CPS Week 2018: 2nd Workshop on Safe control of Autonomous Vehicles

The CAT Vehicle Testbed: A Simulator with Hardware in the Loop for Autonomous Vehicle Applications

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COMPOSITIONAL SYSTEMS LAB

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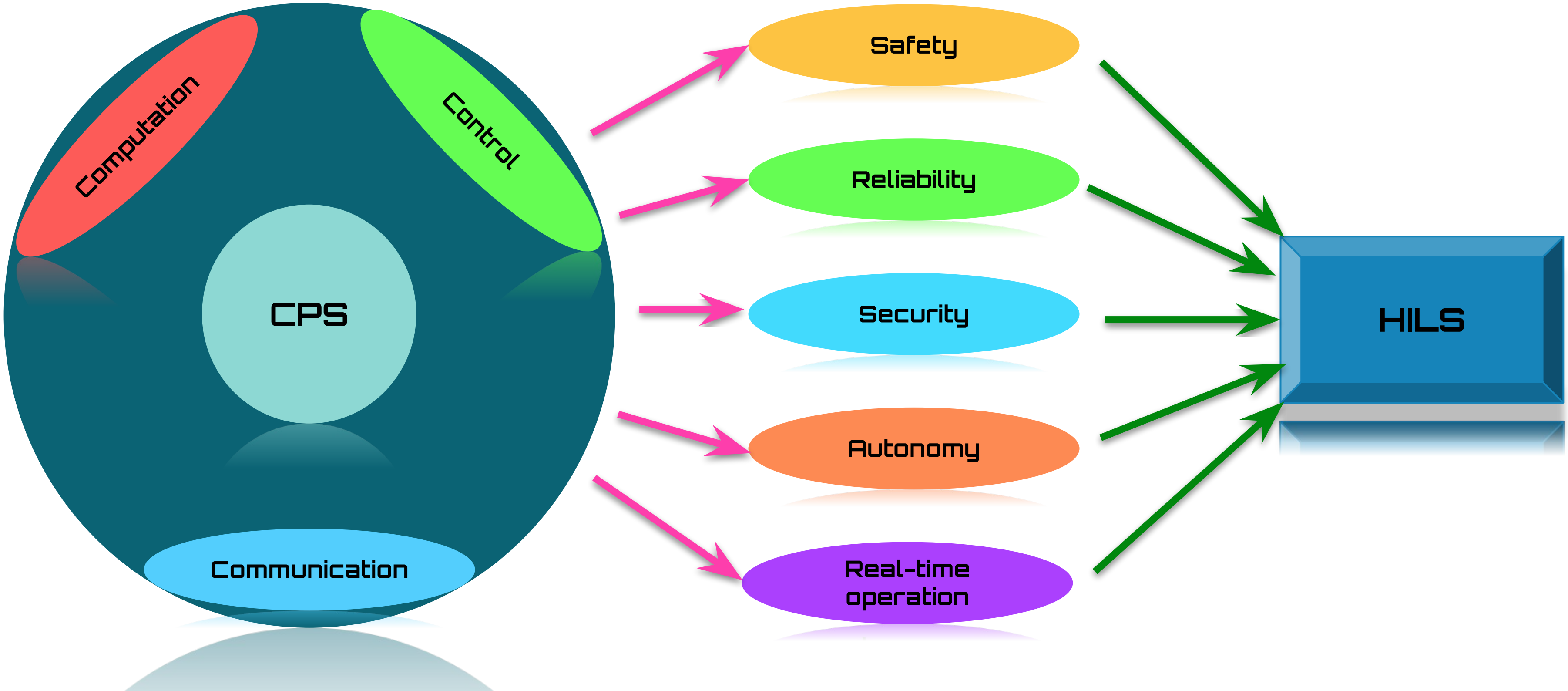
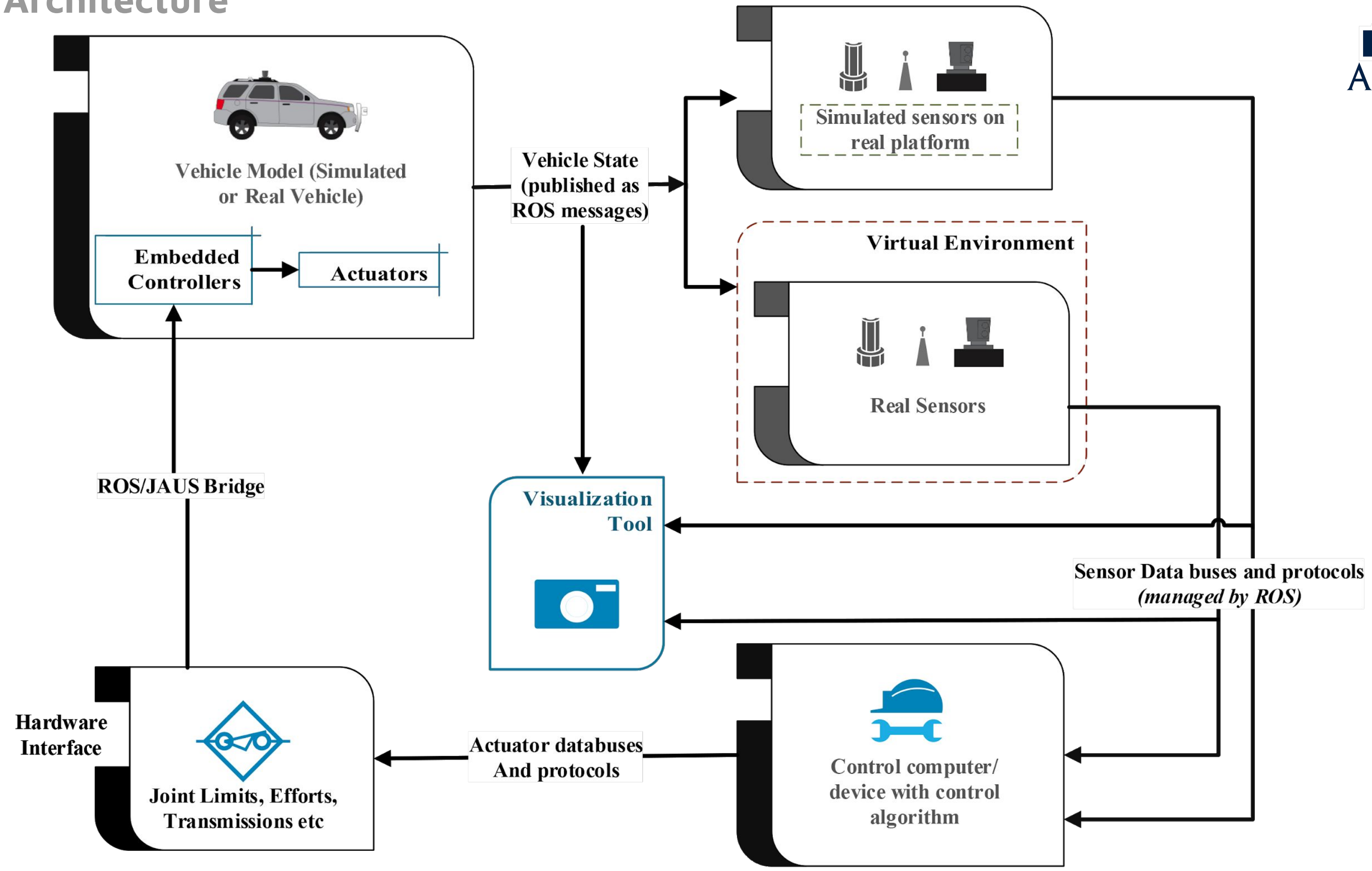
Agenda

- **Motivation**
  - Hardware in the loop simulation in CPS
- **Testbed Architecture**
  - Virtual Environment
  - Physical Platform
- **Modeling and Implementation**
  - System Safety
  - Working with data
  - Demo with the Testbed
- **Research Applications**
  - 22-vehicles experiment
  - Applications on Domain Specific Modeling Language
  - REU Research
- **Discussions and Future work**

Hardware in the loop simulation (HILS) in CPS

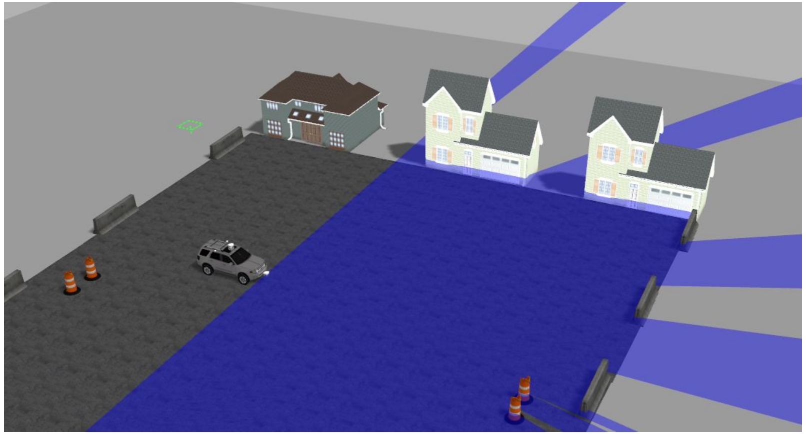


Testbed Architecture



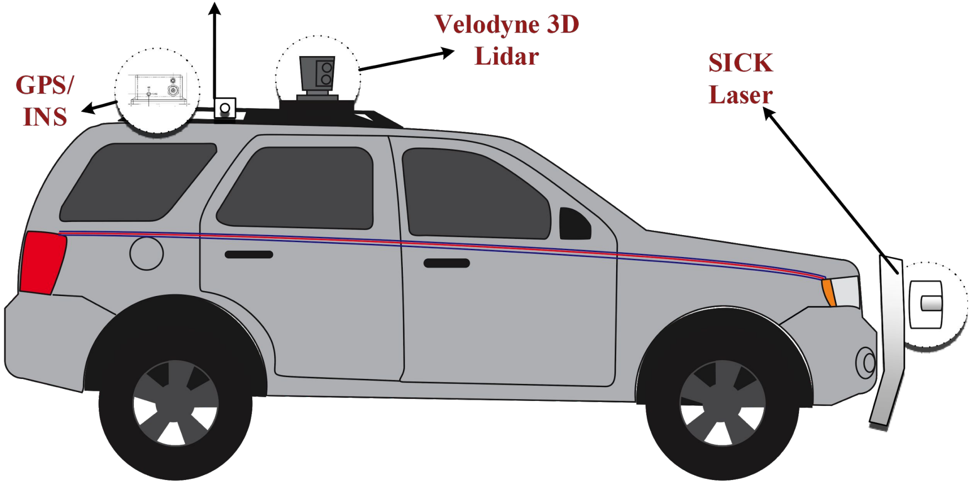
Simulated World

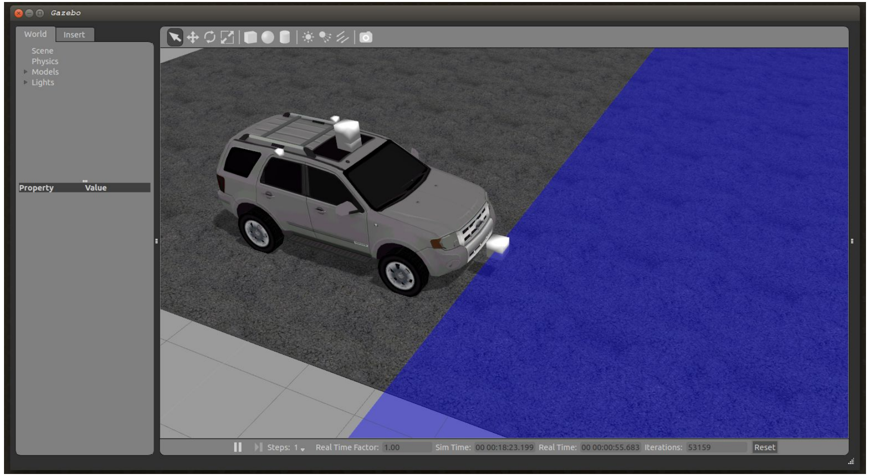
- Uses Gazebo 2.2.3
- ODE Physics Engine
- Ability to manipulate behavior of simulated world
- Supports SDFormat for robot description
- Simulation can be performed in slower or faster than real time.
- Rich libraries to interface with ROS (the Robot Operating System)



Vehicle Model

System Abstraction:
Input $\mathcal{X}$: $f(\boldsymbol{v},\Theta)$
Output $\mathcal{Y}$: $f(\boldsymbol{x},\boldsymbol{v},\Theta)$





Significance of Vehicle Model in Simulation

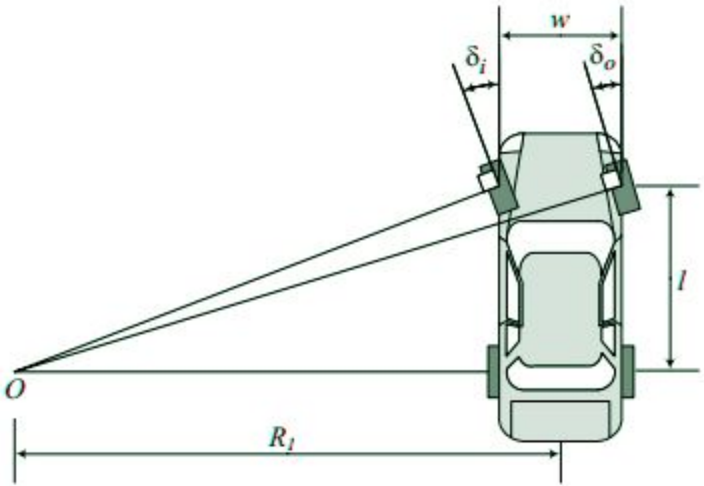
- Runtime solvers approximate motion based on **constraint satisfaction problems**, which can be computationally expensive if the vehicle model's individual components are unlikely to approximate physical performance

- **Kinematic robotic simulation** typically utilizes joint-based control, rather than velocity based (or based on transmission/accelerator angles and settings) like a physical platform

- The dynamics of individual vehicle parts is such that physically unrealistic behavior may emerge, meaning that **physical approximations of linear and angular acceleration should be imposed** on individual joints, to prevent unlikely behaviors.

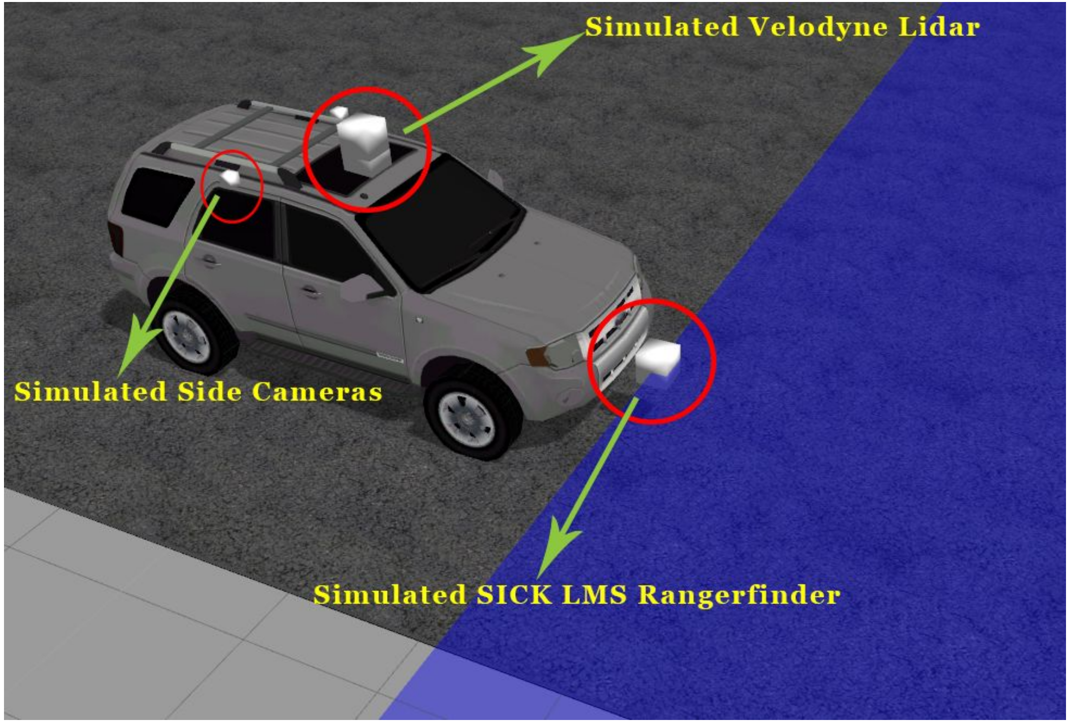
Vehicle Model

- Ackermann Steering Model for steering



Simulated Sensors

- Laser Range finder
- Side cameras
- Velodyne Lidar



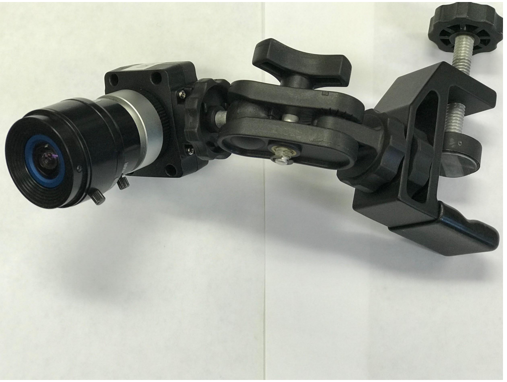
The CAT Vehicle in the simulation loop

- The CAT Vehicle stands for the Cognitive and Autonomous Test Vehicle
- Modified Ford Hybrid Escape vehicle
- Emergency Stop
- Underlying protocol JAUS
- Developed JAUS-ROS Bridge to interface with Low Level Controller.

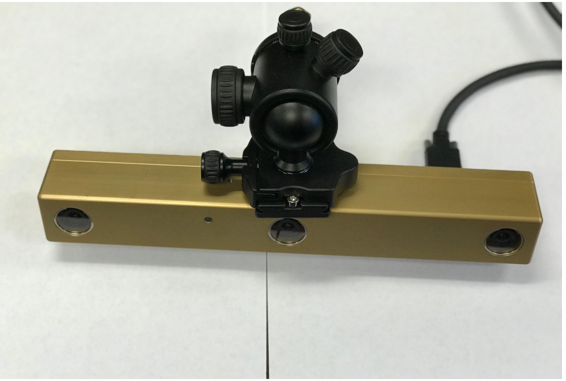
The Perception Unit

Velodyne Lidar

Rangefinder



Pointgrey Side cameras



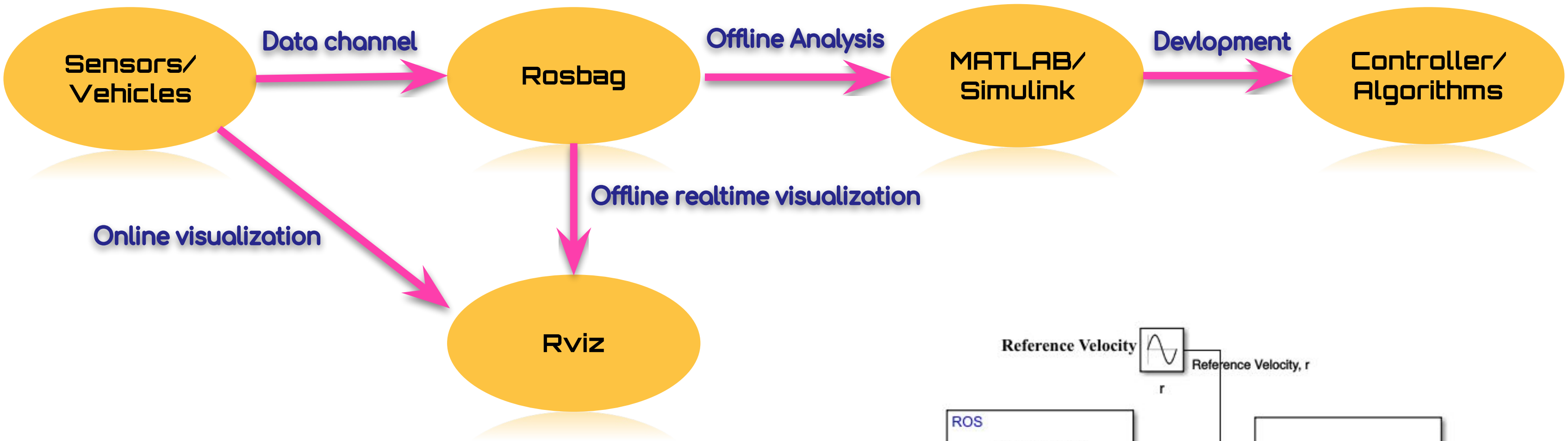
Bumblebee
Stereocamera

System safety

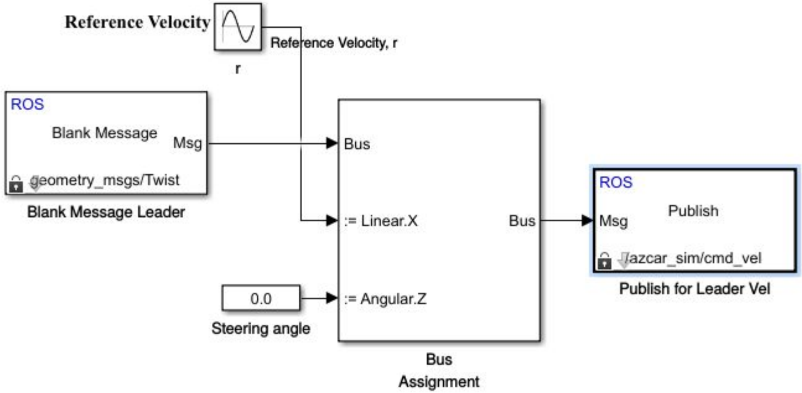
Safety aspect	Approach	Implementation
Permissive Safety ✓	Correct by construction and maximally permissible →	Model-based design
Verification and Validation ✓	Constraints specification →	Wider test coverage with SIL and HIL simulation
Functional Correctness ✓	I/O behavior →	Repeatability with SIL & HIL simulation
Human in the loop ✓	Human in emergency →	E-Stop/Manual mode switching
~~Network Security~~ ✗	Unsecured Communication →	Plain text node to node communication in ROS

- Domain Specific Modeling Language
- Synthetic data for simulation
- Injecting real world data into simulation
- Novel algorithms for sensing and control

Working with data



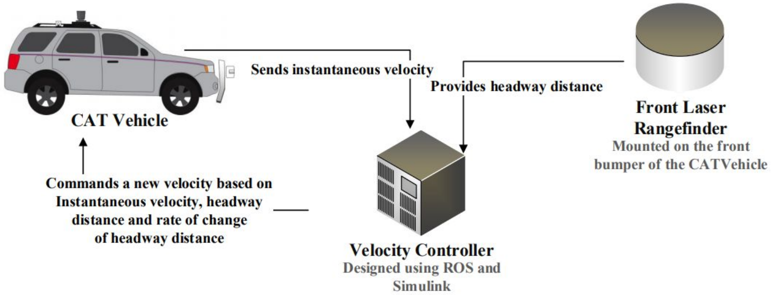
- Data: velocity, brake, throttle, distance information, 3D data from velodyne, GPS Coordinates
- Played back in realtime
- Helpful in regression testing and debugging.
- MATLAB Robotics System Toolbox to offline analysis

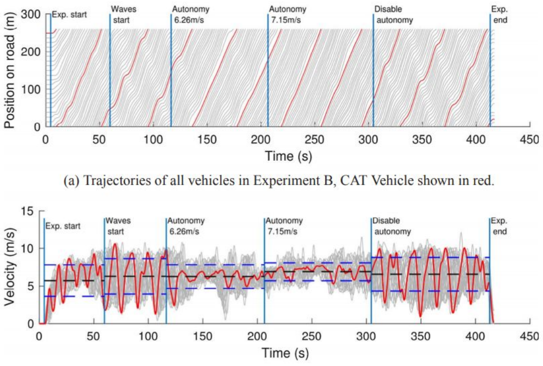


Demo with Testbed

- Download the testbed and compile them
  - git clone https://github.com/sprinkjm/catvehicle.git
  - git clone https://github.com/sprinkjm/obstaclestopper.git
- Simulation in Gazebo
- ROS Visualization
- Multi car simulation
- Modeling with Robotic System toolbox in Simulink
- Using code-generation feature to generate stand alone ROS node.
- How ROSBag file helps?

22-Vehicles Experiment





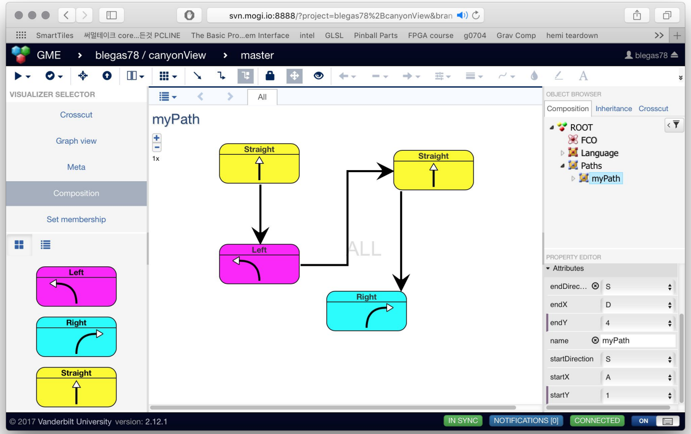
(a) Trajectories of all vehicles in Experiment B, CAT Vehicle shown in red.

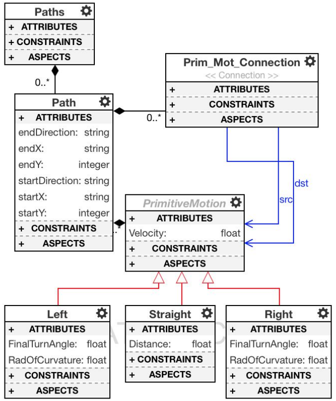
(b) Velocity profiles of all vehicles (gray) and the CAT Vehicle (red) in Experiment B.

Objective: Testing hypothesis that sparse number of autonomous vehicles on the road can reduce congestions

Outcome: Dampening of congestions in terms of velocity standard deviation by 49.5% for one of the experiment.

Applications on Domain Specific Modeling Language

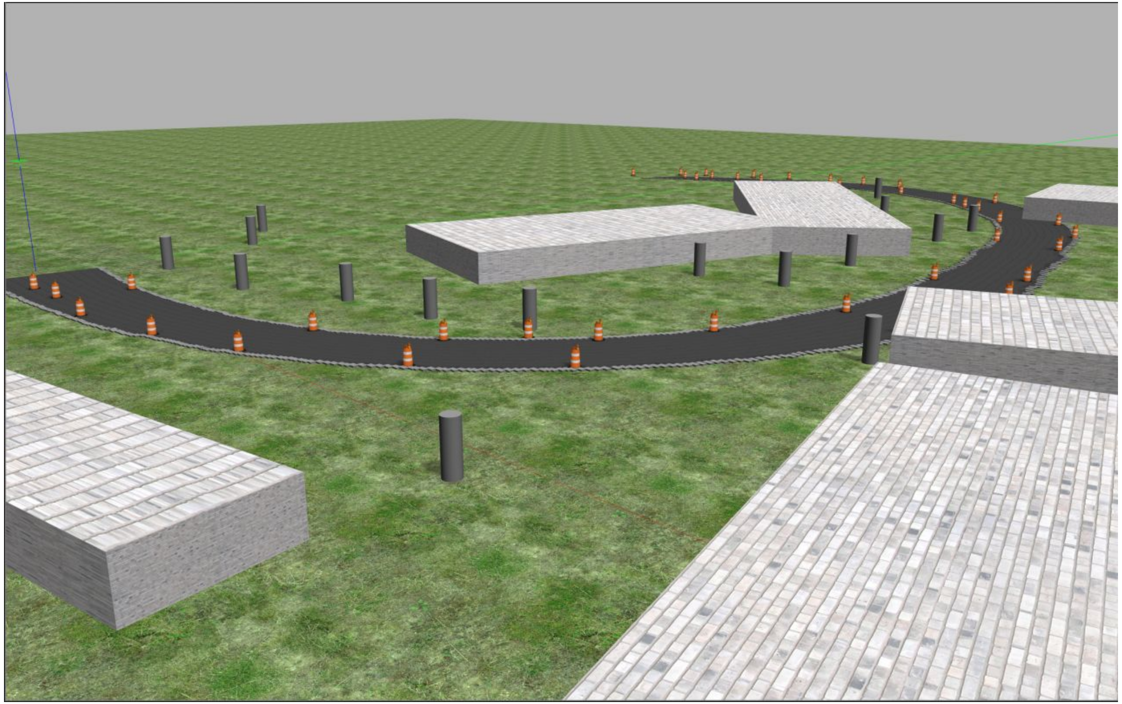




Objective: Enabling non-expert programming for safety-critical applications such as autonomous vehicles

Outcome: 4th/5th graders were able to provide a path using DSML developed for the CAT Vehicle to follow.

CAT Vehicle Challenge



Objective: Producing most accurate visual of environment using least number of sensors on the CAT Vehicle for simulation purposes.

← **Outcome**

CAT Vehicle REU Research

Objective: This research experience for undergraduates (REU) is engaged in the myriad of applications that are related to autonomous ground vehicles.

Outcome: Several papers, improved CAT Vehicle testbed, Research experience for undergraduates

Outcomes

- Matt Bunting, Yegeta Zeleke, Kennon McKeever & Jonathan Sprinkle (2016): **A safe autonomous vehicle trajectory domain specific modeling language for non-expert development**. In: Proceedings of the International Workshop on Domain-Specific Modeling, ACM, pp. 42–48, doi:10.1145/3023147.3023154.
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- Kennon McKeever, Yegeta Zeleke, Matt Bunting & Jonathan Sprinkle (2015): **Experience Report: Constraint-based Modeling of Autonomous Vehicle Trajectories. In: Proceedings of the Workshop on Domain-Specific Modeling**, ACM, ACM, New York, NY, USA, p. 17–22, doi:10.1145/2846696.2846706.
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- Raphael E Stern, Shumo Cui, Maria Laura Delle Monache, Rahul Bhadani, Matt Bunting, Miles Churchill, Nathaniel Hamilton, Hannah Pohlmann, Fangyu Wu, Benedetto Piccoli et al. (2018): **Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments. Transportation** Research Part C: Emerging Technologies 89, pp. 205–221, doi:10.1016/j.trc.2018.02.005.
- F. Wu, R. Stern, S. Cui, M. L. Delle Monache, R. Bhadani, M. Bunting, M. Churchill, N. Hamilton, R. Haulcy, B. Piccoli, B. Seibold, J. Sprinkle, D. Work. "**Tracking vehicle trajectories and fuel rates in oscillatory traffic.**" submitted to Transportation Research Part C: Emerging Technologies, 2017.
- M. Churchill, R. E. Stern, F. Wu, D. Work, M. L. Delle Monache, B. Piccoli, S.Cui, B. Seibold, R. Bhadani, M. Bunting, and J. Sprinkle. "**Reducing Emissions Resulting from Stop-and-Go Traffic Waves with Automated Vehicles**," submitted to the 2018 Transportation Research Board Annual Meeting, 2017.
- F. Wu, M. Churchill, D. Work, M. L. Delle Monache, B. Piccoli, H. Pohlman, S. Cui, B. Seibold, N. Hamilton, R. Haulcy, R. Bhadani, M. Bunting, and J. Sprinkle. "**Dampening Traffic Waves with Autonomous Vehicles**." in Proceedings of the the ITRL Conference on Integrated Transport, Stockholm, Sweden, 2016.

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Discussion

- A Catvehicle Testbed provides an open-source, experimentally validated and scalable testbed with HIL support for autonomous driving applications that uses ROS.
- This work provides an overview of a multi-vehicle simulator that provides a virtual environment capable of testing a research application requiring vehicle to vehicle interaction from the inception of design to realization.
- We talked about a research paradigm that enables distributed teams to implement and validate a proof of concept before accessing the physical platform.
- Hardware-in-the-loop simulation increases development time and makes solution safer by increase test coverage.

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Github repo: https://github.com/sprinkjm/catvehicle

Lab page: http://csl.arizona.edu/

My webpage: http://math.arizona.edu/~rahulbhadani

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Questions