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

Background / Motivation

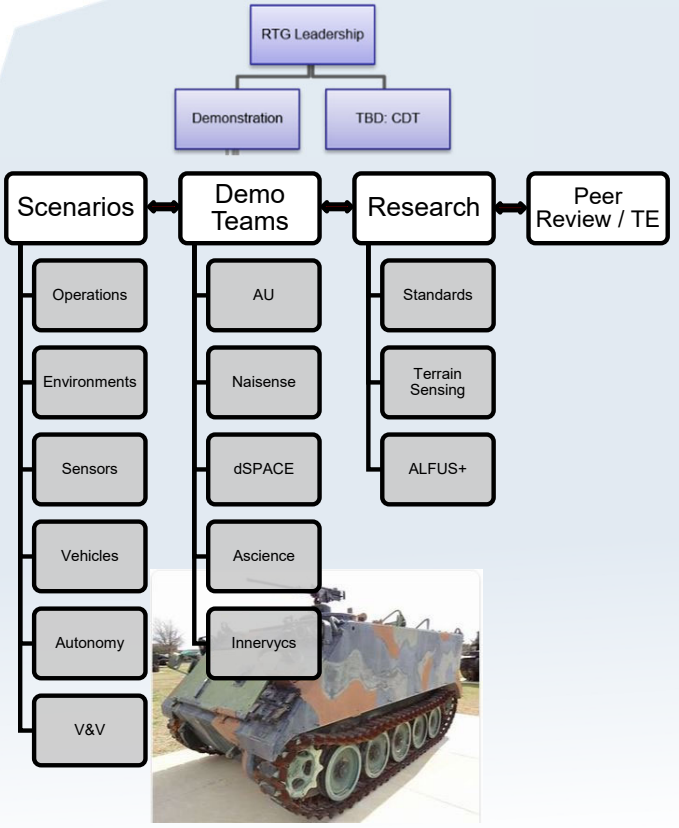
- Autonomous ground vehicles are a key part of the future military strategy for many NATO Nations. In the race to field these systems, there is still a lack of understanding of the capabilities and reliability of these systems.
- The assessment challenges are that:
  - Current autonomy software do not 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

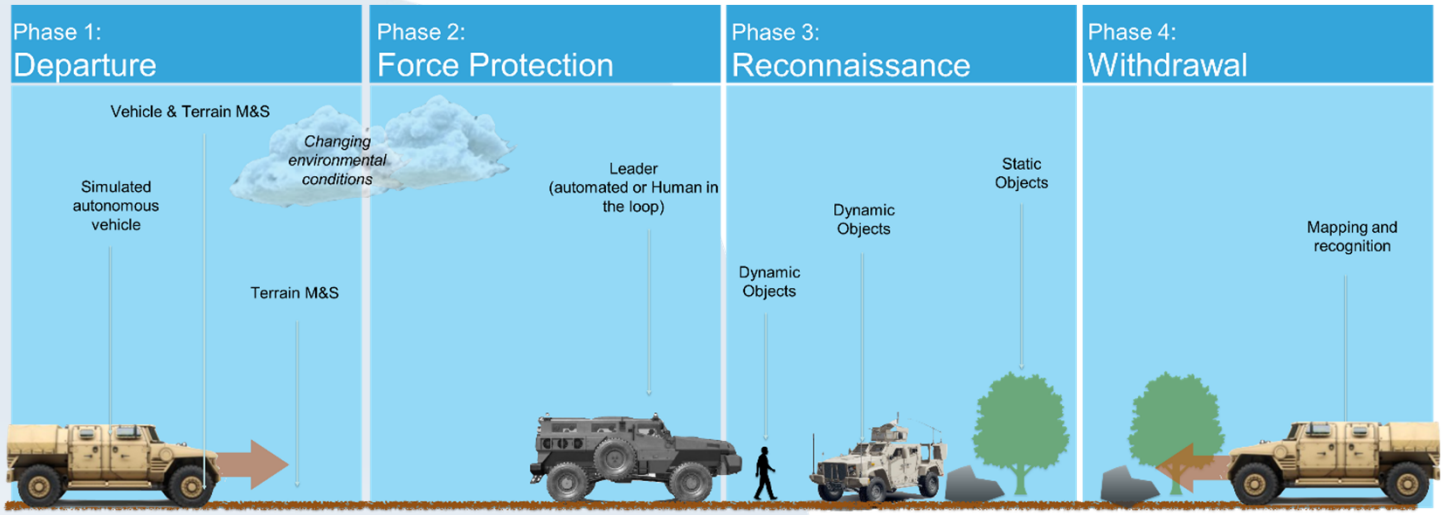
- Establish a mobility assessment framework purposely designed to consider the specific underlying requirements of off-road mobility of military autonomous ground vehicles.
- Demonstrate evaluation of autonomous mobility using integrated autonomy and mobility M&S tools for realistic and relevant scenarios.
- 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.

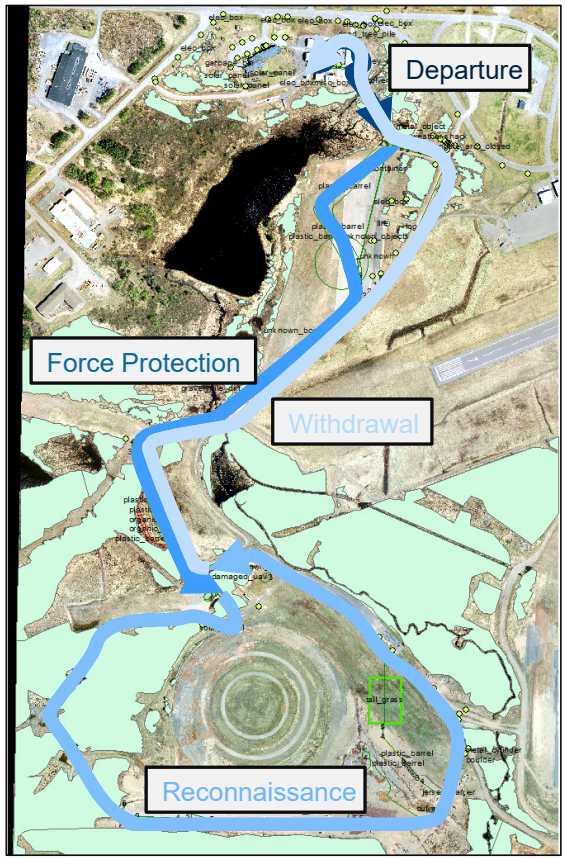
Minimize visual, and auditory signature.

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.

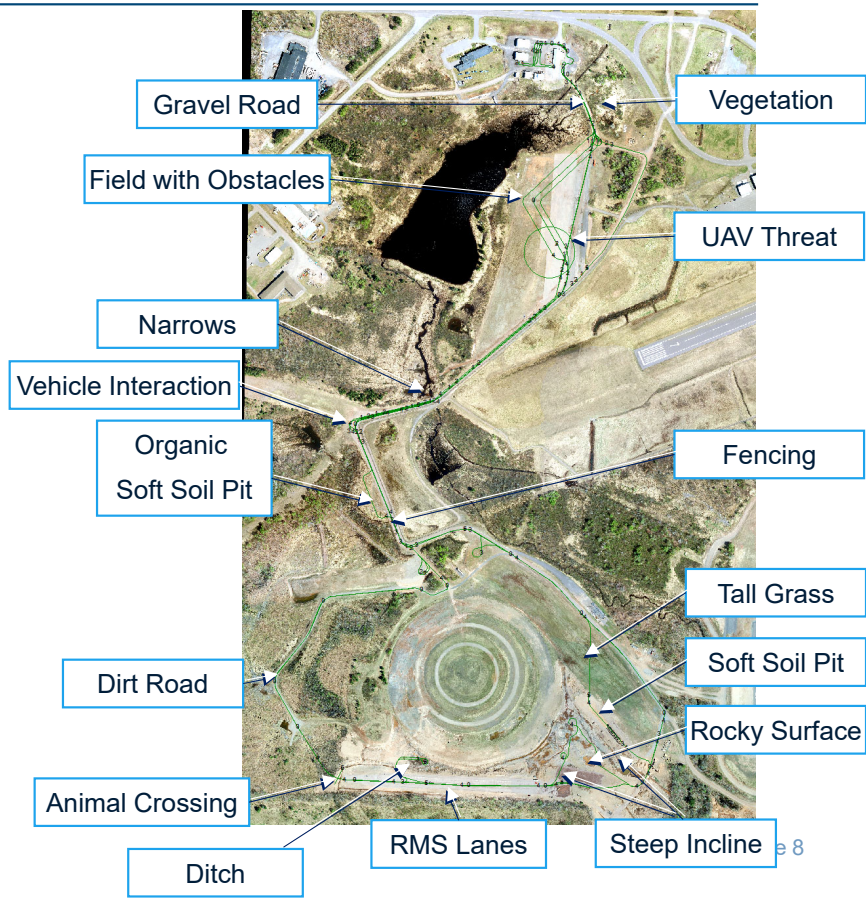


Loyal Wingman Scenario Challenges

- 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

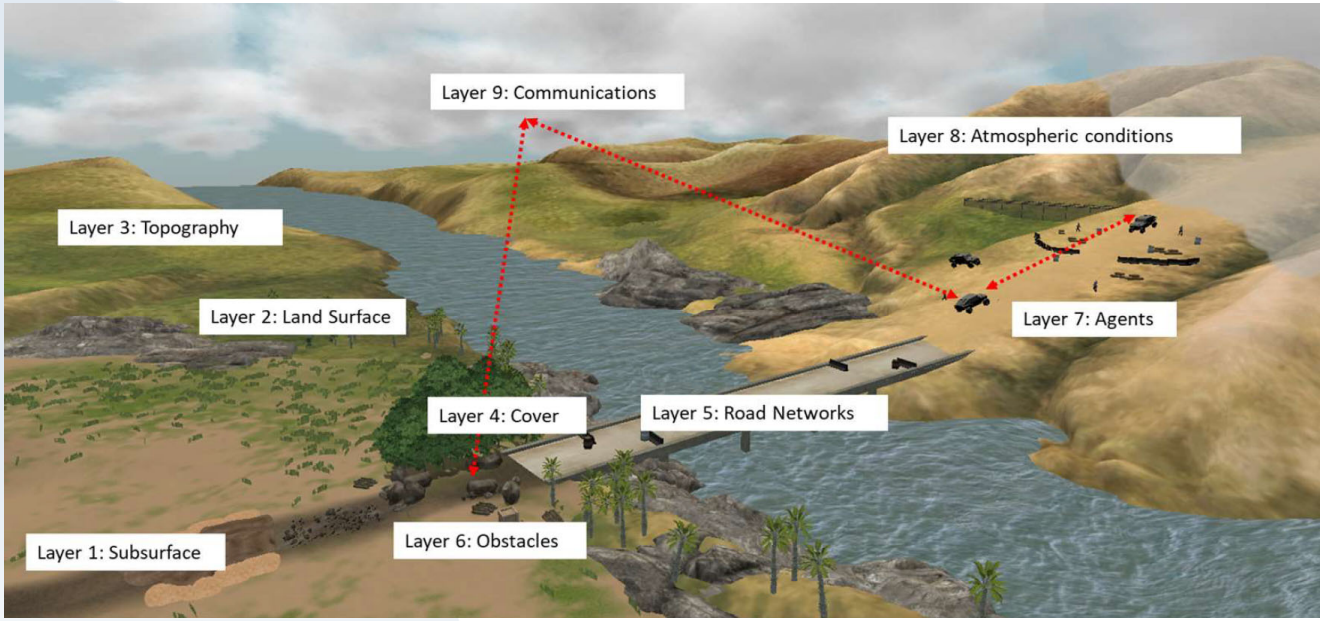
2 Environmental Challenges in Loyal Wingman Scenario

- 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

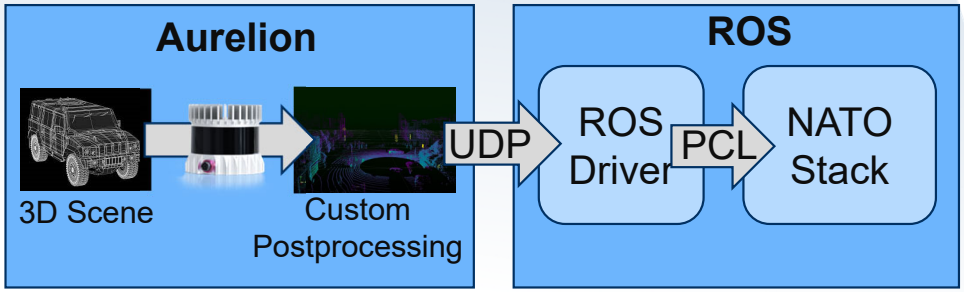
- Subsurface
- Land surface
- Topography
- Cover
- Road Networks
- Objects
- Agents
- Conditions
- Communications

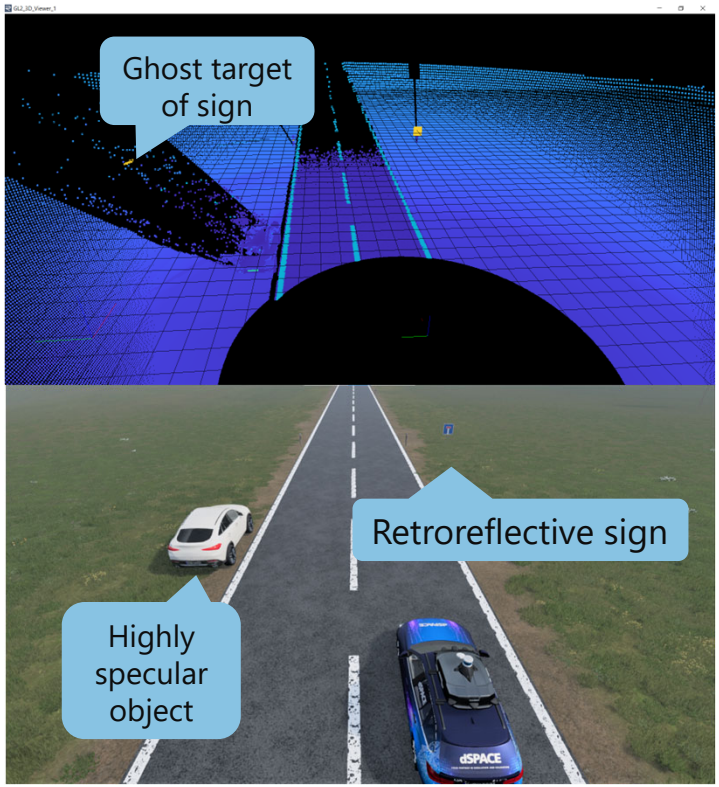


PEGASUS in pink

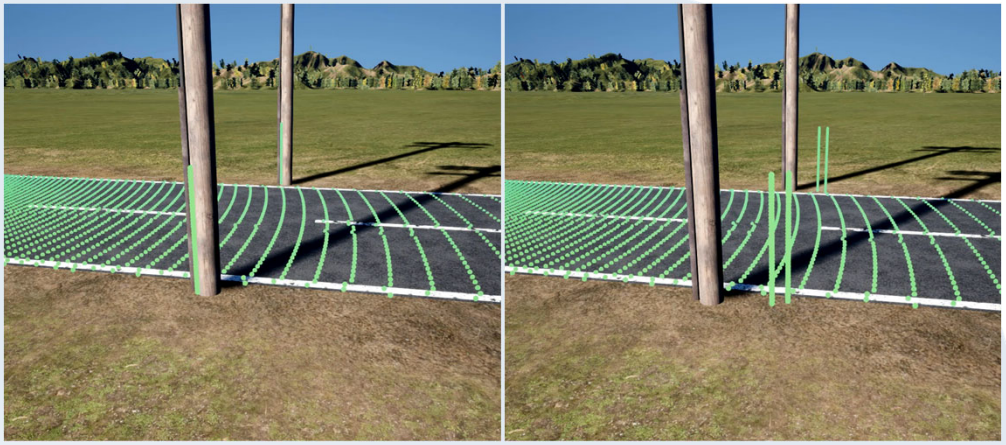
3 Sensor Models: LIDAR

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



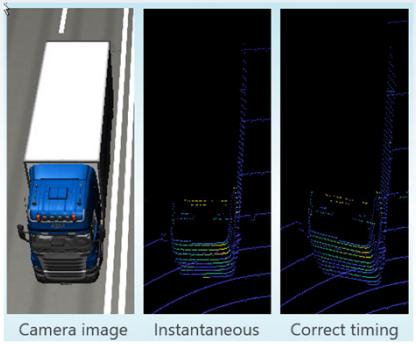


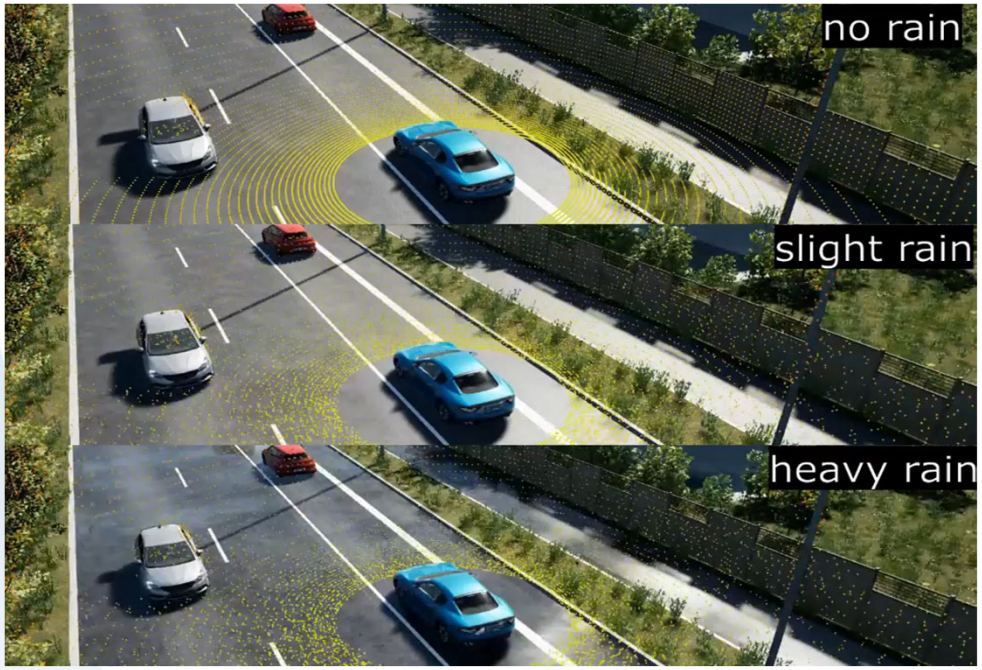
Sensor Models: LIDAR



Motion Distortion: **Disabled**

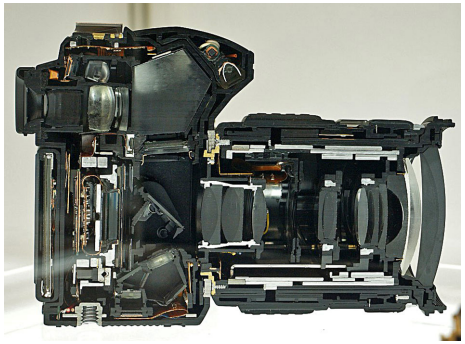
Motion Distortion: **Enabled**

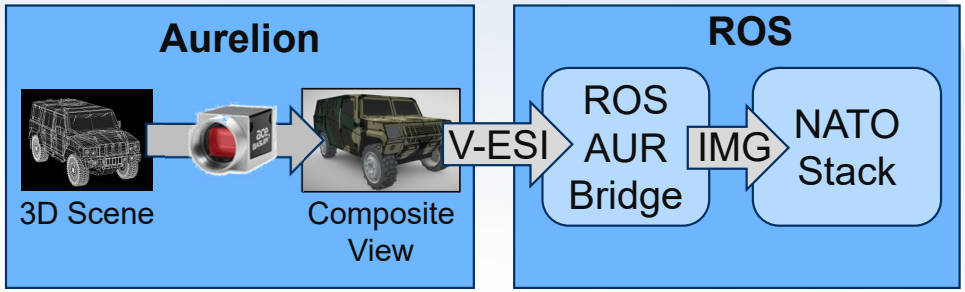


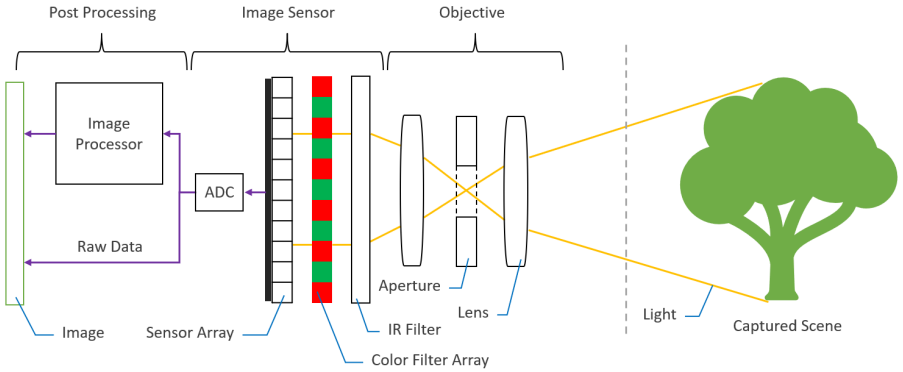


Sensor Models: Camera

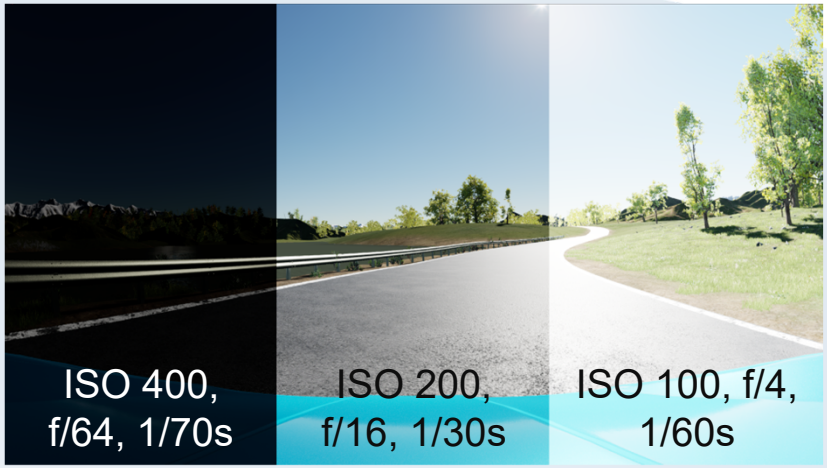
- Camera: FLIR Oryx ORX-10G-51S5C-C
  - Imager: Sony IMX 250 (2448x2048 @ 60Hz)
  - Lense: Edmund Optics 58-001 (12mm FL)
  - Color filter pattern
  - Lense distortion
  - Physically based lighting
  - …

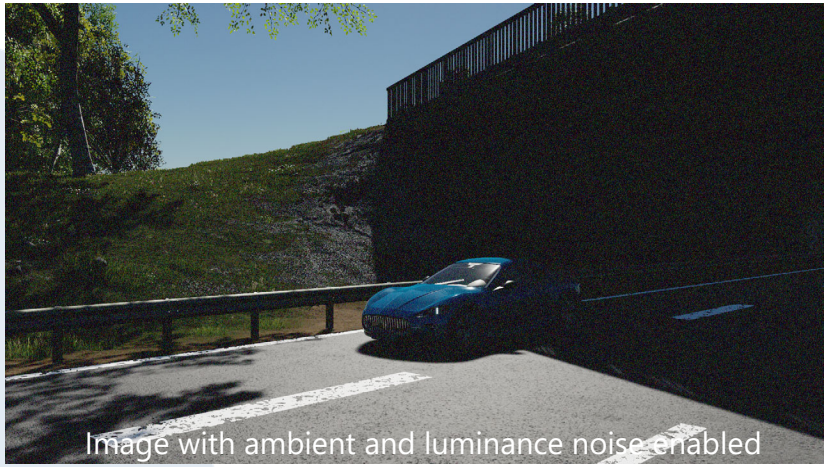


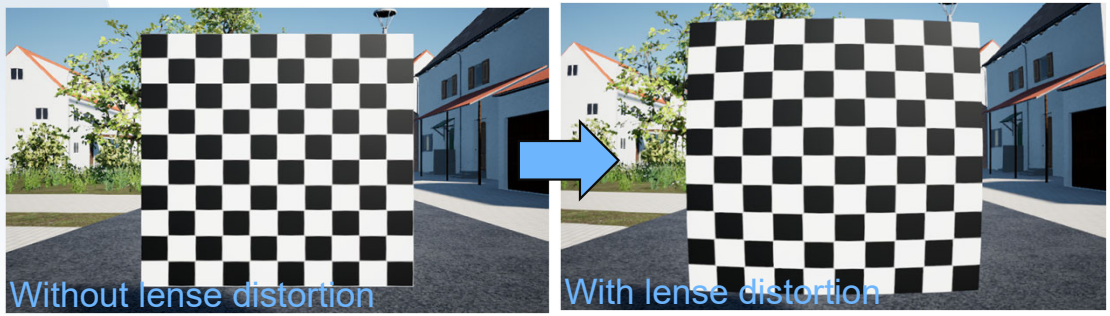




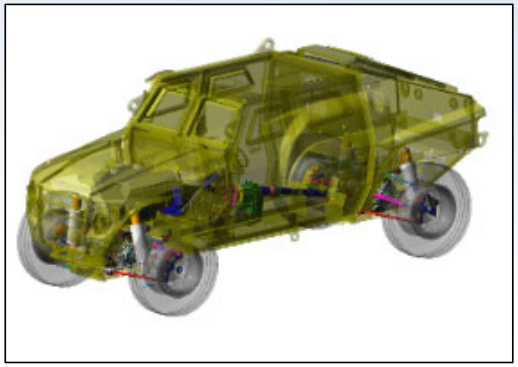
Sensor Models: Camera



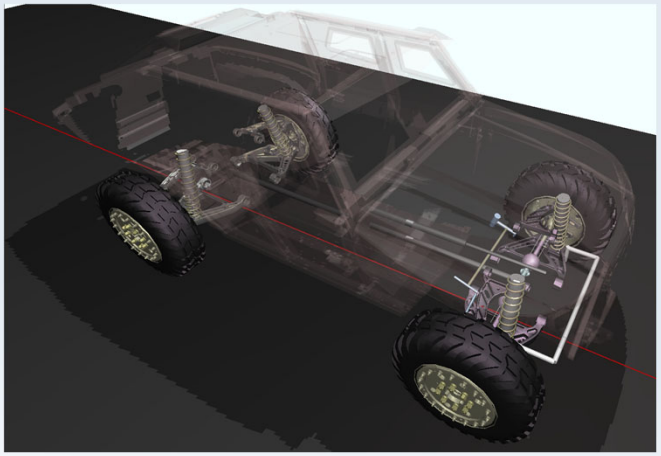


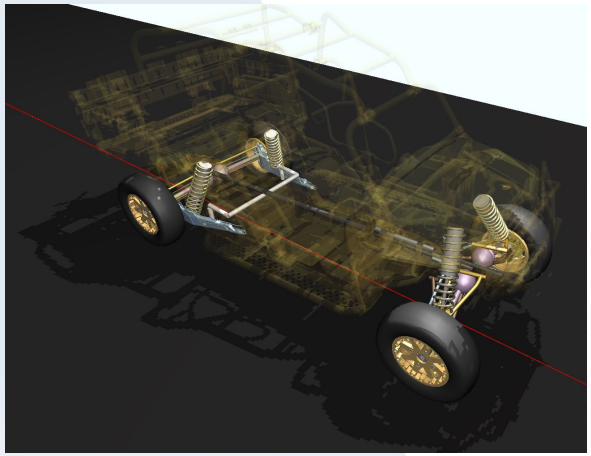


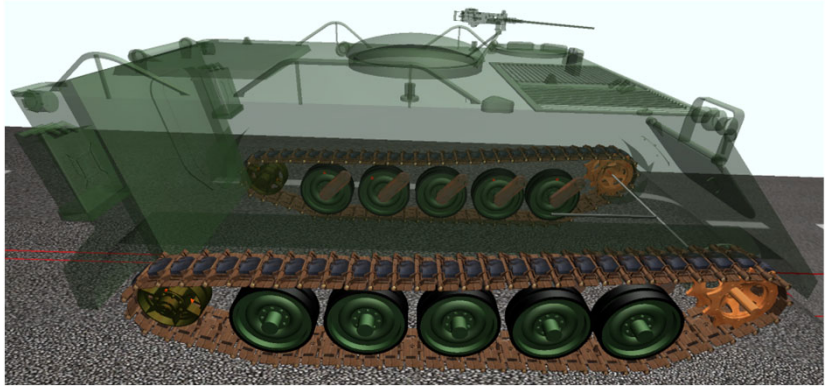
4 Physical Vehicles and Vehicle Models



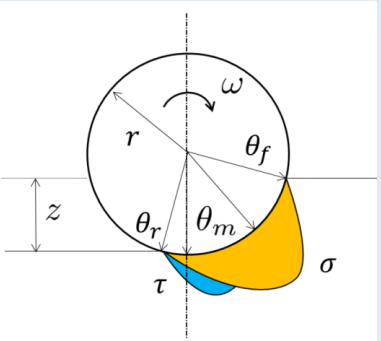
3D Vehicle Dynamics Models





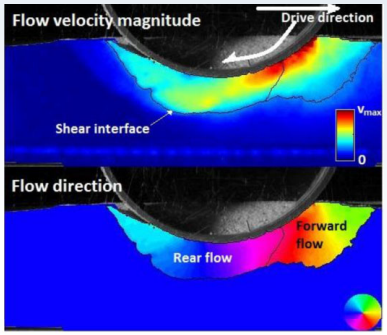


NG-NRMM Simple Terramechanics Model



Bekker-Wong-Janosi Models

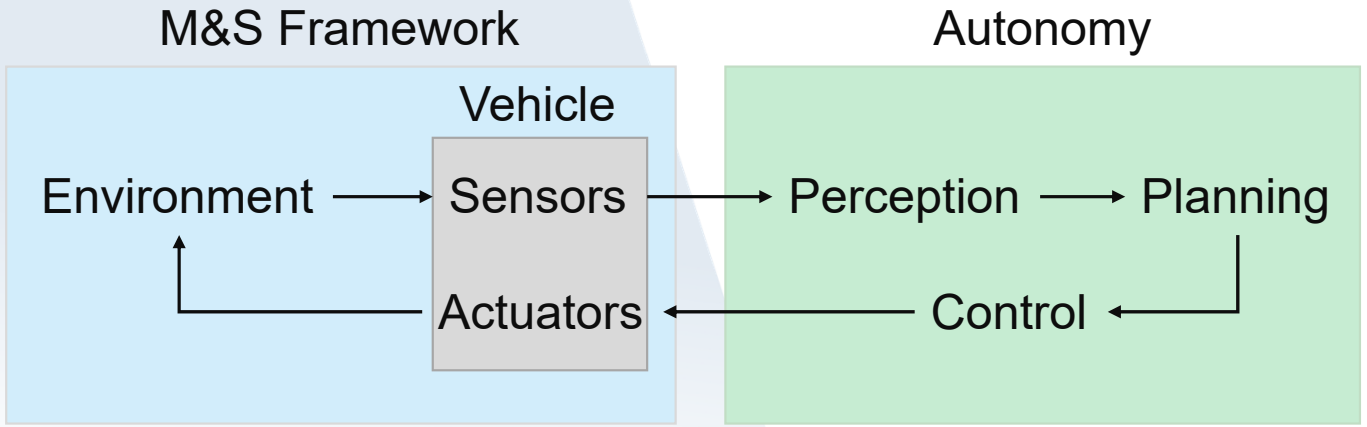
- Bekker-Wong model for normal stress
- Janosi-Hanamoto model for tangential stress
- Mohr-Coulomb criterion



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

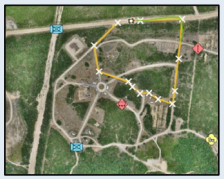
Microsoft AirSim
CARLA
MATLAB

Open source

Autoware
Apollo
Comma.ai openpilot
Stanford's Junior Stack

NATO Autonomy Stack

Scenario / Mission



Mission and Control

Mission Manager
Subscribes: Odometry
Publishes:
- Formation
- Waypoints

Formation Controller

Subscribes: Odometry
Publishes: Waypoints

Supports ROS1/ROS2

Navigation Stack

Sensors

Perception
Subscribes:
- Sensor Data
  - GPS / IMU
  - Point Cloud
  - Image

Publishes:
- Occ/Seg Grid
- Odometry

Slope-based
Image-Seg
Object Class

Global Planning
Subscribes:
- Odometry
- Occ/Seg Grid
- Waypoints

Publishes:
- Global Path

A*
Potential Field

Local Planning
Subscribes:
- Odometry
- Occ/Seg Grid
- Global Path

Publishes:
- Local Path

Potential Field
Spline Planner
DWA
MPC

Motion Control
Subscribes:
- Odometry
- Local Path

Publishes:
- Throttle/Steer/Brake

PID
Pure Pursuit

Vehicle / Actuation

Remote Sensing and Terrain Strength Mapping

UAV-Based Remote Sensing

Sensor Suite

Multispectral | Hyperspectral | Thermal

Pre-Processing

Machine Learning / Deep Learning

Soil Strength Prediction

Model Validation

Training

Testing

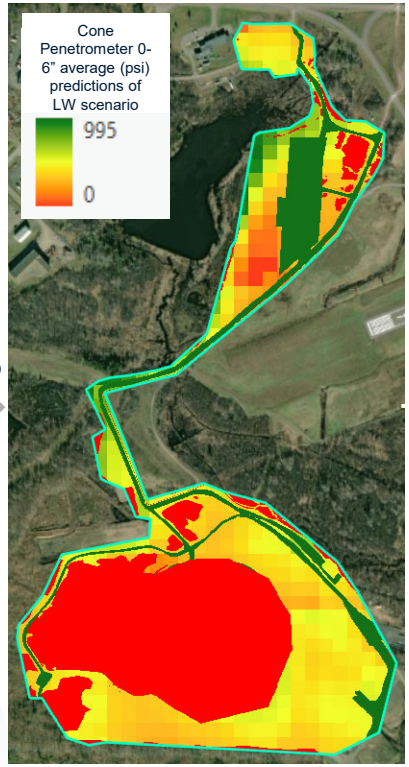
Field Data

Soil Moisture

CP06 & CP12

Strength Map

LW Terrain Strength Map



Cost Map

NATO Autonomy Stack

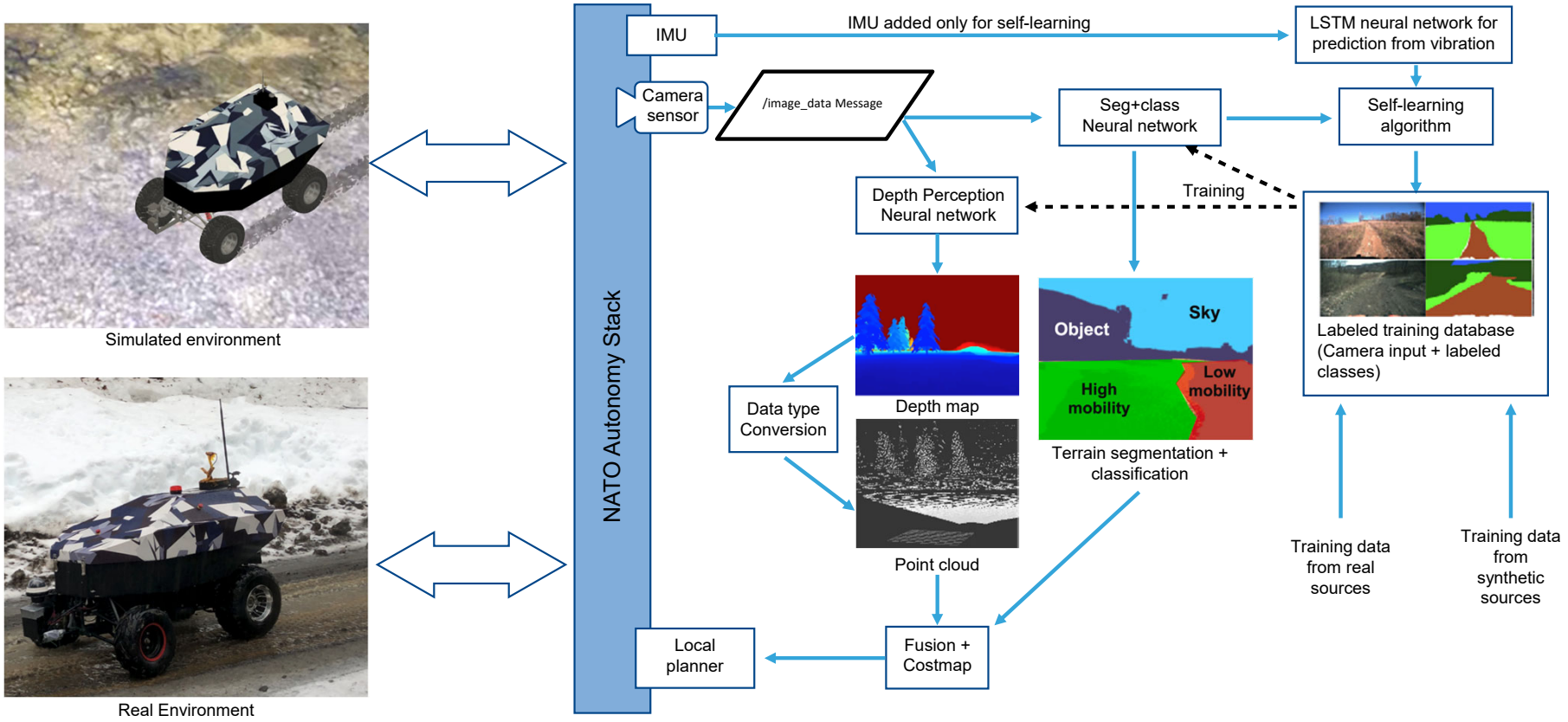
Global Planning

Subscribes:
- Odometry
- Occ/Seg Grid
- Waypoints

Publishes:
- Global Path

A*

Potential Field


Simulated environment
Real Environment
NATO Autonomy Stack
IMU
IMU added only for self-learning
LSTM neural network for prediction from vibration
Camera sensor
/image_data Message
Seg+class Neural network
Self-learning algorithm
Depth Perception Neural network
Training
Depth map
Data type Conversion
Point cloud
Object
Sky
High mobility
Low mobility
Terrain segmentation + classification
Labeled training database (Camera input + labeled classes)
Training data from real sources
Training data from synthetic sources
Local planner
Fusion + Costmap

6 V&V

Scenario

Departure
- *Form a Line*
- *Form a Column*
- *Exit FOB Thru Chicane*
- *Scout Ahead*
- *Column Advance*

Force Protection

Reconnaissance

Withdrawal

Capability/Skill Focus

Localization
Determine Local Position
Monitor Global Position
Recognize Arrival @ Goal

Movement
Motion Control
Perception
Decision & Planning
Terrain Characterization
Trafficability

Challenges Introduced

Completion
Specified Precision
Final Pose
Object Proximity
Efficiency

Methods

Time Allowed
Uneven Surface
Surface Friction
Speed Restriction
Steering Restriction
Alter Chicane Layout
Unexpected Object

Metrics

Segment Completion & Time
Final Position & Pose
Path Compliance Values
Path Deviations & Interventions
Velocity & Dynamic State
Control Command Statistics
Collision Proximity

Autonomy Capability Categories (5)
- **Localization**
- **Movement**
- **Control**
- **Perception**
- **Decision & Planning**

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

Scenario

Departure

Force Protection
- *Maneuver Execution*
- *Formation Movement*
- *Narrows Negotiation*

Reconnaissance

Withdrawal

Capability / Skill Focus

Localization
Movement
Motion Control
Perception
Decision & Planning
Leader Following
Collaborative Planning
Target Investigation
AI (e.g. Threat Potential)
Terrain Characterization
Trafficability

Challenges Introduced

Leader Identification
Leader Hijacking
Leader Changes
Following Parameters
Efficiency

Methods

Path Changes
Object Insertion
Agent Mimic
Object Shadow

Metrics

Segment Completion
Object Details
Loss of Leader Values
Tracking Statistics
Path Compliance Values
Follower Speed & Distance Values
Follower Efficiency
Path Deviations & Interventions
Control Command Statistics
Collision Proximity

- **Localization**
- **Movement**
- **Control**
- **Perception**
- **Decision & Planning**

Autonomy Capability Categories (5)

Here, Blue Highlights Indicate a Similar Cascading Drop Down Capability/Metric Mapping Format

There are Fifteen (15) AV Capability Groups

Capability Groups Fall Under Five (5) Autonomy & Two (2) Mobility Categories

Capabilities are Often Composites of One (1) or More Other Skills and can Contain Subsets

Metrics are Mapped to a Specific Capability Sub Item through a Challenge & Suggested Method

The V&V Group Stopped at 220 Distinct Metrics (Some Metrics Contain Multiple Facets)

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)

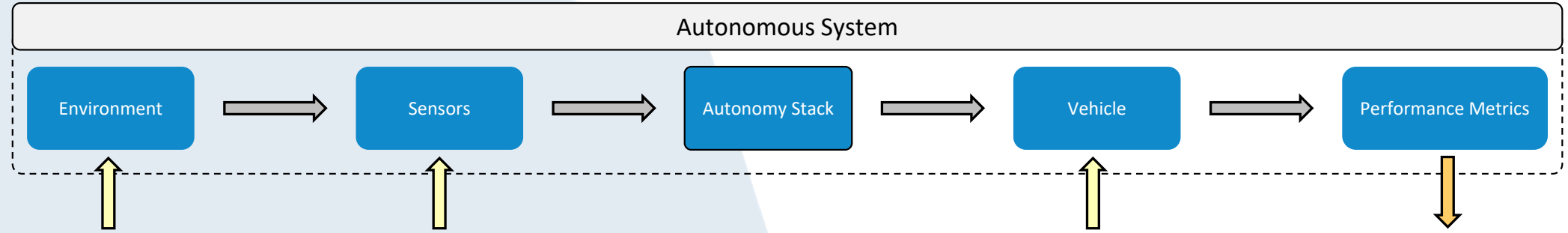
Leader Tracking Metric - Subset 11.c:

(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



Environmental Uncertainties

- Sunny, Cloudy, etc.
- Dry vs. Rain vs. Snow
- Wind Speed
- Rainfall Rate
- Snowfall Rate
- Fog Density
- Dust Density
- Soil Type
- Soil Moisture Level
- Vegetation Size, Height, Density, etc.
- Object Features and Locations
- .....

Sensor Noise

- Sensor Specifications
- Lighting
- Soiling
- Weather
- Temperature
- Position
- Vibration
- Degradation
- .....

Vehicle Characteristics

- Initial State
- Payload
- Tire Size and Pressure
- Suspension Characteristics
- .....

Performance Uncertainties

- Mission Metrics
- Mobility Metrics
- Autonomy Metrics
- .....

Uncertainty Quantification

Simulation

Test

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

Identify Input Variables

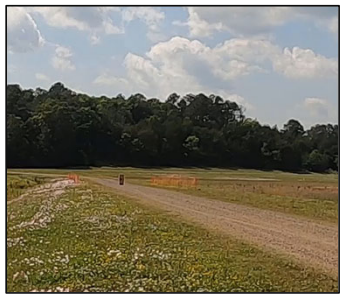
Identify Variability of Input Variables

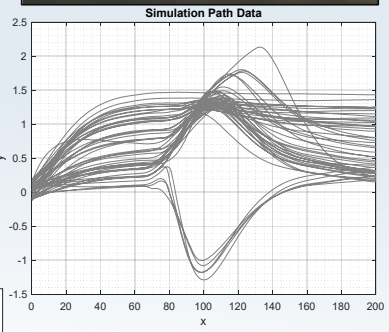
Run Scenario

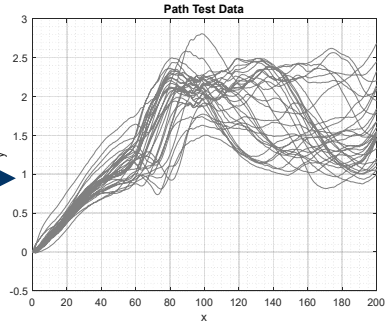
Gather Data

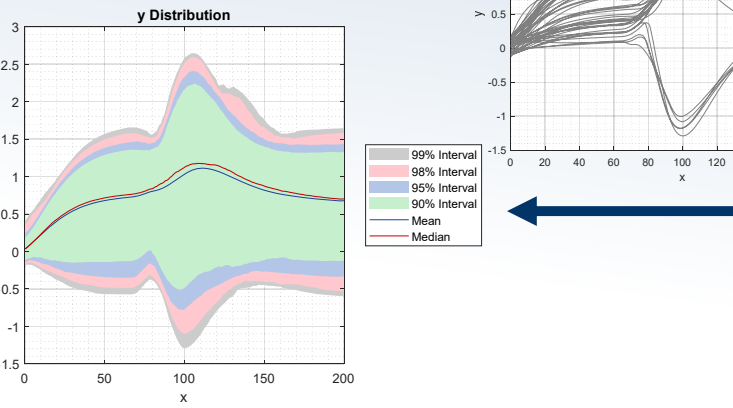
Obtain Performance Metric Distribution

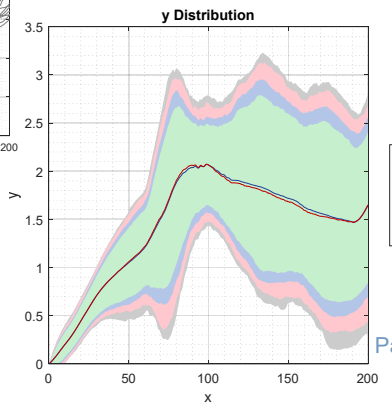
Compare Simulation & Target Distribution

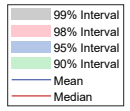




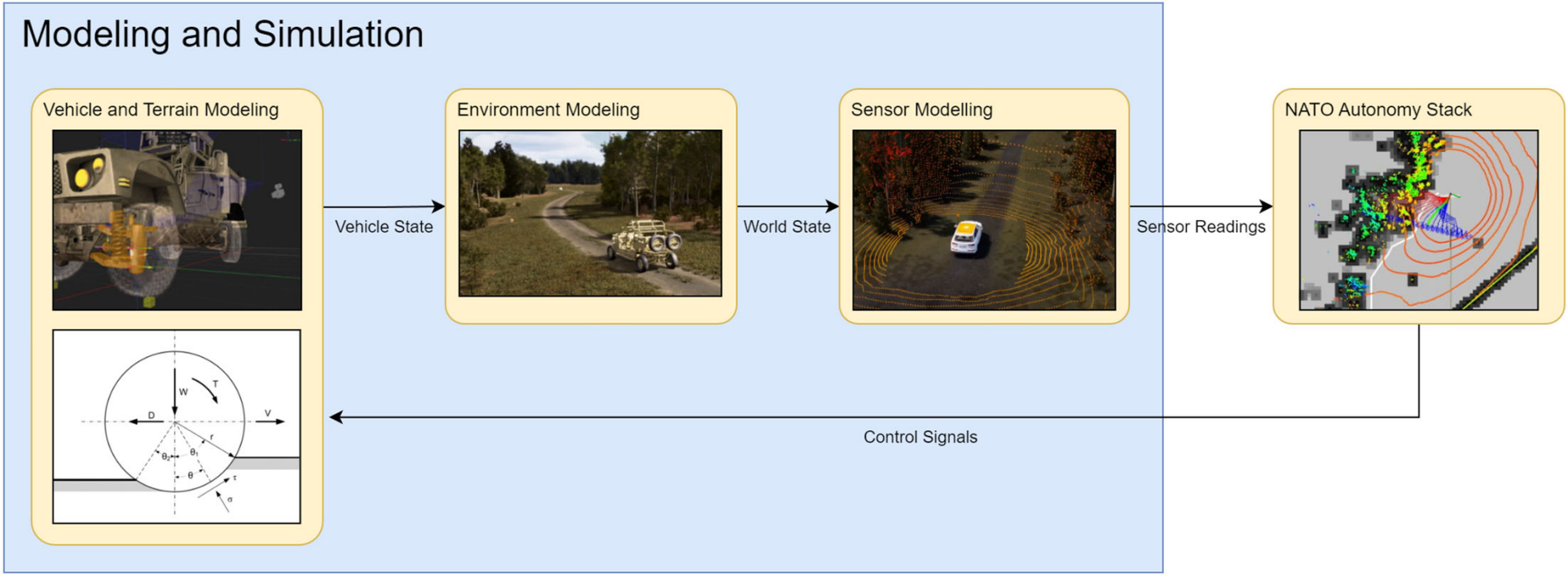






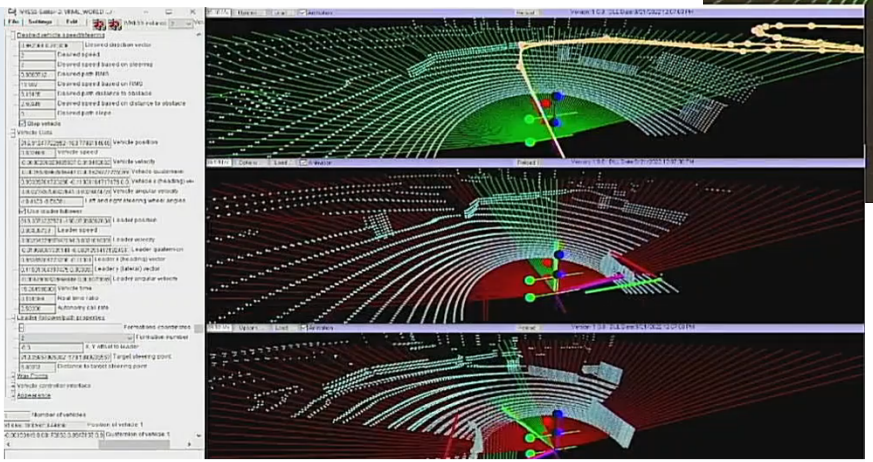


M&S Framework



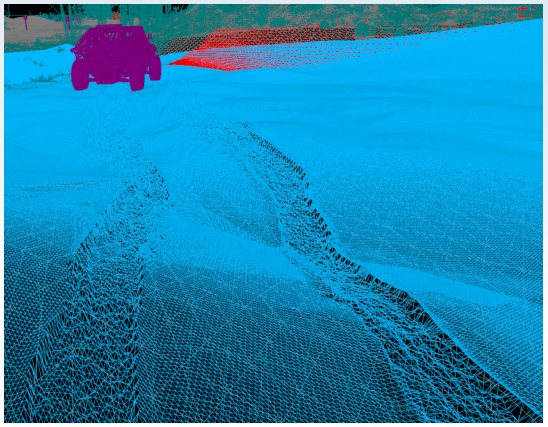
8 LW Phase 1: Departure

- 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.



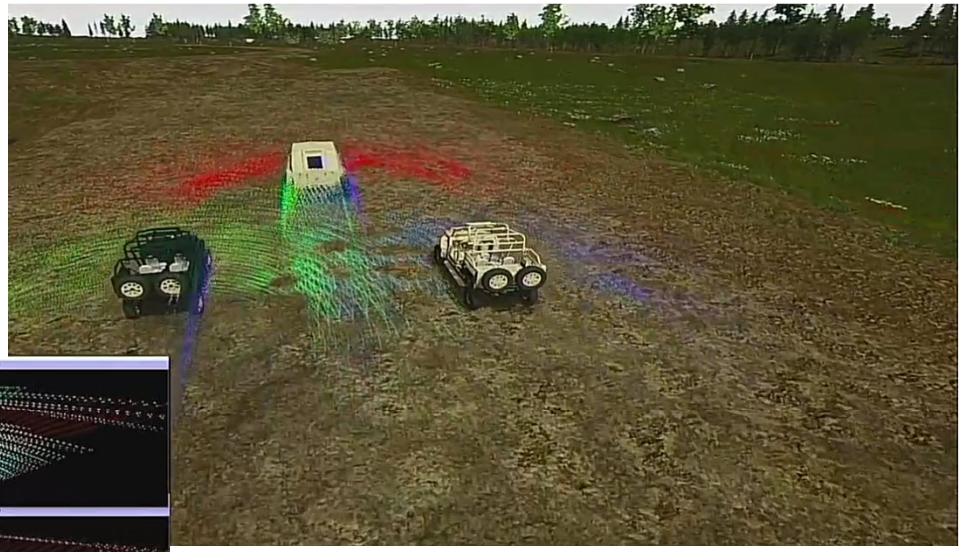
LW Phase 2: Force Protection

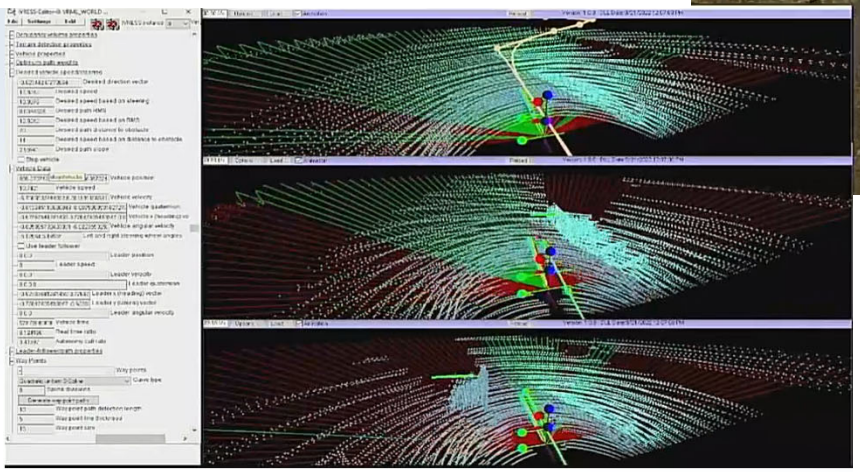
- Autonomy challenges:
  - Follow leader.
  - Detour into soft-soil pit.
- M&S challenges:
  - 2 high-fidelity vehicle models.
  - Deformable soft-soil terrain
- Mobility Challenge: Cross a soft-soil pit.



LW Phase 3: Reconnaissance

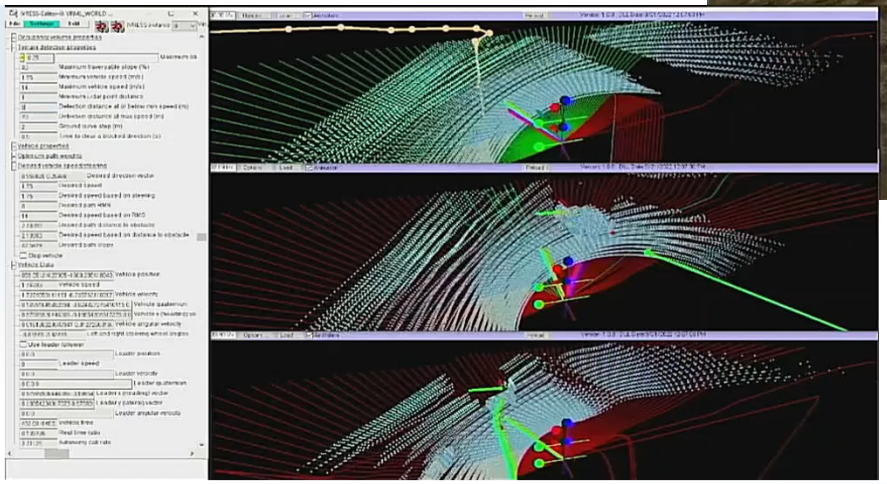
- Autonomy challenges:
  - Maintain a triangular formation
  - Avoid static obstacles (rocks).
  - Path planning.
- M&S challenges: 3 high-fidelity vehicle models.





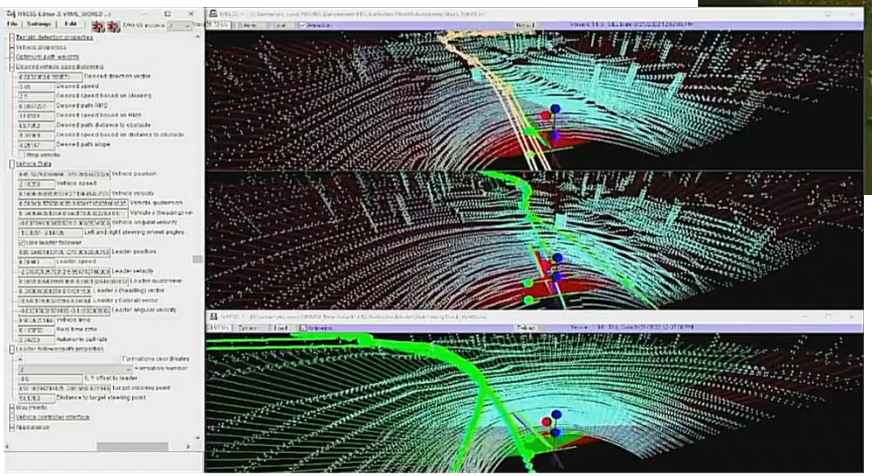
LW Phase 3: Reconnaissance

- 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).