ADOJAM Solid State RADAR SLAM* via Octagonal Beamforming Array System
(Platform Independent, Small UAS SWaP-C Capabilities)

ADOJAM, LLC
Responsive to TTO RFI: DARPA-SN-18-10

- Real time subterranean mapping and navigation
- Works in dark, dusty environments
- Rapidly map unknown, complex environments underground
- Compatible with ADOJAM Team UWB through wall imaging

![SSR-SLAM display concept](image)

Figure 2. SSR-SLAM response to a man made cave

![Octagonal beamforming array and array module](image)

Figure 1. Octagonal beamforming array and array module

- 24 GHz FMCW radar (250 MHz bandwidth)
- Range accuracy: <10 cm
- Range: Up to 130+ meters
- Six antenna elements per facet (48 total)

* SLAM (Simultaneous Localization and Mapping)
* COTS radar array sensor: Flat Earth, Inc.
† UAS platform: Vision Aerial
Objective
Rapid in-situ mapping and navigation of rugged and dynamic underground terrains

Complications
Low-light conditions, low-feature environments, clutter, GPS-denied, stealth

Opportunities
Terrain/geological restrictions, portals, vents, roads, vegetation, intel

Solution

Pre-mission analysis
Use overhead/satellite data, intel and engineering/construction practices to generate plausible layouts

Sensor data collect
Collect imagery/range/odometry data through robotic/drone/soldier-borne low SWaP sensors

Autonomy
Autonomously navigate without prior knowledge of the structure or environment

On-board processing
Use multi-source data to instantly infer skeleton layout maps and generate and enhance 3D models as needed in available time

Navigation
Provide distributable critical information on wearable, handheld, or see-through displays without distracting the operator

Proven Capabilities Developed by ARA

- Underground targeting & analysis system (UTAS)
- Tunnel reconstruction from point cloud and odometry data collected with a human-wearable backpack system
- 360° Panoramas in a low feature tunnel complex with various lighting conditions
- Tunnel reconstruction from imagery with calculated cross-sections
- High accuracy, low latency head tracking system with low SWaP IMU & computer vision-based navigation
- Seamless integration with ATAK and Nett Warrior
- Autonomous navigation in structured and unstructured terrain, obstacle detection and avoidance, wheel placement optimization, complex maneuver planning
- Trail navigation without prior knowledge
- Passive perception for covert navigation using non-emmiting sensing modalities

Agency/DoD Support
DARPA, DTRA, DIA, NVESD, SOCOM, ARL, NRO

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INNOVATIVE SOLUTIONS TO COMPLEX PROBLEMS

Revolutionizing Subterranean Mapping and Navigation: DARPA-SN-18-10

Vision for DARPA’s Subterranean Environment Mapping Challenge:

Data Collection Methods from Industry Partners -> Collected Data Stored / Shared using LTF -> Virtual Reality

- Nurulize Tools
- GOTS Terrain Tools

Collaborative VR World for planning and mission rehearsal

Subterranean data integrated into high-fidelity simulation databases

Layered Terrain Format

- Lightweight storage & transmission of GIS data

Layered nature of LTF is ideal for mobile devices and distributed information sharing in degraded communications environment

World’s most compact and efficient protocol encoding and repository file format for GIS data

Offered as an OGC standard

GOTS Tools

- RUGUD
- ASCEND

Nurulize

- Atom View
- Nu Design

Layered, automatic, efficient world building in the cloud supporting “Source-to-Soldier” training and operational use cases

ARA’s novel component technologies enable distributed information sharing and provide a proven path for rapid transition from disruptive data collection methods to visualization of the collected data in virtual reality and high-fidelity simulations

Manhattan subway tunnel modeled in UE4 using LTF & ASCEND for IITSEC 2017

Mobile terrain analysis using LTF

Streamlined, automatic, efficient world building in the cloud supporting “Source-to-Soldier” training and operational use cases

ARA’s novel component technologies enable distributed information sharing and provide a proven path for rapid transition from disruptive data collection methods to visualization of the collected data in virtual reality and high-fidelity simulations

Access: Animal Carried Compact Exploitation and Exfiltration System for Subterranean Structures
Areté Associates

**Concept**
- Lightweight, small animal-carried tag with IMU, GPS, microphone
- Bats explore cave while searching for a place to roost
- Shrews or rats look for survivors in collapsed structures
- Autonomy and camouflage – bats and rats know and belong in caves!
- Sensor tag falls off in a few days
- Same tag on larger animals or robots could carry other sensors
- VHF radio conveys data back to base station after cave exit

**Perception**
- Microphone records echolocation signals from bats for later processing – to recover size and functionality of space, wall characteristics
  - > 5m range for many bats, some >10 m, some up to 67 m!
  - Recover size and functionality of space, wall characteristics
- IMU magnetometer as proxy for density change detection
- Accelerometer to record pose of animal (sensors)

**Innovations**
- SWAP: State of the art is 1-1.5 g, 20x10x5mm package for smaller bats
  - Larger and heavier for larger bats, rats, other platforms
  - Mostly used to transmit pinger for tracking
- Convincing animal to do our mission
  - To persuade bat to perform mission, transmit echolocation signals already used by bats to coordinate flight and hunting
  - Advance state of the art by decoding in-situ echolocation signals

**Effort**
- PCB-scale prototype for larger or captive bats in 9-12 months
  - Collect data to refine techniques and requirements
- If it works, develop integrated solution in 24 months
Compact, elegant platform designs with efficient mobility.

Transforming chassis for man-portability, ease of shipping and borehole accessibility.

Inflatables to provide extreme mobility, including dry, partially submerged, and fully submerged subterranean environments.

Principle investigators with 40 combined years of subterranean robotics and mapping experience.

Successful record of delivering systems and services all over the world (Australia, Indonesia, South Africa, North America)
“Autonomous Subterranean Vehicle”
Omnidirectional Vision-Based Navigation for Nano Air Vehicles

Centeye response to RFI DARPA-SN-18-10

Summary of past and current work supporting RFI objectives

Objectives:
• Implement GPS-denied hover, obstacle avoidance, and navigation for nano air vehicles in near-Earth environments.
• “Follow-me” and “ingress-egress” planned
• Operation in all light levels- daylight to pure darkness

Approach:
• Custom hardware, lenses, and image sensor chips
• Holistically developed sensing and control algorithms
• Optical flow for hover, stereo and pulsed light for obstacle detection
• Flight testing on Crazyflie nano quadrotor
• Global image statistics for fast room/area identification
• All sensing/processing/control on board; No MOCAP used

Achievements: (All TRL 6 except as noted)
• Hover and obstacle avoidance in all light levels (illuminate to 3m in pure dark)
• Avoidance of obstacles, both textured and blank
• Path adjustment to navigate down tunnel
• Waypoint navigation and limited ingress-egress using organic optical flow waypoints
• Room/area identification (15 rooms, ~90% accuracy) TRL 3-4
• Single Photon Avalanche Diode (SPAD)-based arrays for extreme low light use prototyped TRL 3-4

Funding Credits:
D15PC00165 Phase II SBIR (DARPA TTO)
FA865114C0107 Phase II STTR (AFOSR)

Contact: Geoffrey L Barrows, geof@Centeye.com
### Platform for Fast Underground Mapping and Search and Rescue

#### Function | Type of Sensor/setup | Mobility Mechanism
--- | --- | ---
3D point cloud generation for mapping | Structure sensor | Underground drones/origami robots
Water (level, pH, conductivity, chemical content, etc.) | Wireless micro sensors and micro spectral sensors | Endocapsules + origami robots
Air quality (O₂, CO, CO₂, Methane H₂S, etc.) | Wireless micro sensors | Edocapsules + Origami robots
Rock type and quality mapping | Structure sensor + hyperspectral camera | Underground drones/origami robots
Accessibility | Robotic micro directional drilling | Robotic mobility and automation
Robotic search and rescue with human in the loop | Smart helmet with situational awareness data and tracking guidance | Robotic assisted mobility
Communication | RFID, Zigbee, Wireless sensors | Robotic assisted mobility

- **Endocapsules for water**
- **Structure Sensor for point cloud**
- **Robotic search and rescue with human in the loop**
- **Origami robots for air quality**
- **Robotic micro directional drilling for accessibility**
- **Underground drones for point cloud and rock mass identification**

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**http://medical.olympusamerica.com/products/endocapsule-10-system**

**http://mashable.com/2013/09/17/structure-sensor/#4CXBcJAumqG**


**https://www.wired.com/2016/01/daqri-helmet/**

**https://www.youtube.com/watch?v=FQBVTlcl20c**

**https://www.sciencedirect.com/science/article/pii/S0168169915002379**

**http://www.youtube.com/watch?v=ZpPf91K-JAA**
Bat Robot for Stealth Subterranean Mapping and Navigation
Andrew Petruska, John Steele, Xiaoli Zhang, Qi Han, Hao Zhang

A New Class of Agile Aerial Robots

Winged Flight for Energy Efficiency and Stealth

Current Technology
initial demonstration of autonomous flight underground
• noisy
• short flight time
• environmentally disruptive

Bat with their cutaneous wing membranes fly rather slowly, but are remarkably agile.

Machine Learning to Map Ultrasonic Signals to Spatial Understanding

Ultrasonic Chirps
• navigation
• mapping
• reconnaissance
• search
• communications

EchoLocation from Ultrasonic Chirp

Bats with Ultrasonic Chirps

EchoLocation: navigation, mapping, reconnaissance, search, communications

Swarms for efficiency

Benefits
• Stealth
• Efficient
• Agile
• EchoLocation guidance & communication
• Robust
• Resilient

Robots in the Mine

EchoLocation, Aerial Robots in the Mine
Hovermap is a revolutionary drone autonomy and LiDAR mapping payload which enables autonomous collection of valuable actionable data in challenging GPS-denied environments such as underground tunnels and cavities.

By tightly coupling autonomy and SLAM-based 3D mapping in a revolutionary and symbiotic way, a Hovermap-equipped drone can autonomously and safely explore and map complex underground environments at unprecedented spatial and temporal resolutions.

**Achievements and Tech Maturity**

- World’s first autonomous mapping of underground mine tunnels
- World’s first BVLOS autonomous mapping of a ~150000 m$^3$ underground void in less than 10 minutes
- Conducted 4 trials in underground mines (>7km flown)
- Early Adopter Program (11 early adopters in Australia, Canada, China and Japan)
- Commercial product launch in 2018 through new startup (Emesent Autonomy)

**Team Capabilities**

- Robotics program formed 20+ years ago for mining automation
- Robotics PhDs, hardware and software engineers
- 30+ years combined experience in drone autonomy
- World leaders in 3D LiDAR SLAM
- Extensive field testing experience and developing high TRL systems

**SLAM-based 3D mapping**

- TRL9

**GPS-denied flight and navigation**

- TRL7

**Omnidirectional collision avoidance**

- TRL7

**Single-click advanced autonomy**

- TRL6

**Autonomous exploration and 3D mapping of underground mine tunnels and stopes by a Hovermap-equipped drone**
Autonomous Legged Robots for Underground Sensing and Manipulation – Fred Pauling, Data61 Robotics

Capability
- World-leading legged robot R&D (TRL3-7)
- World-leading SLAM localisation and mapping R&D (TRL3-9)
- World-class multi-modal 3D data fusion R&D (TRL3-6)
- High-accuracy camera-based people detection and tracking systems
- Direct access to CSIRO R&D and deep domain expertise – analytics, cybersecurity, networks, comm’s, mining, nuclear, biosecurity, etc.

Concept for Underground ISR Ops
Ultralight human-scale legged robots for autonomous exploration and mapping of underground environments, with:
- Long mission duration and high payload capacity
- Highly competent mobility over challenging unstructured terrain like rubble, mud, shallow water
- Modular multi-modal sensing payloads for in situ sampling and measurement, e.g., hyperspectral, RF, gas, sound, nuclear, signs of life
- Leg-mediated manipulation and contact-sensing in hard-to-reach locations

Experience and Technology
- 20 years developing high TRL autonomous robotic and sensing systems, with commercial products in the market, including the underground mining industry
- 15 years LiDAR mapping and localisation in complex indoor environments, including caves and underground mines
- Pioneered “ultralight” class of legged robots at human scale – MAX (Multi-Legged Autonomous eXplorer)
DRAPER – Engineering Possibilities

• Independent, not-for-profit commercial laboratory
  – Broad experience in sensor systems and autonomy
  – From Apollo mission guidance to modern autonomous systems

• AUTONOMY – GPS-Denied Navigation and Planning
  – GPS-denied navigation enabling dynamic flight in cluttered environments
  – Demonstrated under DARPA FLA and within enclosed environments (NASA ISS mockup)
  – Expertise in dynamic re-planning, large-scale optimization, and robust planning under uncertainty

• NETWORKING – Magnetic Communications
  – MEMS magnetometer offers orders of magnitude noise reduction in a miniature form factor
  – Advanced clutter rejection algorithms to recover signals below background noise floor
  – Natural pairing with DARPA AMEBA program

• PERCEPTION – Low SWaP Sensing
  – MEMS LiDAR concept with integrated photonics
  – MEMS acoustic arrays provide alternative to light based sensors

POC: Julius Rose jrose@draper.com
Learn more at www.draper.com
**I^2NS**

Image-Inertial Navigation System

D-Vision’s I^2NS Navigation system integrates **single camera image-based structure-from-motion** (aka SLAM) **with inertial navigation**, and **without GPS**, providing position + orientation information and 3D mapping in indoor, outdoor and subterranean environments. Drift error without GPS is 0.5% (CEP50).

**Celestial Location & Attitude System for GPS-denied environment**

**I^2NS** results **without GPS signal** (green), compared to reference (blue). Route - 7.45 miles, drive time - 45 minutes. Drift error at route end - 56.8 yards.

Screenshot of a 3D model reconstructed from tunnel image sequence (White dots), with camera position in every frame (Cyan).
SmarTrack

Product Description:
SmarTrack enables team location reporting in Non/Limited-GPS environments for:
- Tactical level soldiers
- Special Forces
- First Responders

TRL 9, deployed with existing soldier system/first responder ensembles

SmarTrack unit physical dimensions:
- Dimensions: 118 x 88 x 30 mm
- Weight: 300 grams.

Features/Benefits
- Accurate tracking when GPS is unavailable or limited
- Location accuracy of 3 meters RMS
- Tracks from 4 up to 100 persons in a network, up to 300m NLOS between 2 members in the network
- Multi-hop system (up to 5 hops) supports extended range up to several km’s
- IMU-MEMS based inertial sensor (9 degrees of freedom)
- Accurate Barometric Altimeter
- Onboard GPS/Glonass Receiver
- Datalink for C2 and physiological data

Subterranean Application:
The SmarTrack system requires 3 “anchor” units with self-location capability through GPS or known geo-location inputs. With these 3 SmarTrack units placed outside of the subterranean environment a maneuvering sensor network can be established inside the tunnel by deploying participants with additional units. In a tunnel environment line of sight must be kept with at least one unit so units are dropped as ‘bread crumbs’. As additional units are spread through the tunnel mapping of the environment can be performed. In a multi-story urban infrastructure environment, as participants spread out onto the various floors RF ranging techniques are used so that LOS not needed. SmarTrack can also be carried on a robot for search & rescue and reconnaissance missions.

### SmarTrack
Reliable tracking, monitoring and datalink for maneuvering of Blue Forces in subterranean and GPS-challenged domains

Special topography algorithms calculate the relative and absolute positions of the participants in the group by RF ranging using a combination of data from the inertial module and the GPS receiver.
Technology Focus Areas

Perception

- **3D Simultaneous Localization and Mapping** – using FLASH LIDAR and visual odometry. Simulated lighting provides more realistic map creation.
- **Filtered Track Odometry** – Inertial Sensor Fusion, Kalman Filtering
- **Fiducial Marker Correction** – Used for ground truth correction as needed, and UAV launch and recover tasks
- **Object detection** – Trained neural network with map tagging
- **CBRNe sensors** - Plot sensor data on map
- **Obstacle detection** – Incorporated into terrain map for improved navigation
- **3D map data aggregation** – Merge map data between UAV/UGV platforms.

Autonomy

- **Waypoint/Exploration Behaviors** – Autonomous tunnel map creation with no operator communications.
- **Terrain Path Planning** - Finding optimum path using 3D terrain map
- **CG shifting Behavior** - Active shifting using terrain map for improved mobility.
- **Self Righting Behavior** – Autonomously right the platform with no operator communications.
- **Adaptive Illumination Behavior** – Improves mission runtime.
- **Return-to-Home Behavior** – Navigate back to operator for mission data dump and summary.
- **Obstacle Avoidance Behavior** – Avoid obstacles for improved navigation.

Networking/Mobility

- Tracked unmanned ground vehicle with flippers for increased mobility.
- Mesh radio network with option to deploy multiple nodes to extend mission range.

Summary

Endeavor Robotics proposes an integrated solution, combining a battle proven mobility platform, a hybrid simultaneous localization and mapping (SLAM) algorithm, deep learning based object detection, with the ability to operate in a communications denied environment.

In addition to autonomous subterranean exploration, mapping, and object detection capabilities of the base platform, the system may collaborate with an unmanned aerial vehicle (UAV) to extend the mission range. In this robot teaming concept, the ground vehicle deploys the UAV once its mobility limit is reached and aggregates map data from both platforms. For rescue scenarios, an optimal rescue plan may be generated that avoids hazardous areas.
Underground Coherent Imaging Fleet (UCIF)

Overall UCIF Concept

ENSCO UCIF Provides:
- Fusion Algorithms
- Mission Planning
- VR Command and Control
- Scalable Immersive Mapping

Underground Fleet Consisting Of:
UCIF concept includes a dynamically deployable fleet of underground UAV radar and/or ultrasonic imagers that are coherent in time and space:
- **Carrier**: Robotic vehicle deploys and provides power, comms, and compute resources to UAV imaging fleet
- **Coherent UAV Platforms ("BAT" Drones)**: UAVs with µSAR radars and/or ultrasonic radars that send & receive coherent echo returns from underground regions and structures
- **Anchor Nodes**: Deployed by Carrier, able to deploy and charge UAVs, and containing mesh network comms to exfil coherent images, maps, sensor data, and human/machine/utility presence detection

ENSCO Proprietary Technologies Enable:
- **Timing and Positioning** for GPS-denied coherent distributed sensing with the ENSCO Timing, Communications, and Ranging system (TCR SDRs)
- **Human Presence Sensing** (Microsearch)
- **µSAR & Virtual Phased Array Algorithms (VPA)**

ENSCO GPS Denied PNT TCR-D421

SAR/VPA Processing
Millimeterwave (MMW) sensor generating gray scale images, which are analyzed in real time for objects of interest. Cues UGS with high resolution LiDAR for interrogation.

Swarms of sUASs for MMW imaging using distributed arrays. Scene Illumination with LiDAR/MMW.

Distributed Subterranean Tunnel Sensing (DSTS)
Rapid Deployment, Multi-Sized Autonomous Q-UGV Platform
ISR, EOD, Recovery & Utility Mule in Subterranean Domains

**2 ft. Mid-Size Prototype | Mar ‘18 Delivery**

Design Shown: Skeleton w/out Body Panels, Sensors, UAV Battery Swapper or other Electromechanical Payloads

- Low profile & rugged
- Sealed actuators & body
- Mounts & housing design for quick swap of sensors, battery & mechanicals
- Manipulate w/ 250° articulation
- Operates inverted (s/m only)
- Man portable & foldable
- Flexible body design for integrating 3rd party tech

**Next Gen DoD Ecosystem Customizable Q-UGVs: Size-Scalable, Lightweight, All Weather, Very Agile & Long Endurance…**

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<th>Mass</th>
<th>Pay (lbs.)</th>
<th>Endurance (miles)*</th>
<th>Walk</th>
<th>Run (ft./s)*</th>
<th>Man Portable</th>
<th>SDR Mesh Comms</th>
<th>Quick Swap Sensors</th>
<th>Nav &amp; Mapping</th>
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* Use-Case Modeled Specs estimated. Final metrics dependent upon payload mass, sensor & CPU/GPU energy consumption
Humanoid Robots for Subterranean Access and Operations
Underground Communications and Tracking System

- Mine Rescue
- First Responder Teams
- Thermal Vision & Human Detection and Avoidance
- Mine Rescue
- First Responder Teams
- Tracking and Network Maintenance GUI
- Gas Detector
- Handset and Throat Mic

Underground Search and Rescue Communications and Tracking

- Portable Mesh Node
- Smart Battery
- Fiber Optic Switch
- Fixed Mesh Node
- Section Node
- Tracking Beacon
- HDR WiFi AP

HDR WiFi AP

First Responder Teams Tracking and Network Maintenance GUI
LEDGAR-Enabled Subterranean Mapping and Navigation

Technical Concept

LEDGAR-Enabled Subterranean Mapping and Navigation

Technical Solution

• We propose a sensor package for a small UAS
  • The package uses a suite of aligned Light-Emitting Diode (LED) Detection and Ranging (LEDGAR) sensors to actively measure an area of interest.
  • The surrounding volumetric data is compiled, filtered, and used by two sUAS subsystems.
      • The on-board Nav system for active navigation and collision avoidance.
      • The data storage and telemetry systems to generate and distribute a volumetric map for follow-on missions, vehicles, and personnel.

Technical Components and Operations

• Sensors
  • LEDGAR Fan Sensor (Left, Right sides) for Data + Nav
  • LEDGAR Single Sensor (Top, Bottom, Front, Back) for Nav
  • IMU for orientation, velocity

• Datastore
  • Local cache

• Communications
  • Mesh (AES encrypt, serial data rates)

• CONOPS
  • Single or multi node
  • Store and forward comms

  • **Data Collection mode** fuses data to generate point cloud for storage/TM and NAV
  • **NAV mode** uses operational trajectory sweeps coupled with LEDGAR Fan orientation to evaluate path obstructions

Summary

• Our system is a key component technology designed to capture, store, and share information about unknown structural and geological surroundings.
• We have experience designing and operating UAS platforms of all sizes; this package is envisioned to weigh less than 1 kg and be consistent with SWAP requirements for many COTS UAS platforms.
• The system is envisioned to support exploratory (1-way, with telemetered data) and return (2-way, with on-board storage of measured volumetric data) missions.

Leddar™ is a proprietary LiDAR technology owned by LeddarTech.
Background
Fixed-wing unmanned aerial vehicles (UAVs) offer significant performance advantages over rotary-wing or hybrid UAVs in terms of endurance, velocity, payload capacity, and cost. However, the shortcomings of conventional control strategies render fixed-wings less effective with regards to vertical take-off and landing (VTOL) and mobility, and therefore limit their usefulness in complex subterranean environments.

Summary
The research proposes to develop a fixed-wing unmanned aerial vehicle (UAV) for high speed navigation, perching, communication, and sensing in complex subterranean environments. We will employ real-time kinodynamic planning and co-registered long-wave infrared and near-infrared cameras to execute collision-free post-stall aerobatic maneuvers in near total darkness. Our approach will leverage prior work in controller synthesis for post-stall perching and embedded image-based SLAM.

Programmatics
We believe the research to develop this prototype will take one year (12-months) and about $700k. Should the initial experiments prove successful, transition to the field could occur rapidly.

SUB-T UAV Concept
Wingspan: 24 inches
Speed: ~10 m/s
Sensing: FLIR Boson, Ximea MU9PC-MH

Depiction of post-stall 90 degree turn
Open Poster Session
POSSE Concept

Multiple robots cooperating to accomplish the mission. For the most challenging case of volume constrained passageways where longer endurance and range are required, POSSE encompasses remotely-operated tethered train of mini-bots that can perform ISR, deliver various payloads, and/or execute numerous procedures. This concept and associated technologies are easily scalable in size and capabilities. The bots can be ground, water, and/or air-based and may involve the hybrid systems such as natural drones. For larger volume applications, the leader “scout” bot may still involve a fiber tether to provide a local reference point for accurate mapping, deliver and distribute additional resources, High bandwidth (BW) external communication and lower BW for site com with other bots, and potentially C2 for more autonomous missions. The leader bot can potentially pull a conduit that would further enable the fast deliver of additional recourses and/or enable external expert physical access to remote locations in the site.

Cynthia Moss, Ralph Etienne-Cummings, Steven Filo, Samuel Smith, Charbel Rizk

Natural Drones

Biological creatures are highly efficient, mobile, and exist in various sizes and optimized for their environments but have limited reasoning and specialized sensory capabilities. The natural drone concept involves biological platforms augmented with energy harvesting, sensory, and cognitive payload that is integrated with the nervous systems of the live host to collect, process, and extract actionable information and autonomously and/or cooperatively change behavior of said animal to support and/or accomplish specified mission objectives. In addition, some of the hosts naturally operate in packs or swarms. For caves and tunnels, bats would be an attractive candidates for small payload applications.

Innovative Technologies

- High-Precision Orientation, Distance, and Location Measurements Using Distributed Fiber-Optic Sensors
- Low C-SWaP Multi-mode SoC Computational Sensors
  - Structured lighting for 3D mapping
  - Optical flow for accurate navigation
  - Compressive sensing
- Energy harvesting
- Pattern centric reasoning
- Scalable mobility
- Tight integration of engineered and biological subsystems
- Cooperative behavior and networking

Scalable Mobility Examples

Johns Hopkins University, Prosapien LLC, JHU Applied Physics Lab  crizk1@jhu.edu
Marsupial Ground-Aerial Robots for Subterranean Disaster Exploration

Prof. Robin Murphy


- UGV navigates to choke point or branch.
- UAV explores vertical cavities, over obstructions; returns to UGV for charging.
- UGV uses map from UAV to navigate further and more intelligently. Cycle repeats until UGV battery limit is reached. Return using learned map.
- Enables much greater exploration distances and durations.
- Active sensing control to minimize power consumption.
- Vision and 3D-based mapping and precise navigation in extreme conditions.
System Approach
- Leverage Leidos qualifications in:
  - Structure-from-Motion (Parallax 3D software)
  - GPS-Denied Navigation (ASPN ADEPT software)
  - Autonomy & Manned/Unmanned Teaming
  - Lightweight Software-Defined Radios

Benefits of the Approach
- Lightweight sensor package enables rapid transit and extended flight times
- GPS-denied nav provides needed metric scale
- Mature software components serve as foundation for further technology development

Leidos Experience
- Developed high-resolution 3D maps of Crozet Tunnel (VA) using single UAV under IRAD
- Supported multiple distributed dismount, UGV, and UAV GPS-denied demonstrations under DARPA Squad-X and ASPN

Technology Focus Area: Perception and Autonomy

Example: Parallax 3D Crozet Tunnel models from UAV

Example: UGV GPS-Denied: 5.9 m RMS after 6.8 km
Subterranean GPS-Denied Navigation, Comms, and Mapping

BACKGROUND
GPS-denied navigation is becoming increasingly important in ground, air, and maritime domains.
Subterranean domain is innately GPS-denied.
Accurate navigation and 3D mapping is infeasible without a precise positioning solution.
Commercial state-of-the-art navigation/imaging is not sufficient for subterranean applications.

DESCRIPTION
Visual Inertial Odometry (VIO) enables real-time 3D mapping at the tactical level. SWaP decreases make 3D sensing feasible on small UAVs/UGVs.
LGS MIMO and adaptive beam-forming technology enables transient high-bandwidth links in challenging environments.
New algorithms enable LGS to implement real-time VIO and point-cloud meshing at the tactical level.

MANET: Mobile Ad Hoc Network
- Deployed radios
- Rover
- Processing system
- Dynamically optimized routes

Radio nodes
- Low-SWaP, rugged “breadcrumb” radios

Mobile Computation System
- Real-time on-site VIO and mesh processing for rovers

Rover
- 3D sensing and comms to computational system

Visual Inertial Odometry
- 3D sensing
- Point cloud registration
- Aggregation
- IMU
- EKF
- 6D pose

ANTICIPATED IMPACT
Popular 3D sensing technology for defense platforms requires high-precision location/odometry. The proposed system allows for 3D sensors to be leveraged in GPS-denied environments.
Real-time meshing allows faster data offload and visualization, as well as analysis/use of mesh data for pathfinding, signal propagation estimation, change detection, etc.
MANET comms supports unmanned platforms and small teams in challenging RF scenarios.

GOALS
- Generate geo-located 3D meshes of subterranean environments in real-time.
- Provide subterranean team comms and live 3D map view for manned missions.
- Enable UAVs/UGVs as sensor platforms for 3D imagers and computational systems.
**LMAS Capabilities**

- **3D Common World Model (TRL-7)**
  - Distributed 3D Common World Model (3D-CWM) with intelligent sharing of updates in degraded comms
  - Fusion of incomplete, uncertain, & conflicting multi-modal data in austere environments (EO, Lidar, sonar, radar, haptic, and a priori models when available (e.g. surface models)
    - SLAM for modeling and GPS denied autonomy
  - Deployed on mix of platforms: UAVs, UGVs, UUV, Air (TARDEC AMAS, DARPA SQUAD-X, RDECOM MMSF, Commercial Ventures)

- **Collaborative autonomy framework with distributed replanning and MUM-T in degraded comms**
  - Collaborating UAVs and missiles (DARPA CODE)
  - Human, UGV, and UAV teams (DARPA SQUAD-X)
  - Amphibious teams (ONR MARS⁴)

**Approach to Subterranean Dynamic Terrains**

- Swarm subterranean exploration and mapping
  - Collaborative heterogeneous teams with distributed embedded sensing, autonomy, and mapping
  - Spoke and hub resupply/exploration with marsupial power, data, and communications support
    - Extensible Architecture (Air, Ground, Nano, snakes)
  - Robust distributed multi-sensor Simultaneous Localization and Mapping (SLAM)
    - Multi-sensor fusion: EO/IR, Lidar, sonar, radar, haptic, and a priori models when available (e.g. surface models)
    - SLAM using low-light, low power sensors, and nano-UAVs
  - Improved autonomy and MUM-T through deep learning and fused geometric and semantic models

---

⁴ - In negotiations
AMICABLE\textsuperscript{1}-Enabled Heterogeneous Swarms

**Benefits**

- **Key mission elements are dynamically optimized at runtime using AMICABLE**, a framework that takes a set of independent autonomous vehicles and produces a coordinated autonomous swarm. The resulting collaborative UxV behaviors are optimized with respect to environment and mission goals.
- **Swarm of aerial and ground robots with multiple sensing modalities** provides map fidelity in varied environments.
- **Terrain-adaptive runtime behavior synthesis** enables each vehicle to adapt pre-specified exploration/mapping behaviors and synthesize new behaviors to optimize performance in response to changing or \textit{a priori} unknown geophysical characteristics of the subterranean terrain.
- **Key-point descriptor data matching across heterogeneous platforms** allows coordination of UxV mobility and payload/sensing behaviors across the entire team.
- **Scalable, Open Architecture** allows a variety of sensors and algorithms to be fused within AMICABLE’s decentralized, computationally efficient coordination architecture.

**Innovations & Key Attributes**

- **Co-optimization of sensing, exploration, vehicle assignment and communication** maximizes information gain and speed of mapping, while satisfying energy constraints and maintaining communications between vehicles and human operators.
- **Terrain-adaptive runtime behavior synthesis** enables each vehicle to adapt pre-specified exploration/mapping behaviors and synthesize new behaviors to optimize performance in response to changing or \textit{a priori} unknown geophysical characteristics of the subterranean terrain.
- **Key-point descriptor data matching across heterogeneous platforms** allows coordination of UxV mobility and payload/sensing behaviors across the entire team.
- **Scalable, Open Architecture** allows a variety of sensors and algorithms to be fused within AMICABLE’s decentralized, computationally efficient coordination architecture.

\textsuperscript{1}Autonomous Mission-aware Collaborative Behaviors – Adaptable

Heterogeneous Architecture Enables Flexibility in Choice of Platform, Sensors, and Perception
Multi-modal Sensor Fusion Indoor / Underground Mapping

Advanced Mapping and Positioning System (AMPS) Developed for Army (TRL5)

- Localization
- IMU
- Wide Beam Ultrasound
- Narrow beam Ultrasound
- Magnetic North bearing
- Node ID
- Distance/orientation vector
- Self-leveling enclosure

VitalWave: UWB Micro-Doppler Radar Remote Triage System, Army (TRL5)

- Detachable Antenna Array
  - Detachable
  - Handheld
  - Tripod compatible
- Full Unit with Antenna Attached

Multi-modal
- Vision based: Stereo-imaging, laser
- Time of flight based: RF, acoustic, optical

Multi-tiered
- Flexibility in sensor combinations

Data fusion
- Infer map features and resolve conflicts based on multiple sensor tiers and sensor nodes

Multi-output
- Building floor plans and subterranean layout mapping
- Imagery for surveillance followed by advanced image recognition algorithms
- Personnel tracking and

Wireless
- Sensor nodes communicate with control nodes to enable high bandwidth sensory streams (e.g., surveillance)

UWB - Radar Based Vital Sign Detection
- Detect heart/respiratory rates, blood pressure, oxygen saturation with a minimum of 95% accuracy through obstacles and debris made of materials such as wood, plaster, rock, metal and concrete at a minimum distance of 50 meters

mm-wave Based Highly Integrated Digital Beam-former & Beam-scanning (TRL4+)

- Produce high resolution images of the surrounding environment and objects

Small SWaP
- Suitable for both wearable & unmanned autonomous vehicles and robots
Autonomous Aerial Drone System for 3D Mapping (AADS-3D)

Continuous mapping of subterranean systems using SONAR equipped onto a particle swarm optimization system

**AADS-3D Particle Swarm Concept**

- Particle Swarm Analysis enables groups to explore multiple caverns simultaneously.
- Here a swarm of 6 drones with blue primary control transmitter splits into two sets to explore different caverns simultaneously.
- One of the red receiver drones knows to become the green transmitter drone in the new smaller sub group.
- Groups of drones allow for more data points collected in each location, one from each receiver drone.

**Locations for AADS-3D Testing Accuracy**

- Missouri S&T Experimental Mine
  - Mine is surveyed annually with a land survey total station for comparison
  - Layout of the mine can easily be changed with temporary walls, to simulate different subterranean environments.
  - Variable wind speed to simulate potential wind speeds in subterranean environments.
- Missouri Cave Systems
  - Missouri has 7,300 caves that can be used to examine the applicability of the AADS-3D

**Sonar Advantages**

- Lower Cost
- Light Weight
- 5cm resolution
- Works in poor visibility

**Sonar Cave Mapping Result**

(W. Sellers, A. Chamberlain 1997)

**Impact and Benefits**

- Autonomous continuous mapping of subterranean systems
- Multiple transmitter and receivers for multiple point cloud analysis

---

Directed by Catherine Johnson (johnsonce@mst.edu) and Phillip Mulligan, Missouri S&T; Simone Silvestri, University of Kentucky
3D Path Planning and Control

Current AM3P Capabilities

Advanced Modular Mobility Maneuver Planner (AM3P)
- Off-Road Motion Planning System That Incorporates Vehicle Models To Assure Stability And Safety
- Operates in GPS-denied Environments
- Optimal Trajectory Selection in 2.5D
- Dynamic Planning in Complex Terrains
- Selective Reasoning of Individual Wheel Placement on Uneven Terrain
- AM3P incorporates modeling of vehicle dynamics which allows it to plan and operate in rugged and dynamic terrains that require planning in three-dimensions.

Planned Enhanced AM3P Capabilities

Bandwidth and Latency-Scalable Control
- Provides robust long distance safe-guarded teleoperation in high-latent, low-bandwidth environments. Provides a novel high-dimensional user control interface and world model data compression capabilities.
Wave Relay® Mobile Ad Hoc Network (MANET)

GO WHERE OTHER RADIOS CAN’T

Persistent Systems’ Wave Relay® product line bypasses the traditional communication infrastructure to build scalable, reliable networks where others fail.

Integrate your current system with the network…

...using multifunctional connectors

(3) USB, Ethernet, HDMI In/Out, PTT Audio, (3) RS-232, Radio over IP, 3G-SDI & Composite, Wave Relay MPU5 and Embedded Module
Narrow-Band Impulse Radio (NBIR™) for Subterranean Comms, Location, and Detection (SCLAD)

A Revolutionary Breakthrough in Low-Frequency Wireless:

Features:
- Merges CW & Impulse Radio to Deliver Unprecedented Performance for ELF & VLF Wireless links.

Benefits:
- Better Penetration,
- Faster Data,
- Low Probability of Intercept (LPI)
AUGERS –
Automated UnderGround Exploration, Reconnaissance & Surveying
Colin Shellum, Raytheon-BBN Technologies, cshellum@raytheon.com (703-282-3614)

Subterranean (SubT) and Underground Facility (UGF) Navigation Challenges
- Wide Range of Environments—man-made and natural / damaged or operational
- Confined multi-dimensional environment requires precision horizontal and vertical mobility
- Large size and highly complex 3D layout—calls for endurance and potentially parallel teams
- Limited Line-of-sight stresses communications—calls for mesh relays and/or VLF frequencies
- Autonomy and inter-platform collaboration required if no human entry (austere environments)

Raytheon-BBN Technologies Team Expertise
- SMEs in UGF characterization, Geophysics, Counter-UG sensing, UG Navigation and PNT
- Expertise: LiDAR-based sensing, MANETS; multi-modal sensor fusion from fixed and mobile autonomous sensors; UAV swarm mission planning, management & control

Mobility
- Our experience in DARPA and DTRA CUGF programs, the Hard Target Research and Analysis Center (HTRAC), and tunnel prosecution from our Army Border Tunnel Activity Detection System (BTADS) gives us broad knowledge of all subterranean and underground facility environment & mobility challenges.
- Flexible platform approach capable of rapidly, accurately, and collaboratively negotiating unknown SubT 3D features (tunnels, shafts, rubble, small openings, equipment, vents, etc.)

Perception and Sensing
- Multi-vehicle exploration teams use COTS Image/LiDAR/IMU-based SLAM augmented with novel Optical/Ultra-Wide Band (UWB) RF inter-platform localization to cost-effectively minimize IMU/dead-reckoning integration drift
- When available VLF "underground GPS" developed by DARPA RSN program can provide integration-free UG location fixes
- Multi-modal active/passive EO, UWB-RF, IR, & ultrasonic acoustic sensors enable operations in austere (dust, smoke, etc.) environs
- Integrated domain-specific sensor fusion optimally combines expected features and phenomenology of all major types of UGFs (e.g., 3D layout, air flow/temp/humidity, IR for rescue/ID, seismo-acoustic for detection & equipment ID, etc.)

Comms, Data and Networking
- Depth and complex UG 3D terrain will require multi-platform and/or "bread-crumbs" LOS relays for "long-haul" team to portal C2/Exfil comms with high-reliability VLF Surf-SubT back-up C2 comms
- Local SWARM inter-platform communications and data sharing required for collaborative autonomy provided by UWB-RF used for intra-swarm relnav
- Content-aware networking paradigms and scalable heterogeneous MANET developed on the DARPA CBMEN, C2E, and DYNAMO programs to maximize network performance

Mobility
- Scalable/Modular design for single platform or heterogeneous team, variably configured for UGF-specific mission/task
- Onboard AI domain-specific knowledge of expected UGF conditions, SLAM, and perception/sensing support collaborative mission autonomy optimizing balanced energy consumption, maintenance of RF exfiltration/C2 links, and mission performance (rapid, flexible and accurate).

- Mission/Function
- Status/Age/Condition
- Design, 3D Layout and Depth
- Operational Complexity
- Mission Equipment
- Support Equipment
- Security/Protective Systems
- Personnel
- Environmental
- Geotechnical/Geology

Raytheon-BBN Technologies - DARPA-SN-18-11 Dynamic Terrains

Ver. 2
Family of systems Localization and Mapping in GPS denied areas

**Technology Focus Areas: Perception/Mapping**

Under the DTRA MACS-B program Robotic Research LLC has been equipping warfighters and robotic systems for underground missions. The family of systems includes localization, coordinated mapping and communication infrastructure that provides situational awareness for a mixed robotic/human mission. The figure to the left shows the localization of warfighters and robotic systems in an underground facility for a four hour mission. Much of the technology requested in this RFI is already implemented and soon to be deployed by our SF community.

### What is MACS-B?

- Mobile Autonomous Counter-WMD System, Increment B
- Heterogeneous unmanned platforms able to autonomously operate together, performing high-level mission tasks in a dynamic environment with minimal operator involvement
- Systems can also be remotely controlled by an operator to compliment the human element during the completion WMD-elimination missions
- Current Components – UAV/UGV platforms with collaboration capabilities, through-the-earth communications, UAV mapping sensor, 3D-printed hybrid UAV/UGV, autonomous/wireless snake, perch and stare sensor capabilities

### Purpose:

- Provide innovative capabilities to accomplish functional defeat and subterranean mission objectives.
  - Mapping and reconnaissance capabilities
  - Locate and characterize the presence of WMD materials
  - Relay intelligence and situational awareness back to ground forces and commanders to make informed decisions to support functional defeat of targets
- Expand autonomous/collaboration capability to include UAVs
- Future Efforts: Payload development, platform integration and collaboration

### Summary/Notes

**Contact**: Alberto Lacaze, Robotic Research  
240/631-0008  
lacaze@roboticresearch.com

**Casevac, Medevac assessment map generation**

**Cooperative mapping of outdoor areas using photogrammetry and ladar mapping**

**Cooperative 3D modeling of underground areas with cooperative ground and air platforms**

**EOD related model generation both from ground and air platforms**

**“Warfighter Robotic Teammates”**
Autonomous Unmanned Systems Technologies to Support Subterranean Operations

Rapid Abstraction in Confined Environments (RACE)

Challenge: Autonomous sit. awareness in denied interior environments
- Interior ops require high level of autonomy due to limited comms, high uncertainty
- State of art mapping algorithms return only geometric data; missions require semantic info

Goal: Geometrically & semantically map interior env. simultaneously – fast!

Three-pronged approach:
- Classify rare / important objects: Leverage pre-trained CNN’s, but extend to classify targets with sparse or nonexistent training data
- Active perception: Close control loop around classification; autonomously move sensing agent(s) to reduce uncertainty
- Multi-physics integration: Framework to integrate RGB, depth data with other sensing physics (multispectral, magnetic, acoustic, spectroscopy,...) to support classification

Synergies: Classification & mapping / segmentation processes bootstrap each other
- Ongoing internally-funded R&D

Relevant Mobility Exemplars

Gemini Scout Mine Rescue Robot
- Mature platform developed / hardened for mine rescue ops
- Multi-segment tracked body makes radical mobility over rubble, stairs, etc. easy

Small Hybrid Driving / Hopping Robots
- Specialized combustion process enables hops of >20x vehicle length
- Core tech from DARPA IMLM & Urban Hopper pgms

Versatile, Energy-Efficient Legged Robots
- Legged platforms handle terrain but use 10-100x energy of wheeled/tracked counterparts
- Novel silent drive systems & tailored passive mechanisms enable 10x increase in endurance
- DARPA M3 program

Neural-Inspired Architectures for Efficient SLAM

- Brain-inspired SLAM algorithms leveraging deep learning processed sensor inputs, hippocampal algorithms and neuromorphic hardware
- Energy efficient implementations in emerging low-power neuromorphic computing hardware
- Adaptation via hippocampal-like functions

Specialized Access

- Novel technologies enable compact, mobile, high-speed drilling
- Autonomous drilling through layered composite structures
Shield AI provides autonomous, intelligence collection and synthesis in hostile / denied areas for achieving precision effects. Our aim is to provide better mission outcomes with dramatic reduction in individual, mission, and political risk.

We focus on collection in dense urban environments, subterranean structures, industrial facilities, building interiors in support of direct action, C-WMD, force protection, combat search and rescue, special reconnaissance missions, security force assistance, and maritime operations.

Shield AI is a fast growing, venture backed start up with world-class expertise in artificial intelligence, autonomy, and aerial robotics/ drones.

Shield AI is led by a seasoned executive team with deep experience and understanding of the complex problems faced by the US military, including the subterranean mission set. We have a track record of successfully building award-winning products and engineering technological breakthroughs for intelligent, multi-robot systems that continuously learn from their experience.

Shield AI has been awarded contracts by the DoD and DHS; and the capabilities and products derived from these efforts have been described as “game-changing” by customers.
SoarTech – Subterranean Robotics Capabilities

• Challenges of Subterranean Environments:
  • Vast networks of locally confined environments.
  • Good local communications, but relays are required for communications outside of local area.
  • In emergency situations, paths may be fully or partially blocked, and can change quickly during mission execution.

• Approach
  • Use heterogeneous teams of robots that can spread out over the global subterranean network quickly.
  • Ground/airborne teams can cooperate locally to maximize travel distance and sensing capabilities

<table>
<thead>
<tr>
<th>Feature</th>
<th>Innovation</th>
<th>Benefit</th>
<th>Related Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactical Behavior Model</td>
<td>- Implements least-commitment decision strategy with awareness of team roles and overall mission plan.</td>
<td>- Platforms can adapt to novel environments and team structures to complete tasks.</td>
<td>SquadX-CT (DAPRA/TTO), TacAir-Soar (DARPA STOW, J-9, Navy FBE), Helo-Soar (Army SBIRs)</td>
</tr>
<tr>
<td></td>
<td>- Allow entities to collaborate based on their roles, requesting data and actions that complete their own tasks.</td>
<td>- Platforms can collaborate based on roles and unique capabilities.</td>
<td></td>
</tr>
<tr>
<td>Swarming-based Team Management</td>
<td>Nature-inspired approach that produces emergent, robust, team based behaviors</td>
<td>Large teams can spread out and explore environments quickly with limited comms.</td>
<td>DARPA ADAPTIV/WASP, JFCOM LOE, NAVAIR</td>
</tr>
<tr>
<td>Cooperative Multi-platform sensing</td>
<td>Create team structures that enable ground and air platform to coordinate sensing. Combine sensor data with multi-view stereo and SLAM algorithms.</td>
<td>Combines benefits of air/ground platforms for exploration time and sensing flexibility. Improves sensor reach/coverage in challenging environmental conditions.</td>
<td>SquadX-CT (DAPRA/TTO), AirAsst (AF Civil Engineering Center)</td>
</tr>
<tr>
<td>Adaptive Deep Learning</td>
<td>Deep learning classifier that can leverage user feedback to re-train in near real time.</td>
<td>Object classifiers perform better in operational conditions that differ from training environment.</td>
<td>SID-Packbot (MCWL), AirAssist (AF CEC)</td>
</tr>
</tbody>
</table>
Cosmic ray muons penetrate deep into the earth. They are easily detectable with low SWaP-C hardware that may be incorporated into a soldier’s gear, or handheld sensor. A measurement of the muon rate in the detector is an indication of depth.

**Depth measurement:**
1. User with muon sensor constantly monitors muon rate
2. Rate is proportional to depth (model well characterized)
3. A 1 sq-ft area system under 50 m rock can measure depth to ±10% in 17 min, ±5% in 60 min.

Muons may be detected with cheap plastic scintillator at ~ 100% efficiency. The rate of muons detected depends on the amount of rock overburden. A barometer may be confused by pressure variations in an underground area due to ventilation system settings. A simple muon rate measurement is immune to most environmental parameters.

High energy protons hitting the earth’s upper atmosphere create showers of particles, including muons. Muons are highly energetic and minimally ionizing, allowing them to penetrate deep into the earth (~ few km).

Their attenuation as a function of depth is well characterized. A simple rate measurement can be used to measure the depth of a detector.

At left, a low-cost muon detector built at SRI using plastic scintillator, silicon photomultipliers, and an Arduino is able to measure muons at near 100% efficiency.
Collaborative Autonomy: Trust and Mission

Heterogeneous collections of robots engaged in cooperative behavior to conduct a search in subterranean domain require an integrated and balanced system approach to support communications, perception, mobility and control. Our design involves:

- **Collaborative Autonomy Architecture**: SRI incorporates robotic behaviors into an existing, mature open architecture and extensive mission platform-agnostic behavior library.
- **Driven by the mission**: We decompose real-world search, locate and report object-of-value scenarios into robotic functions based on defined tasks and mission targets.

Scenario: Locate and report

Target: Valued Object

Task: Build/Env’t in-storemap | Establish Comm Network | Detect Valued Object

Functions: Explore Environment | Map Local Obstacles | Aggregate Map with | Plan Deployment Positions | Group Deployment Positions into Teams | Object recognition | Object verification | Object Reporting

Networking: Impromptu wireless communications

Large networks for subterranean domain search mission must rapidly configure themselves without human intervention; moreover, they must rapidly reconfigure themselves to generate new formations as conditions change. Today it takes a day to configure a 100-node network and the resulting network is fragile and unable to adapt to changing environments. We propose:

- **Dynamically reconfigurable mesh network created from small UAVs that act as packet forwarding routers**
- **Packet Forwarding Routers** form a comprehensive wireless communication network without any pre-existing infrastructure
- **Ad-hoc routing protocol** forwards each packet to its final destination among the nodes in the network even in subterranean environments

Mobility: Ingress/egress in challenging terrain

Achieving extreme mobility in unstructured environments while minimizing robot complexity and cost, and achieving mission-length power autonomy, all remain challenging problems. We offer:

- **Electrostatic clutches** allow one motor to control 100’s of DOF
- **Twisted String actuators** offer ultra light weight and ultra low cost
- **Flexible braided mesh body enables multiple modes of locomotion**

Perception: Navigating an unknown environment

Standard approaches to localization attempt to determine the pose of robots with respect to a fixed global coordinate system. These approaches require environmental landmarks whose position must be either known *a priori* or determined during mission execution. Unfortunately, a priori models are generally not available, and maintaining such models in dynamic environments remains an unsolved problem. Our approach includes:

- **Robot Teams as Landmarks**: Robots make use of each other as the sole landmarks for localization. Robots describe their pose with respect to every other robot in the team
- **Data Sharing**: Robots retain the ability to share sensor data, build real-time maps and coordinate their activity
- **Dual-Mode Loop Closure**: Robotic team uses a dynamically reconfigurable particle filter that recognizes revisited locations using both semantics and the sensor net node

RFI Response - Dynamic Terrains

Nahid Sidki, SRI International, nahid.sidki@sri.com (650) 859-6126

Heterogeneous teams of autonomous cooperative agents
Cave Exploration and Mapping

Concept

- Exploration range = 2 x (wheeled path range + UAV flight to overcome obstruction)
- Mobile Stations: Shared comms Hub / Map Integrator
- Dual drone system: Distributed Perception, Additional range, either could be stationary

Challenges - Expertise

- Optimal Route Planning
- Obstacle Avoidance & Navigation
- Sensing

- Enhanced NIR and LWIR Scene understanding
- Realistic simulation for NIR, Laser, and Sonar Sensors using Unreal Engine (AirSim)
- LWIR & Sonar
  - Visual-inertial Odometry, mapping, and obstacle detection
  - No illumination required (power, stealth)
  - Smoke-tolerant
  - Low SWaP-C
  - Complementary sensor modality
- Closed loop sensing
  - Reactive replanning to optimize detection and mapping
- Autonomy
  - Integrate route planning, navigation, sensing and obstacle avoidance.
  - Intelligent switching between air and ground mode

Innovation

- LWIR Camera
- TeraRanger Tower

Partnership Opportunities

- Platform design for a versatile and hybrid vehicle saving energy while driving and flying when obstructions
- FOCUS - SquadX
- DARPA: generates UAV search route plans to maximize threat detection
- R-Advance – FLA / SA3
- DARPA: navigate fast in unknown environments. No GPS
- R-Advance – FLA / SA3
- DARPA: navigate fast in unknown environments. No GPS
- Optimal Route Planning
- Obstacle Avoidance & Navigation
- Sensing

Contact: Hector.Escobar@ssci.com
Acoustic Mapping and Structural Characterization in Subterranean Environments

Objective: Design and prototype an acoustic payload system that maps and characterizes a low-light or obscured subterranean environment.

Description of effort:
- **Mapping:** Frequency-diverse active ultrasound array for mapping and forward-obstacle awareness.
- **Motion Detection:** Alternative waveform allows Doppler processing for LOS/NLOS (around corner) moving object detection
- **Platform Location:** Mapping data can be used to simultaneously refine platform IMU
- **Structural Characterization:** Probing with low-frequency acoustic exciter and laser Doppler vibrometer (LDV) identifies objects with differing material responses (e.g. infrastructure, doors, debris).

Benefits:
- Acoustics functions in low-light conditions, is not disturbed by obscurants, and provides NLOS propagation.
- Acoustic component technology well established.
- Payload concept extends beyond mapping
  - Active Motion Detection
  - Structure characterization based on acoustic excitation response

Technical Challenges:
- Developing algorithms that use results from multiple acoustic modes to isolate returns
  - Multipath for around-corner Doppler detection
- SWaP of LDV and acoustic exciter practical for crawling and hovering autonomous robotic platforms
- Adapt existing acoustic ground mapping methodology to enable characterization of underground structures
- Operational trade between advance rate for mapping relative to characterization

Progression to TRL-6 Prototype

**Phase 1: Proof of Concept (6 months)**
- Initial payload design and prototype component development
- Ultrasonic room mapping and motion-detection development
- Offline signal processing development to address multipath and structural characterization
- Proof of concept testing to validate performance model

**Phase 2: Initial development (9 months)**
- Final payload design and prototype development
- Real-time implementation of mapping, detection, characterization, and noise isolation algorithms
- Validation off-platform (payload on skids)

**Phase 3: Final Development (9 months)**
- Test and evaluation against diverse environments
- Sensor and signal processing improvements
- Final test and demonstration
DISCUS (DISruptive Concepts for Underground Swarms)
Technology focus area: Autonomy

New Paradigm in Autonomous Navigation
- Vision cued random access LIDAR
- 3 orders of magnitude data reduction
- High resolution point cloud at regions of interest (ROI) only
- High precision navigation in GPS Denied environments
- Deep learning classifiers
  - Small world models, shared across platforms
  - Find targets efficiently and reliably
  - Mission-driven guidance and mapping
  - Collaborative missions

Innovative Sensors
- MOABB LIDAR
  - Fast, random access, photonic, chip-scale
- Teledyne EO/IR fusion - deep learning camera
  - Vision cued LIDAR based localization
- Optical communication
- Laser geospatial referencing
  - Mark terrain features on the go
  - RF silent, non-line-of-sight comm.

Innovative Underground Swarm Platforms
- 9” GaurdBot is an amphibious ground vehicle capable of carrying multiple sensors
- Spherical quadcopter for rough terrain capable of mixed flight and ground missions

Vision detects wires
Vision defines ROI
Vision cued LIDAR test bed data (ROI: electrical wire at 27 m)
Algorithmic real time detection of electrical wires
Teledyne’s Novel EO/IR Fusion-Deep Learning Camera
GuardBot spherical ground vehicle (9.5”) with side pods for sensors
Spherical quadcopter with side pods for rolling and vertical operations
Point cloud measurement of object of interest
Dynamic Terrains Networking

Barrage Relay™ Networking (BRN)-Autonomous combining of energy from multiple transmissions

SwA P optimized SDR for autonomous platforms

Robust physical layer processing combats severe multipath

System level MIMO enhances diversity to combat terrain
Co-located MIMO cannot overcome correlated shadowing

Integrated RF ranging for enhanced GPS-denied localization

Robust physical layer processing of energy from multiple transmissions

Advanced networking enables collaborative autonomy and sensing

BRN enables synergistic integration with autonomous swarms for operations in extremely challenged RF environments
The purpose-designed UAV will enable rapid exploration and evaluation of this confined space environment ahead of mine rescue teams.
**Capabilities**

- Through-The-Earth (TTE) / Barrier network connectivity demonstrated 300m – 450m into SubT, Caves, Tunnels....
- Various soil types, rock, reinforced concrete, buildings....
- Suitable data rates for voice / text / PLI / sensor data
- Easily integrated with conventional or mesh radios / networks
- Positional Information in GPS denied SubT Environments

**Discriminators**

- Above to Below Ground / Through barrier connectivity w/o use of wires or repeaters (RF denied areas) – infrastructure free
- Patented digital modulation provides superior performance
- Portable – Low Size Weight & Power, software programmed
- Performance able to be modeled with software application

**Target Applications / Requirements**

- Communications in / into Subterranean (SubT) operations
- Buried sensor / tunnel perimeter breach detection
- Rescue operations post kinetic action / remote demolition
- DARPA A MEchanically Based Antenna (AMEBA) project leverage
- Positioning in GPS denied areas / collision avoidance

**Key Engagements / Highlights**

- Leverages Los Alamos Labs patented technology
- Initially utilized in mining industry and MSHA approved
- New York City Subway adaptation
- Toyota-ITC positioning detection project
- Technology adapted in support of other agency projects
- Numerous DoD / DHS Experiments / Demos supported
- Demonstrated with Military MANET / MESH technologies

**Opportunities**

- Vital Alert is transitioning this technology from a commercial mining space into new SWAP constrained applications where the unique network through earth / barrier connectivity and positional information extrapolates to solving new problems.
- We have focused application of the technology into two primary areas:
  - Network connectivity where other methods are impractical and / or impossible – voice / data / sensor
  - Positional reference in GPS denied areas

**Touchpoint**

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Felix.Boccadoro@VitalAlert.com
Open Poster Session