Micro Autonomous Systems and Technology

Collaborative Technology Alliance

Joseph N. Mait
Cooperative Agreement Manager
Autonomous System Technologies provide the Soldier with superior situational awareness in mounted and dismounted operations.
To enhance tactical situational awareness in urban and complex terrain by enabling the autonomous operation of a collaborative ensemble of multifunctional, mobile microsystems.
**Small Scale**
- Maneuver in confined spaces
- Organic asset for small units
- Stealth
- Reduced logistics

**Single Platform Autonomy**
- Reduced human control for navigation

**Collective Behavior**
- Reduced human control for mission completion
  - e.g., spatially locating potential threats based on sensor signatures
Operational Scenarios

- **Scenario #1**: small unit building search
  - Autonomous navigation in benign indoor environment with human mission control

- **Scenario #2**: small unit cave search or demolished building
  - Autonomous navigation in complex environment with human mission control

- **Scenario #3**: small unit perimeter defense
  - Autonomous navigation in complex environment with autonomous mission control
Scenarios 1 through 3 describe a vision of future capabilities

Mobility and collective behavior of small platforms are two critical capabilities that have operational significance

- **Tagging, tracking, and locating:** use a single mobile, autonomous ground platform to plant tags surreptitiously on persons or conveyances

- **Communications in complex terrain, e.g., buildings or caves:** use a mobile platform collective to establish a robust communications link matched to local topography without the need for hand emplacement

- **Deception and diversion:** use a mobile platform collective mounted with nonlethal pyrotechnics to create a diversion prior to building assault

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**Scenario 0: Operationally-significant capabilities demonstrations**
• Integrated Academic-Industrial-Government Alliance
  – Basic research
  – Facilitate transition of results for use by government and industry
• 5-10 year program (award FY08Q2)
• ~$7.5M per year
• Builds on success of previous Collaborative Technology Alliances
Scale imposes fundamental limits on system design. It is not possible to scale down existing macro-scale systems.

Stanley
Winner, 2005 DARPA Grand Challenge
Performance Limiters

• Environment
  – Disturbances larger than vehicle size complicate stability and control issues
  – Unstructured environment complicates guidance, navigation, and distributed behavior due to lossy communication & lack of GPS
  – Dynamics in unstructured environment complicates distributed behavior

• Low power, palm-sized platform
  – Affects guidance, navigation and control for single platform autonomous operation
  – Affects computation, sensing, & communication for distributed autonomous behavior
  – Increases need for multifunctional structures to increase efficiency
  – Increases requirements for energy management (recovery)
  – Increases requirements for direct chemical-to-mechanical conversion

• Fabrication
  – Increased friction & heat transfer due to increased surface-to-volume ratio
  – Reduced system reliability due to small mass
  – Increased complexity due to need for multifunctional structures
MICROSYSTEM MECHANICS
• Achieve stable aerodynamic performance in unsteady vortex-dominated flows at low Reynolds number
• Create lightweight materials and mechanically efficient structures for articulated and adaptive small-scale air and ground platforms

MICROELECTRONICS
• Increase understanding of physics of electrical and optical characteristics when scales are comparable to wavelengths and minimum feature sizes
• Develop new computing architectures to insure stable and reliable operation for low power operation

PROCESSING FOR AUTONOMOUS OPERATION
• Achieve animal-like intelligence and navigation with limited power, limited resolution sensing, limited bandwidth, and low level processing
• Understand fundamental limits and tradeoffs in processing, communication, sensing, and mobility

INTEGRATION
• Understand and exploit intra-platform interactions and efficiencies in a collaborative ensemble of microsystems
• Understand the relationships between goals, system characteristics, and physical structure, e.g., performance vs. flexibility trade-offs
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<thead>
<tr>
<th>Category</th>
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<tr>
<td>Platform Integration</td>
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<td>Processing for Autonomous Operation</td>
<td>Univ. of Pennsylvania</td>
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<td>General Members</td>
<td>North Carolina A&amp;T, Caltech, JPL, UC-Berkeley, Univ of New Mexico, Georgia Tech</td>
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Nature utilizes hair for a variety of sensing and control functions, e.g., air flow, temperature, humidity, and body temperature control.

Hair-based Sensing And Actuation
Khalil Najafi, University of Michigan

High-aspect ratio polymer hairs, that are transferred on top of CMOS circuits

Hair-Like Sensing & Actuating Elements can be fabricated using MEMS technology in arrays with various shapes & functionality.
Scenarios for capability challenges will be designed using performance metrics for individual and system collective capabilities.

Capability Challenge will occur inside MAST simulation environments.

- Benign outdoor terrain plus office-like environment
- Abstract models of candidate microsystems will be developed and the experiment will be conducted via simulation
- Non-traditional metrics studied in System of Microsystems project and MIDAS will provide required capabilities for MAST systems

- Office-like Environment (2D)
- Modest Obstruction
- Mirrors/Transparent Obstacles
Capability Challenge Inputs

Processing for Autonomous Operations Research Center
- Navigation Sensing Perception
- Communication Algorithms Simulation tools

Integration Research Center
- Performance metrics from SoM/MIDAS analyses

Microelectronics Research Center
- Characteristics and dynamics of future MAST sensors/power modules/processing/communication devices

Micromechanics Research Center
- Kinematic/dynamic models, payload, and locomotion characteristics of future MAST platforms

Capability Challenge FY09
Capability Challenge Outcomes

Results from the Capability Challenge will provide

- **Microsystem Mechanics Center**: quantitative data on steerability of micro-platforms with remote commands
- **Microelectronics Center**: propagation models for indoor environments
- **Processing for Autonomous Operations Center**: quantitative data on limitations of indoor coordination given limited flight space and visibility
- **Integration Center**: quantitative data for mission planning models, e.g., mobility and communication ranges, duration of operations, and common mission failure modes
Experimentation Site

- Establishes a research epicenter for MAST technology integration & demonstration
- Facilitates collaborative research & experimentation by providing:
  - Rotational office space
  - Innovative, collaborative workspace
  - Lab space
  - Well instrumented facilities

Outdoor Facility
- Situational Realism
- Modular Structures
- Reconfigurable
- Transportable

Indoor Facility
- 45' x 40' x 25'
  - Vicon Tracking system

Available June 2009
MAST seeks to advance capabilities in future autonomous platforms through multidisciplinary research that emphasizes both individual technologies and their interactions.
• Backup
Microsystem Mechanics

- Increase understanding of aeromechanics and ambulation at small scale
- Increase efficiency of small-scale air and ground platforms
- Increase mobility and maneuverability of small-scale air and ground platforms

- Fundamental understanding required in:
  - Biological navigation and control
  - Aerodynamic performance in unsteady vortex-dominated flows at low Reynolds number
  - Lightweight materials and adaptive structures for articulated and adaptive small-scale air and ground platforms
  - Actuation and articulation for small-scale air and ground platforms
  - Efficient mechanisms for propulsion
  - Efficient mechanisms for efficient power generation and distribution
Microsystem Mechanics Projects

• Aeromechanics
  • Fundamental bio-inspired principles of flapping flight physics
  • Dual-plane particle image flow diagnostics of flapping-wing unsteady aerodynamics
  • DNS/LES/RANS analysis for rotary and flapping-wing-based MAVs
  • Flight dynamics simulation modeling of MAVs
  • Aeromechanics of Revolutionary Cyclocopter and Flapping Rotors
  • Bio-inspired flexure-based wings and airframes
  • Avian-based Wing Morphing

• Ambulation
  • Bio-inspired dynamic modeling and simulation with parameters for ground contact model
  • Bio-inspired principles of appendage and actuator design
  • Ambulatory design of body and appendages
  • Bio-inspired crawling, running, climbing robots

• Hybrid Aeromechanics-Ambulation
  • Thrust augmented entompter: A revolutionary hover-capable high-speed MAV
  • Bio-inspired hybrid aerial and terrestrial locomotion
  • Multi-Body Microsystem Analysis Code for Rotary-Wing, Flapping-Wing, and Ground-Based Systems

• Multifunctional Actuation and Propulsion
  • High Performance Microactuators
  • Smart Composite-based Rapid Fabrication of Micromechanical and Micromechantronics Structures
  • Ultra Lightweight Multifunctional Composite Structures based on Electrospun Fabric
  • Chemical Energy Conversion System
  • Distributed Propulsion System for Power Efficiency
Aeromechanics of microsystems is fundamentally different than that of larger platforms

- Low Reynolds number (ratio of inertial forces to viscous forces) implies large viscous forces and thick boundary layers
  - Reduces platform efficiency

- Assumptions for full-scale vehicles not applicable at the micro-scale

- Bio-inspired appeal to flapping-wing animals (insects and birds) leverages thick boundary layer-induced leading-edge separation vortex to improve efficiency
  
  M. Dickinson, CalTech
  S. Humbert, University of Maryland
Dual-Plane Particle Image Flow Diagnostics of Flapping-Wing Unsteady Aerodynamics
Gordon Leishman, University of Maryland

(a) Shed vortices
(b) Starting vortex
(c) Starting vortex
(d) Starting vortex
(e) LEV
(f) LEV
(g) LEV
(h) LEV
(i) LEV
(j) New LEV
(k) New LEV
(l) New LEV

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.
Microelectronics

Provide functionality and performance of large scale microelectronics subject to constraints of reduced size and reduced power.

- Reduced size increases level of integration and increases number of interfaces between different layers and different materials
- Low power operation increases need to increase efficiency and develop new architectures for computing, communication and sensing

• Challenges
  - Increase understanding of physics of electrical and optical characteristics when scales are comparable to wavelengths and minimum feature sizes, e.g., relative size of defects at interfaces and impurities in materials
  - Develop understanding of and technologies for heterogeneous integration at small scales, e.g., chemistry at interfaces and multiple layers
  - Develop new computing architectures to insure stable and reliable operation for low power operation
  - Develop efficient communications systems subject to small size and low power
  - Develop efficient sensors subject to small volume and low power
Microelectronics Projects

- **Power**
  - Quantum-Dot Solar Cell
  - Transpiration-Based Power Generation
- **Navigation**
  - HAIR sensors for Inertial Navigation
  - mm-wave Radar
- **Communication**
  - Flexible Direct Digital Modulation
  - RF MEMS Signal Processors
  - Switchable BST Filters
  - Miniature Antennas for Wireless Communication
  - Maple Seed Sensor/Radio
- **Sensing**
  - Micro Gas Chromatography
  - Nuclear Radiation Sensor
  - HAIR: Sensing and Actuation
- **Processing**
  - Low-Voltage Logic
  - Sub-Threshold SRAM Development
  - Logic Families and Architectures for Low Power Design
To increase autonomous capabilities, multiple, heterogeneous Autonomous Mobile, Multifunctional Microsystems (AM³) must
- function as a single cohesive unit
- respond adaptively as an ensemble to human commands
- be resilient to adversarial conditions
- integrate control, sensing, communication, perception, and planning

Challenges
- Achieve autonomy for micro-scale, resource-constrained agile platforms in 3-D unstructured environments
- Achieve group autonomy at the micro-scale
Processing for Autonomous Operation Projects

- **Control & Mobility**
  - Abstraction-Based Control of MAST Platforms
  - Model-Predictive Navigation in Unstructured Environments
  - Navigation Using Spatio-Temporal Gaussian Processes

- **Sensing & Estimation**
  - Distributed Inference
  - Simultaneous localization and mapping (SLAM)

- **Communication between AM3 platforms**
  - Communication-aware Exploration
  - A Simulation Environment for the Integration of Communication and Navigation in MAST Scenarios

- **Model-based System Architecture Design and Analysis for Autonomy**
  - Model-based design, integration and verification of software
  - Design of Simulation Tools for MAST Applications

- **Control for Situational Awareness in 3-D Dynamic Environments**
  - Active SLAM
  - Decentralized Coverage Verification and Cooperative Surveillance
  - Autonomous adaptive mobility of heterogeneous MAST teams
  - Composition of group behaviors for scouting, reconnaissance, and surveillance

- **Communication and Control for Autonomous Operation**
  - Integration of Communication and Control in MAST platforms
  - Coordinated control of a small team of heterogeneous robots in partially-known environments
  - Path Planning for Multi-Agent Teams in dynamic environments

- **Distributed Perception for Harsh Environments**
  - Mapping and localization in 3-D, unstructured, dynamic environments
  - Classification and Recognition Using Dynamic Texture and Spatia-Temporal Features
  - 4-D structure and semantics for situational awareness
Environment Complexity vs. Task Complexity

1. Navigation, mapping, SA in 2D and 2.5D indoor environments

2. Navigation, mapping, SA in 2D and 2.5D indoor/outdoor environments

3. Navigation, mapping, SA in 3D, feature-rich environments (rubble, caves)

4. Perimeter surveillance and coverage in outdoor environments

Number of features in the environment (Complexity of the environment)

Number of required nodes

complexity of mapping and providing situational awareness

State of the art

Number of MAST nodes required for situational awareness

10^0

10^1

10^2

10^3

10^4

10^5

10^6

Environment Complexity vs. Task Complexity

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.
Composition of group behaviors for scouting, reconnaissance, and surveillance
Vijay Kumar, University of Pennsylvania

Scalable, decentralized, nonlinear controllers developed and tested in a dynamic simulation
- Close formation navigation in MOUT site
- Heterogeneous team of 25 MAST platforms
  - 5 rotor craft
  - 25 wheeled platforms
To achieve desired capabilities in palm-sized platforms, radical design and engineering methodologies are necessary in which system-level performance is emphasized over the optimization of individual functions.

Research Issues

• Understand fundamental physical limits of palm-sized platforms
• Understand and exploit intra-platform interactions and efficiencies in a collaborative ensemble of microsystems
• Understand the relationships between goals, system characteristics, and physical structure, e.g., performance vs. flexibility trade-offs.
• Understand traditional goals of function, performance, and cost against non-traditional engineering goals such as flexibility, robustness, scalability, and sustainability.
Integration Projects

- Systems of Microsystems
  - Strategic Planning and Prioritization Process
  - Interactive System Level Simulation
  - Analytic Architecture for Capability Planning
  - Non-Traditional Metrics for MAST Systems
- Intra-Platform Interactions and Efficiencies
  - Bio-Inspired Integration concepts
  - Efficiency of Microsystems
- Scenario Driven Experimentation & Capability Challenges
  - Mission Scenarios for testing MAST Technologies
• Comprehensive understanding across the consortium can
  – promote discovery of complex interaction between multiple, disparate
technologies
  – guide the study of phenomena that may be most productive
  – identify discoveries that can be pulled into invention and innovation
    sooner than others

• Integration and experimentation are required to
  – promote discovery
  – validate phenomena
  – generate empirical data for modeling
Cross-Cutting Thrusts

• Adaptive, Agile Mobile Systems for Operation in Complex Environments
• Integrated, Multifunctional Sensing, Communication, & Computing at the Micro-Scale
• Autonomous Group Behavior
• Systems of Microsystems Design, Simulation, Experimentation, & Validation