Anytime Perception and Control for Safe and Intelligent Urban Air Mobility

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We need intelligent perception and control capabilities

blade runner 2049 concept art from
https://www.artstation.com/artwork/PxvJ1

Perception Latency

- Q. How fast can the human perceive images?

Visual stimulus

A cat is chasing a butterfly!

Recognition

Processing in brain

time

13 ms

(fastest)

[In the blink of an eye | MIT News | Massachusetts Institute of Technology]

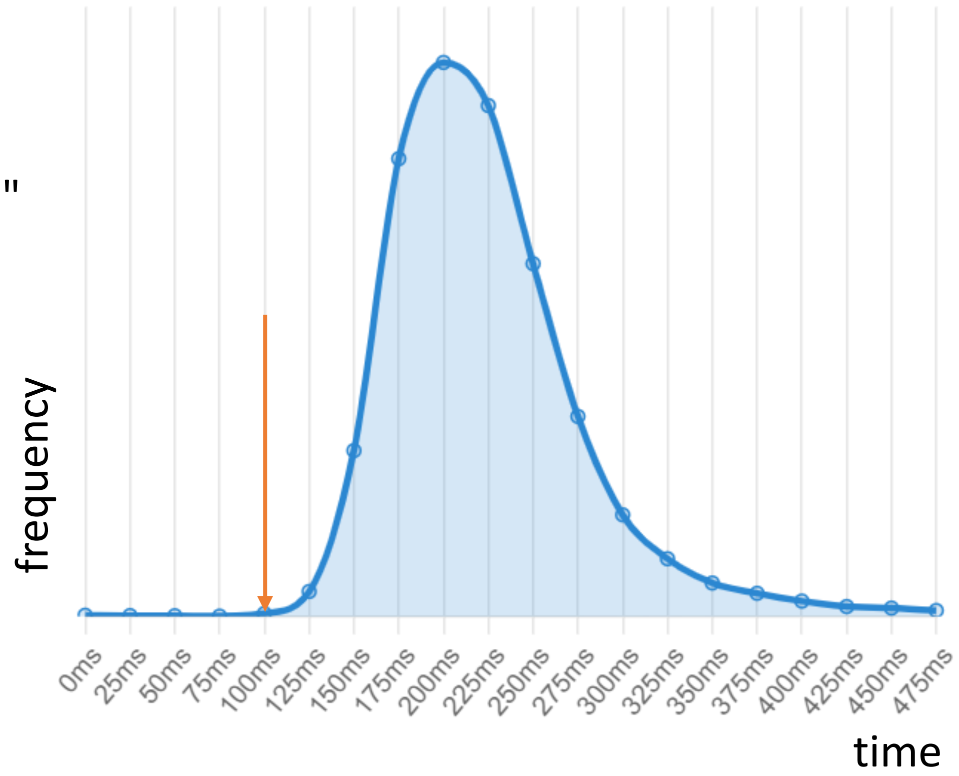
Reaction (Perception and Control) Latency

- Q. How fast can the human react to a stimulus?

"when the red box turns green, click as quickly as you can"

100 ms

(fastest)



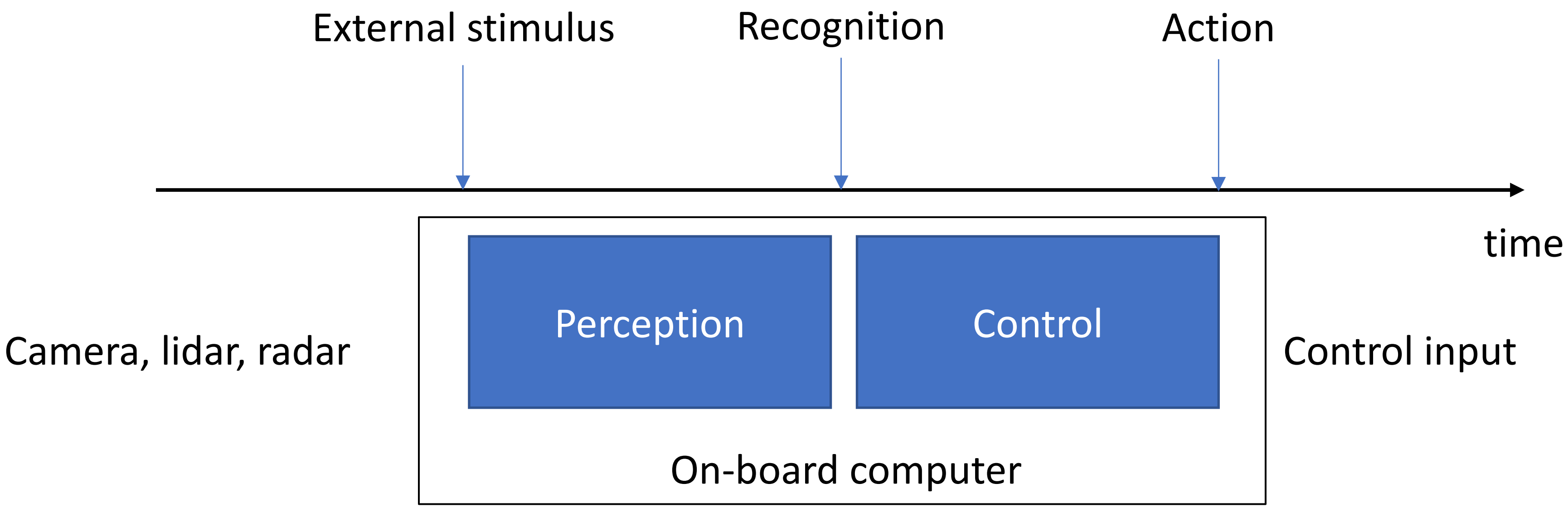
[Reaction Time Test - Human Benchmark]


SNACK HELLAS
ELLAS
SNACK "PLAKA"
PITA GYROS
ATHENES
Pitta Gyros
Dürüm
Pitta grecque
Pitta Hellas
Coca-Cola

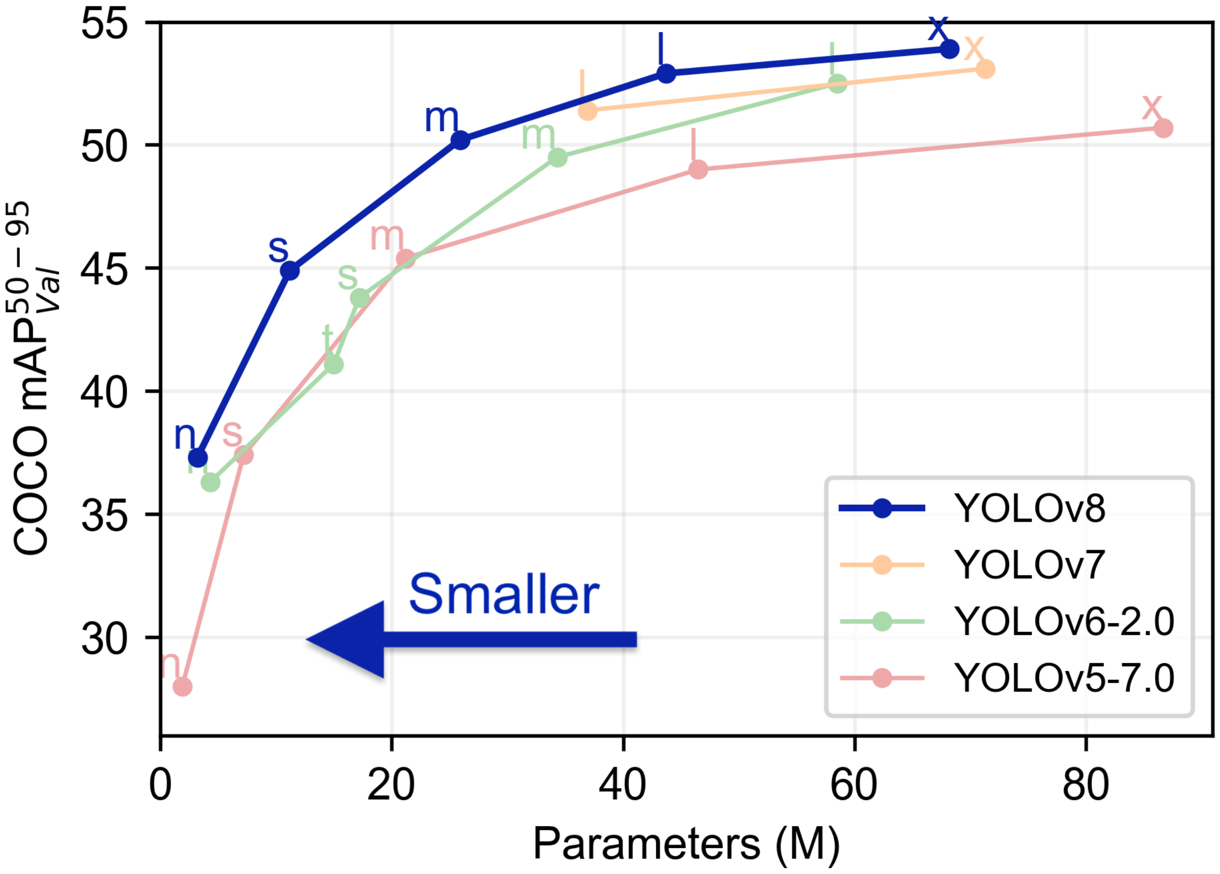

dreamstime

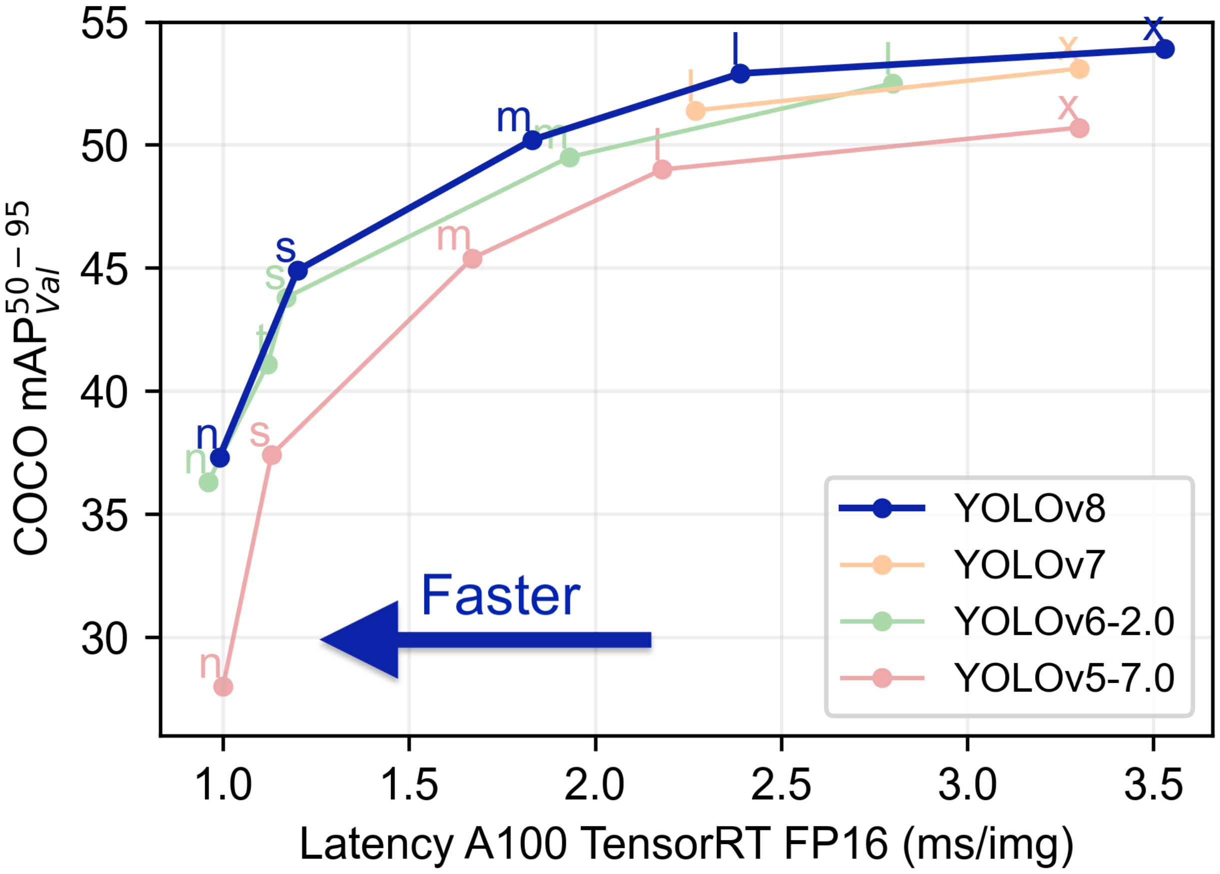
Artificial Perception & Control Systems

- Use on-board sensors and computers for perception and control
- Advanced perception (e.g., DNN) systems can achieve human-like accuracy
- **But are they flexible and adaptable as humans?**



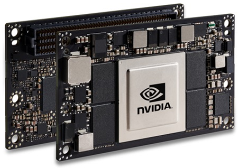
Accuracy vs. Latency

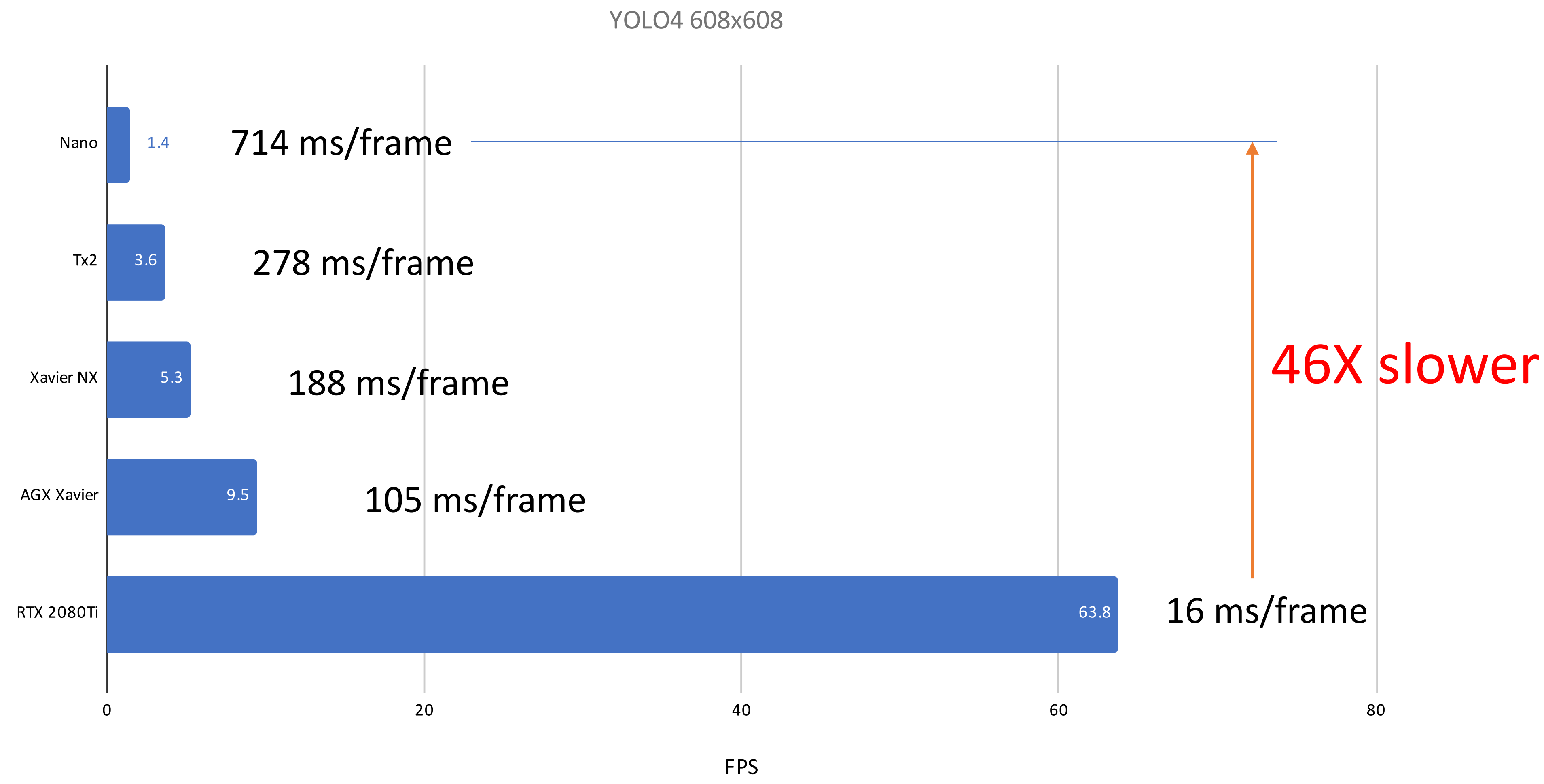




https://github.com/geoffrey-g-delhomme/yolov8-lard

Latency vs. GPU





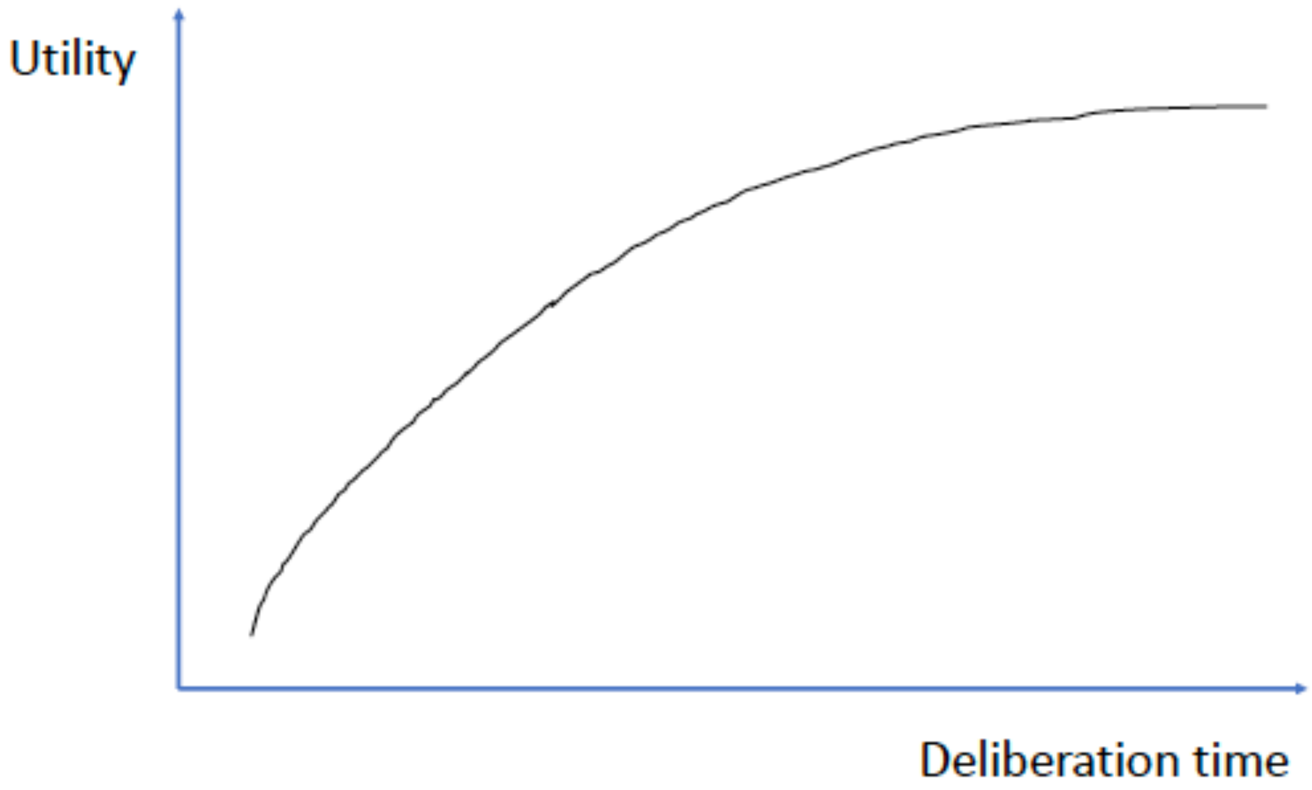
Data source: https://github.com/ceccocats/tkDNN

Challenges

- Which perception model to use may depend on:
  - Speed of the vehicle (affect needed perception and reaction time)
  - Surrounding environment (e.g., urban vs. rural)
  - On-board computing capability
- On-board computing capability is limited
  - Due to size, weight, and power (SWaP) constraints and cost

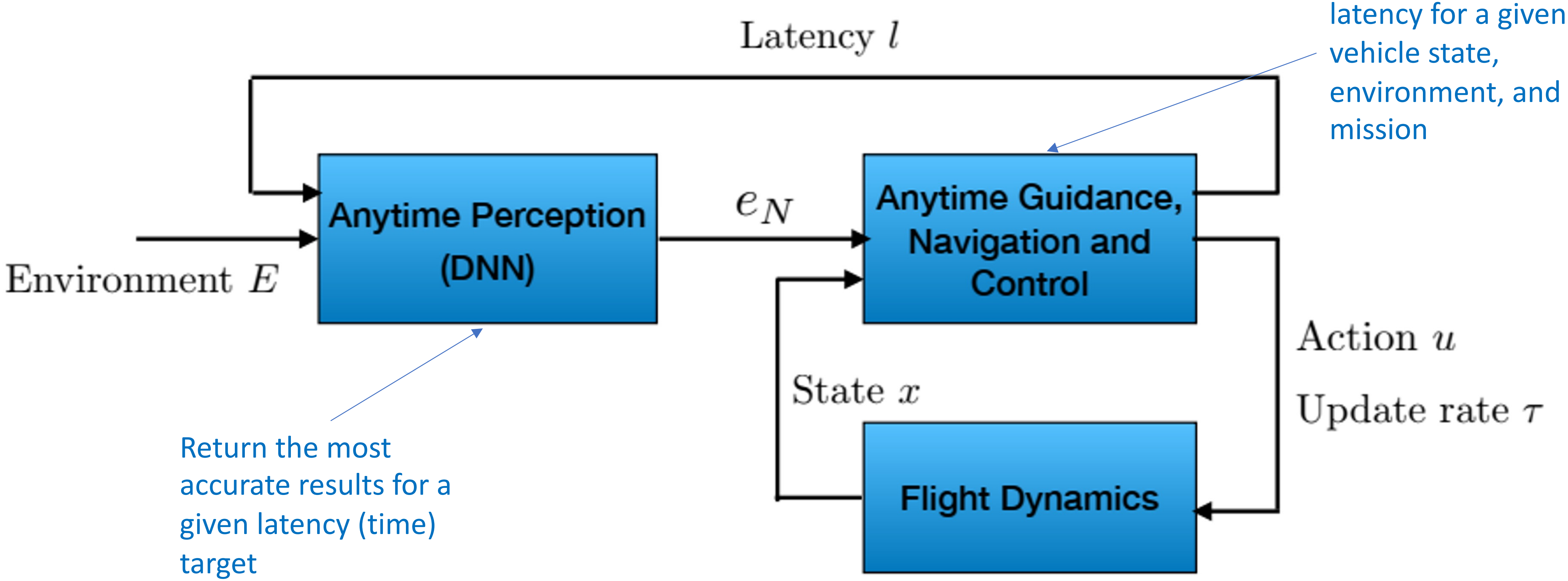
Can we *dynamically* and *automatically* adapt our perception and control systems to find right latency, accuracy, and performance trade-offs on the fly just as humans do?

Anytime Algorithms



Boddy, M., and Dean T. L. "Solving Time-Dependent Planning Problems." *In Proceedings of the Eleventh International Joint Conference on Artificial Intelligence*, 1989.

Our Vision: Anytime Perception and Control



Decide the target latency for a given vehicle state, environment, and mission

Return the most accurate results for a given latency (time) target

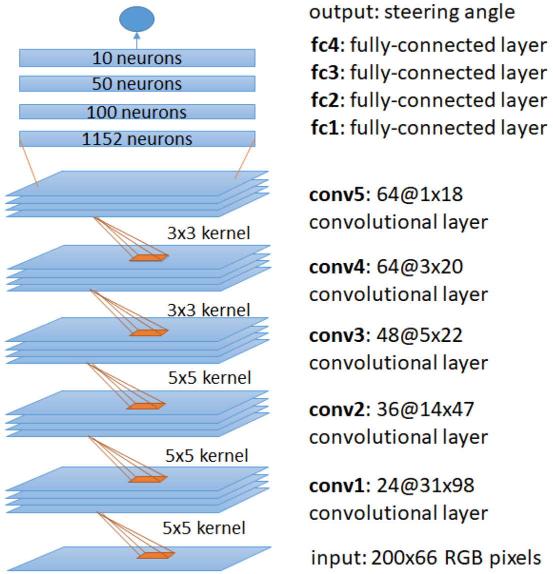
Outline

- Introduction
- **A case study**
- Anytime perception and control for UAM/UAS
- Conclusion

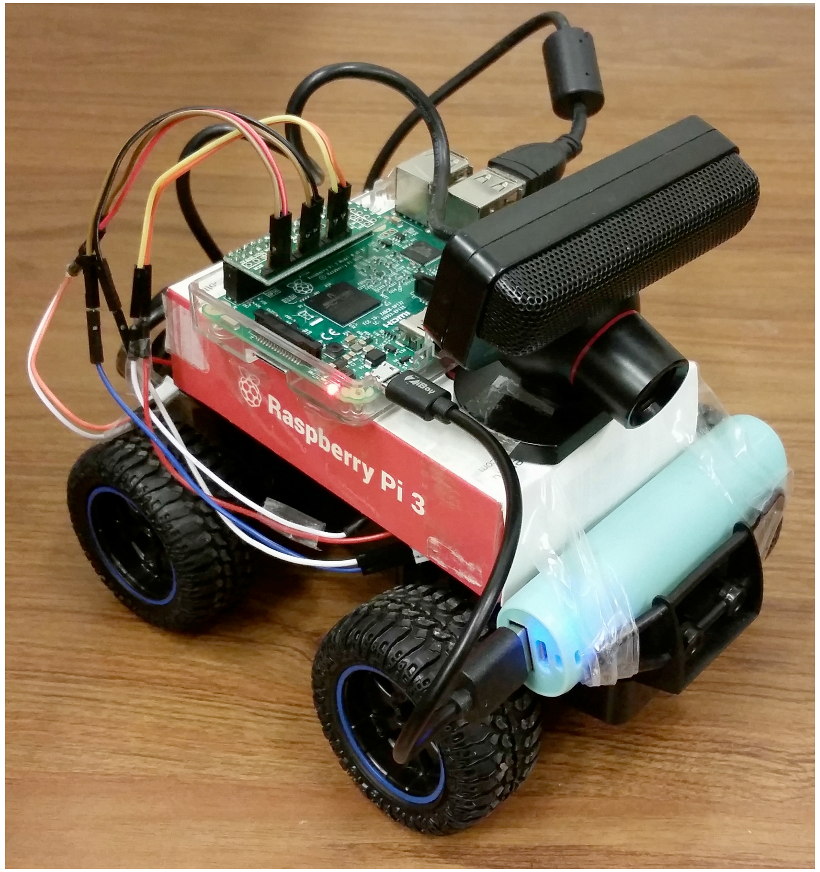
DeepPicar

- End-to-end deep learning: *pixels* to *steering*
- Using identical CNN with NVIDIA's DAVE-2

DAVE-2



PilotNet



DeepPicar

Michael G. Bechtel, Elise McEllhiney, Minje Kim, Heechul Yun. "DeepPicar: A Low-cost Deep Neural Network-based Autonomous Car." In *IEEE RTCSA*, 2018.

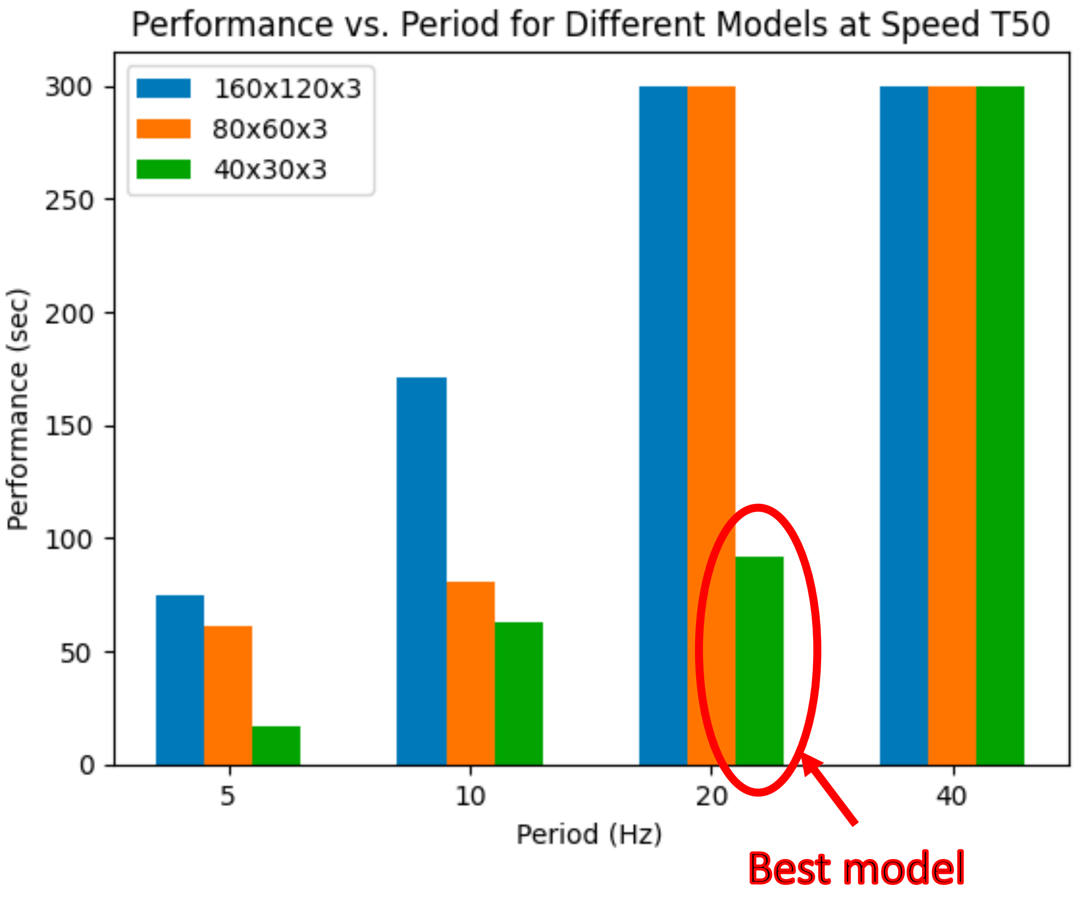
DeepPicar

Big, Medium, Small PilotNet Variants

Model (input res.)	MACs	Params
160x120x3	47186K	802K
80x60x3	14202K	367K
40x30x3	7230K	175K

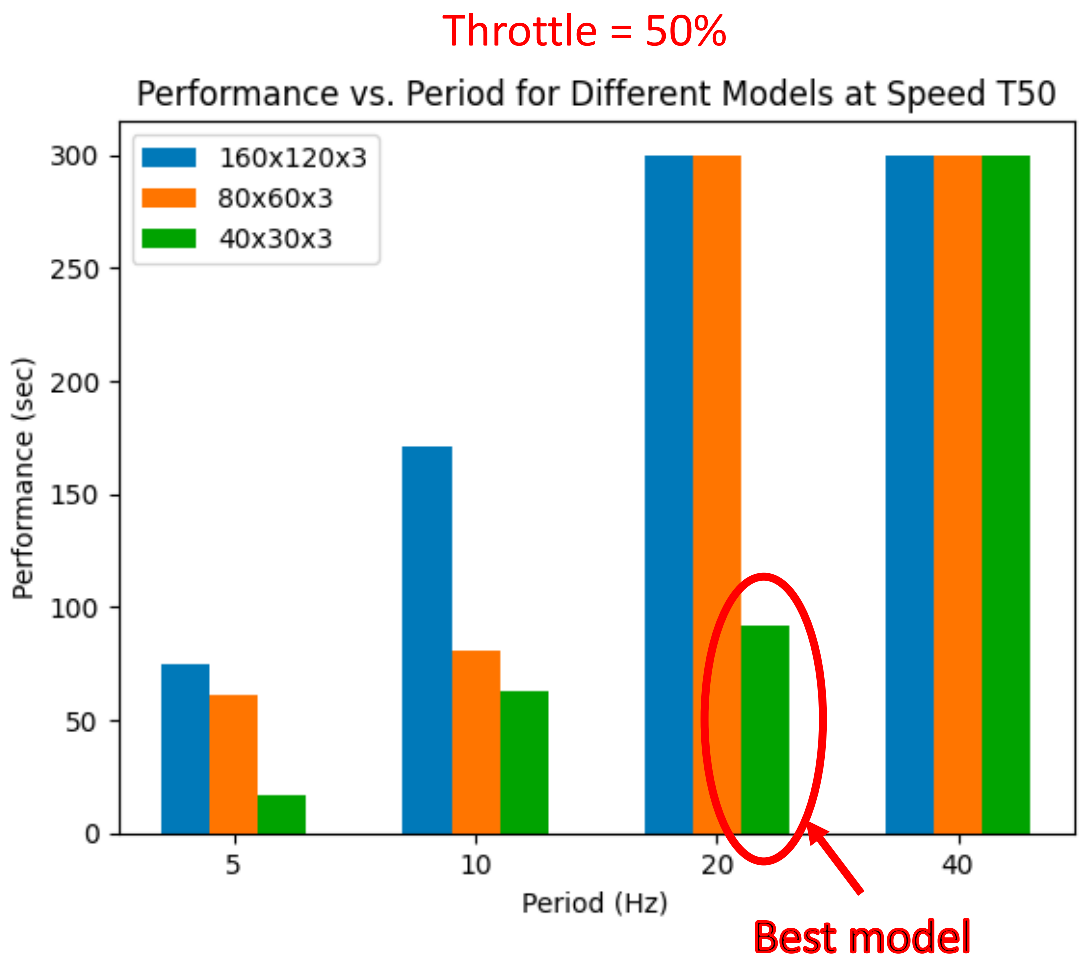
Used a same dataset to train all three models

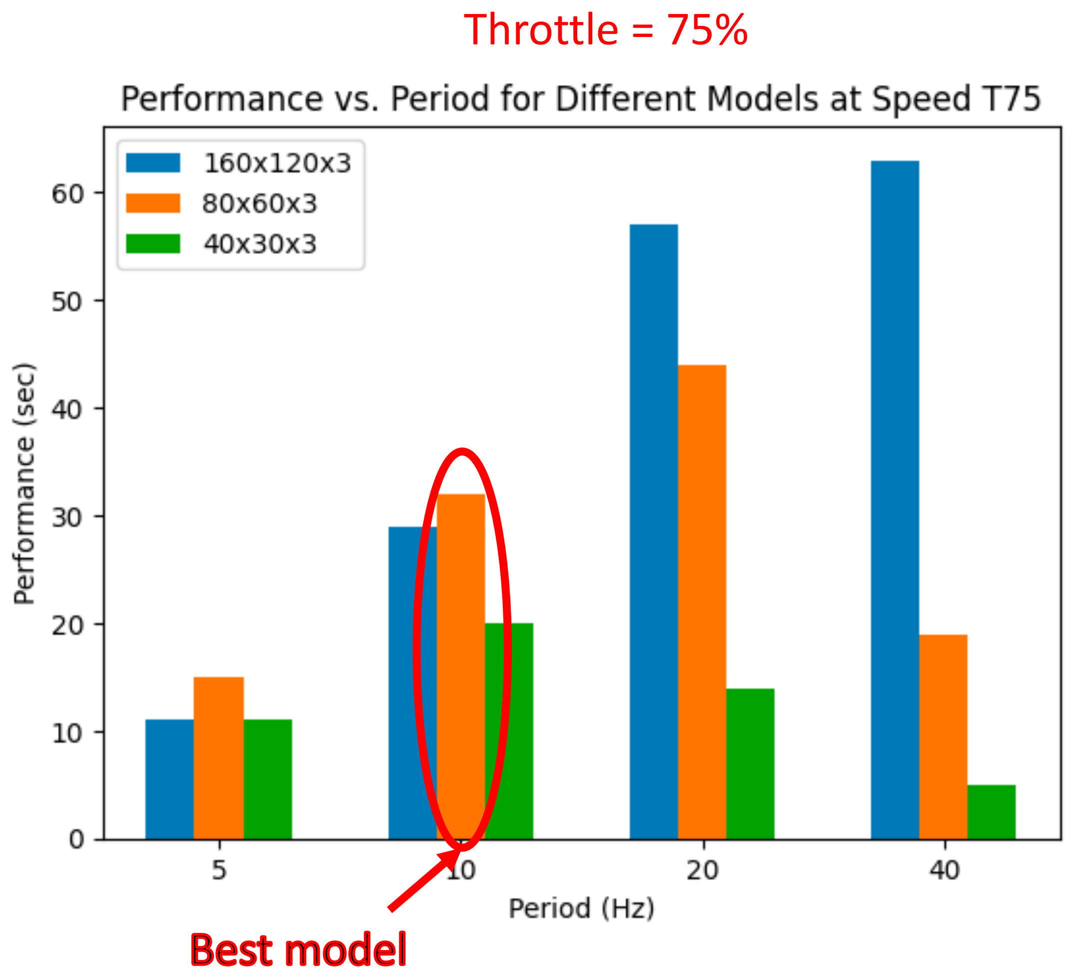
Accuracy, Latency, and Performance



- Bigger model performs better (drive longer w/o crash)
- Lower latency (higher update rate) improves performance
- Ideally, bigger & faster model performs better
- But, you cannot have both at the same time in practice!

Accuracy, Latency, *Speed* and Performance





Takeaways

- In a modern perception system

  Performance = f (accuracy, latency, environment)

- Anytime perception enables runtime adaptation to maximize performance on limited on-board embedded computing resources

- Co-designing anytime perception and control can further improve intelligence and safety of urban mobility vehicles

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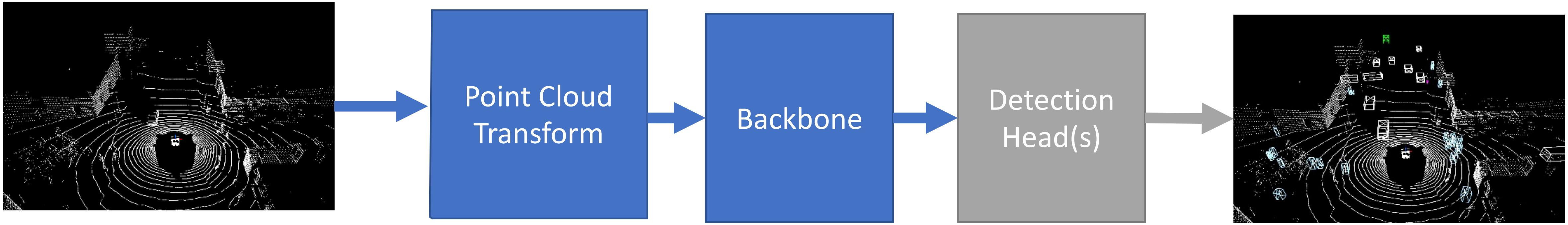
Anytime Perception

- Target applications
  - Sense and avoid (bird, other UAM/UAS, buildings, trees, etc.)
  - Agile navigation/planning
  - Autonomous takeoff/landing
- Target sensor types
  - Camera, lidar
- Target perception tasks
  - Object detection/classification
  - Odometry/SLAM

Lidar-based 3D Object Detection

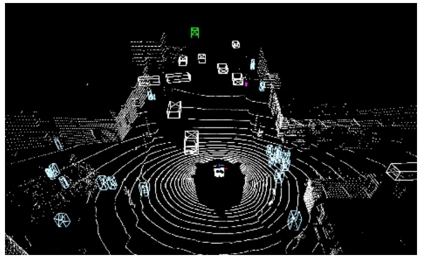
- Point cloud to 3D bounding boxes and classifications
  - Examples: Voxelnet, SECOND, PointPillars, CenterPoint
- High computational cost, **deadline-unaware**

250 ~ 330 ms

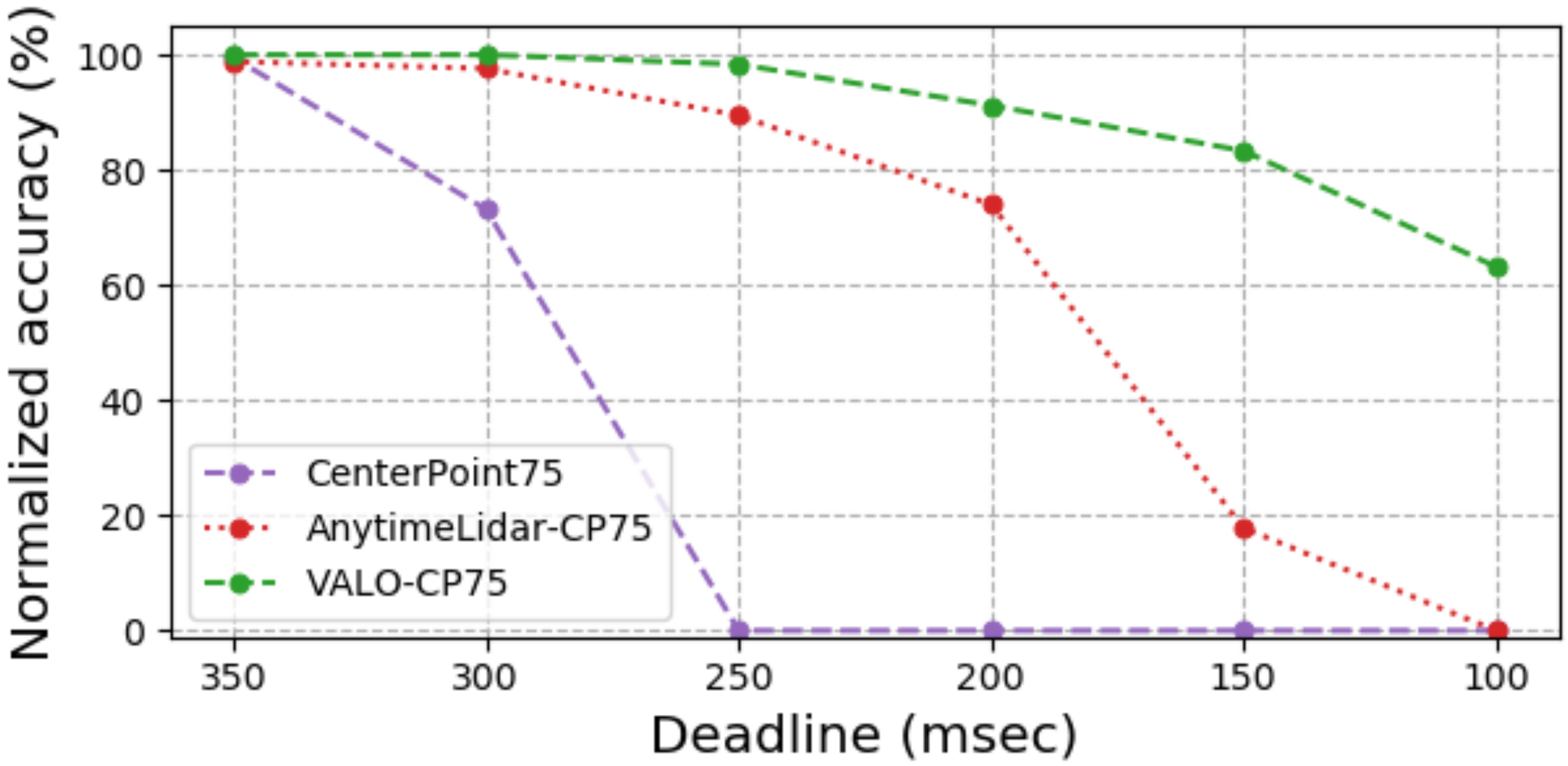


NVIDIA Jetson AGX Xavier
512 core GPU, 8-core CPU, 16G RAM

Anytime 3D Object Detection



- maximize detection accuracy for a given (arbitrary) computing budget



CenterPoint:
SOTA 3D object detector

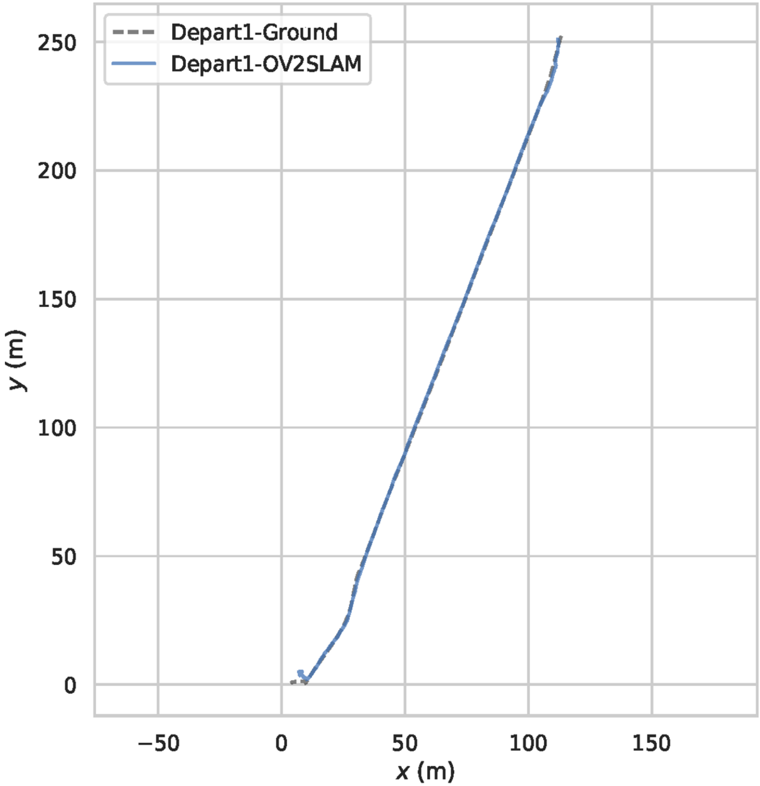
Anytime-Lidar:
our prior work

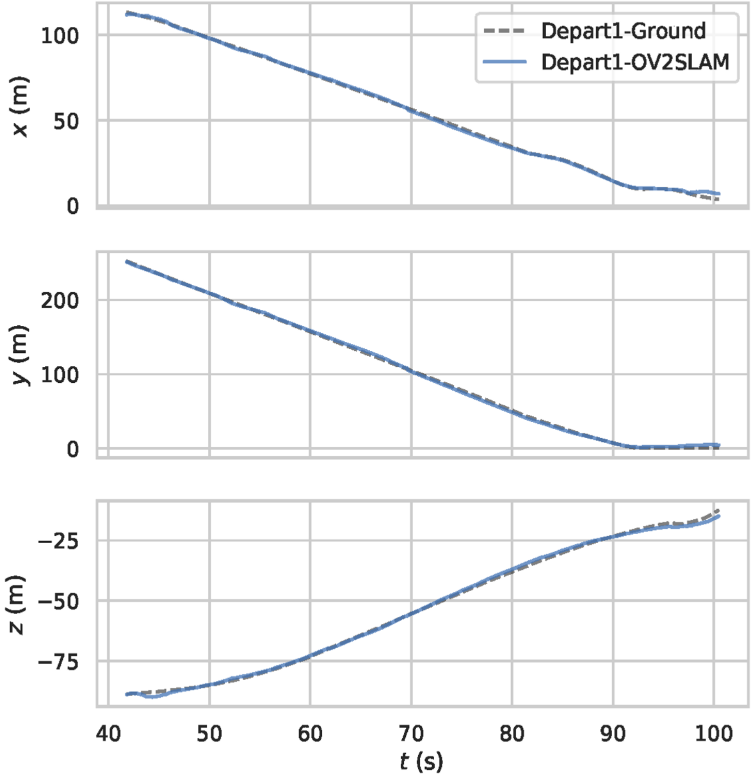
VALO:
our approach

Ahmet Soyyigit, Shuochao Yao and Heechul Yun. "Anytime-Lidar: Deadline-aware 3D Object Detection." *IEEE RTCSA'*2022
Ahmet Soyyigit, Shuochao Yao and Heechul Yun. "VALO: Versatile Anytime Algorithm For Lidar Object Detection." In *submission*

Visual Odometry

- Estimate position and pose from the camera input in real-time



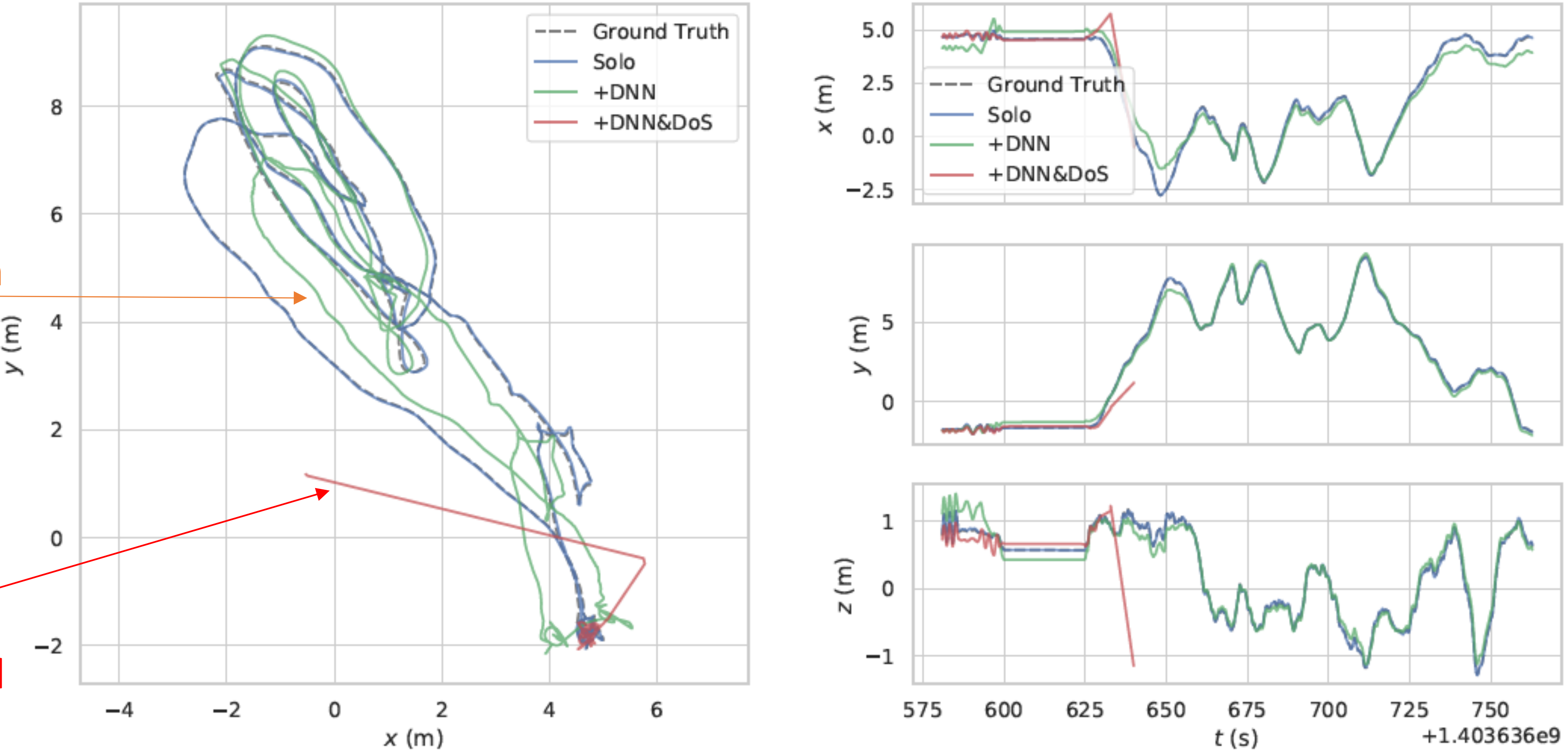


OV^{2}SLAM on NASA Alta8 Dataset

Impact of DNN and DoS attacks on OV^{2}SLAM

Significantly deviated from the true trajectory

Completely failed to generate valid trajectory

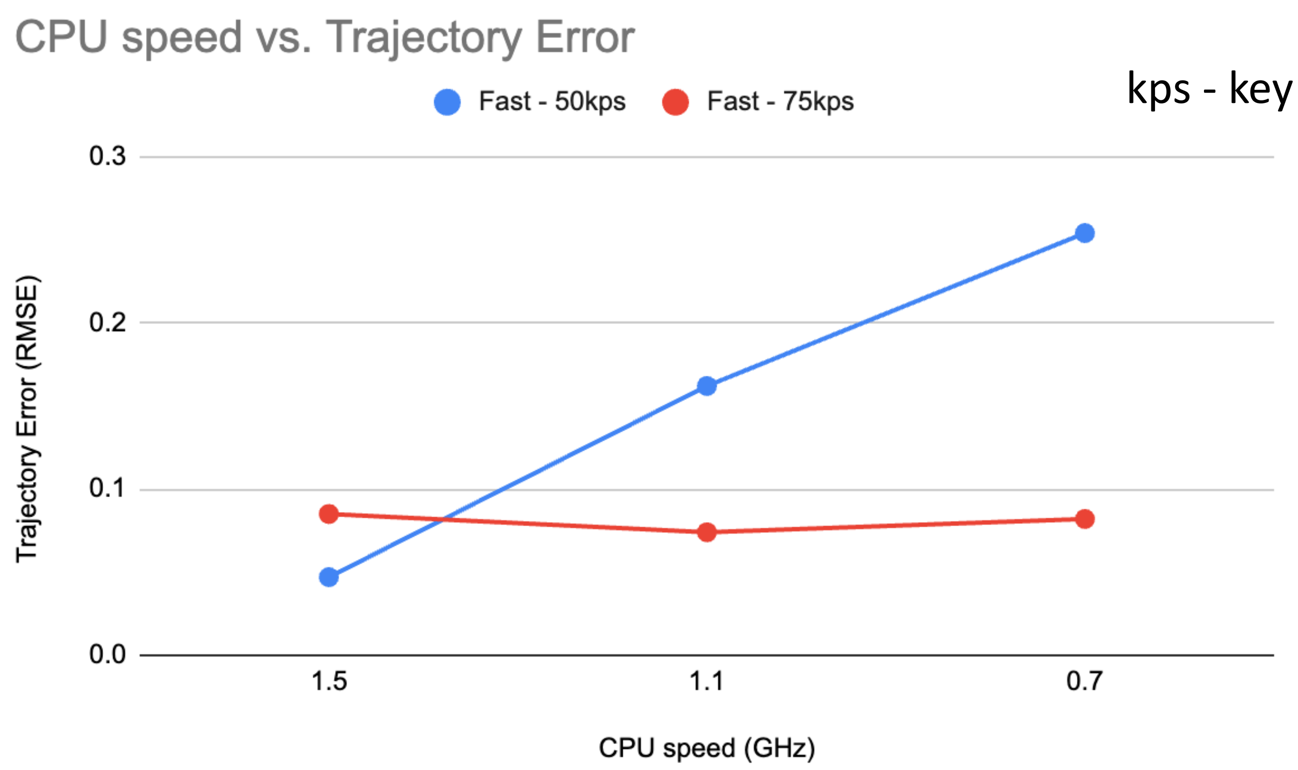


(a) Trajectory in XY plane

(b) X, Y and Z positions over time

Michael Bechtel and Heechul Yun. "Analysis and Mitigation of Shared Resource Contention on Heterogeneous Multicore: An Industrial Case Study." arXiv:2304.13110, 2023

Anytime Visual SLAM

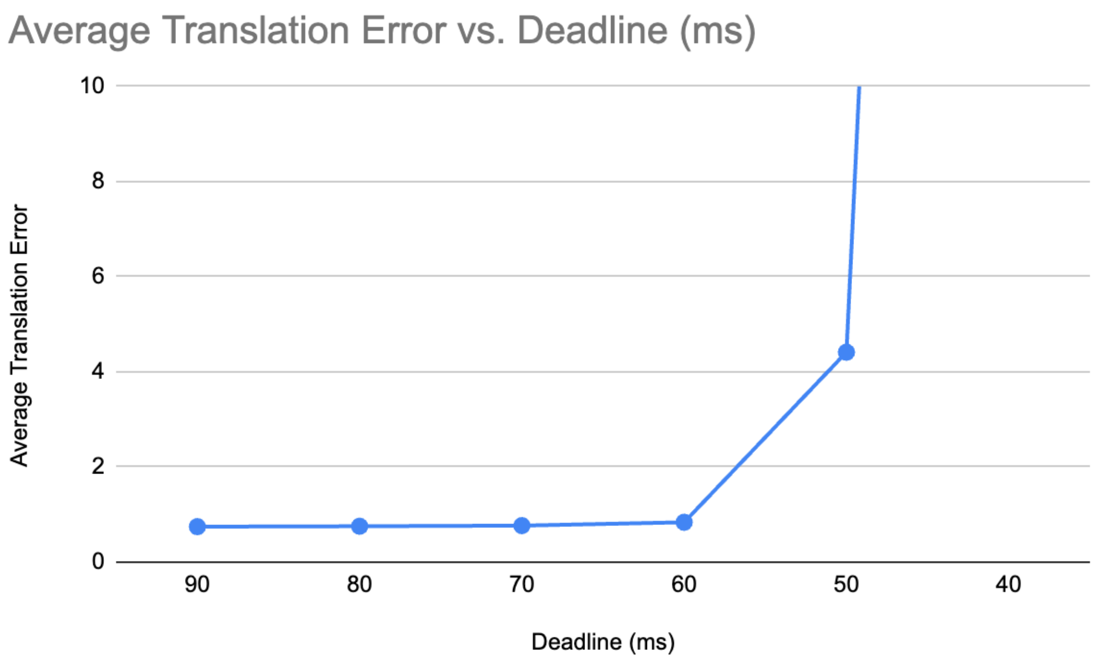


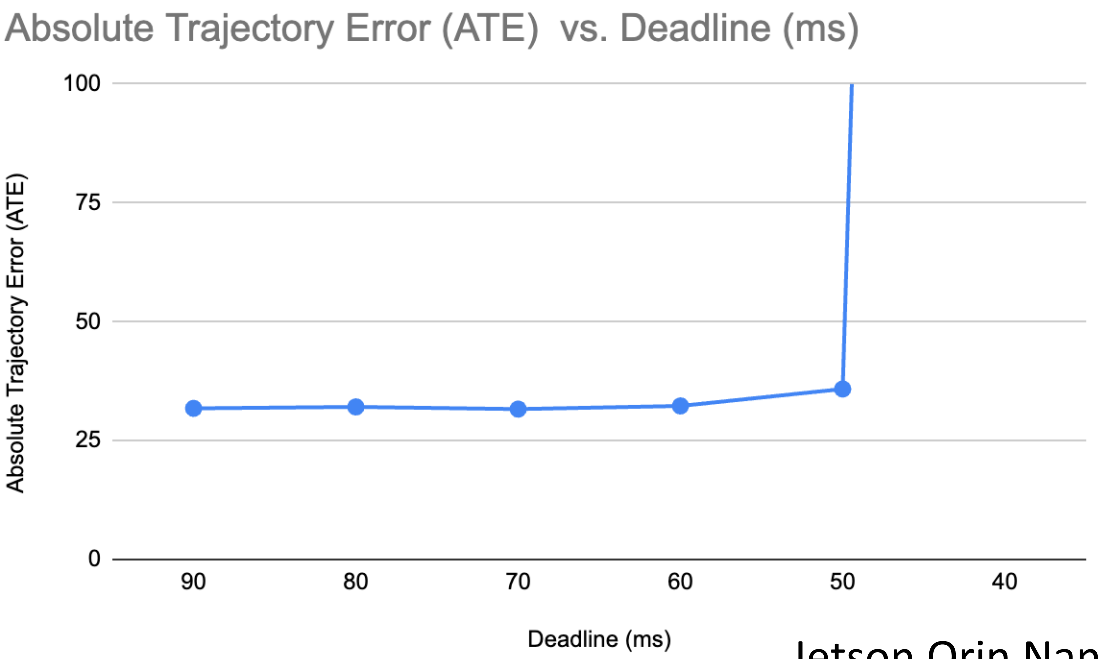
kps - key point cell size

Jetson Nano,
OV2SLAM
EuRoC Dataset

- Depending on available computing speed, the optimal algorithm varies

Anytime Lidar Odometry





Jetson Orin Nano,
KISS-ICP (modified)
KITTI Dataset

- Finishing early (up to a point) did not significantly impact accuracy

Evaluation Methods

- NASA sUAS dataset and others
- AirSim simulator
- Aurelia X4 VTOL testbed

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Conclusion

- UAM requires powerful perception and control for high intelligence and safety

- Sophisticated perception and control algorithms are computationally expensive and require trade-offs in time, accuracy, and performance.

- Anytime perception and control enables runtime adaptation to maximize system performance on limited on-board computing resources

Thank You!

Acknowledgements:

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