

**SPAWAR**



*Systems Center  
San Diego*

# **Current Thrusts in Ground Robotics: Programs, Systems, Technologies, Issues**

**Dr. Douglas W. Gage**

**SPAWAR Systems Center, San Diego**

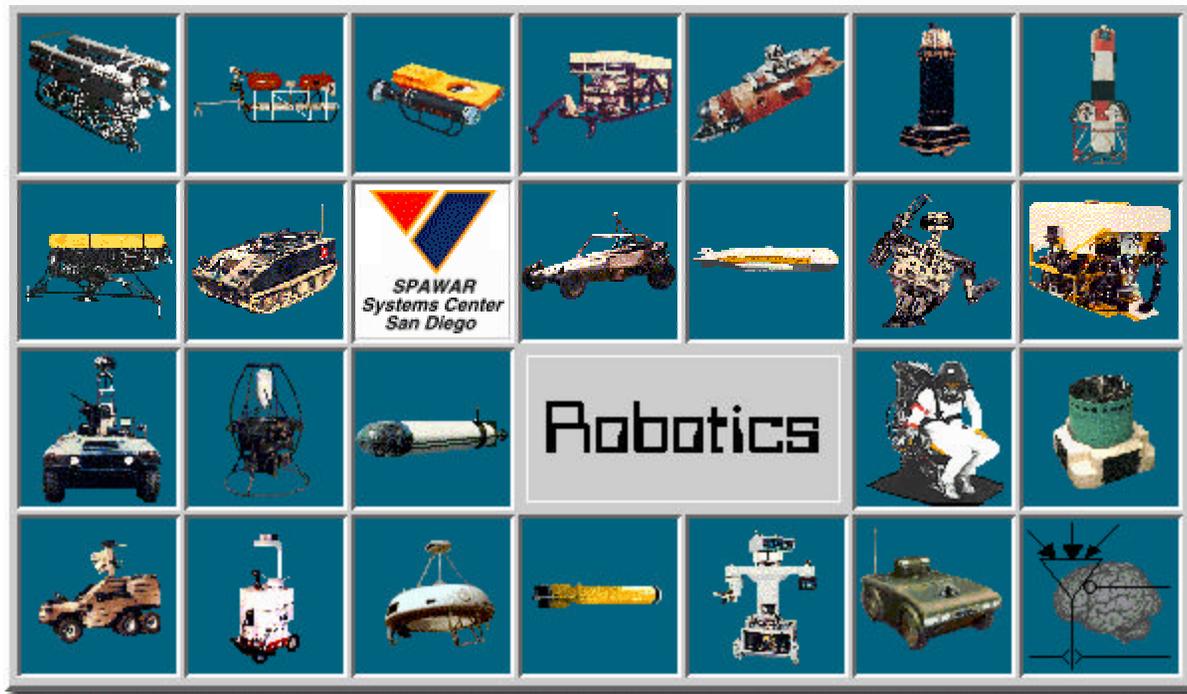
**gage@spawar.navy.mil**

**(619) 553-3673**

**Fourth International Symposium on  
Technology and the Mine Problem  
Monterey CA, 12-16 March 2000**



<http://www.spawar.navy.mil/robots/>



**Space and Naval Warfare Systems Center  
(formerly NELC, NUC, NOSC, NRaD)  
UUVs since early 1960s, UGVs since early 1980s  
Prototype system development, not “basic research”  
Many technical papers on line at above URL**

**SPAWAR**



*Systems Center  
San Diego*

## Overview

- **Brief survey of US DoD ground robotic programs**
  - DARPA Programs
  - Joint Robotics Program (JRP)
  - Future Combat Systems (FCS)
- **Discussion of some key technologies and issues**
  - Communications and power
  - Perception and autonomy
  - Modularity and interoperability
  - Integration and implementation
- **This presentation will be available online at:**
  - <http://www.spawar.navy.mil/robots/pubs/demine00.pdf>

**SPAWAR**



*Systems Center  
San Diego*

# DARPA Robotics Programs

- **Tactical Mobile Robots (TMR)**
  - DARPA/ATO
- **Mobile Autonomous Robotic Software (MARS)**
  - DARPA/ITO:
- **Distributed Robotics (DR)**
  - DARPA/MTO:
- **Software for Distributed Robotics (SDR)**
  - DARPA/ITO
- **Future Combat Systems (FCS)**
  - DARPA/TTO

**SPAWAR**



*Systems Center  
San Diego*

## **Tactical Mobile Robotics (TMR)**

- **DARPA Advanced Technologies Office (ATO)**
- **Initiated by Dr. Eric Krotkov in 1997**
- **Program Manager is LTC John Blich**
- **BAA 98-08, BAA 97-20, BAA 96-26, SBIRs, etc**
- **Principal Agent is TACOM-TARDEC**
- **SPAWAR provides technical guidance**

– **See E. Krotkov and J. Blich, “The DARPA Tactical Mobile Robotics Program”, The International Journal of Robotics Research, Vol. 18, No. 7, July 1999, pp. 769-776.**

**SPAWAR**



*Systems Center  
San Diego*

## The Technical Goal of TMR

Development of a system of robots capable of

operator-tasked and -monitored

perception-based

autonomous mobility

in diverse unstructured environments

that can fit into a rucksack

and be employed in coordinated groups

as a tool for the dismounted warfighter

**SPAWAR**



*Systems Center  
San Diego*

## **TMR-Specific Challenges**

- **Acquiring critical non-robot-specific component technologies**
  - power, displays, communications, etc
- **Being small enough and big enough**
  - Implementation fitting in rucksack envelope
  - Achieving functionality, performance
- **Supervised autonomous navigation**
  - How operator tasks, monitors, overrides
  - How robots actually execute moves
- **Implementation: making it all actually work**
  - Robotic system decomposition/architecture(s)

**SPAWAR**



*Systems Center  
San Diego*

# TMR Technology Wish List

## •Well defined capabilities

- Power source: higher energy density, power density
- Processing: higher MIPS per mass/volume/power
- Sensors: higher resolution, range; lower size, weight, power
- Communications anywhere: unimpeded through matter
  - »higher B/W: video -> color -> stereo -> omnidirectional
- Localization: equivalent of CP-DGPS anywhere

## •Subtler capabilities

- Locomotion schemes: go anywhere
- Perception: obstacles, landmarks, threats, friends, etc
  - »detect, classify, identify, localize, track
- “Effective and efficient” operator interface
- Sensor-guided mobility

**SPAWAR**



*Systems Center  
San Diego*

# TMR Phase I Core Performers

## **BAA 98-08 Part A Performers (Technology)**

**Mobility: MIT**

**Sensors: U Michigan**

**Perception: Yale, SRI Intl**

**Autonomy: SRI Intl, CMU, Stanford, USC, Georgia Tech**

**Mission Packages: Foster-Miller**

## **BAA 98-08 Part B Performers (System Design)**

**SAIC, Draper Lab, Raytheon**

## **BAA 97-20 Phase II Performer Team**

**Jet Propulsion Lab (lead), CMU (navigation), IS Robotics  
(mobility), Oak Ridge National Lab (group behaviors), USC  
(OCU)**

**(plus SBIR and other ancillary participants)**

**SPAWAR**



*Systems Center  
San Diego*

## **Joint Robotics Program (JRP)**

- **Sponsored by OSD**
  - Executed by UGV/S-JPO and others
- **JRP Master Plan updated annually**
  - available at <http://www.jointrobotics.com/>
- **Projects and Activities include:**
  - **BUGS**
  - **MPRS**
  - **Demo III**
  - **MDARS-E and MDARS-I**
  - **JAUGS**

**SPAWAR**



*Systems Center  
San Diego*

## **Basic UXO Gathering System (BUGS)**

**Use tens of cheap small robots to gather surface-litter submunition UXO and pile it in designated collection areas for destruction (handling UXO is dangerous)**

**Robots supervised by team of EOD technicians**

**Limited ops area under friendly control (200 x 400 m)**

**Precision localization system installed**

**CP-DGPS or CONAC or ?, 2-10 cm precision**

**Allows robot to "find" object without perception**

**Humans can handle perception tasks**

**Pre-survey targets, obstacles, "highways"**

**Confirm UXO id (operator on call)**

**"Rescue" robots in trouble**

**Evolve autonomous capabilities as P3I**

**SPAWAR**



*Systems Center  
San Diego*

# **Man-Portable Robotic System (MPRS) Tunnel Robot Development**

- **Application: to support combat engineers in clearing tunnels**
- **Concept Experimentation Program (CEP)**
  - Fort Leonard Wood MO, Nov-Dec '99
  - TMR Pool: Foster-Miller, IS Robotics robots
  - MPRS/SPAWAR first generation prototype
- **Training Exercises (CPX, FTX)**
  - Fort Drum NY, Mar-Jun '00
  - 41st Engineer Bn, 10th Mountain Div
  - 4 MPRS/SPAWAR second generation robots
- **JCF AWE**
  - Fort Polk LA, Aug-Sep '00

**SPAWAR**



*Systems Center  
San Diego*

## **MPRS Tunnel Robot vs DARPA TMR**

- **Big and heavy**
- **Limited mobility, speed**
- **Limited to one class of missions, one class of environments**
- **No autonomy**
  - **Strictly teleoperated**
- **TMR “LugBot” or “SlugBot” :-)**

**SPAWAR**



*Systems Center  
San Diego*

# MPRS Tunnel Robot: Key Features

- **Completely invertible (no preference)**
  - Top- and bottom-mounted driving cameras show front of vehicle in image
- **COTS camcorder camera module**
  - On tilt platform  $\pm$  90 deg, halogen lights
  - Color, 12x optical zoom, 2x electronic zoom
  - Electronic image stabilization
  - Autofocus etc, with software override
- **Single digital link for control, video, audio**
  - High quality video

**SPAWAR**



*Systems Center  
San Diego*

# **Tunnel Robot Key Features (continued)**

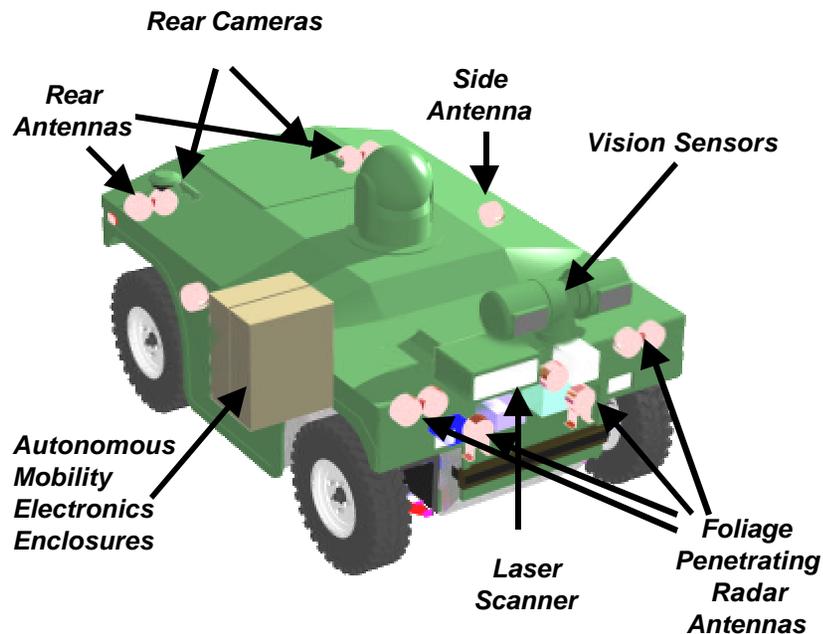
- **Incorporation of oversized idler wheel greatly enhances turning efficiency by reducing tracks' effective contact area**
- **Heavy on batteries**
- **Significantly hardened and waterproofed**
- **Tactics, techniques, procedures, documentation, training, logistical support**

**SPAWAR**



*Systems Center  
San Diego*

## Demo III XUV (Experimental Unmanned Vehicle)



- **Perform scout mission**
  - Autonomous mobility
  - On-road, off-road, all-weather
- **Follow on to AUV, Demo II**
- **Upsized MDARS-E vehicle**
  - Diesel hydrostatic drive
  - 2500 pound target
  - Fits in to V-22 Osprey
- **4D-RCS architecture**
- **ARL, GD-RS**
- **Demos 10/99, 10/00, 10/01**

**SPAWAR**



*Systems Center  
San Diego*

## Mobile Detection Assessment Response System (MDARS)

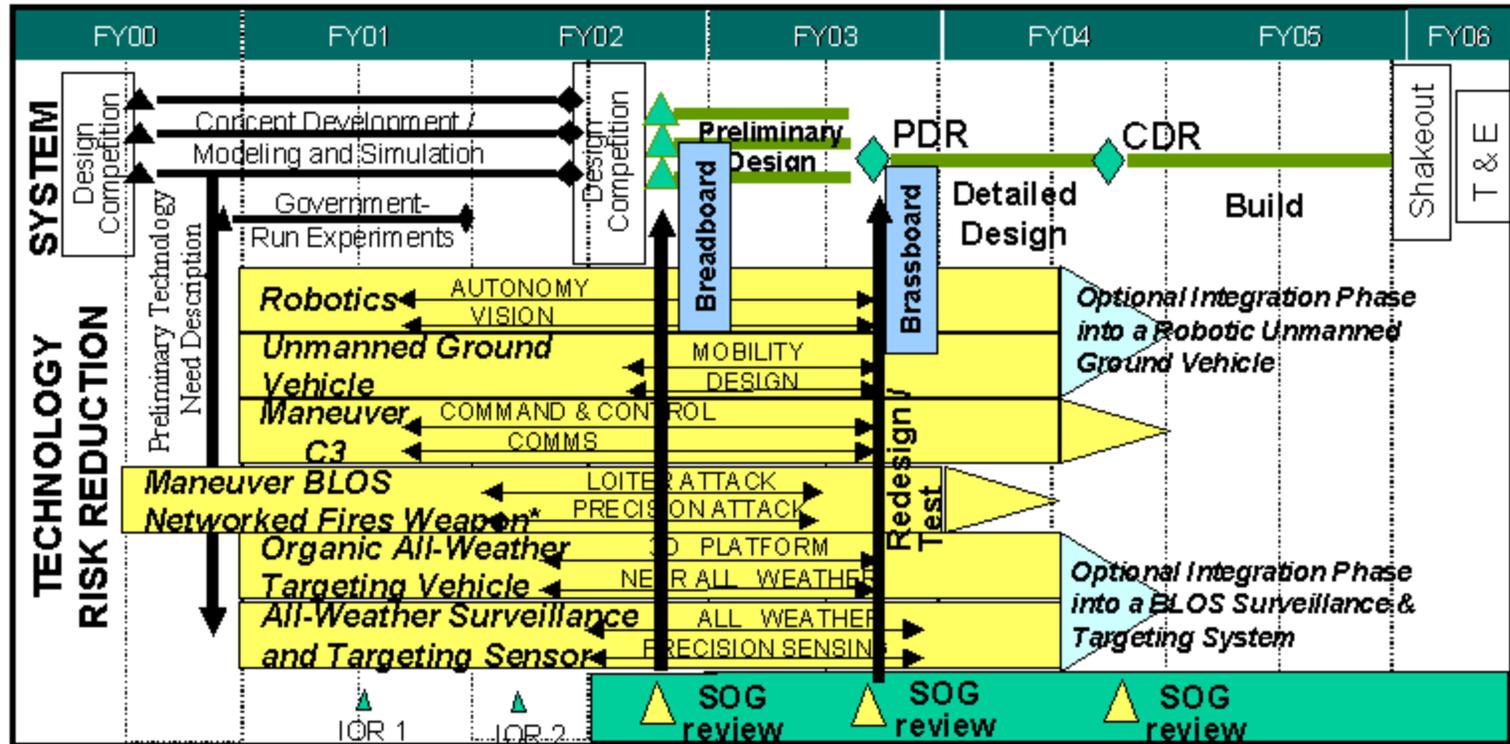


- Up to twenty sentry robots on preprogrammed patrols
- Interior and Exterior Programs for warehouses and outdoor storage sites
- Detect intruders, smoke, fire, flood, etc.
- Track tagged inventory
- Operators are real security guards
- Coordination by MRHA
- PM-PSE, GD-RS, SPAWAR



Systems Center  
San Diego

# Future Combat System (FCS)



- Comprehensive system including UGVs and UAVs
- “800 pound Gorilla?”
- DARPA/TTO BAA currently open

– <http://www.darpa.mil/tto/FGCSS/FGCSBAA.html>

**SPAWAR**



*Systems Center  
San Diego*

## Some Key Technologies and Issues

- **Communications and power**
  - Must leverage non-robotic developments
- **Perception and autonomy**
  - Recognized as core robotics technologies
- **Modularity and interoperability**
  - Provide major payoffs for the future
- **Integration and implementation**
  - Requires more than “best systems engineering practice”

**SPAWAR**



*Systems Center  
San Diego*

## **Technologies and Issues: Communications and Power**

- **Communications and power requirements of robotic systems parallel those of many other non-robotic applications**
- **Continuing development of these technologies is being pursued for many other military and commercial systems**
  - **Huge investments, compared to robotic budgets**
- **Robotic programs must leverage these other developments**
  - **Can not afford to develop this stuff on our own**
- **Also applies to some sensor and vehicle technologies**

**SPAWAR**



*Systems Center  
San Diego*

## **Technologies and Issues: Perception and Autonomy**

- **Human experience confuses “sensing” and “perception”**
- **Perception is DIFFICULT**
- **An incremental evolutionary approach (TMR):**
  - **Require only well-defined and bounded perceptual capabilities**
  - **Rely on operator monitoring and override capabilities to guarantee system performance**

**SPAWAR**



*Systems Center  
San Diego*

# Human Perception-based Navigational Capabilities

**Every human naturally acquires the skills to**

- avoid bumping into anything while moving
- understand where he or she is trying to go
- figure out how to get there

**Humans are therefore able to accept and execute tasking presented in terms like:**

**"Go down this road about a mile and turn left on Union Street --it's the second or third light, I think -- and then turn right into the alley just past the McDonald's; it's the second house on the left, the green one with an elm tree in front -- you can't miss it."**

**One key is that a human can detect, localize, classify, and identify specific environmental features:**

- under widely varying environmental conditions
- independent of relative orientation and distance

**But a robot's perceptual capabilities are extremely limited**

**Sensing is NOT necessarily perceiving**

**SPAWAR**



*Systems Center  
San Diego*

## **The Distinction Between Sensing and Perception**

**Robotics researchers, being human, are so completely immersed in the world created by our vision-oriented perception capabilities that we tend to mistake it for the actual physical world around us, and are therefore constantly surprised and disappointed by the comparatively pitiful capabilities of our robots' sensors.**

**Practical and affordable sensor systems simply do not provide enough accuracy or resolution to make up for a robot's lack of human-level perceptual processing.**

**SPAWAR**



*Systems Center  
San Diego*

# TMR Evolutionary Strategy for Achieving Autonomous Navigation

- **Supervised perception-based navigation commands**
- **Path-referenced navigational functions**
- **High-level mission-oriented autonomous tasks**
  - (Multiple coordinated robots)
  - Mapping and monitoring building interiors
  - Adaptive maintenance of communications connectivity
  - ...

**SPAWAR**



*Systems Center  
San Diego*

## Perception-Based Navigation Commands

- **Move Under <this> Vehicle**
- **Climb <how many> Flights Up <these> Stairs**
- **Climb <how many> Flights Down <these> Stairs**
- **Take <this> Elevator to the <number> Floor**
- **Cross <this> Street (and don't get hit)**
- **Hide in <this> Vegetation**
- **Move Along <this> Wall (until...)**
- **Open <this> Door (and Enter... and Close)**
- **Move in <this> Direction (until...)**
- **Wait until... (humans are (not) present...)**

**SPAWAR**



*Systems Center  
San Diego*

# Path-Referenced Navigation Capabilities

- **“Been There, Done That”**
  - Follow the leader (without interfering)
  - Route replay
  - Retrotraverse
  - “Go back to <this> previous location” (how to specify?)
- **Big operational payoff**
  - Tasking in terms of mission events
  - Classic “what do you mean you can’t...” stuff
- **DGPS Based --> Perception-Based**
- **System level capability, requires stored data**
  - Representation is key -- what level of abstraction?
  - Maximum leverage of limited perception capabilities

**SPAWAR**

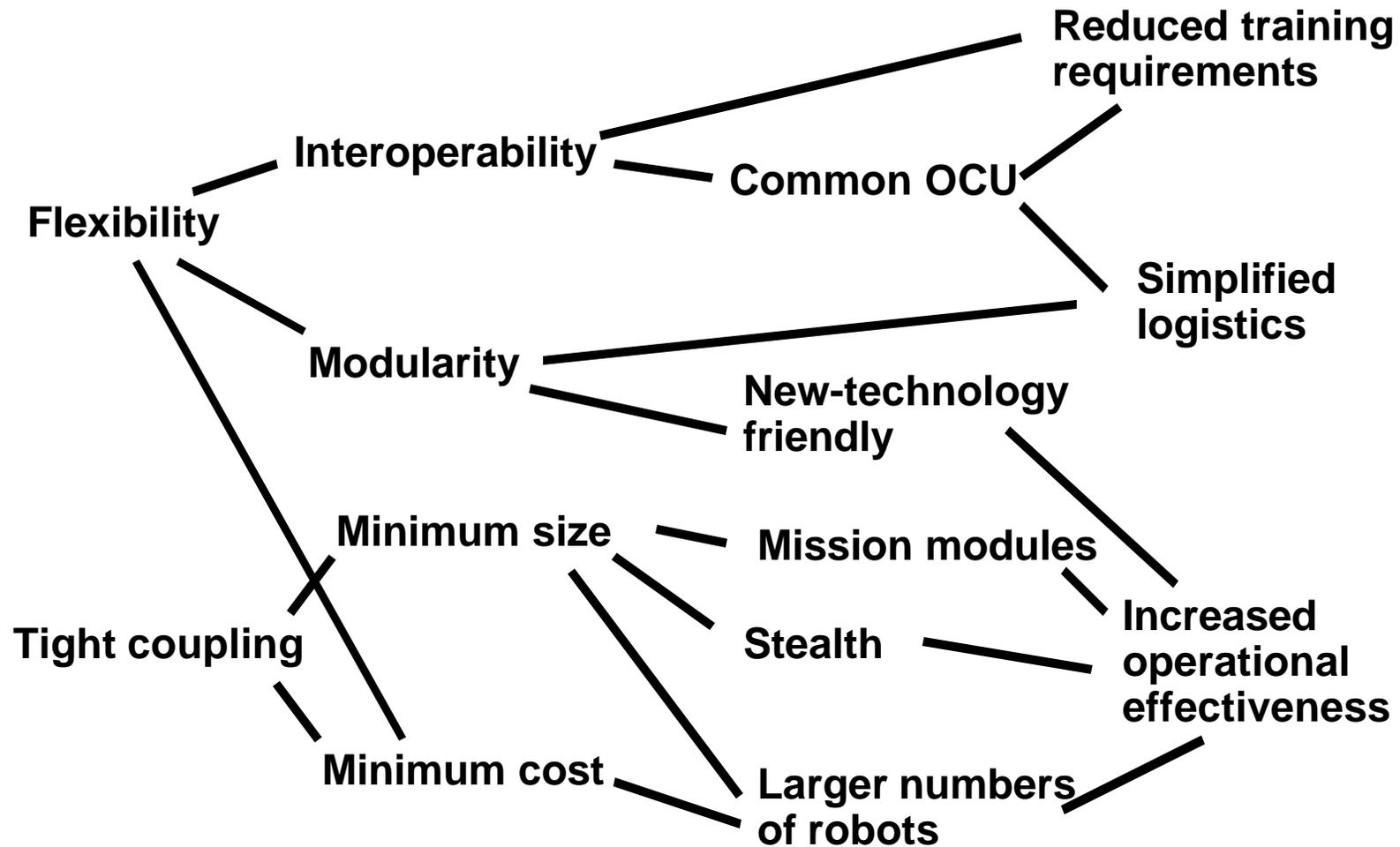


*Systems Center  
San Diego*

## **Technologies and Issues: Modularity and Interoperability**

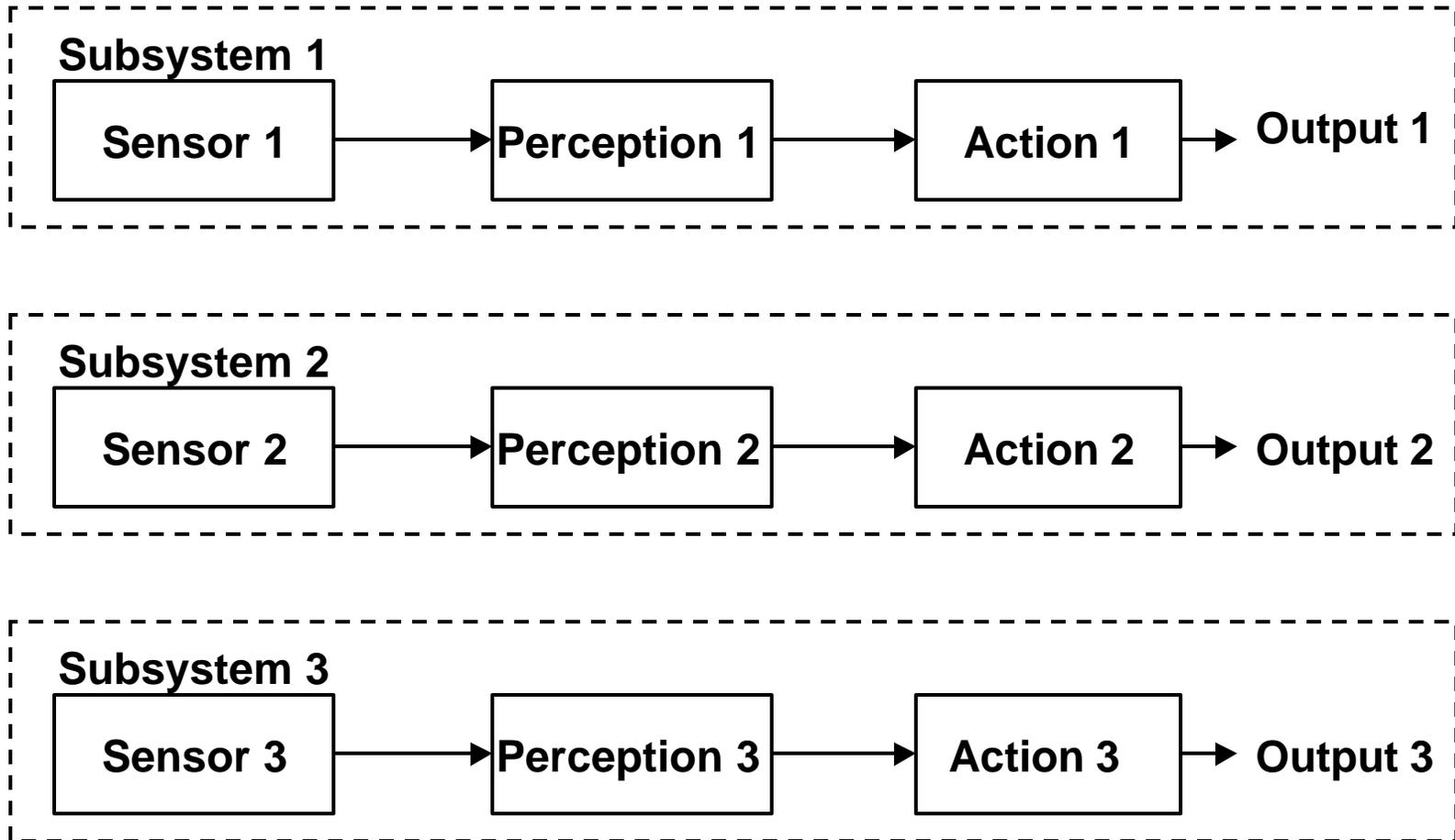
- **Tension between integration flexibility (modularity) and tight subsystem coupling**
- **Modularity minimizes needless duplication of sensor and processing resources**
- **Modularity improves sensor fusion for alarms and alerts**
- **Joint Architecture for Unmanned Ground Systems (JAUGS)**

# Integration Flexibility & Tight Subsystem Coupling Provide Operational Payoffs



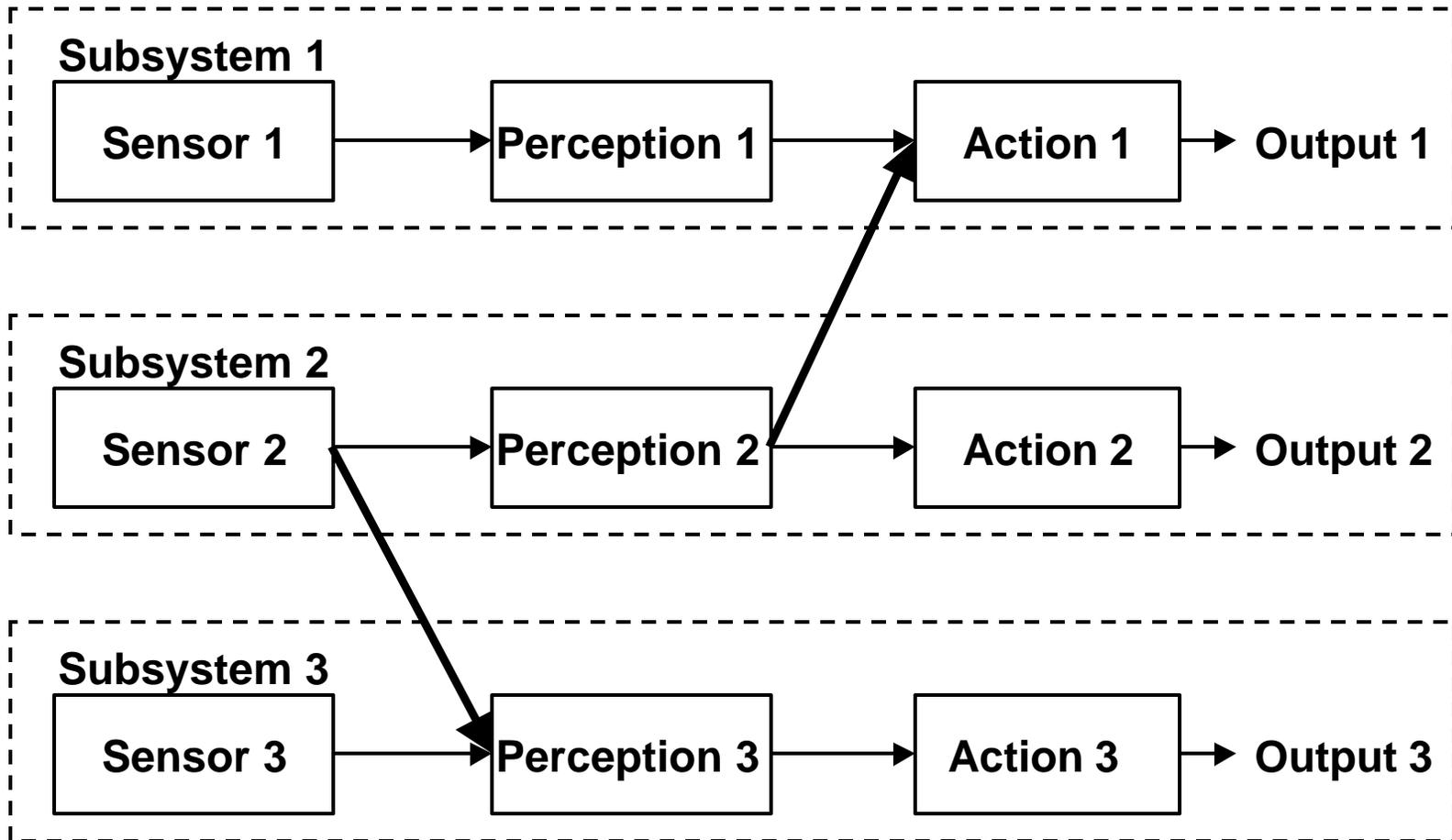


# Eliminate Duplication of Sensors and Processing





# Eliminate Duplication of Sensors and Processing

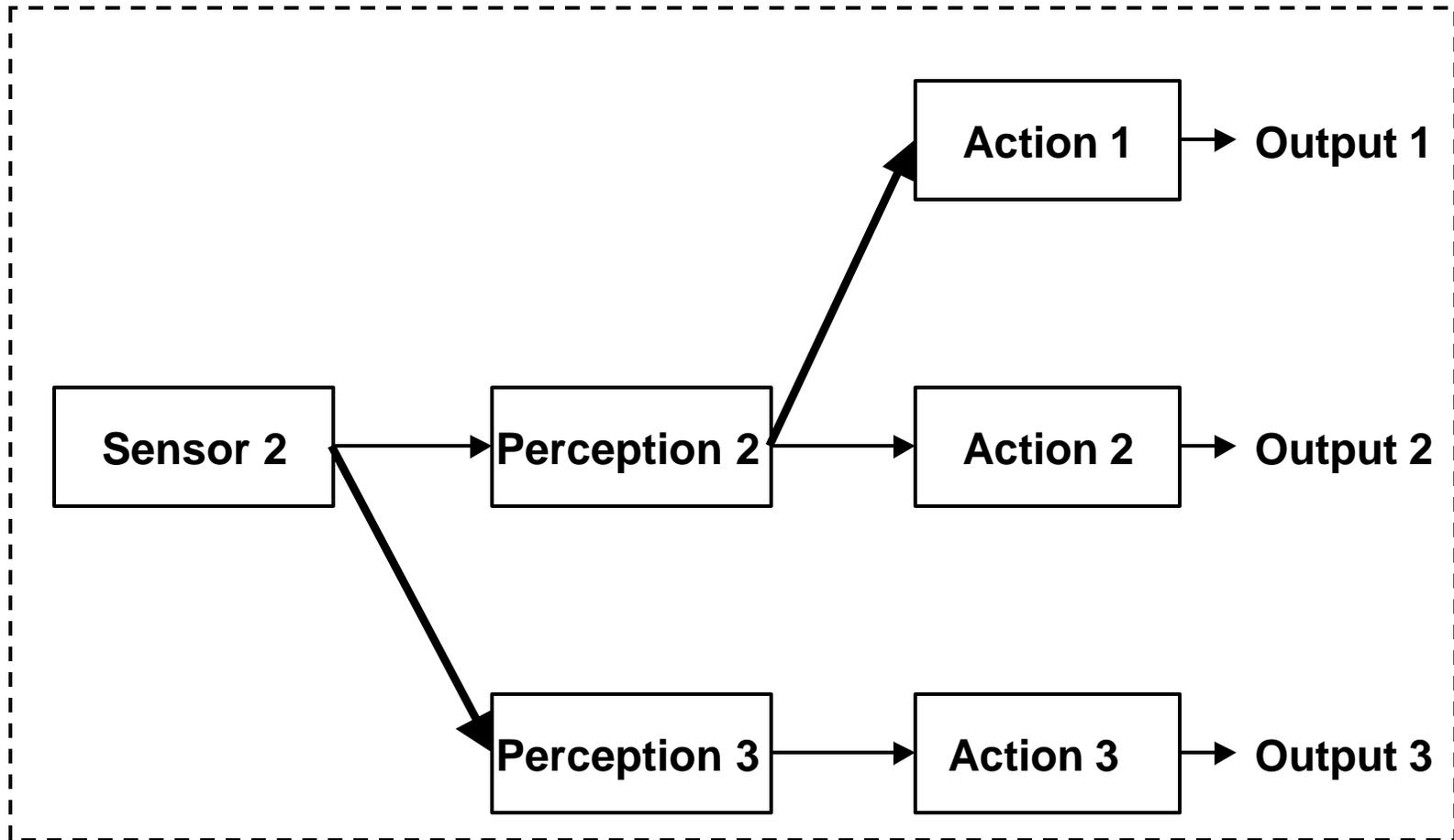


**SPAWAR**



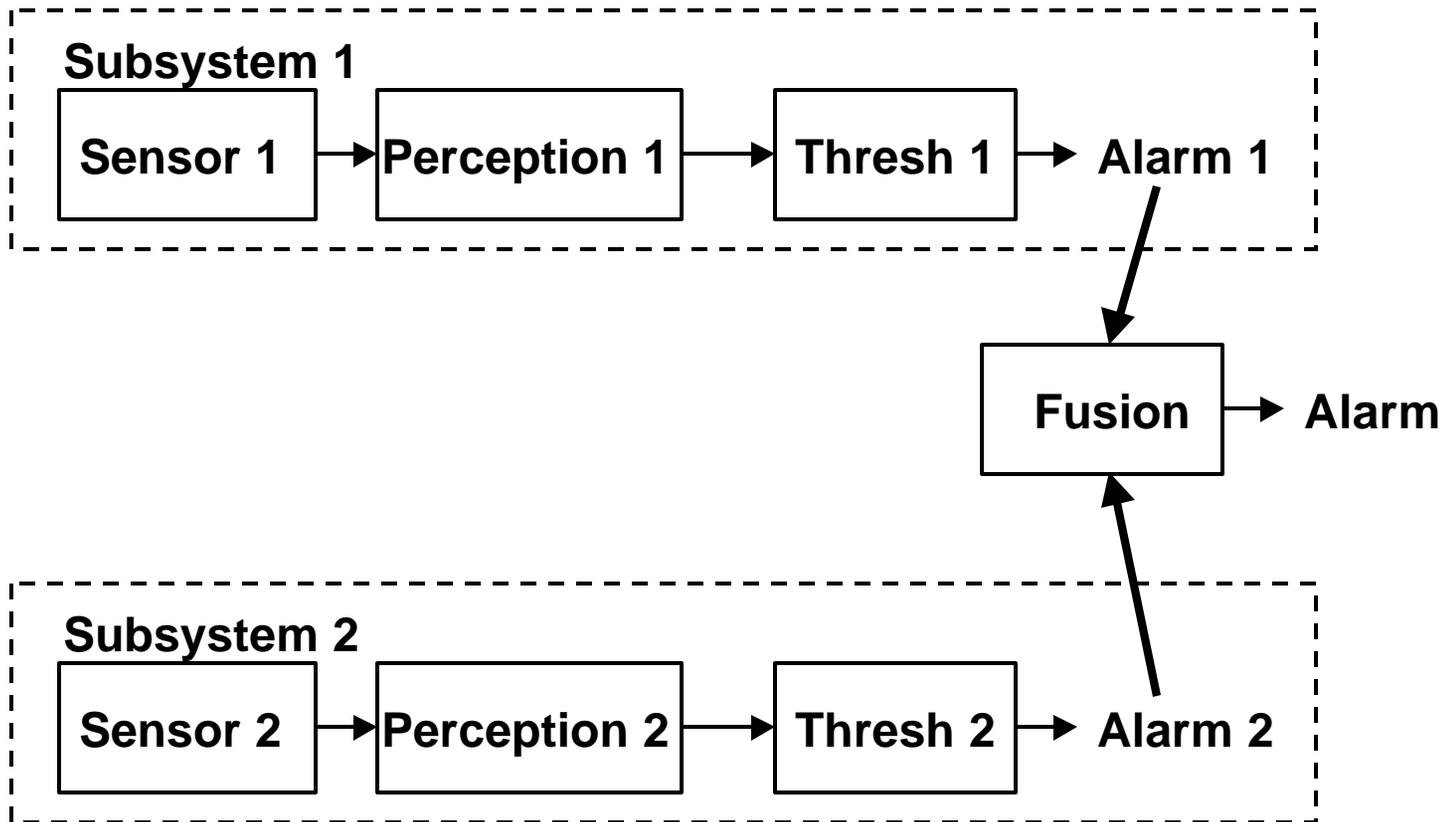
*Systems Center  
San Diego*

# Eliminate Duplication of Sensors and Processing

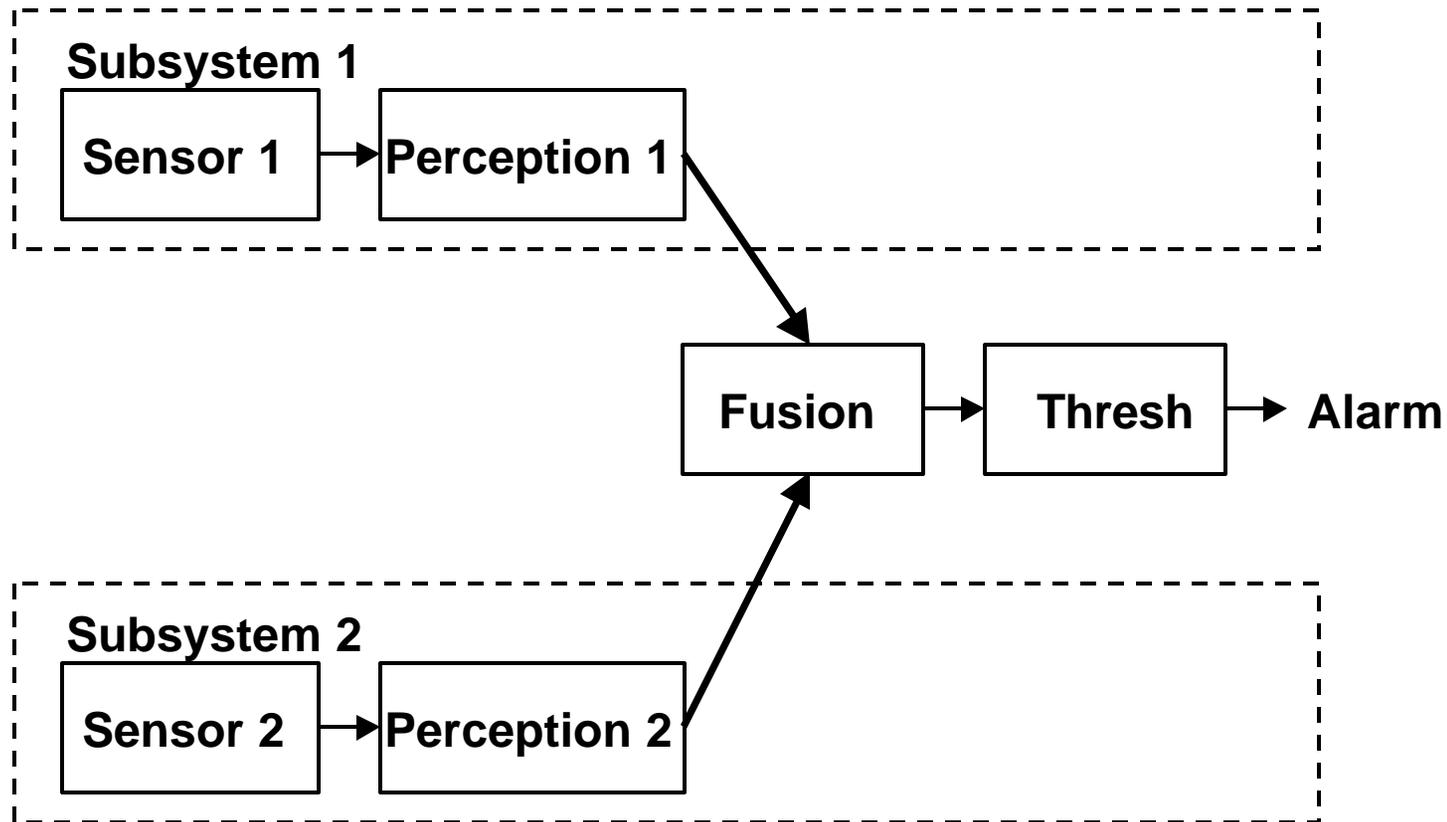




# Defer Alarm Thresholding to Improve Sensor Fusion



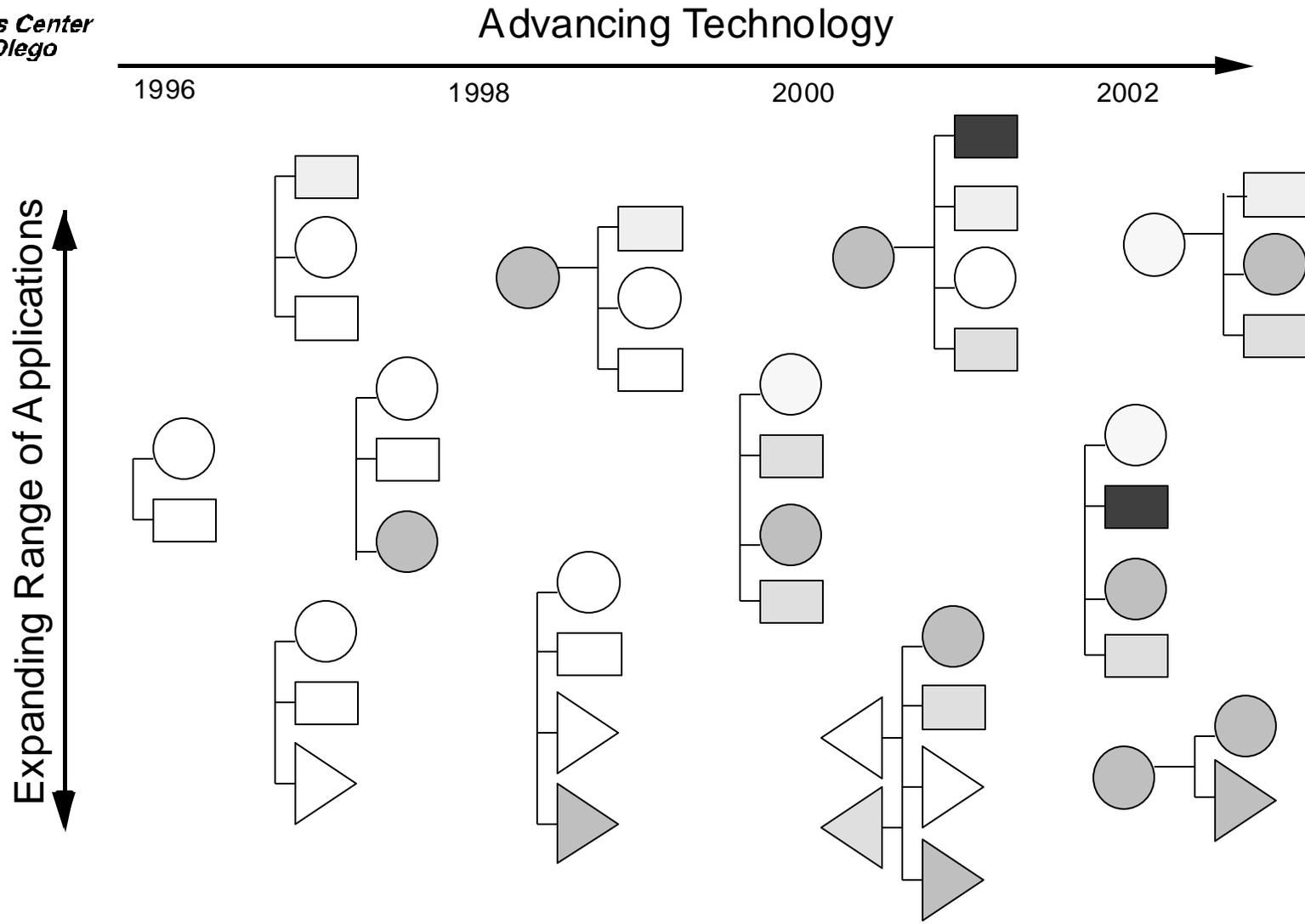
# Defer Alarm Thresholding to Improve Sensor Fusion





Systems Center  
San Diego

# Goal: An Evolving Family of Systems



**SPAWAR**



*Systems Center  
San Diego*

## **JAUGS: Joint Architecture for Unmanned Ground Systems**

- **OSD Initiative to ensure interoperability of future unmanned ground systems**
- **Use will be mandatory in all Joint Robotics Program systems**
- **Current “Domain Model” completely focused on remote driving of large UGVs**
  - TMR goal of human-level mobility (indoor, stairs, rubble, etc.) not incorporated
- **Lacks clear distinction between intravehicle and intervehicle integration**
- **see <http://www.jointrobotics.com/Jaugs/>**

**SPAWAR**



*Systems Center  
San Diego*

# Technologies and Issues: Integration and Implementation

- **Developing a robotic a system requires MUCH more than simply using “best systems engineering practice”**
  - Think: airplane design in 1902

**SPAWAR**



*Systems Center  
San Diego*

# General Lessons Learned From MDARS-I (1)

Moving a robot from one environment to another invites unanticipated problems; typical causes include:

- hardware and software errors that haven't been manifested in the previous environment
- sensor modes or processing algorithms tuned too tightly to specific characteristics of the initial development environment
- unexpected breakdowns due to subtle interactions between multiple hardware and software components

A well implemented adaptive behavior can mask faults; should instrument behavior to report a problem such as steering that constantly "pulls left"

**SPAWAR**



*Systems Center  
San Diego*

## **General Lessons Learned From MDARS-I (2)**

**If a complex robot is to operate robustly, its world model must take adequate account of the relevant dimensions of variability of the environment, as they will be reported by the sensor subsystems.**

- **A robot's world model is much simpler than a human's**
- **Unintended aspects of the model can creep in as consequences of various software design decisions**
- **The developer must understand the limits of his system's world model**

**Behavioral robustness is required if mobile robots are to find viable markets; the designer must accommodate the full range of variability within:**

- **manufacturing processes: no handcrafting**
- **target operating environments: no manual "tuning"**

**SPAWAR**



*Systems Center  
San Diego*

## General Lessons Learned From MDARS-I (3)



**Expect the unexpected!**

**SPAWAR**



*Systems Center  
San Diego*

# 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**

**SPAWAR**



*Systems Center  
San Diego*

## 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

**SPAWAR**



*Systems Center  
San Diego*

# Conclusions

- **DoD is actively pursuing the development of ground robotic vehicles**
  - To address a variety of applications with varying requirements
  - Possessing varying degrees of (supervised) autonomy
  - FCS may assume a dominant role in the next couple of years
- **Key technical issues remain**
  - Communications and power (leverage work of others)
  - Perception and autonomy (core robotic technologies)
  - Modularity and interoperability (carry important benefits)
  - Integration and implementation (difficulties abound)
- **This presentation will be available online at:**
  - <http://www.spawar.navy.mil/robots/pubs/demine00.pdf>