

Off-Road Mobility Assessment Methods and Tools for Autonomous Military Ground Systems

NATO Research Task Group AVT-341

Dr. Paramsothy Jayakumar

U.S. Army DEVCOM Ground Vehicle Systems Center

Keynote, Annual Program Review, Automotive Research Center

DISTRIBUTION A. Approved for public release; distribution unlimited. OPSEC#7468



Background / Motivation

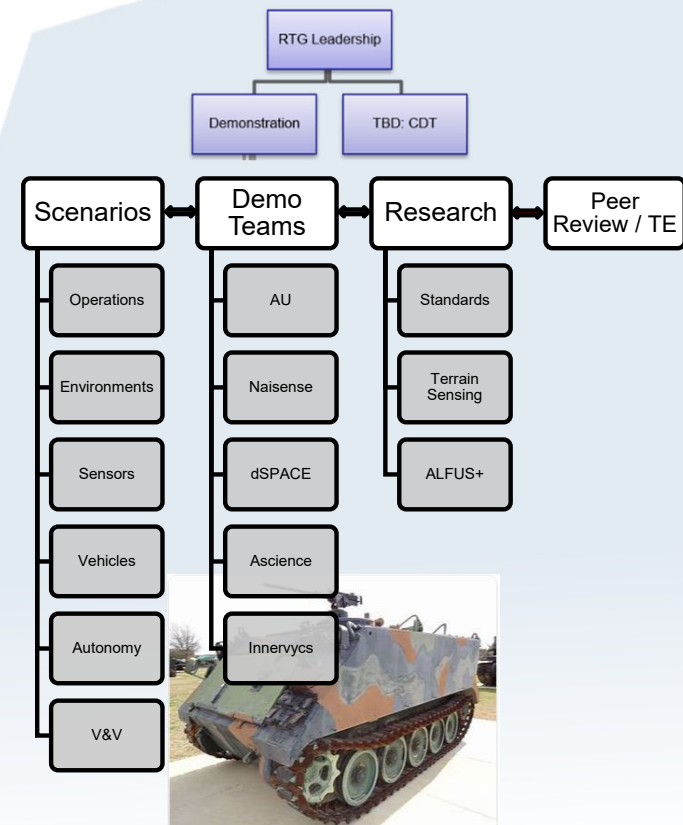
- Autonomous ground vehicles are a key part of the future military strategy for many NATO Nations. In the race to field these systems, there is still a lack of understanding of the capabilities and reliability of these systems.
- The assessment challenges are that:
 - Current autonomy software do not address off-road or unstructured environments
 - Available M&S software do not have integrated autonomy capabilities
 - Military scenarios are not readily available in the tools for running simulations

Mission and Scope

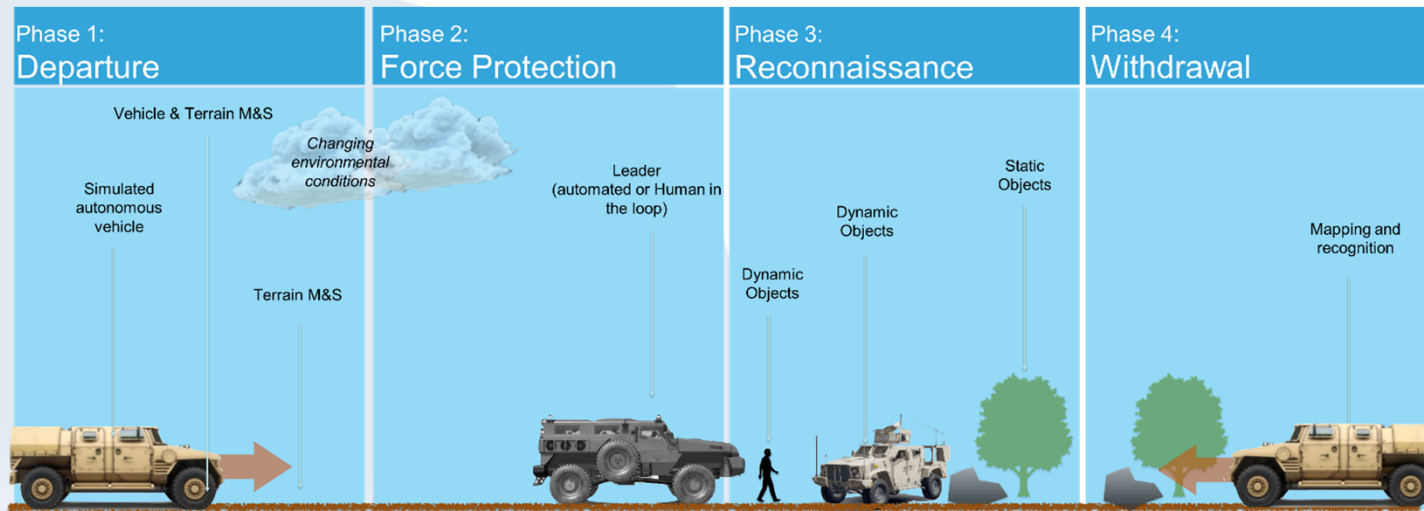
- Establish a mobility assessment framework purposely designed to consider the specific underlying requirements of off-road mobility of military autonomous ground vehicles.
- Demonstrate evaluation of autonomous mobility using integrated autonomy and mobility M&S tools for realistic and relevant scenarios.
- Focus research efforts at solving autonomous mobility capability gaps.
- Develop NATO STANDARDS consisting of PEGASUS+, ALFUS+, and NG-NRMM+ Standards.

Technical Team

- USA: Paramsothy Jayakumar (Co-chair)
- Sweden: Johannes Andersen (Co-chair)
- Canada: Arnold Free (Co-chair)
- Number of Nations: 19
- Number of Members: 70



Operation: Loyal Wingman Scenario



A platoon comprised of two (2) manned and two (2) unmanned vehicles is to conduct a **route reconnaissance** mission.

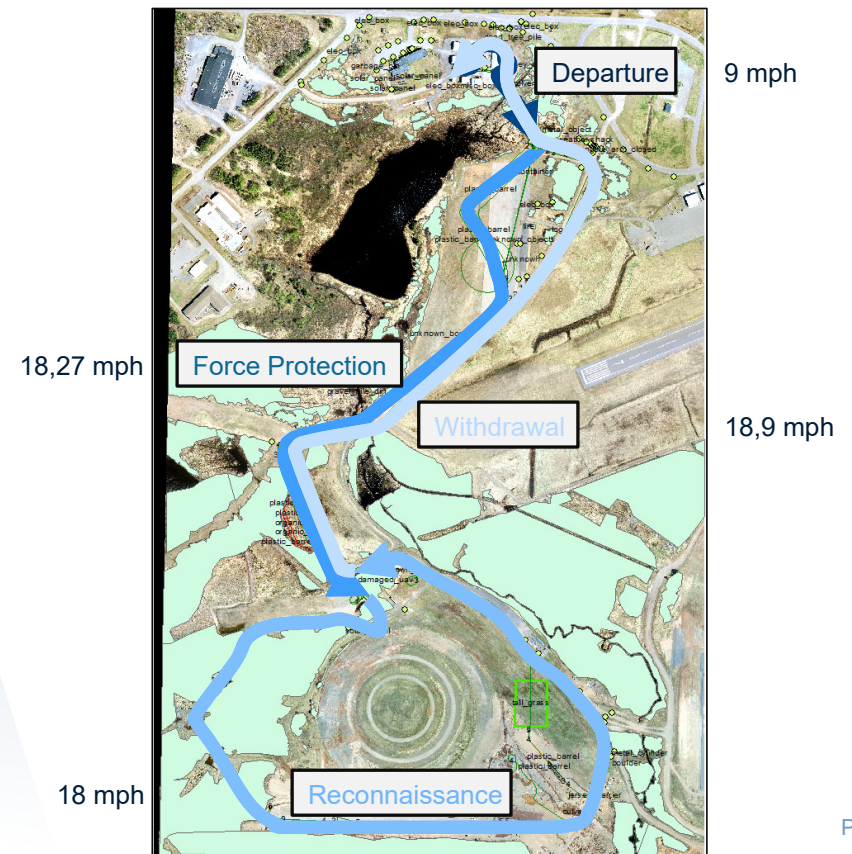
Start from base, perform mission and return to base.

Minimize visual, and auditory signature.

Contingency plan: seek cover, if possible, withdraw to base.

Loyal Wingman Scenario Map

- **Departure Phase**
 - Vehicles join formation and move out of the FOB
- **Force Protection Phase**
 - Crewed vehicles escort AGVs to reconnaissance area
- **Reconnaissance Phase**
 - AGVs investigate the area
- **Withdrawal Phase**
 - AGVs rejoin crewed vehicles and return to FOB
- All phases have mobility, autonomy, and M&S challenges built in.

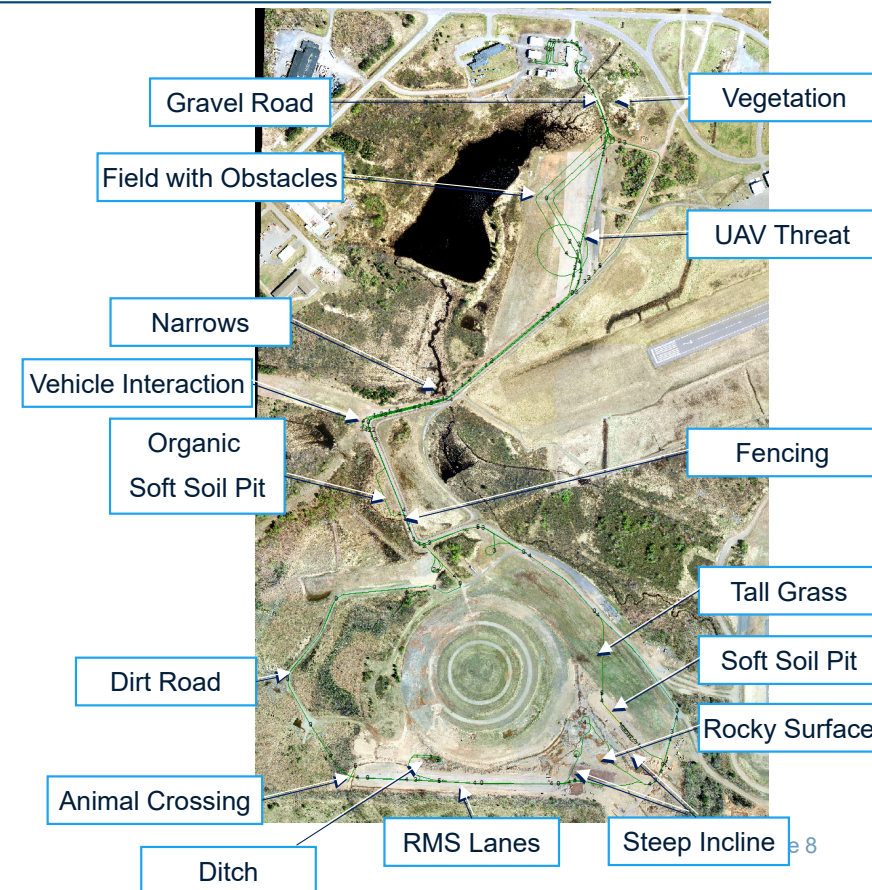


Loyal Wingman Scenario Challenges

- **Teaming - Autonomy**
 - Leader-Follower
 - Formations: Line, Column, Diamond
 - Switching to/from solo, pair, and squad groupings
 - Collaborative movements, overwatch, monitoring progress
- **Navigation - Autonomy**
 - Map terrain, routes, features
 - Move to named reference point
 - Point-to-point route planning
 - Return to start position
- **Obstacles - Autonomy**
 - Static Obstacles (barrels, jersey barriers)
 - Dynamic Obstacles (deer, other vehicles)
 - Moving through narrow spaces (chicane, narrow bridge, gaps in obstacles)
- **Control - Autonomy**
 - Steering and speed control
 - Startup/Shutdown
- **Target Detection - Autonomy**
 - Detect, Approach, Encircle, Identify Type, Return to Primary Mission
 - Detect an Aerial Threat
- **Terrain - Mobility**
 - Gravel and Dirt Roads
 - Rough and Rocky Terrains
 - Ditches
 - Soft Soil Regions
 - Fields
 - Dense Vegetation
 - Tall Grass
 - Grade Climb and Descent
- **Communication**
 - Assume LOS C2 radio communication
 - Simulated via server-client ethernet communication between vehicles using basic command encoding

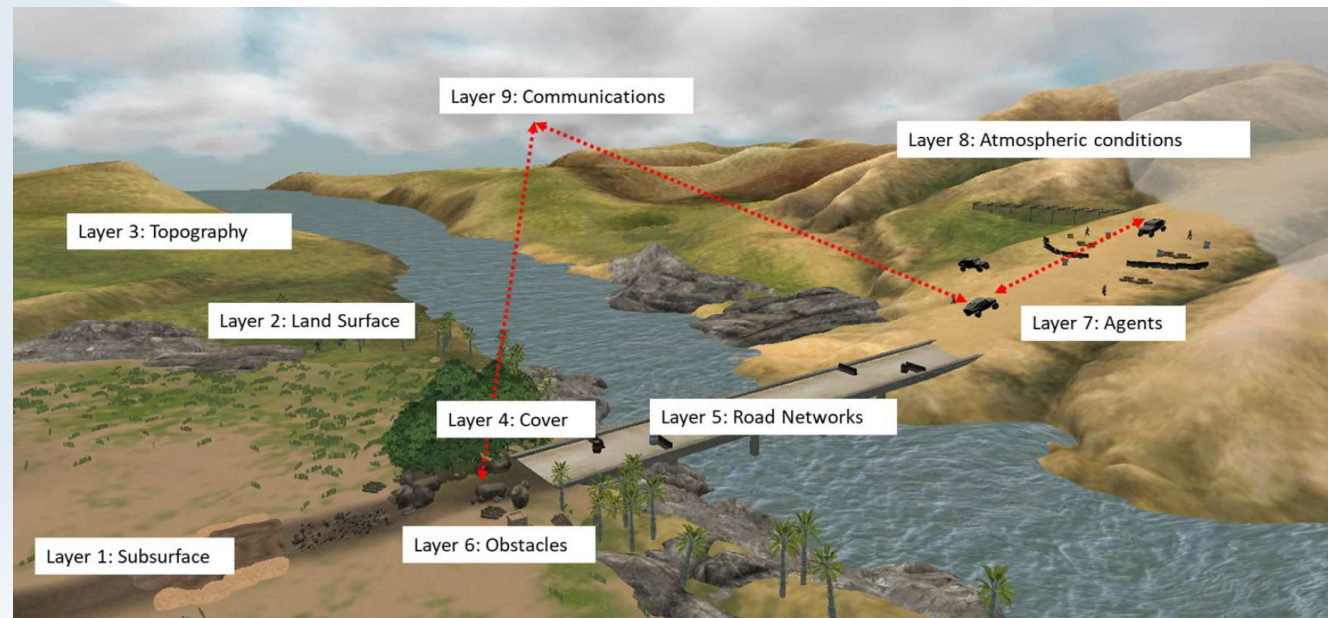
2 Environmental Challenges in Loyal Wingman Scenario

- 35 Scenario Segments
- Gravel, dirt, grass, peat, soft, rock surfaces
- Jersey barriers, barrels, buildings, and other obstacles
- Deer, vehicles, UAV
- Downed UAV and ground vehicle targets
- Inclines, RMS lanes, Soft soils, Hard terrain
- Narrow spaces and obstacles



PEGASUS+ Virtual Environment Data Requirements

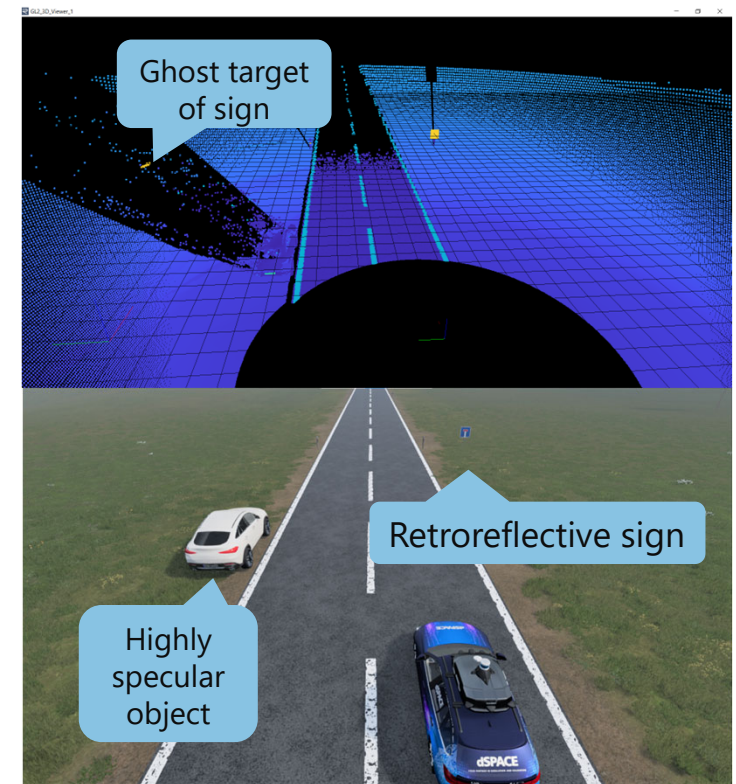
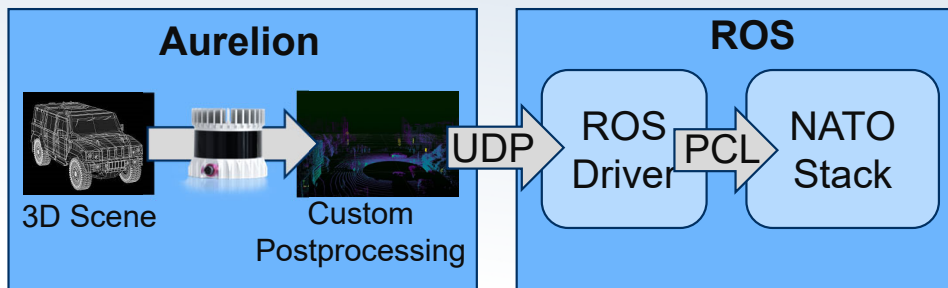
- Subsurface
- Land surface
- Topography
- Cover
- Road Networks
- Objects
- Agents
- Conditions
- Communications



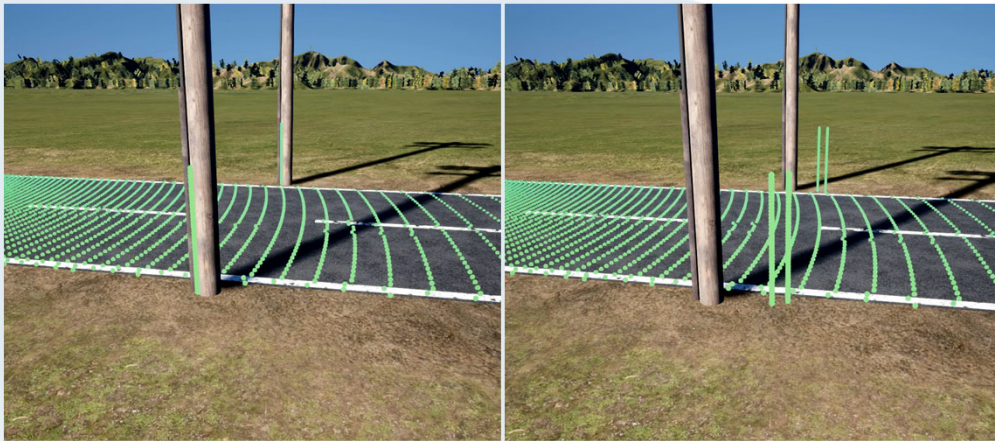
PEGASUS in pink

3 Sensor Models: LIDAR

- LIDAR: Velodyne VLP 16
 - Raytracing
 - Ghost targets
 - Motion distortion
 - Realistic materials (BRDF)
 - Vendor specific output
 - ...

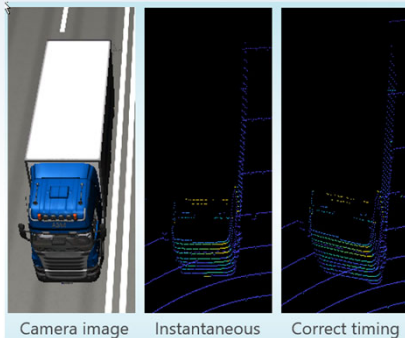
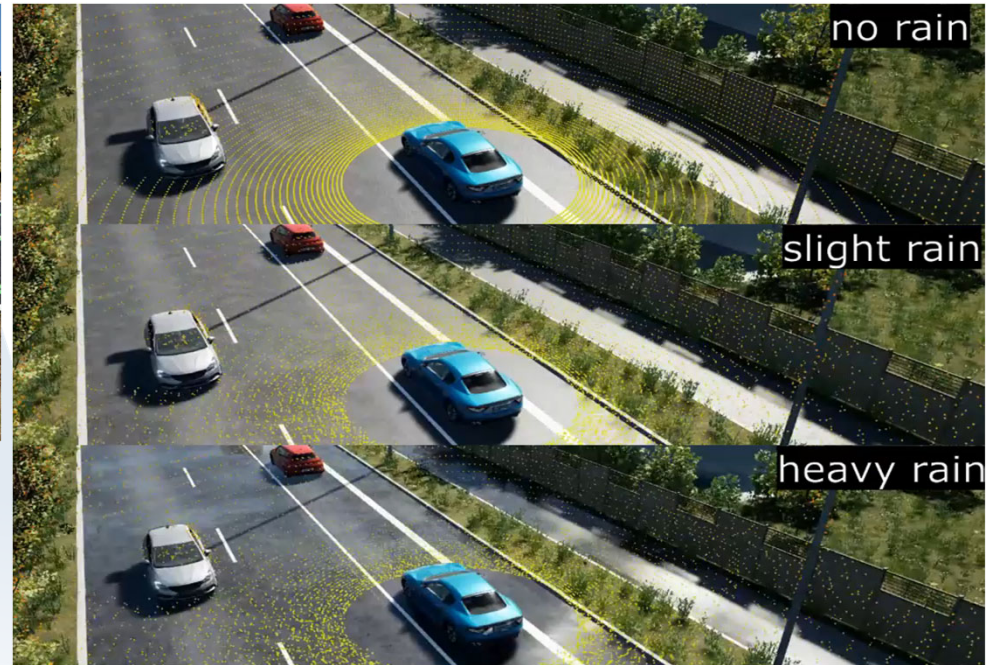


Sensor Models: LIDAR



Motion Distortion: **Disabled**

Motion Distortion: **Enabled**



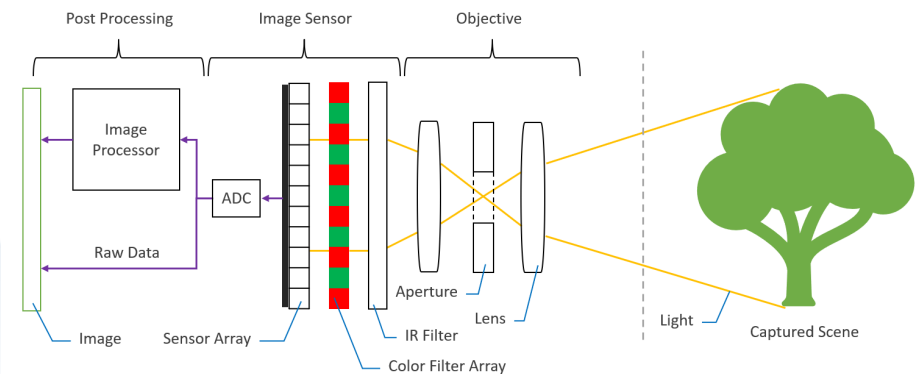
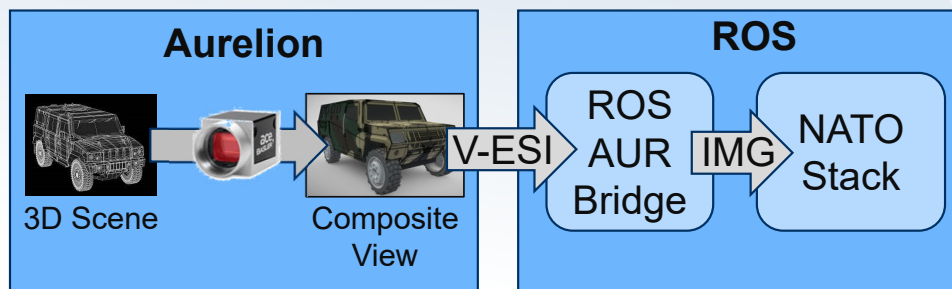
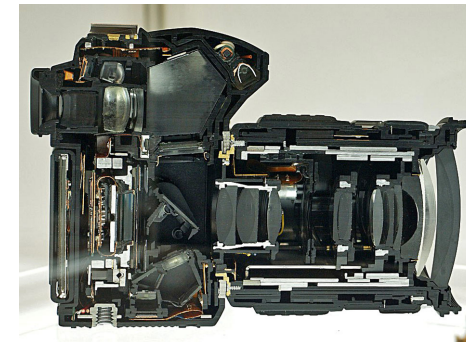
Camera image

Instantaneous

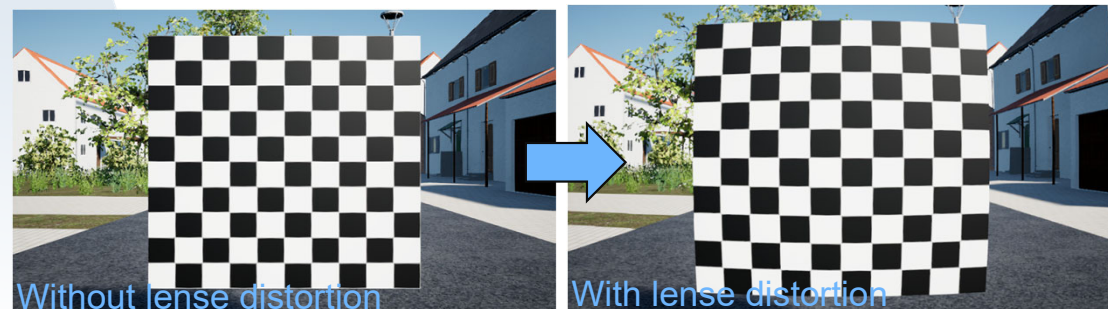
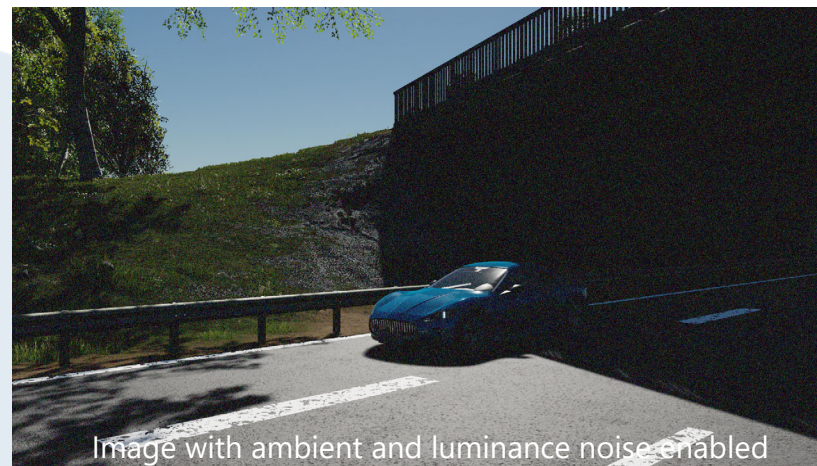
Correct timing

Sensor Models: Camera

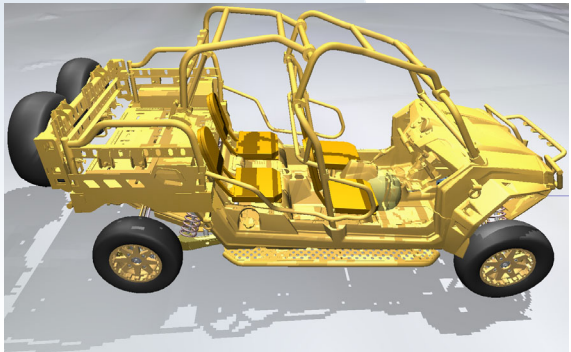
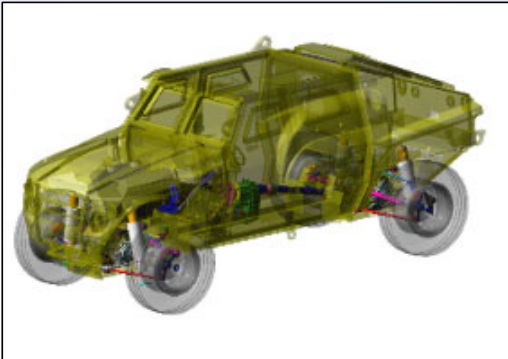
- Camera: FLIR Oryx ORX-10G-51S5C-C
 - Imager: Sony IMX 250 (2448x2048 @ 60Hz)
 - Lense: Edmund Optics 58-001 (12mm FL)
 - Color filter pattern
 - Lense distortion
 - Physically based lighting
 - ...



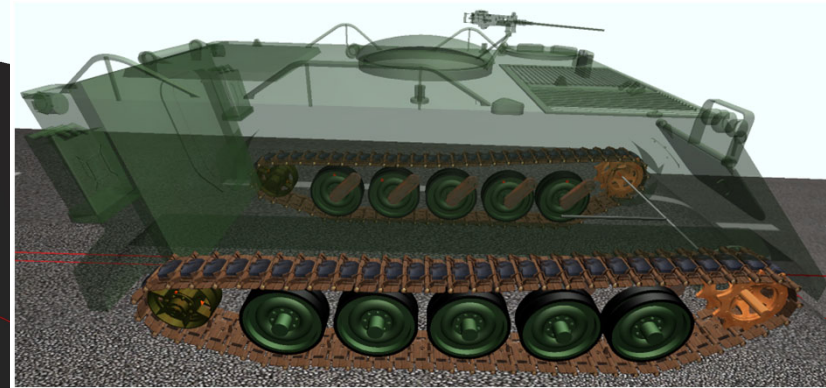
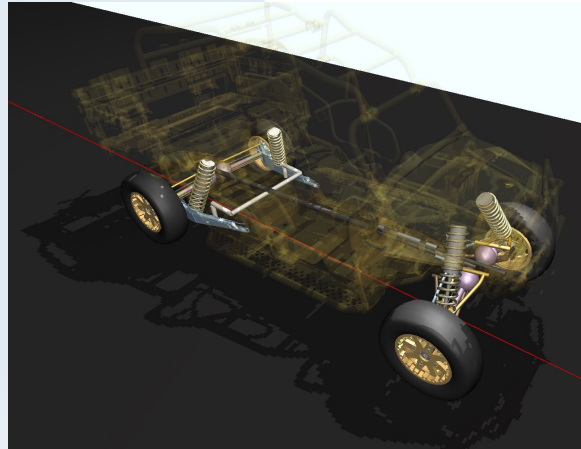
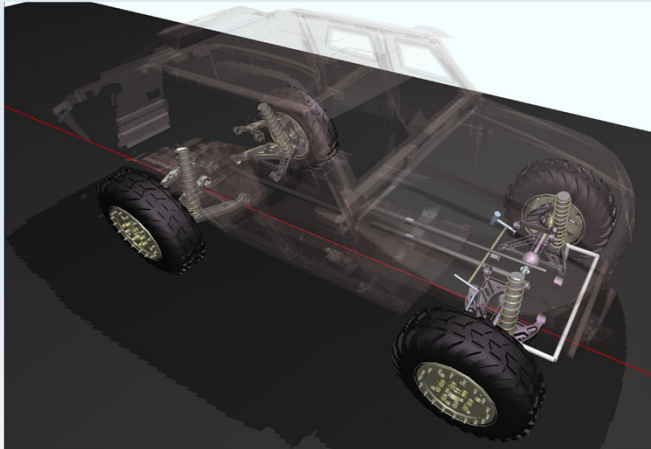
Sensor Models: Camera



4 Physical Vehicles and Vehicle Models



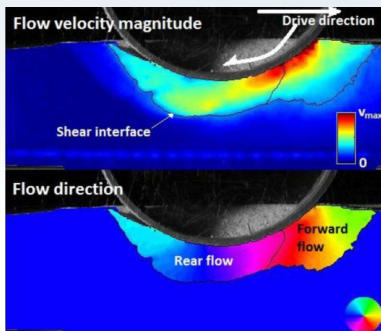
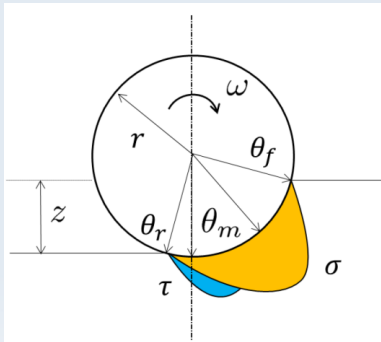
3D Vehicle Dynamics Models



NG-NRMM Simple Terramechanics Model

Bekker-Wong-Janosi Models

- Bekker-Wong model for normal stress
- Janosi-Hanamoto model for tangential stress
- Mohr-Coulomb criterion

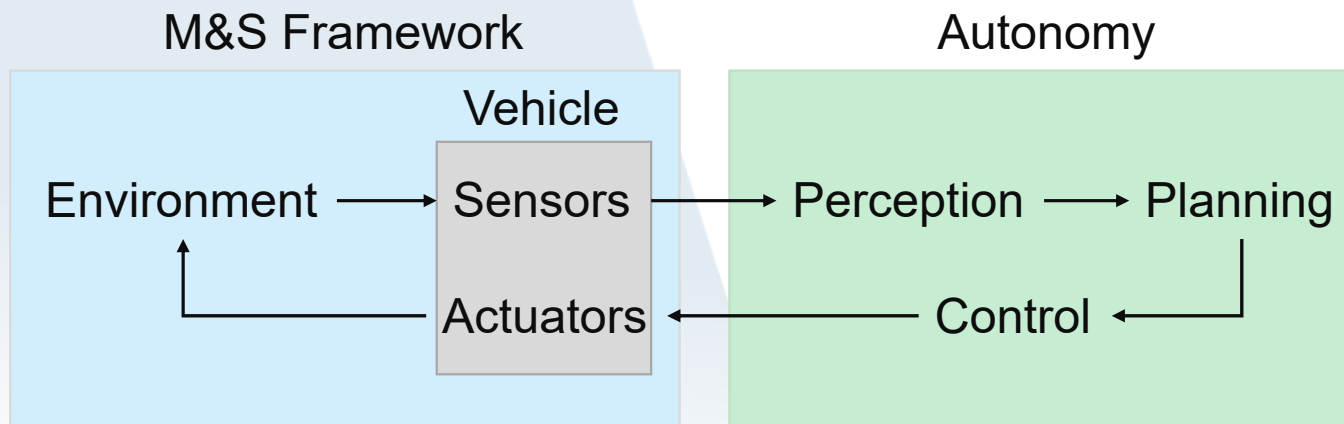


Particle Image Velocimetry



5 Autonomy

**Goal: Assemble an autonomy stack
to meet autonomy challenges of loyal wingman scenario**



Stack: integrated capabilities of perception, planning, and control

3 Rationale for Developing the NATO Autonomy Stack

State-of-the-art stacks did not meet our needs

Desired criteria

1. **Integrity:** integrated perception, planning, and control capabilities instead of individual capabilities
2. **Range of capabilities:** covering as many of the loyal wingman scenario needs as possible
3. **Extendibility:** being easily expandable by augmenting with new capabilities
4. **Transferability:** ability to transfer the stack from simulations to physical vehicles
5. **Interface:** direct support for ROS
6. **Openness:** open source without limitations for distribution and use
7. **Support:** good developer or community support
8. **Liveliness:** being in continuous development
9. **Cost:** No or minimal cost for any licensing and support

Resources considered



Community

AVT-341 Members
US DoD Programs
CMU NREC
MTU
Robonity
SafeAI



Literature

Individual capabilities



M&S tools

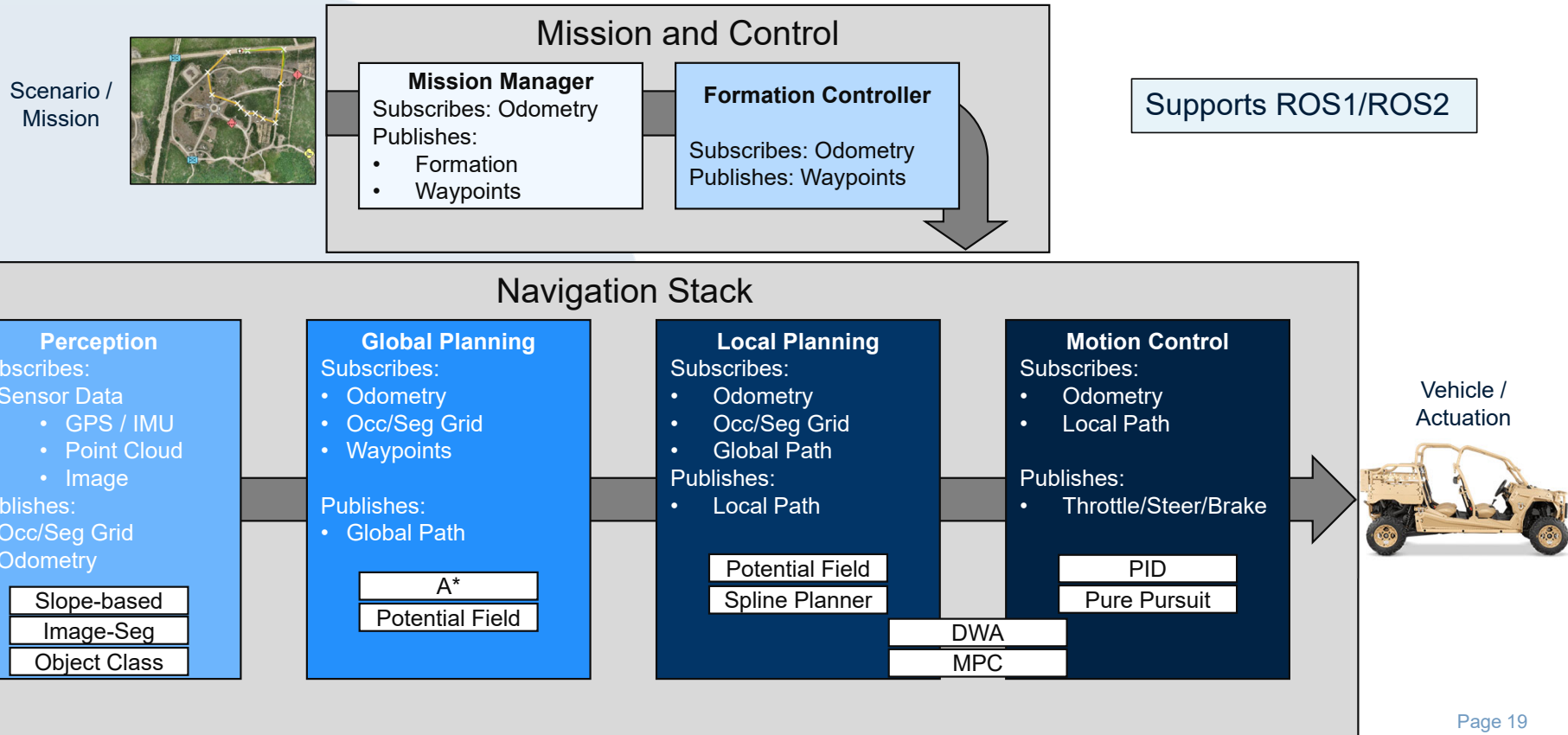
Microsoft AirSim
CARLA
MATLAB



Open source

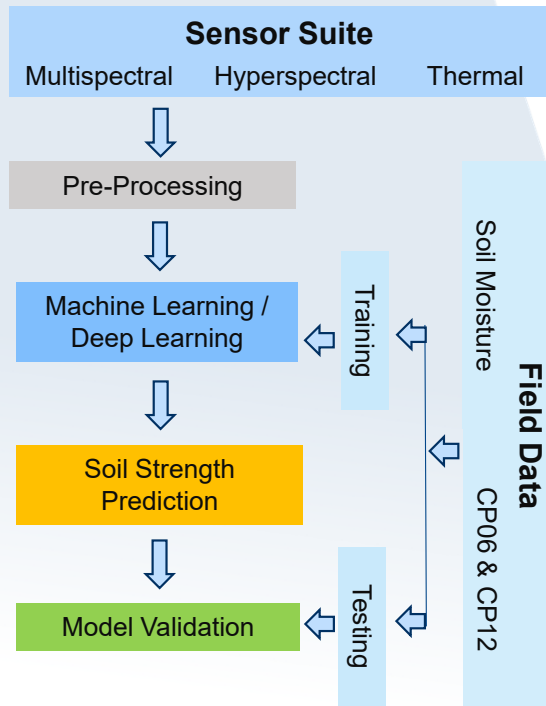
Autoware
Apollo
Comma.ai openpilot
Stanford's Junior Stack

NATO Autonomy Stack



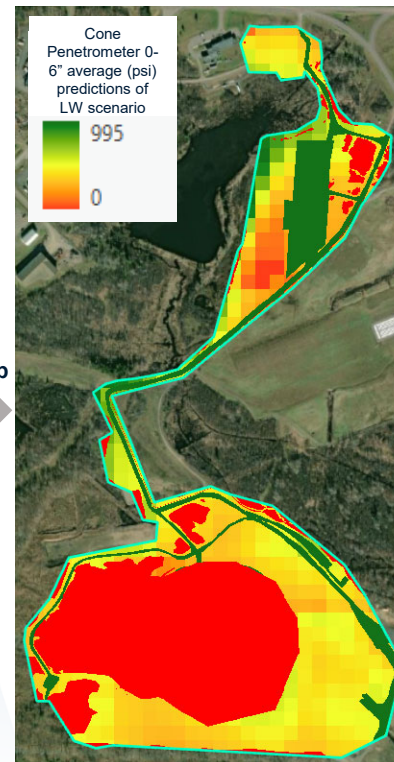
Remote Sensing and Terrain Strength Mapping

UAV-Based Remote Sensing



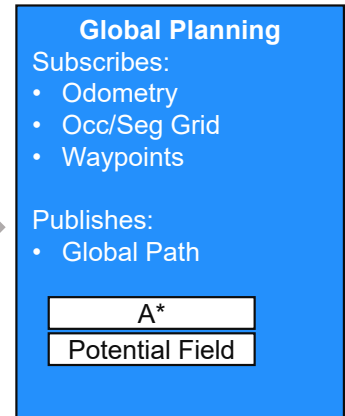
Strength Map

LW Terrain Strength Map



Cost Map

NATO Autonomy Stack

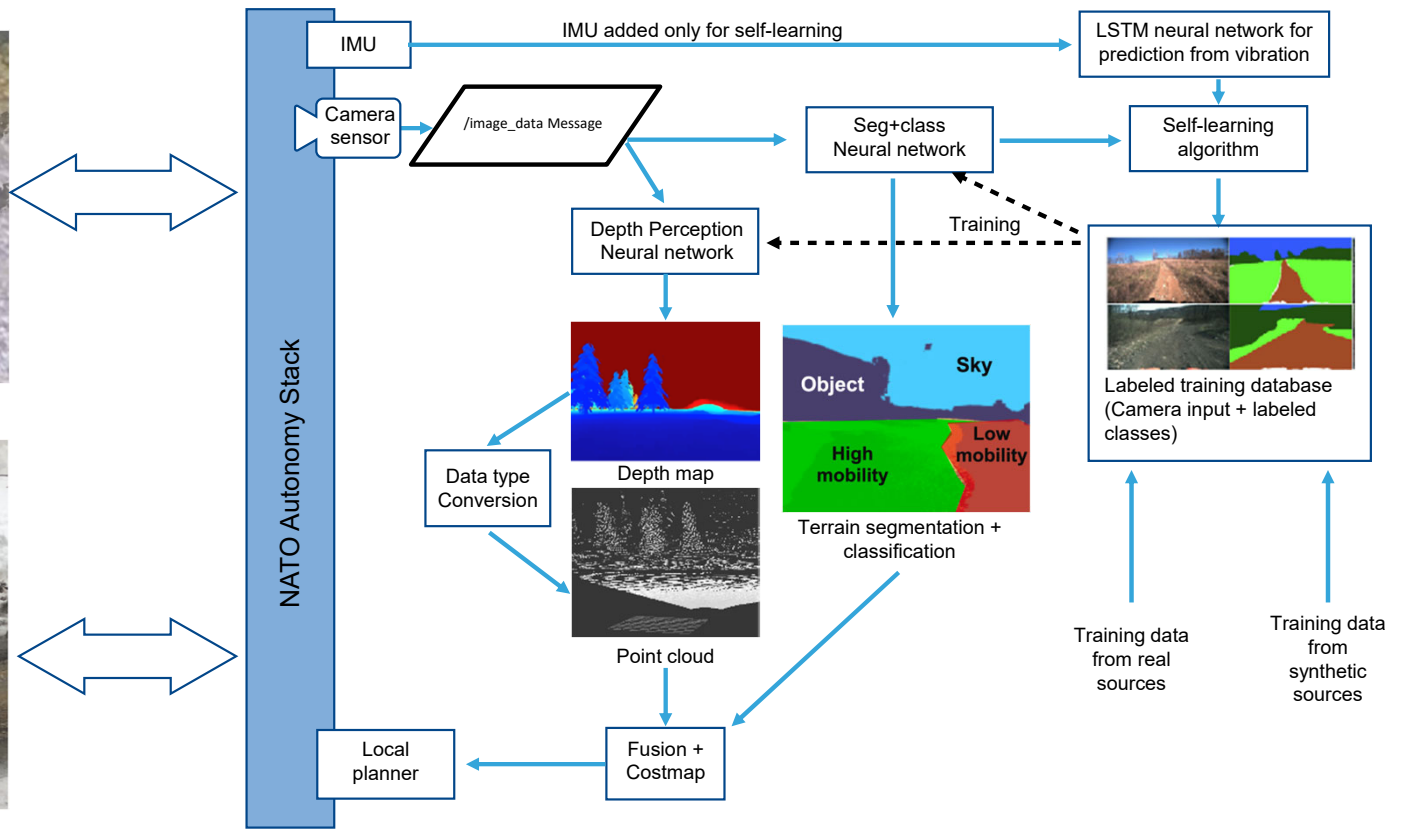




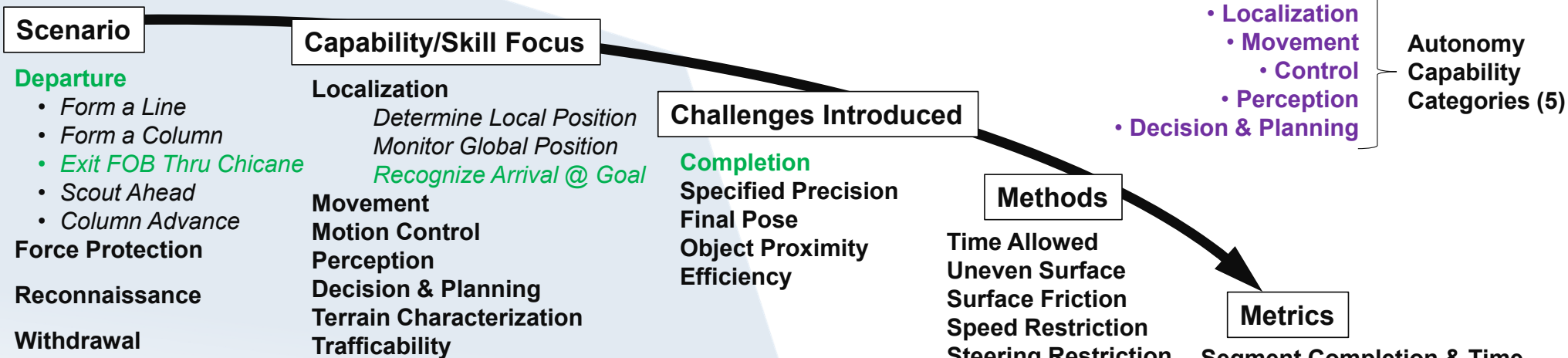
Simulated environment



Real Environment



6 V&V



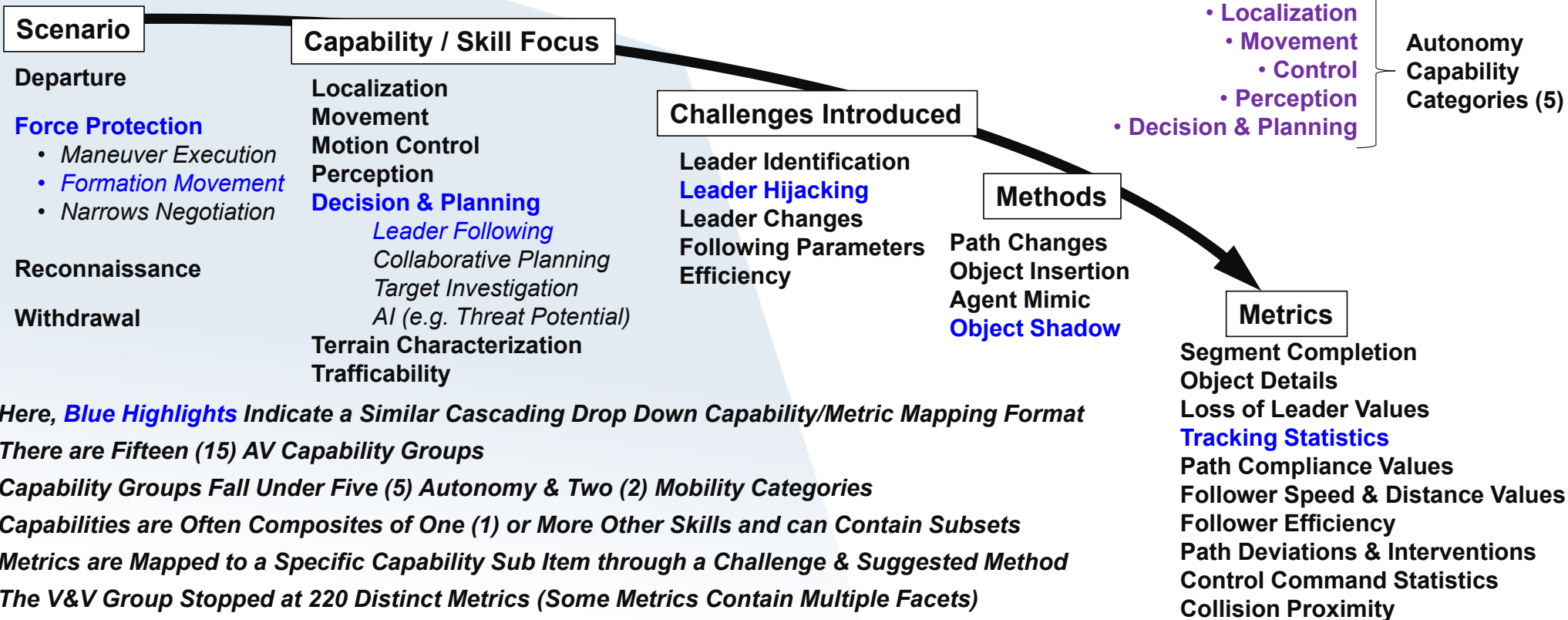
The Scenario Phases are Further Broken into Segments – 35 Total for the Entire Scenario

Segments May Contain More than One (1) Capability Challenge

Autonomy Metrics are Grouped into Five (5) Basic Capability Categories (Expanded from PPC)

*Here, **Green Highlights** Indicate Capability/Metric Mapping within a Cascading Drop Down Menu Format*

V&V



V&V Metrics

Localization Metric – Subset 2.c:

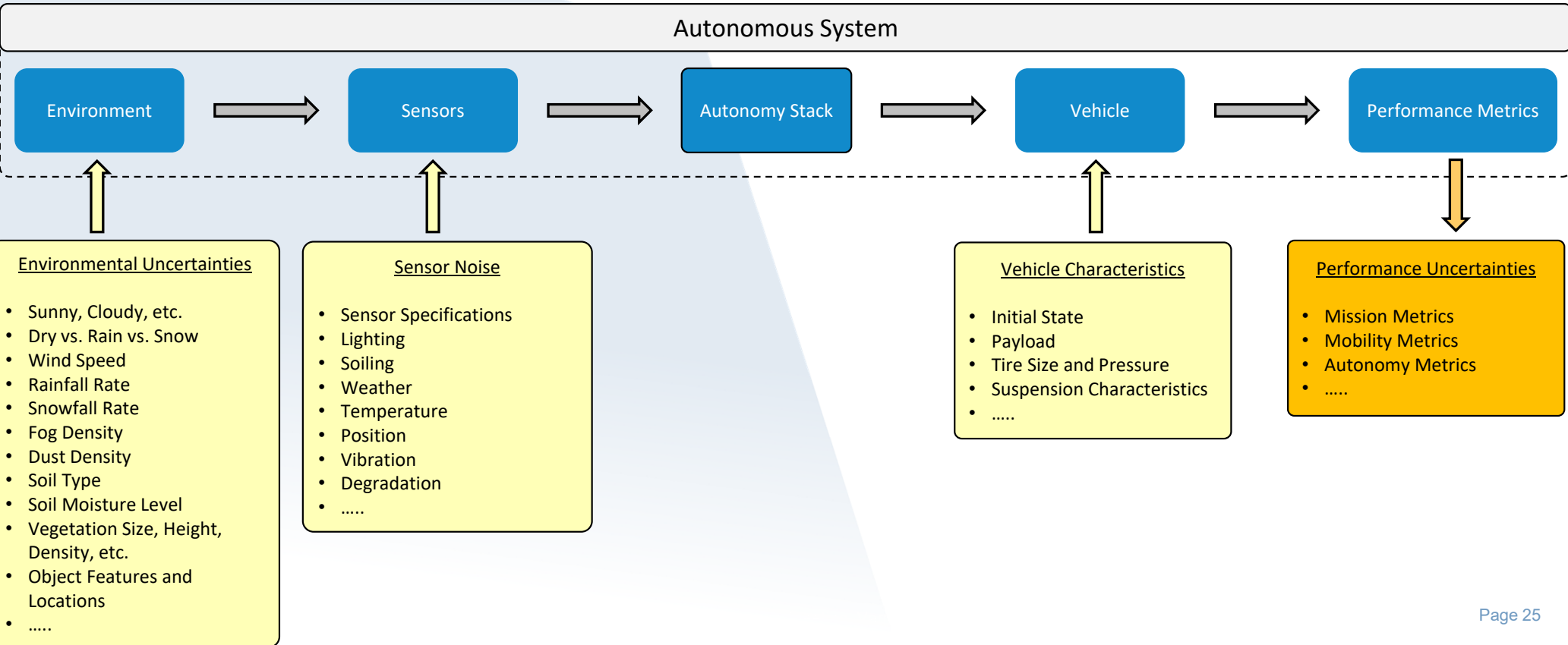
- (Metric 1) Challenge Completion Statistics (Arrival time, Distance Traveled, **Final Location & Heading**)
- (Metric 3) Does the simulated AV position trace match actual from physical test?
- (Metric 5) Does the simulated AV velocity trace match actual from physical test?
- (Metric 6) Do the simulated AV dynamic state traces (roll/pitch/yaw) match actual from physical test?
- (Metric 11) Compare Steering, Throttle, & Brake (STB) requests, actuation, & response data (Use in conjunction with scene elements to determine perception, decision & response speed)

Leader Tracking Metric - Subset 11.c:

- (Metric 175) Depending upon the instructions to follow the leader, did the AV;
 1. Maintain specified straight-line distance from the lead vehicle?
 2. Match path of lead vehicle within a specified max and min distance?
 3. How far out of position did the AV travel?
 4. For how long was the AV out of position?
 5. Match the speed of the lead vehicle within a specified max and min range?

One Metric / Multiple Facets

7 Uncertainties in Autonomous Systems



Uncertainty Quantification

Simulation

Test

- Environmental Uncertainties
- Sensor Noise & Specifications
- Vehicle Capabilities & Specifications

Identify Input Variables

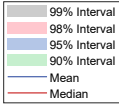
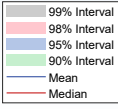
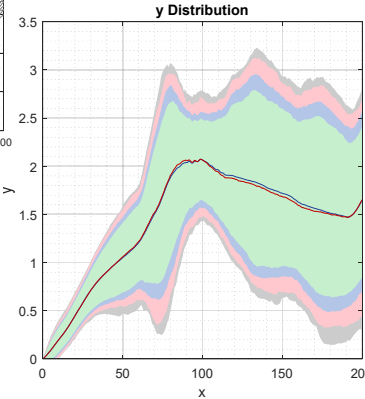
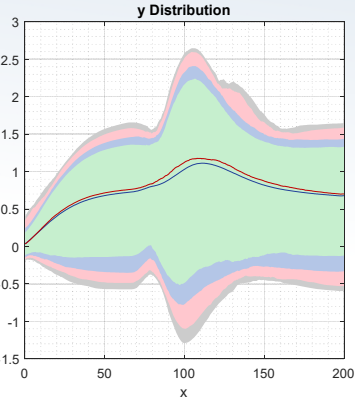
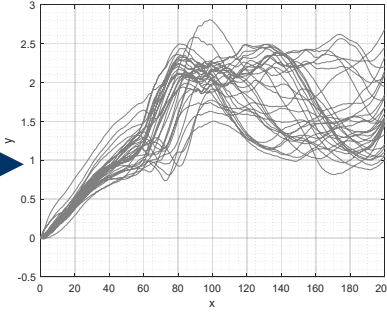
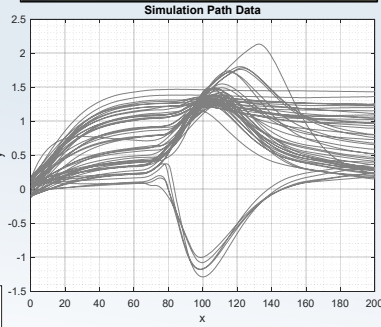
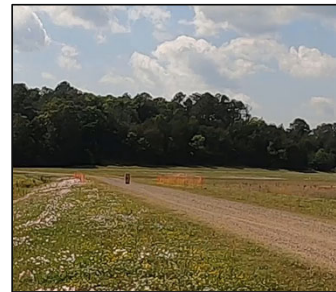
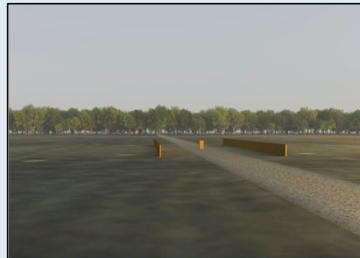
Identify Variability of Input Variables

Run Scenario

Gather Data

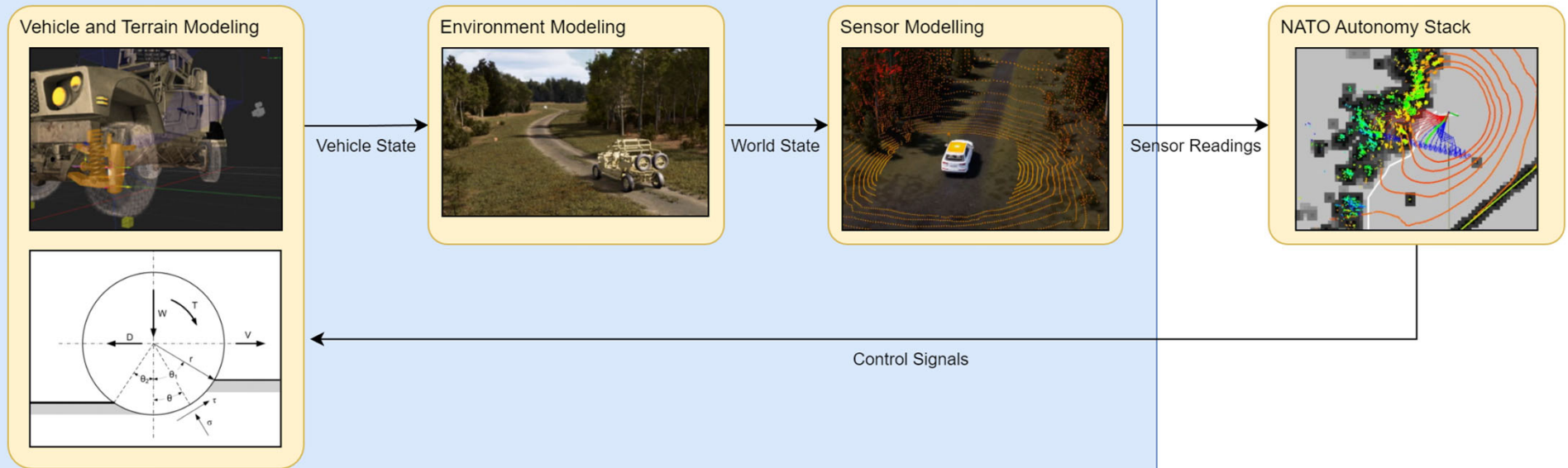
Obtain Performance Metric Distribution

Compare Simulation & Target Distribution



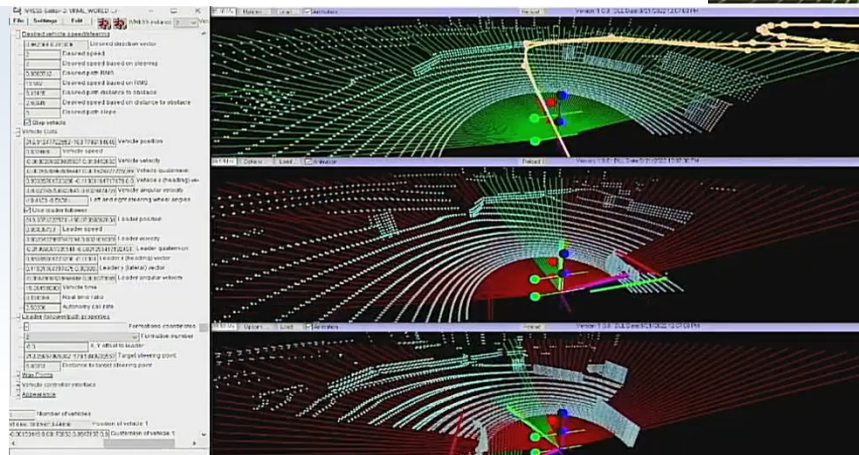
M&S Framework

Modeling and Simulation



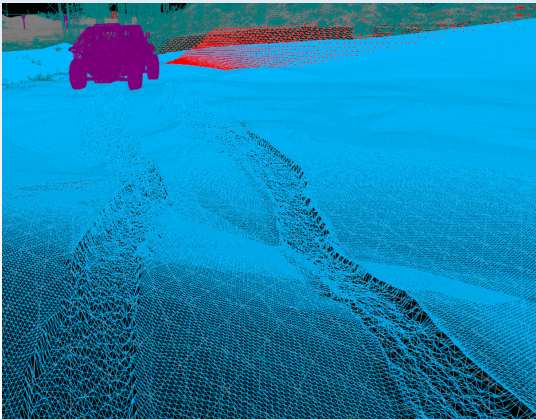
8 LW Phase 1: Departure

- Autonomy challenges:
 - Navigate through a narrow passage/chicane.
 - Start in line formation and change to column.
 - Avoid ground personal and static obstacles.
 - Path planning.
- M&S challenge: 3 high-fidelity vehicle models.



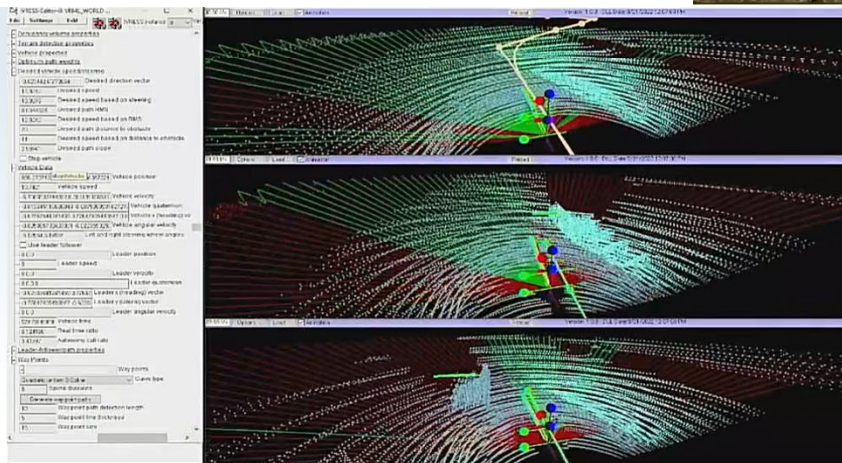
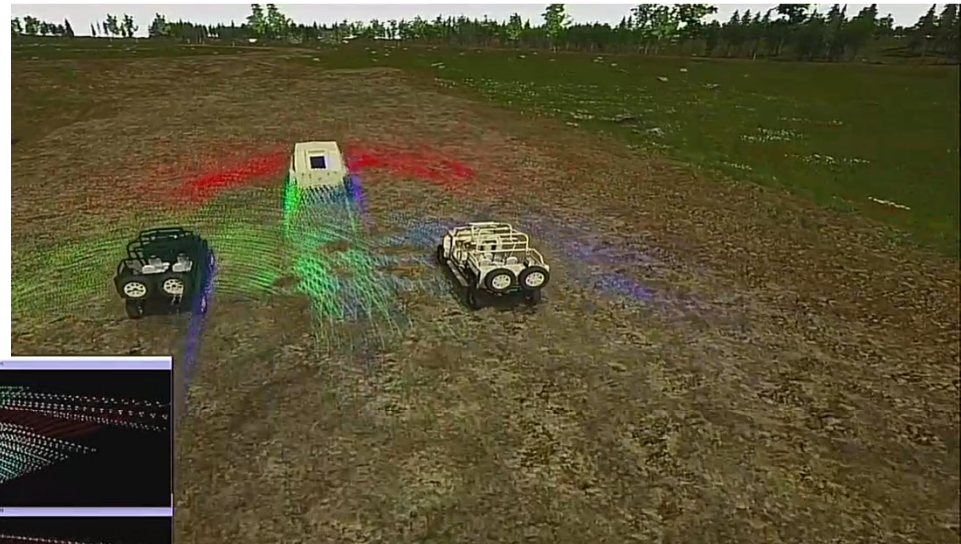
LW Phase 2: Force Protection

- Autonomy challenges:
 - Follow leader.
 - Detour into soft-soil pit.
- M&S challenges:
 - 2 high-fidelity vehicle models.
 - Deformable soft-soil terrain
- Mobility Challenge: Cross a soft-soil pit.



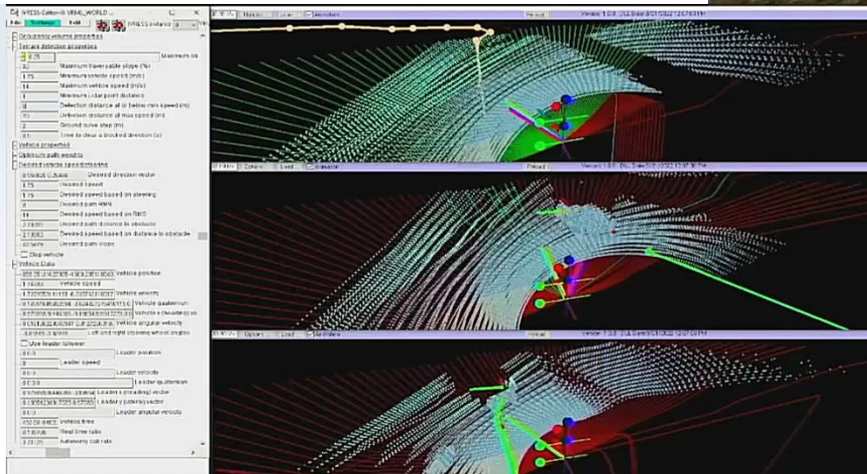
LW Phase 3: Reconnaissance

- Autonomy challenges:
 - Maintain a triangular formation
 - Avoid static obstacles (rocks).
 - Path planning.
- M&S challenges: 3 high-fidelity vehicle models.



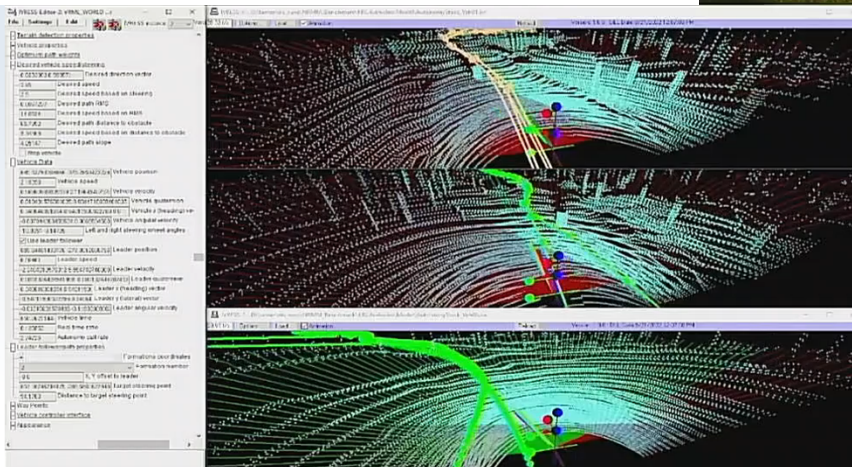
LW Phase 3: Reconnaissance

- Autonomy challenges:
 - Maintain a column formation
 - Navigate a slope.
- M&S challenge: 3 high-fidelity vehicle models.
- Mobility challenge: Traverse a side slope.



LW Phase 4: Withdrawal

- Autonomy challenges:
 - Navigate through a narrow passage/chicane.
 - Avoid ground personal and static obstacles.
 - Park the vehicles in the designated spots.
- M&S challenge:
 - 3 high-fidelity vehicle models.
 - Detect vehicle body collision with pedestrians.



Summary: NATO AVT-341

- developed a military relevant operational scenario, Loyal Wingman (LW).
- established an M&S framework for off-road autonomous mobility assessment.
- developed NATO Autonomy Stack.
- virtual demonstration of LW and autonomous assessment are in progress.
- V&V and vehicle demonstration may follow in a NATO Cooperative Demonstration of Technology (CDT).