Air Force Science & Technology
Issues & Opportunities Regarding
High Performance Embedded Computing

23 September 2009

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Air Force Research Laboratory
Information Directorate
The mission of the United States Air Force is to fly, fight and win... in Air, Space and Cyberspace.
AFRL Mission

Leading the discovery, development, and integration of affordable warfighting technologies for our air, space and cyberspace force.

It’s not just about the science…
…it’s about leadership in S&T
Challenges by Domain

• Air: Persistant air dominance is at risk
  – Increasingly effective air defenses
  – Proliferation of 5th gen fighters, cheap cruise missiles, and UASs
  – Light-speed war possibilities are terrifying

• Space: Now a contested domain
  – Increasingly important
  – Increasingly vulnerable

• Cyber: Cyber warfare has begun
  – We don’t control the battlespace
  – We rely on it more and more
  – We can’t find the enemy
Opportunities – Air: Across the Technology Spectrum

• **Endurance** – Efficient aerodynamics, efficient propulsion, lightweight structures
• **Alternative Fuels** – Fischer-Tropsch, biomass, carbon sequestration
• **Sensors** – 360 degree coverage, structural load-bearing antennas
• **Speed** – Hypersonics, thermal, flight controls, maneuverability, payloads
• **Thermal Management** – Produce less heat, tolerate more heat, dissipate more efficiently, convert more effectively
• **Modeling & Simulation** – Virtual prototyping, live-virtual-constructive environments
• **Manufacturing Technology** – Lean, diagnostics, just-in-time production
• **UASs** – Swarming, semi-autonomous then autonomous, learning, healing
• **Micro Air Vehicles** – Sensor miniaturization, flight agility, autonomy
• **Integrated Systems Health Management** – Self-reporting systems, autonomous reconfiguration to maintain mission capability
• **Responsive** to needs of sister services, needs of the Nation
Opportunities – Air: “We Can Control the Vertical”

- **C²ISR (High-to-Medium Altitudes)**
  - Endurance
    - Aerodynamics
    - Propulsion
  - Layered Sensing
    - Sensors
    - Processing & Integration

- **ATTACK (Medium Altitudes)**
  - Swarming Brains (UAVs)
    - Programming & Processing

- **URBAN & SOLIC (Low Altitudes)**
  - Maneuverability
    - Morphing structures, bio-mimetics
  - Miniaturization
    - Micro- & Nano-
  - Autonomy
    - Sensors
    - Game Theory & Processing
Opportunities – Space: SSA & ORS

• **Space Situational Awareness**
  - High resolution imaging
  - Electro-optical phenomenology
  - Advanced astrodynamics
  - Modeling and decision aids

• **Operationally Responsive Space**
  - Plug ‘n’ Play Satellites
  - Small vs Large Satellites
  - Quick Launch
  - Fast On-Orbit Checkout
• Must be able to take a series of punches, jabs, feints...and survive!
• “Fight through the Attack!”
  – Endure...mitigate...recover... reconstitute...get up...move forward!
• Move beyond “One Air Force – One Network” to “Defending the Nation”
• Evolve to a polymorphic system of systems that naturally favors:
  – Stability
  – Security
  – Cyber-Sensing
  – Partitionable
  – Rapid Reconstitution
  – Focus on Protecting & Delivering Data
Ten Technical Directorates

- Directed Energy
- Space Vehicles
- Human Effectiveness
- Sensors
- Munitions
- Propulsion
- Information
- AFOSR
- Materials & Manufacturing
- Air Vehicles
Major AFRL Facilities

AFRL HQ

40 Sites World-Wide
Focused Long Term Challenges and Discovery

FLTC #1  Anticipatory Command, Control & Intelligence (C2I)
FLTC #2  Unprecedented Proactive Intelligence, Surveillance and Reconnaissance (ISR)
FLTC #3  Dominant Difficult Surface Target Engagement/Defeat
FLTC #4  Persistent & Responsive Precision Engagement
FLTC #5  Assured Operations in High Threat Environments
FLTC #6  Dominant Offensive Cyber Engagement
FLTC #7  On-demand Force Projection, Anywhere
FLTC #8  Affordable Mission Generation & Sustainment
Discovery  Questions the Air Force doesn’t even know to ask
Rapid Reaction Solution for Brownout

PhLASH - Photographic Landing Augmentation System for Helicopters

Problem

• Helicopter landings at arid sites stir up blinding dust clouds (Brown-out)

Solution

• High resolution image of the landing zone and fly into the image

Technologies

• High Resolution Near-IR flash photography
• Advanced Image processing / reconstruction based on GPS location

9 months from Idea to Demo
Micro Air Vehicle Development

• Built many mission specific development designs
  • Bomb Damage Information sensing, chem/bio sensing, terminal guidance improvements, weaponization, and general R&D activities for both AFRL and other government agencies
  • Optimized Tandem wing design
  • Air launch and dismount tube launch
  • Pictures show the family of AFRL MAVs from 2003 to present
Bio-Inspired Micro Air Vehicles

- Characterize aeromechanics and scalability of bat flight
- Bat wing motion has many Degrees of Freedom, unlike insects/birds
- Highly flexible wing structure & membrane
- Arrays of raised hair sensors-actuators that may provide flow sensing & influence flight control
- Active vision control (fly eye) for imaging, tracking and guidance

2015 Goal: Bird-Sized MAV  
2030 Goal: Insect-Sized MAV
Multi-Layer Sensing

Global Access
“Episodic” - Synoptic

Architectural Tenets
- Layered Sensing
- “air deliverable” Lower Tier
- integrates phenomenological diversity
- regional perspective with up-close detail
- intrinsically integrates into “Ground Ops”

Regional, Persistent,
High Altitude Surveillance

“Cordonning” Surveillance
Continuous “Forensics”

UGS
Foliage
Urban
Mountains & Caves
AFRL Staring Sensor Technology

Day (AngelFire)

IR (Night Stare)

Multispectral (SPIRITT) Sensor

Radar
All Weather

Video SAR (Gotcha)

IRAQ

Area B

Area B
Synthetic Aperture LADAR (SAL)

- Image resolution of current systems limited by size of physical aperture
- Synthetic and sparse aperture methods provide resolution better than allowed by the aperture and the atmosphere

- Single SAL beam ideal for high resolution imaging

Synthetic Aperture LADAR for Tactical Imaging (SALTI)
- Demonstrated world’s first airborne synthetic aperture LADAR
- ACC Commissioned Advanced Technology Demonstration (ATD)
COUNTER: Cooperative Operations in Urban Terrain

- Automated control system for multiple UASs
  - Allocate Resources
  - Route Vehicles
  - Avoid no-fly zones
  - Respond to alarms

- Data collection interface for ISR
  - Steer sensors
  - Fuse Information

Yuma Flight Test – Nov 08
(4 Vehicles – 2 Zaggi’s, 1 Bat-III, 1 Acturus T-16)
Operationally Responsive Space

- Apply operational aircraft concepts to space systems
  - Tailored mission capabilities
  - Rapid Build-Up/Turn times
  - Air Tasking Order responsiveness
  - Satellite buses with plug-and-play payloads
  - Sustained high operations tempo
Software Defined Command Center is a synthesis of hardware, software and conceptual approaches with potential application to multiple command centers in the Air Force.
### SensorCraft
Future High Altitude Long Endurance ISR Platform

**Global Hawk** | **Next Generation System**
---|---
24+ Hours of endurance | Highly fuel efficient, 40-50 hours of endurance
Single Band (X) Air to Ground sensing payload | Dual Band (UHF and X), Air to Air and Air to Ground sensing for small and hidden targets
Side looking | 360 degree coverage
Raw data to Mission Control Element | Fused data to user
Conventional antennas, radomes | Large, embedded structural arrays
Conventional wings, 139 ft | Flexible active wings, 200+ ft
The Cell Cluster has a peak performance of 51.5 Teraflops from 336 PS3s and additional 1.4 TF from the headnodes on its 14 subclusters.

Cost: $361K ($257K from HPCMP)
  - PS3s 37% of cost

Price Performance: 147 TFLOPS/$M

The 24 PS3s in aggregate contain 6 GB of memory and 960 GB of disk. The dual quad-core Xeon headnodes have 32 GB of DRAM and 4 TB of disk each.
This project provides the HPCMP community with early access to HPC scale commodity multicore through a 336 node cluster of PS3 gaming consoles (53 TF).

Applications leveraging the >10X price-performance advantage include:

- large scale simulations of neuromorphic computing models
- GOTCHA radar video SAR for wide area persistent surveillance
- Real-time PCID image enhancement for space situational awareness

Dr. Richard Linderman, AFRL/RI, Rome, NY

... but beginning to perceive that the handcuffs were not for me and that the military had so far got...

Neuromorphic example:
Robust recognition of occluded text

Gotcha SAR

PCID Image Enhancement

Solving the hard problems . . .
An Integrated Framework for Visual Cognition

Cogent Confabulation
Context Recognition & Prediction

BSB Neural Networks
Object Recognition

Visual Front End
Object/Feature Extraction

Visual Signal Receivers

Concept-level learning, recognition and prediction
Recognition based on raw visual data
Extract important visual objects and features
...but beginning to perceive that the handcuffs were not for me and that the military had so far got....

Perception based on neural network models

Prediction

Word Level Confabulation

Knowledge Base (KB)

Sentence Level Confabulation

Knowledge Base (KB)

...but beginning to perceive that the handcuffs were not for me and that the military had so far got....
Text Recognition Workflow on PS3 Cluster

Single PS3 sub-cluster: 1 head-node + 24 Playstation3 (PS3) workstations

Head-node

Collect and prepare character images

Send images to PS3 workstations

Wait for BSB* recall results

Compute word-level confabulation

Compute sentence-level confabulation

ps1-1, ps1-2, ..., ps1-24

Wait for character images

Perform BSB* recall operations

Check and compare convergence results

Send character candidates to head-node

* BSB: Brain-State-in-a-Box neural network model
Scaling the Hierarchical Temporal Memory Model

### Run Time Performance

- **Graph 1:**
  - Title: Run Time Performance
  - X-axis: PS3s
  - Y-axis: Nodes per Second
  - Lines:
    - Blue line: 8000 Nodes per PS3
    - Red line: 500 Nodes per PS3

### Network capability

- **Graph 2:**
  - Title: Network capability
  - X-axis: PS3s
  - Y-axis: Maximum number of nodes
  - Line: Red line

The graphs illustrate the performance and capability of the system under different conditions.
Scaling Spiking Neural Net Models

Run Time Performance

Network capability*

*Note that the number of neurons and synapses that could be implemented are heavily determined by the specific network structure developed. More biologically accurate models are currently being studied and are likely to yield different numbers.
96 PS3’s (576 SPU cores) processing 5km Gotcha SAR

Each square (.0256km²) represents processed data from an SPU
Results: Gotcha VideoSAR Scalability

- At 256 PS3s, each send 6 MB/sec and receives 8.4 MB/sec while headnodes each receive 200 MB/sec and send 140 MB/sec
Great News for HPEC!

MEMORANDUM FOR DEPUTY ASSISTANT SECRETARY OF THE ARMY (RESEARCH AND TECHNOLOGY)
CHIEF OF NAVAL RESEARCH
DEPUTY ASSISTANT SECRETARY OF THE AIR FORCE
(SCIENCE, TECHNOLOGY AND ENGINEERING)
DIRECTOR, PROGRAM ANALYSIS AND EVALUATION
DIRECTOR, TEST AND EVALUATION AND TECHNOLOGY
REQUIREMENTS, DEPARTMENT OF THE NAVY
DIRECTOR, MISSILE DEFENSE AGENCY
DIRECTOR, DEFENSE ADVANCED RESEARCH PROJECTS
AGENCY
DIRECTOR, DEFENSE THREAT REDUCTION AGENCY
DIRECTOR, TEST AND EVALUATION MANAGEMENT
AGENCY, DEPARTMENT OF THE ARMY
DIRECTOR, TEST AND EVALUATION DIRECTORATE,
DEPARTMENT OF THE AIR FORCE

SUBJECT: FY 2010 DoD High Performance Computing Modernization Program Dedicated
HPC Project Investment Awards

Reference: Office of the Director, Defense Research and Engineering Memorandum, Subject:
Call for DoD FY 2010 Dedicated High Performance Computing Project Investment (DHPI)
Proposals, December 2008

Dedicated HPC Project Investments (DHPIs) are modest-sized HPC systems that are awarded to
technically sound, mission critical projects which cannot be performed at DoD Supercomputing
Resource Centers (DSRCs) due to classification level, special operational requirements (e.g.,
real-time turnaround), and/or use of emerging technologies. DHPIs are a vital part of the DoD
HPC Modernization Program’s mission to address the most pressing HPC needs of the DoD
S&T and T&E communities.

All proposals were subjected to rigorous independent review by the DHPI Technical Evaluation
Panel (which includes HPC subject matter experts from Government, industry, and academia),
the Service/Agency Principals, and the DUSD(S&T) Directors. I would like to thank the
Service/Agency Principals for their careful review and refinement of this year’s DHPI proposals.
As a result, the process was more competitive and aligned with DoD priorities.

It is my pleasure to announce that the following DHPIs have been selected for award for FY
2010:

<table>
<thead>
<tr>
<th>DHPI</th>
<th>Organization</th>
<th>Project Leader</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 Tllop/s Cluster for Real-Time Neuromorphic Computing and Gotcha Video SAR</td>
<td>Air Force Research Laboratory, Information Directorate (RITB)</td>
<td>Mr. Mark Barnell</td>
</tr>
<tr>
<td>Persistent Surveillance Supercomputing</td>
<td>MIT Lincoln Laboratory</td>
<td>Dr. Jeremy Kepner</td>
</tr>
</tbody>
</table>

I ask your assistance and continued involvement to ensure that the HPC assets being acquired
under these awards are best employed to meet the specific needs of the selected DHPI projects.
Please join me in congratulating the awardees.

André van Tilborg
Deputy Under Secretary of Defense
(Science and Technology)

cc:
PD, DDR&E
DoD High Performance Computing Advisory Panel
Project Leaders
### Top 500 Supercomputers June 2009

<table>
<thead>
<tr>
<th>Rank</th>
<th>Site</th>
<th>Computer/Year Vendor</th>
<th>Cores</th>
<th>R\text{max}</th>
<th>R\text{peak}</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>DOE/NNSA/LANL</strong> United States</td>
<td><strong>Roadrunner - BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 Ghz / Opteron DC 1.8 Ghz, Voltaire Infiniband / 2008 IBM</strong></td>
<td>129600</td>
<td>1105.00</td>
<td>1456.70</td>
<td>2483.47</td>
</tr>
<tr>
<td>2</td>
<td><strong>Oak Ridge National Laboratory</strong> United States</td>
<td><strong>Jaguar - Cray XT5 QC 2.3 GHz / 2008 Cray Inc.</strong></td>
<td>150152</td>
<td>1059.00</td>
<td>1381.40</td>
<td>6950.60</td>
</tr>
<tr>
<td>3</td>
<td><strong>Forschungszentrum Juelich (FZJ)</strong> Germany</td>
<td><strong>JUGENE - Blue Gene/P Solution / 2009 IBM</strong></td>
<td>294912</td>
<td>825.50</td>
<td>1002.70</td>
<td>2268.00</td>
</tr>
<tr>
<td>4</td>
<td><strong>NASA/Ames Research Center/NAS</strong> United States</td>
<td><strong>Pleides - SGI Altix ICE 8200EX, Xeon QC 3.0/2.66 GHz / 2008 SGI</strong></td>
<td>51200</td>
<td>487.01</td>
<td>608.83</td>
<td>2090.00</td>
</tr>
<tr>
<td>5</td>
<td><strong>DOE/NNSA/LLNL</strong> United States</td>
<td><strong>BlueGene/L - eServer Blue Gene Solution / 2007 IBM</strong></td>
<td>212992</td>
<td>478.20</td>
<td>596.38</td>
<td>2329.60</td>
</tr>
</tbody>
</table>

By comparison, the world’s largest HPC (Roadrunner at Los Alamos) is 2800 teraflops (single precision) and runs in batch mode.
500 TFLOPS Interactive Cluster (300 Cell, 200 GPGPU)

Sub-Cluster Server
32GB – 4TB
2 Nvidia TESLA

24 1GE Port
2 10GE Uplink
Sub-Cluster SWITCH

1

Sub-Cluster Server
32GB – 4TB
2 Nvidia TESLA

24 1GE Port
2 10GE Uplink
Sub-Cluster SWITCH

2

Sub-Cluster Server
32GB – 4TB
2 Nvidia TESLA

24 1GE Port
2 10GE Uplink
Sub-Cluster SWITCH

88

Infiniband Network

DREN
1GE
INF

DREN
1GE
INF

90-node Emulab Cluster

10 GE Cross-Cluster Switches

Phantoms (1-88)
Range of Wire in One Clock Cycle*

From 2003 ITRS Roadmap

- 3D Integration increases accessible active devices

*After S. Amarasinghe, MIT Laboratory for Computer Science and Artificial Intelligence
Cross-Section of 3-Tier 3D-integrated Circuit

3 FDSOI CMOS Transistor Layers, 10-levels of Metal

Tier-1: 180-nm, 1.5V FDSOI CMOS
Tier-2: 180-nm, 1.5V FDSOI CMOS
Tier-3: 180-nm, 1.5V FDSOI CMOS

Tier-1: Transistor Layer
Tier-2: Transistor Layer
Tier-3: Transistor Layer

3D-Via
Stacked Vias
Back Metal
Metal Fill
3-Level Metal
Oxide Bond Interface

Craig Keast,
HPEC-06

10 μm
Pushing 3D Multicore Architecture

16 cores / chip  \rightarrow  50 chips / stack \rightarrow  10 x 10 stacks / board

At 100 GFLOPS/Watt (45 nm):

- 0.32 watts  \rightarrow  32 watts  \rightarrow  1.6 kwatts
- 16 cores  \rightarrow  800 cores  \rightarrow  80K cores
- 32 GFLOPS Single Precision  \rightarrow  1.6 TFLOPS  \rightarrow  160 TFLOPS
- 16 GFLOPS Double Precision
Some Daunting HPEC Challenges

Information System Complexity

Physical System Complexity

Autonomous Systems

Fusion, Automatic Target Recognition

Situational Awareness

Keep redoubling the performance/dollar!

But also make the entire HW/SW system timely and affordable