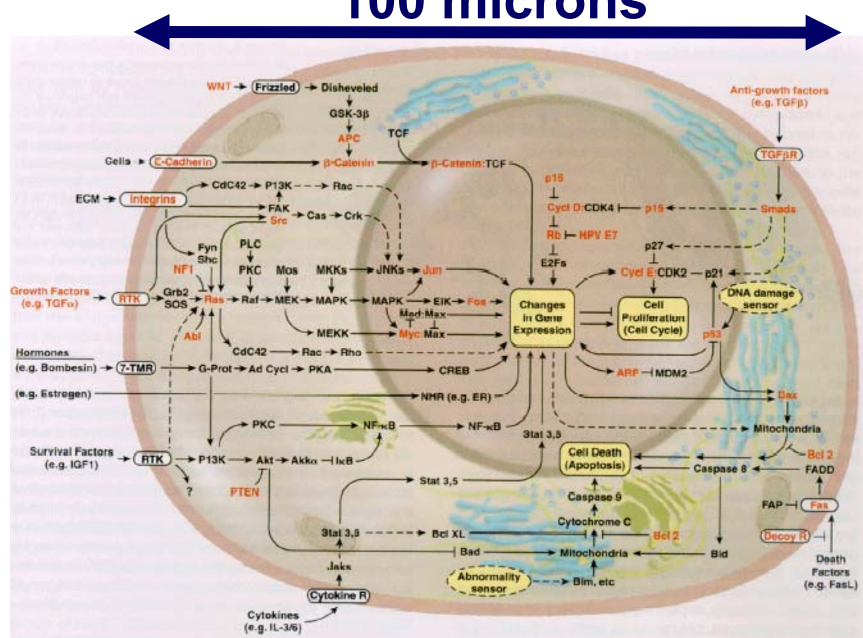
Bio:Info:Micro Program

Idea: Establish basic research environments for training a new generation of students and postdocs who will be “trilingual” in the modern research languages of biology, information science, and microsystems technology

Approach: Focus on two broad biology areas that provide fertile ground for interdisciplinary research as well as high potential for DOD impact: neurobiology and cell regulatory networks



10^5 neurons
10^8 connections



specified by 10^9 base pairs and approx. 10^5 proteins

Bio:Info:Micro Program

- **Neurobiology**
  - **Impact**: augment/repair human cognition and motor performance; neuronally-based algorithms for computation
  - **Technical Challenges**: develop advanced nanodevices to probe mammalian cortex function and advanced signal processing to classify and interpret neuronal electrical patterns
- **Cell Regulatory Networks**
  - **Impact**: augment/repair human physiological responses to injury and stress; novel therapeutic targets; biologically inspired algorithms for information processing and decision making
  - **Technical Challenges**: develop advanced nanodevices to probe genetic and metabolic regulatory networks in single cells and advanced modeling and simulation tools to represent and predict the dynamic behavior of cells

Observations, Opinions, and Predictions

- "OOPs!"
- Realization of predictions seems to bifurcate:
  - Either way sooner than predicted
  - Or way later than predicted
- Sooner than predicted:
  - Engineering challenges of many varieties
- Later than predicted:
  - Anti-gravity
  - Time travel
  - Generalized Machine Intelligence
  - Anything related to "mind"

Exploiting Neurobiology

- **Intellectually, neurobiology is "pregnant"**
  - I expect at least one revolutionary breakthrough in understanding within 5-10 years
- **Real opportunity for a "full court press"**
  - Neurophysiology, ontogeny, phylogeny, deficits, psychology, …
- **Nevertheless, today we do not understand how the brain works well enough to build brain-mimetic systems**
- **Therapy will precede full understanding**
  - Therapy will depend on exploiting plasticity
  - Exploit human reporting and training
  - Build a constituency for funding
- **Real opportunity for militarily significant capabilities**

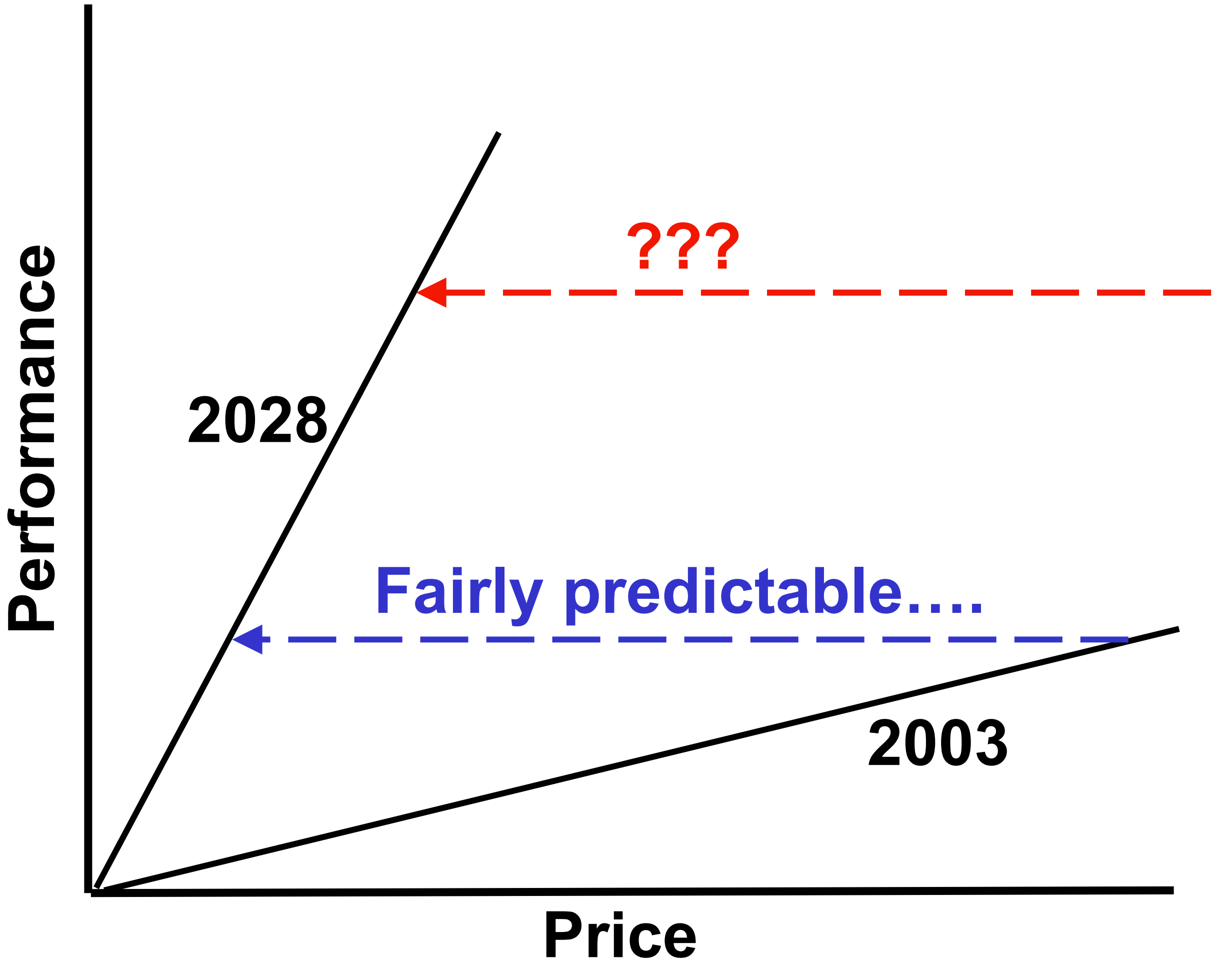
Machine Intelligence…

- No “Singularity” (Kurzweil)
- No Gates > Neurons Miracle (Moravec)
- No Spontaneous ANS Miracle (Hecht Neilson)
- No Ultra-Intelligent Machine (IJ Good)

- Exponential Growth is the bottom of an S Curve
- It’s the Synapses, not the Neurons!
- Intelligence (intrinsic) is not Knowledge (extrinsic)
  - Imagine the computing in the connector…
  - Computing is free? So what?
  - Need data as well as processing
  - Reasoning is easy, Perception is hard

“Impossible” as “meaningless” vice “too hard”

…Machine Intelligence…



…Machine Intelligence

- **Ubiquitous Intelligence**
  - Things are not necessarily what they seem
  - Ubiquitous Spoofing
- **Identify areas of vulnerability**
  - Machine Intelligence not perfect
  - Compute “Novelty Quotient” (NQ) of situation
  - Raise NQ to defeat intelligent systems
- **Graceful Degradation**
  - Avoid overdependence on any one capability
  - Build on basics
  - No “fault conditions,” just “operating modes”

Thinking Outside the Box

- **Terrorism is "open source" military power**
  - How much damage can one person do?
  - Technology eliminates the need for suicide
- **The problem is the "immune response"**
  - "Denial of service" as immune response
  - Only we have the power to destroy ourselves
  - Accept predator-prey dynamic (?)
- **Long term strategy for dealing with radical Islam:**
  - Demonetize petroleum
  - Break our addiction to oil