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Hands-On Field Operational Test Dataset of a Multi-Controller CPS: A Modeled Case Study on Autonomous Driving

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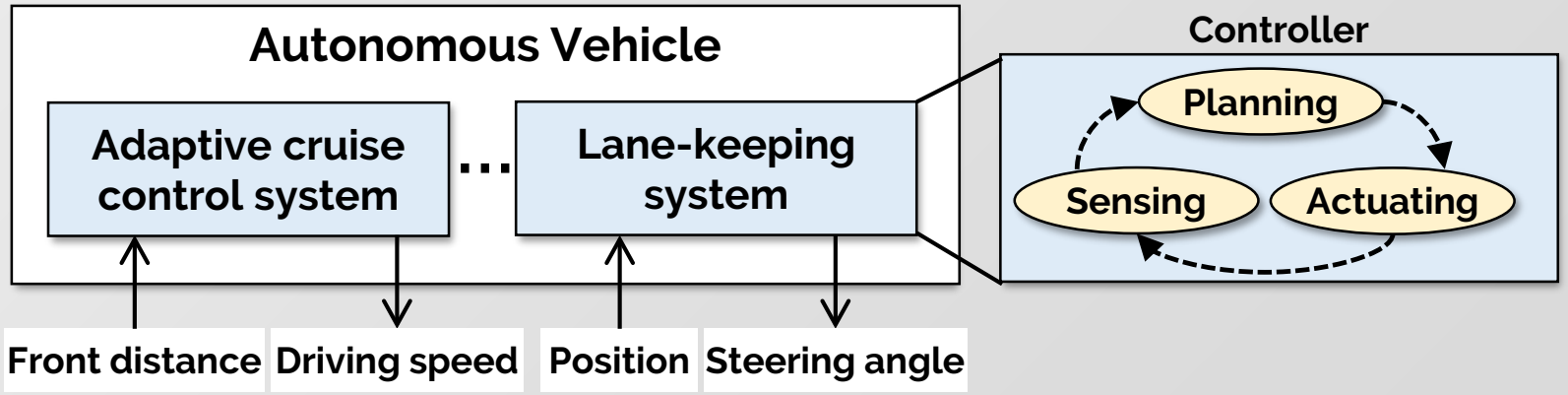
Introduction

Multi-Controller CPS Development

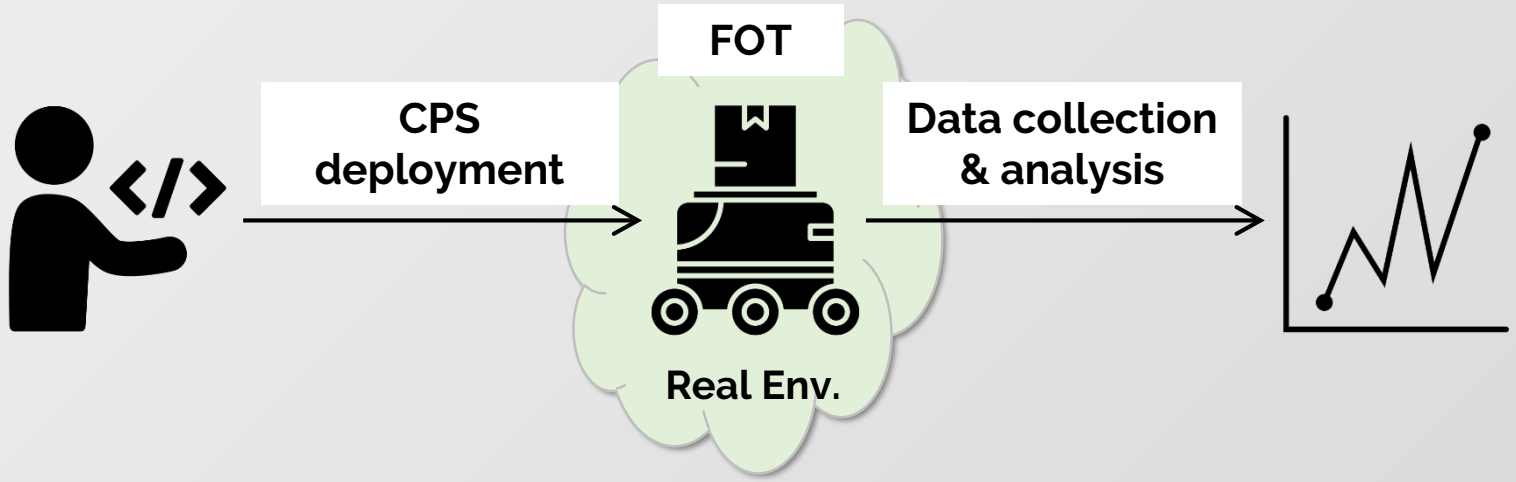
- A Cyber-Physical System (CPS) can be developed by assembling **multiple controllers** in the view of System-of-Systems to achieve multiple goals simultaneously[1-2].
- The CPS controllers **sense the physical environment**, **decide the CPS actions** and **actuate the CPS** to achieve their goals.



[1] Zhang, Lichen. "Applying system of systems engineering approach to build complex cyber physical systems." Progress in Systems Engineering. Springer, Cham, 2015. 621-628.
[2] Zhang, Lichen. "Modeling large scale complex cyber physical control systems based on system of systems engineering approach." 2014 20th International Conference on Automation and Computing. IEEE, 2014.

CPS Goal Verification with Field Operational Tests

- CPS goal verification (evaluation of how well CPS controllers achieve their goal specifications[1]) is a significant engineering problem.
- "**The Field Operational Test (FOT) is an essential step towards deploying the CPS**"[2] to evaluate the goal achievement in the real environment[3-4].



[1] Zheng, Xi, et al. "Perceptions on the state of the art in verification and validation in cyber-physical systems." IEEE Systems Journal 11.4 (2015): 2614-2627.
[2] The FOT-Net Consortium (European Commission). "FIELD OPERATIONAL TESTS Evaluating ITS-applications in a real-world environment", 2010
[3] Barnard, Yvonne, and Oliver Carsten. "Field Operational Tests: challenges and methods." Proceedings of European conference on human centred design for intelligent transport systems. Lyon: HUMANIST publications, 2010.
[4] Barnard, Yvonne, et al. "Methodology for field operational tests of automated vehicles." Transportation research procedia 14 (2016): 2188-2196.

The motivations of the Hands-On FOT Experience

- **To provide a re-implementable case study of a multi-controller CPS FOT**
  - Model, software, and also hardware implementation manuals
- **To provide an open autonomous driving FOT log dataset**
  - Data obtained from about 100 hours of robot vehicle driving
  - Possible applications for future research
- **To reveal open challenges in the multi-controller CPS FOT**

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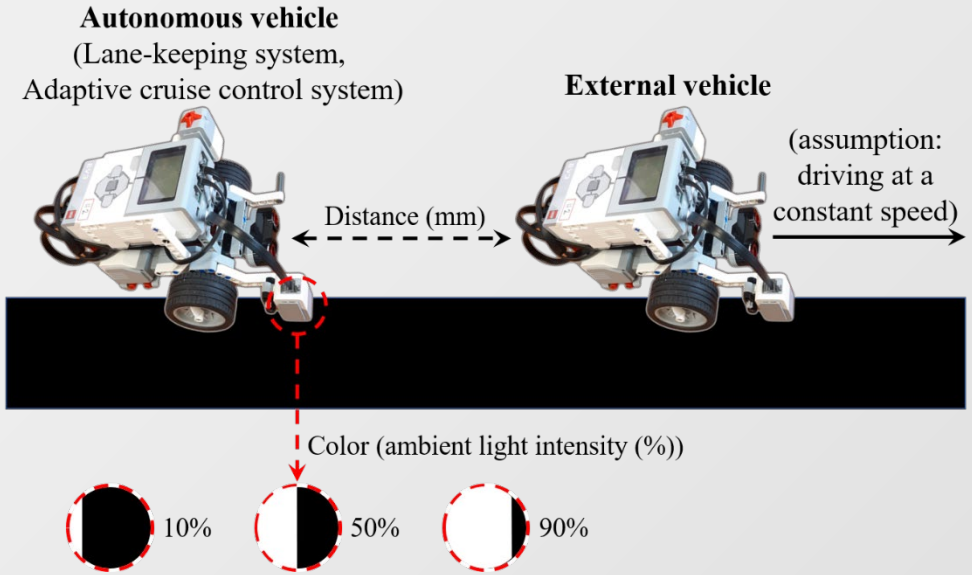
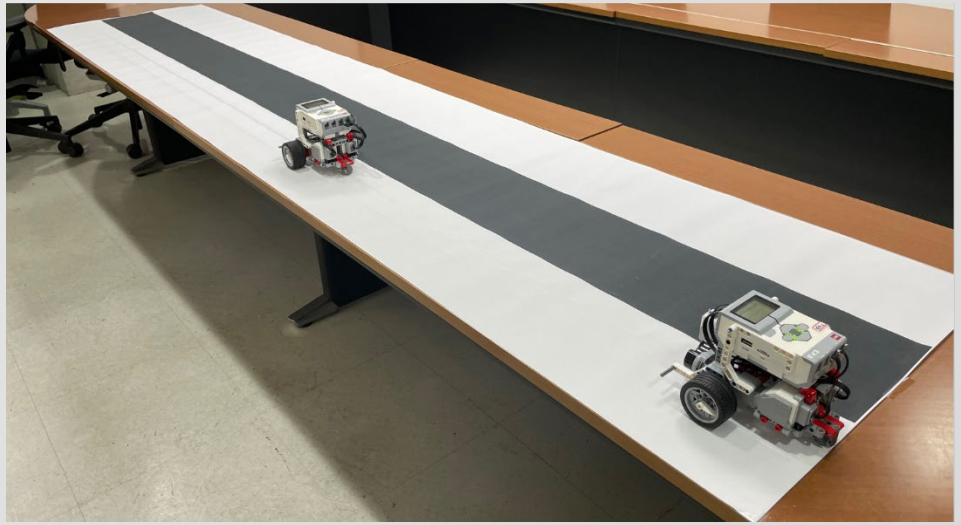
Field Operational Test Design

Autonomous Vehicle Modeling and Implementation

- **Implemented case study with a programmable LEGO robot vehicle [1]**
- **Modeled autonomous vehicle as a multi-controller CPS**
  - Equipped with a lane-keeping system and an adaptive cruise control system



An autonomous robot vehicle case study design

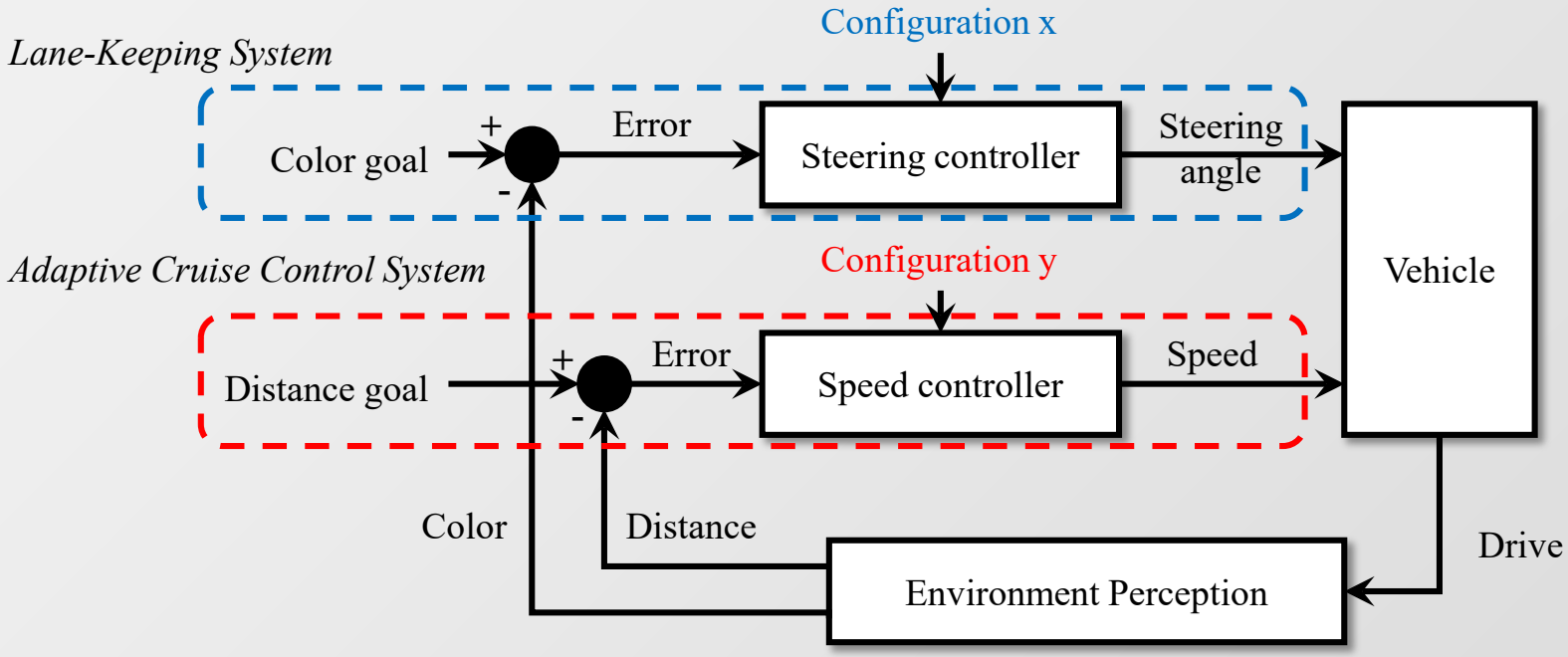


Implemented robot vehicles and the FOT environment

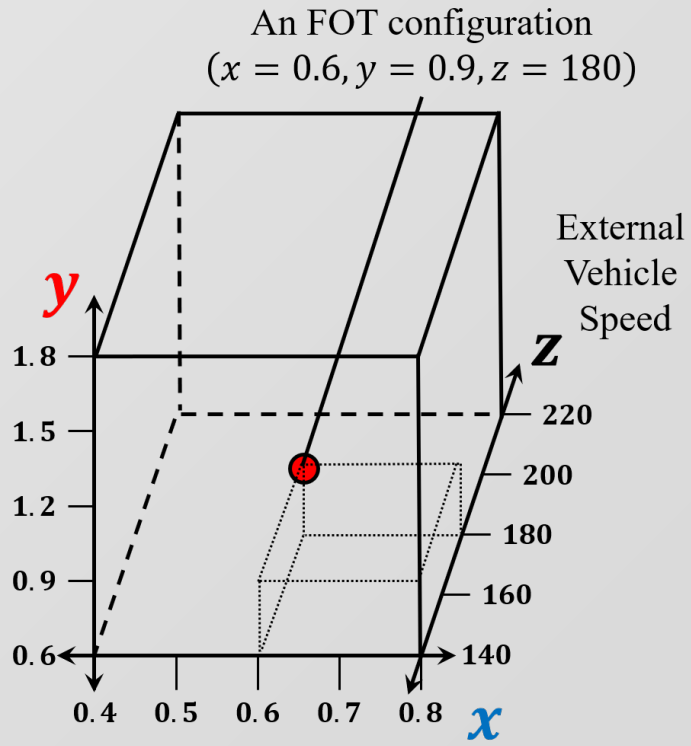
[1] Shin, Y.J., Liu, L., Hyun, S. and Bae, D.H., 2021, May. Platooning LEGOs: An Open Physical Exemplar for Engineering Self-Adaptive Cyber-Physical Systems-of-Systems. In 2021 International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS) (pp. 231-237). IEEE.

Configuration Space of the Autonomous Vehicle

- **3-Dimensional configuration space defined by two controllers and an external vehicle speed**
  - Discretize the space to **125** possible configurations



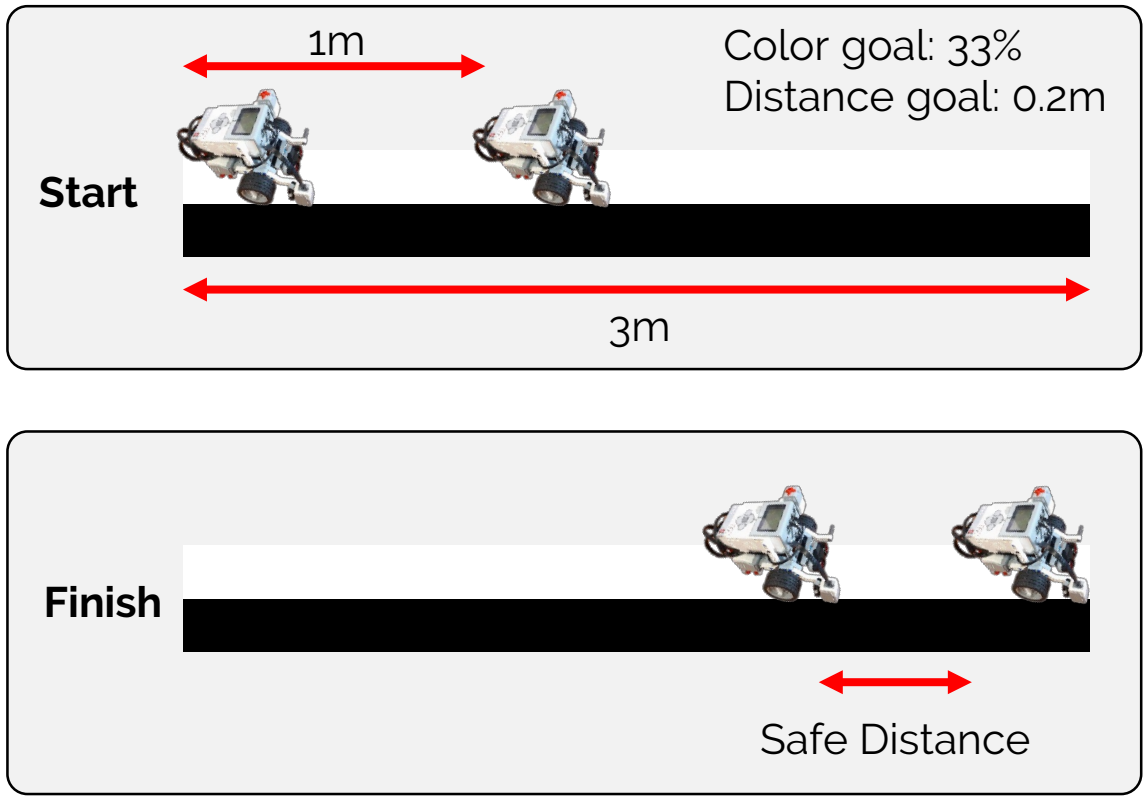
Autonomous vehicle controllers



Autonomous vehicle FOT configuration space

FOT Setup and Data Collection

- **Repeated the FOT scenario 50 times each for 125 configurations**



FOT Scenario

	Sensor Value		Actuation Value	
time	color	angle	distance	speed
0	22	-11	853	587.7
52	22	-6.6	857	395.4
105	24	-5.7	865	401.4
157	31	-0.6	848	383.7
210	39	3.7	863	402.3
269	53	14.3	850	386.1
321	55	11.3	841	381.9
372	51	8.5	826	371.1
430	47	8.3	808	359.4
485	42	6.7	800	357.6
539	40	8.1	792	352.8

Collected Data

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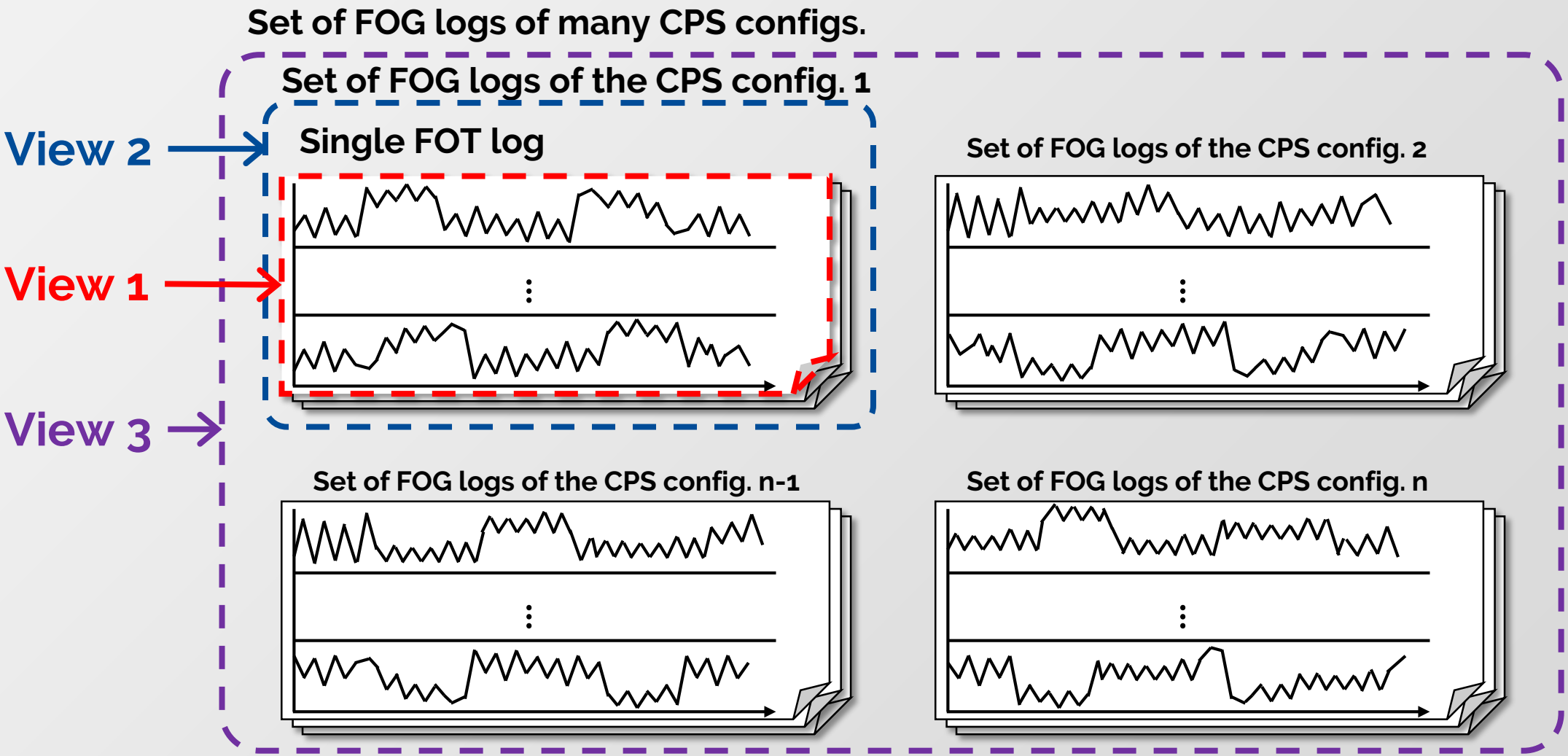
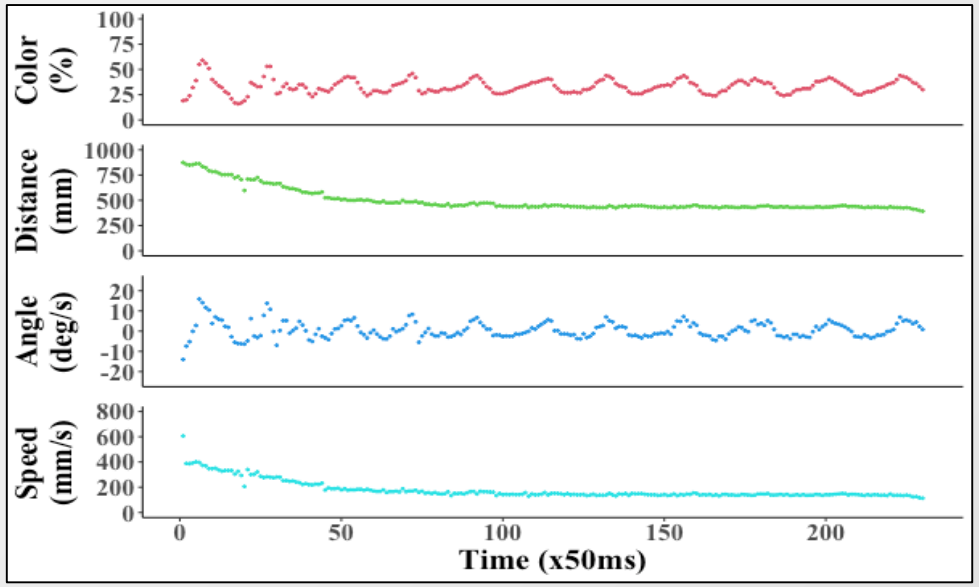
Field Operational Test Data Analysis

Viewpoints of the FOT Data Analysis

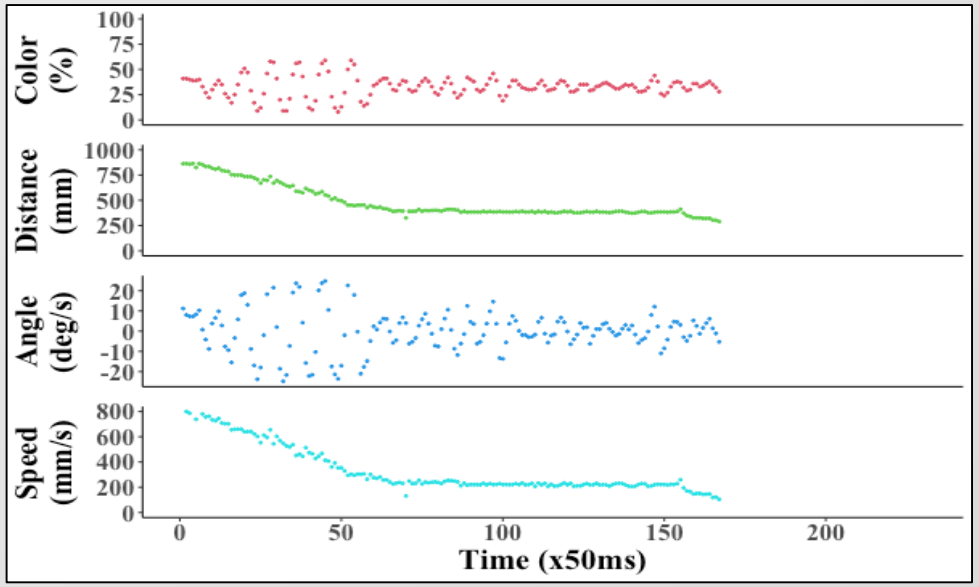


Viewpoint 1: Single FOT Result

- We can evaluate a vehicle's **driving performance** with a specific configuration by analyzing the time-series data.



Configuration (x=0.4, y=0.6, z=140)



Configuration (x=0.8, y=1.2, z=220)

The CPS configuration directly affects the CPS behavior and goal achievements.

Viewpoint 2: FOT Results of a Configuration

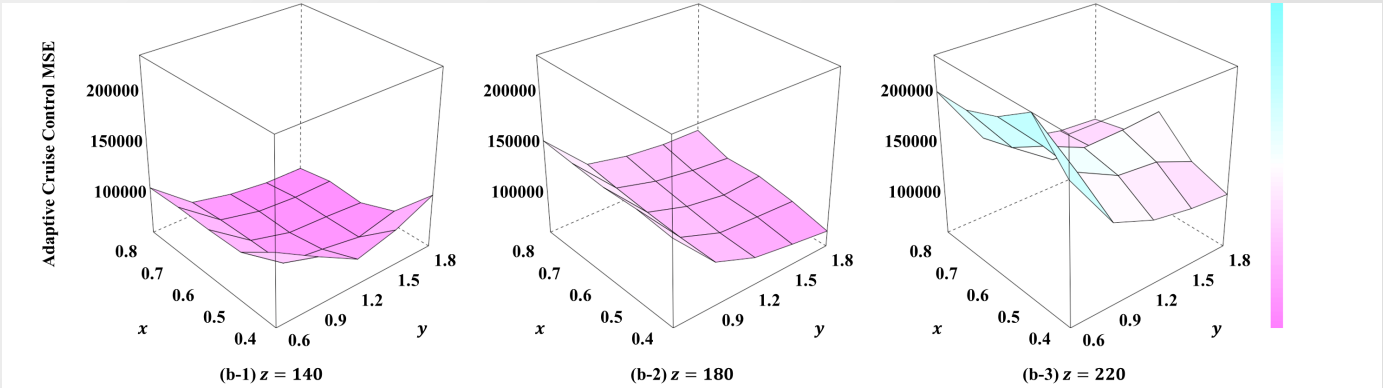
- We can **statistically evaluate the goal achievement** of a configuration.

Distribution of achievement of two autonomous driving goals obtained through repetitive FOTs

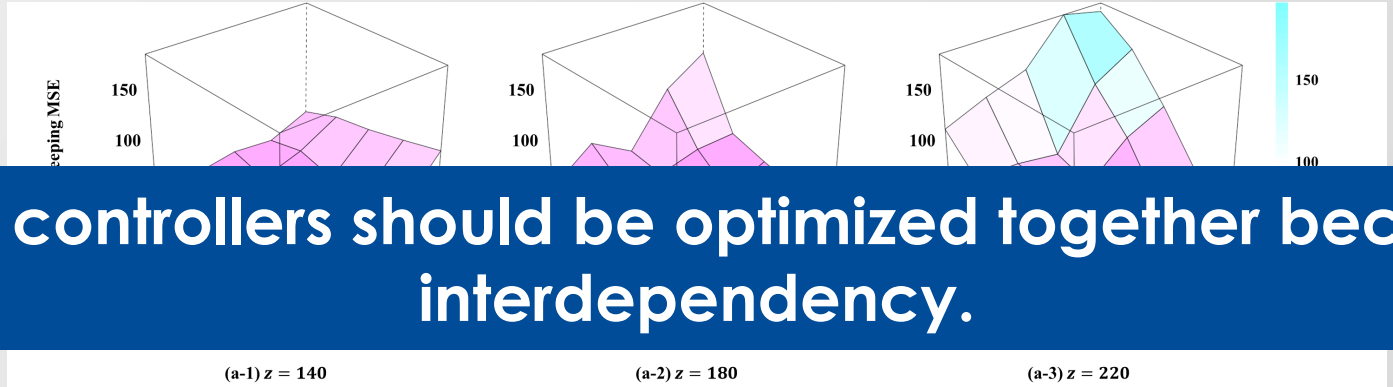
FOT results are stochastic because of the environmental uncertainty of the CPS.

Viewpoint 3: FOT Results of Many Configurations

- We can also explore changes in goal achievement by varying configurations **to optimize the controllers** of the autonomous vehicle.



Lane-keeping goal achievements of various configurations



Adaptive cruise control goal achievements of various configurations

Multiple CPS controllers should be optimized together because of their interdependency.

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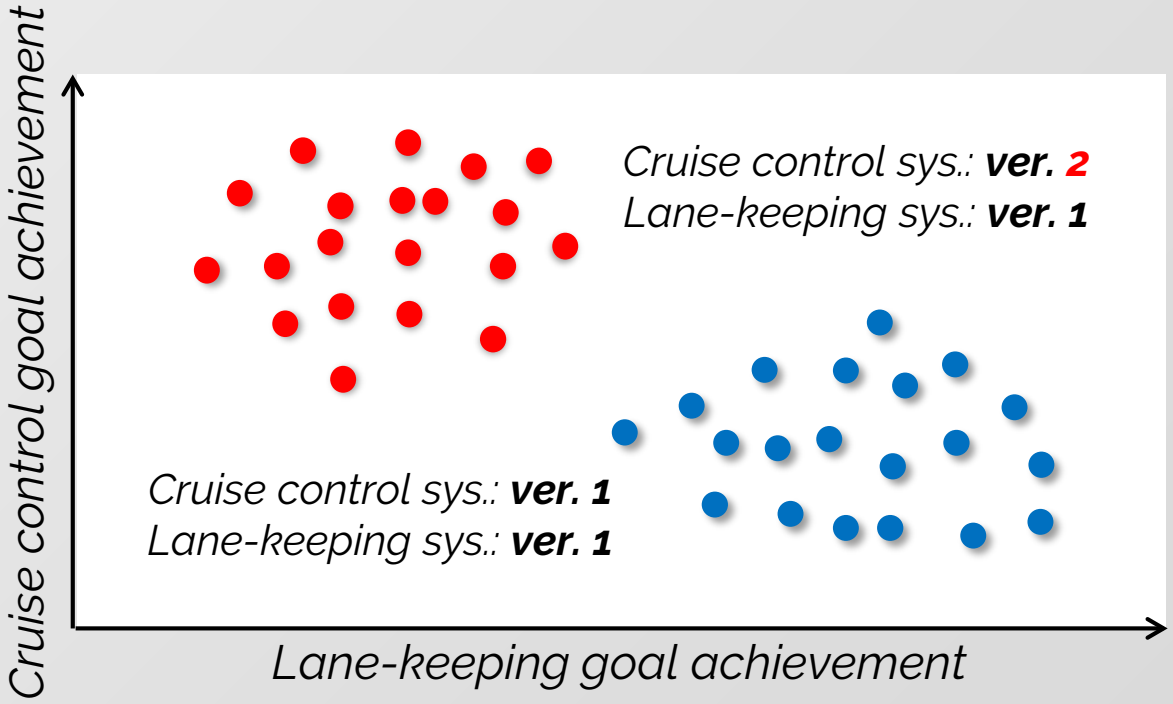
Discussion

Challenges in the Multi-Controller CPS FOT

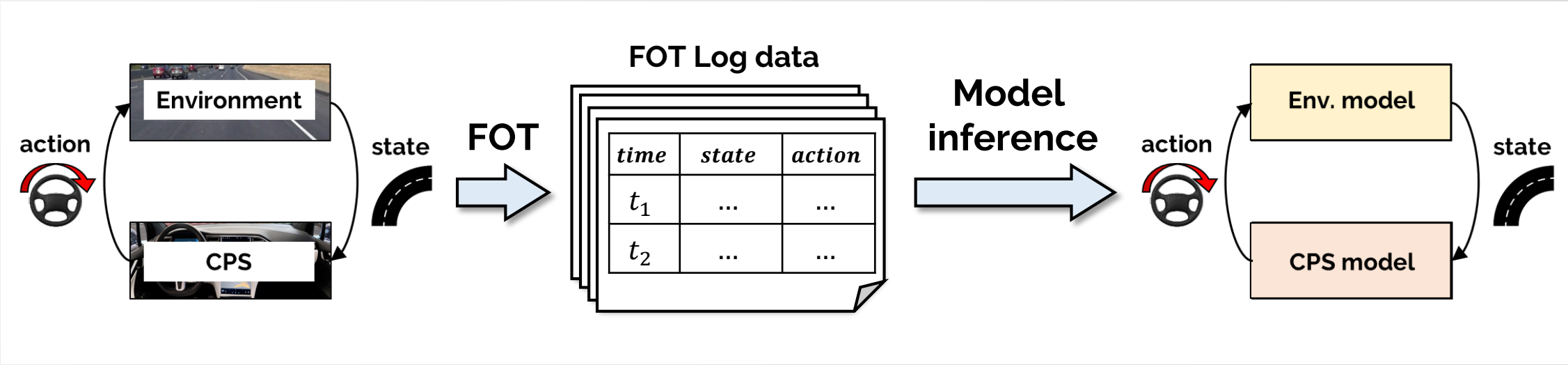
- **Expensive CPS FOT Cost**
- **Environmental uncertainty in multi CPS FOT**
- **Unknown interdependency of the multiple controllers**
- **Big FOT log data analysis**



Autonomous robot vehicle FOT results

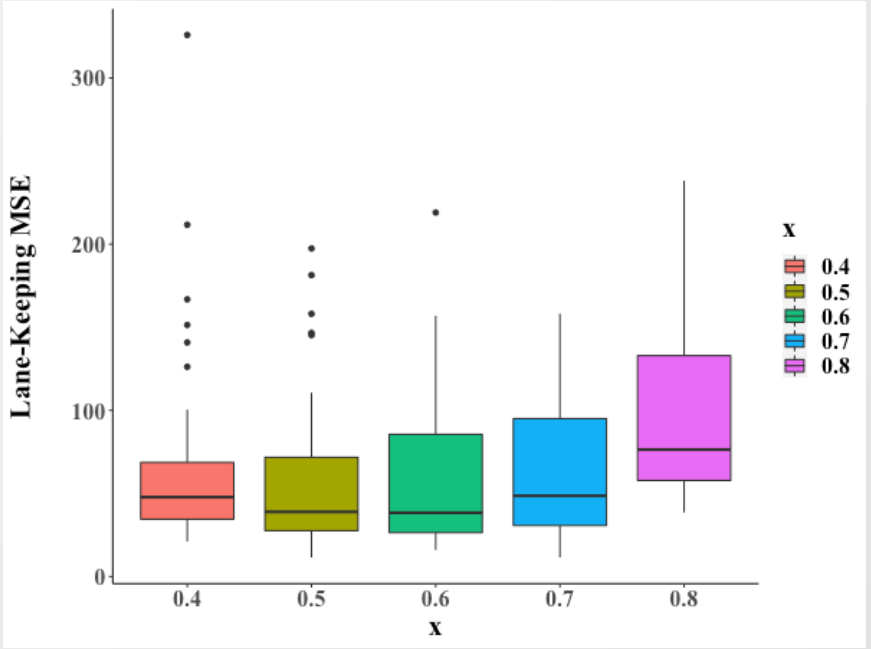
Possible Applications of the FOT Dataset (1/3)

- **Data-driven CPS-Environment interaction modeling**
  - The FOT log shows the sequential transition of the CPS actions and environmental states, so the log data can be used to extract valuable interaction models of the CPS and its physical environment.

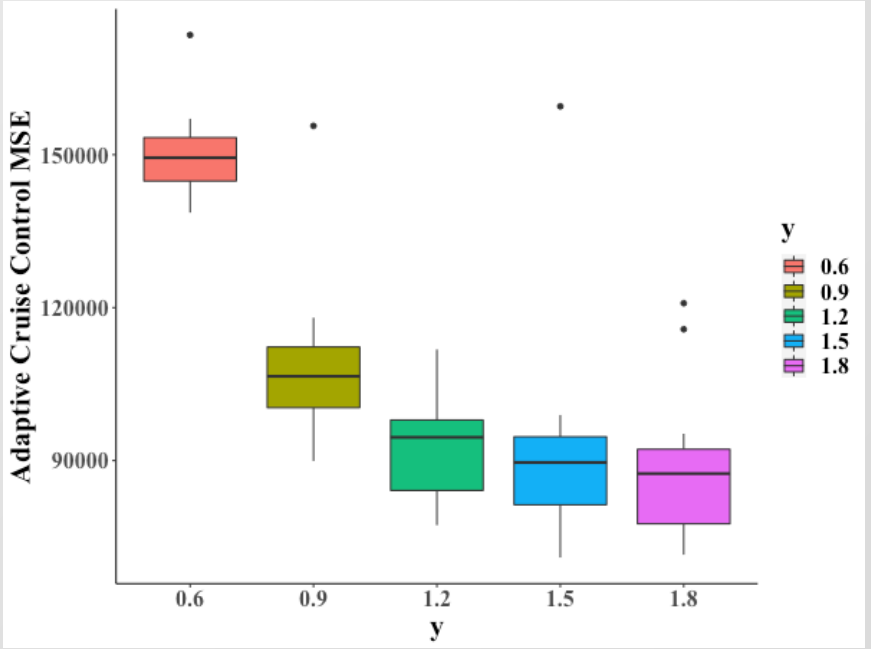


Possible Applications of the FOT Log Dataset (2/3)

- **Quantifying uncertainties of multi-controller CPS**
  - FOT log can be further analyzed to quantify the degree of uncertainty of the CPS operation.



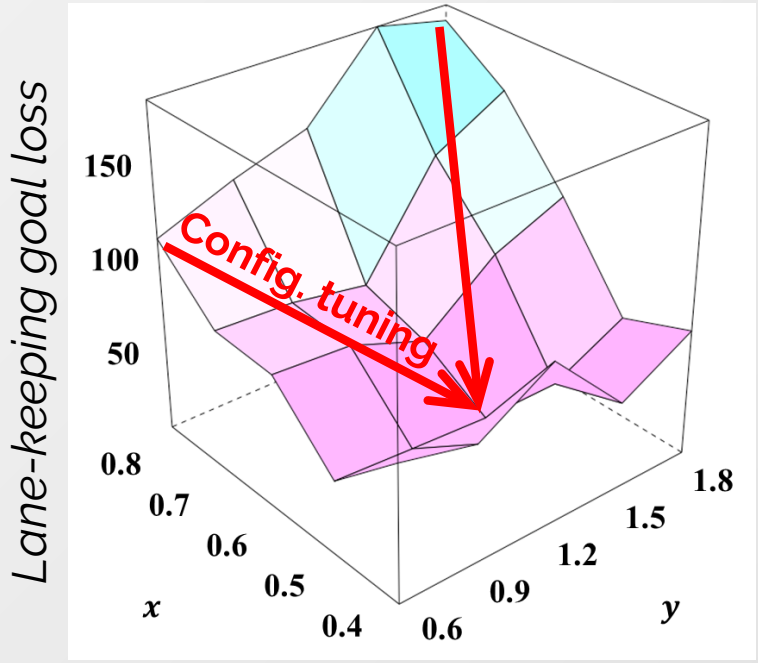
Uncertain lane-keeping goal achievements



Uncertain cruise control goal achievements

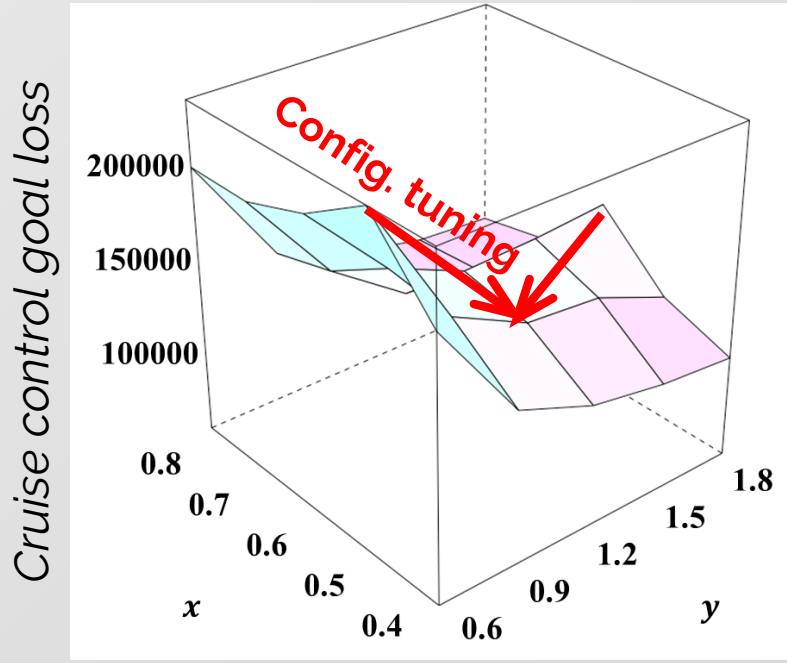
Possible Applications of the FOT Dataset (3/3)

- **Multi-objective CPS optimization**
  - FOT results can guide optimization of the controllers of the CPS to simultaneously maximize the multiple goals.



Possible configurations

Multi-objective Optimization



Possible configurations

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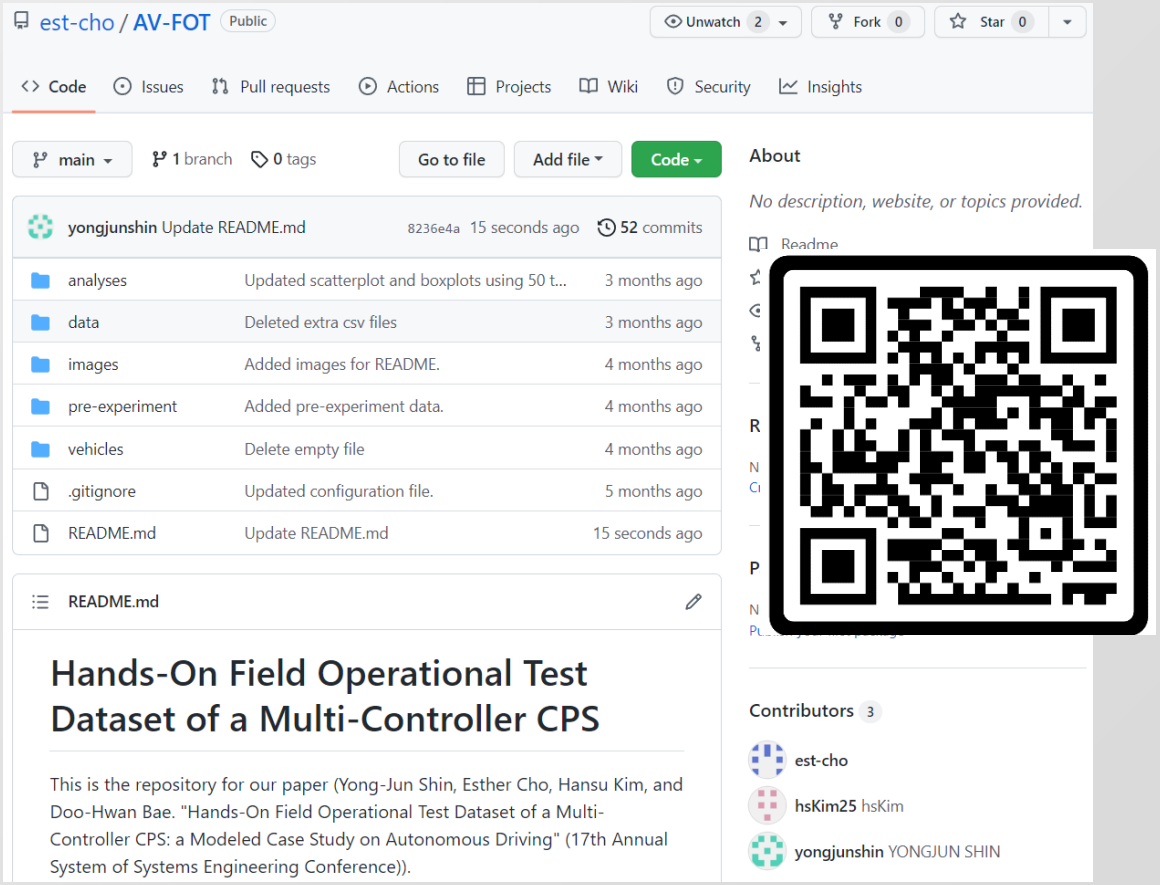
Conclusion

Conclusion

- We had a hands-on experience conducting **many FOTs of a multi-controller CPS** (autonomous robot vehicle) and shared lessons learned and related artifacts.
  - Model
  - Software
  - LEGO vehicle implementation manuals
  - FOT log dataset



https://github.com/est-cho/AV-FOT

Thank You.

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