U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

NEXT GENERATION TECHNOLOGIES FOR ROBOTICS

2022 Future Force Capabilities Conference

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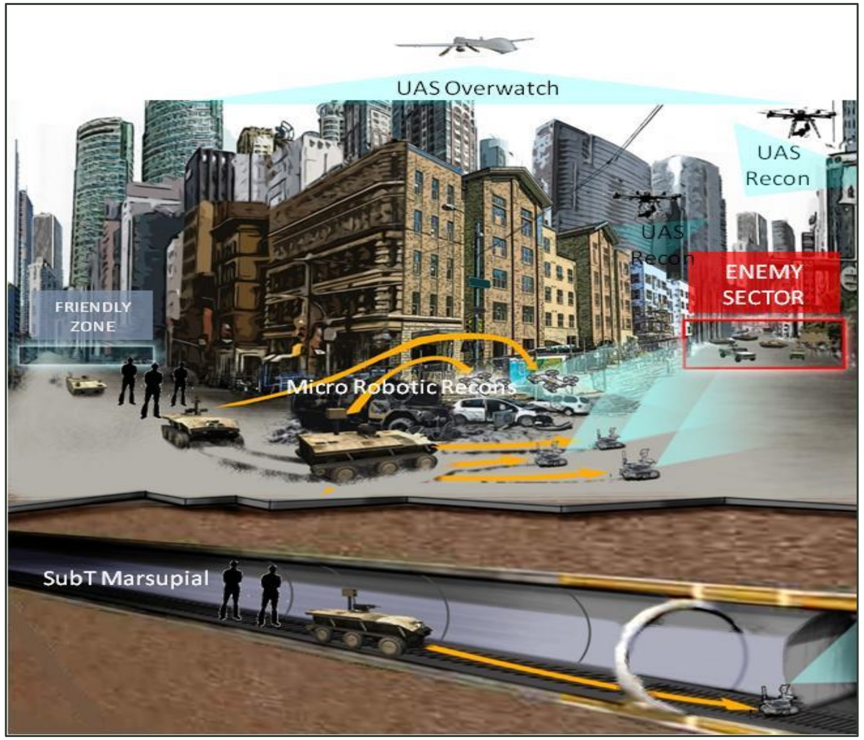
NEXT GENERATION TECHNOLOGIES FOR ROBOTICS

Future MDO concepts:

- Require maneuvers to penetrate and operate in complex and contested areas.
- Rely heavily on advancements RAS.



RAS are being explored to:

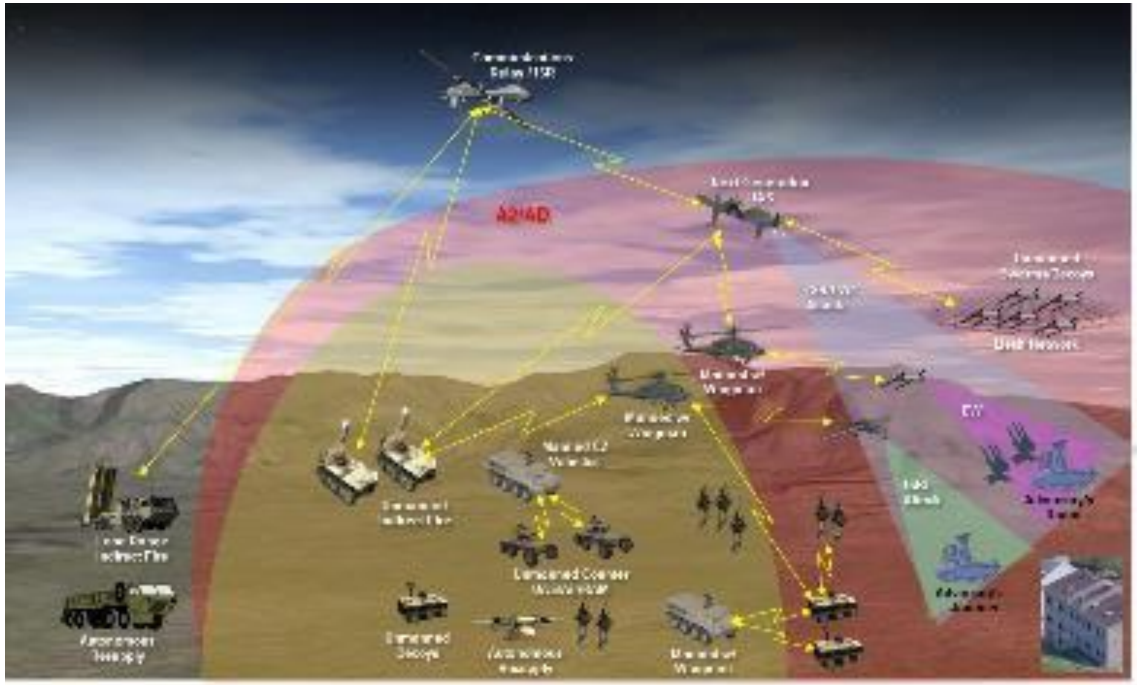
- Operate across all Army relevant environments.
- Provide better situational awareness.
- Increase warfighter standoff.
- Increased coverage and dilemmas to the adversary.
- Enable faster decision making.
- Extend maneuverability in ways yet-to-be-imagine.

RAS will be required to:

- Assess scene and create and share both local and common world models.
- Coordinate actions, decisions, and maneuver across echelons, teams, sub-teams, and individual systems (including humans) at the scale and speed of the fight.
- Adapt and be resilient to large disturbances and changes in the environment and adversarial operations.

NEXT GENERATION TECHNOLOGIES FOR ROBOTICS

Future concepts rely on "Scalable Teams of Autonomous Systems" consisting of:



- Scalable #'s of agents from tens to hundreds+
- Heterogeneous mix of systems:
  - Large/Small, Air/Ground/Sea, Manned and Unmanned
  - Humans in multiple roles (Commanders, Teammates, bystanders)
  - Systems with varying levels of autonomy, sensors, processing, and operational payloads
  - Collaborative systems with adaptable roles operating in distributed, decentralized, and layered operations
  - Increased team-based cognitive and tactical behaviors, dynamic tasking, and real-time distributed perception and decision making
  - Operation in complex and contested environments – peer adversarial capabilities
  - RAS will operate as part of joint inter-service and multinational teams

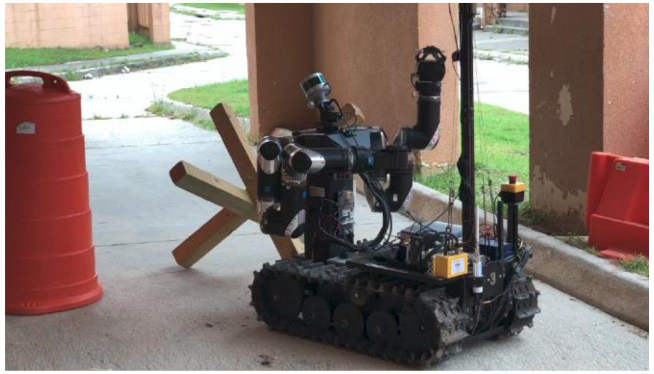
NEXT GENERATION TECHNOLOGIES FOR ROBOTICS

Univ. Penn

TRV-150 UAS
w/ Resupply Payload

Autonomous Air and Ground Systems that can Operation in Structured and Unstructured Terrain

Scalable UAV with Hybrid and Extreme Endurance, Payload and Agility Performance



Unique Mobility for Extreme Terrain and Manipulation of the Physical World

Autonomous Systems that can Operate in Homogeneous and Heterogeneous Teams

APPROVED FOR PUBLIC RELEASE

THE ARMY CHALLENGE

<u>Most autonomy efforts today are done with either:</u>

- Small numbers of systems
- Limited environmental complexity
- Established/known supporting infrastructure
- Only homogeneous platforms and platform roles
- Engage in only single task missions
- Limited ability to represent the world beyond geometric information
- Large errors and uncertainty in aligning information between distributed platforms
- Solutions are brittle to large disturbances in the environment, the team composition, or the context of the mission

Scale

Mobility

Networking

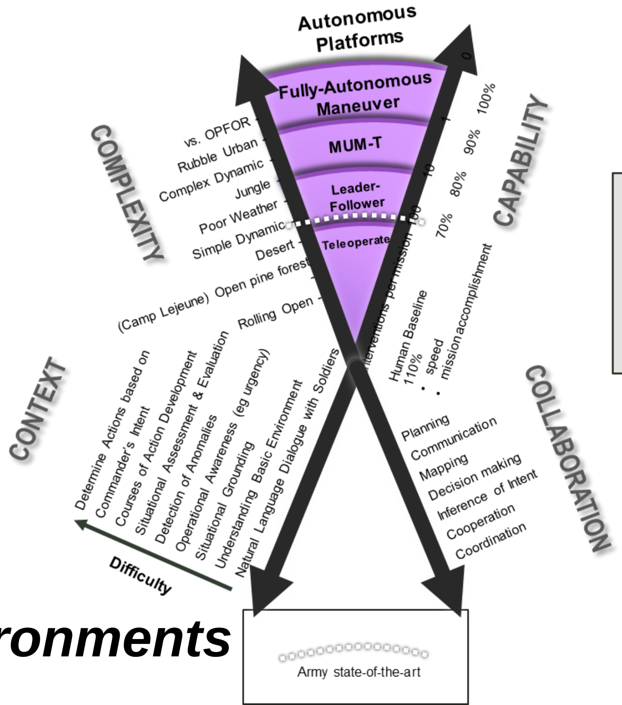
Plan Adapt
Control
Communicate

Team-of-Teams

Adversary

Environment

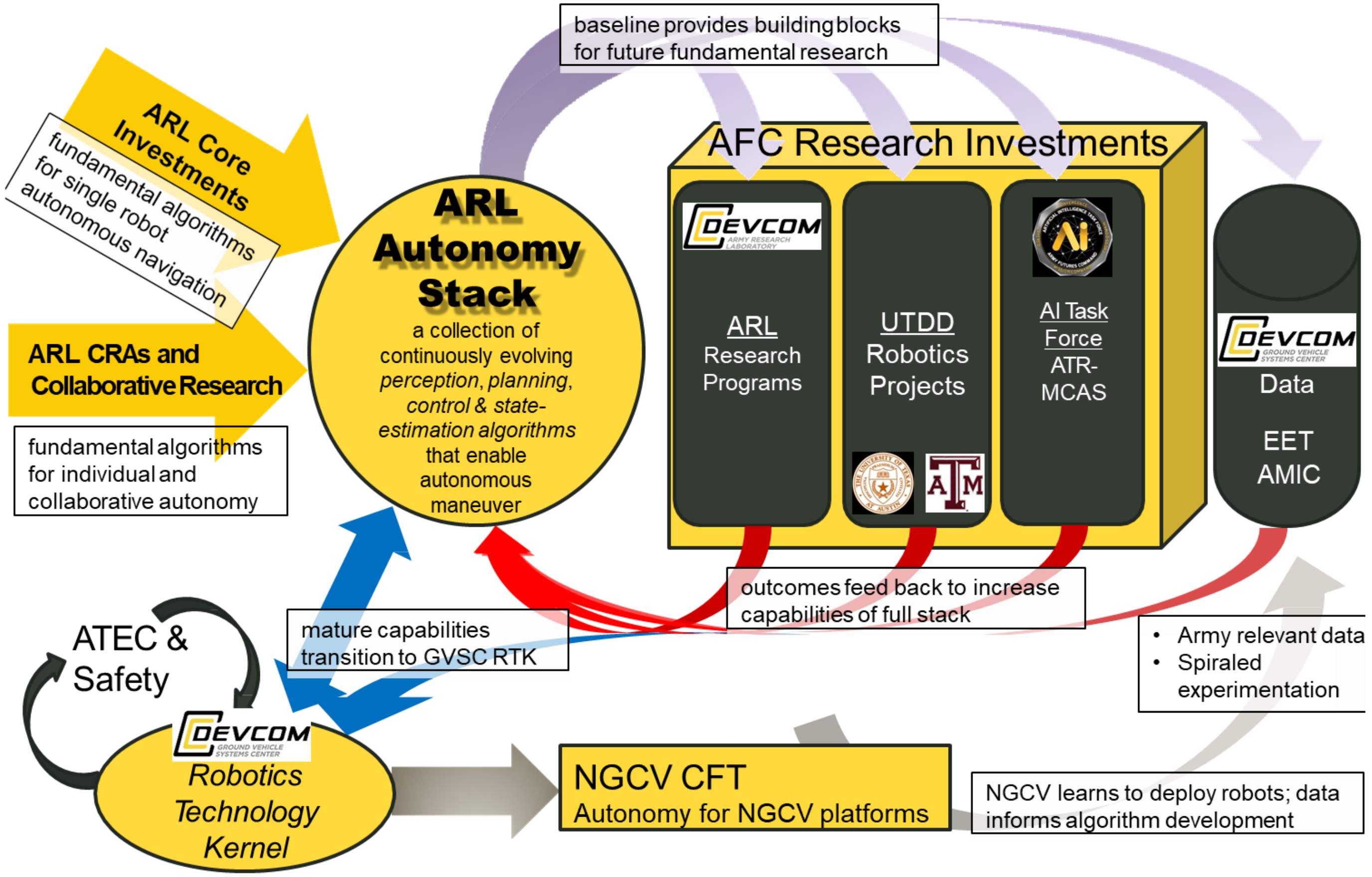
Energy



Axes of Complexity:
- Mission
- Environmental
- Adversarial

Real Robots in Real Environments

ARL GROUND AUTONOMOUS SYSTEMS



Testbeds include:

- **This picture can change** - there are *lots* of ways to run a robot and we need a flexible architecture to explore innovative solutions with collaborative partners.
- Enables **innovative solutions to component technologies** but **assessment within a full autonomy stack**.
- Builds a **cumulative capability** and ensures a **pathway to transition** to higher TRL and Protected Autonomy Solutions.
- Open Source/Gov. Purpose Rights stack with Open Stack and Protected Enclaves and Integrations ensures that **ARL can share and ingest code with Industry and Academic partners**.
- Enables research to support many stakeholder applications and future concepts.

OFF-ROAD MOBILITY

Challenge:

- Speed – moving at OPTEMPO from point A to point B
  - Uncertainty and risk-aware perception
  - Fast and efficient local planning
  - Terrain awareness and adaptation
  - Improve planning speed and travel distance, with lower overall algorithmic cost
- Robustness – reducing # of Soldier interactions required
- Complexity of terrain – navigating steep inclines, through thick brush, reasoning about the environment

Terrain awareness and adaptation

Courtesy Colorado School of Mines

MULTI-ROBOT MAPPING AND NAVIGATION

Challenge:

- **Centralized approaches** are impractical with large teams or in the presence of tight communication constraints
- Need to go beyond **metric to metric-semantic information for planning and reasoning**
- **Requires fast and robust outlier-rejection and pose estimation**

Fully distributed Kimera-Multi

Approach & Results:

- Kimera estimates local trajectory and mesh. Robots then communicate to perform distributed loop closure detection, outlier rejection, and PGO.
- Alignment & fusion of maps generated by robots with heterogeneous localization and mapping pipelines
- Similar performance as centralized system, but reduces communication 2-20x
- Correct frame-alignments in high-outlier regimes (> 95% outlier associations) & low runtime (< 30 ms)

Y. Tian et al., IEEE TRO, 2021, Y. Chang, et al., ICRA 2021, P. Lusk et al. ICRA 2021, K. Fathian, et al. IEEE TRO 2020.

ARL AIR AUTONOMOUS SYSTEMS

- **Small UAS (< 20 lbs) software platform focused on vision aided flight, detection and localization, onboard decision making and multi-agent teaming.**
- **Comprised of DoD owned and open-source software:**
  - ROS2 based autonomy platform; PX4 based flight controller running on a pixhawk
- **Examples:**
  - Machine learning for perception and decision making
  - Vision enabled/GPS denied flight
  - Air-ground and multi-agent teaming
- **Target a common software environment that can build on and expand these capabilities over time.**

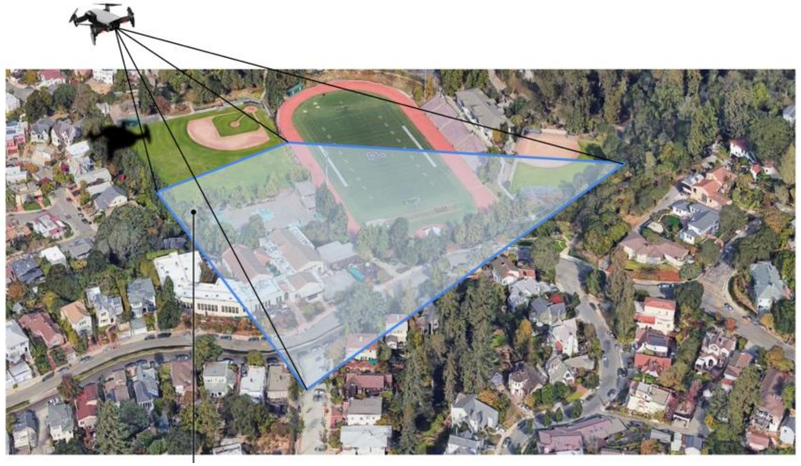
- **Examples of current platform users:**

  Texas A&M, University of Delaware, UC Berkeley, NYU, USMA, University of Maryland, University of Texas at Austin
- **Supported by DEVCOM Soldier Center**
- **Leverages DIU Blue UAS Architecture**

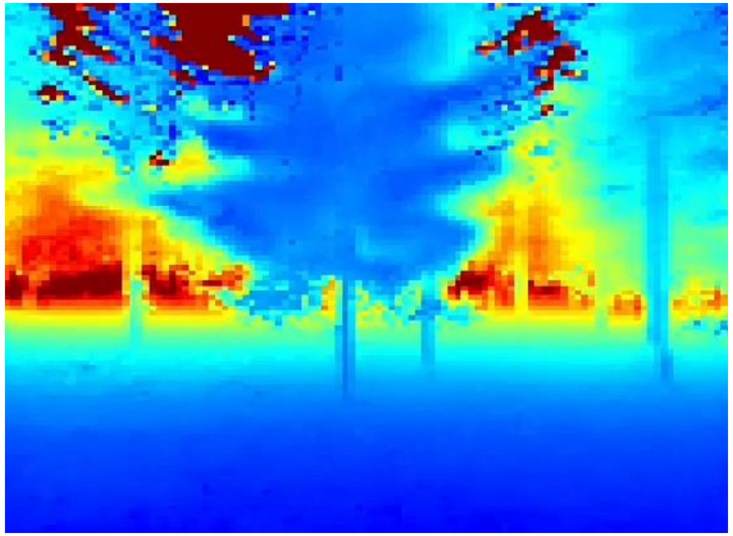
Modal AI VOXL m500	Modal AI Sentinel	ARL WARDEN	ARL VICTOR CPR-Quad
			

SINGLE AGENT PROJECTS AND COLLABORATIONS

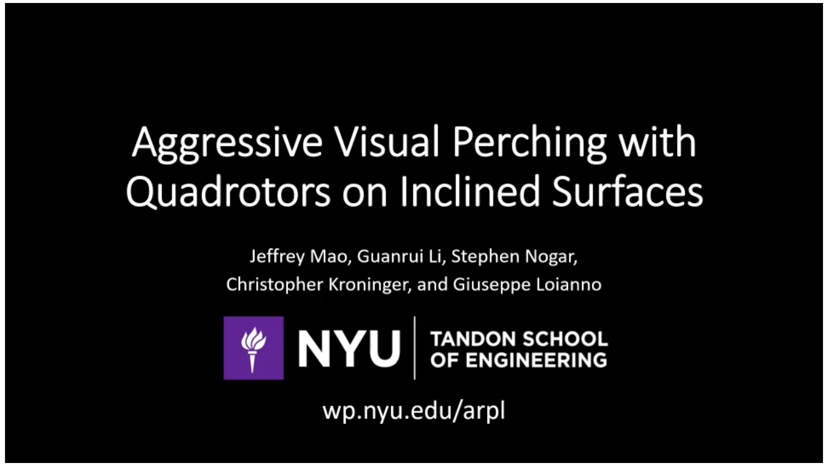
UC Berkeley Obstacle Avoidance and Global Localization



U. Del. Depth from Monocular on SWAP Constrained Systems



NYU Perching



Autonomous landing on a moving ground platform

On-Board Perception

Multi-Agent with ROS2 decentralized communications

DYNAMIC TEAMING OPERATIONS IN CONTESTED ENVIRONMENTS

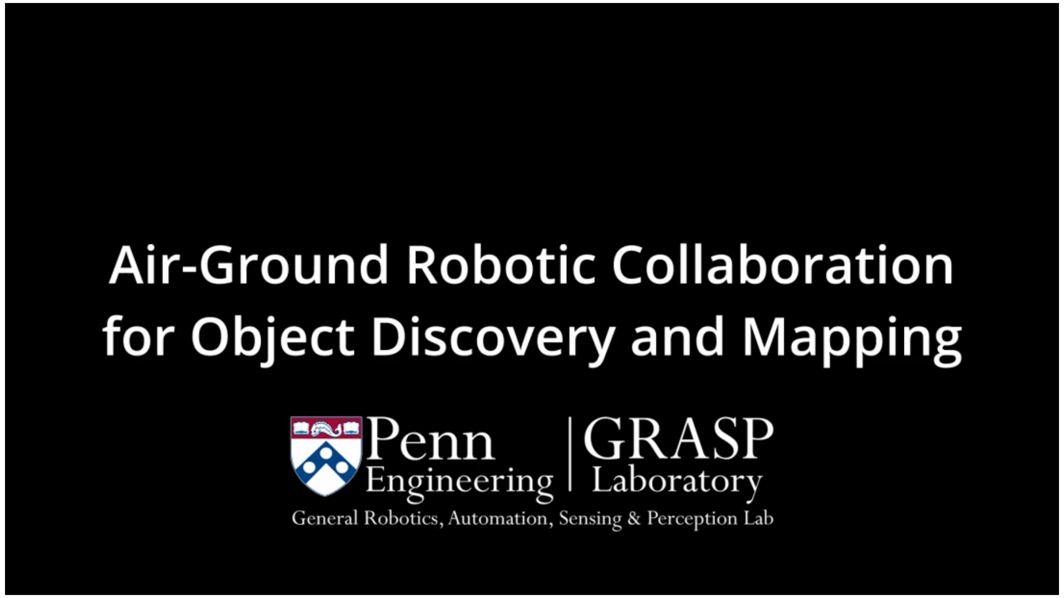
Air-Ground Collaboration with Human Operator

Objective:

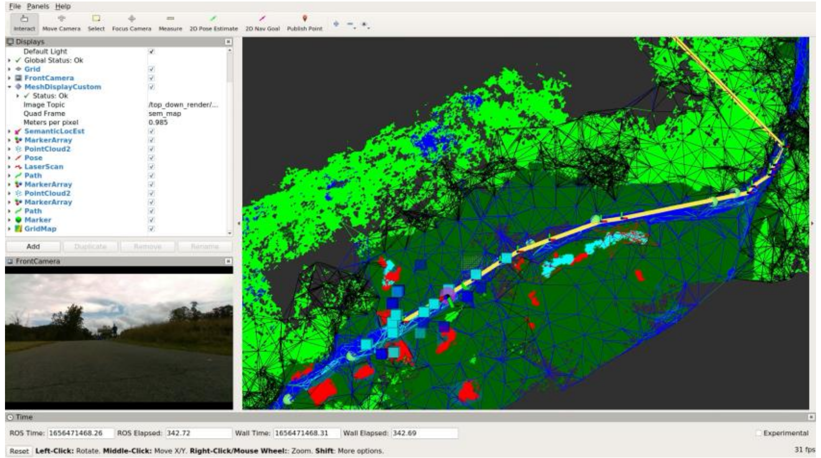
- UAVs and UGVs that work collaboratively on missions and enable an operator to task a robot team with high level goals without needing to specify trajectories or other low-level details.

Outcome for air/ground coordination:

- UAV constructs a photogrammetric map that is used for localization and planning by UGVs.
- UGVs perform mission to search site and localize objects of interest within map and without GPS.
- UAV deployed over site relays information and object detections back to ATAK base station using mesh networking and distributed database.
- Interfaced with ATAK server. Semantic maps (with fuller scene understanding) provides richer situational awareness and better decision making to human partner.



Two UGVs tasked to explore site and relay object detections back to the base station using the distributed database and the UAV generated overhead map



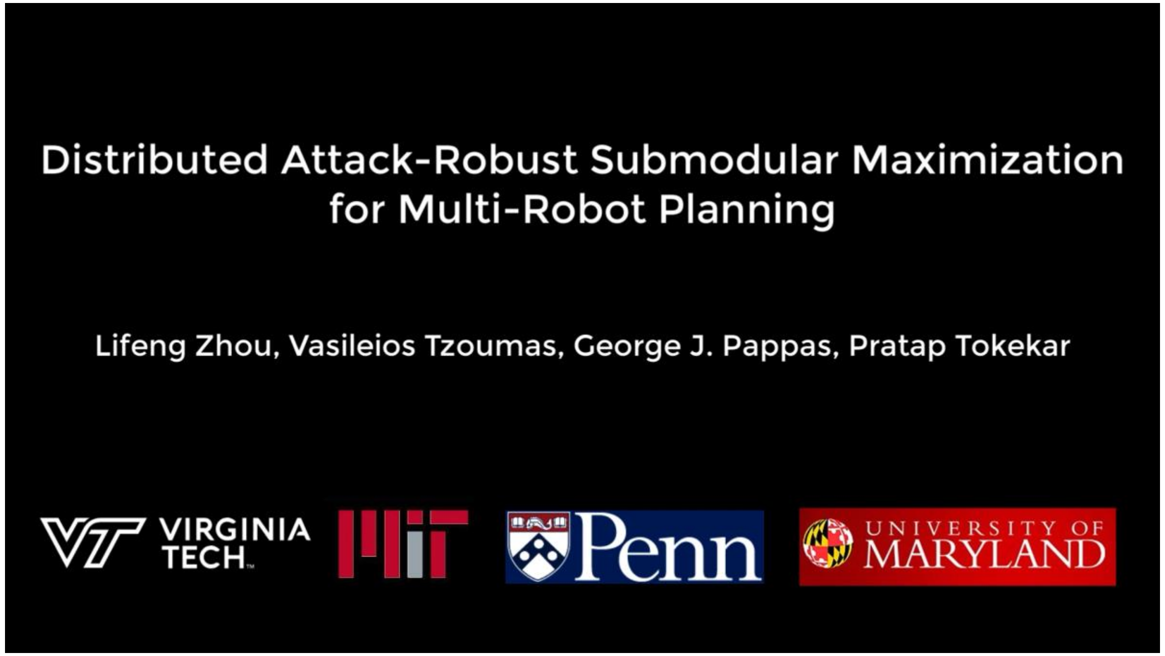
UGVs operating in a Aerial Generated Semantic Map at Scale

COLLABORATIVE DEPLOYMENT

RESILIENCE MULTI-AGENT ACTIVE INFORMATION GATHERING

Challenge:

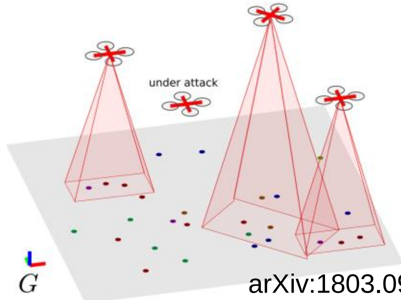
- Attack-robust multi-robot planning is computationally hard and **centralized approaches do not scale**
- **Communications may not be possible** because of scale, environment, or adversarial actions
- Information gathering must be **resilient to system or sensor degraded performance or loss**



Ten aerial robots track fifty ground mobile targets with limited communication range and resilience to sensor failures.

Approach & Results:

- Partition the problem among cliques of robots with local communications
- Uses Improved **Distributed Robust Maximization (DRM) where cliques optimize in parallel**
  - DRM is faster up to a factor $1/K^2$ (where K is the number of cliques)
  - Near-to-centralized performance having a suboptimality bound



arXiv:1803.09730v3 [cs.RO] 2 Sep 2018
arXiv:1910.01208v3 [cs.RO] 1 Nov 2020

MOBILE WIRELESS NETWORK INFRASTRUCTURE ON DEMAND

DEVCOM ARMY RESEARCH LABORATORY

Challenge:

- Providing wireless connectivity at scale requires both coordinating large distributed systems and deploying and maintaining costly infrastructure
- Need methods that scales in a manner suitable for online applications for more than a handful of agents

Approach and Results:

- Uses a supervised learning approach that learns to place communication agents from an optimization-based strategy
- Relay nodes strategically position to facilitate communication between task-oriented robots
- Runs 1-2 orders of magnitude faster than optimization methods for teams of 10-20 agents

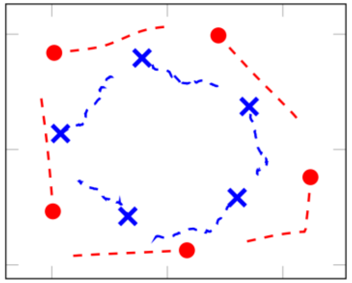
Learning Connectivity-Maximizing Network Configurations

Daniel Mox*, Vijay Kumar*, Alejandro Ribeiro†

* GRASP Lab, University of Pennsylvania
† Electrical and Systems Engineering, University of Pennsylvania

Learning Connectivity Maximizing Network Configurations:

- Blue – Relay nodes
- Red – Task Agents



arXiv:2002.03026v2 [cs.RO] 24 Mar 2020
arXiv:2112.07663v1 [cs.RO] 14 Dec 2021

Penn MIT Georgia Tech USC University of Cambridge UC San Diego Berkeley George Mason University UCSB University of California Santa Barbara UNC Charlotte Mines West Point

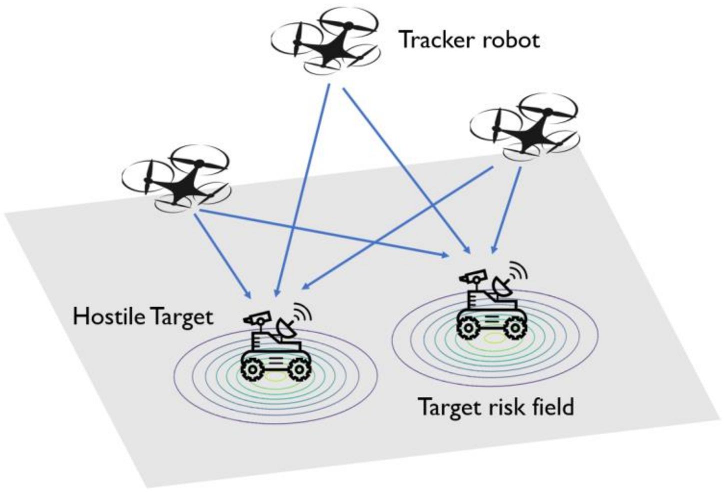
ADAPTIVE AND RISK-AWARE TARGET TRACKING WITH HETEROGENEOUS ROBOT TEAMS

Challenge:

- Addressing the competing objectives of performance maximization and sensor preservation to include:
  - A predictive component—which accounts for the risk of being detected by the target
  - A reactive component— which maximizes the performance of the team regardless of the failures that have already occurred
- How to systematically balance the objectives of risk-aversion and performance-focused adaptiveness in heterogeneous multi-robot teams?

Approach and Results:

- Risk-aversion and tracking performance maximization are automatically traded off by considering the **sensing margin**
- Prioritizes performance when the sensing margin is large and switches to risk-averse behaviors as the sensing margin of the team decreases
- Risk-aware adaptive controller continues operations in the face of sensor failures and operates longer by accounting for future failures



A team of robots equipped with heterogeneous noisy sensors tracks a set of mobile targets where:

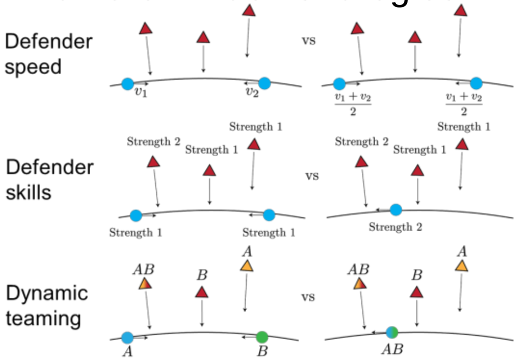
- Targets are moving and can induce failures in the robot sensors based on the proximity between them
- Robots must position themselves close to the targets to generate accurate estimates but must simultaneously account for the risk of failures

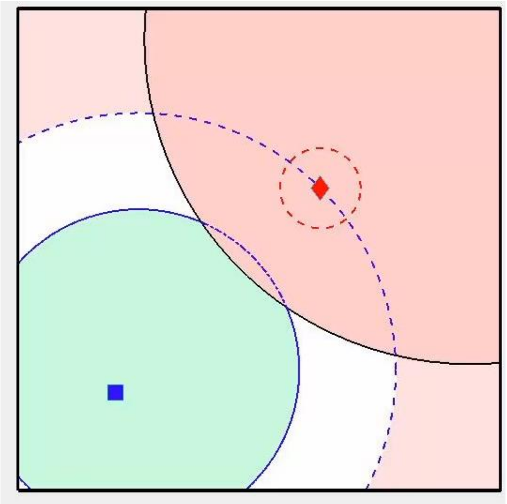
arXiv:2105.03813v1 [cs.RO] 9 May 2021

ADVESARIAL ENGAGEMENT and COLLABORATIVE TACTCAL BEHAVIORS

Tactical Behaviors in Sensing Limited Perimeter Defense Games

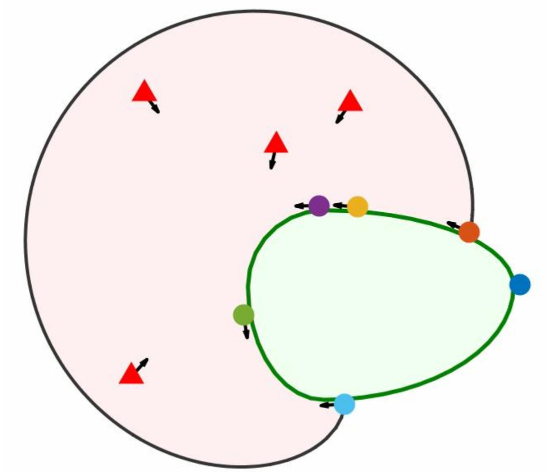
- Heterogeneity in Asymmetric Information Games - asymmetric sensing / communication ranges result in states with different Nash strategies



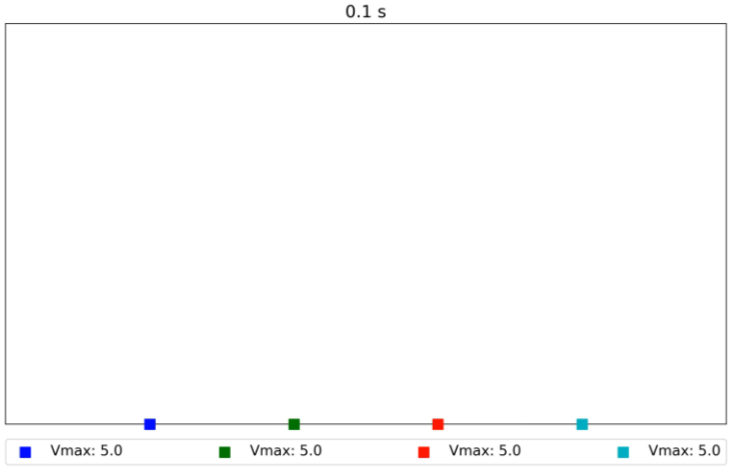


Scalable Cooperative Team Strategies

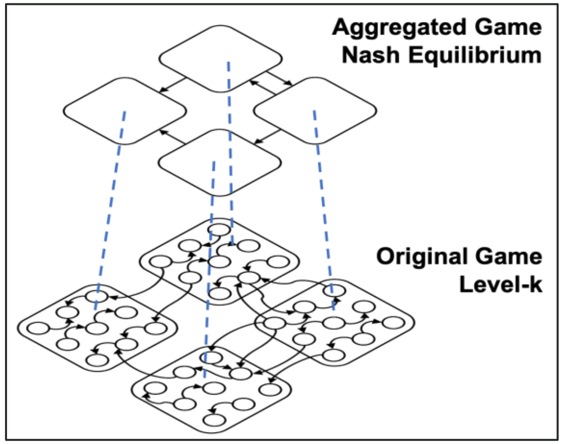
Perimeter Defense



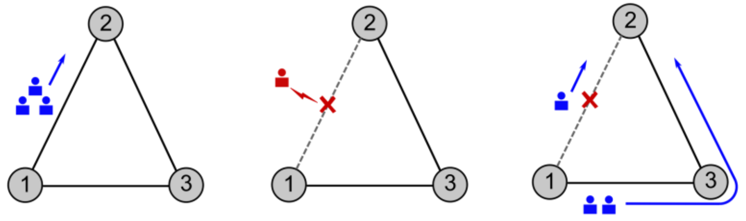
“Wave” Attack



Hierarchical structures in stochastic games to reduce computational complexity



Resilient Resource Allocation



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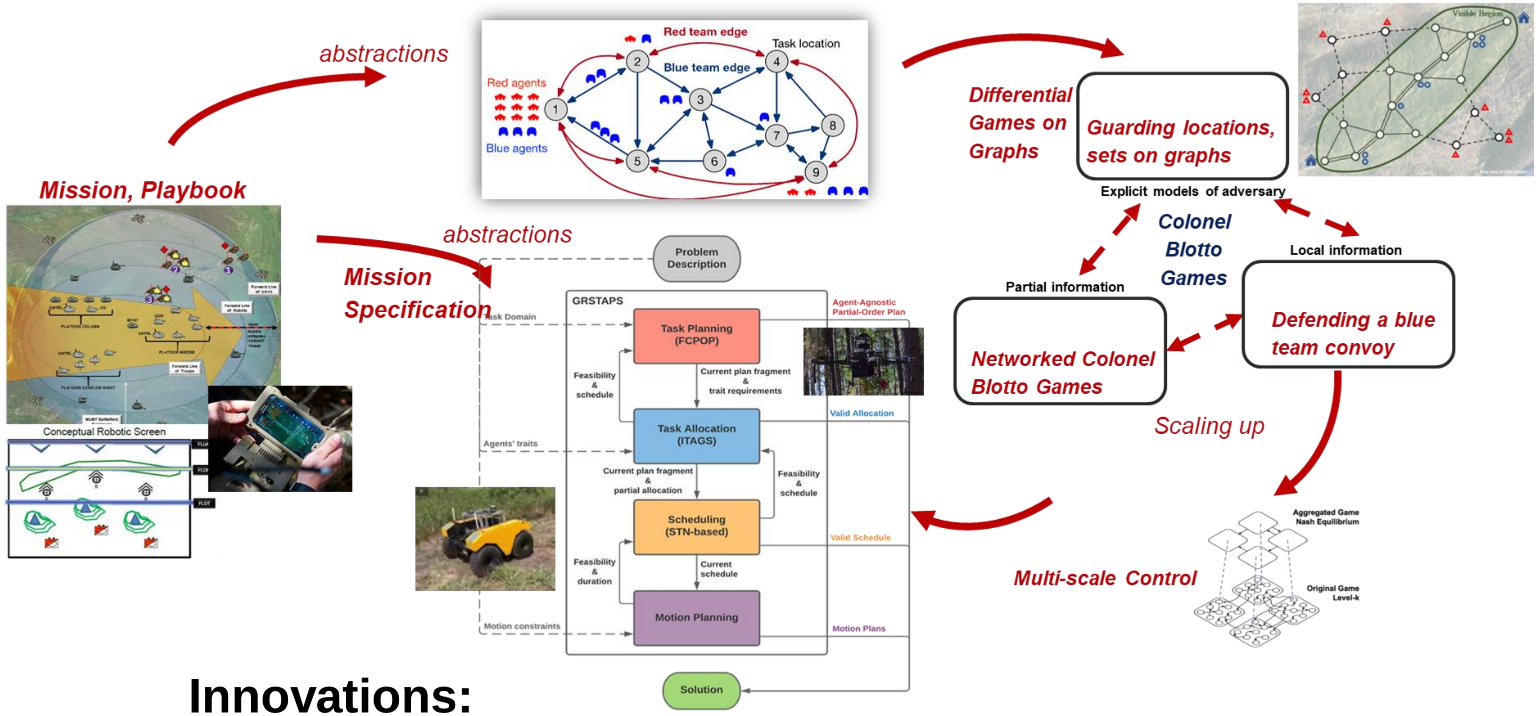
FRAMEWORK FOR MISSION SPECIFICATION, TASK ALLOCATION AND MOTION PLANNING FOR HETEROGENEOUS TEAMS

Enabling a human commander to specify a mission that can be compiled into tasks and motion plans that can be evaluated, verified and then executed



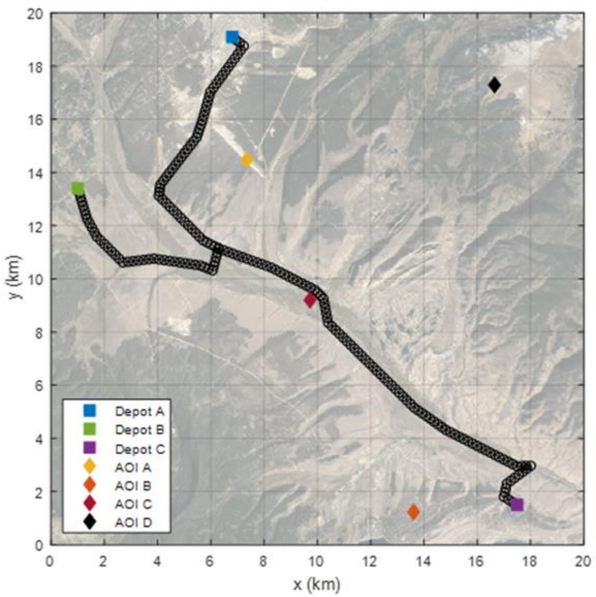
Primary research questions:

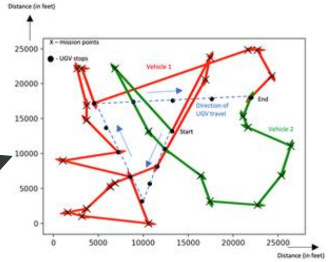
- How to **mathematically model a mission with a team of heterogeneous agents** in adversarial, dynamic settings?
- How should **information inconsistencies** be modeled, and how should robots **act based only on local information/models**?
- How do we **plan at the task and agent level**?
- How can we **scale up to large environments and large number of team members**?

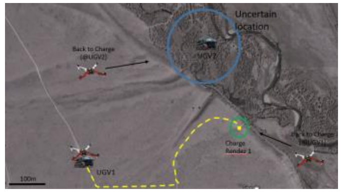
Innovations:

- Hierarchical consideration of optimal and bounded-rational decision making, leading to scalable solutions
- Differential games on graphs with blue and red teams
- Abstractions of missions from playbooks derived from end-users
- Mission/task planning, asset allocation and motion planning for heterogeneous assets
- Explicit modeling of local information and decentralized control, and inconsistencies in agents' local information

ENERGY AWARE MISSION PLANNING







Ops Time

Gal Fuel

Batts

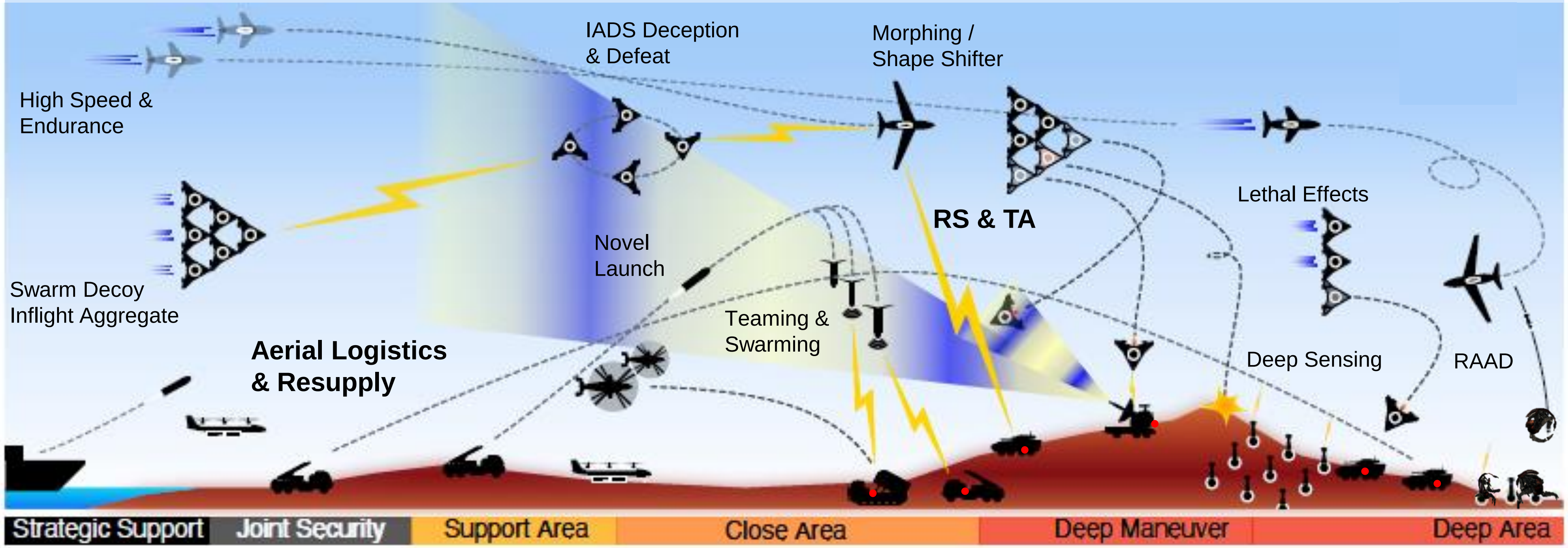
Fundamental Questions:

- Under resources constrained environments balancing task priorities, energy limits, and time. What are the best methods to use in various representative squad mission scenarios to maintain 72hrs of operation of a set UGV-sUAS team?
- How does the impact of heterogeneous agents influence energy demands and tasking?
- What are the elements of state uncertainty that cause the most impact on energy resources (agent location, energy consumption, energy remaining, task success, etc.) and what are best mitigating contingency methods that reduce their impact?
- How many agents and what types ought you to field given certain mission scenarios?
- How does improved planning impact the logistics chain (less fuel, reduced batteries, more operation time, etc.) ?

Emerging and unexplored opportunity space for disruptive impact

MOVEMENT OV1

Multi-domain Operations through VTOL and Extreme Mobility in all ENvironments and Terrains



The Army must engage in "transformational change" to achieve overmatch, deter great power competition, and win the future fight : *Army Chief of Staff Gen. James McConville*

RS & TA: Reconnaissance, Surveillance & Target Acquisition
RAAD: Robotic Air Assault Drones

WHAT IS *X*UAS?

S&T research-oriented effort in key vehicle platform technologies to address the Army's Aviation capability gaps by advancing UAS performance, agility and survivability attributes

Operational Capability

Increase capabilties to 'see', 'move', and 'neutralize' to achieve transformational overmatch in MDO

Technical Challenge

- How do you enable UAS platforms and CONOPS with extreme performance, agility, and survivability attributes ?

Technical Capability

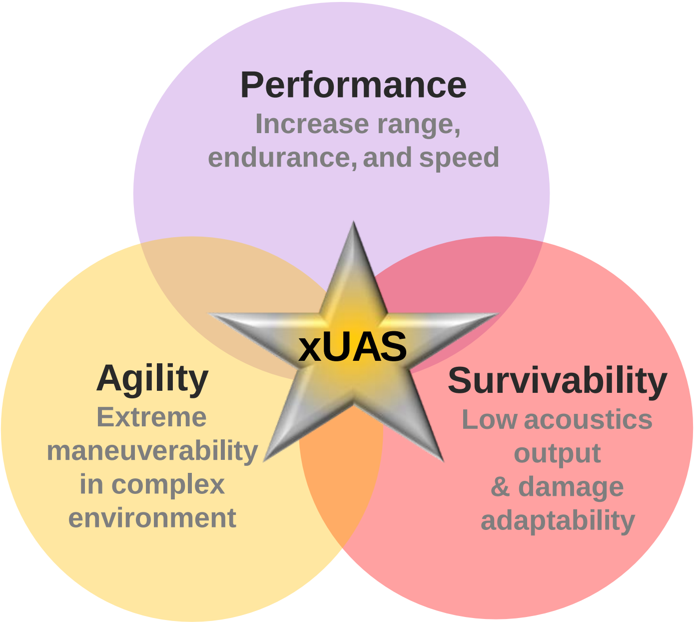
Understand and exploit

- Scalability of fluid and structural dynamics processes
- Adaptable material and reconfigurable structures
- Robust flight control and guidance for novel configurations

- **Aeromechanics, structures, and controls research operationalized into knowledge products**
  - Conduct exploratory, high-risk high-payoff research efforts for disruptive gains
  - Understand UAV platform architectures and identify CONOPS
  - Coordinate with on-going research programs in propulsion, autonomy, and payload technologies

XUAS : ENABLING TRANSFORMATIONAL CAPABILITIES

CAPABILITY for:
- Improving desired UAV attribute without compromising others
- Accelerate design-build-fly process
- Exploit advances in emerging technologies to enable next generation UAVs and CONOPS



EXTREME UAS CAPABILITY for:
- Increased reach, payload capacity at reduced power demand and lower detectability
- Enhanced maneuverability for operations in congested spaces
- Intelligent autonomy to learn, adapt & reason faster than the adversary

Key Knowledge Products to Operationalize Science

HYDRA
Hybrid Design & Rotorcraft Analysis

Analytical tool for:
- UAS design for prescribed requirements
- Inverse performance analysis
- Technology impact evaluation

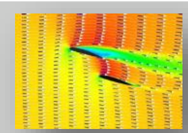
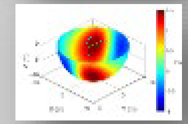
MUTANT
Morphing UAS Technologies for Adaptive Novel Tactics

Concepts and technologies for:
- Wing-span morphing
- Ultra-flexible rotor
- Smart material with tailored properties

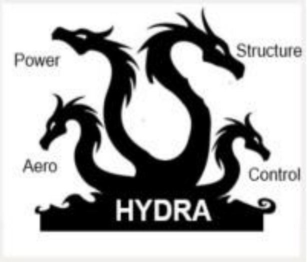
STADIUM
Simulation Theatre for Autonomy Development for Intelligent Unified Mission

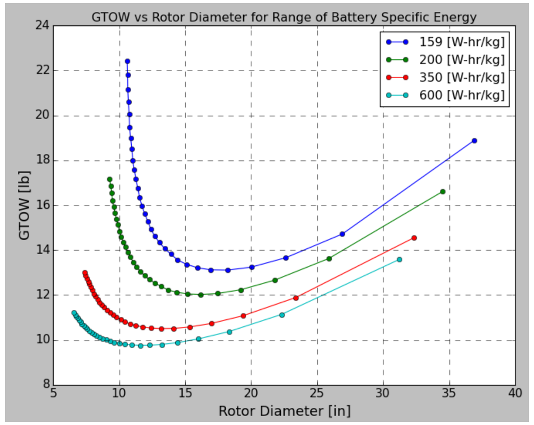
Virtual simulation environment for:
- Autonomy methods evaluation
- Teaming concepts development
- C-UAS ,EW payload integration

XUAS RESEARCH AREAS

Tech Domain	Sub-domain
Design & Aeromechanics	 **Aerodynamics:** Experimental and computational studies of flow interactions
	 **Aero-acoustics:** Acoustic source modeling and propagation
	 **Vehicle Design:** Novel vehicle and rotor concepts for extreme attributes
Structures & Mechanics	**Smart Materials:** Highly adaptive materials with tailorable responses
	Structural Morphing: Reconfigurability for aerodynamics & geometric shaping
Guidance & Control	**Flight Control:** Robust and adaptive flight controls for autonomous flight
	Intelligent Guidance: Vehicle-state informed autonomous trajectory planning

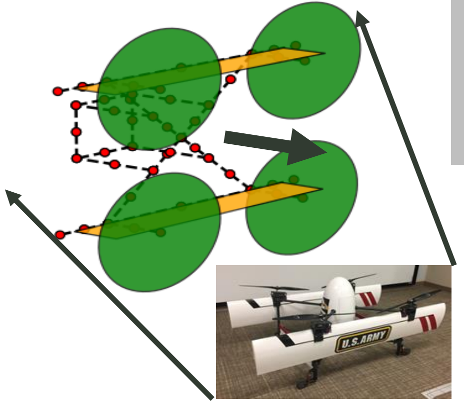
HYDRA: HYBRID DESIGN AND ROTORCRAFT ANALYSIS

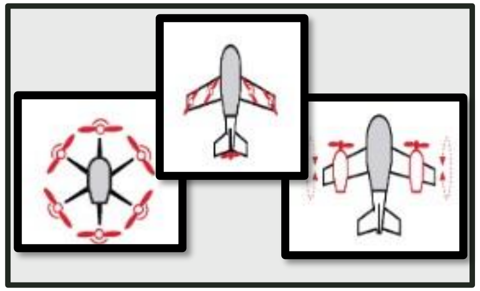




Challenge:

- How can we assess complex configurations with little prior data?
  - Performance and sizing of vehicle configurations proposed to DoD.
  - Evaluation of systems being used by adversaries (perhaps based only on a single photograph).
- Can we blend conceptual and preliminary design techniques?
  - As hardware becomes more powerful, higher fidelity sub-system performance and weight models are on the table.





Approach and Results:

- Using physics-based models derived from first principles allows HYDRA to evaluate configurations in all size/weight categories.
  - Built in FEA; compatible with higher fidelity aero.
  - Empirical models can be used when applicable
- HYDRA uses a robust optimization-based trim algorithm, handling (tilt)rotors, (tilt)wings, and wing-embedded control surfaces.
- State-of-the-art electric and hybrid-electric powertrain models for assessment of the latest Group 1-3 platforms.

Using a model of a proposed or existing vehicle concept, HYDRA can perform sizing based on mission requirements, or performance analysis for a fixed vehicle size.

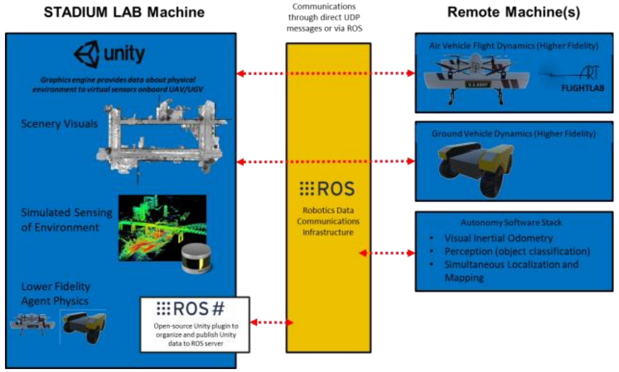
STADIUM: SIMULATION THEATER OF AIRCRAFT DYNAMICS FOR INTELLIGENT UNMANNED MANEUVER

Challenge:

- Autonomous UAS need an improved development pipeline to avoid the high time/cost developing controllers and autonomy, especially when working with unconventional platforms (tail-sitter, eVTOLs, compound)
- How can we push the state of the art for faster than real time dynamic simulation modeling of multi-rotor UAS?
- How can autonomy be designed to make the use of a vehicle's entire performance envelope?

Approach and Results:

- Integrated simulation environment with native vehicle dynamics, graphical + physics environment, and sensor models
- Development of validated physics-based models for ground effect, rotor inflow, motor dynamics, and rotor interactional aerodynamics
- Integration with MAVericks autonomy stack allows more advanced decision-making with autonomy, such as wing stall estimation, rotor power measurement, and battery depletion



STADIUM flight simulator can simulate:

- FVL-scale piloted platforms
- Unmanned Air Systems
- Heterogeneous teams including both UAS and ground systems

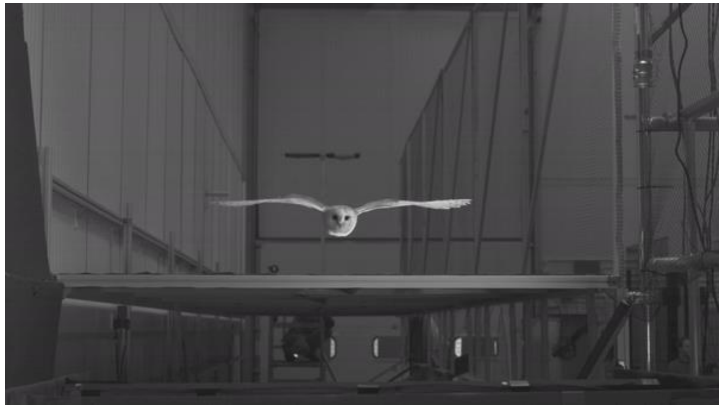
INSPIRATION

Nature shows us certain tasks that are possible, but not with current technology

Physically Complex

(top) “Goshawk Flies Through Tiny Spaces….”
https://www.youtube.com/watch?v=2CFckjfP-1E
(bottom) “Super Agile Owl in Slow Motion”
https://www.youtube.com/watch?v=gD3_0Ue6uJs

Aerodynamically Complex



Cheney JA et al., Bird wings act as a suspension system that rejects gusts. Proceedings of the Royal Society of London B 2020; 278: 20201748 1-9.

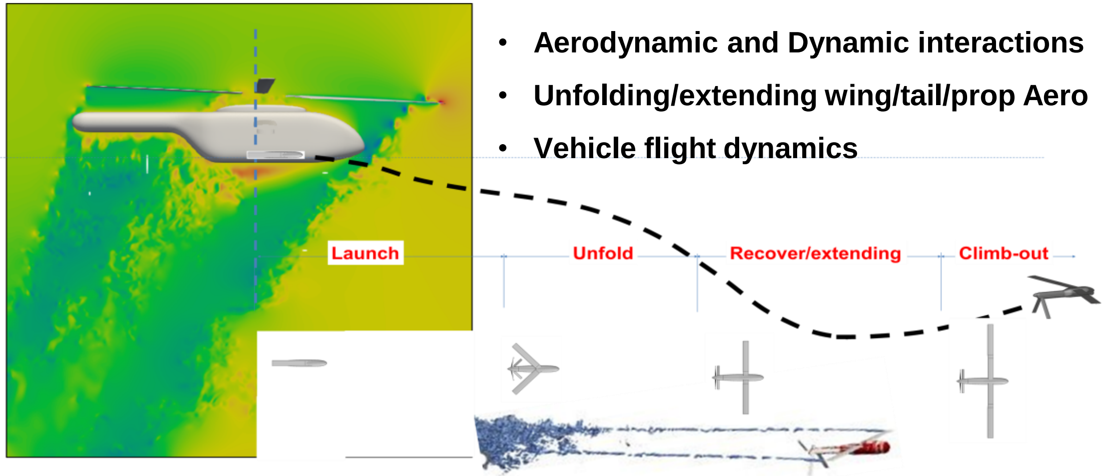
Complex Controls

“Beautiful Kestrel Hovers in Hunting Mode”
https://www.youtube.com/watch?v=mDRcLAkRZ50

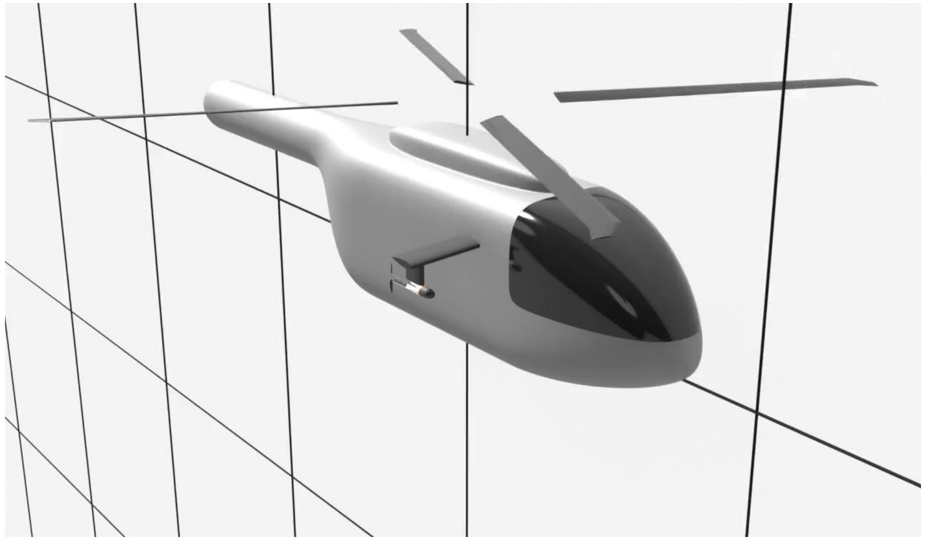
Multi-Fidelity Aeromechanics Models for Reconfigurable Air Vehicle

Challenge:

- Developing multi-fidelity modeling capabilities for air vehicle (Air-Launched Effects) with reconfigurable platform or morphing structures to address:
    - Vehicle-to-vehicle dynamic interaction modeling
    - Unfolding/extending wing/tail/prop dynamics and aerodynamics(airloads/wake)
    - Aerodynamic interference (vehicle-to-vehicle, aero surfaces-aero surface)
    - Different time scales between parent aircraft rotor and UVA propeller



Air Launched Effects (ALE)



Approach and Results:

- Flexible multi-body dynamics-based model with lifting-line theory for aerodynamic loads, finite state dynamic wake and vortex wake for rotor and wing wake, and vortex wake for aerodynamic interference
    - Able to simulate ALE launched or dropped from parent rotorcraft
    - Initial ALE analysis shows a fair agreement with flight test data
- Reduced-Order Aerodynamic model (ROAM) with actuator-line for aerodynamic loads and Computational Fluid Dynamics (CFD) for off-body aerodynamics
    - Aerodynamic forces predicted using ROAM tracked well with loads found with full CFD model but a significant reduction in computational time
- Fully coupled CFD for aerodynamics and Computational Structural Dynamics (CSD) for structural dynamics.

HIGH ENDURANCE AUTONOMOUS SOLDIER PORTABLE UAS

Challenge:

- Range and endurance of most small UAS are limited by the aircraft design – quad-rotor
  - Vehicle must always produce Thrust equal to the weight
- Fixed wing aircraft need runways or some other launch assistance
- Pilot is primarily responsible for directing the aircraft
  - Often responsible for interpreting video feed
  - High cognitive burden

Approach and Results:

- Leverage autonomous flight control, novel vehicle design, and AI/ML techniques to reduce burden while extending range and endurance
- Transitional VTOL vehicle - Vertical take-off and transition to forward flight
  - Generate thrust needed to overcome drag
  - Rotors maintain stable forward flight through thrust differentials
- On-board object detection stores objects of interest
- Autonomous flight mode enables disconnect from ground station
  - GPS guided

ADVANCING NEXT GENERATION ROBOTICS AND AUTONOMOUS SYSTEMS