Synergistic Perception and Control Simplex for Verifiable Safe Vertical Landing

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Hyung-Jin Yoon, Hunmin Kim, Naira Hovakimyan, Lui Sha

2024 AIAA Science and Technology Forum and Exposition

January 9, 2024

MERCER UNIVERSITY

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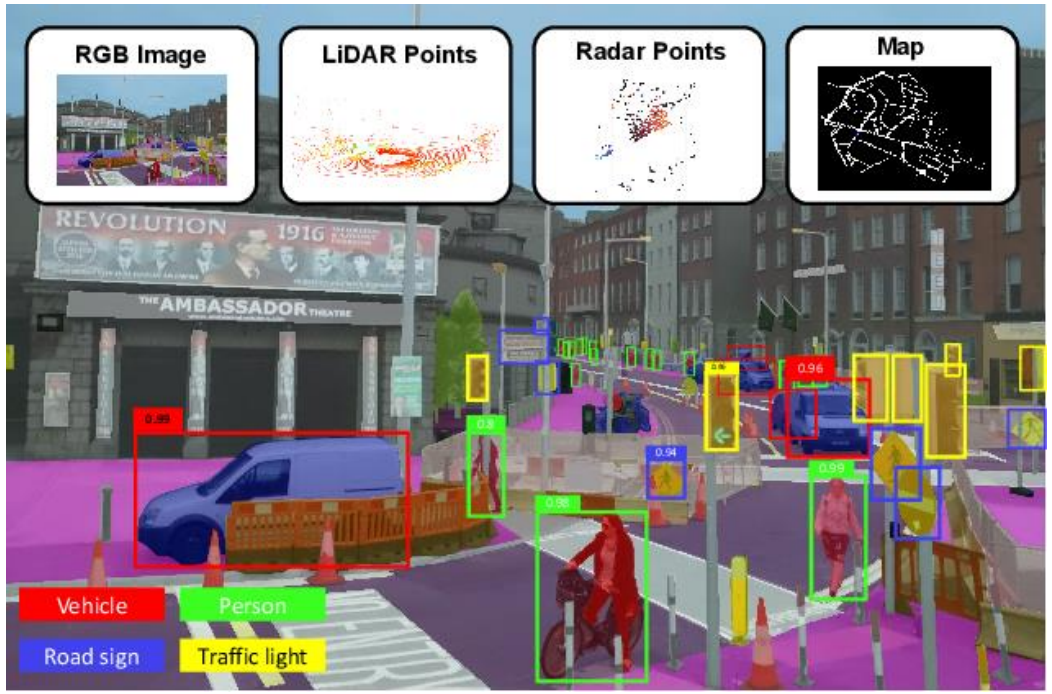
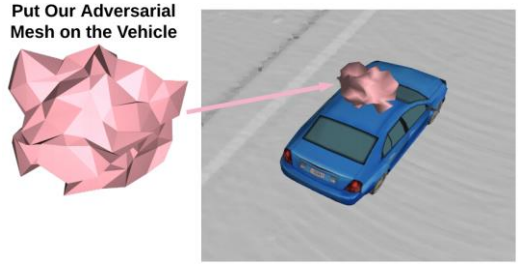
Tennessee TECH

Necessity of Deep Learning

Capabilities



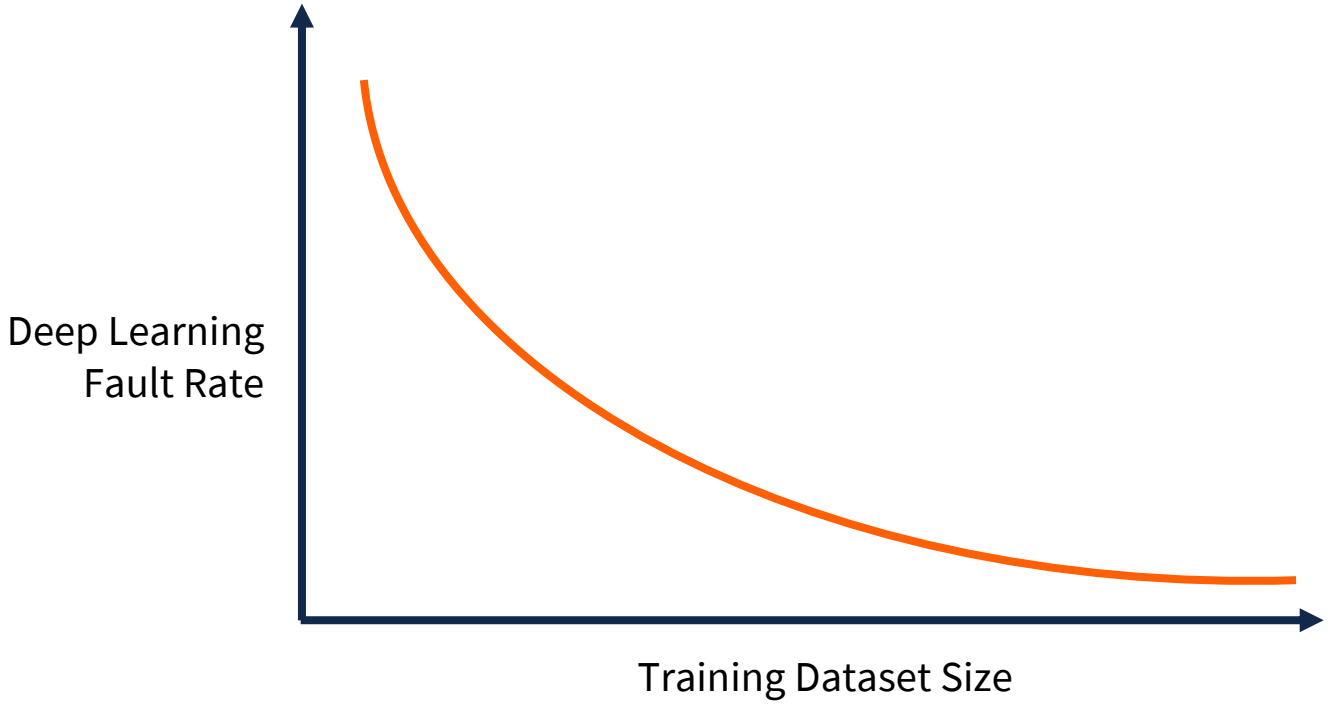
Safety



Perception & prediction present a uniquely difficult assurance challenge

2017. Autonomous vehicle safety: An interdisciplinary challenge. IEEE Intelligent Transportation Systems Magazine. Koopman and Wagner.
2019. Why deep-learning AIs are so easy to fool. Nature. D. Heaven.
2020. Physically realizable adversarial examples for lidar object detection. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. Tu, et al.
2020. Deep multi-modal object detection and semantic segmentation for autonomous driving: Datasets, methods, and challenges. IEEE Transactions on Intelligent Transportation Systems. Feng, et al.
2022. Explainable deep learning: A field guide for the uninitiated. Journal of Artificial Intelligence Research. Ras, et al.
2022. Autonomous Vehicle Standards & Open Challenges. P. Koopman.
2023. Dense reinforcement learning for safety validation of autonomous vehicles. Nature. Feng, et al.

Unavoidable Long Tail

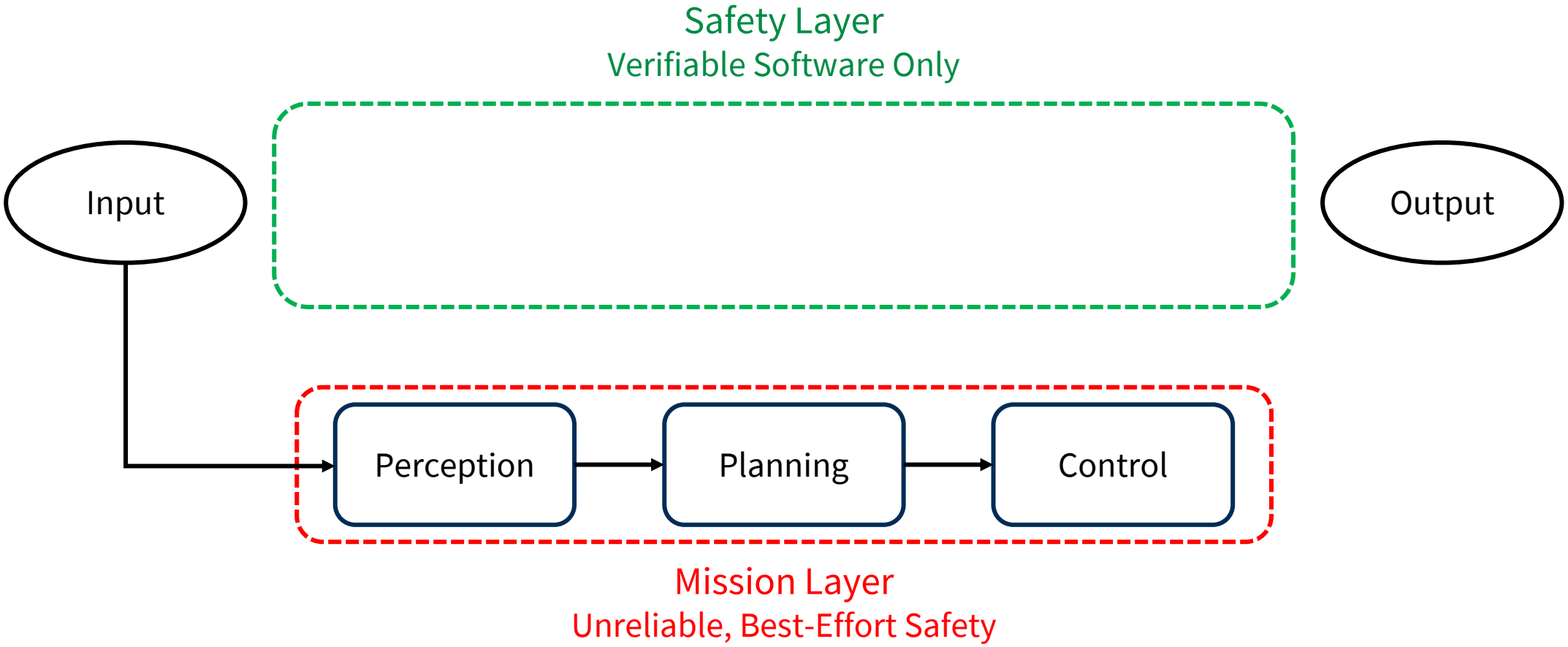


System Design to Mitigate Impact of Faults

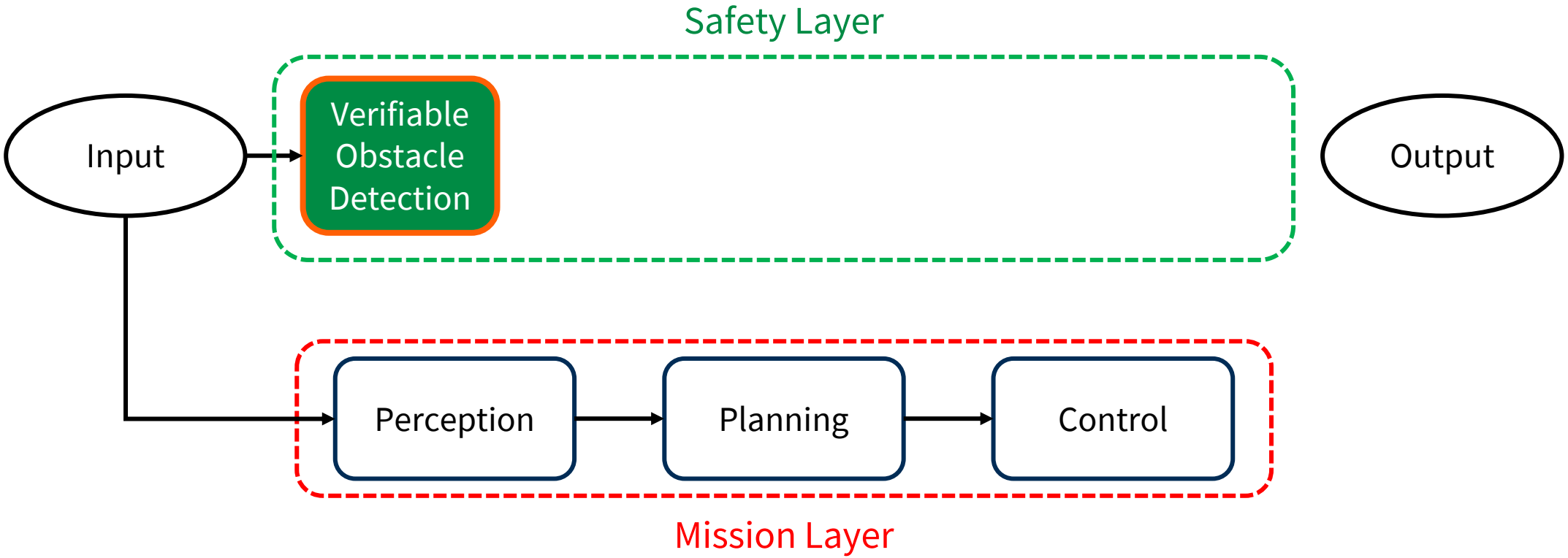
Obstacle Existence Detection Faults

2019. Why deep-learning AIs are so easy to fool. Nature. D. Heaven.
2023. Deep long-tailed learning: A survey. IEEE Transactions on Pattern Analysis and Machine Intelligence. Zhang, et al.
2022. Verifiable obstacle detection. In 2022 IEEE 33rd International Symposium on Software Reliability Engineering (ISSRE), pp. 61-72. IEEE, 2022.
Ayoosh Bansal, Hunmin Kim, Simon Yu, Bo Li, Naira Hovakimyan, Marco Caccamo, and Lui Sha.

System Architecture



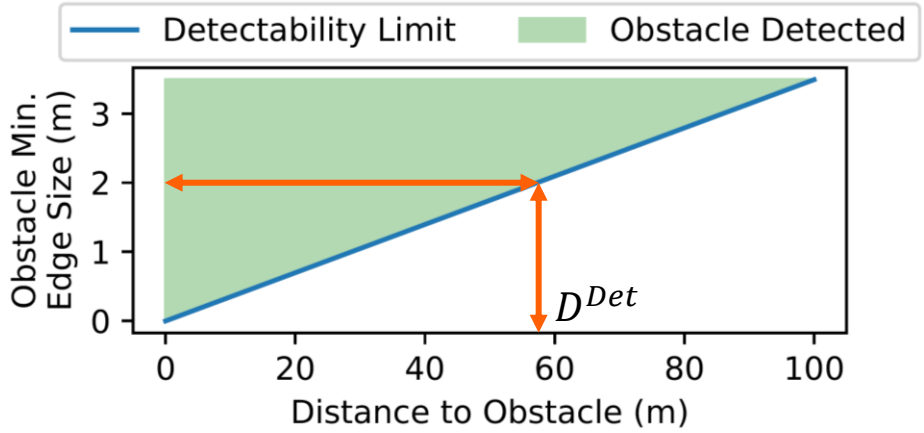
System Architecture - Obstacle Detection



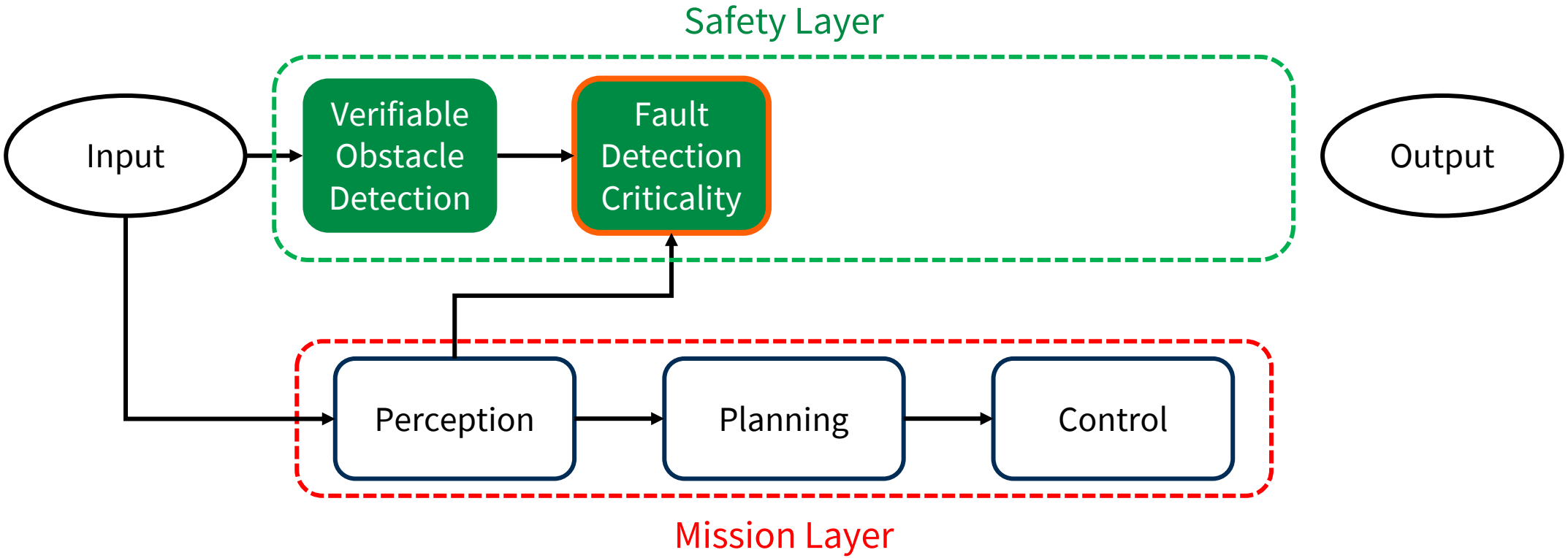
Obstacle Detection

- **Goals**
  - Verifiability
  - Detectability
- **Constraints**
  - No Loss Range
  - Obstacle Properties

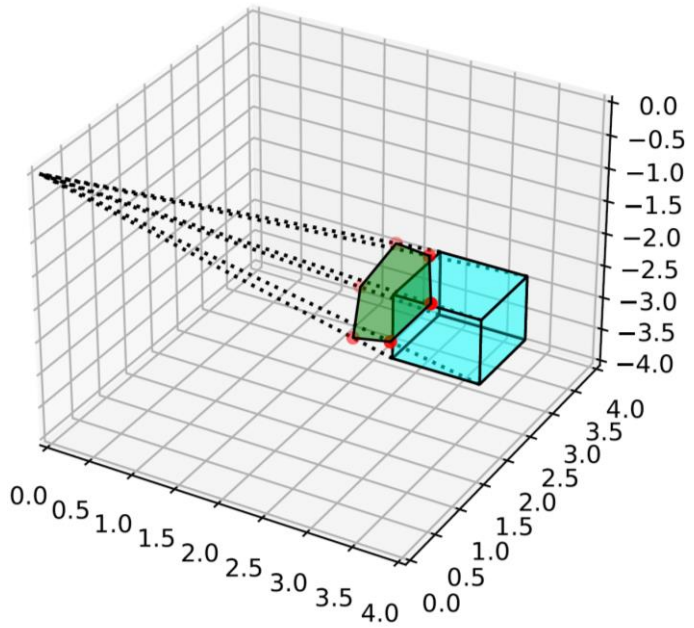
$$Obstacle\ Edge \geq 2 \times Max\ Beams\ Separation\ Angle \times R\pi$$



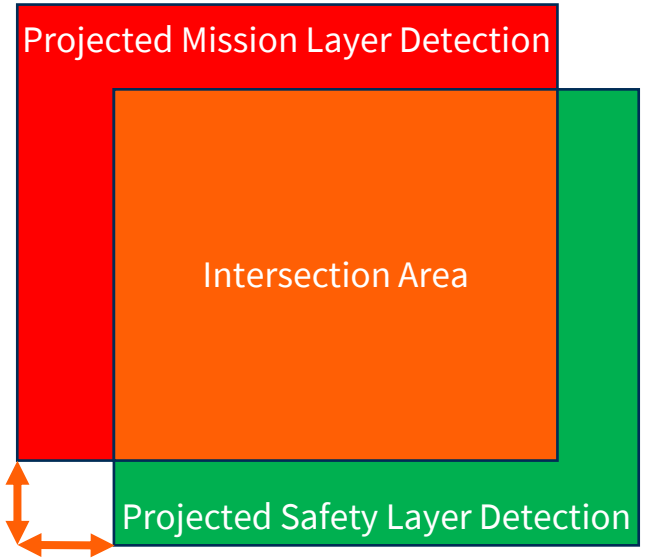
System Architecture - Fault Detection and Criticality



Fault Detection



Projection Towards Air Taxi



✖IOU ✓IOV

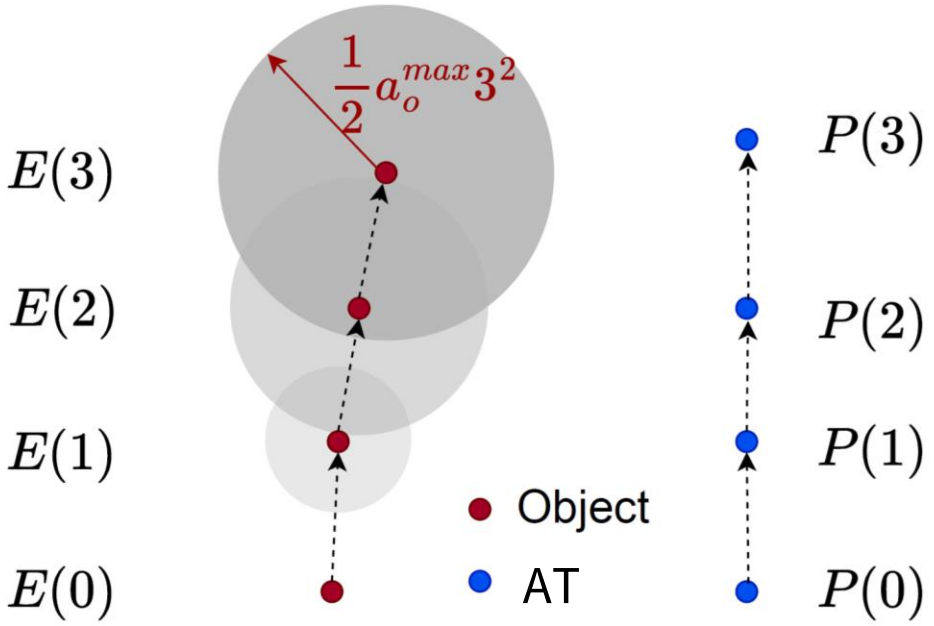
Intersection \ Verifiable Detection

Edge Separation

2021. Risk ranked recall: Collision safety metric for object detection systems in autonomous vehicles. In 2021 10th Mediterranean Conference on Embedded Computing (MECO).
Ayoosh Bansal, Jayati Singh, Micaela Verucchi, Marco Caccamo, and Lui Sha.
2022. Verifiable obstacle detection. In 2022 IEEE 33rd International Symposium on Software Reliability Engineering (ISSRE).
Ayoosh Bansal, Hunmin Kim, Simon Yu, Bo Li, Naira Hovakimyan, Marco Caccamo, and Lui Sha.

Fault Criticality

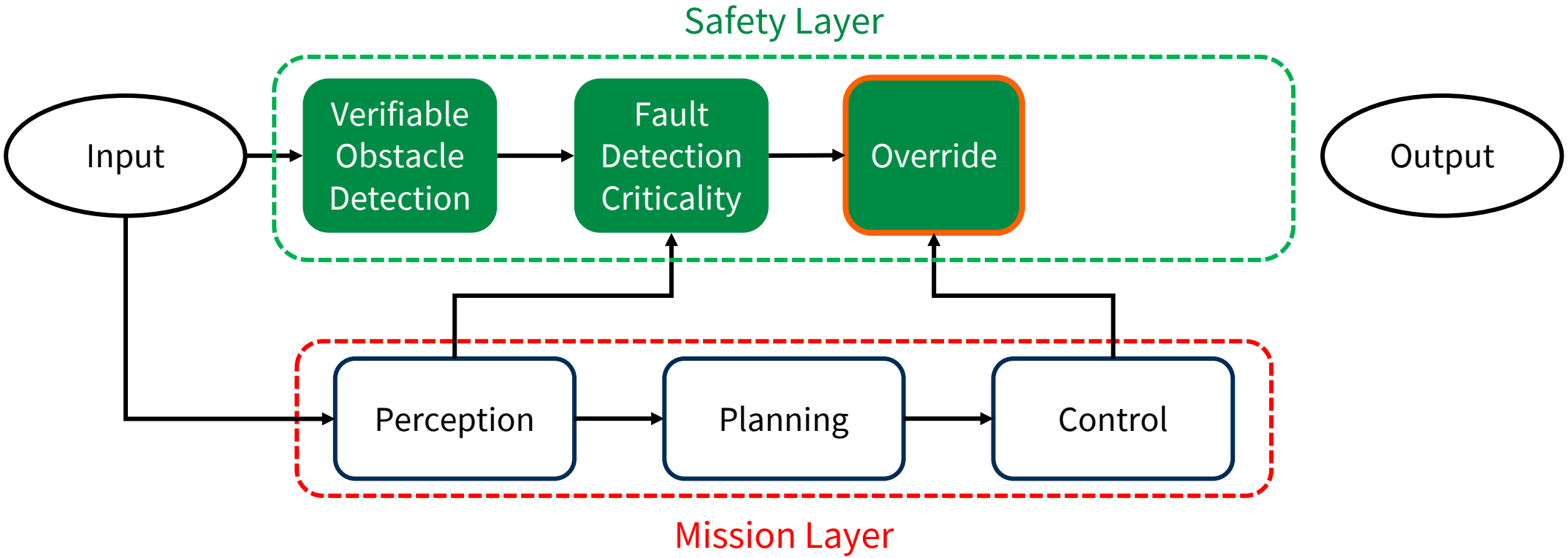
Existence Region
For Obstacle



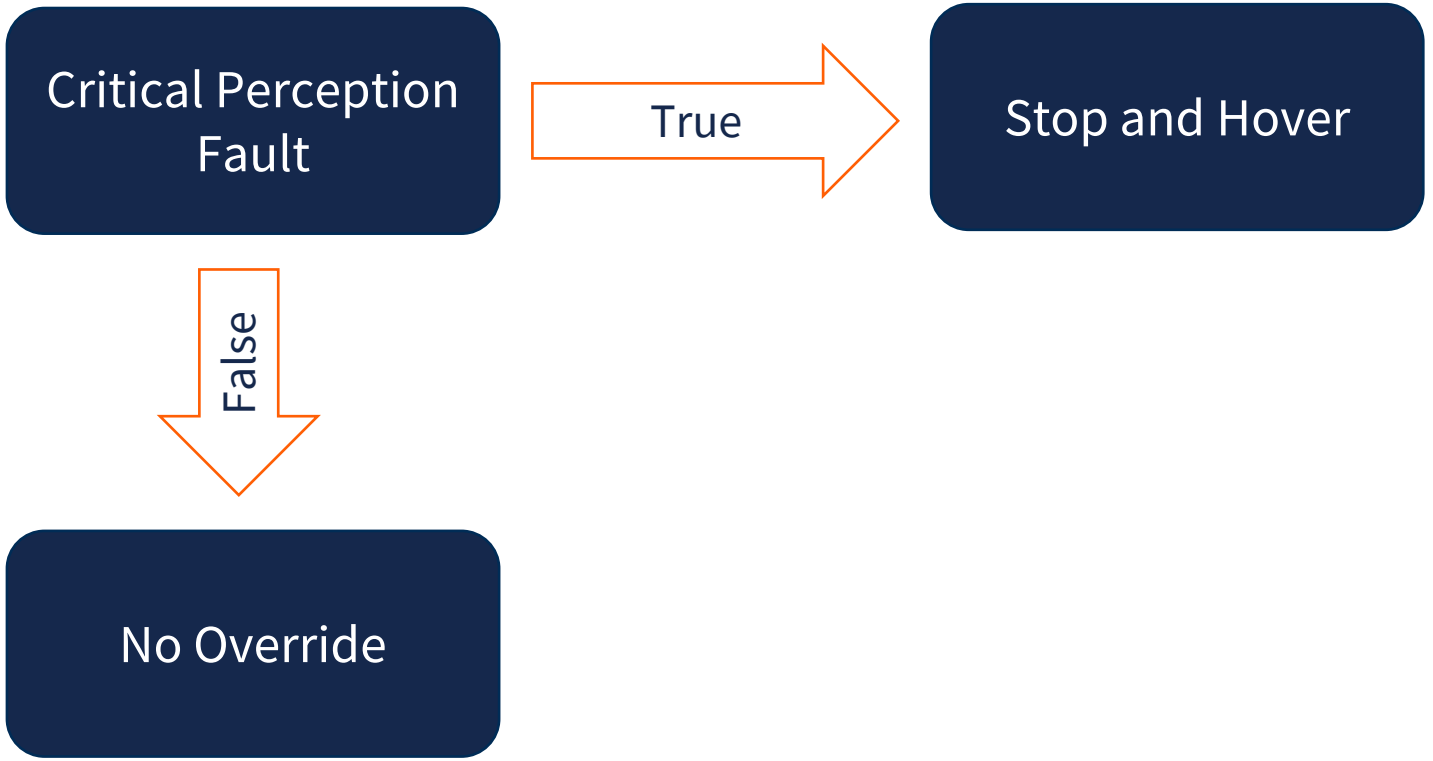
Air Taxi Position

2006. Research on trajectory planning in emergency situations with multiple objects. In 2006 IEEE Intelligent Transportation Systems Conference. Schmidt, et al.
2021. Risk ranked recall: Collision safety metric for object detection systems in autonomous vehicles. In 2021 10th Mediterranean Conference on Embedded Computing. Ayoosh Bansal, Jayati Singh, Micaela Verucchi, Marco Caccamo, and Lui Sha.

System Architecture - Override

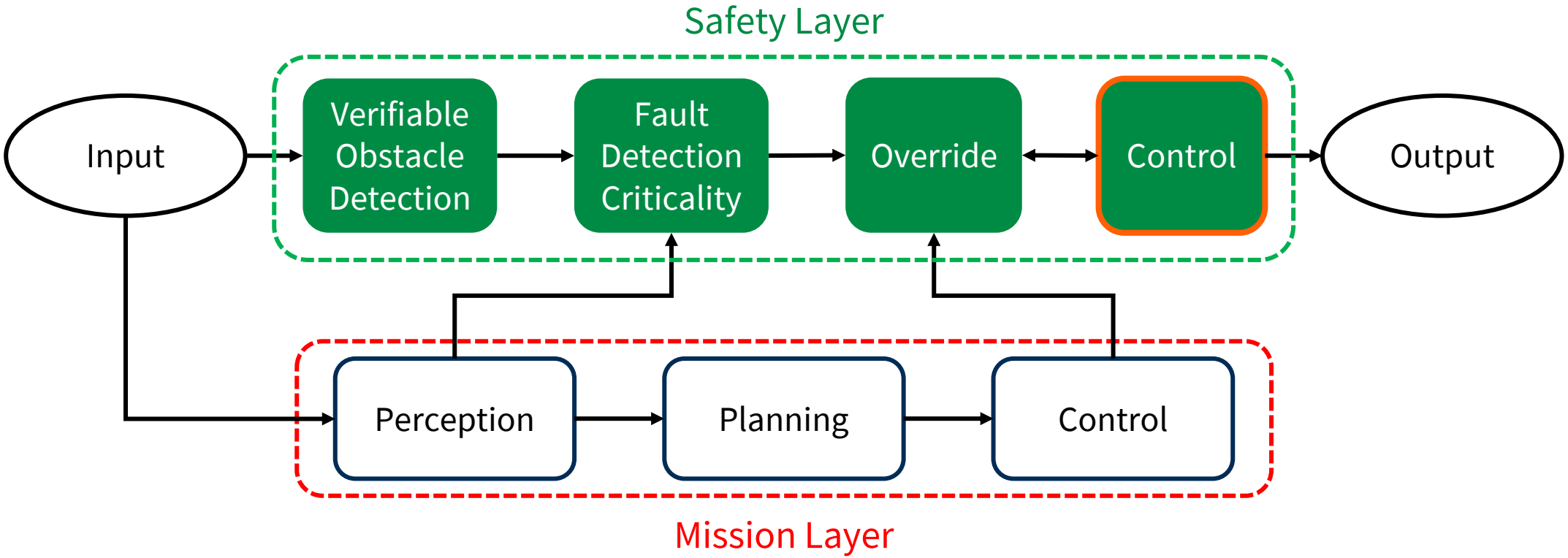


Override

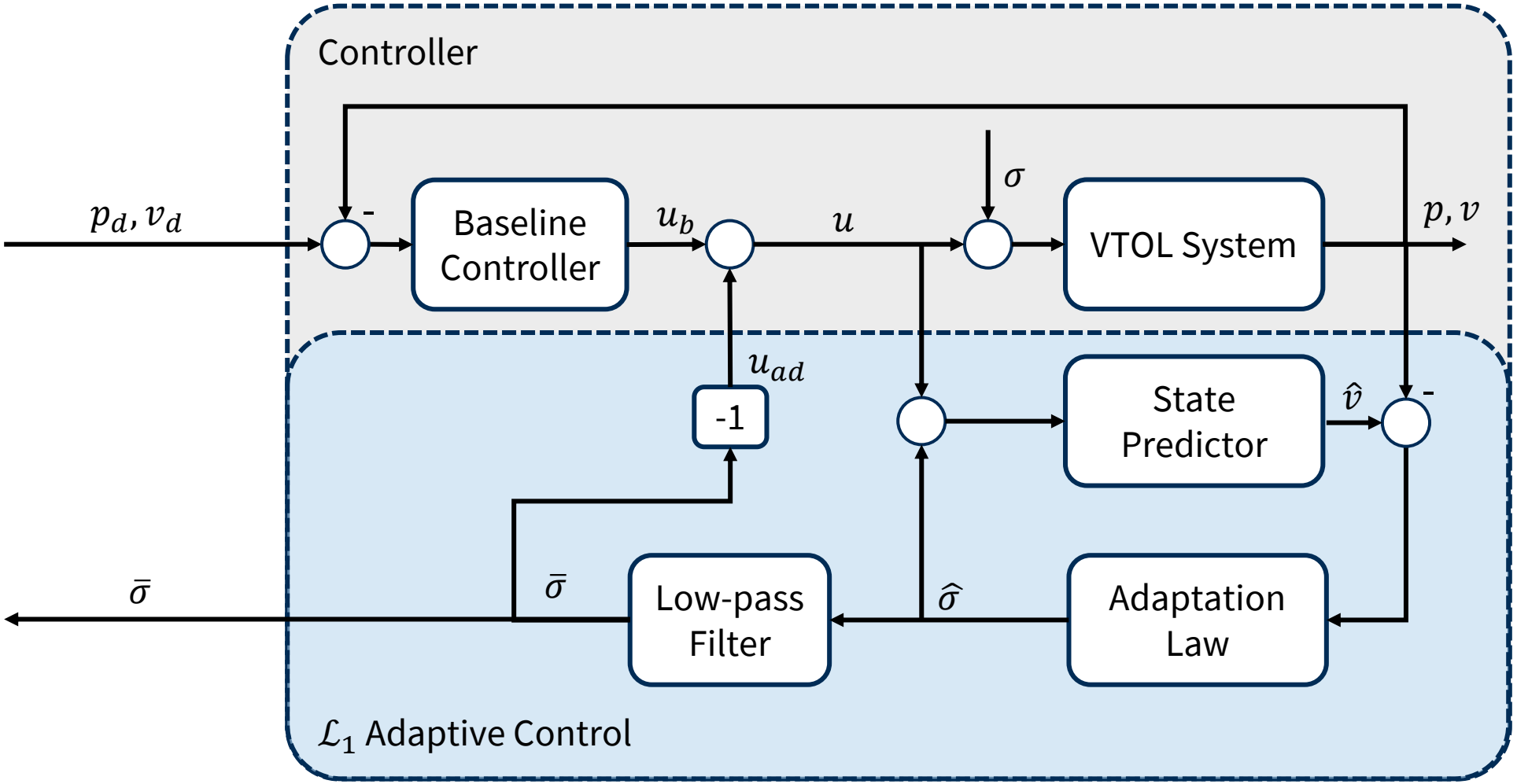


$$D^{Det} \geq D^{stop}_{max}$$

System Architecture - Control

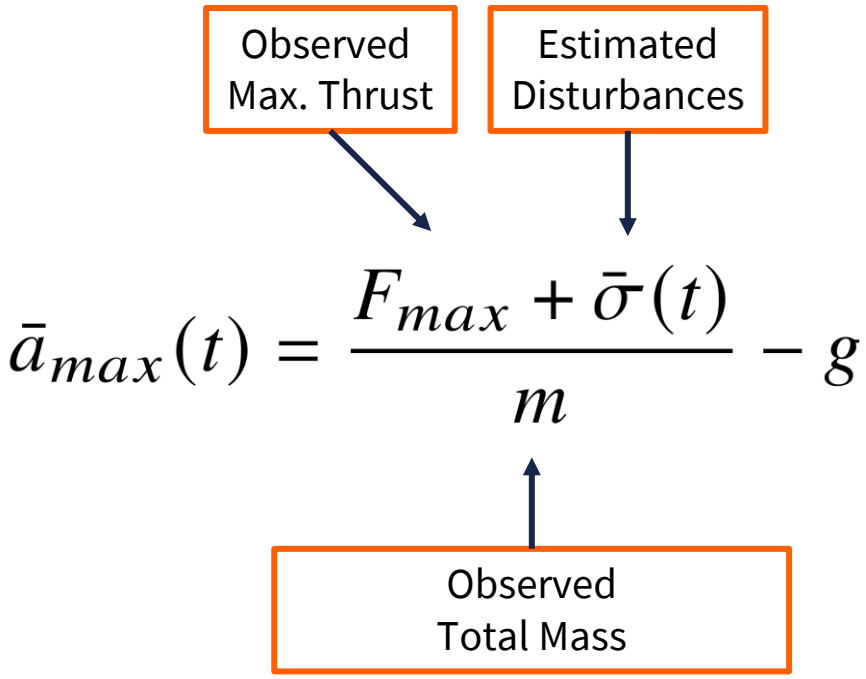


Control

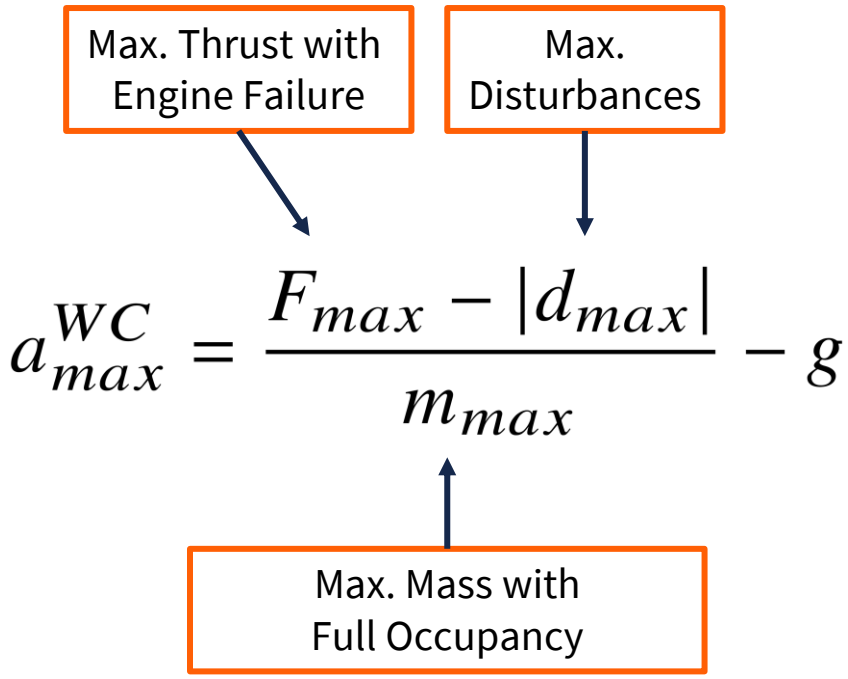

Controller
p_d, v_d
-
Baseline Controller
u_b
u
σ
VTOL System
p, v
u_{ad}
-1
State Predictor
$\hat{v}$
-
$\bar{\sigma}$
$\bar{\sigma}$
Low-pass Filter
$\hat{\sigma}$
Adaptation Law
$\mathcal{L}_1$ Adaptive Control

Maximum Acceleration

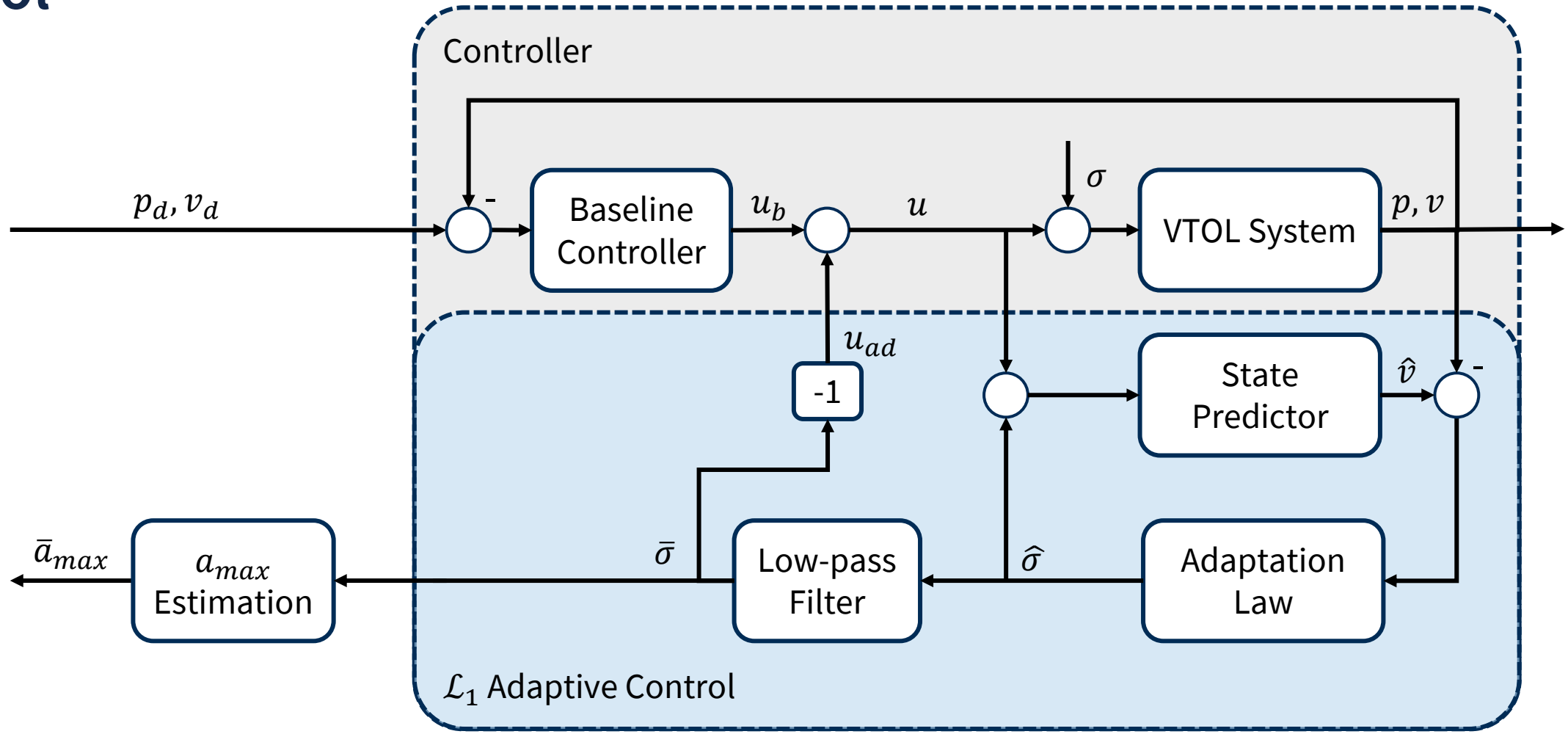
Observed Max. Acceleration



Static Worst-Case

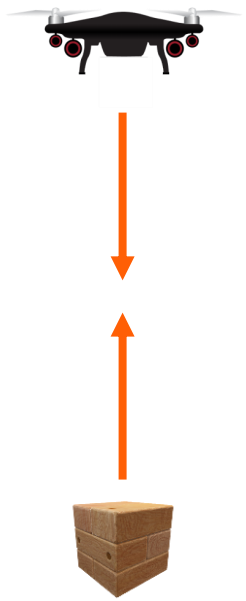


Control

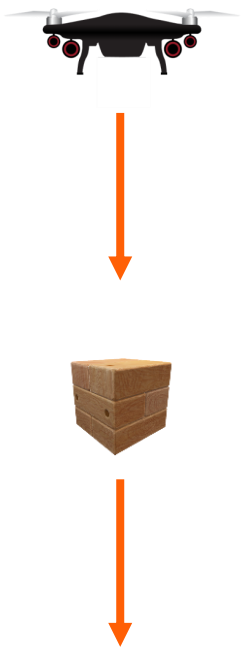

Controller
p_d, v_d
-
Baseline Controller
u_b
u
σ
VTOL System
p, v
u_{ad}
-1
State Predictor
$\hat{v}$
-
$\bar{a}_{max}$
a_{max} Estimation
$\bar{\sigma}$
Low-pass Filter
$\hat{\sigma}$
Adaptation Law
$\mathcal{L}_1$ Adaptive Control

Scenarios

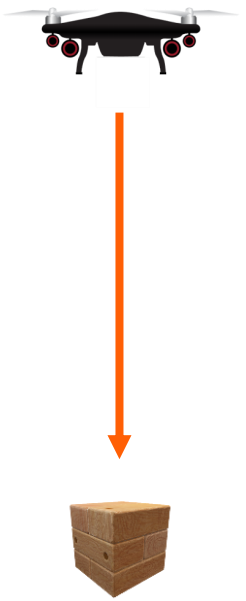
Evasion



Obstacle Approaching



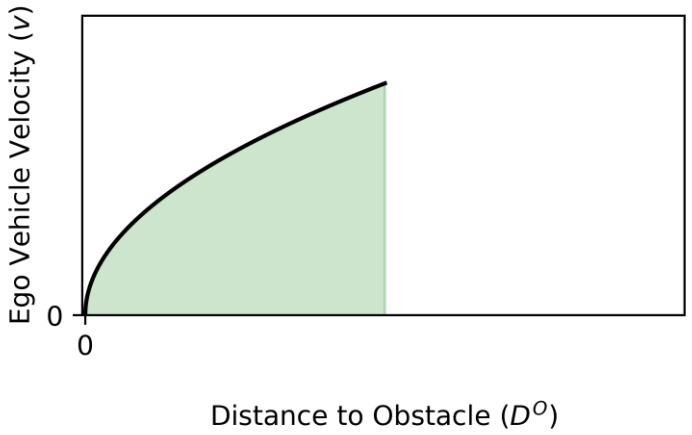
Obstacle Moving Away

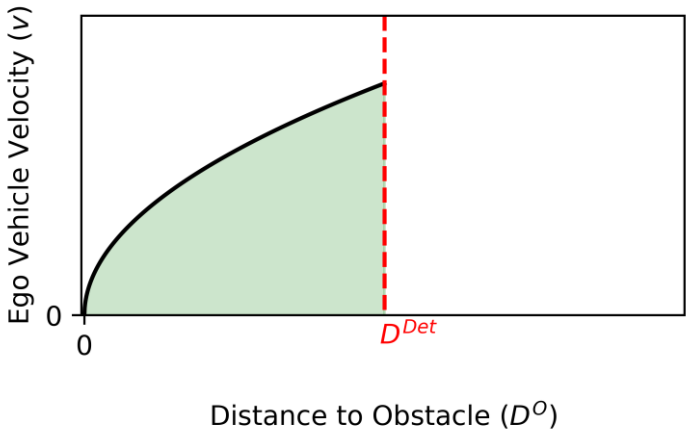


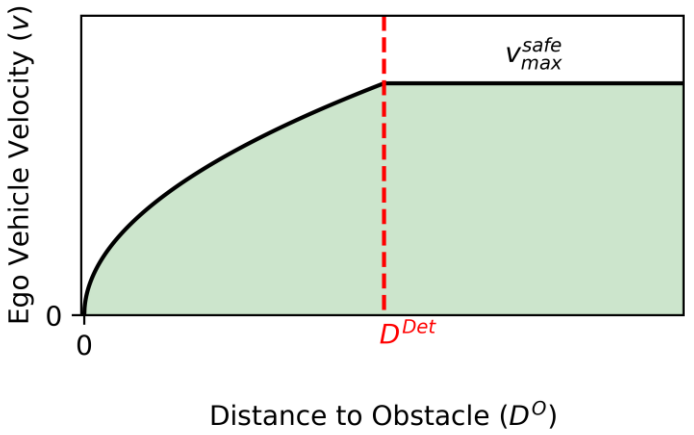
Stationary Obstacle

Safety Envelope

$$D^{Stop} \leq D^{O}$$





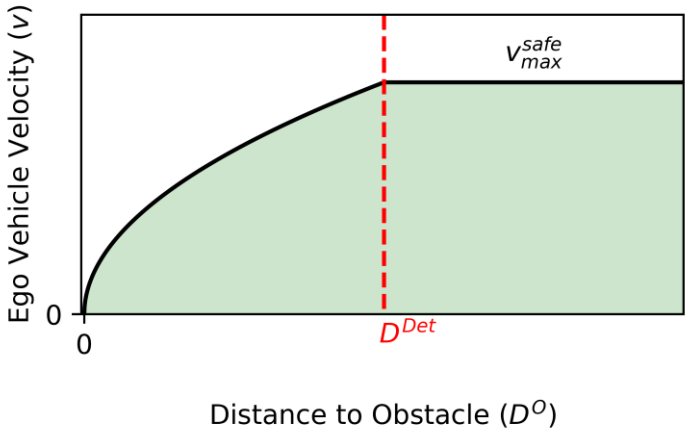


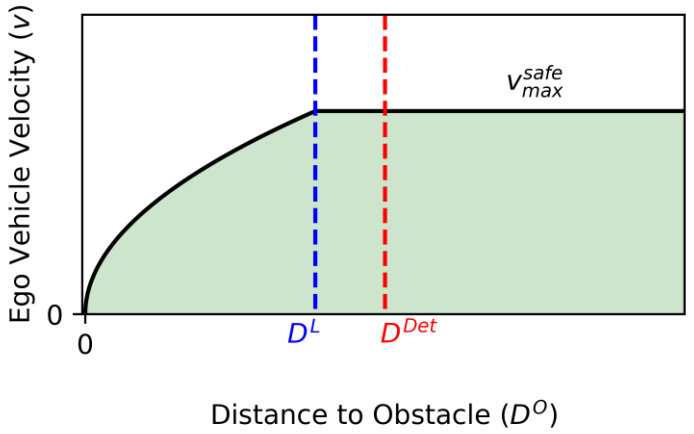
$$v \leq \sqrt{2a_{max}D^{O}}$$

$$v \leq \sqrt{2a_{max}D^{O}} \; \forall \; D^{O} \leq D^{Det}$$

$$v \leq \sqrt{2a_{max}D^{Det}} \; \forall \; D^{O} > D^{Det}$$

Safety Envelope – Computation Delay

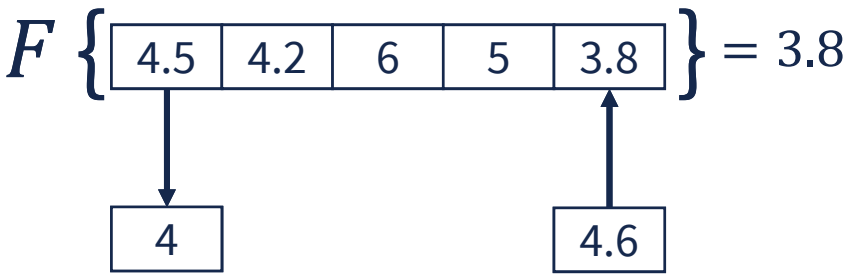




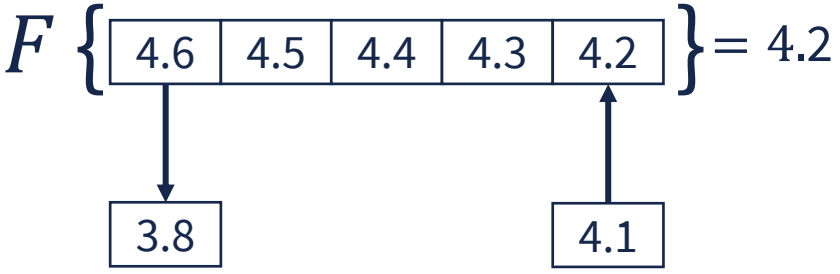
$$D^L = v_{max}^{safe} * L_{max} + \frac{(v_{max}^{safe})^2}{2a_{max}}$$

$$a_{max} = ?$$

Dynamic Confirmation – Sliding Window



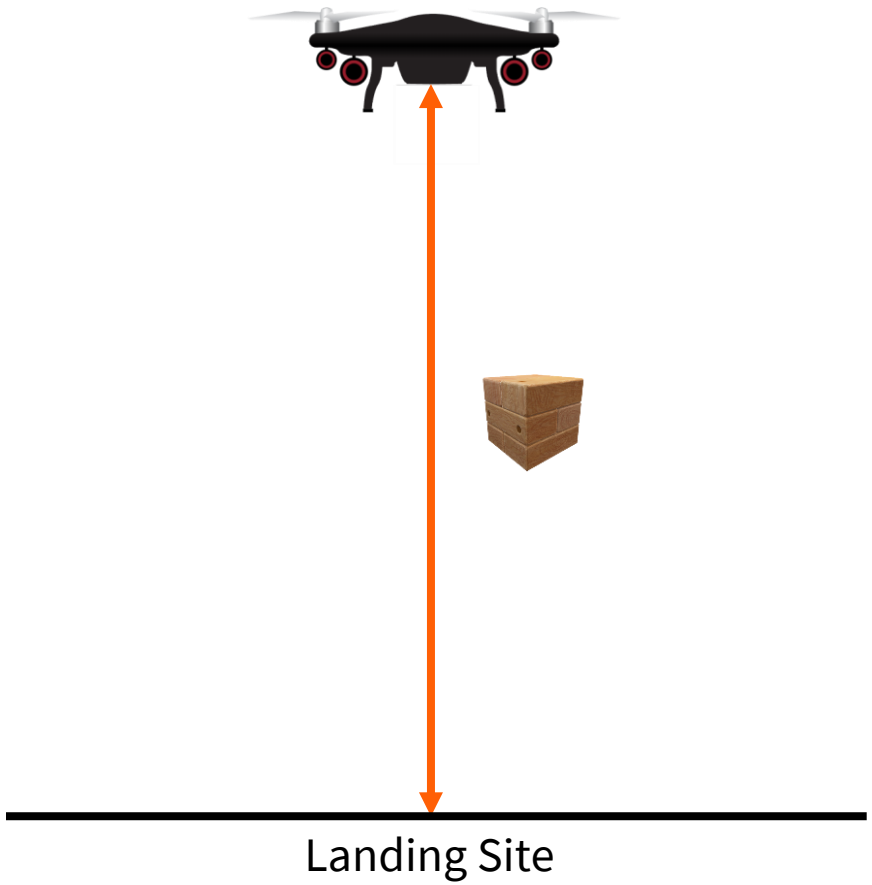
Real Time Adaptation
Immediate Response to
New Observed Worst-Case



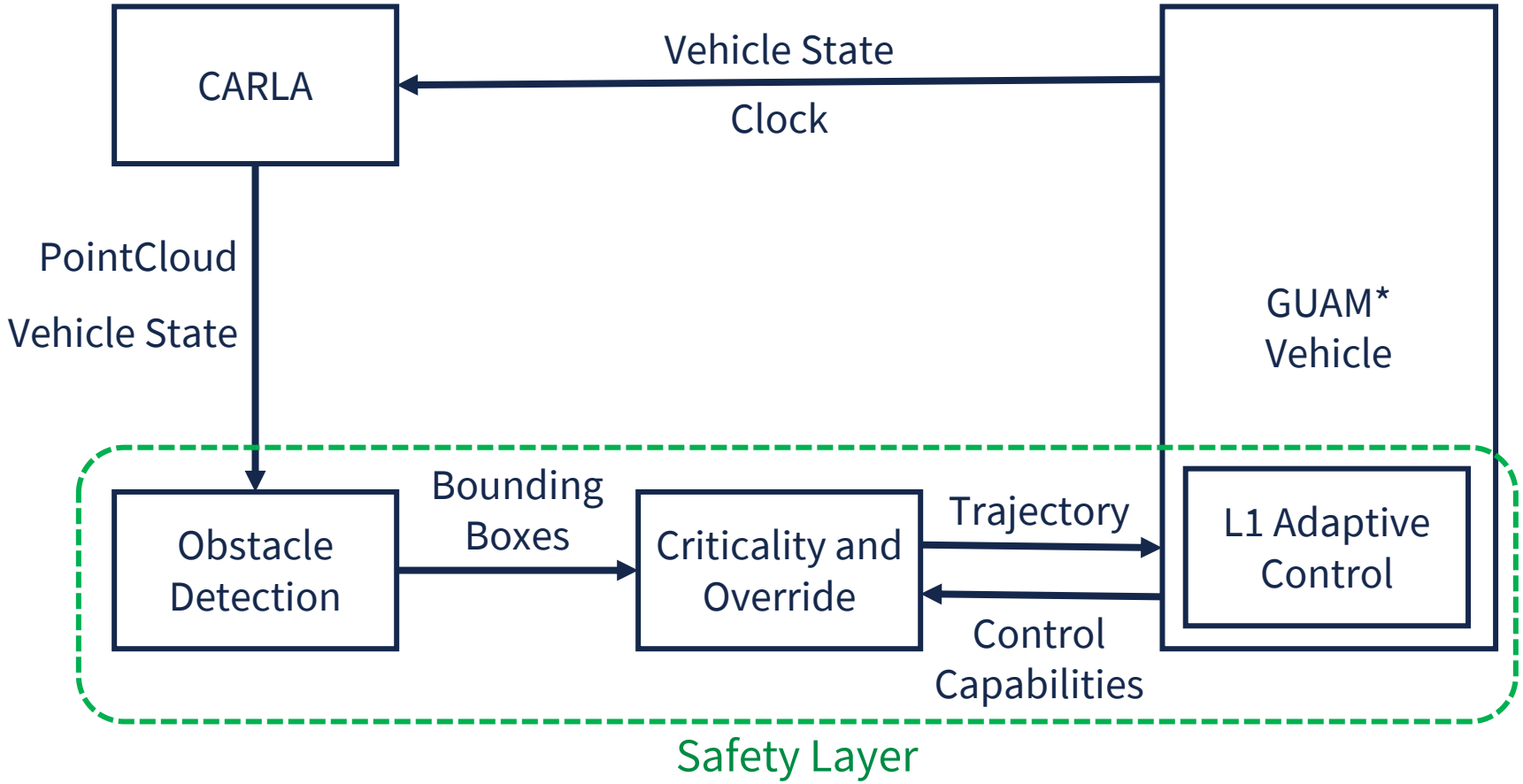
Slow Recovery
Controlled with Window Size

Evaluation Scenario

- Air Taxi 100 m above landing site.
- Stationary obstacle at different positions
- No mission layer
  - All obstacles considered FN
  - Simple Trajectory Planner
  - Single Vehicle Landing
- Static vs Observed Worst Case accelerations



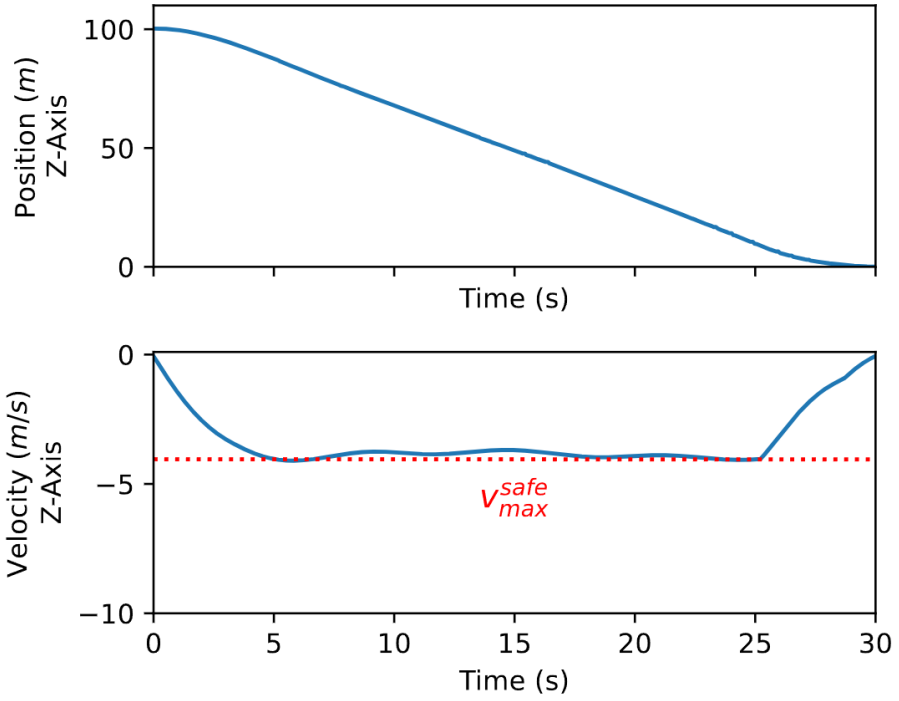
Evaluation Setup



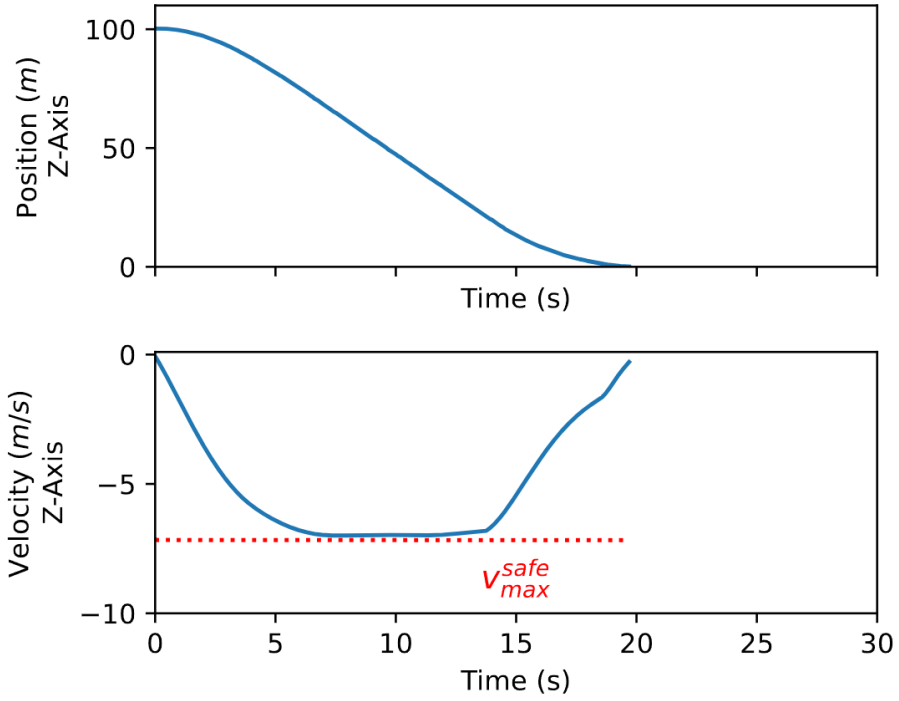
*Generic Urban Air Mobility Vehicle model developed by NASA.

2016. Fast range image-based segmentation of sparse 3D laser scans for online operation. In 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). Bogoslavskyi and Stachniss.
2017. Efficient online segmentation for sparse 3D laser scans. PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science. Bogoslavskyi and Stachniss.

No Obstacles

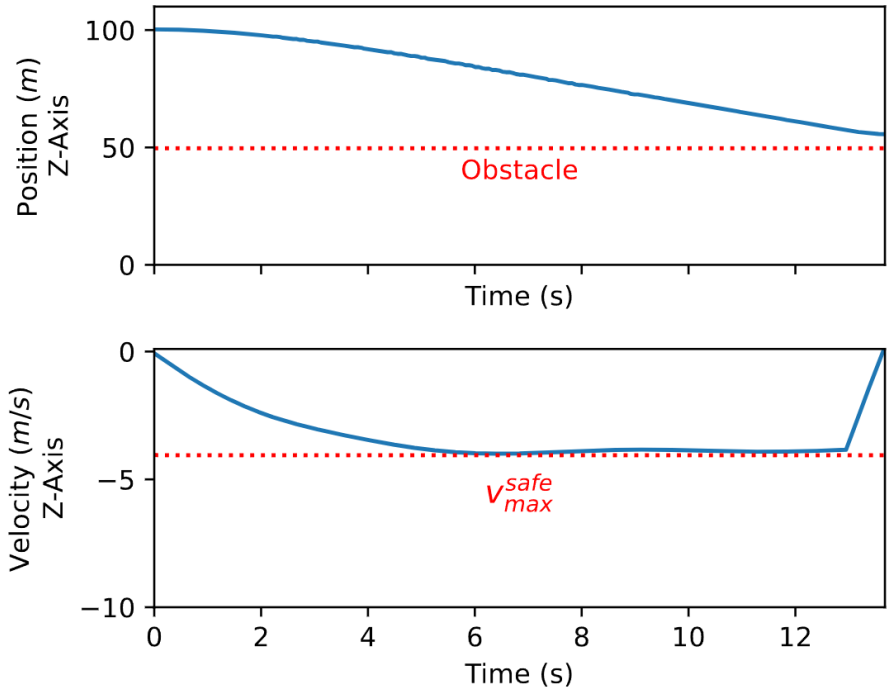


(a) Deceleration Limit $a_{max}^{WC} = 1.34m/s^2$

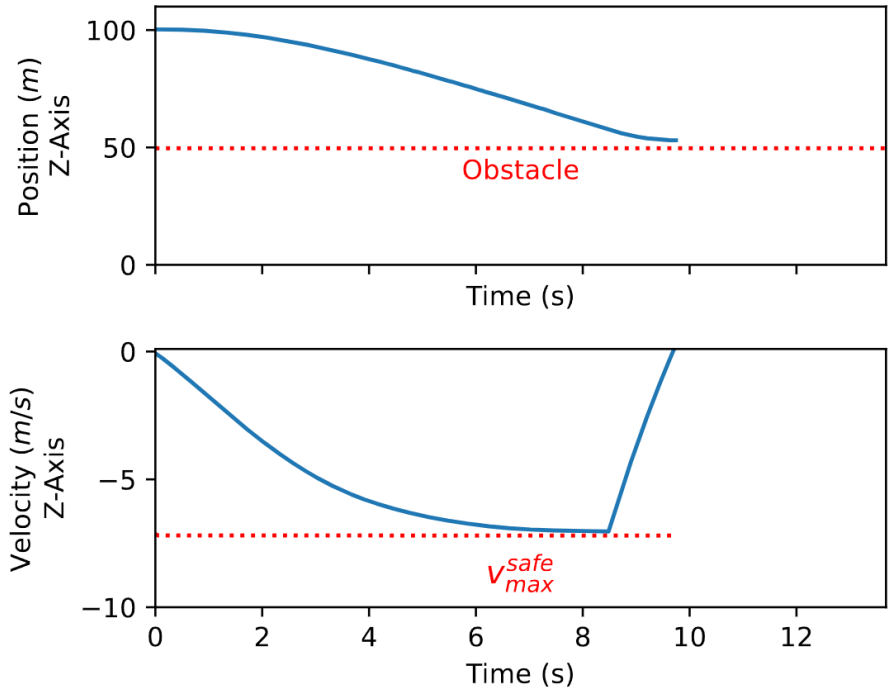


(b) Deceleration Limit $a_{max}^{DC} = 4.25m/s^2$ (avg.)

Obstacle in Path



(a) Deceleration Limit $a_{max}^{WC} = 1.34m/s^2$



(b) Deceleration Limit $a_{max}^{DC} = 4.25m/s^2$ (avg.)

Limitations and Future Work

Real World Deployment


Expanded Detectability Model


Sensor Fusion


Expanded Fault Coverage


Real-World and Simulation Testbeds


Real – Time Analysis

Performance


Synergistic Interactions between Mission and Safety layers


Expanded Overrides and Recovery

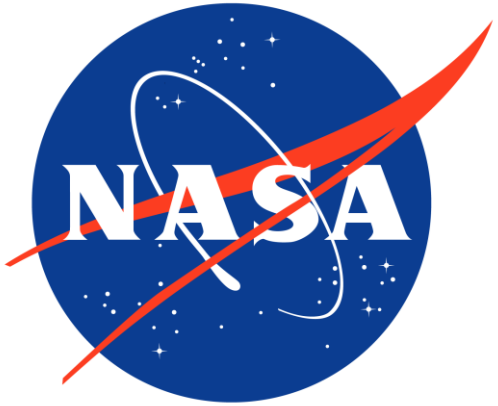

Fail Operational Best-Effort


Proactive Adaptation


Platform Design

2022. Synergistic Redundancy: Towards Verifiable Safety for Autonomous Vehicles. arXiv preprint arXiv:2209.01710. Ayoosh Bansal, Simon Yu, Hunmin Kim, Bo Li, Naira Hovakimyan, Marco Caccamo, and Lui Sha.
2023. Robust vehicle lane keeping control with networked proactive adaptation. Artificial Intelligence. Hunmin Kim, Wenbin Wan, Naira Hovakimyan, Lui Sha, and Petros Voulgaris.

Acknowledgements



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ECCS 2311085

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