

# **Accelerating Innovations for Robotics in Complex Real World Environments**

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**Dr. Timothy H. Chung, Program Manager**

Defense Advanced Research Projects Agency

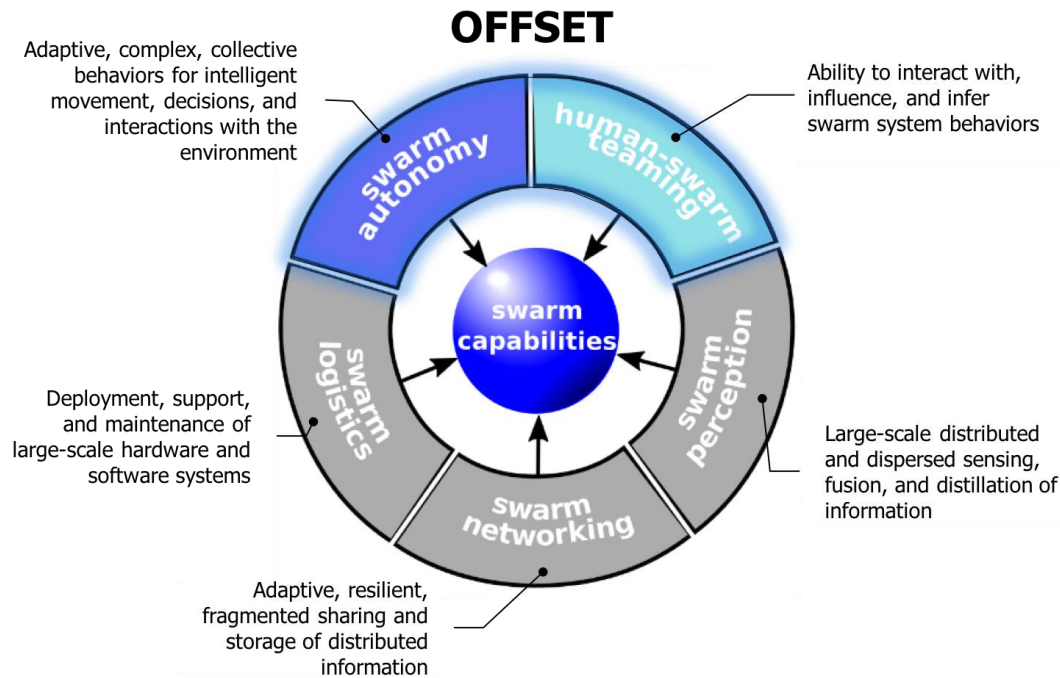
Tactical Technology Office

Briefing Prepared for Defense Systems Information Analysis Center (DSIAC) Webinar

February 9, 2022



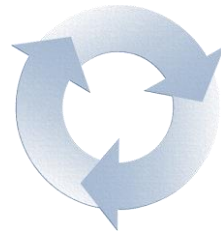
Discover innovative technologies to enable **large-scale teams of air and ground robots** to support **small-unit forces** operating in **complex urban environments**



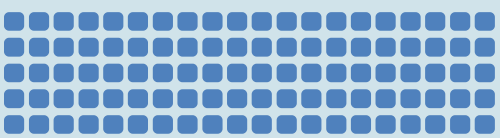
Objective Capability
<b>Seize key urban terrain</b>
4-6 hours
Approx. 8 square city blocks

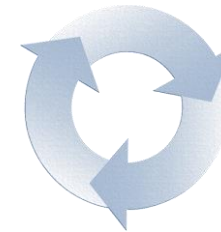
Vignette 1
<b>Isolate an urban objective</b>


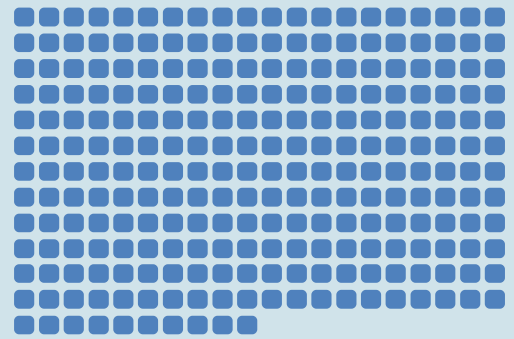
15-30 minutes
Approx. 2 square city blocks

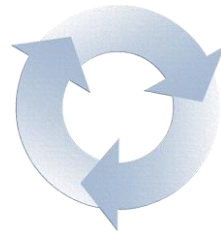
Vignette 2
<b>Conduct an urban raid</b>

1-2 hours
Approx. 4 square city blocks


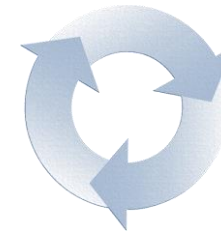


Objective Capability
<b>Seize key urban terrain</b>

4-6 hours
Approx. 8 square city blocks


Vignette 1	
<b>Isolate an urban objective</b>	
FX-1	FX-2
OCT 2018	JUN 2019
Camp Roberts	Fort Benning



Vignette 2	
<b>Conduct an urban raid</b>	
FX-3	FX-4
DEC 2019	AUG 2020
Camp Shelby	Joint Base Lewis-McChord



Vignette 3	
<b>Seize key urban terrain</b>	
FX-5	FX-6
JAN 2021	NOV 2021
Camp Shelby	Fort Campbell





*Highlights from OFFSET FX-6 @ Fort Campbell, KY*

<https://www.darpa.mil/news-events/2021-12-09>

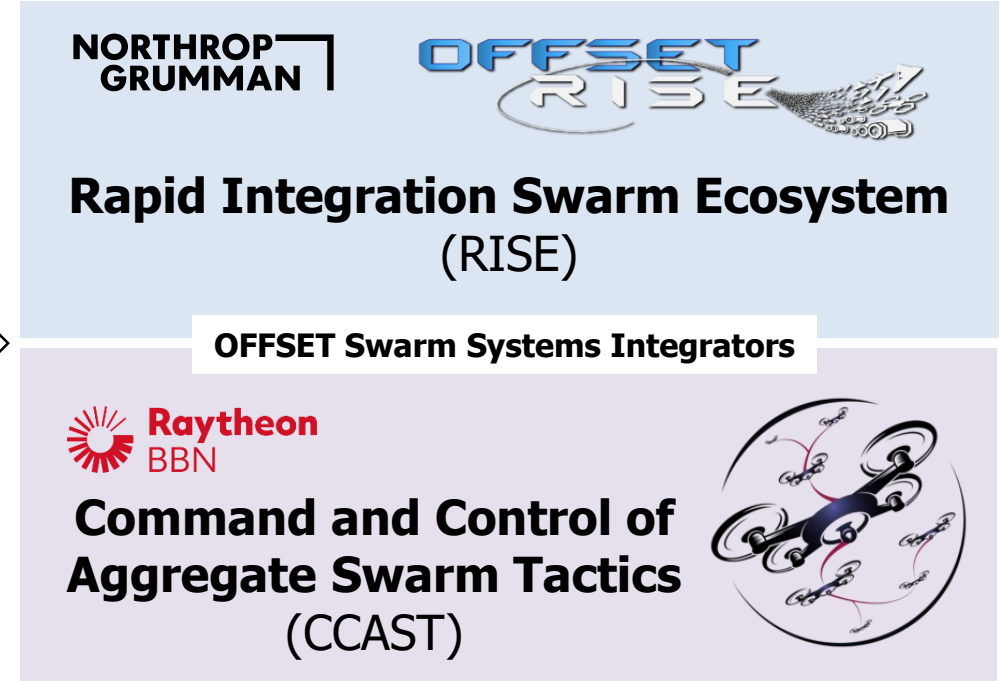
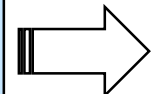
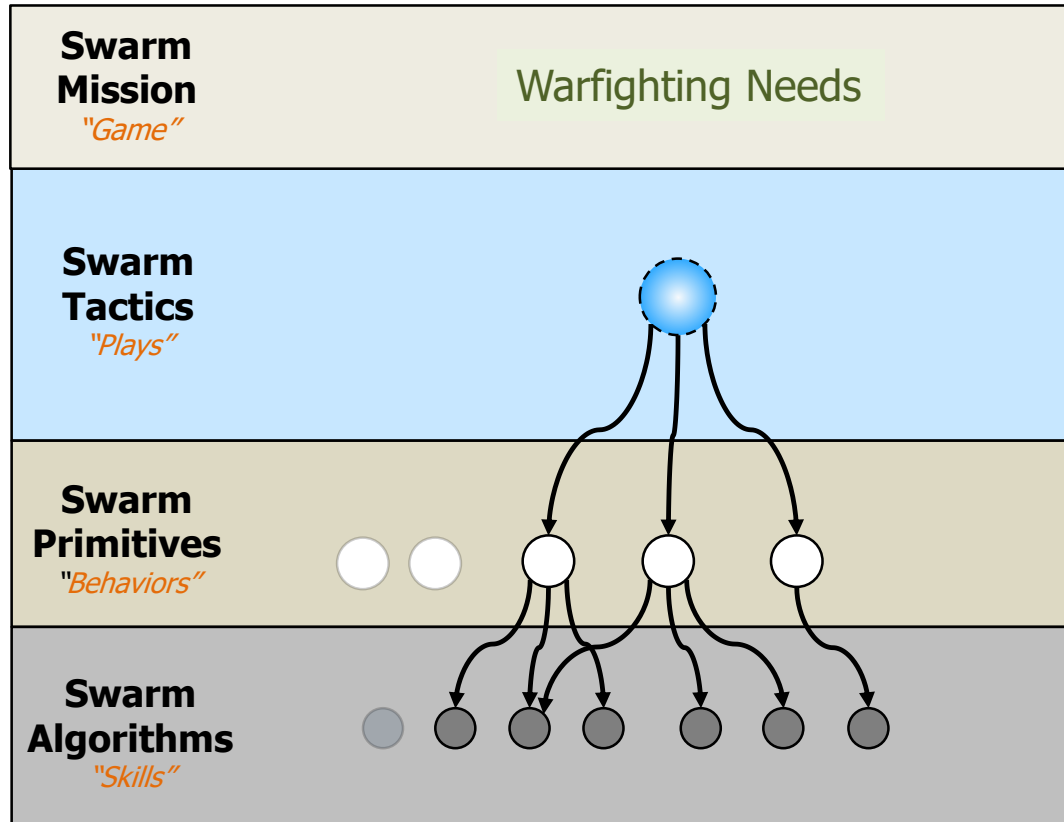
## Swarm Tactics

Swarm Systems Architectures

Scalable Swarm Simulators

Modular Swarm Testbeds

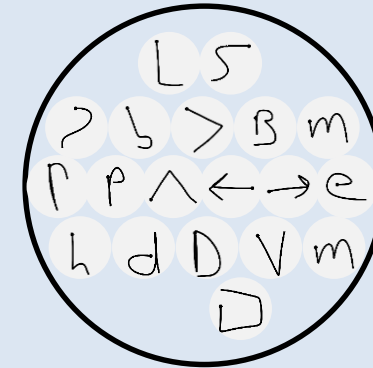
### OFFSET Focus



**OFFSET Impact:** Software Repository of swarm tactics code, user tutorials, and developer documentation

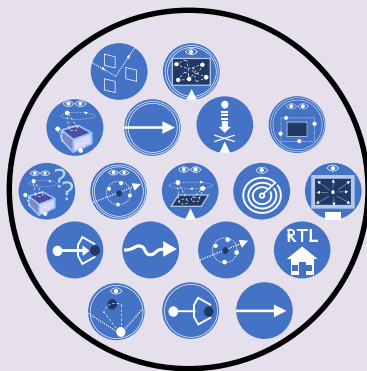
## RISE Swarm Tactics Exchange

- |  |  |  |
|--|--|--|
| <ul style="list-style-type: none"> <li>• Examine Objective</li> <li>• Follow Route</li> <li>• Hold Position</li> <li>• Hover Above Current Location</li> <li>• Inward Scan</li> <li>• Move To</li> <li>• Multi-agent inward scan</li> <li>• Overhead scan</li> <li>• Ring around POI</li> <li>• UAV Test POI</li> <li>• RADAR scan for ST-MTRI</li> <li>• Safe Land</li> <li>• Sector split leader follower</li> </ul> | <ul style="list-style-type: none"> <li>• Platform test</li> <li>• Building scan</li> <li>• Waypoint navigation/POI</li> <li>• Tornado scan</li> <li>• Hover</li> <li>• Ring around POI</li> <li>• Overhead Scan</li> <li>• Multi-agent inward scan</li> <li>• Examine Object</li> <li>• Safe Land</li> <li>• Outdoor to indoor transition</li> <li>• Indoor exploration</li> <li>• Artifact handler</li> </ul> | <ul style="list-style-type: none"> <li>• Artifact secure</li> <li>• Building perimeter scan</li> <li>• Outdoor exploration</li> <li>• GPS to indoor explore</li> <li>• GPS to indoor non-explore</li> <li>• Indoor ramp traversal</li> <li>• Leader follower (follower)</li> <li>• Leader follower (leader)</li> <li>• Platform Test</li> <li>• Approach area</li> <li>• Breach Building</li> <li>• Waypoint Navigation/POI</li> <li>• Approach target area leader follower</li> </ul> |
|--|--|--|



*Sketch gestures for NGMS RISE swarm tactics*


## CCAST Swarm Tactics Exchange



*Virtual reality icons for RBBN CCAST swarm tactics*

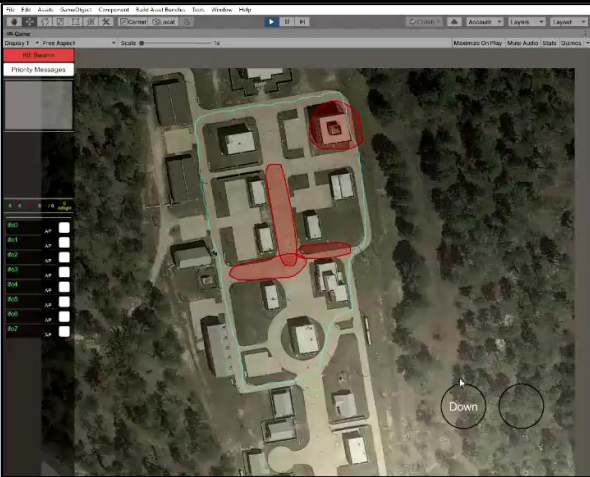
- |  |   |  |
|--|---|--|
| <ul style="list-style-type: none"> <li>• Add To Replacements</li> <li>• Amass</li> <li>• April Tag Scan</li> <li>• Area Survey</li> <li>• Cordon Area</li> <li>• Cordon Building</li> <li>• Explore</li> <li>• Explore Building</li> <li>• Flock To LLA</li> <li>• Follow Object</li> <li>• Gather Ground Imagery</li> <li>• Go To</li> <li>• Go To – Complex</li> </ul> | <ul style="list-style-type: none"> <li>• Interact</li> <li>• Interact Go To</li> <li>• Join Quick Reaction Force</li> <li>• Land In Area</li> <li>• Land In Place</li> <li>• Look At</li> <li>• Maintain Proximity to AT</li> <li>• Patrol</li> <li>• Process Obstacles</li> <li>• Proximity</li> <li>• Relieve agent</li> <li>• Rendezvous at Point</li> <li>• Report Objects</li> </ul> | <ul style="list-style-type: none"> <li>• Return To Launch</li> <li>• Revive at Medic</li> <li>• Route Nav</li> <li>• Split</li> <li>• Stage In Area</li> <li>• Stop</li> <li>• Stop/Estop</li> <li>• Surveil Ground</li> <li>• Surveil Object</li> <li>• Surveil Area</li> <li>• Transition To Region</li> <li>• Watch Entry Points in Zone</li> <li>• Designate Quick Reaction Force</li> </ul> |
|--|---|--|

### **Overhead Scan**




```
parameters = [
  Altitude
  Cell Size
  Agent Count]
```

**Description:** Fly UAVs over area to find artifacts

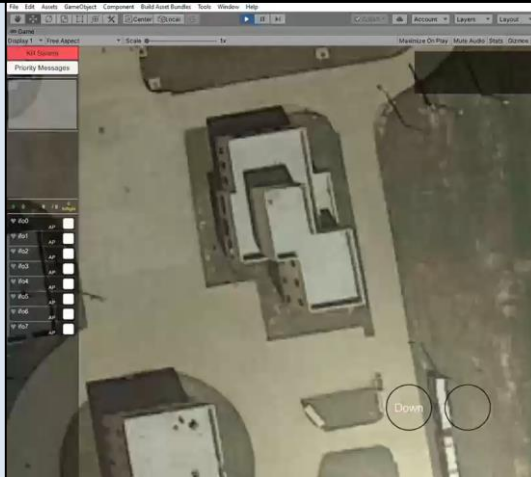


### **Multiagent Inward Scan**



```
parameters = [
  Starting Altitude
  Level Count
  Distance Between Levels
  Agent Count
  Outward]
```

**Description:** Use multiple UAV agents to scan enclosed area specified by path stroke.



### **Surveil Area**

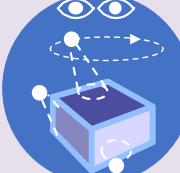


```
parameters = [
  Polygon
  Agent(s)
  Concluding Action]
```

**Description:** Command wildcard agent(s) to travel to user input area




### **Surveil Object**



```
parameters = [
  Building (spatial database)
  Agent(s)
  Concluding Action]
```

**Description:** Command agent(s) to travel to and surveil an object in the spatial database





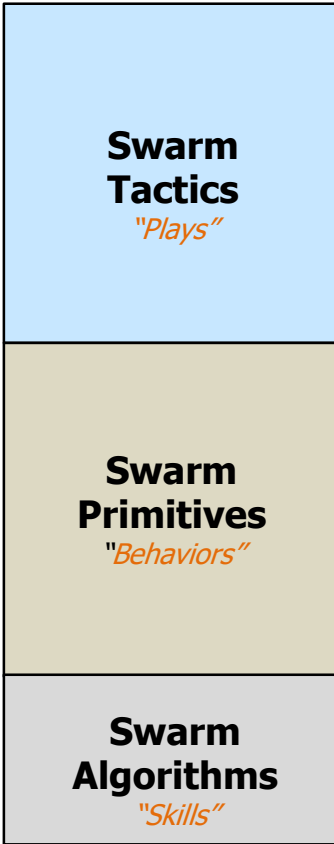
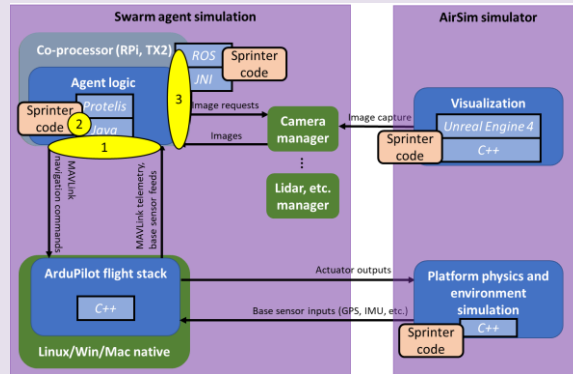
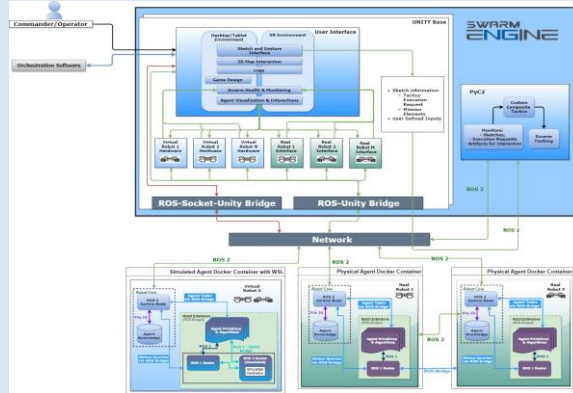
## Swarm Tactics

## Swarm Systems Architectures

## Scalable Swarm Simulators

## Modular Swarm Testbeds

**NORTHROP GRUMMAN**



**Swarm Tactics**  
"Plays"

**Swarm Primitives**  
"Behaviors"

**Swarm Algorithms**  
"Skills"

**Fact 1:** real-world missions requires *composability*  
*Different approaches, different assumptions, different context*

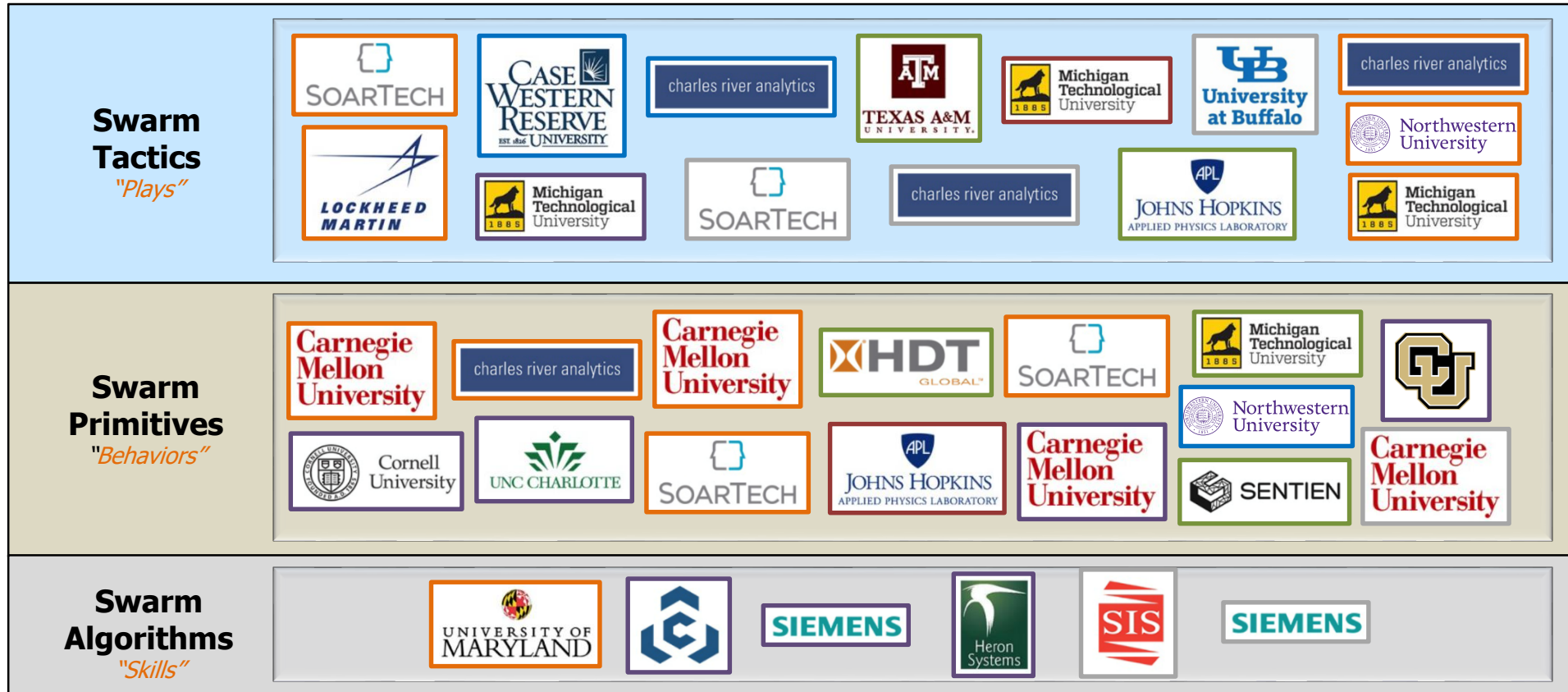
**Fact 2:** adopting new innovation requires *flexibility*  
*Novel ideas don't come in just one shape and size (or interface)*

OFFSET relies on **composable** and **flexible swarm autonomy**

*swarm tactics | swarm primitives | swarm algorithms*

**OFFSET Impact:** Swarm Sprinter-exercised *design patterns* for how to contribute novel swarm tech through flexible architecture interfaces

“Open architecture” means open to **diverse and flexible pathways** for integrating novel technologies



35 Swarm Sprinter efforts across five Swarm Sprints



**ACCIPTER:** Aerobatic Control and Collaboration for Improved Performance In Tactical Evasion and Reconnaissance



**HIVE-XL:** Automated UAS Launch, Recovery, and Recharge at Large Scale



**TGD:** The Grand Deception



- Base + Option completed
- ⊖ Base only completed
- In-progress
- ⊕ Extension to Field Experiment 6



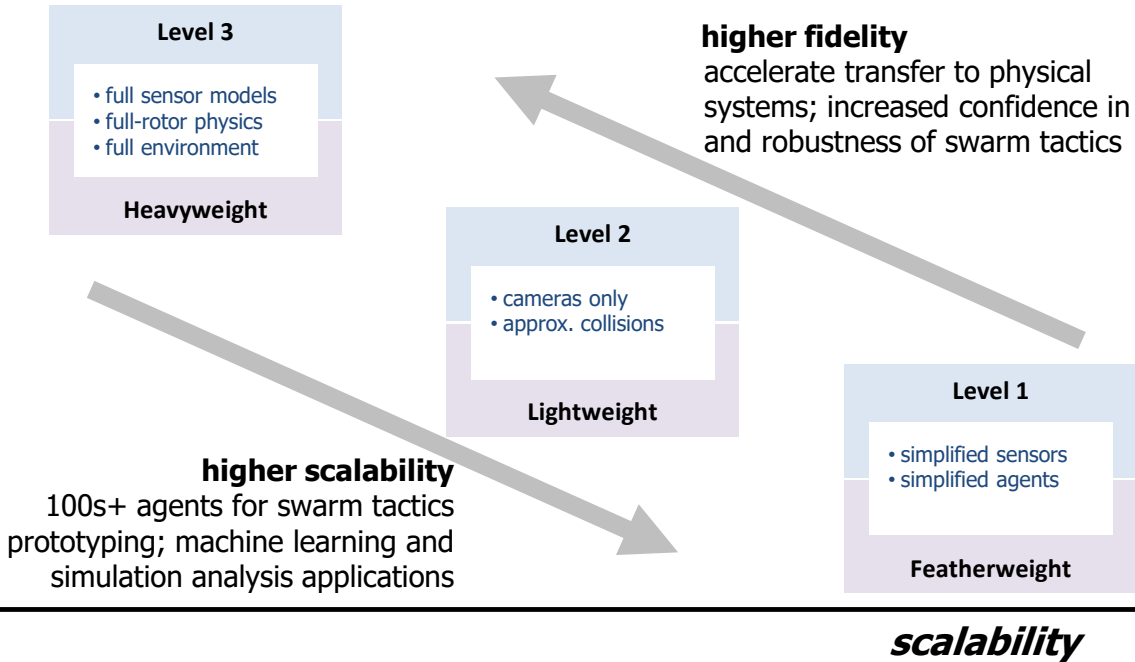
## Swarm Tactics

## Swarm Systems Architectures

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## Modular Swarm Testbeds

*fidelity*



**OFFSET Impact:** Two extensible virtual environments for integrated autonomous systems simulation + development + testing



**OFFSET Virtual Environments**







*Large-scale swarm mission scenario play*

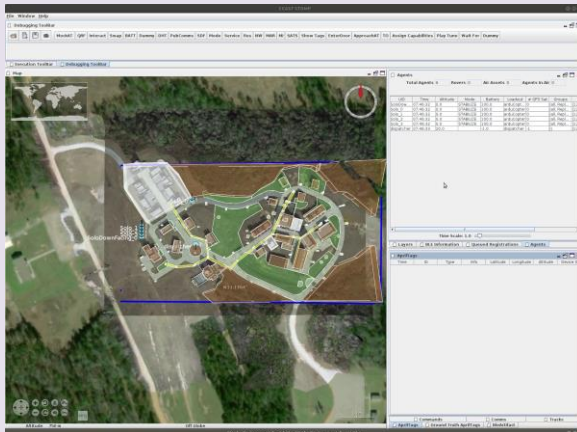


*Temporal coverage sensor modeling*



*Multi-host swarm tactic execution*

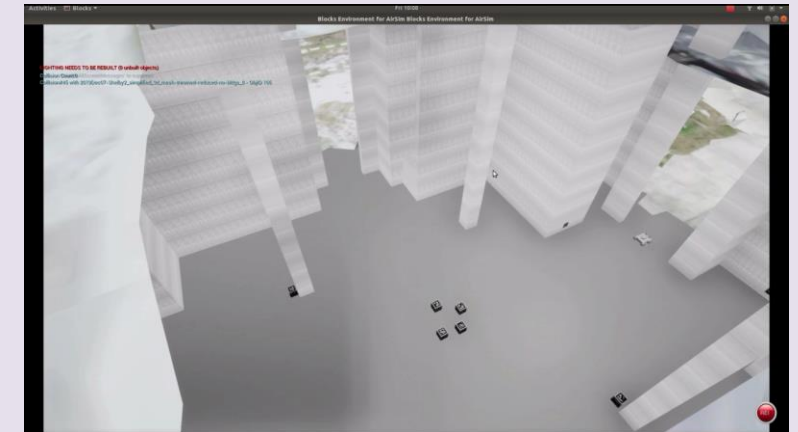
*Variable faster-than-real-time simulation*



*Field test swarm mission rehearsal*



*Multi-robot environment interactions*



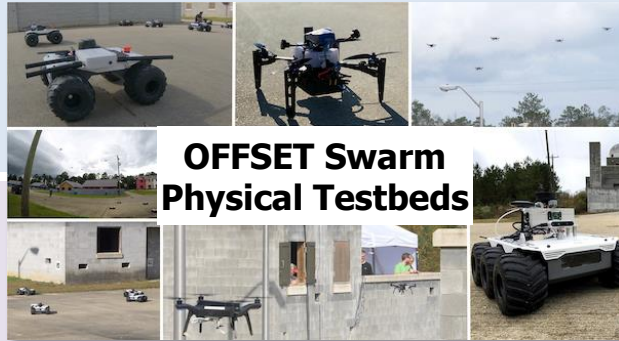
## Swarm Tactics

## Swarm Systems Architectures

## Scalable Swarm Simulators

## Modular Swarm Testbeds

**NORTHROP GRUMMAN**



**OFFSET Swarm Physical Testbeds**



**Raytheon BBN**

Selection of **swarm tactics** directly impacted by swarm capabilities

- Swarm tactics requiring large, simultaneously amassed forces need high **swarm power generation rate**
- Lower swarm power generation rate better suitable for longer endurance swarm platforms and/or longer missions

Fast-changing COTS hardware components require **easily extensible** swarm systems architecture

- Value of newest feature versus scaled cost (per-unit labor/time) to retrofit new COTS platform with swarm systems architecture
- Software-defined vs. hardware-defined swarm tactics is more extensible

**OFFSET Impact:** Field-tested swarm autonomy stacks, using open-source software packages and integrated with diverse COTS platforms, sensors, and radios

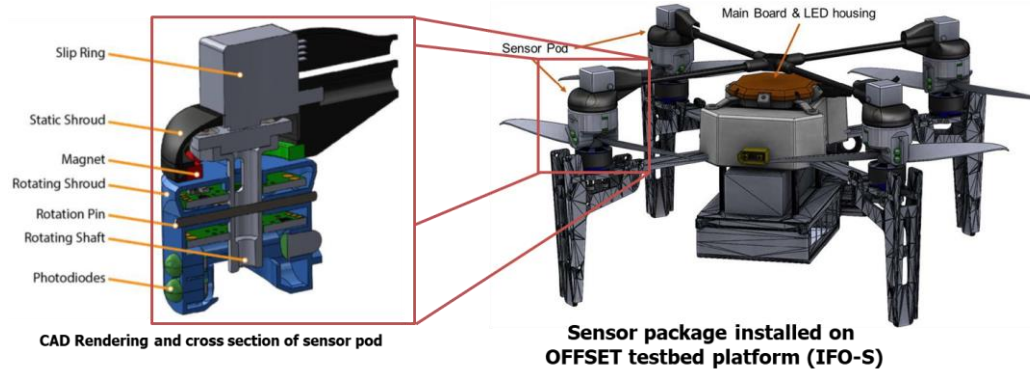
- Swarm robot code repositories and build/deployment instructions on DI2E



## Swarm Sprint 5 Sprint Topic: Enhancements and Enablers for Swarm Physical Testbeds



**Johns Hopkins University: ACCIPITER**

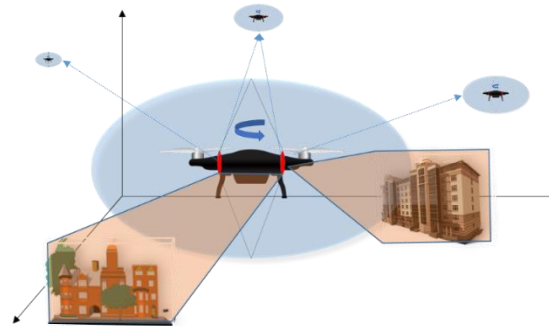


**HDT Global: Rotor Mounted B+E Sensor**

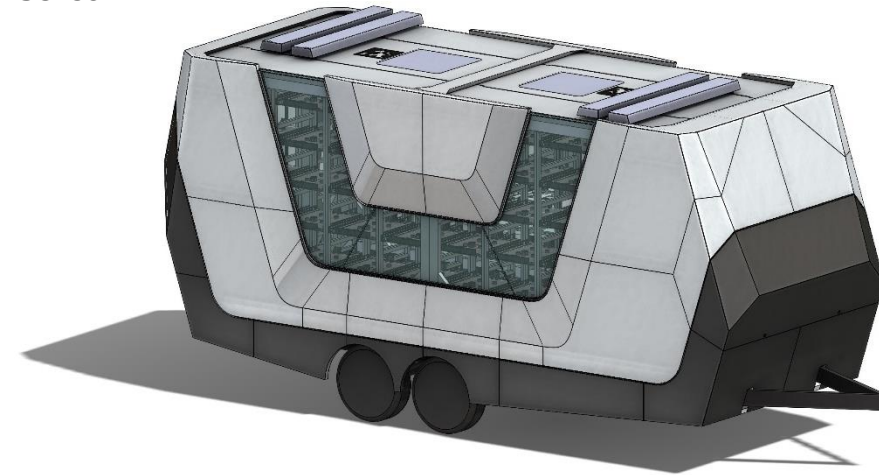
**ACCIPITER:** Aerobic Control and Collaboration for Improved Performance in Tactical Evasion and Reconnaissance  
*α-WaLTR:* Adaptive Wheel-and-Leg Transformable Robot  
**OMNI 360-VIS:** Odometry and Machine Navigation Inferred from 360° Video and Image Sources  
**B+E:** Bearing + Elevation



**Texas A&M: α-WaLTR**

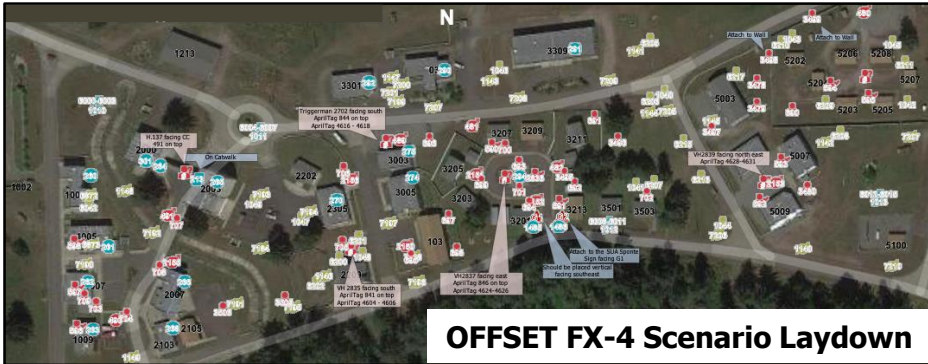


**Michigan Tech Research Institute: OMNI 360-VIS**



**Sentien Robotics: HIVE-XL**

## 1. Design scenario for offensive urban operations



Joint Base Lewis-McChord "Leschi Town" CACTF

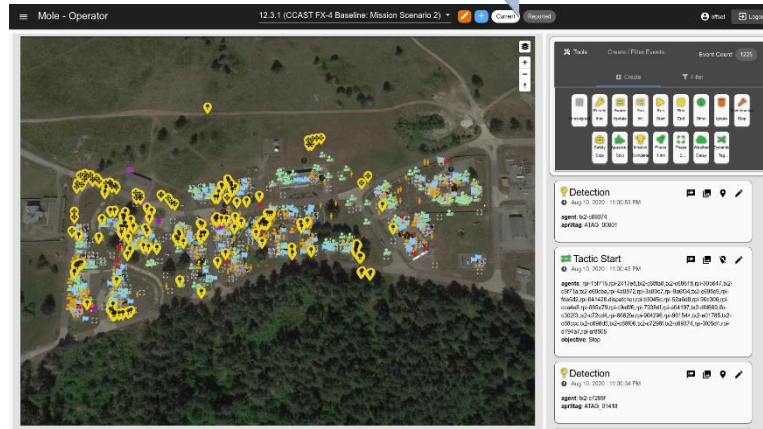
## 2. Rapidly instrument large-scale urban test sites



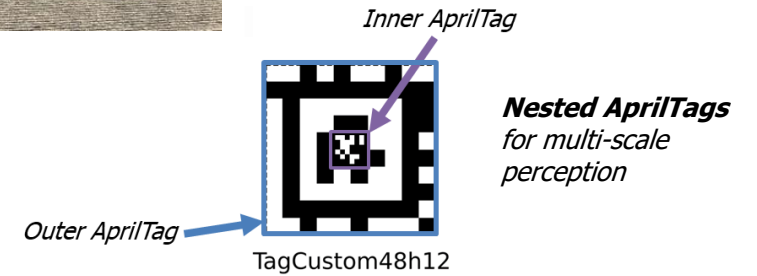
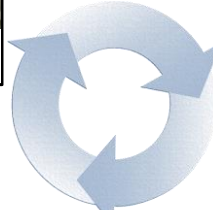
### FX-4 Infrastructure Measures

- 5300+ meters of Ethernet
- 600 meters of optical fiber
- 811 Unique AprilTags
- 83 Raspberry Pi Nodes
- 26 network switches
- 14 USG team members

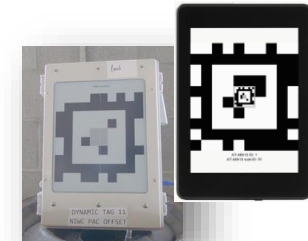
## 3. Orchestrate and capture real-time assessments of "Swarm Under Test"



Screenshot of networked orchestration software frontend (a.k.a. Mole)



**Dynamic AprilTags:**  
E-ink screens for evolving scenarios







The icons on the map indicate simulated High Value Targets (HVTs) The swarm is tasked to find, isolate, and prosecute the targets



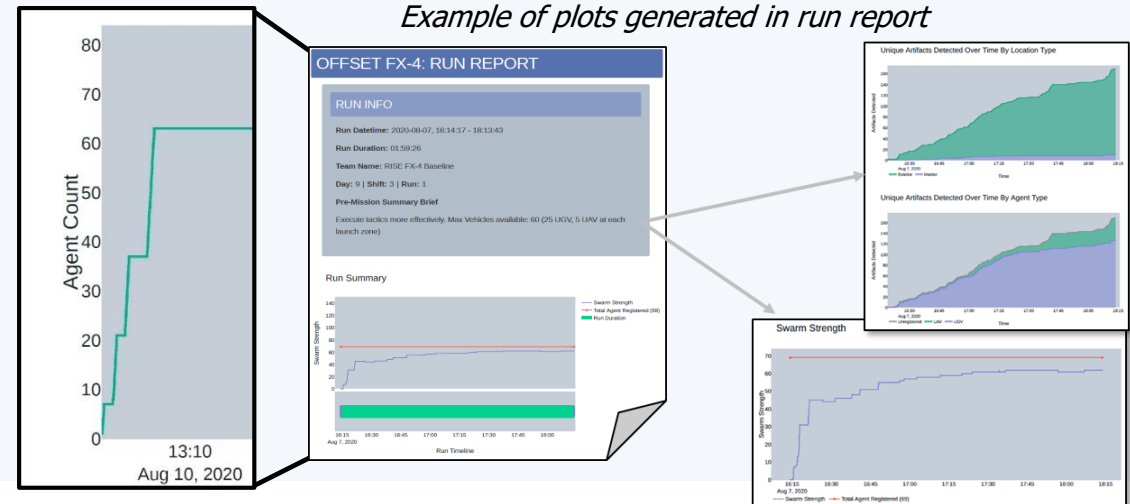
Coverage maps showcasing **Swarm Activity** during exercise runs.  
Top: RBBN, Right: NGMS

## Benefits of Swarms

- Constant coverage and situational awareness in complex urban terrain (e.g., occluded visibility)
- Manage multiple objectives simultaneously
- Dispersed mass
- Obfuscation of commander's intent

## Takeaways from auto-generated experiment performance reports

- Integrators have reached the ability to deploy 60+ agents in 5 minutes
- Sustaining large swarm sizes requires constant stream of swarm reinforcements
- Swarm logistics is difficult, i.e., transporting, staging, and recovering swarm systems is labor-/time-intensive



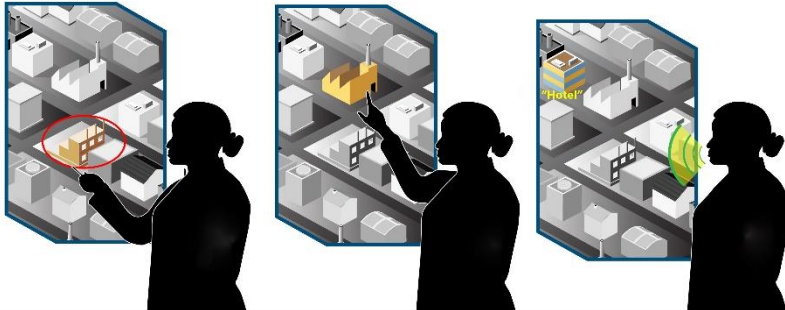


Swarm Mission Planner

*Each "Swarm Persona" could require different input devices (command) and output devices (feedback)*



Swarm Tactician, Rear



**OFFSET Impact:** Multiple Swarm Interfaces available for Various Operational Users "Swarm Personas"

higher proximity to operations



Swarm Tactician, Forward



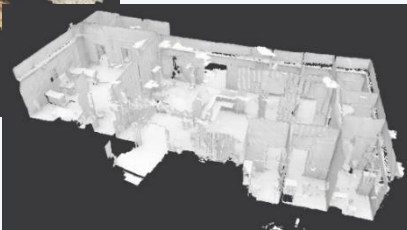
## OFFSET Urban Scenario Reference Dataset



*High-resolution 3D photogrammetric mesh*



*Interior 3D mesh scans of all 33 building interiors in-play*



*Exterior building scan videos (by drone) for all 40 buildings in-play*

*Scenario walkthrough videos (outdoor/indoor) of entire test range*



### What has OFFSET created?

- Library of collaborative autonomy software
- Swarm virtual environments as bridge to real-world
- Unique swarm datasets

### What are (actionable) OFFSET lessons learned?

- Define point-of-departure swarm autonomy capabilities
- Seek applications needing high + fast "swarm power"

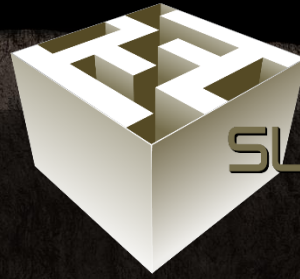
### What comes next after OFFSET?

- Urban maneuver-capable platforms
  - **Still** need agile and adaptable robotic systems
- Swarm logistics enablers
  - On-the-move and/or federated swarm deployment
  - Swarm replenishment, recharge, and recovery technologies
- Counter swarm/autonomy



[www.darpa.mil](http://www.darpa.mil)





# DARPA SUBTERRANEAN CHALLENGE

**Vision:** To inspire and discover robotic technologies enabling *actionable situational awareness* across diverse underground environments



## TUNNEL SYSTEMS

Tunnels can extend many kilometers in length with constrained passages, vertical shafts and multiple levels.



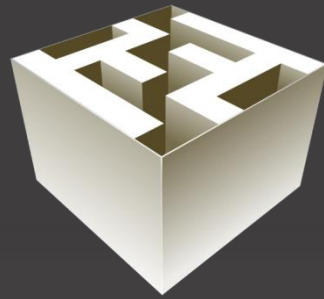
## URBAN UNDERGROUND

Urban underground environments can have complex layouts with multiple stories and span several city blocks.



## CAVE NETWORKS

Natural cave networks often have irregular geological structures, with both constrained passages and large caverns.

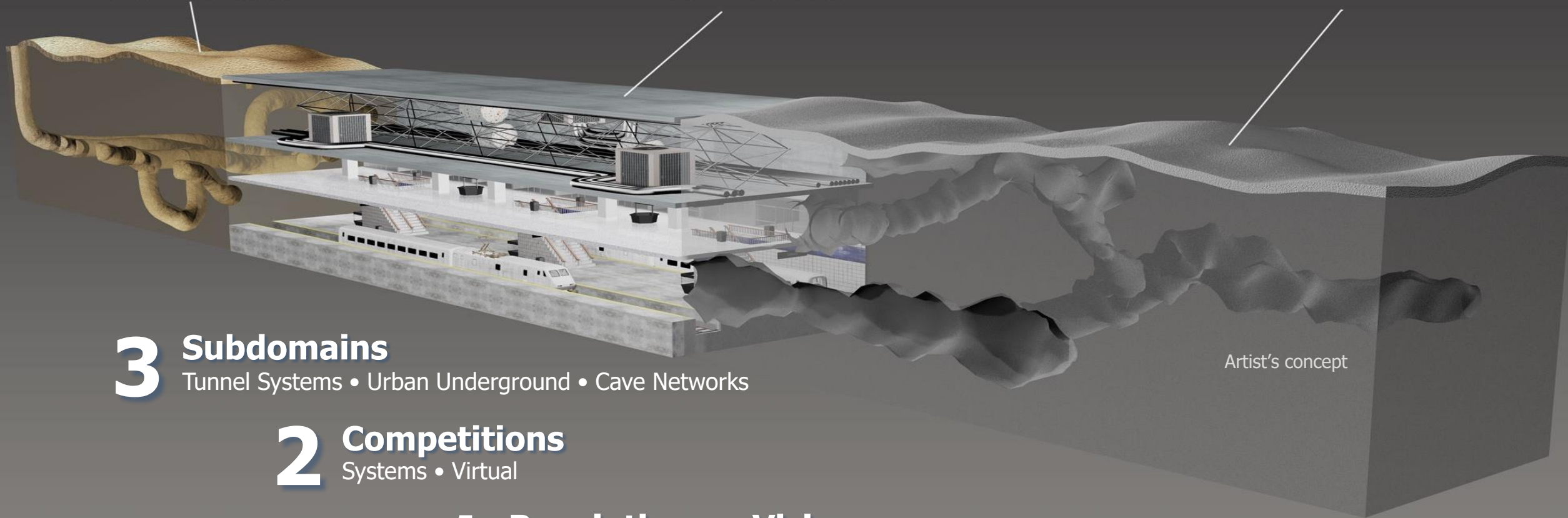


# DARPA SUBTERRANEAN CHALLENGE

Tunnel Environment

Urban Environment

Cave Environment



## 3 Subdomains

Tunnel Systems • Urban Underground • Cave Networks

## 2 Competitions

Systems • Virtual

## 1 Revolutionary Vision

Create breakthrough technologies and capabilities for underground operations



## Providing actionable situational awareness in unknown underground settings

**actionable** – artifact locations to within <5 meter global error and correct artifact type classification



SubT Challenge: How Scoring Works [[YouTube link](#)]





**Andersons**



**CSIRO Data61**



**Flying Fitches**



**BARCS**

*Bayesian Adaptive Robot Control System*



**CTU-CRAS-NORLAB**

*Czech Technical University in Prague –  
Center for Robotics and Autonomous  
Systems - Northern Robotics Laboratory*



**MARBLE**

*Multi-agent Autonomy with Radar-Based  
Localization for Exploration*



**CERBERUS**

*CollaborativE walking & flying RoBots for  
autonomous ExploRation in Underground  
Settings*



**Dynamo**



**Robotika**



**COLLEMBOLA**

*Communication Optimized, Low Latency  
Exploration, Map-Building and Object  
Localization Autonomy*



**Explorer**



**SODIUM-24 Robotics**

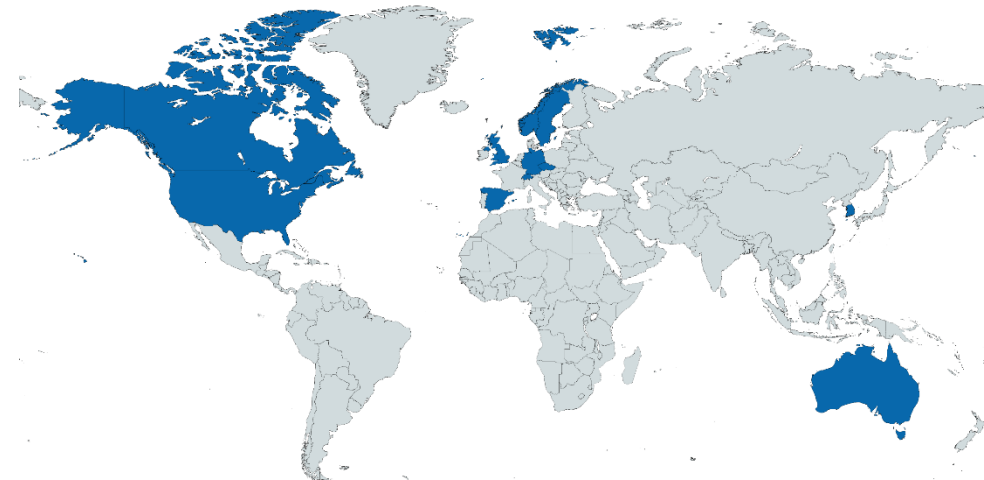


**Coordinated Robotics**



**CoSTAR**

*Collaborative SubTerranean  
Autonomous Resilient Robots*



Systems Competition



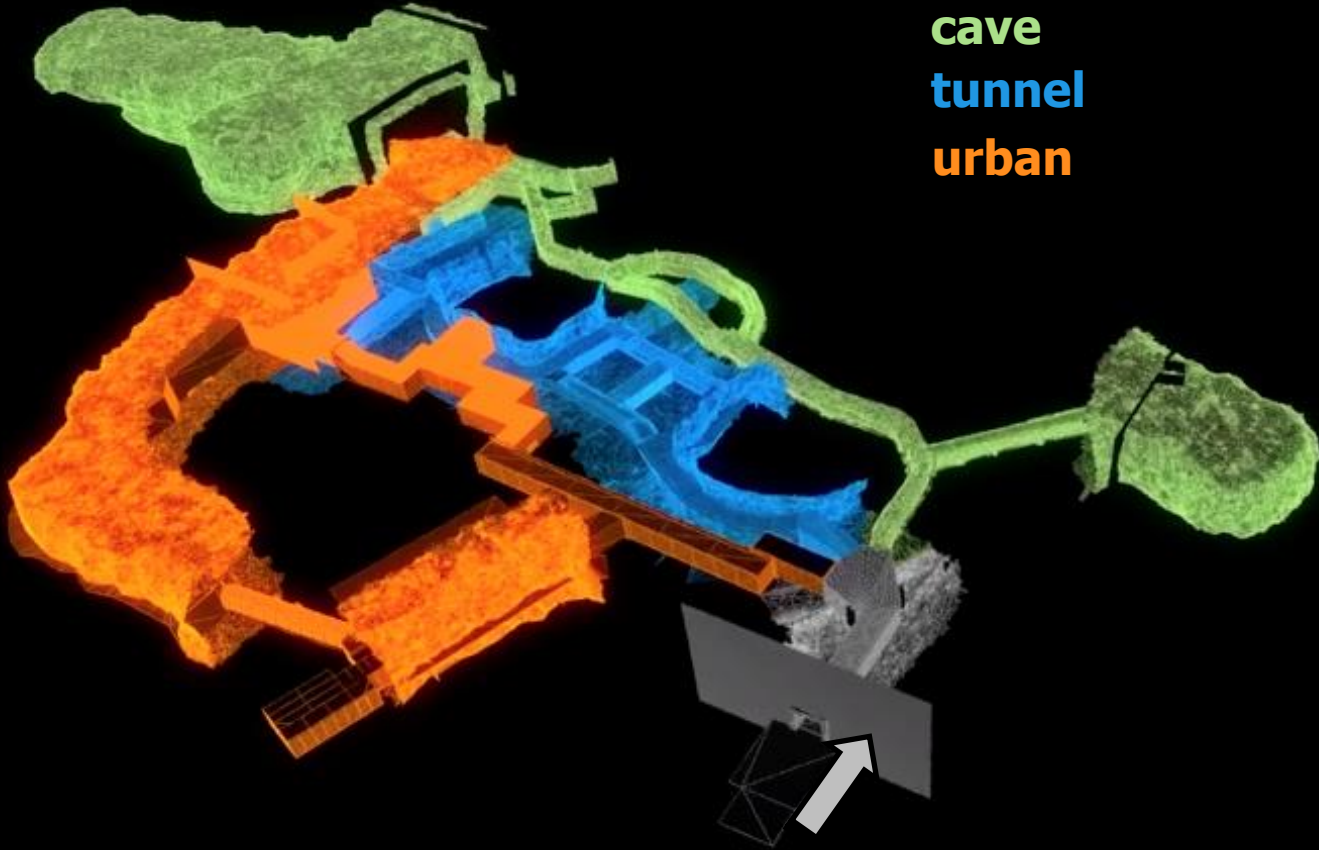
Virtual Competition

**DARPA-funded**  
**Self-funded**



# Finals Course Design: A One-of-a-Kind SubT Environment

cave  
tunnel  
urban





# Generating high-fidelity 3D info: **Mapping Results**

**CSIRO Data61**



**Explorer**



**CERBERUS**



**CoSTAR**



**MARBLE**



**CTU-CRAS-NORLAB**



**Coordinated Robotics**



**Robotika**





## SubT Virtual Testbed Repo:

- Prize Round Worlds: [SubT Tech Repo](#)
- Prize Round Logs Released to each team
- Virtual worlds for each Finals Systems Configuration

## Finals Course Ground Truth:

- [https://bitbucket.org/subtchallenge/finals\\_ground\\_truth/](https://bitbucket.org/subtchallenge/finals_ground_truth/)
- Artifacts Ground Truth Spreadsheet
- Fiducials Ground Truth Spreadsheet
- Low and High Resolution Ground Truth Point Clouds
- Course Design Callouts Deck
- Course Graphics and Artwork

## Point Cloud Flythrough Videos

- Finals Course Tunnel Flythrough: <https://youtu.be/0brZuy6Qq2E>
- Finals Course Urban Flythrough: <https://youtu.be/odE8a-5CW6A>
- Finals Course Cave Flythrough: [https://youtu.be/uXaj\\_M6L5oo](https://youtu.be/uXaj_M6L5oo)
- Finals Course Tunnel 360° Flythrough: <https://youtu.be/G8SLE7phtLY>
- Finals Course Urban 360° Flythrough: [https://youtu.be/yTecsOv\\_1Rw](https://youtu.be/yTecsOv_1Rw)
- Finals Course Cave 360° Flythrough: <https://youtu.be/DCE59ViPoMY>

## Course Walkthrough Videos

- Finals Course Preliminary Round 1: <https://youtu.be/i-8aPpJfGS0>
- Finals Course Preliminary Round 2: <https://youtu.be/zqRuBJ-VxMg>
- Finals Course Prize Round: <https://youtu.be/6Fte0KipSfk>

## Full Run Videos Playlist:

- <https://youtube.com/playlist?list=PL6wMum5UsYvZd6VwOZVZHu9QldFp8vEgX>

