F1TENTH Autonomous Racing

Automatic Emergency Braking

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Penn Engineering

F1 TENTH

Safe Autonomy Lab
University of Pennsylvania

Acknowledgements

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We are grateful for learning from each other

Lesson Plan

Part I: Automatic Emergency Braking (AEB) on the road

Part II: Range sensors for autonomous vehicles

Part III: Working with laser scan data

Part IV: Measuring safety

Part V: Lab overview

AEB on the road

Automatic Emergency Braking (AEB)

Stop the vehicle before you collide with an obstacle…

Source: Nissan USA

IEEE Spectrum FOR THE TECHNOLOGY INSIDER

24 DEC 2021

FEATURE | TRANSPORTATION

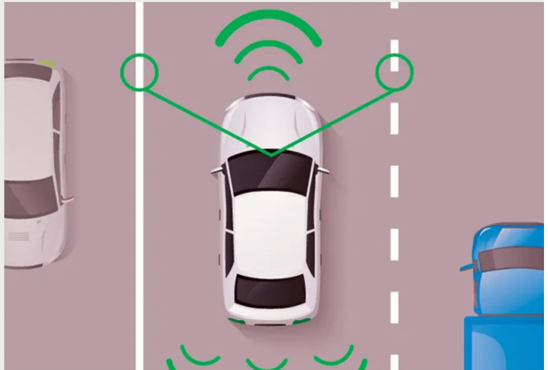
EUROPE MANDATES AUTOMATIC EMERGENCY BRAKING

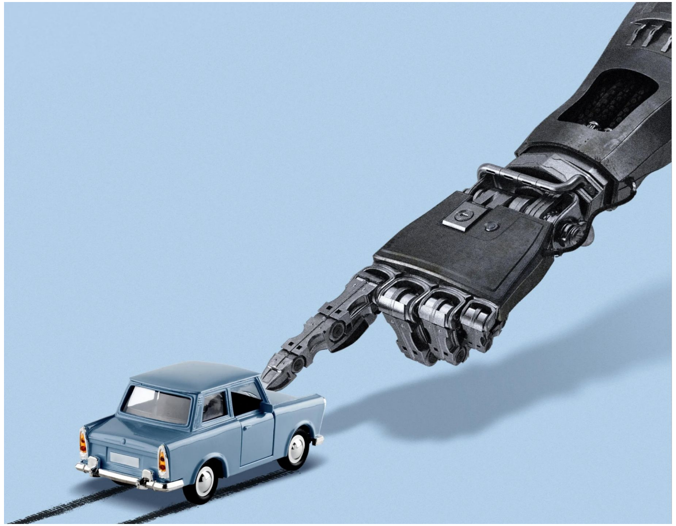
Safety advocates project it could save 4,000 lives per year

NEWS | TRANSPORTATION

Vehicle Safety Ratings Will Soon Include Marks for Crash Avoidance Tech › Starting in 2018, U.S. vehicle safety ratings will account for technologies meant to keep cars from crashing

BY JEREMY HSU | 11 DEC 2015 | 2 MIN READ





crash-avoidance technologies

- forward collision warning
- crash imminent braking
- dynamic brake support
- lane departure warning
- rollover resistance
- blind spot detection.

Safety Lab: AEB on the F1Tenth race car

Problem:
Prevent the car from crashing while trying new algorithms.

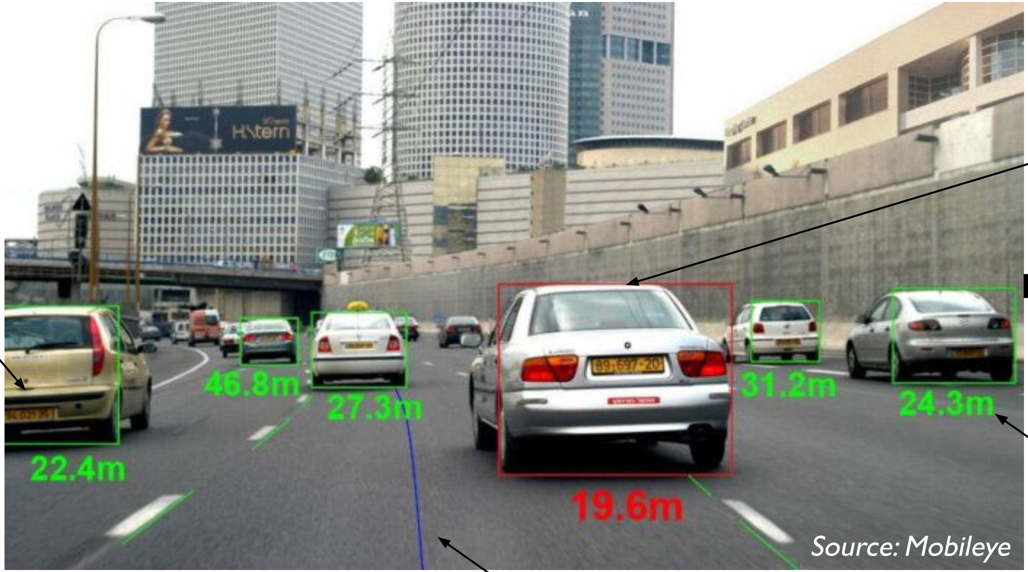
Understand:
Real-life implementations, sensors, failure modes.

Implement: Time-to-collision based braking

AEB in Today's Vehicles

Fuse radar and calibrated vision pipeline (object detection, tracking, visual odometry)…

1. Detect Objects



Source: Mobileye

3. Determine Critical Object

2. Find range, heading and velocity

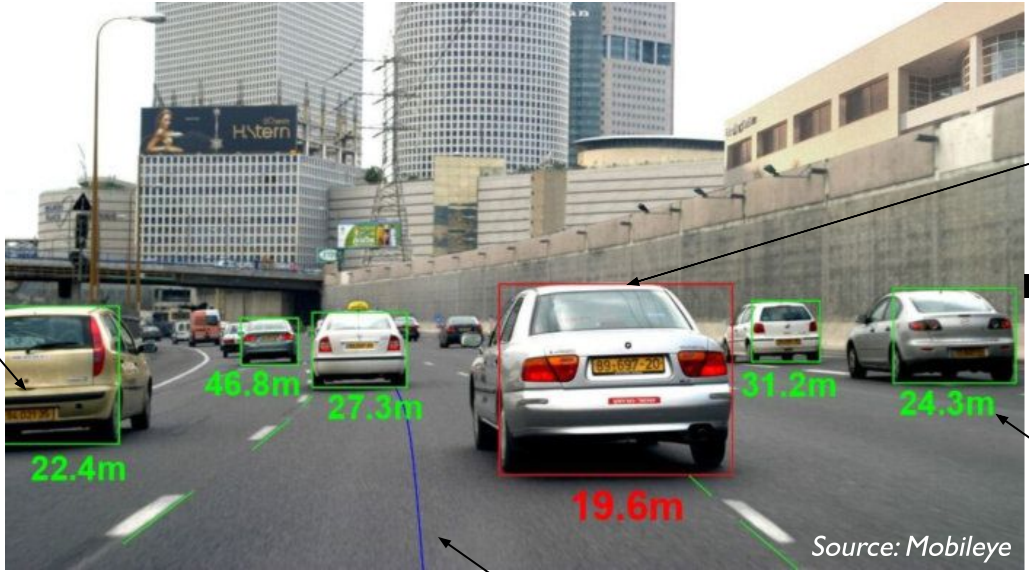
4. Check trajectory for imminent collision

Apply AEB?
T/F

Quiz: AEB in Today's Vehicles

What type of model is this system? Regression? Deep Network? Or something simpler?

1. Detect Objects



3. Determine Critical Object

Apply AEB?
T/F

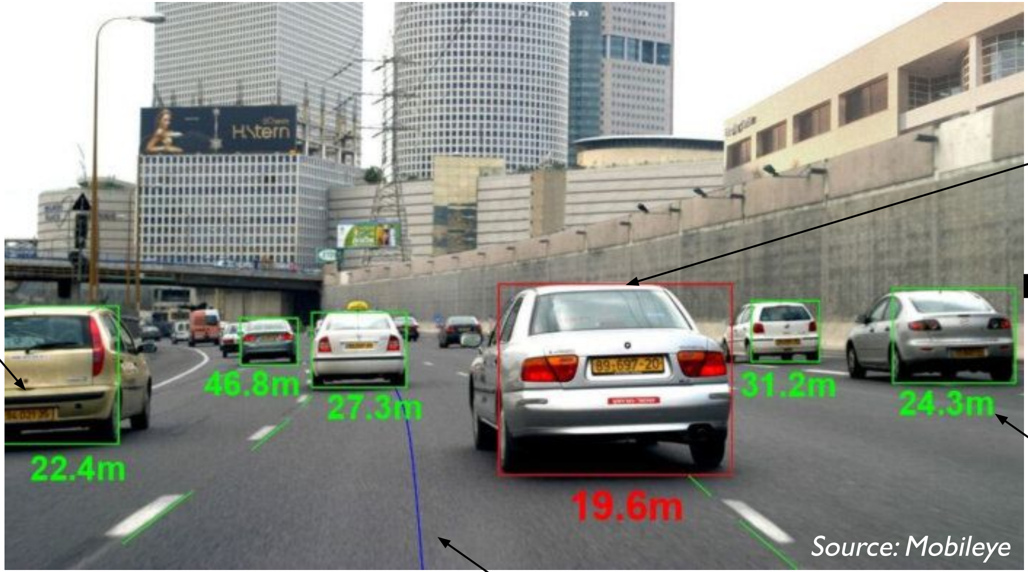
2. Find range, heading and velocity

4. Check trajectory for imminent collision

Answer: AEB in Today's Vehicles

What type of model is this? ***Binary Classifier.***

1. Detect Objects



Source: Mobileye

3. Determine Critical Object

Apply AEB?
T/F

2. Find range, heading and velocity

4. Check trajectory prediction for imminent collision

Quiz: Types of Failures

Can you fill in this table?

		Ground Truth	
		True	False
Classifier Output	True		
	False		

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Quiz: Types of Failures

Which one of these is a serious problem?

Ground Truth

Classifier Output

True Positive	False Positive
False Negative	True Negative

Answers: Types of Failures

Quiz: Which one of these is a serious problem?

It's not this...

Ground Truth

Classifier Output		
	True Positive	False Positive
	False Negative	True Negative

Engineering incentives aligned.

But… no one will buy a system with false positives.

Answers: Types of Failures

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Answers: Types of Failures

Quiz: Which one of these is a serious problem?

Ground Truth

Classifier Output

True Positive	False Positive
False Negative	True Negative

False negatives kill innocent people. Regulatory & insurance provide incentives.

Types of Failures: False Negative

Uber autonomous car kills a pedestrian

Viewer discretion is advised

Source: *The Guardian*

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Is this problem solved?

AEB could have stopped the vehicle, but was turned off because the vehicle had frequent false positives.

Source: Unknown

False Positives & False Negatives

You will need to tune this for lab

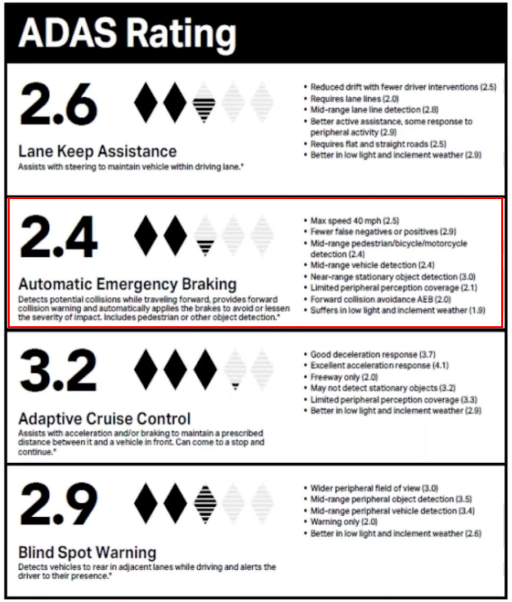
Ground Truth

Classifier Output

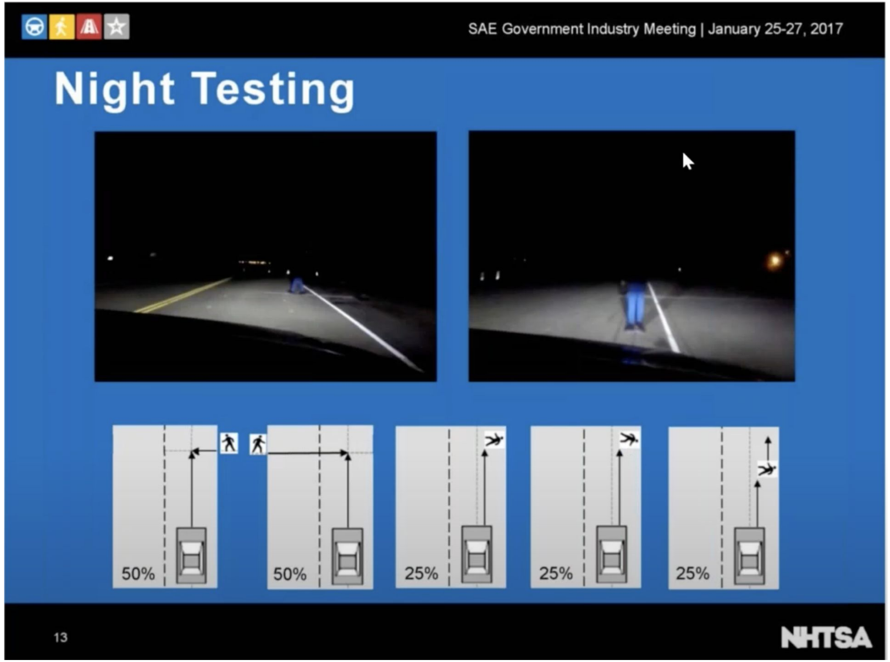
HIGH True Positive	NO False Positive
LOW False Negative	HIGH True Negative

Addressing AEB false negatives in the Automotive Industry

Vehicle System Performance Criteria	◆	◆◆	◆◆◆	◆◆◆◆	◆◆◆◆◆
Max Speed	10 mph	30 mph	50 mph	65 mph	75 mph
Detection Reliability	Frequent false negatives or positives	Fewer false negatives or positives	Occasional false negatives or positives	Extremely rare false positives or negatives	Extremely rare false positives or negatives
Pedestrian, Bicycle, Motorcycle Detection and Classification Range	Near range detection, no classification	Mid-range detection	Mid-range detection and classification	Mid-range detection and classification	Far-range detection and classification
Vehicle Detection and Classification Range	Near range detection, no classification	Mid-range detection	Mid-range detection and classification	Far-range detection and classification	Far-range detection and classification
Stationary Object Detection and Classification Range	May not detect	May not detect	Near range detection	Mid-range detection and classification	Far-range detection and classification
Peripheral Object Detection and Classification Coverage	No perception coverage	Limited perception coverage	Limited perception coverage	Improved perception coverage	Excellent perception coverage
Dynamic Driving Intervention Capability	AEB for crash mitigation	Forward collision avoidance AEB	Forward collision avoidance with steer and brake control	Forward and side collision avoidance with steer and brake control	Forward and side collision avoidance with steer and brake control
Light and Weather Performance	Suffers in low light and inclement weather	Better in low light and inclement weather	Better in low light and inclement weather	Performs well in all light and most weather	Performs well in all light and most weather



Example car sales labels



Test Results S4

25%

Scenario	Pedestrian Speed (km/h)	Pedestrian Size	Pedestrian Type	Light	Vehicle Speed (km/h)	SV Headlight State	No Impact Tests / Test Conducted		
							Vehicle 1	Vehicle 2	Vehicle 3
S4	0.0	Adult	4a Posable	Day	16	-	5/7 (0.8)	7/7	7/7
				Night	16	Lower	2/7 (3.6)	0/3 (0.5)	7/7
						Upper	?	7/7	-
				Day	40	-	6/7 (15.9)	6/6	4/7 (12.6)
				Night	40	Lower	4/7 (22)	0/2 (0.8)	0/7
						Upper	?	7/7	0/3 (23.4)

25%

Scenario	Pedestrian Speed (km/h)	Pedestrian Size	Pedestrian Type	Light	Vehicle Speed (km/h)	SV Headlight State	No Impact Tests / Test Conducted		
							Vehicle 1	Vehicle 2	Vehicle 3
S4	0.0	Adult	4a Posable	Day	16	-	5/7 (7.7)	7/7	7/7
				Night	16	Lower	0/7 (1.6)	0/5 (0.4)	7/7
						Upper	3/7 (3.5)	7/7	-
				Day	40	-	5/7 (34.1)	7/7	7/7
				Night	40	Lower	3/6 (19)	0/2 (1.2)	7/7
						Upper	?	7/7	-

25%

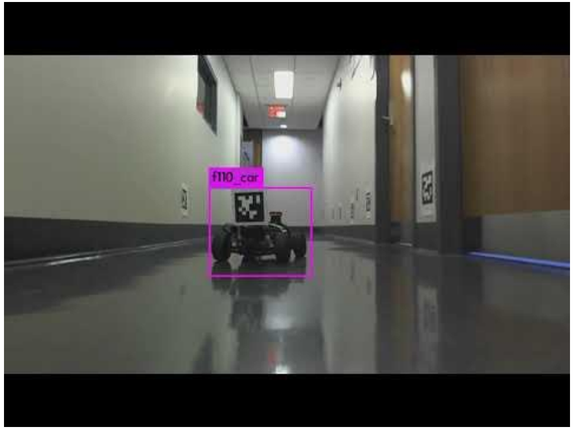
Scenario	Pedestrian Speed (km/h)	Pedestrian Size	Pedestrian Type	Light	Vehicle Speed (km/h)	SV Headlight State	No Impact Tests / Test Conducted		
							Vehicle 1	Vehicle 2	Vehicle 3
S4	5.0	Adult	4a Posable	Day	40	-	5/7 (21.1)	7/7	4/7 (13.5)
				Night	40	Lower	3/7 (13)	0/2 (1.4)	6/7 (19.8)
					40	Upper	?	7/7	-

Later in the course...

Not just about safety, can lead to better racing:

Lecture 21 & 22: *Vehicle detection & tracking*

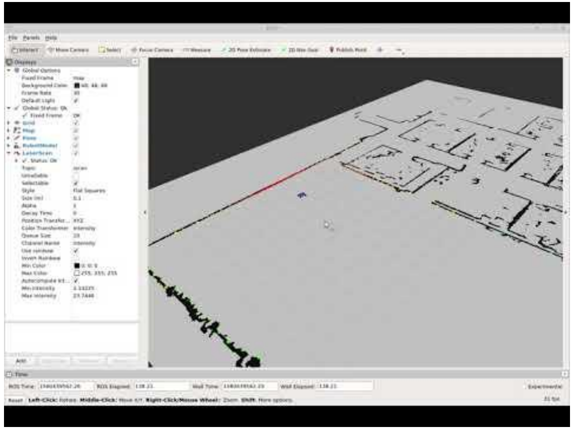
- Similar to commercial AVs, but for overtaking rather than braking.



Consider implementing AEB based on CV Pipeline. Details in Lecture 21 & 22.

Lecture 23 & 24: *Reinforcement learning*

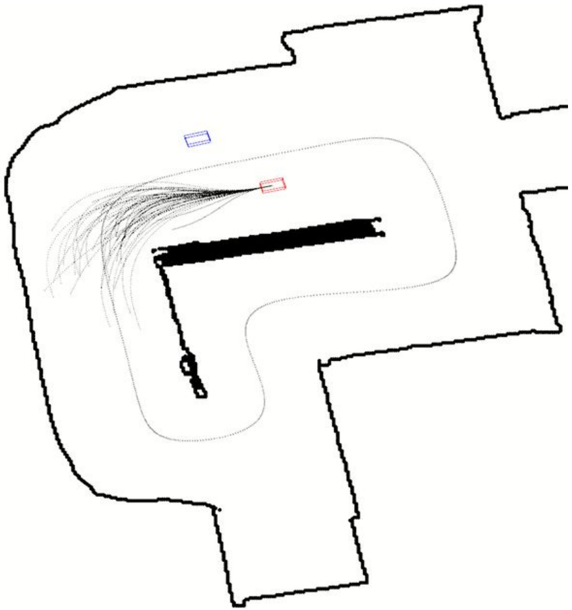
- Safely explore end-to-end driving policies.



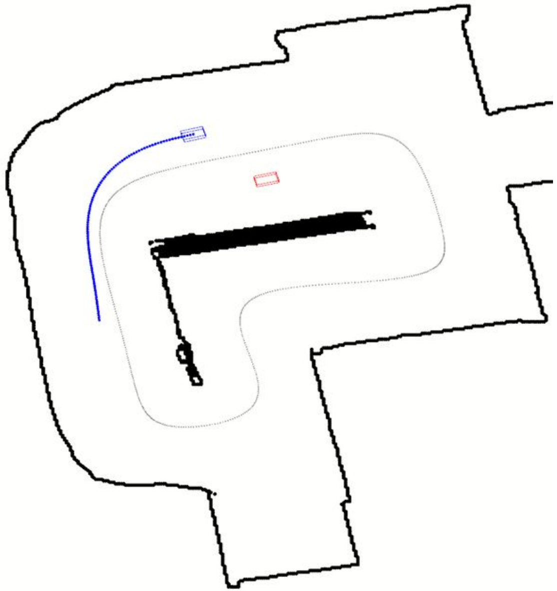
Use concepts presented in this lecture as a signal to switch to a safer policy. Lecture 23 & 24.

Later in the course

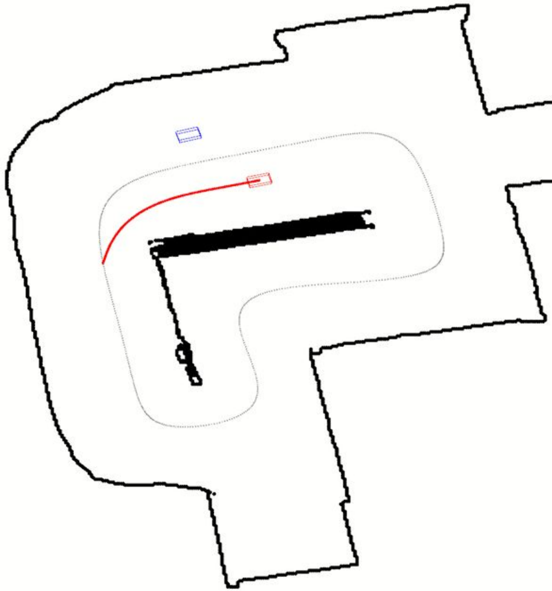
Detect opponent and generate candidate goals



Predict Opponent Behavior



Choose the “best” trajectory



Later in the course...

Range sensors for AVs

Range Sensor Overview

Structured Light

Stereo Camera

Monocular Camera

Radar

Ultrasonic

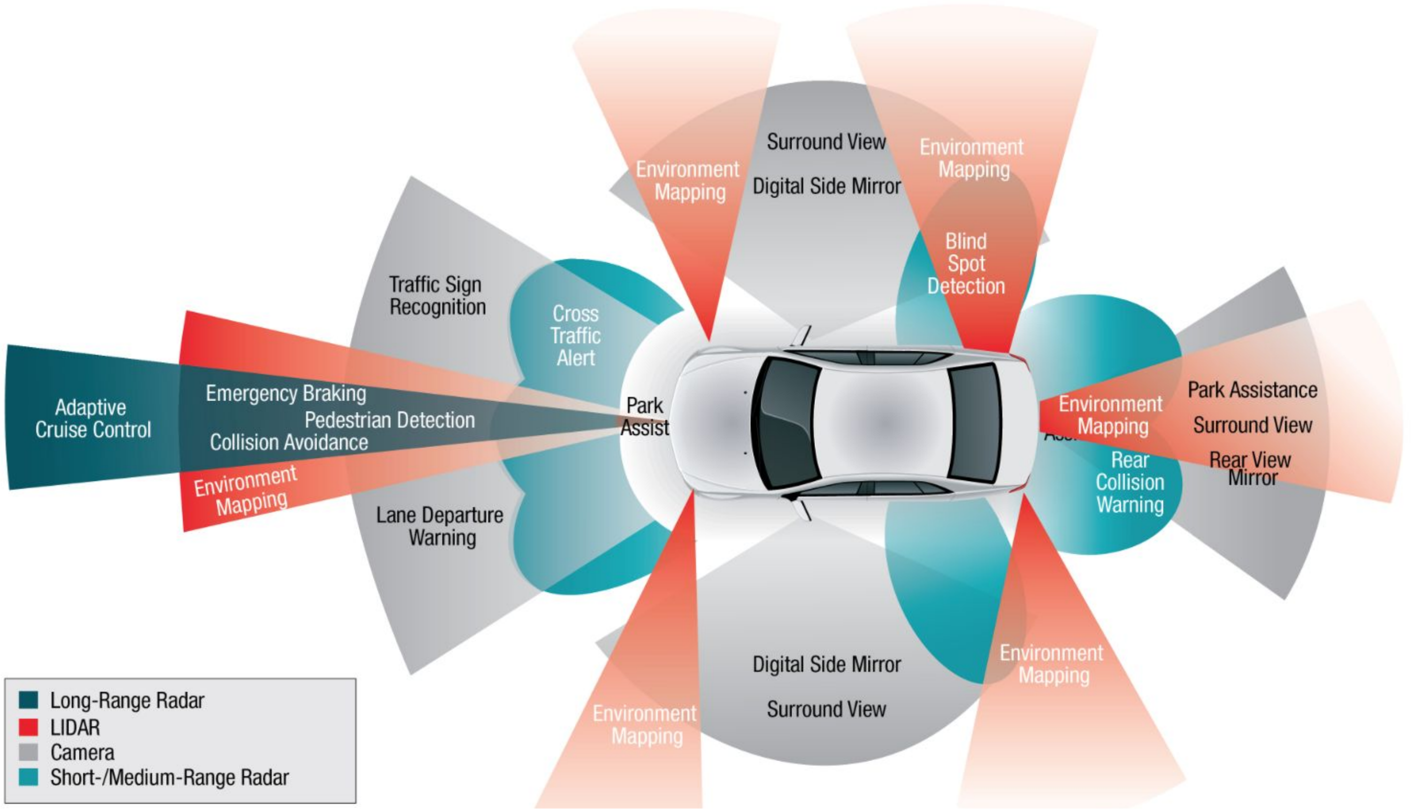
Planar LIDAR

3D LIDAR

Solid State LIDAR

Source: Intel realsense, Zed, Pointgrey, Continental, Hukoyu, Velodyne and Vex

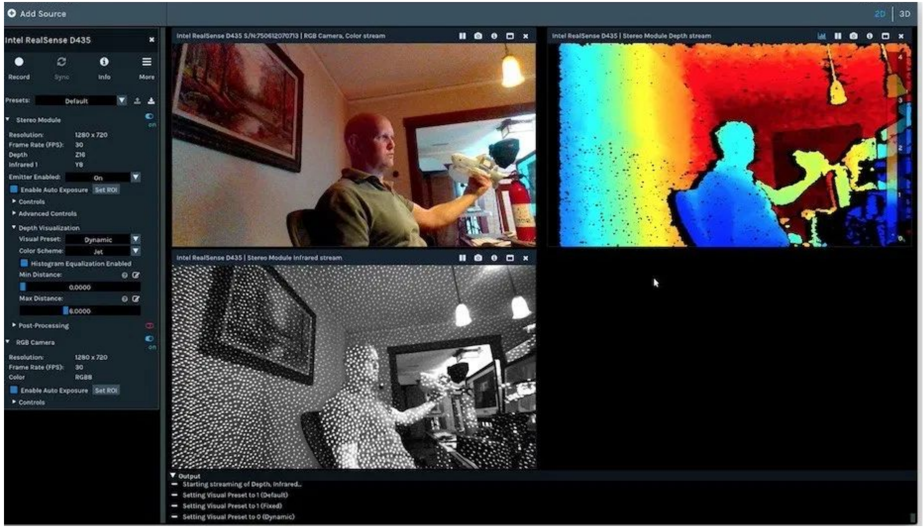
Range Sensor Suite on a Typical AV



Source: Vivota.com

RGB-D Camera

Demo Hardware: Intel Realsense D435i

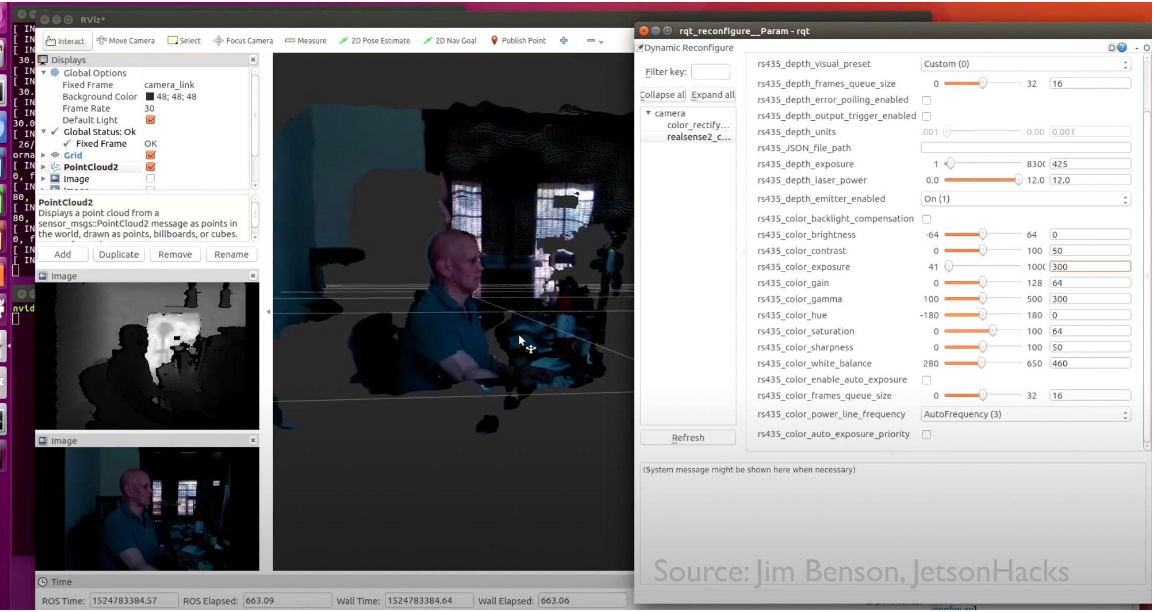


Working Principle: Active Infrared Stereo

Advantages: 3D point cloud - great for visuals SLAM, IR Stereo works in any environment, Mature SDK, widely used, calibrated IMU

Disadvantages: Limited range, can be noisy, lighting conditions affect performance, requires building Linux kernel

Realsense RGB-D Camera



About how to use Realsense D435i on F110 cars

Team SAZ

November 29, 2019

1 Keypoints

To use the Realsense D435i camera on F110 cars, we need to:

1. Recompile the Linux kernel
2. Install Realsense 2 SDK
3. Install ROS wrapper for Realsense

2 Details

1. Intel doesn't support realsense on Jetsons so we need patch some video driver in Linux kernel to let the camera function correctly. A guy at JetsonHacks wrote scripts for doing this and it's been tested to work well.

   Follow the scripts from https://github.com/jetsonhacks/buildLibrealsense2TX.

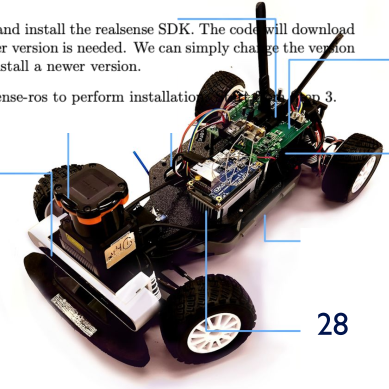
   Run ./buildPatchedKernel.sh to recompile the kernel.

   This script is written for L4T version up to 28.2.1. Make sure the battery is charged and the jetson clocks .sh is used.

2. We can use ./installLibrealsense.sh to download and install the realsense SDK. The code will download SDK version 2.13.0 but for some cameras, a higher version is needed. We can simply change the version number in ./installLibrealsense.sh to 2.30.0 to install a newer version.

3. Follow https://github.com/IntelRealSense/realsense-ros to perform installation step 3.

RBG Depth Camera



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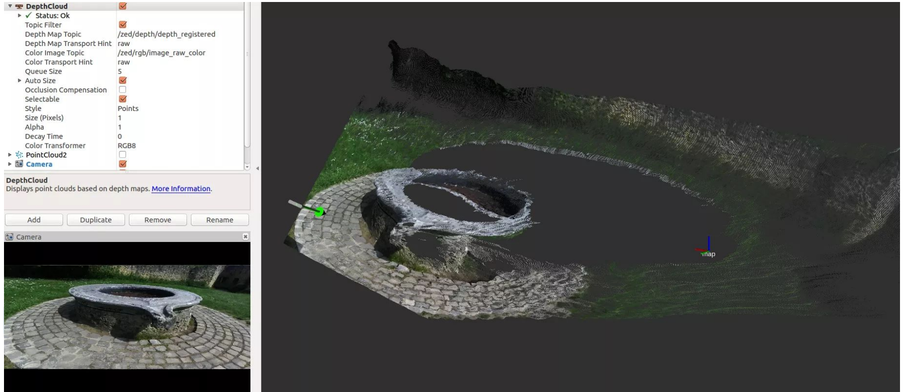
Stereo Camera

Demo Hardware: ZED Camera

Working Principle: Stereo/Multiview Geometry

Advantages: Range, outdoor performance, ‘scalability’, calibrated IMU

Disadvantages: Low texture surfaces, baseline width determines range, processing requirements.



ZED 2 Stereo Camera

Producer: Stereolabs

Type: RGB Stereo

Price: $449

Range: 0.2-20m

Depth Resolutions:

- 672*376@100 FPS
- 1280*720@60 FPS
- 1920*1080@30 FPS
- 2208*1242@15 FPS

Color Resolutions:

- 672*376@100 FPS
- 1280*720@60 FPS
- 1920*1080@30 FPS
- 2208*1242@15 FPS

Observation:

- Needs feature rich environment
- SDK contains some MV services
- Long range

Size: 175*30*33 mm

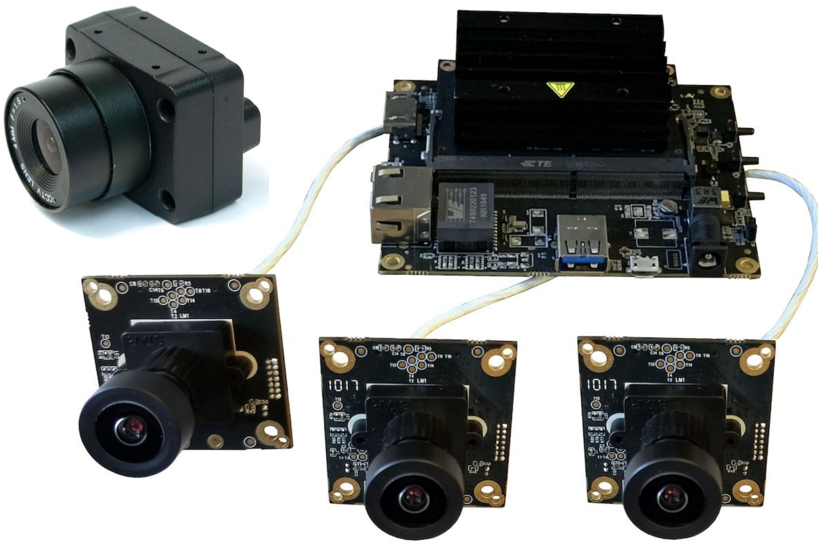
Monocular Depth

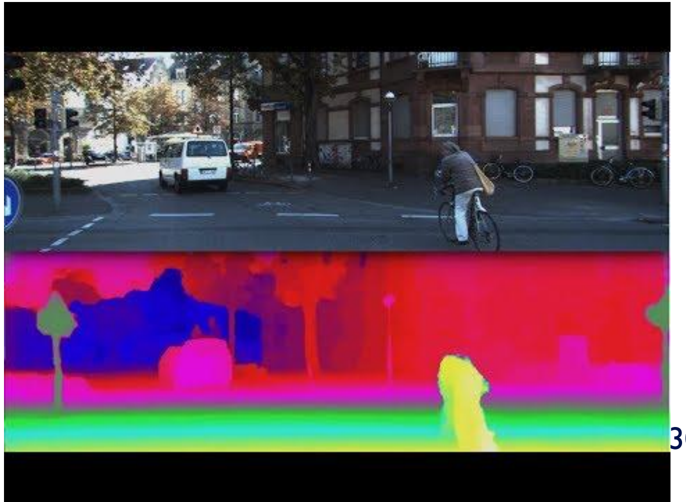
Example Hardware: Logitech Webcam & Monodepth Net

Working Principles: Learn from stereo camera data (unsupervised) to map monocular to depth.

Advantages: No special hardware, orthogonal failure modes to other options

Disadvantages: Relative poor accuracy (good for near vs. far questions).





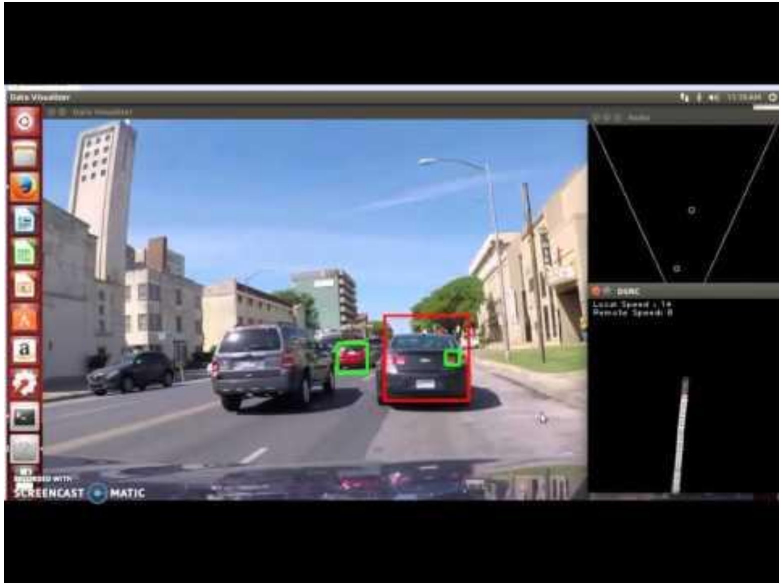
RADAR

Example Hardware: Continental (etc)

Working Principles: Emit RF energy and measure 'echo', can use doppler shift etc to get velocity.

Advantages: Cheap, long range, orthogonal failure modes.

Disadvantages: Poor spatial resolution and field of view, false positives on overhead signs etc.



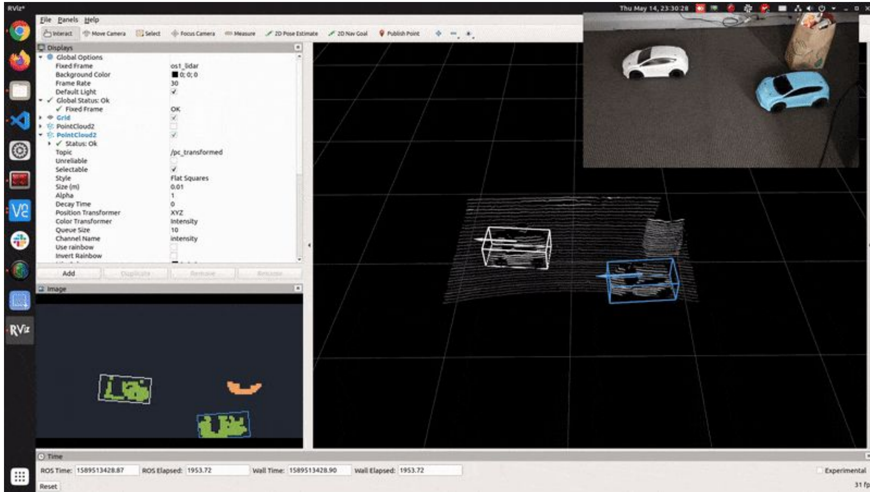
Ultrasonic Proximity Sensor

Example Hardware: VEX IQ Ultrasonic Distance Sensor

Working Principle: Measures time of flight of high-frequency sound waves.

Advantages: Accuracy, cost, size

Disadvantages: Range, resolution, only good enough for parking applications (eg. 5m)



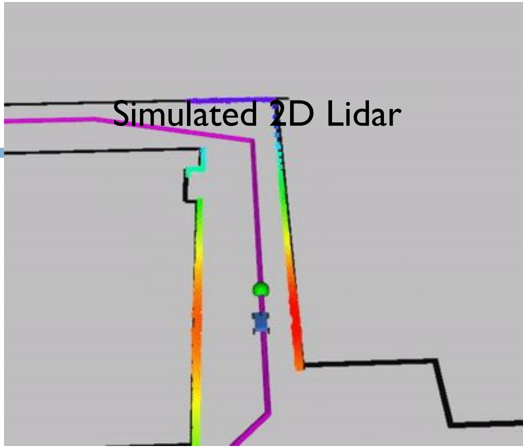
Planar 2D LIDAR

Demo Hardware: Hokuyo 30LX

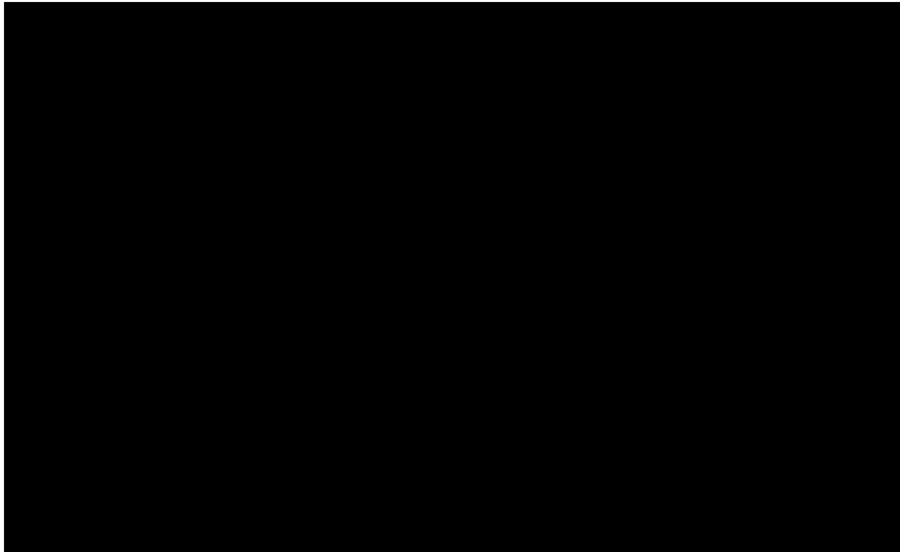
Working Principle: Time-of-flight using laser.

Advantages: Relatively low cost, simple data structure, high update rate, low processing requirements

Disadvantages: Primarily working in flat environments, harder to detect objects etc.



Actual 2D Lidar



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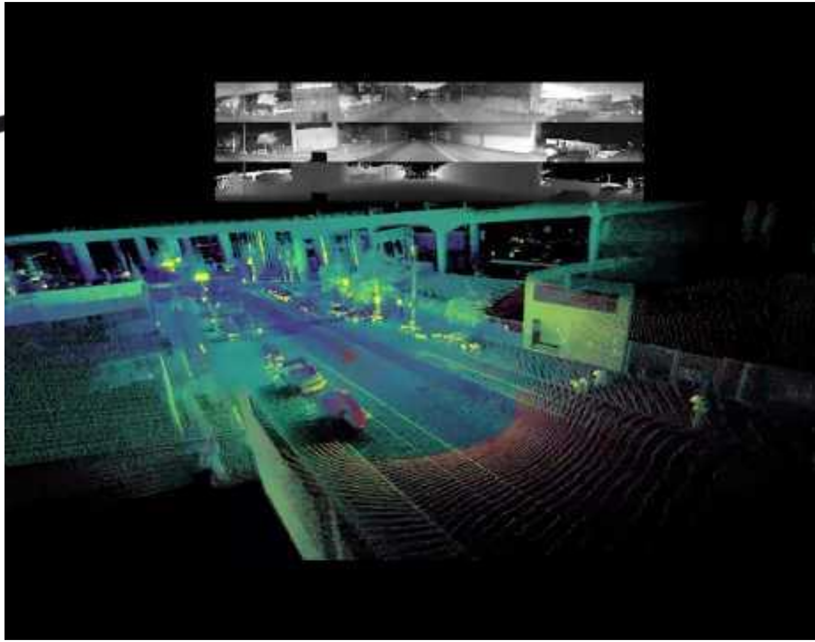
3D LIDAR

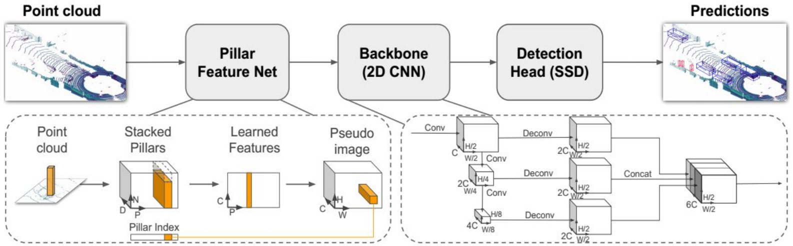
Demo Hardware: Ouster OS-2



Working Principle: Time-of-flight, laser, note different wavelength of this product

Advantages: Full 3d information, can get image like information

Disadvantages: Cost, reliability (mechanical), processing point cloud.



PointPillars: Fast encoders for object detection from point clouds

Solid-State LIDAR

Demo Hardware: Velodyne Velarray

Working Principle: Time-of-flight, steer laser with solid-state components.

Advantages: Compact, no moving parts, range etc

Disadvantages: Field of view, availability, technical feasibility.

Working with Laser Scan Data

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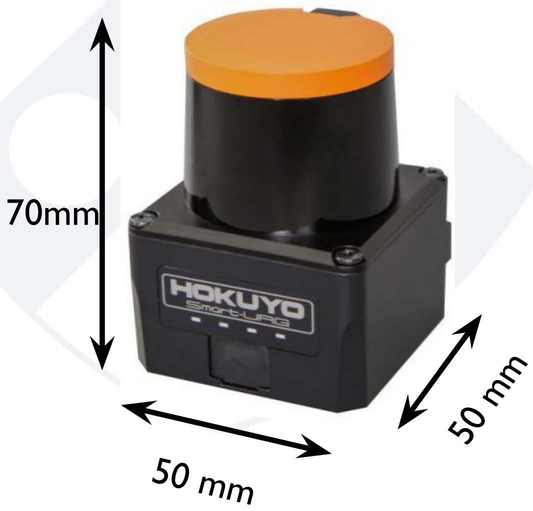
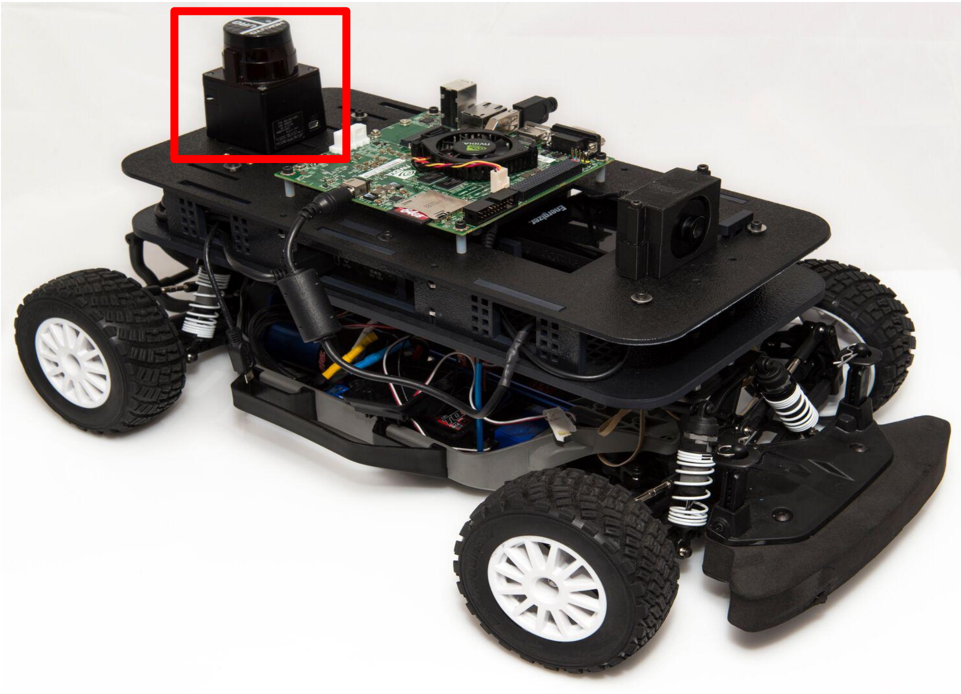
LIDAR on F1Tenth

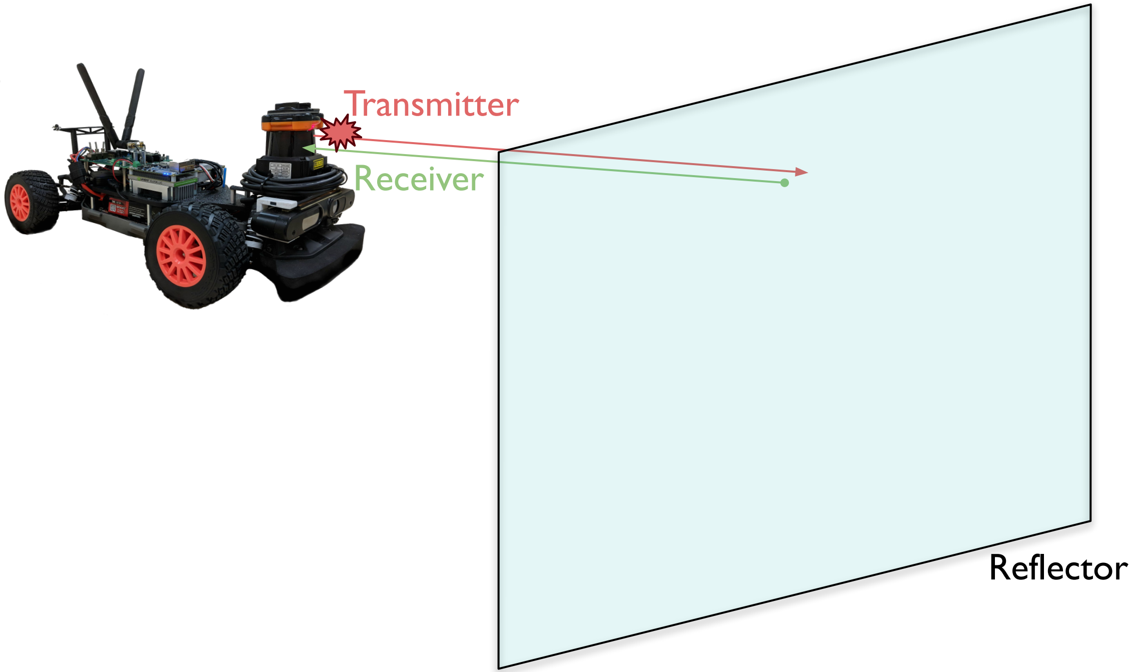




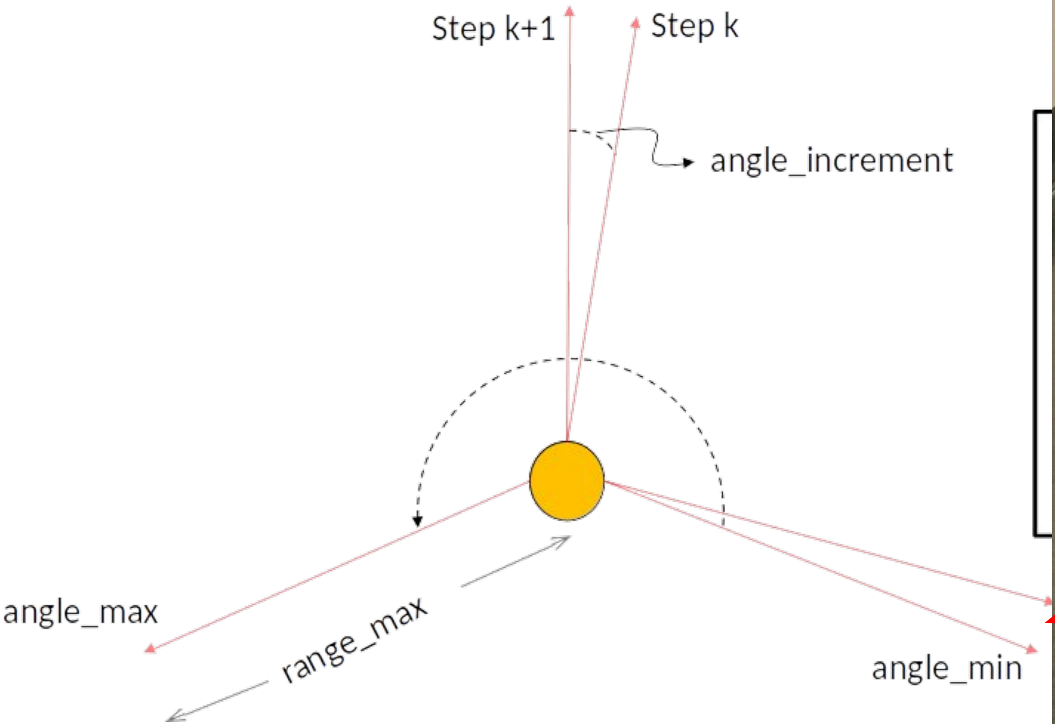
Planar LIDAR

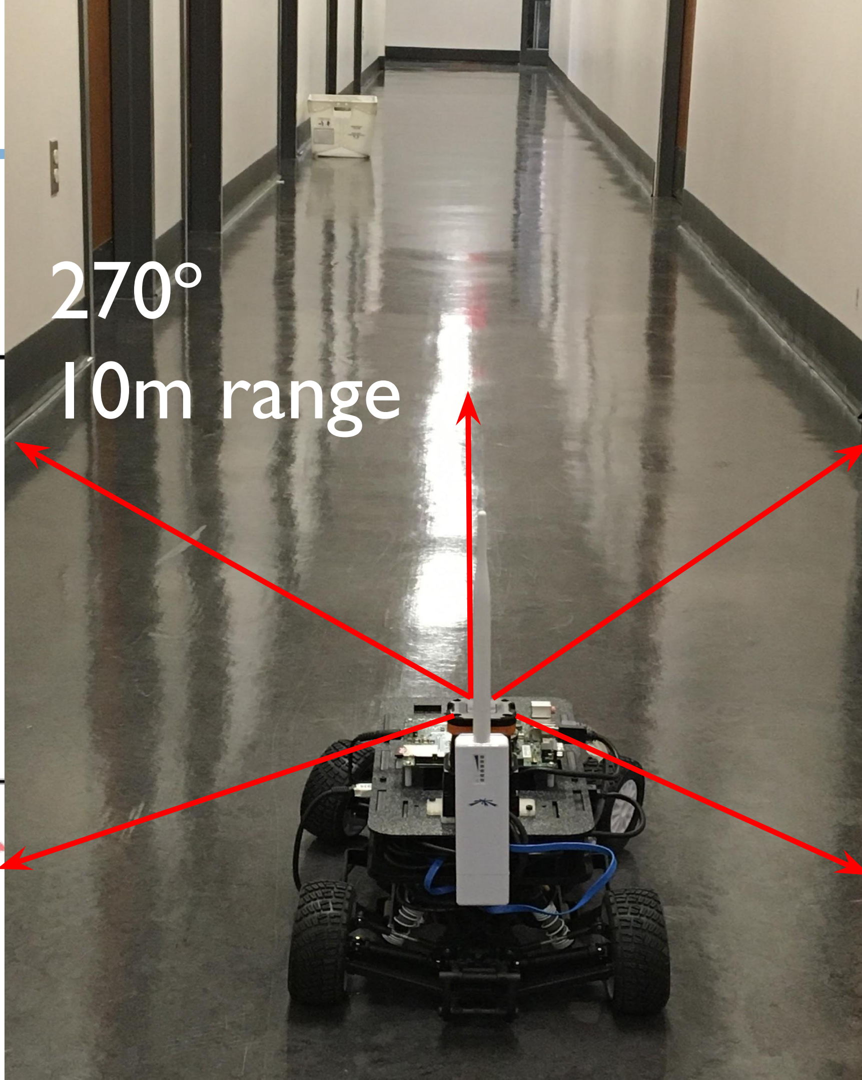
Distance to obstacle = (speed of light * time traveled)/2

- Maximum range is constrained by laser energy
  - Need a large Signal-to-Noise ratio
- Energy of reflected ray depends upon:
  - Divergence of laser
  - Bouncing reflections
  - Humidity
  - Reflectivity of target
  - Detector sensitivity



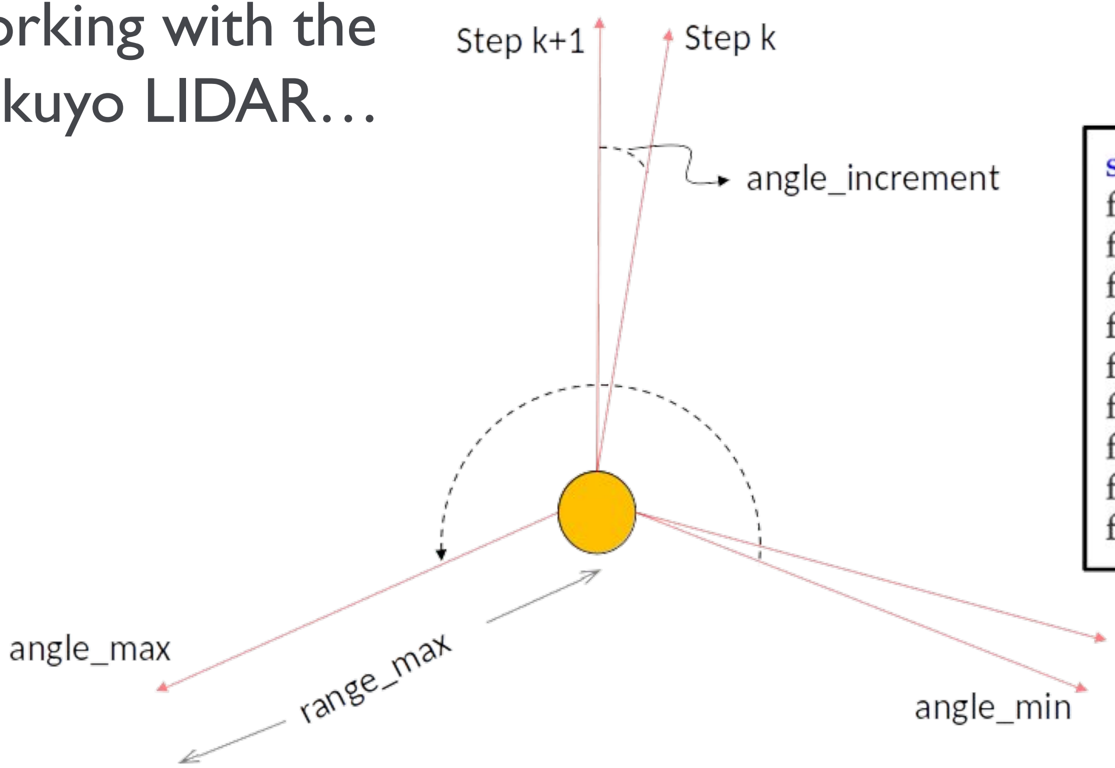
Planar LIDAR





Planar LIDAR

Working with the Hokuyo LIDAR…




```
std_msgs/Header header
float32 angle_min
float32 angle_max
float32 angle_increment
float32 time_increment
float32 scan_time
float32 range_min
float32 range_max
float32[] ranges
float32[] intensities
```

LIDAR: ROS message structure

```
# Single scan from a planar laser range-finder

Header header                  # timestamp in the header is the acquisition time of
                               # the first ray in the scan.

float32 angle_min              # start angle of the scan [rad]
float32 angle_max              # end angle of the scan [rad]
float32 angle_increment        # angular distance between measurements [rad]

float32 time_increment         # time between measurements [seconds]
float32 scan_time              # time between scans [seconds]

float32 range_min              # minimum range value [m]
float32 range_max              # maximum range value [m]

float32[] ranges               # range data [m]
                               (Note: values < range_min or > range_max should be discarded)
float32[] intensities          # intensity data [device-specific units].
```

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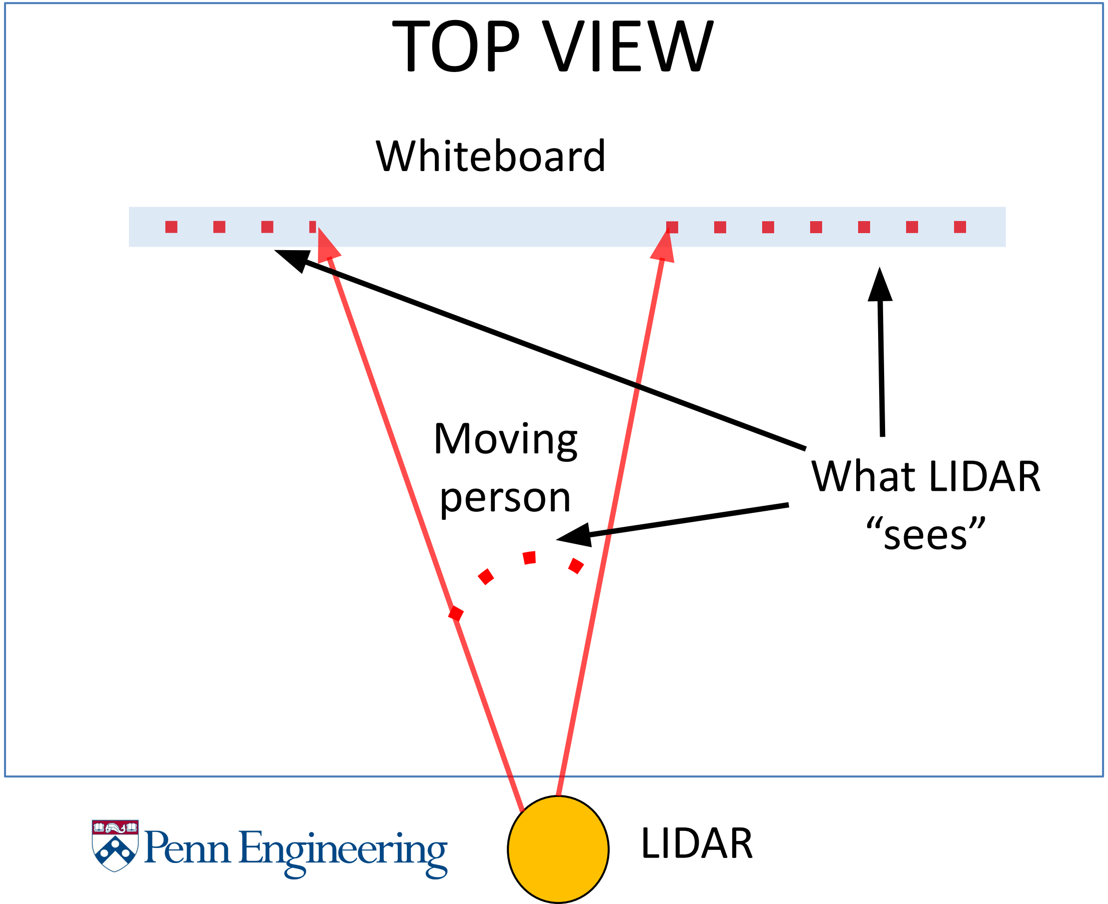
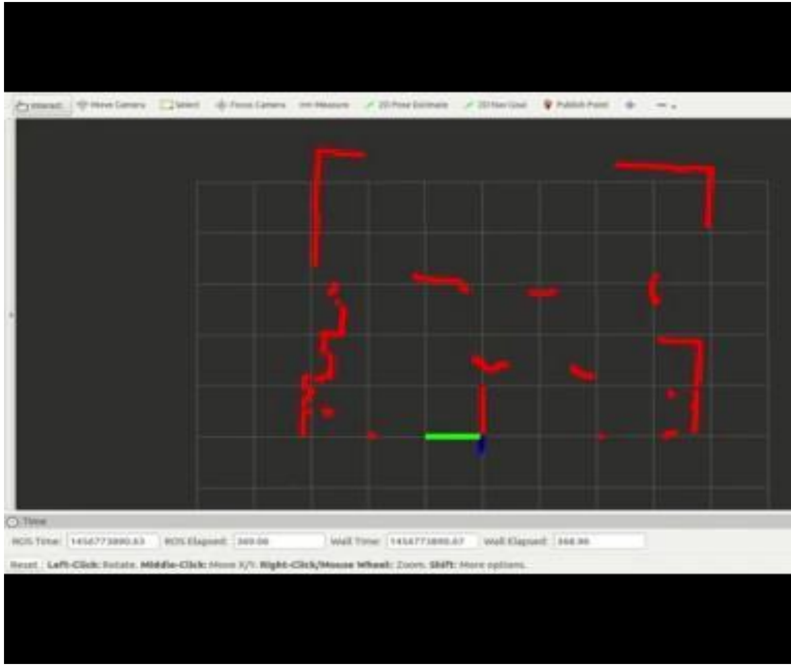
A simple scan sequence





LIDAR: range data

Array A[1080]: A[i] is distance measurement of i^{th} step.

Measurements beyond the min and max range (like inf) *should be discarded.*

```
 inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf,
 inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf,
 inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf,
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0679016, inf, inf, inf, inf, inf, inf, inf, inf, inf, inf, nan, inf, inf, nan, i
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nf, nan, nan, nan, nan, nan, nan, inf, inf]
intensities: []
---
```
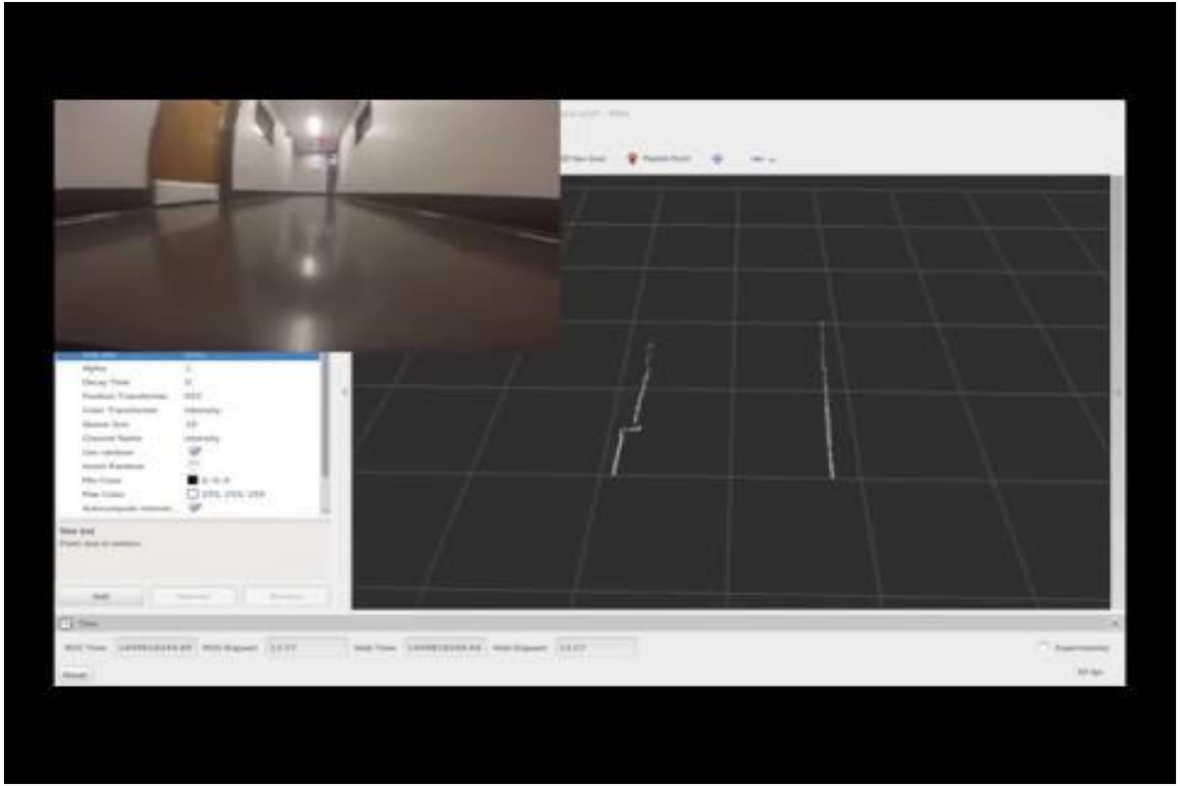

LIDAR scan in hallway



Measuring Safety

Safety as an Indicator Function

Safe

Safe AEB with moving vehicles + successful evasion maneuver

Unsafe

No AEB triggered for stationary object in the driving path

From Binary Safety to Continuous Safety…

Safe

Marginal

Unsafe

Why not Euclidean Distance?

Pros: Easy to compute, have sensors which can measure accurately with well understood uncertainty.

Why not Euclidean Distance?

Cons: Classifies safe things as 'near' unsafe. Slam on the brakes when you are already stopped at T-junction? Tailgater etc…

Time-to-collision

TTC is defined as the time it would take for the ego-vehicle and an object to intercept one another given that they each maintain their current heading and velocity.

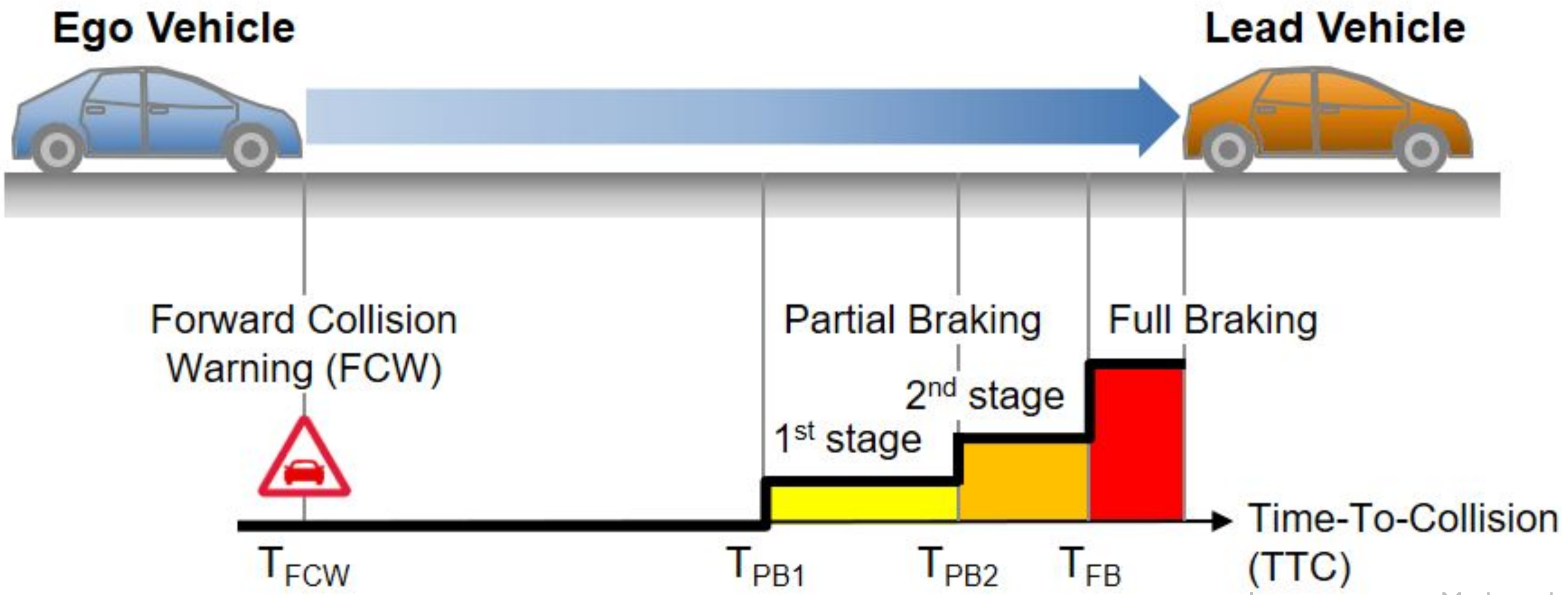


Image courtesy: Mathworks

Time-to-collision

TTC is defined as the time it would take for the ego-vehicle and an object to intercept one another given that they each maintain their current heading and velocity.

Range between vehicle and object

Note: $TTC_i(t) = \infty$
for $\dot{r}_i(t) \geq 0$

$$TTC_i(t) = \frac{r_i(t)}{[-\dot{r}_i(t)]_+}$$

Operator defined as:
$[x]_+ := \max(x, 0)$

Time derivative of range between vehicle and object "range-rate"

How to Compute Range-rate

Range-rate is the time derivative of this distance which is simply computed by projecting the relative velocity of vehicle onto the vector between the vehicles and object's poses…

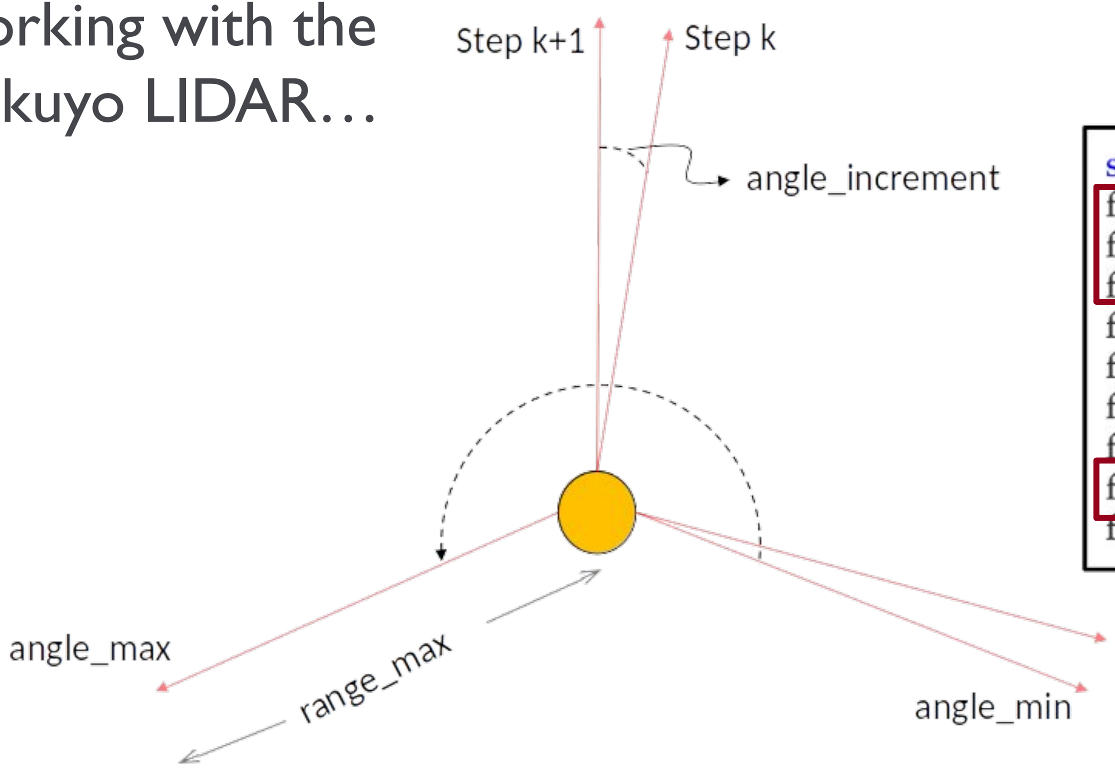
$$\dot{r}_i = v_X \cos(\theta_i)$$

Forward speed in the vehicles reference frame, this is simplified because we are not dealing with moving obstacles

Multiply by the cosine of the beams angle.

Planar LIDAR

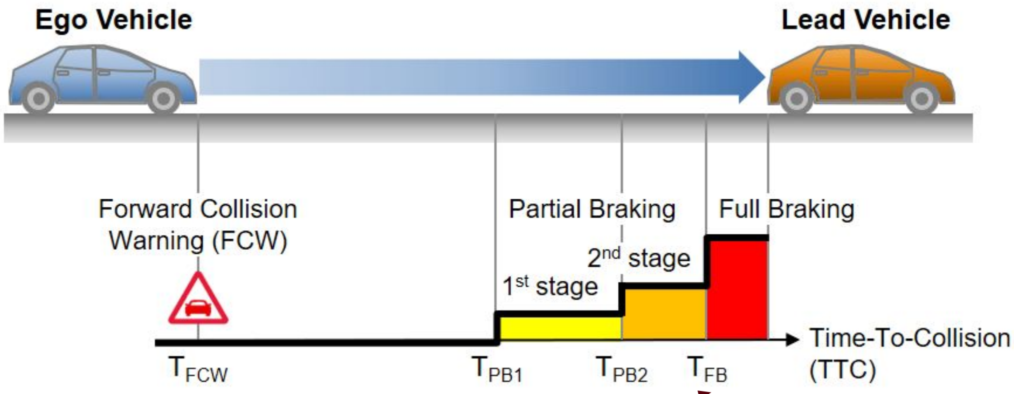
Working with the Hokuyo LIDAR…



std_msgs/Header header
float32 angle_min
float32 angle_max
float32 angle_increment
float32 time_increment
float32 scan_time
float32 range_min
float32 range_max
float32[] ranges
float32[] intensities

How to Compute Range-rate

If T is less than your acceptable threshold, apply the brakes…



$$T \leq \min_i TTC_i$$

Quiz: Sample Interview Question...

Describe a feature which captures the relative pose of all vehicles in the vicinity of the car.

Quiz: Sample Interview Question…

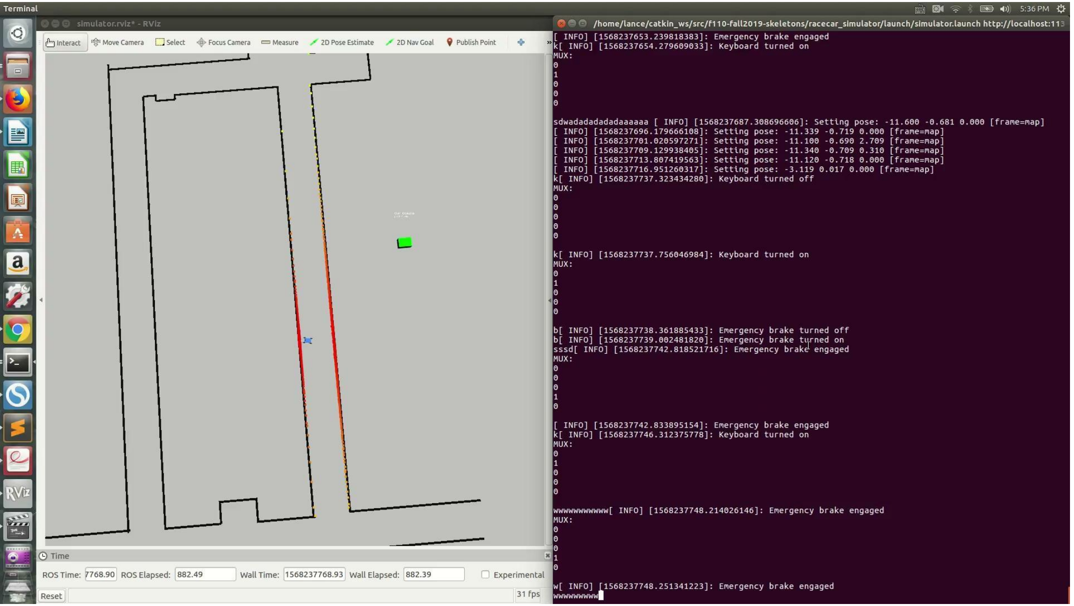
What if you that feature as input to a neural network and the number of vehicles changes, will this be a problem? Why or why not?

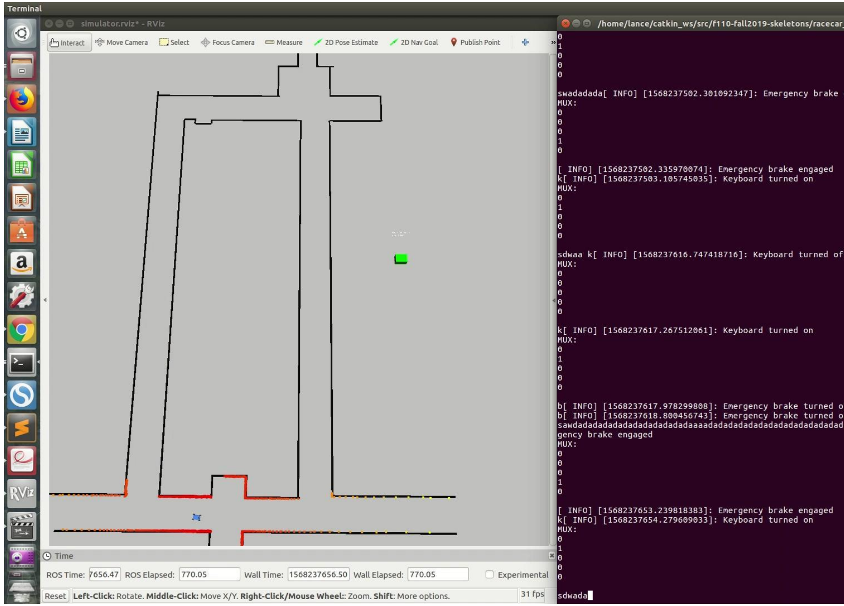
What's Next?

Safety Lab Overview

Implement TTC based safety node in simulator.

Tune implementation to reduce false positives and avoid false negatives





Penn Engineering

Keyboard control - try to crash the car into the wall. AEB should engage

Demonstrate a crash-free lap with AEB activations

Safety Lab Overview

Implement TTC based safety node in simulator.

Tune implementation to reduce false positives and avoid false negatives

Demonstrate it on the F1Tenth race car

Next Lectures

Pose transformations

Map-less autonomous navigation

Build your car!