

# Micro Autonomous Systems and Technology at the Army Research Laboratory

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**Abstract**—The Micro Autonomous Systems and Technology program is conducting research to develop small air and ground robotic systems for acquisition and delivery of improved situational awareness to warfighters.

## I. INTRODUCTION

The Army Research Laboratory (ARL) has positioned itself strategically to contribute to the development of small scale autonomous platforms. ARL's vision is to enhance tactical situational awareness in urban and complex terrain by enabling the autonomous operation of a collaborative ensemble of multifunctional, mobile microsystems. ARL's goal is to provide mobile sensor platforms small enough that several can be carried by a soldier and deployed when necessary. The platforms must be able to autonomously travel hundreds of meters and maneuver in confined spaces such as alleyways and inside buildings, caves, and tunnels. Perception capabilities will include obstacle avoidance, navigation, and the detection, location, and tracking of humans and vehicles. Sensor data must be processed and fused to create useful information that can be efficiently communicated to the operator. Inherent in the MAST concept is the notion of autonomously coordinated mobility, sensing, distributed processing, and networked communication. Given a mission, the designated team of platforms must autonomously perform all the necessary steps to acquire and communicate the required information in a timely manner to the people who need it, possibly through connections with the larger networked force. This makes the ARL MAST program highly compatible with the AFRL Layered Sensing technology construct [1].

ARL's internal research program is part of a Strategic Technology Initiative in Autonomous Systems Technology that also includes man-packable robots and full-size robotic vehicles. Research conducted as part of the initiative addresses Perception and Control, Intelligence, Mobility and Manipulation, Power, Integration, and Human Interface.

As an adjunct to its internal program, ARL recently established the Micro Autonomous Systems and Technology (MAST) Collaborative Technology Alliance (CTA). In the MAST program, research is performed by a consortium of academic and industrial researchers in active collaboration with scientists and engineers from the Army Research Laboratory and other Army, DoD, and government agencies. The MAST program is organized around four technologies necessary to provide tactical situational awareness under the constraints of small-scale, low power, autonomous platforms: Microsystem Mechanics led by the University of Maryland, Microelectronics led by the University of Michigan, Processing for Autonomous Operation led by the University of Pennsylvania, and Microsystem Integration led by BAE Systems. Other consortium members include the University of California Berkeley, the California Institute of Technology, NASA's Jet Propulsion Laboratory, the Georgia Institute of Technology, the University of New Mexico, and the North Carolina Agricultural and Technical State University.

A common theme among the technical areas is the study of small biological systems as examples of highly integrated solutions for sensing, mobility, control, navigation, and communication. For example, birds and flying insects use optical flow for obstacle avoidance and navigation, and this principle is now being applied to robotic motion control.

Another common theme is a heavy emphasis on modeling and simulation combined with frequent validation experiments. A particular challenge will be the need to combine the separate software applications used by the various disciplines into a comprehensive modeling and simulation tool for system-level design and optimization.

The small size of the planned MAST platforms puts significant constraints on the available power/energy, sensing, processing, and bandwidth, and this requires a global optimization approach that can only be achieved by a high degree of multi-disciplinary collaboration, as evidenced below.

## II. MICROSYSTEM MECHANICS

Microsystem mechanics is focused on improved small-scale mobility. Rotary and flapping wing platforms will benefit from better understanding of low Reynolds number aerodynamics, techniques to achieve stability in gusts and turbulence, and mechanical resonances and feedback in actuators and platforms. Investigations of insects have produced much experimental data, initial models, and some insight into the aerodynamics of small-scale flapping wing flight [2,3]. Additional efforts are required to validate the models and produce efficient mechanical designs.

Multi-legged ground platforms will require further advances in high power and large displacement actuators, materials, feedback strategies for stability, and validated multi-scale modeling from component level to whole platform mechanics [4]. Current models will be extended to incorporate the interaction of legged platforms, both mechanical and biological, with a variety of natural substrates, including vertical surfaces [5-8].

Multidisciplinary collaboration is exemplified by the task to develop control strategies for flight in gusty conditions and walking or running over complex terrain, which will require considerable cooperation between sensing, processing, and actuator/platform researchers.

## III. MICROELECTRONICS

Research in microelectronics concentrates on miniaturizing sensors, processing, and communication hardware, with a focus on 215 GHz radar. The proposed design uses a frequency-scanning approach with pseudo-noise code modulation, low-loss dielectric antennas, and a highly integrated CMOS circuit for the RF front end. Performance goals include a range of 100 m with peak power of 200 mW in a package of 50 cm<sup>3</sup> and 50 g.

The performance of existing state-of-the-art inertial sensors [9] will be improved to 0.1 °/hr by a combination of environmentally resistant packaging and improved design of the readout circuitry. This will allow precise navigation in GPS-denied environments, and could enable system designs without GPS.

The proposed communications transceiver will move the analog/digital interface close to the antenna, and use RF MEMS for a combined mixer-filter [10] at lower frequencies and thin-film barium strontium titanate (BST) for higher frequency switchable filters [11]. The intended frequency range is 100 MHz to 5 GHz with power consumption of 10 mW. The projected transceiver size is 2 cm<sup>3</sup> including the high frequency antenna, with the lower frequency antennas incorporated into the platform structure.

Low-power analog-to-digital converters (ADC's) are critical to the proposed communications architecture and to the millimeter-wave radar. Current state-of-the-art ADC's achieve 5-bit resolution at 3.5 giga-samples per second (GS/s) [12]. New techniques, including digital calibration, clock jitter cancellation, scrambling, and inductive comparator speed enhancement, will be employed to achieve 12-bit resolution at 10 GS/s, which should enable true digital radio.

Many signatures in nature, such as optical and acoustic intensities, are best expressed on a logarithmic scale, and logarithmic ADC's can achieve high dynamic range with very good energy efficiency. Within a few years, digitization of sensor signals can realistically be achieved at 100 MS/s with dynamic range of 100 dB and power consumption of 1 mW. Asynchronous conversion techniques promise further dramatic power reductions.

The low power Phoenix processor has recently been implemented at the University of Michigan [13] in a 0.18  $\mu$ m process with an area less than 1 mm<sup>2</sup>. It features a custom low-leakage memory cell and unique power management techniques that result in 30 pW power draw in sleep mode and less than 3 pJ/cycle in active mode. This work will be extended using direct-mapped special purpose blocks for common signal processing tasks such as Fast Fourier Transforms [14], modest data storage capacity (several Mb), and 100 or more simple pipeline cores for general purpose processing. Each simple processor will operate at 10 MHz and 10  $\mu$ W for a total power draw of 1 mW. Collaboration with software developers will be necessary to match hardware capabilities with algorithm processing requirements, and to ensure power-aware programming takes full advantage of the hardware power management features.

## IV. PROCESSING FOR AUTONOMOUS OPERATION

Processing for Autonomous Operation challenges span the range from low-level routines for platform control and communications waveforms to more complex optical flow analysis for autonomous navigation to intelligent behaviors such as simultaneous location and mapping, reconfigurable network communications, and distributed sensor fusion for target detection, location, and tracking.

Both navigation in an unknown environment and determination of target locations require that the sensor platforms localize themselves in the environment, even without GPS. This can be accomplished by distributed Simultaneous Localization and Mapping (SLAM) [15], which is based on previously developed Distributed Data Fusion techniques [16]. In complex environments, the SLAM problem can be simplified by using MAST platforms themselves as intrinsic landmarks [17]. To scale the distributed SLAM algorithms to feature-rich environments, we will integrate the smoothing and mapping concepts [18] derived from sparse linear algebra for a computationally tractable implementation.

Coordinated movement of multi-platform teams will be enabled by the development of computationally inexpensive navigation functions [19] and bio-inspired strategies for group consensus behaviors with optimized use of limited communication, sensing, and control resources [20,21]. System-level control software will build on our previous work [22] and will be incorporated into a Service Oriented Architecture.

The simulation environment will be based on Player/Stage/Gazebo [23], an open source simulation package that can model 3-D geometry, kinematics, and dynamics for MAST platforms and can also model the associated sensors.

## V. MICROSYSTEM INTEGRATION

Microsystem Integration is critical to incorporating a sufficient number of useful capabilities into a suitably small package. Integration also includes the system-level design of multiple heterogeneous platforms that cooperate to accomplish a mission [24]. The process begins with user definition of mission requirements, which then determine the necessary platform capabilities [25]. This will define the benefits of e.g. flapping-wing designs versus rotary- or fixed-wing air vehicles for the targeted missions. Capability-based system-level design will seek to optimize performance of the overall platform, not any individual component or subsystem. System-level design will also develop the necessary guidance to focus the research activities and products of each of the technical areas.

Again, we take inspiration from biological models that demonstrate efficient system architecture characteristics, such as multi-functional materials and components. An equivalent MAST example could be structural batteries. An important consideration will be the trade-off of the convenience and flexibility of modular design versus the inherent efficiencies of integration. Innovative packaging concepts will be evaluated, including the solid-to-flat mapping program addressed by the field of computational origami [26]. Validated modeling and simulation will have a large role in the design activities. The extensive capabilities of the Georgia Tech Collaborative Design Environment (CoDE) and Collaborative Visualization Environment (CoVE) facilities [27] will be used in conjunction with the JPL Dynamic Algorithms for Real-Time Simulation Shell (DARTS Shell or DShell) [28]. The MAST program will require frequent experimentation at both the component level and the system level to validate the modeling efforts and to determine the extent to which objective mission capabilities are being met.

## VI. POWER AND ENERGY

Although not specifically included as a research topic in the MAST CTA, power and energy generation and storage is a critical issue in ARL's research portfolio and must be a consideration in all aspects of system design. The on-board power and energy generation/storage capacity will ultimately limit mission duration. Batteries, fuel cells, solar cells, power scavenging, and energy management and recovery techniques are a few of the topics being investigated.

## VII. SUMMARY

The MAST CTA program is a broadly scoped research effort to advance the state-of-the-art in technical areas necessary for the development of small air and ground robotic platforms capable of providing improved situational awareness to warfighters.

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