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

SPAWAR Systems Center, San Diego
San Diego CA 92152-7383

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
MAR 2000	**N/A**	**-**

4. TITLE AND SUBTITLE
Current Thrusts in Ground Robotics: Programs, Systems, Technologies, Issues

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Space and Naval Warfare Systems Center San Diego, CA 92152-7383

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

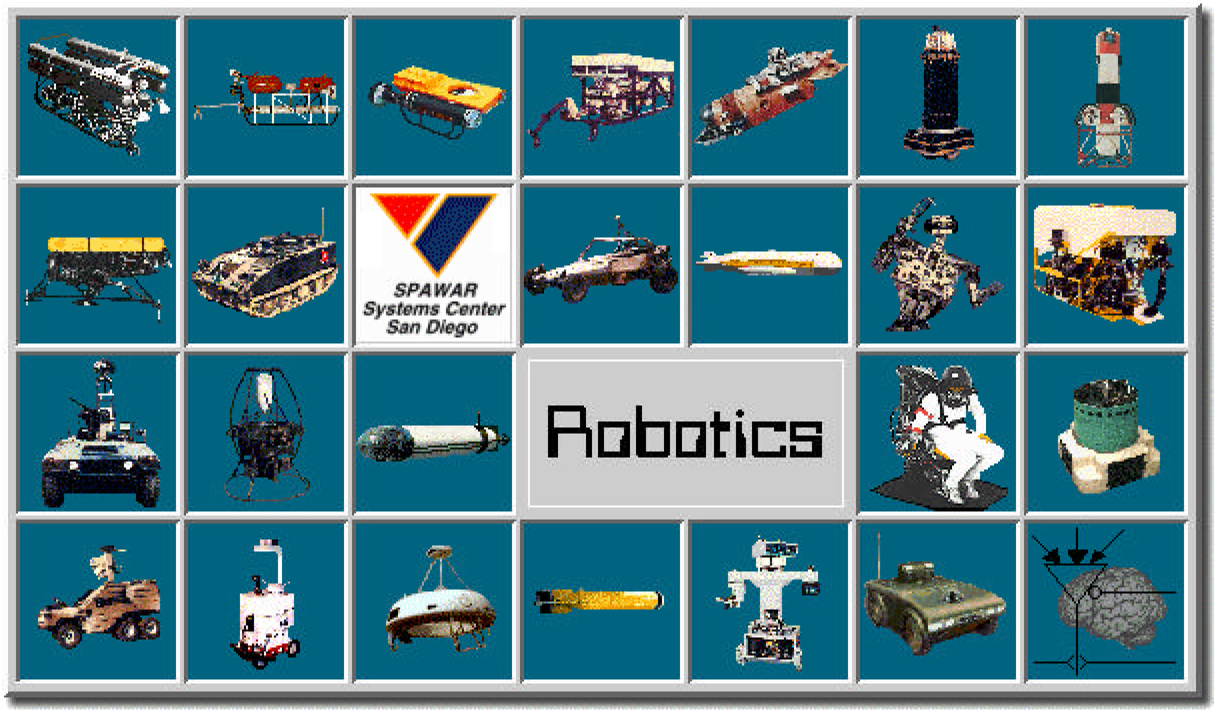
14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**42**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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
San Diego CA 92152-7383

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**

Tactical Mobile Robotics (TMR)

- DARPA Advanced Technologies Office (ATO)
- Initiated by Dr. Eric Krotkov in 1997
- Program Manager is LTC John Blitch
- 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. Blitch, “The DARPA Tactical Mobile Robotics Program”, The International Journal of Robotics Research, Vol. 18, No. 7, July 1999, pp. 769-776.

The Technical Goal of TMR

Development of a <u>system</u> of robots capable of

<u>operator-tasked and -monitored</u>

<u>perception-based</u>

<u>autonomous</u> <u>mobility</u>

in <u>diverse unstructured environments</u>

that can <u>fit into a rucksack</u>

and be employed in <u>coordinated groups</u>

as a <u>tool</u> for the <u>dismounted warfighter</u>

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**

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)

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

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

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 Excercises (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” :-)**

Systems Center San Diego

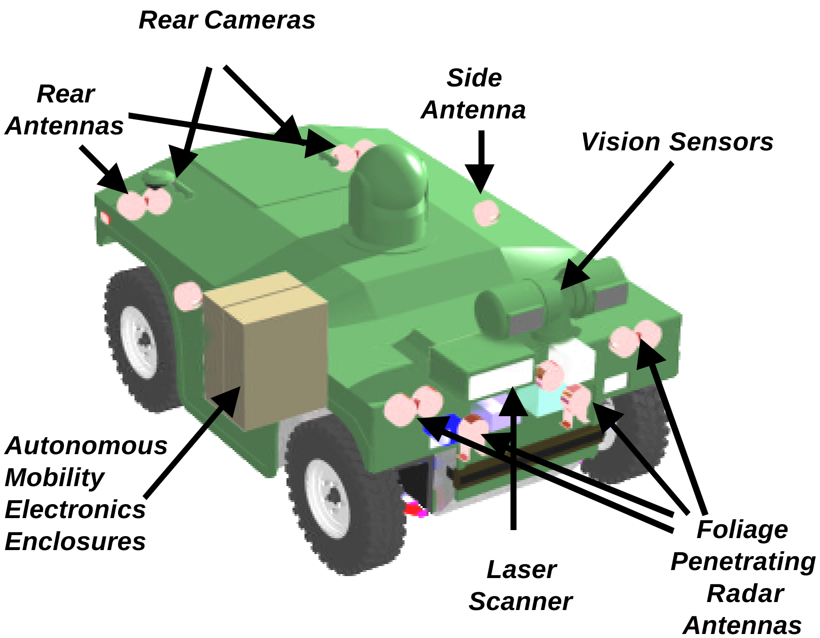
MPRS Tunnel Robot: Key Features

- **Completely invertible (no preference)**
  - **Top- and bottom-mounted driving cameras show front of vehicle in image**
- **COTS camcorder camera module**
  - **On tilt platform =/- 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**

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

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)

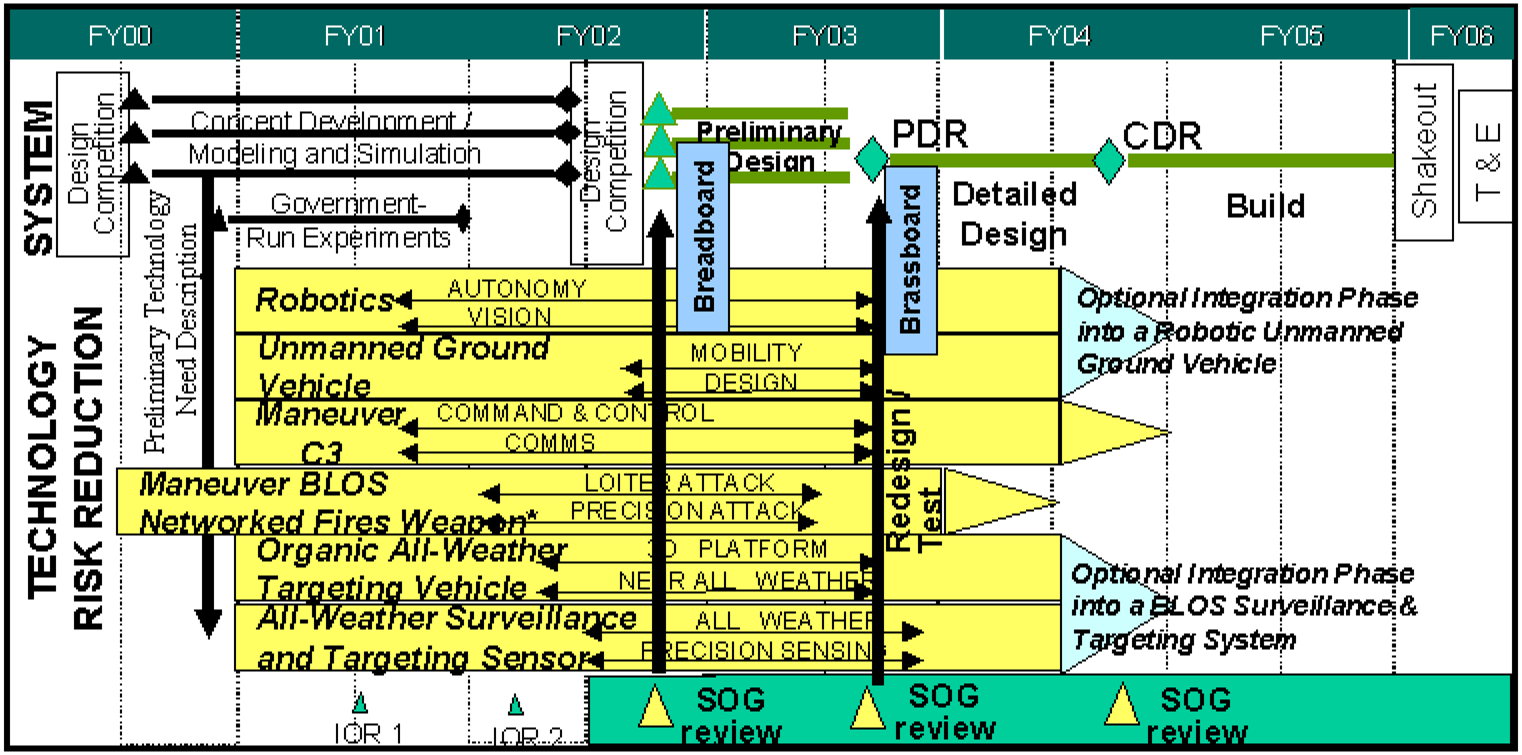
- Up to twenty sentry robots on preprogrammed patrols
- Interior and Exterior Programs for warehouses and outdoor storage sites
- Detect intruders, smoke, fire, flood, etc.
- Track tagged inventory
- Operators are real security guards
- Coordination by MRHA
- PM-PSE, GD-RS, SPAWAR

SPAWAR Systems Center, San Diego
San Diego CA 92152-7383

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"**

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

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**

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 <u>specific</u> environmental features:

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

But a <u>robot's</u> perceptual capabilities are extremely limited

<u>Sensing</u> is NOT necessarily <u>perceiving</u>

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**
  - **...**

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

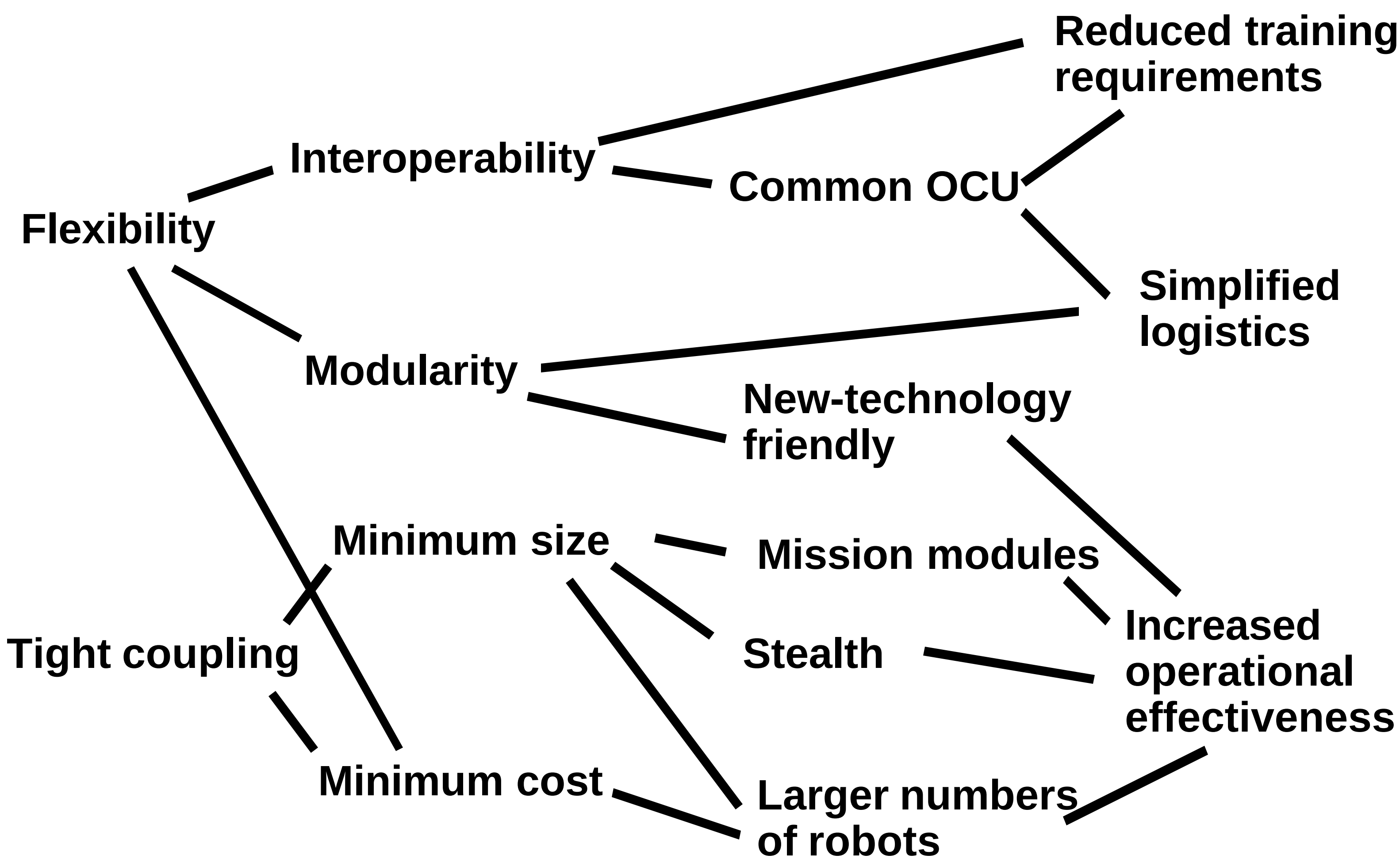
Path-Referenced Navigation Capabilities

- "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

Technologies and Issues: Modularity and Interoperability

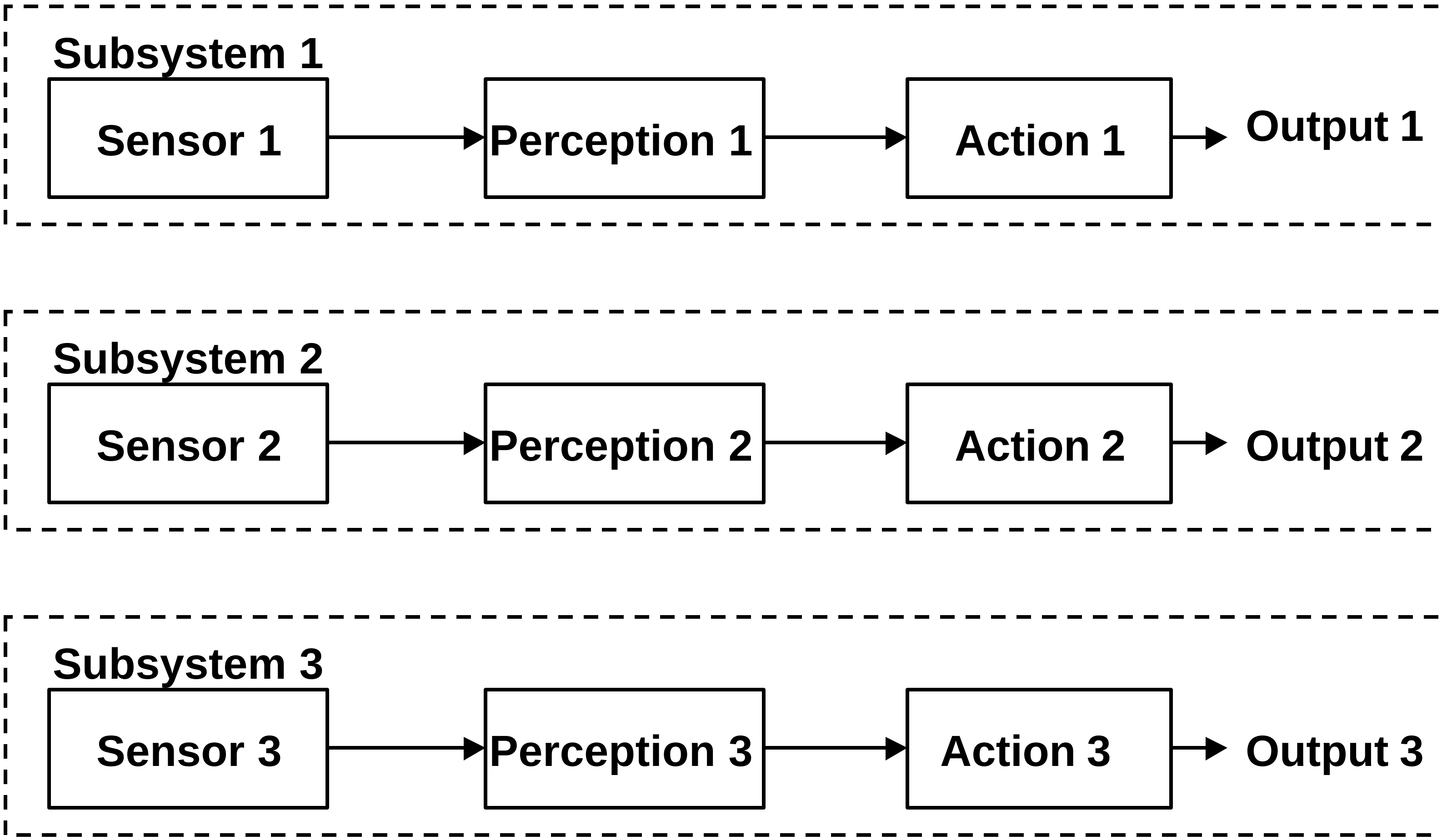
- **Tension between integration flexibility (modularity) and tight subsystem coupling**
- **Modularity minimizes needless duplication of sensor and processing resources**
- **Modularity improves sensor fusion for alarms and alerts**
- **Joint Architecture for Unmanned Ground Systems (JAUGS)**

Integration Flexibility & Tight Subsystem Coupling Provide Operational Payoffs

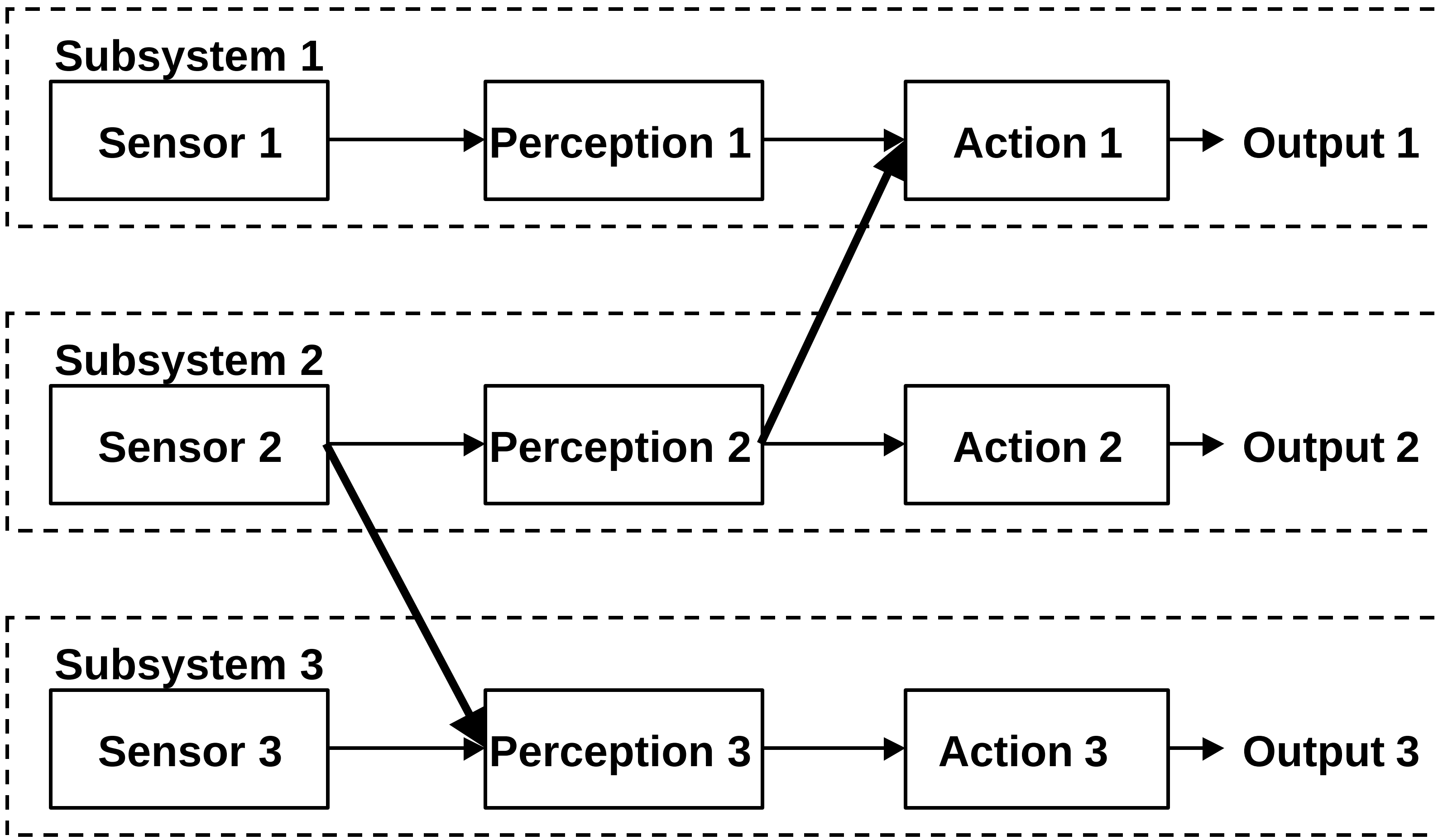


SPAWAR Systems Center, San Diego
San Diego CA 92152-7383

Eliminate Duplication of Sensors and Processing

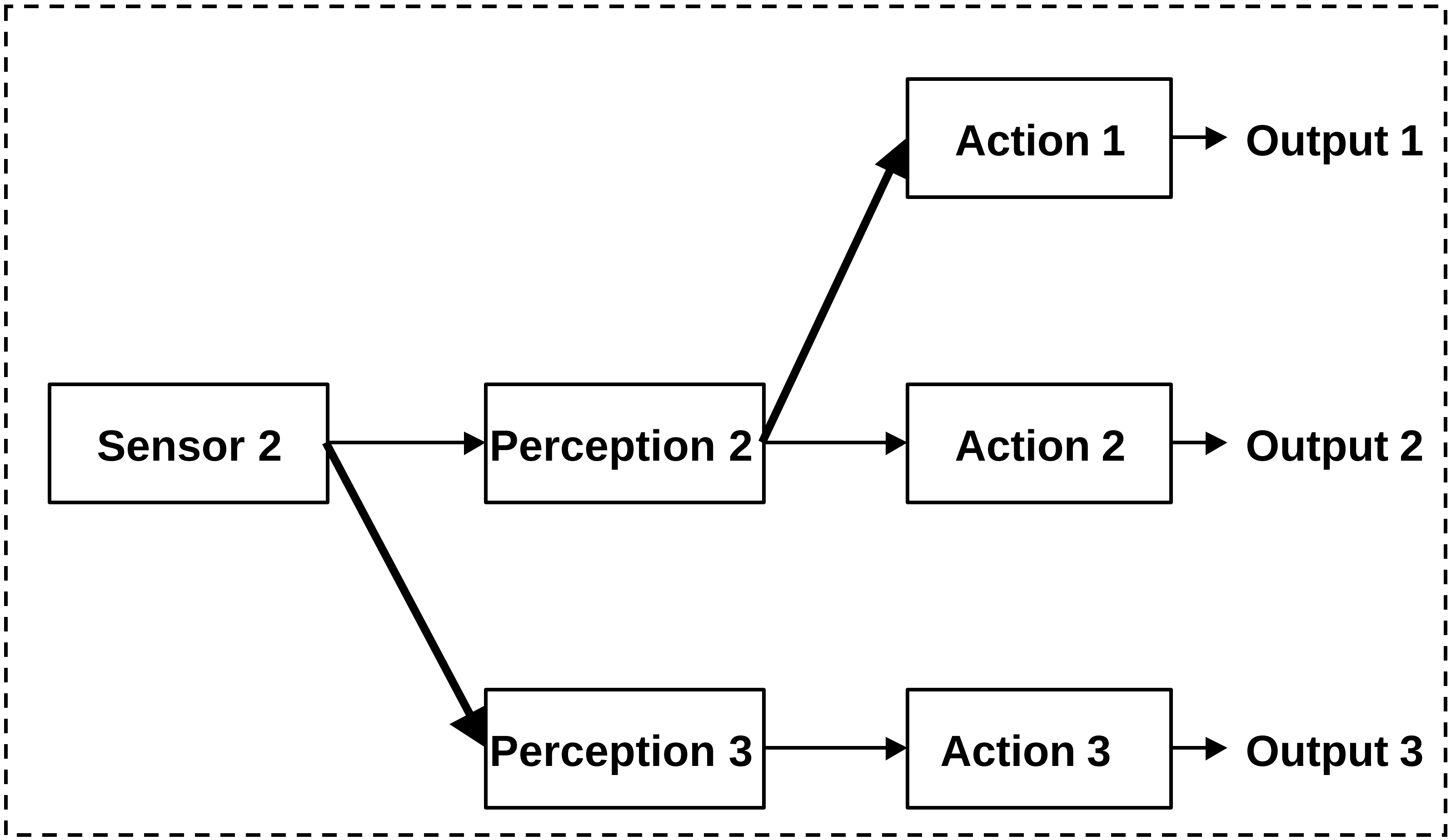


Eliminate Duplication of Sensors and Processing

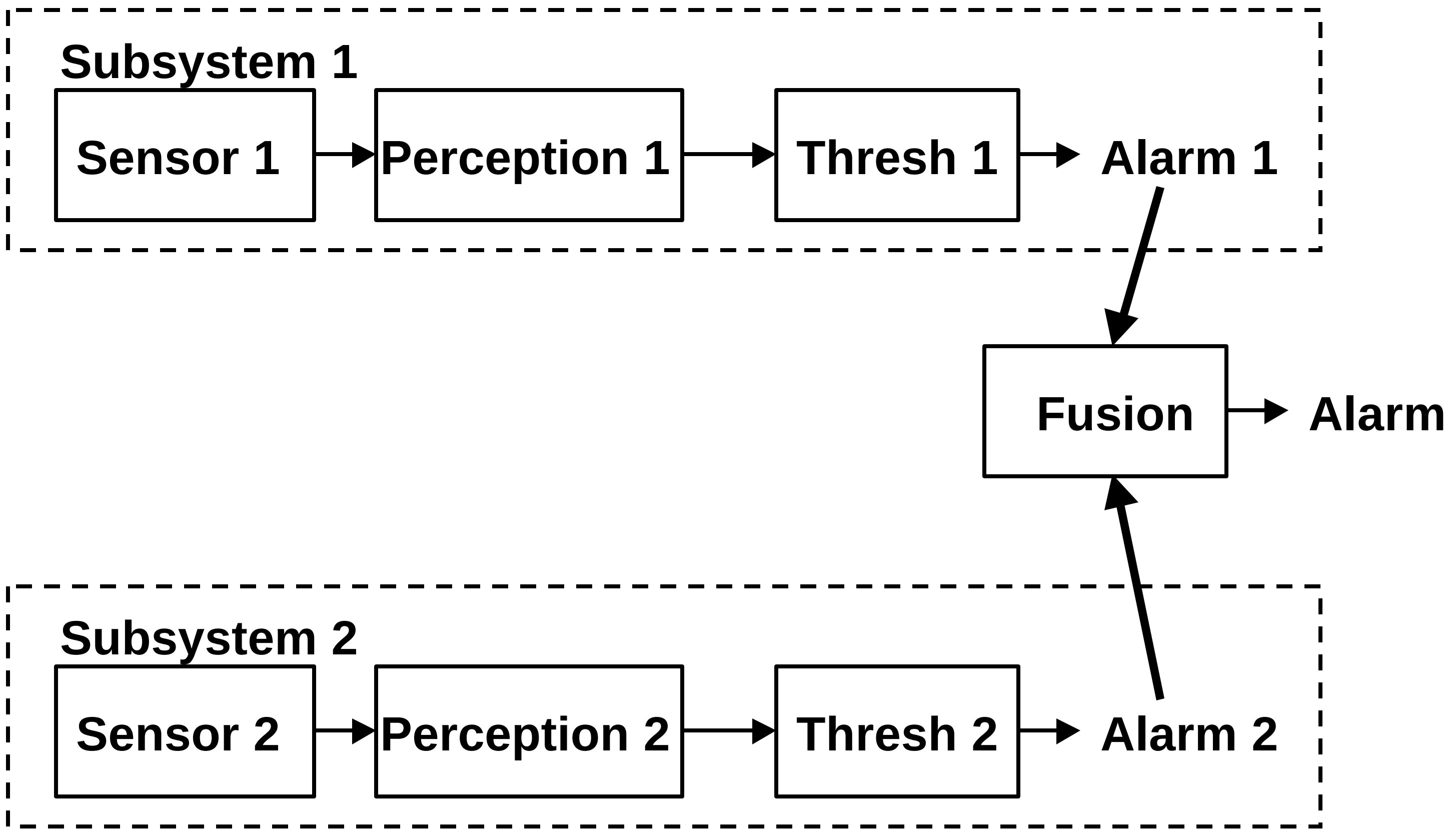


SPAWAR Systems Center, San Diego
San Diego CA 92152-7383

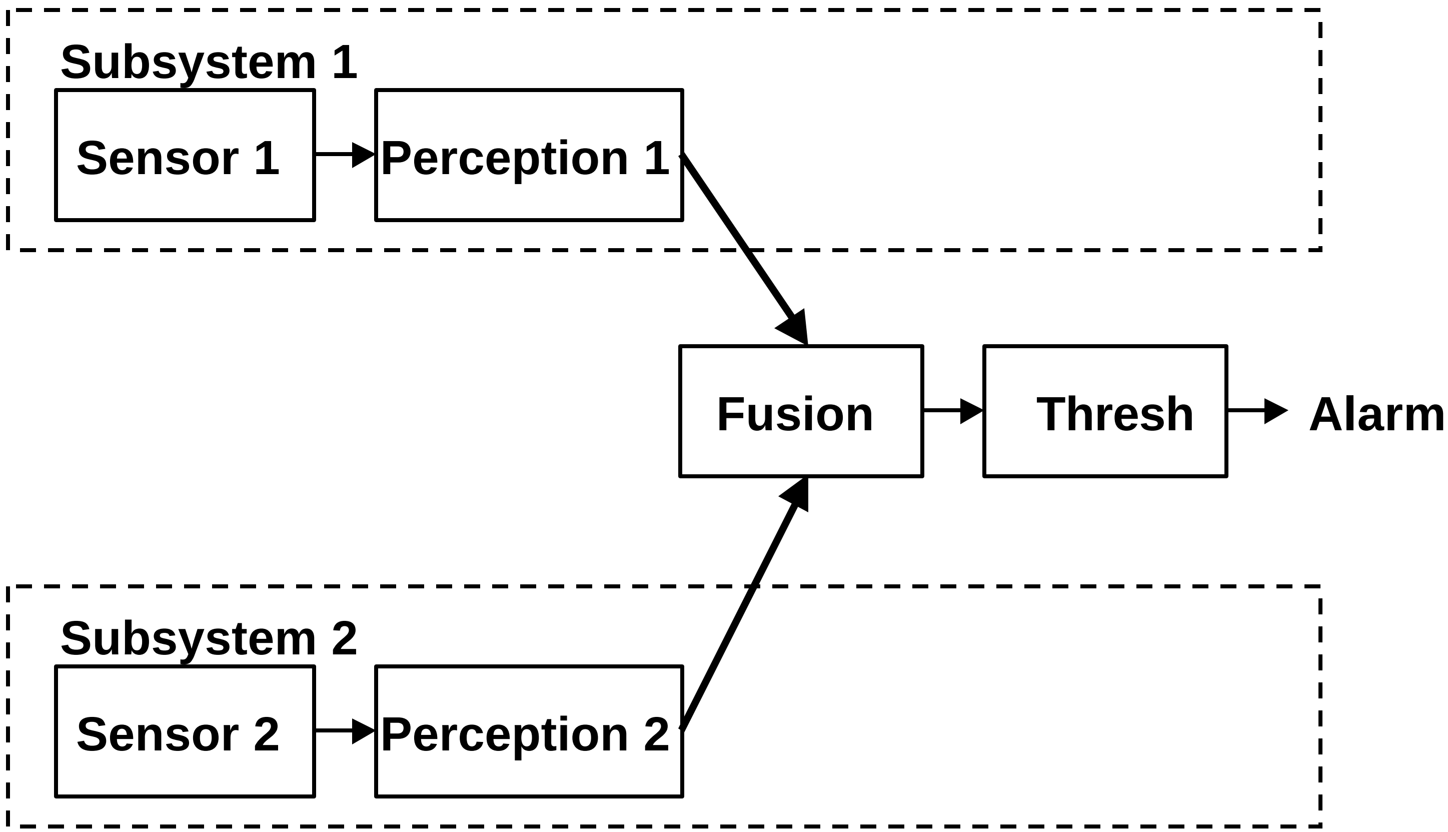
Eliminate Duplication of Sensors and Processing



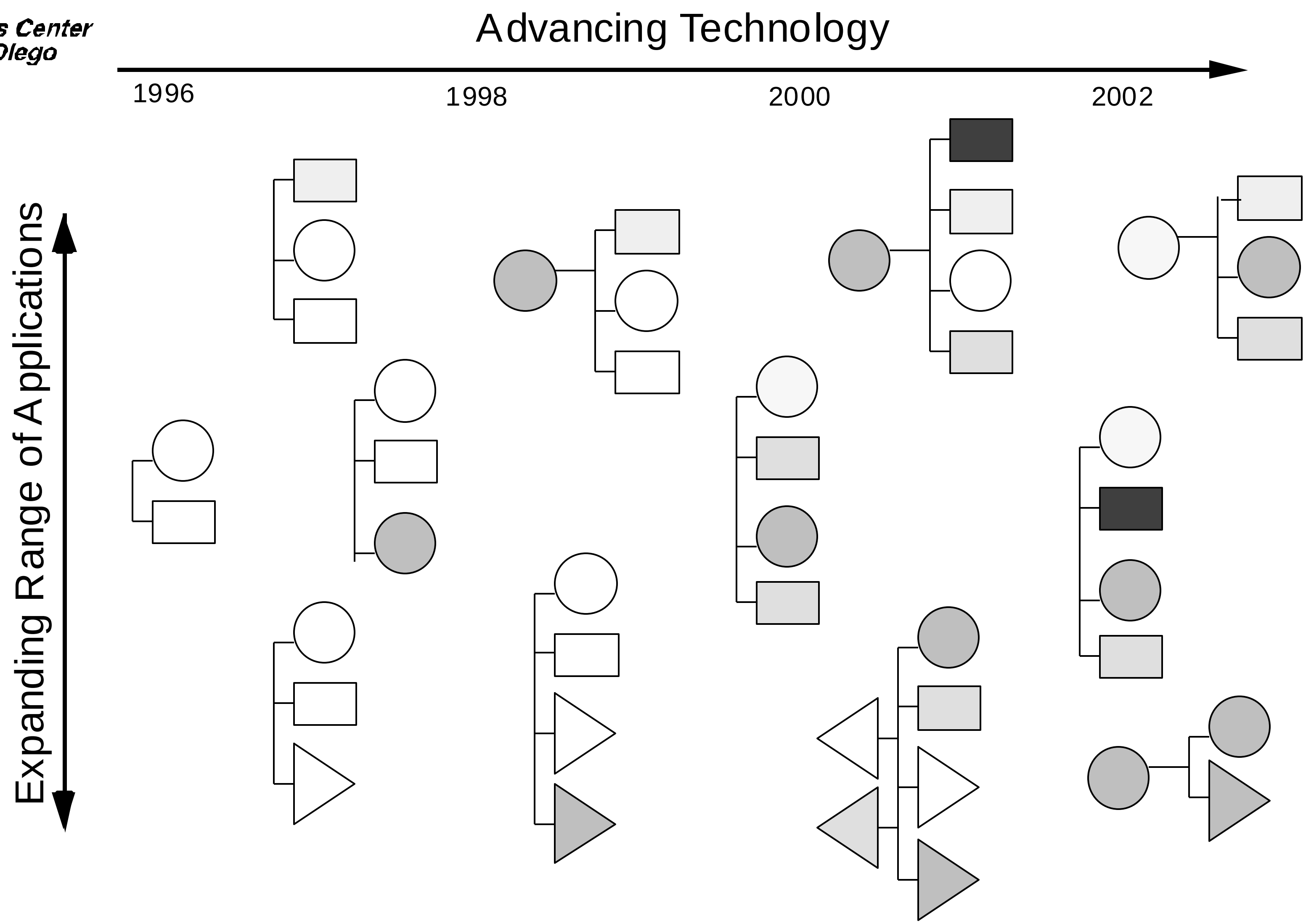
Defer Alarm Thresholding to Improve Sensor Fusion



Defer Alarm Thresholding to Improve Sensor Fusion



Goal: An Evolving Family of Systems



SPAWAR Systems Center, San Diego
San Diego CA 92152-7383

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 <u>intra</u>vehicle and <u>inter</u>vehicle integration
- see http://www.jointrobotics.com/Jaugs/

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**

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"

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 <u>much</u> 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"**

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

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**

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