Autonomous Racing

Rahul Mangharam

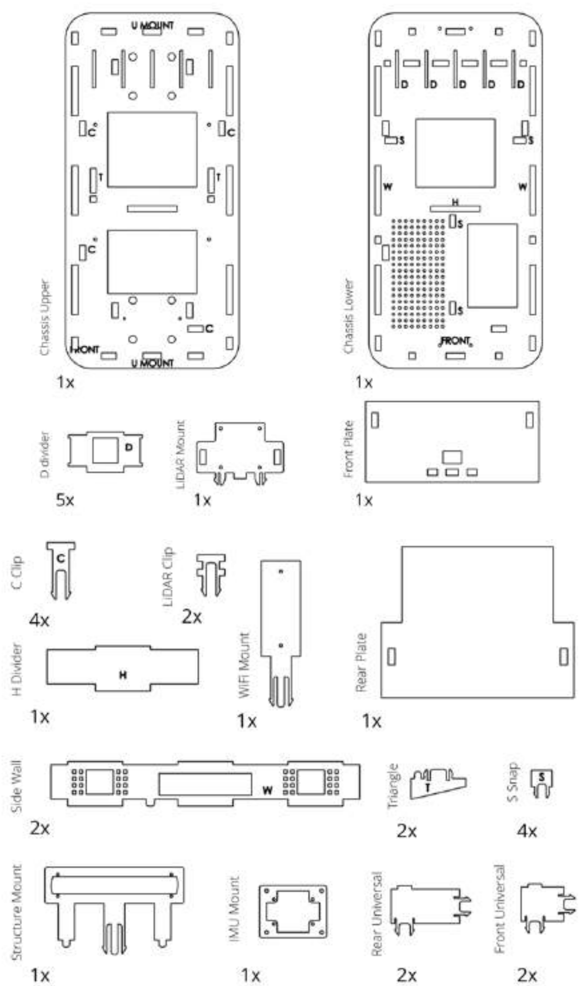
So what is F1/10 ?

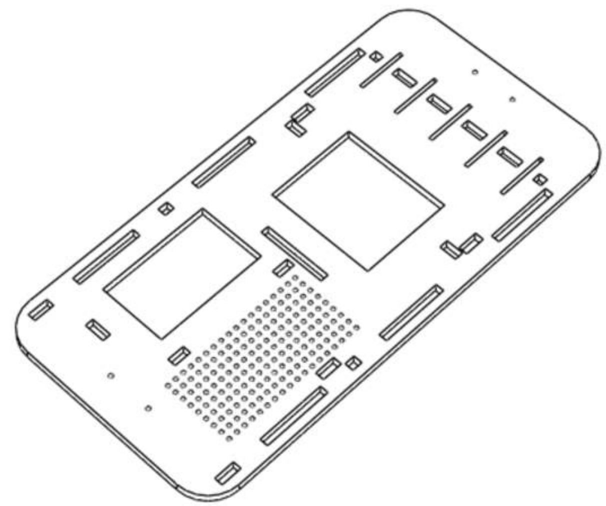
Build

Easy to build in 3 hours.

F1/10 racing platform

With simple IKEA style instructions at http://f1tenth.org



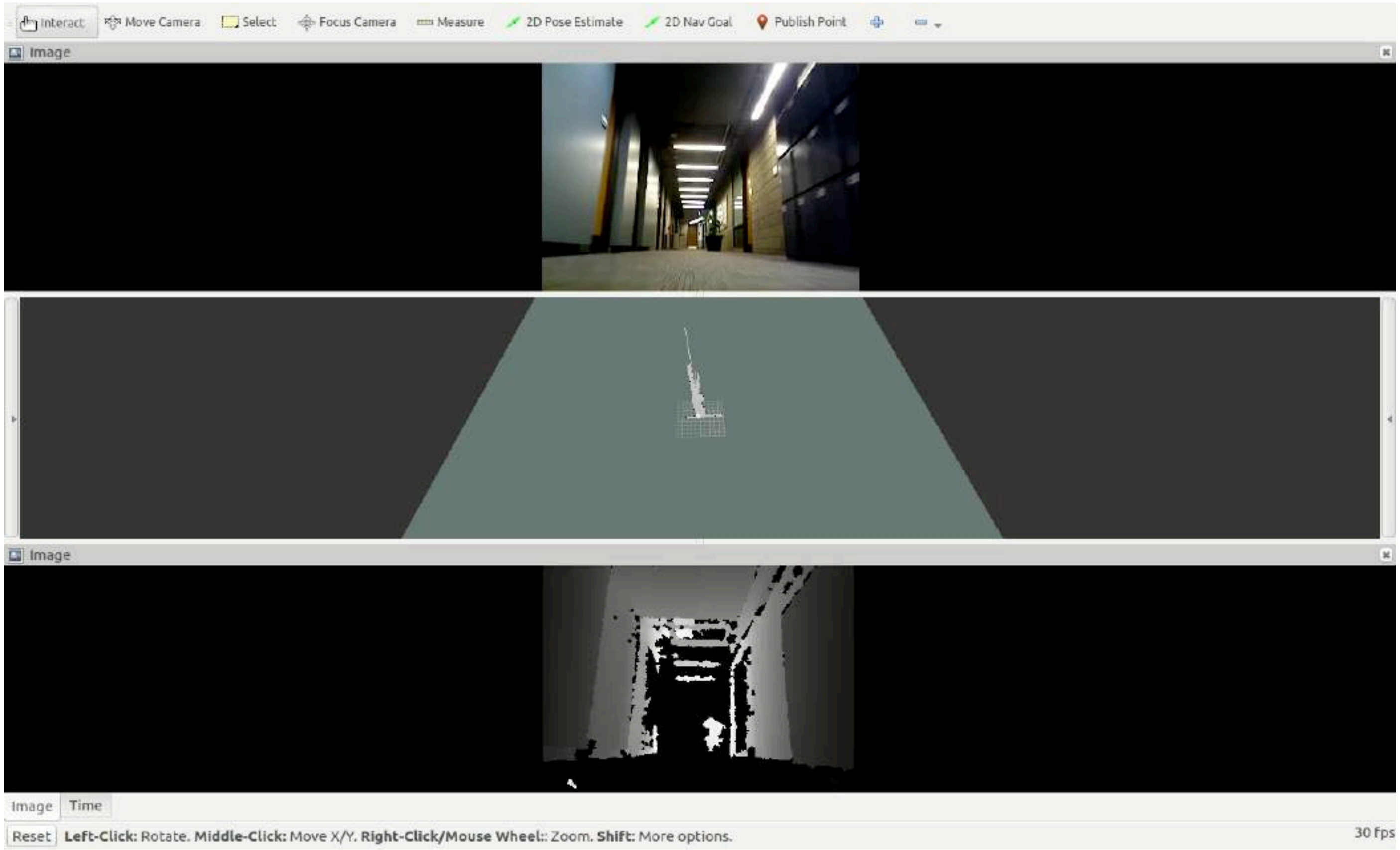


Learn

Perception. Planning. Control
All lectures at http://f1tenth.org

Learn about Autonomy

SLAM, AMCL, Scan matching, planning algorithms, optimal control strategies for the fastest autonomous driver, safe decision making..



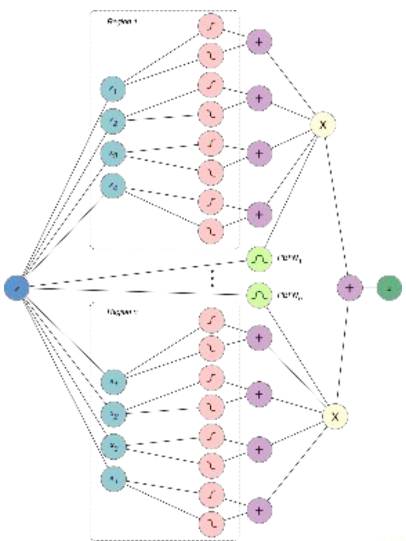
Note: Map based approach where loop closure fails…

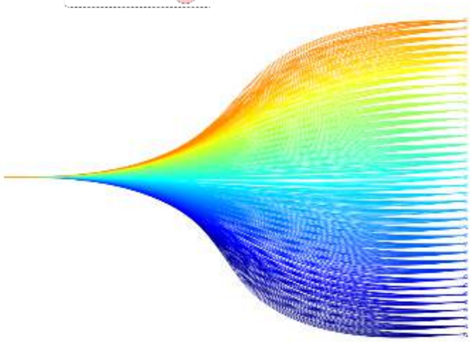

huluTECH

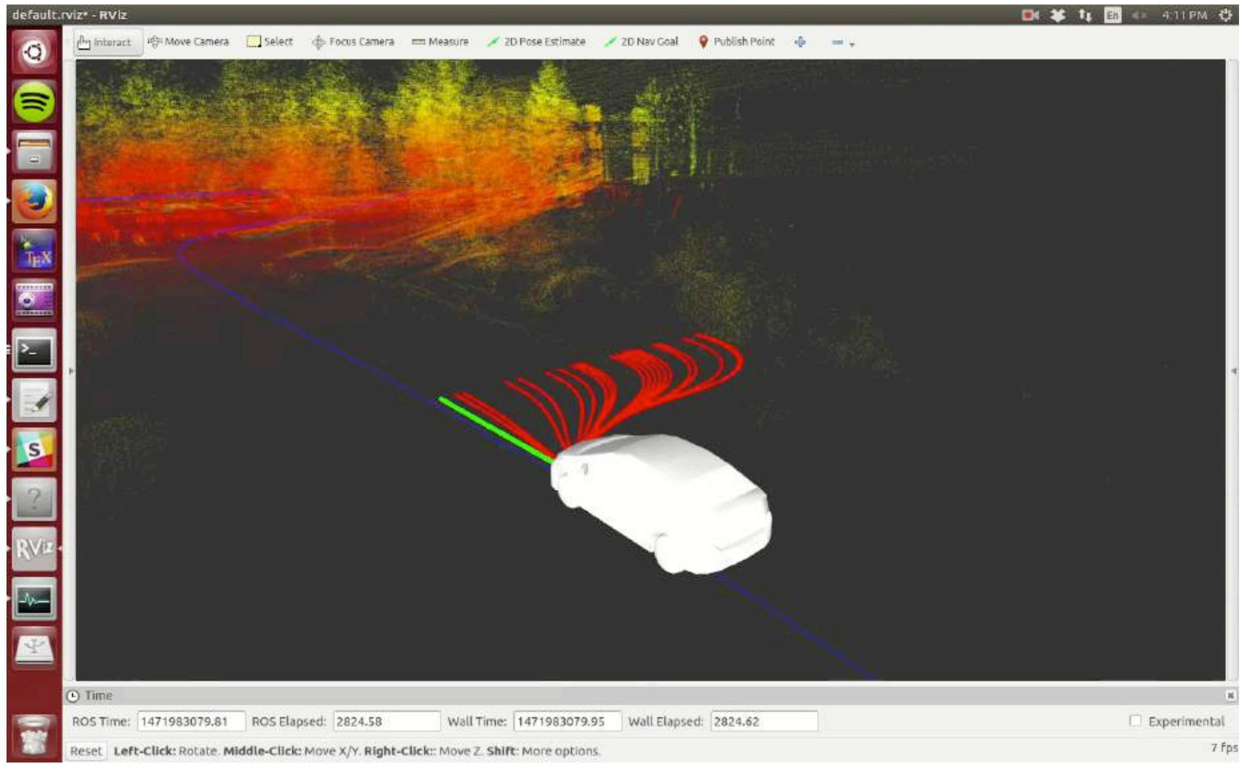
Research

Closing the loop fast enough.

Map Free Approach





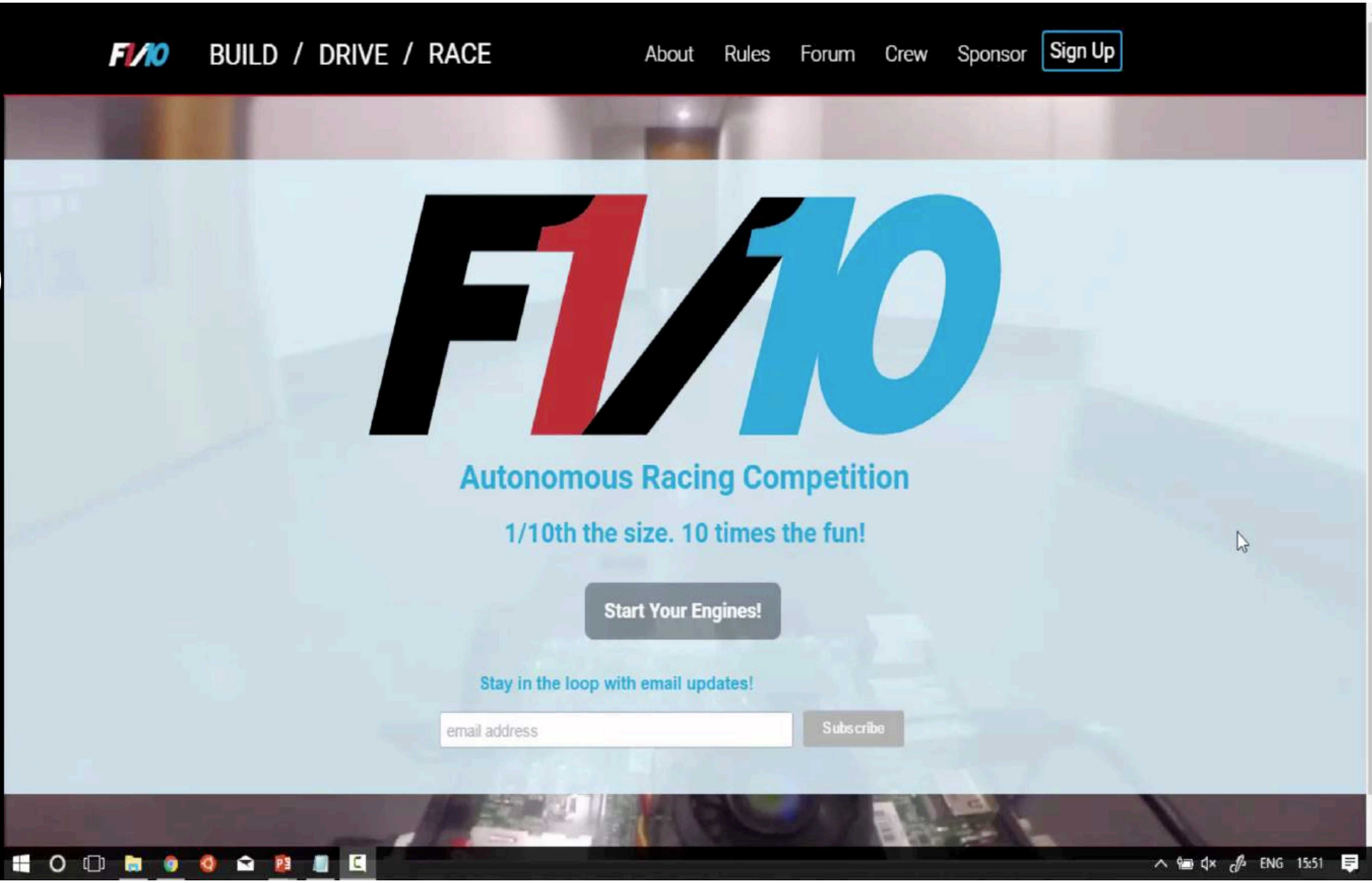


Efficient Adaptive State Lattice Planning

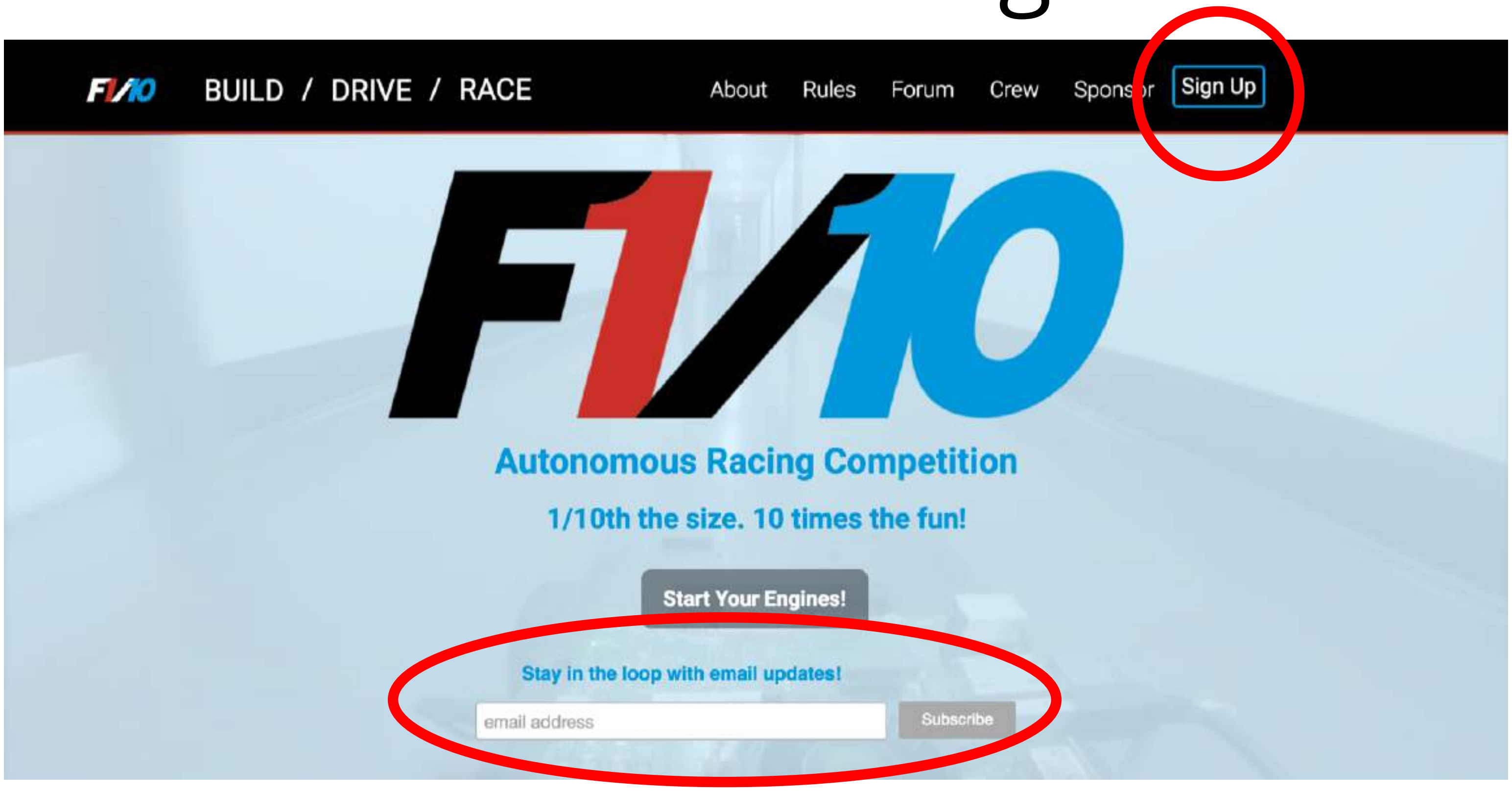
Use linear optimization to learn weights for a network of radial basis functions. Quickly compute a variety of trajectories in the configuration space of the robot in order to create local plans…

Open Source

f1tenth.org


F1/10
BUILD / DRIVE / RACE
About
Rules
Forum
Crew
Sponsor
Sign Up
F1/10
Autonomous Racing Competition
1/10th the size. 10 times the fun!
Start Your Engines!
Stay in the loop with email updates!
email address
Subscribe
ENG
15:51

f1tenth.org



Get Involved !

Compete

October 1st-2nd

Wean Hall, Carnegie Mellon University

To compete, **register** your team name on our **sign up sheet**

Look at the progress of the Fall 2016 F1/10 teams

Directions/Accomodations

ES Week Track Layout

Wean Hall, 7th Floor

Sector 1:	Width: **8'**
Sector 2:	Width: **6'-8'**
Sector 3:	Width: **6'-8'**

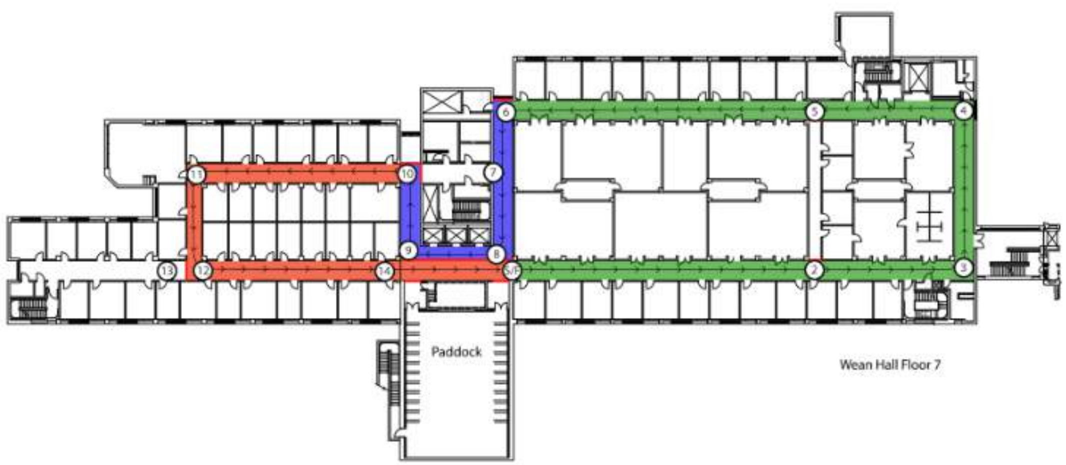
Track length **812** Feet

7 Left Turns

2 Right Turns

Download ROSbags

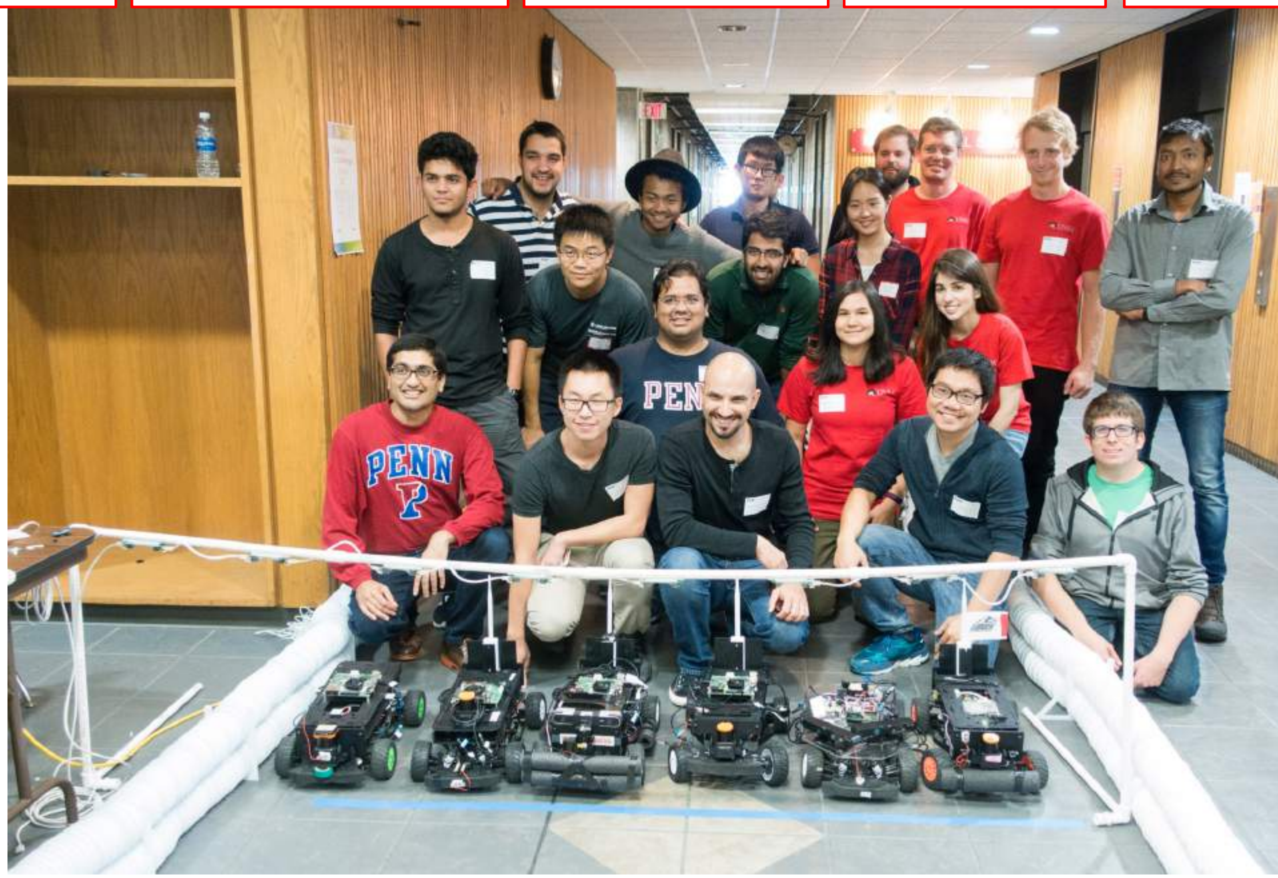
Download DWF



1st F1/10 Autonomous Racing Competition

[Oct 1-2, 2016, CMU, Pittsburgh]

U. Of Penn | U. Of New Mexico | Arizona State | ETH, Zurich | Temple



1st F1/10 Autonomous Racing Competition

[Oct 1-2, 2016, CMU, Pittsburgh]

Fastest Lap

812 ft 63.6 secs Avg 8.7mph Top ~16mph

F1/10

1/10th the scale. 10 times the fun!

Autonomous Racing Competition | F1Tenth.org

Cyber Physical Systems (CPS) Week 2017
April 18-21, Pittsburgh, PA

1st F1/10 Autonomous Racing Competition

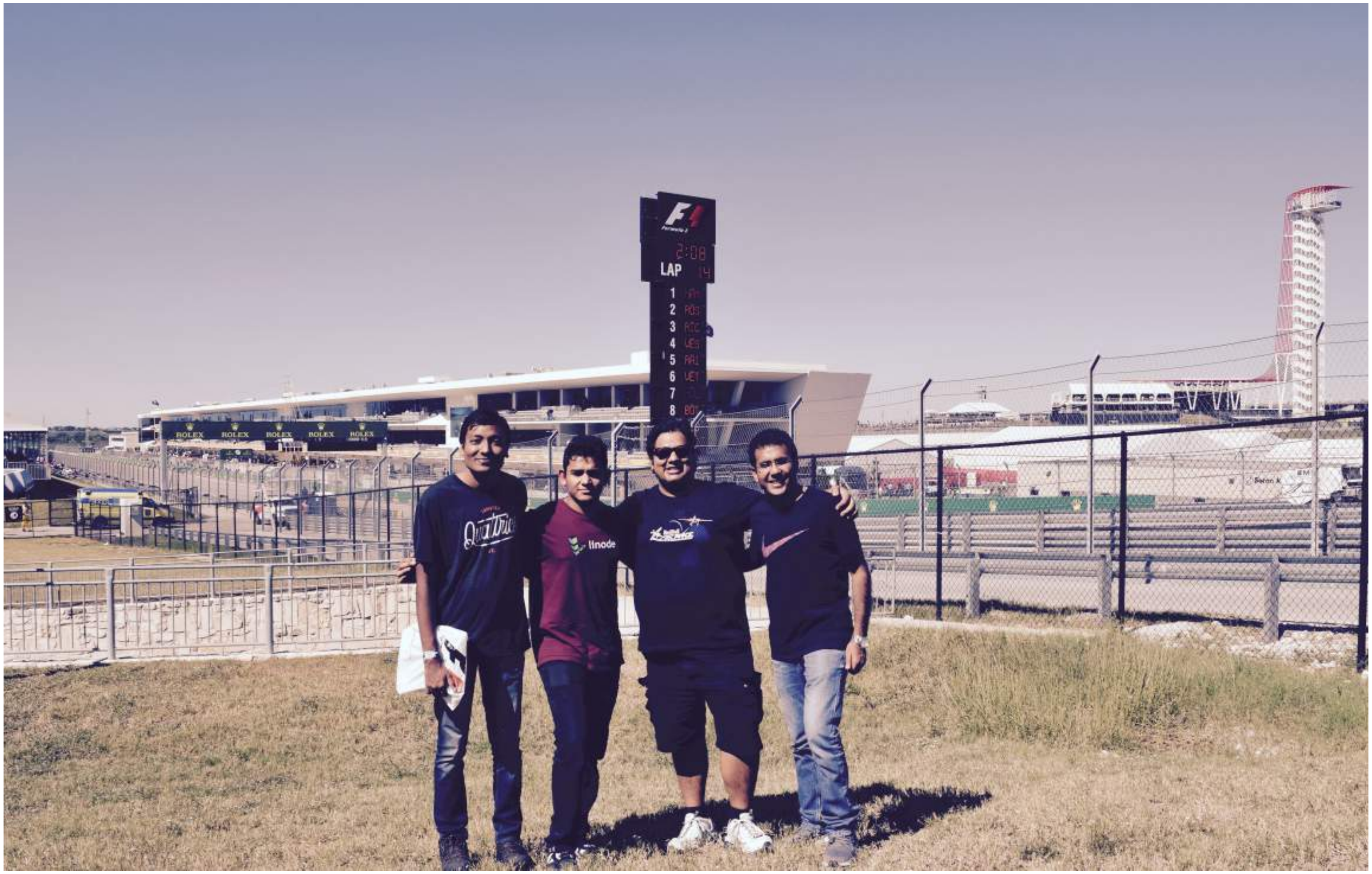
[Oct 1-2, 2016, CMU, Pittsburgh]

Fun!

F1/10

1/10th the scale. 10 times the fun!


GROSSER PREIS VON
SPIELBERG, 01. - 03.
WWW.PROJEKT-SPIELBERG.COM
TOTAL



2016 Formula One United States GP, October, Austin, TX

Accessible Autonomy

Expensive, power hungry, large…

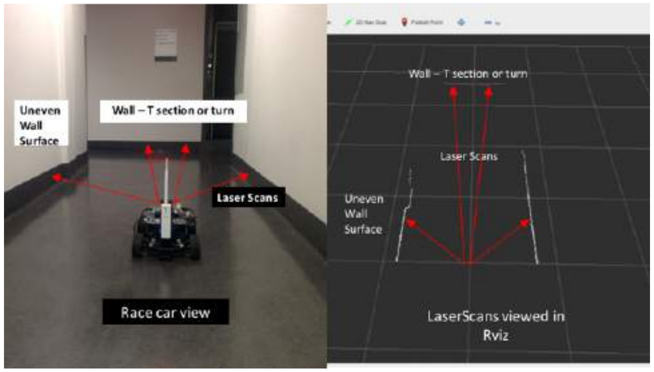
Cheap, low power, small…

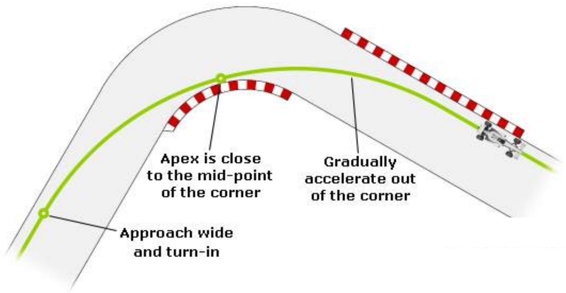
Same dynamics (different parameters), similar algorithmic challenges…

Build. Drive. Race.

Perception. Planning. Control

Making sense of the surroundings

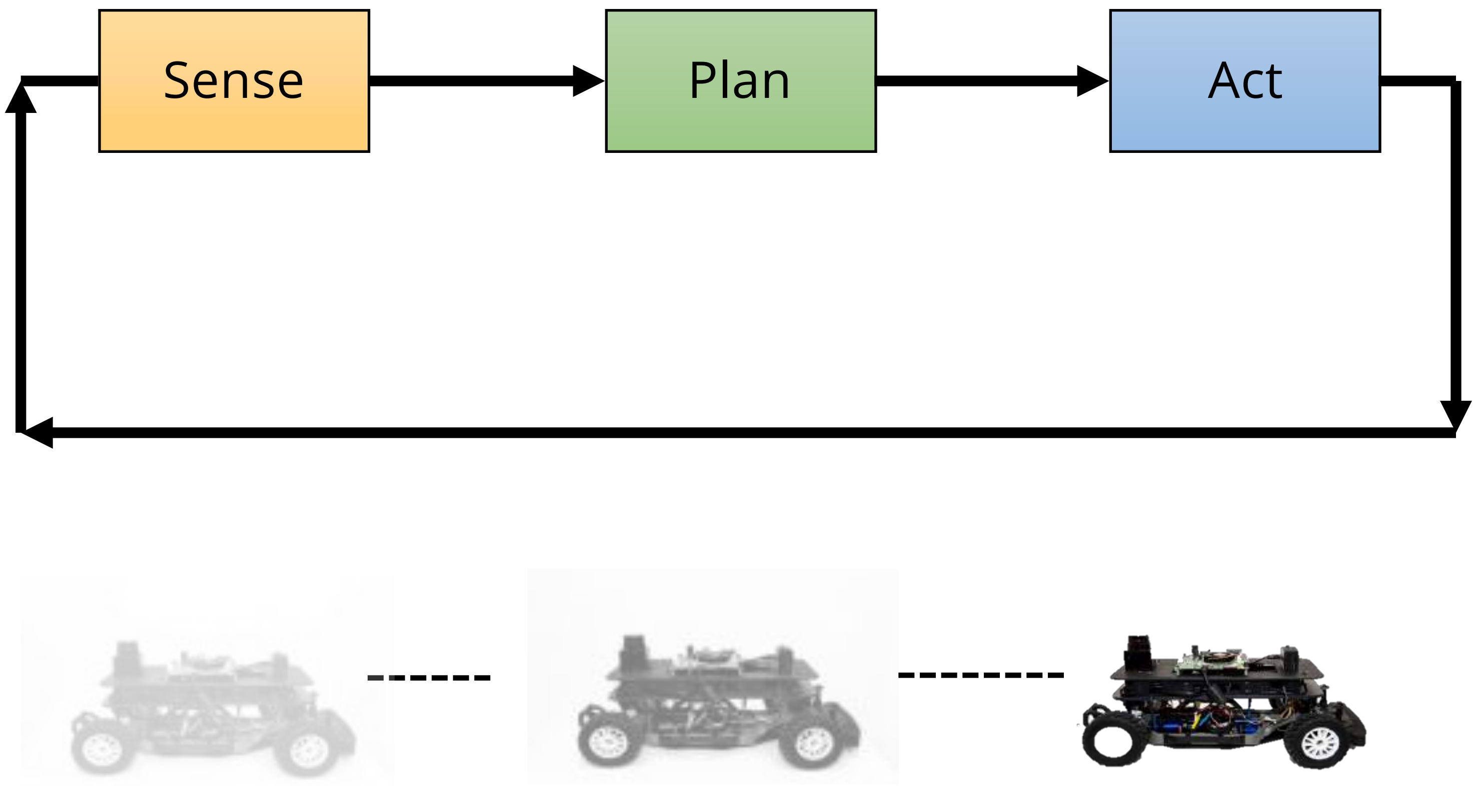




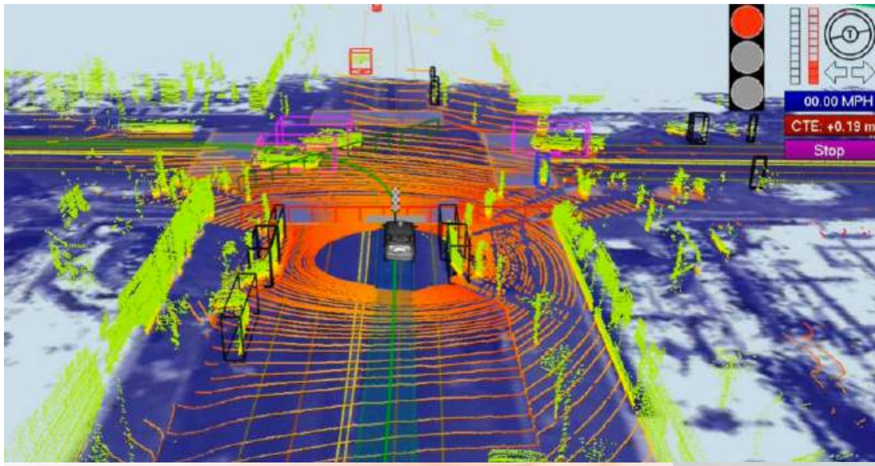
Planning the fastest racing line

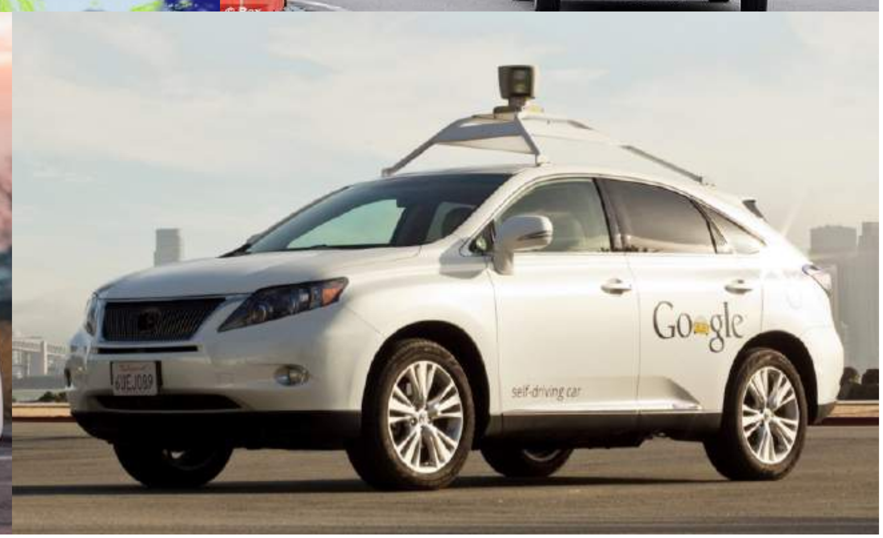
Controlling the car to follow the planned path

Closing the loop



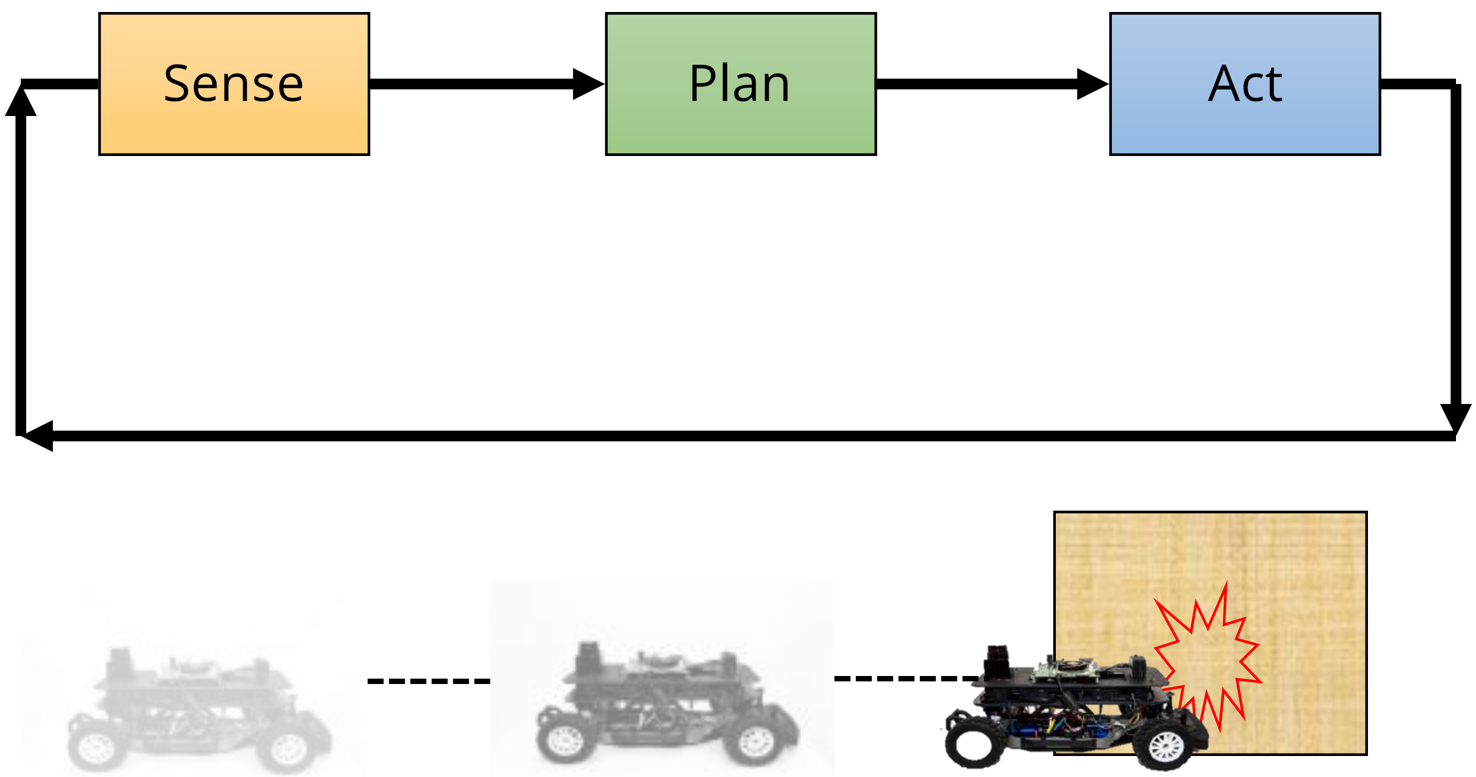
Self driving cars: Safety and Comfort

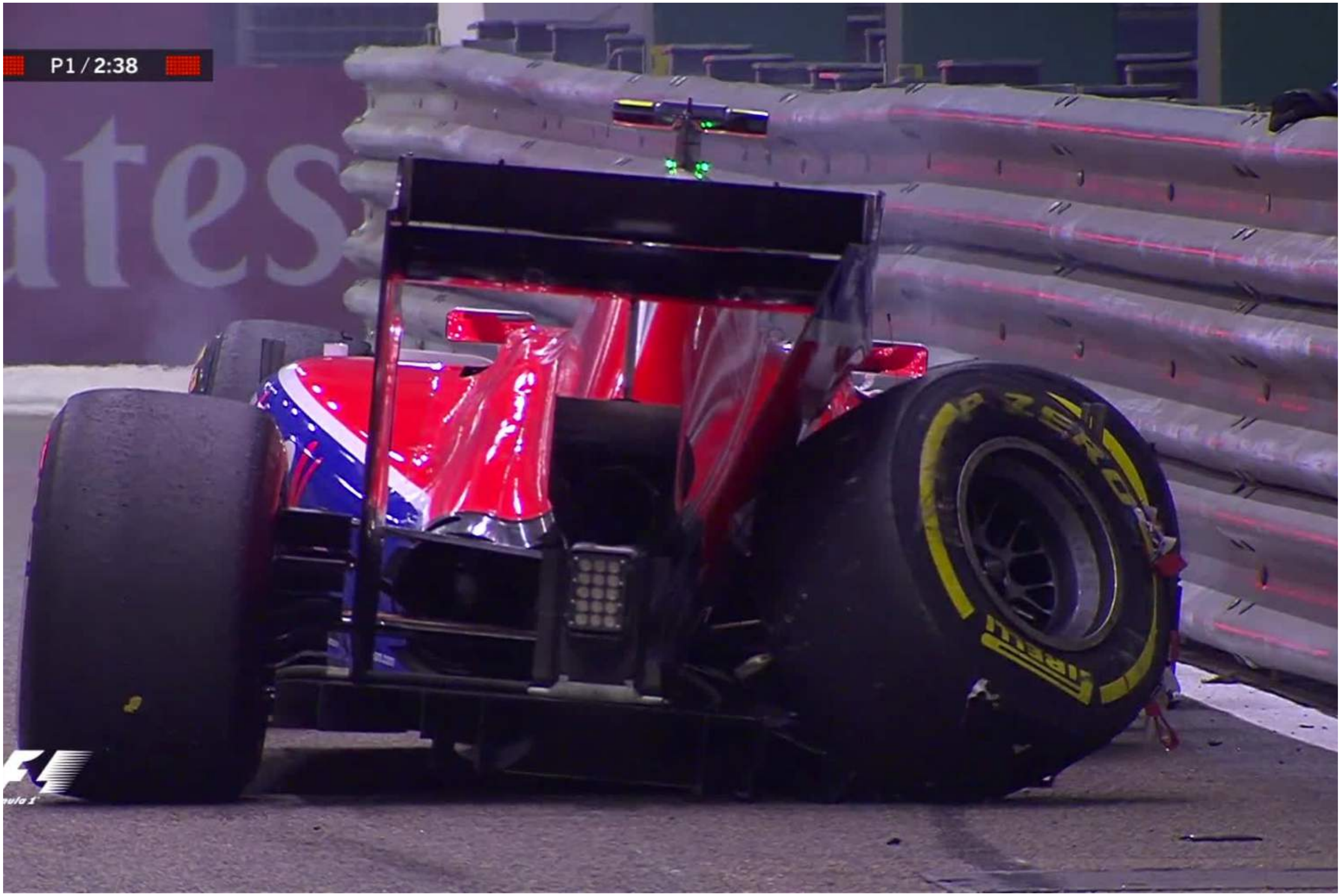





"If everything seems under control,
then you are not going fast enough"
Santander
FIAT

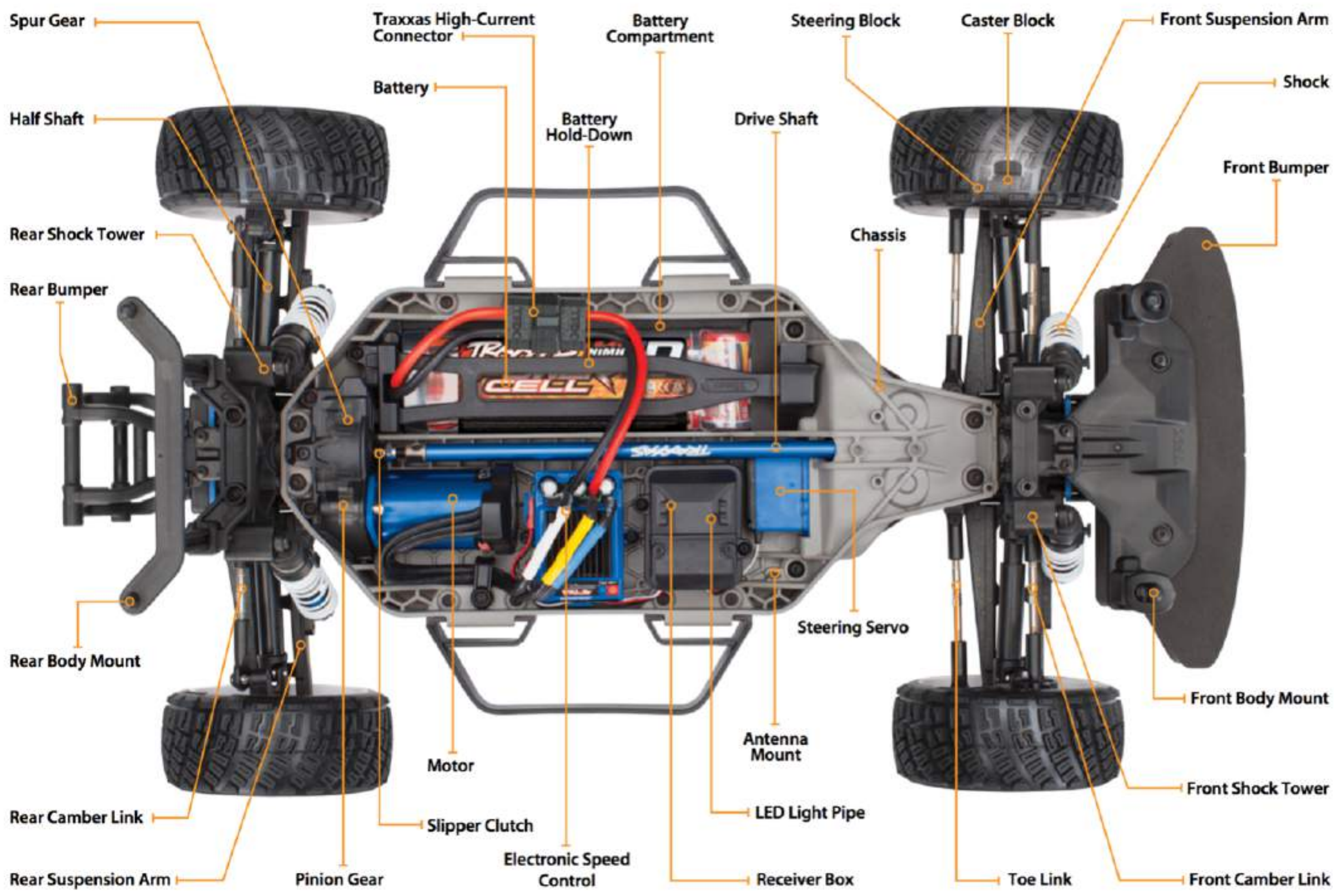
Closing the loop *fast*



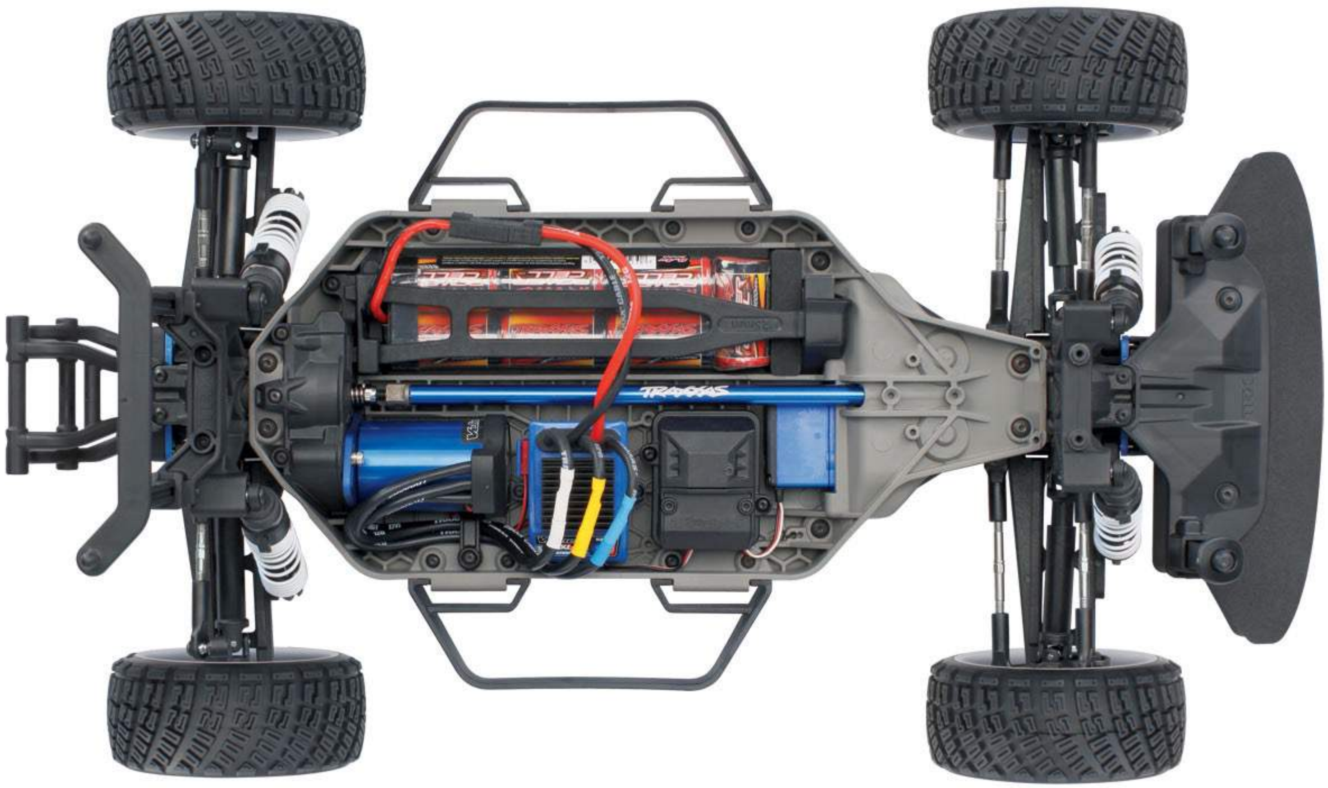

P1 / 2:38
P ZERO
PIRELLI

Build.

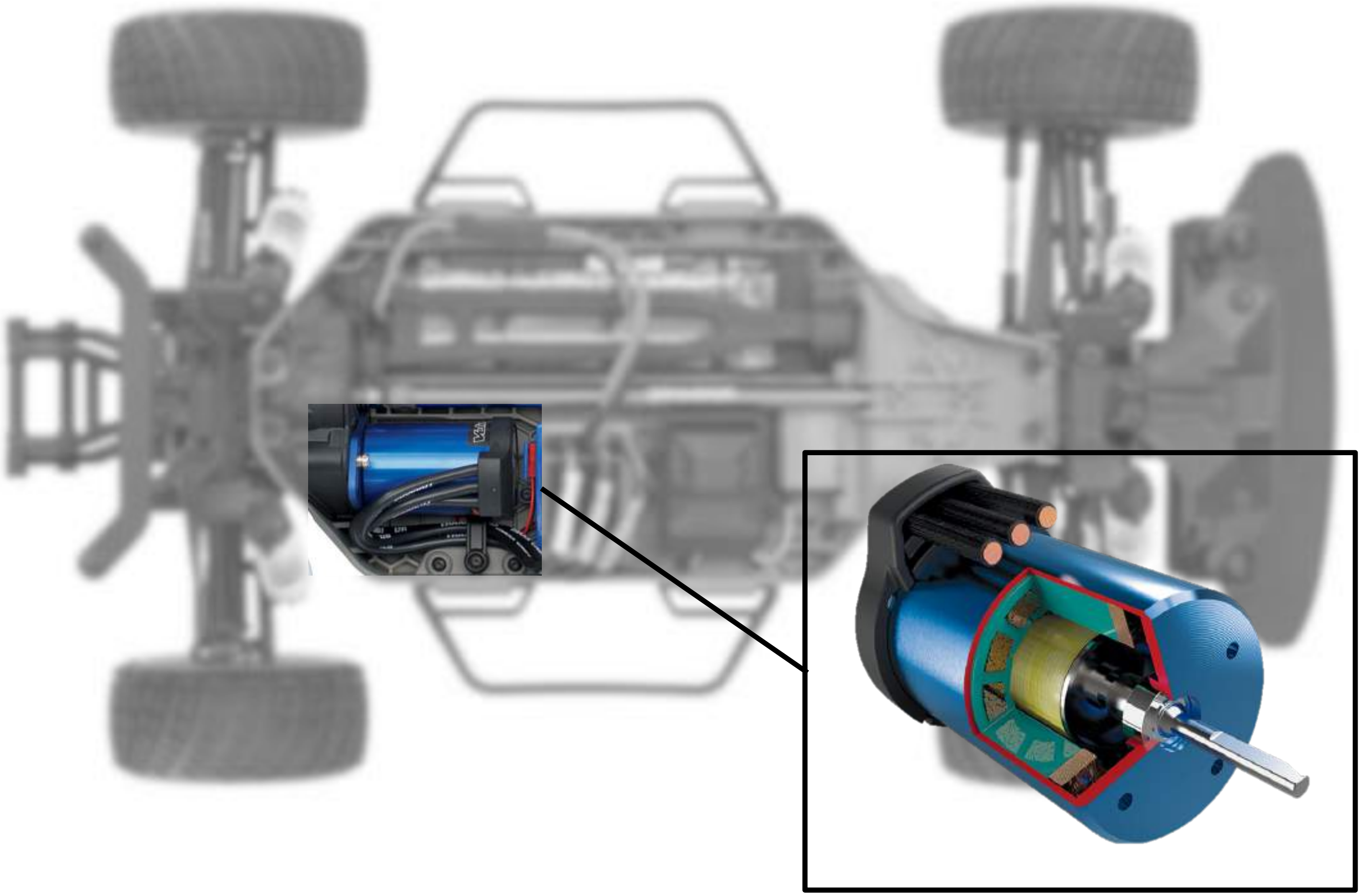
Traxxas 1/10 scale RC race car



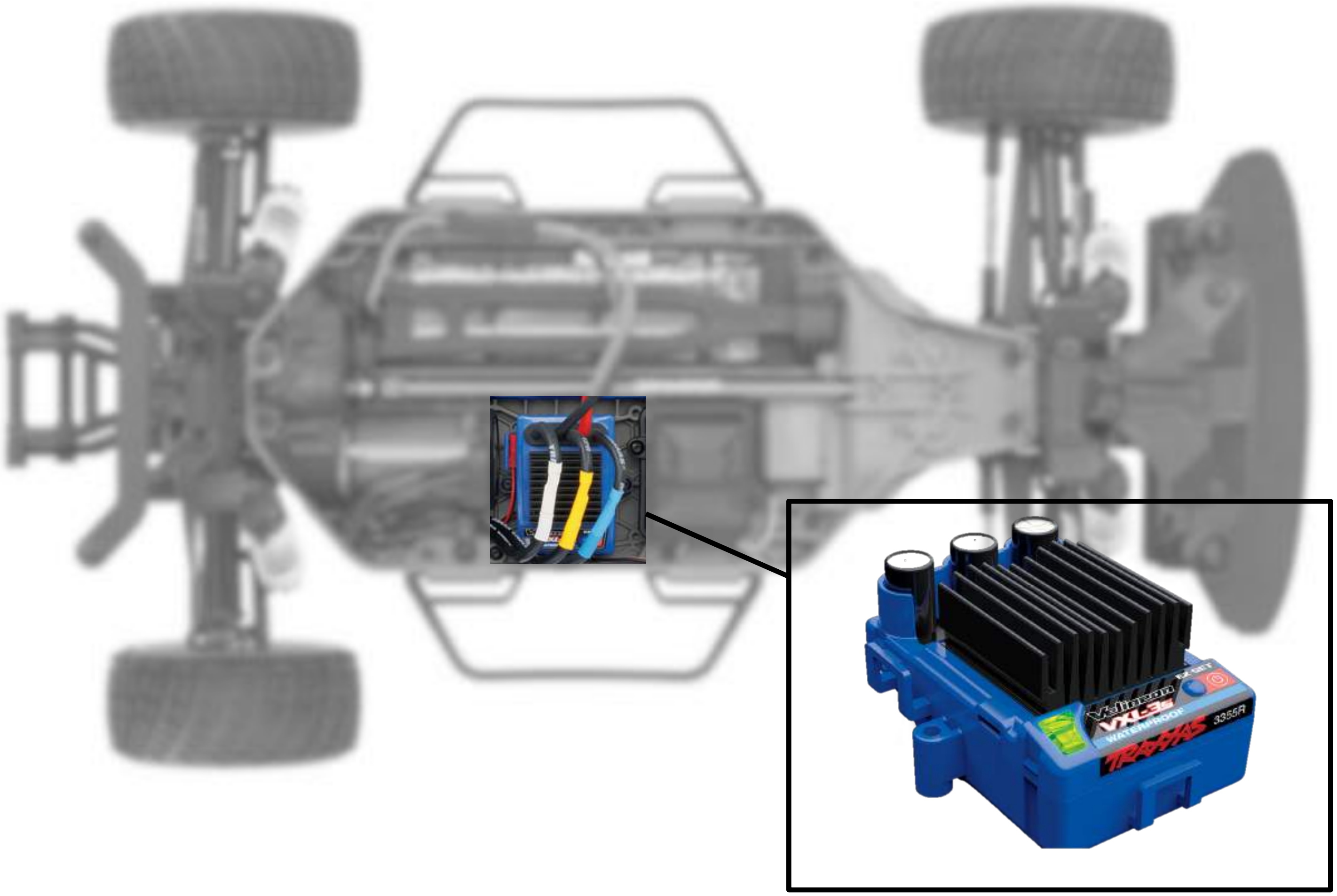
Traxxas 1/10 scale RC race car



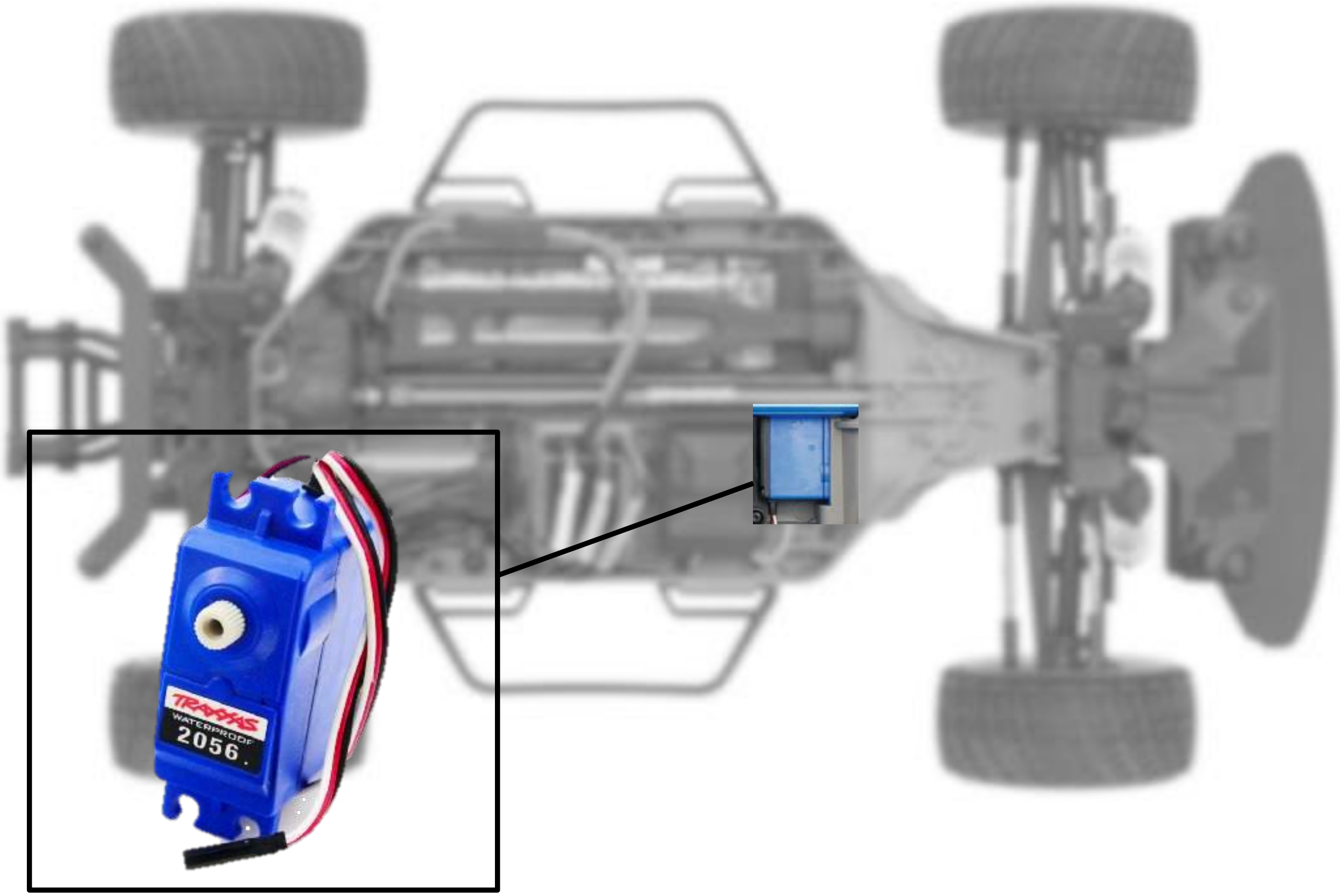
Brushless DC motor



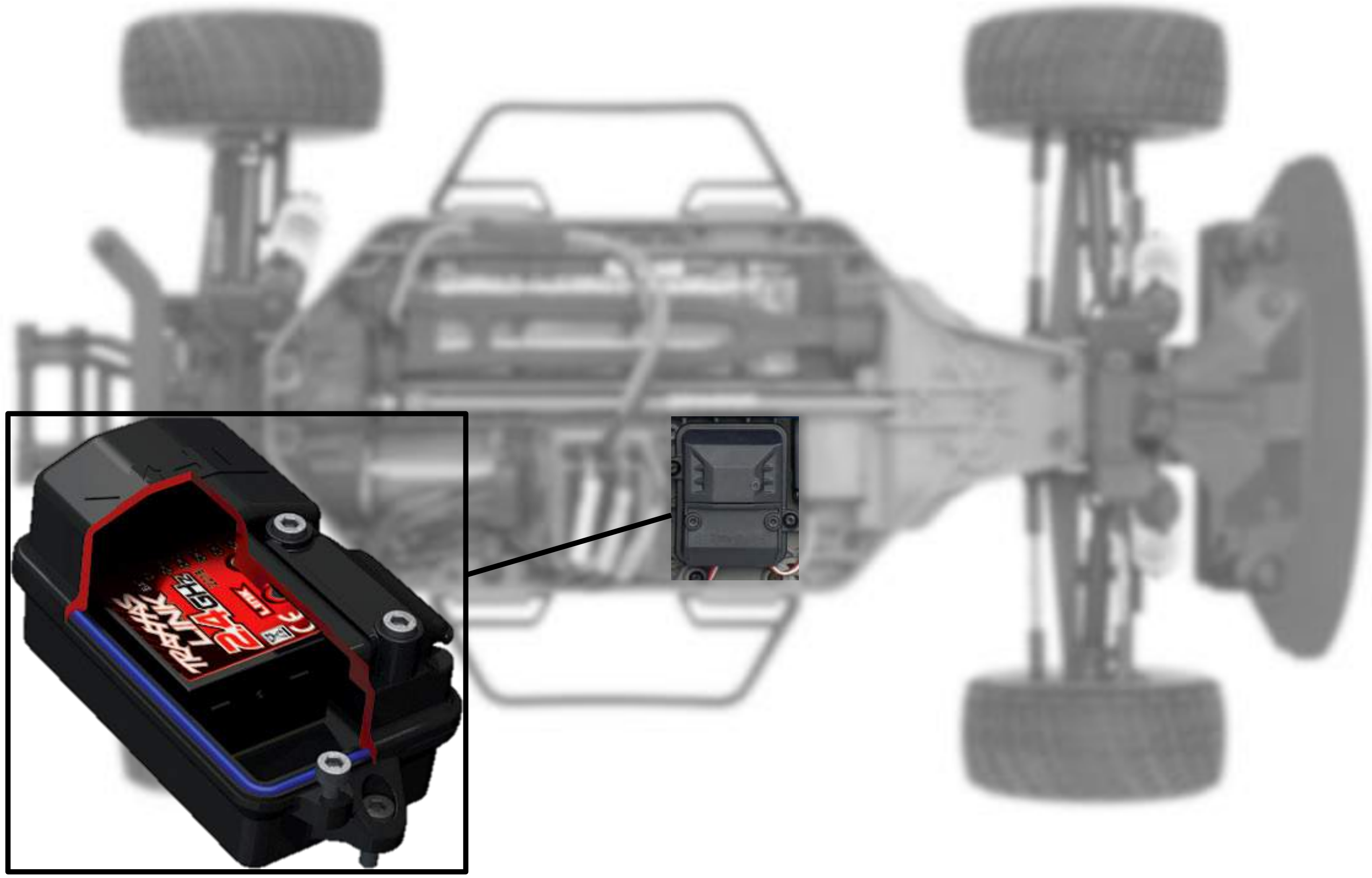
Electronic Speed Control (ESC)



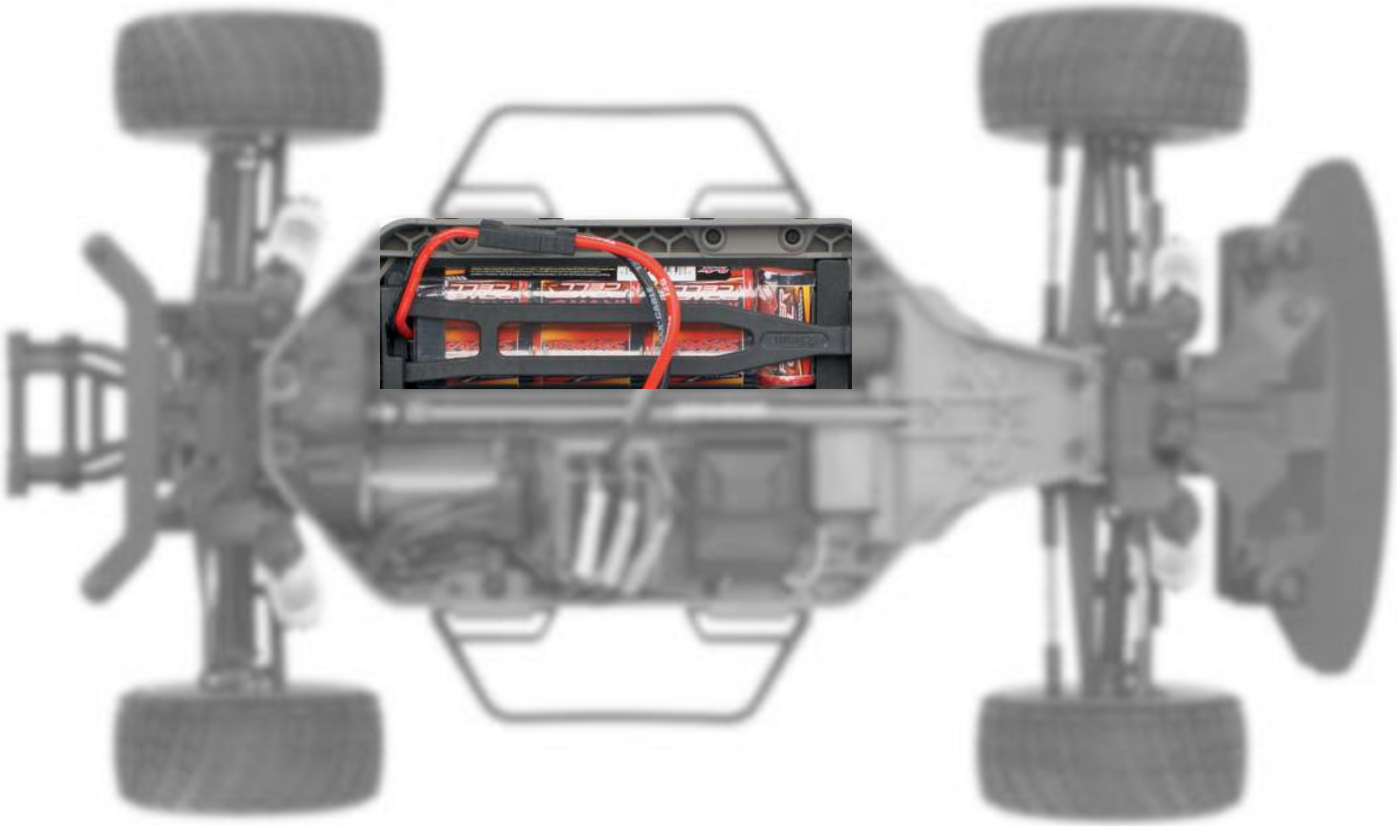
Servo motor for steering



Radio receiver



Battery pack



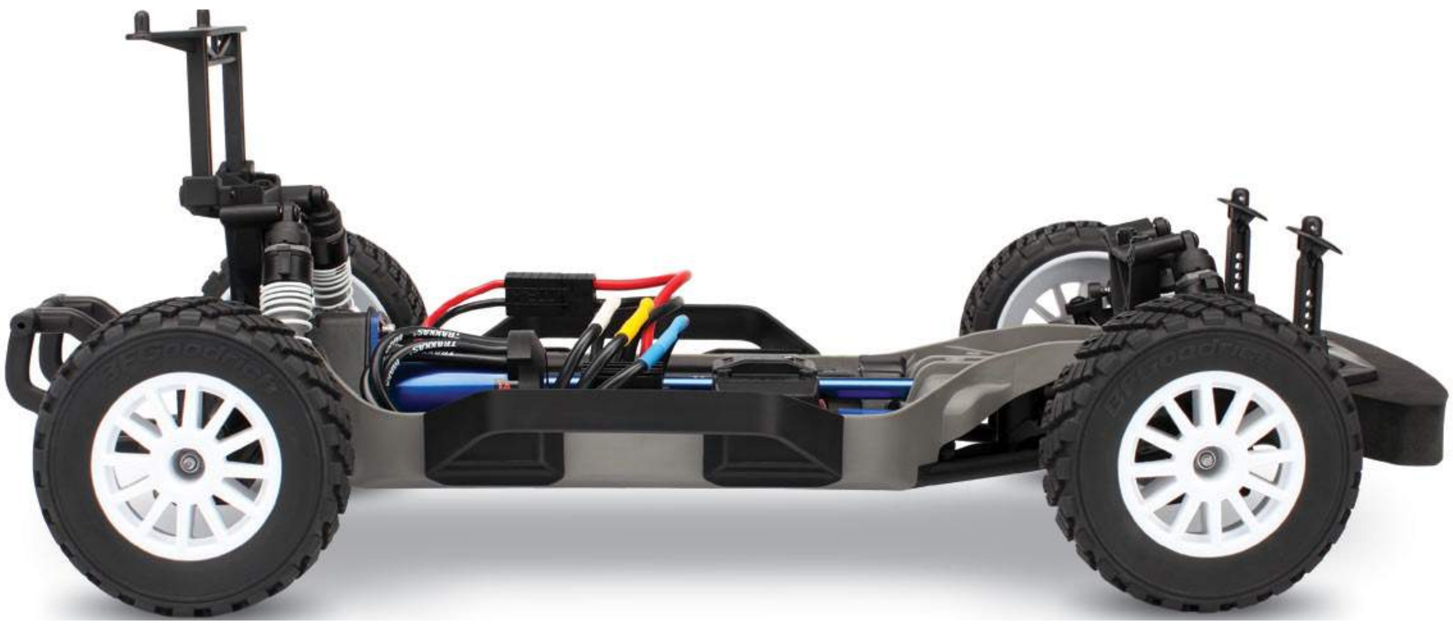
Sensor Integration

LiDAR

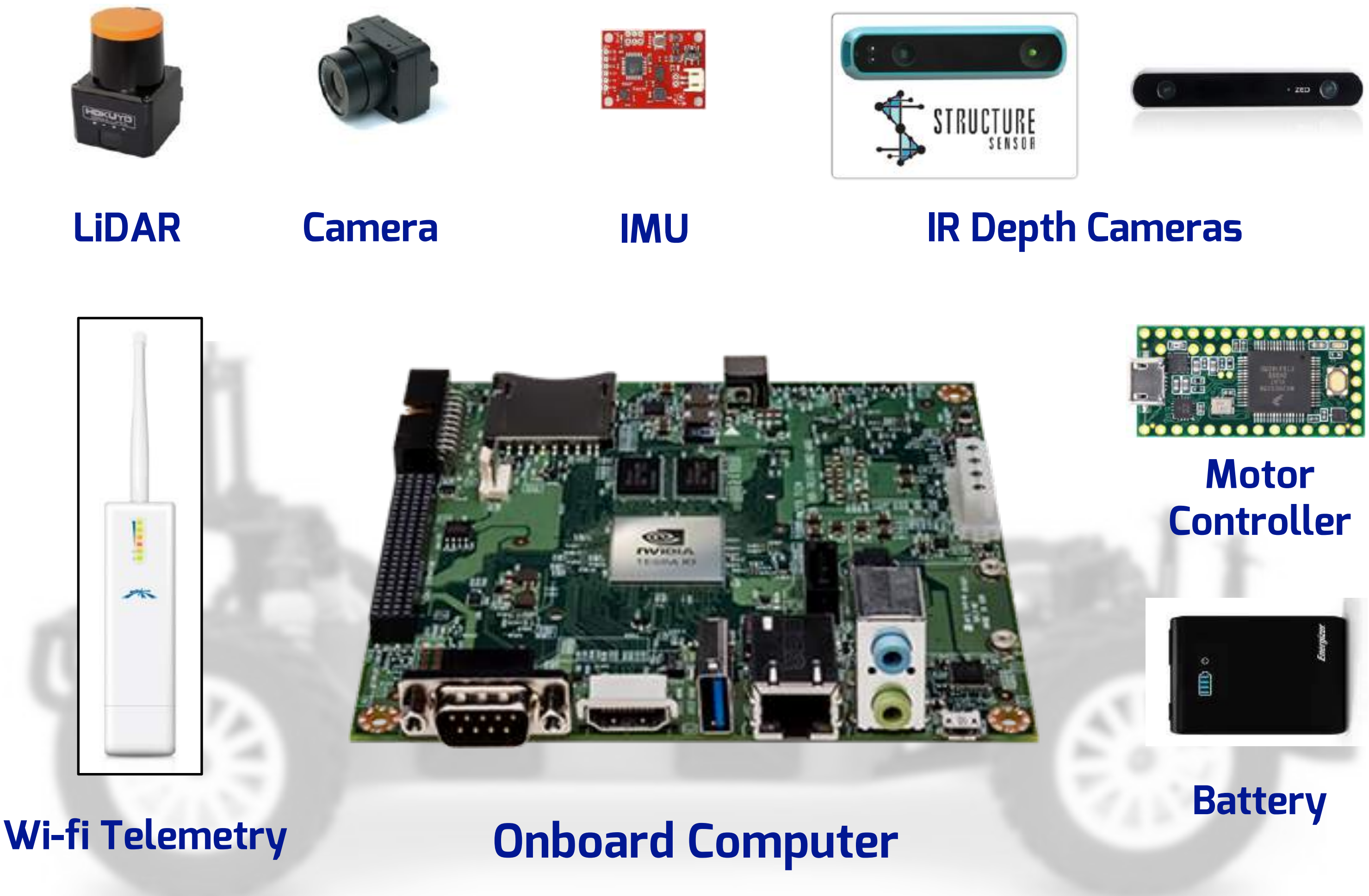
Camera

IMU

IR Depth Cameras

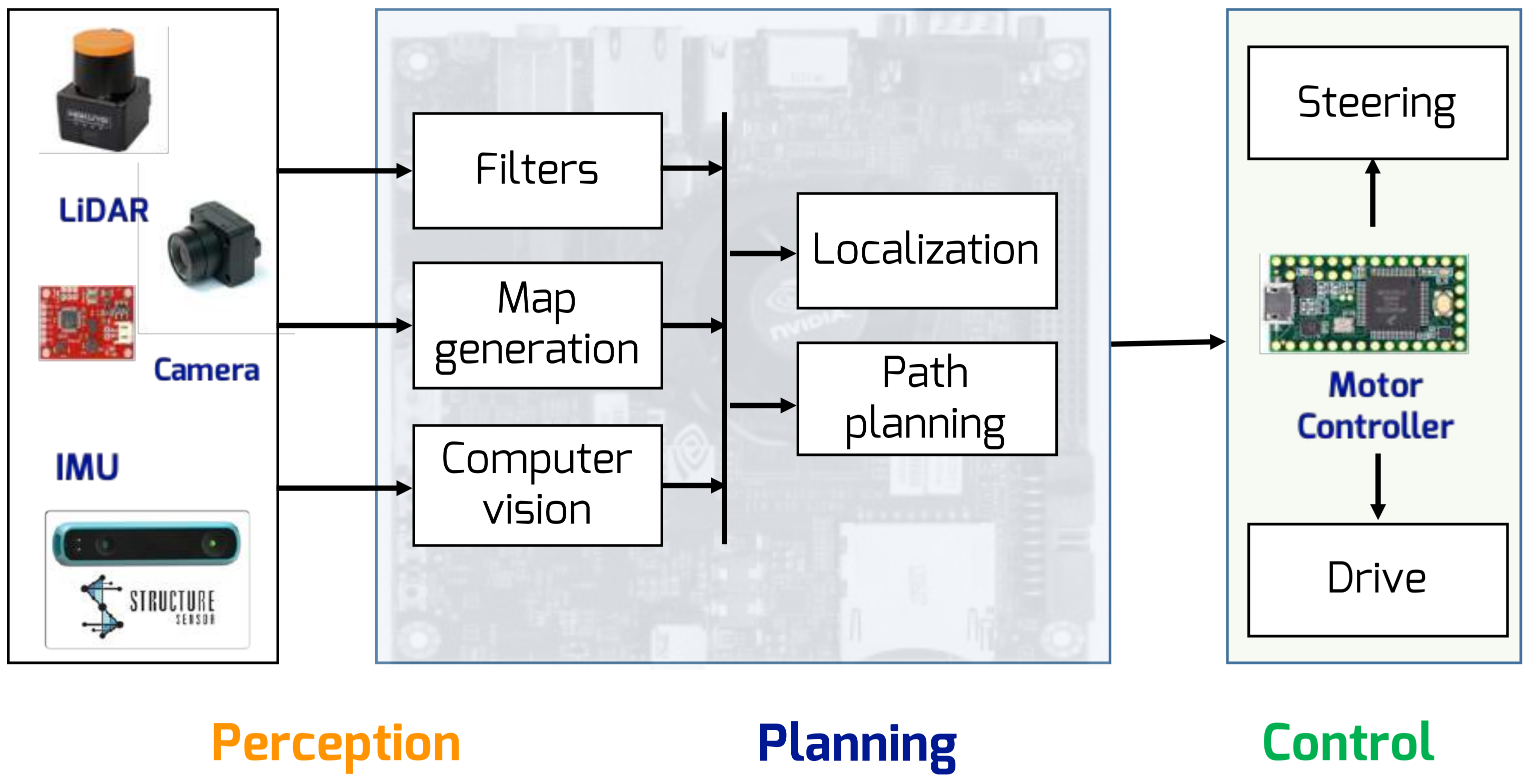


Sensor Integration

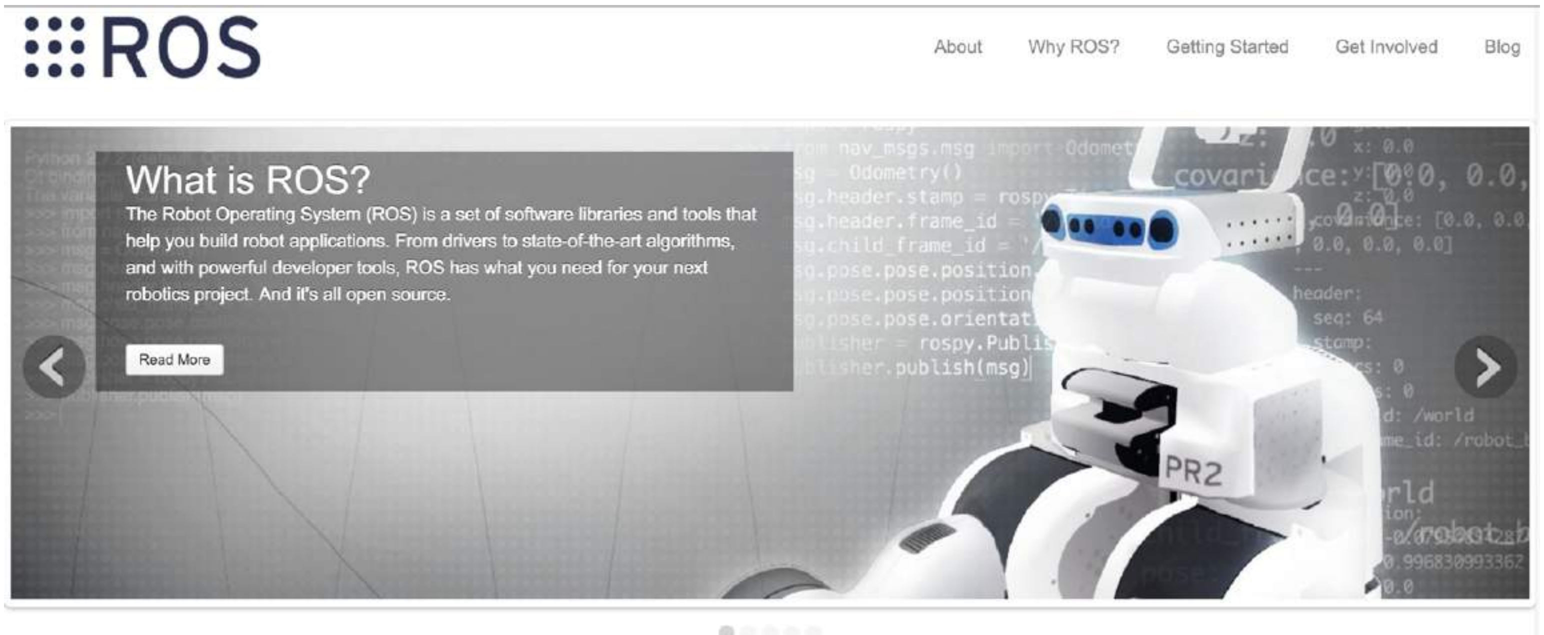


~~Ready to race !~~ Not quite..

System Architecture



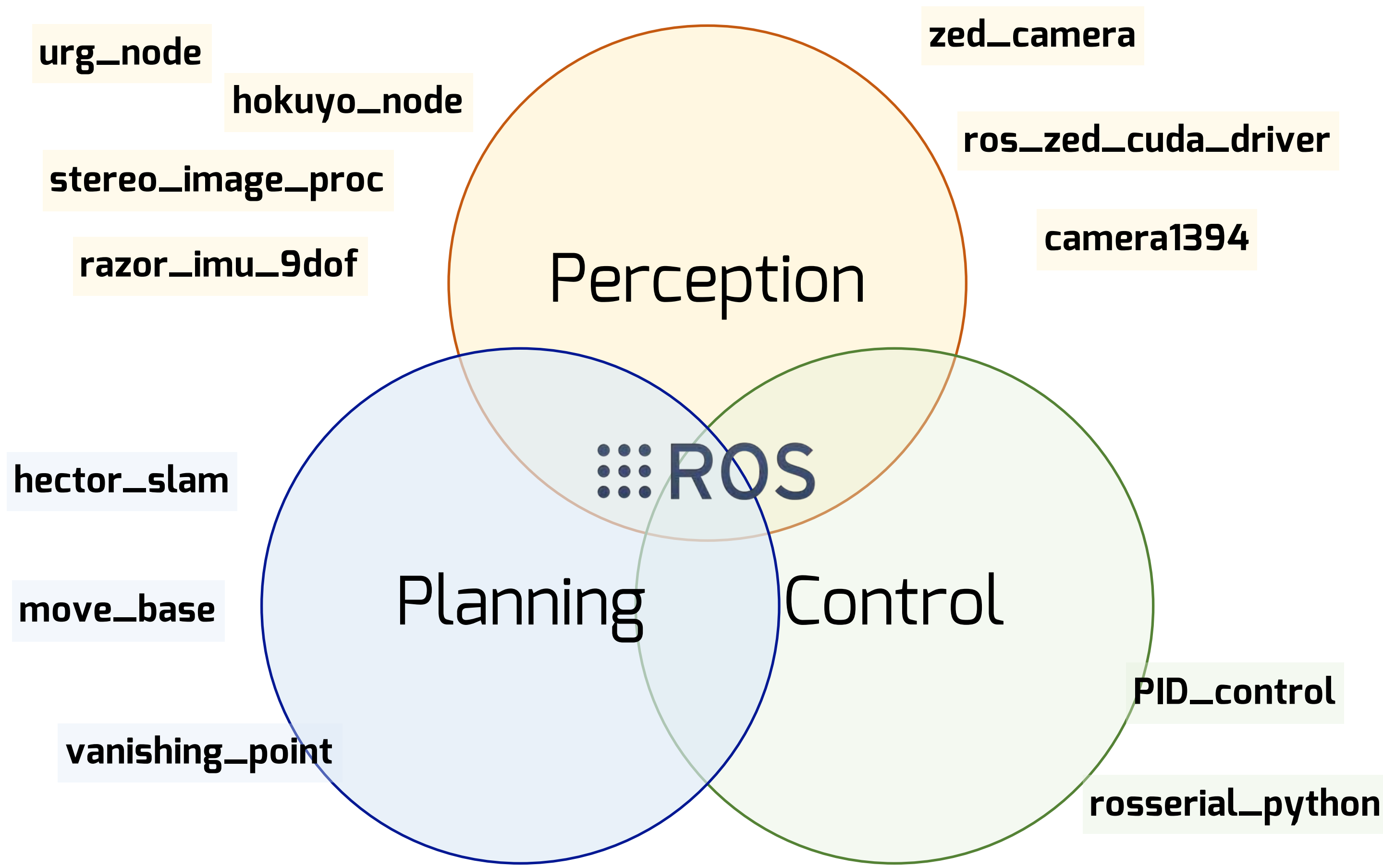
ROS: Robot Operating System



ROS.org

Open Source Robotics Foundation

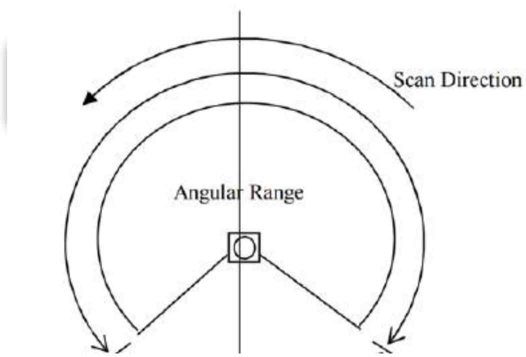
ROS Capabilities



ROS: Messages

Messages are the strongly-typed **data structure** for a topic.

hokuyo_node




```
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
```

Subscriber Node

Basic ROS commands: `roscore`

`roscore` is the first thing that you should run when starting ROS.

```
$ roscore
```

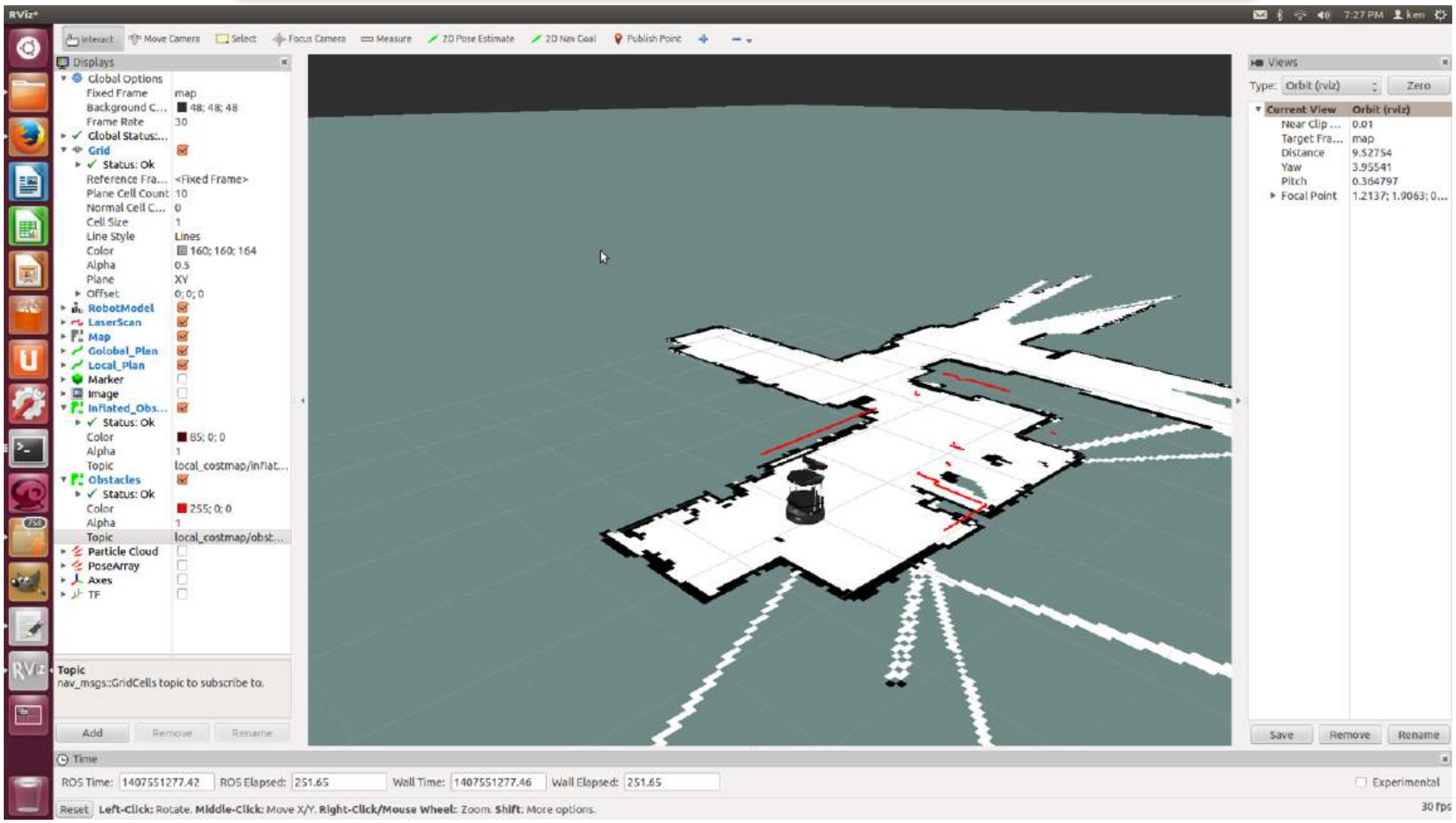
Collection of nodes and programs that are pre-requisites of a ROS-based system.

It starts up:

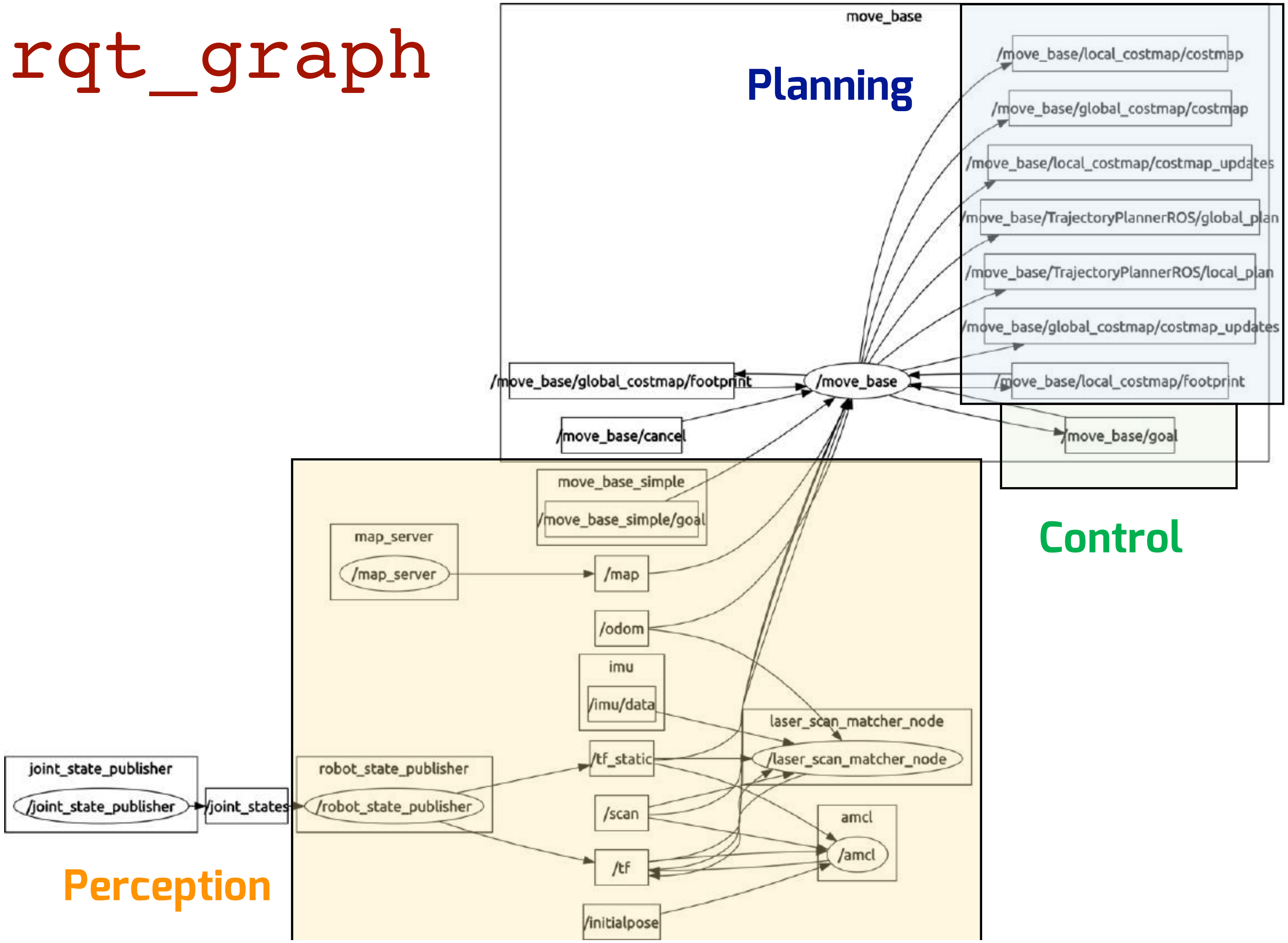
- The ROS Master
- A rosout logging node.

3D visualization tool: `rviz`

```
$ rosrun rviz rviz
```



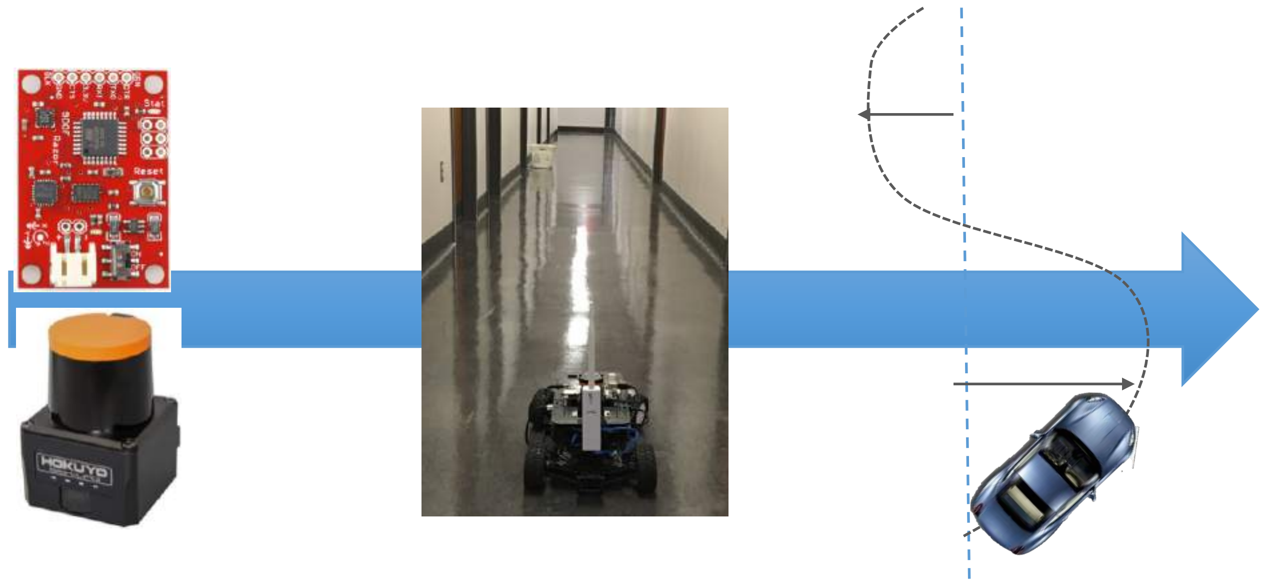
rqt_graph



move_base
Planning
/move_base/local_costmap/costmap
/move_base/global_costmap/costmap
/move_base/local_costmap/costmap_updates
/move_base/TrajectoryPlannerROS/global_plan
/move_base/TrajectoryPlannerROS/local_plan
/move_base/global_costmap/costmap_updates
/move_base/global_costmap/footprint
/move_base
/move_base/local_costmap/footprint
/move_base/cancel
/move_base/goal
Control
move_base_simple
/move_base_simple/goal
map_server
/map_server
/map
/odom
imu
/imu/data
laser_scan_matcher_node
/laser_scan_matcher_node
joint_state_publisher
/joint_state_publisher
/joint_states
robot_state_publisher
/robot_state_publisher
/tf_static
/scan
amcl
/amcl
/tf
/initialpose
Perception

Drive

Perception. Planning. Control



IMU and
LIDAR

Mapping/Localization

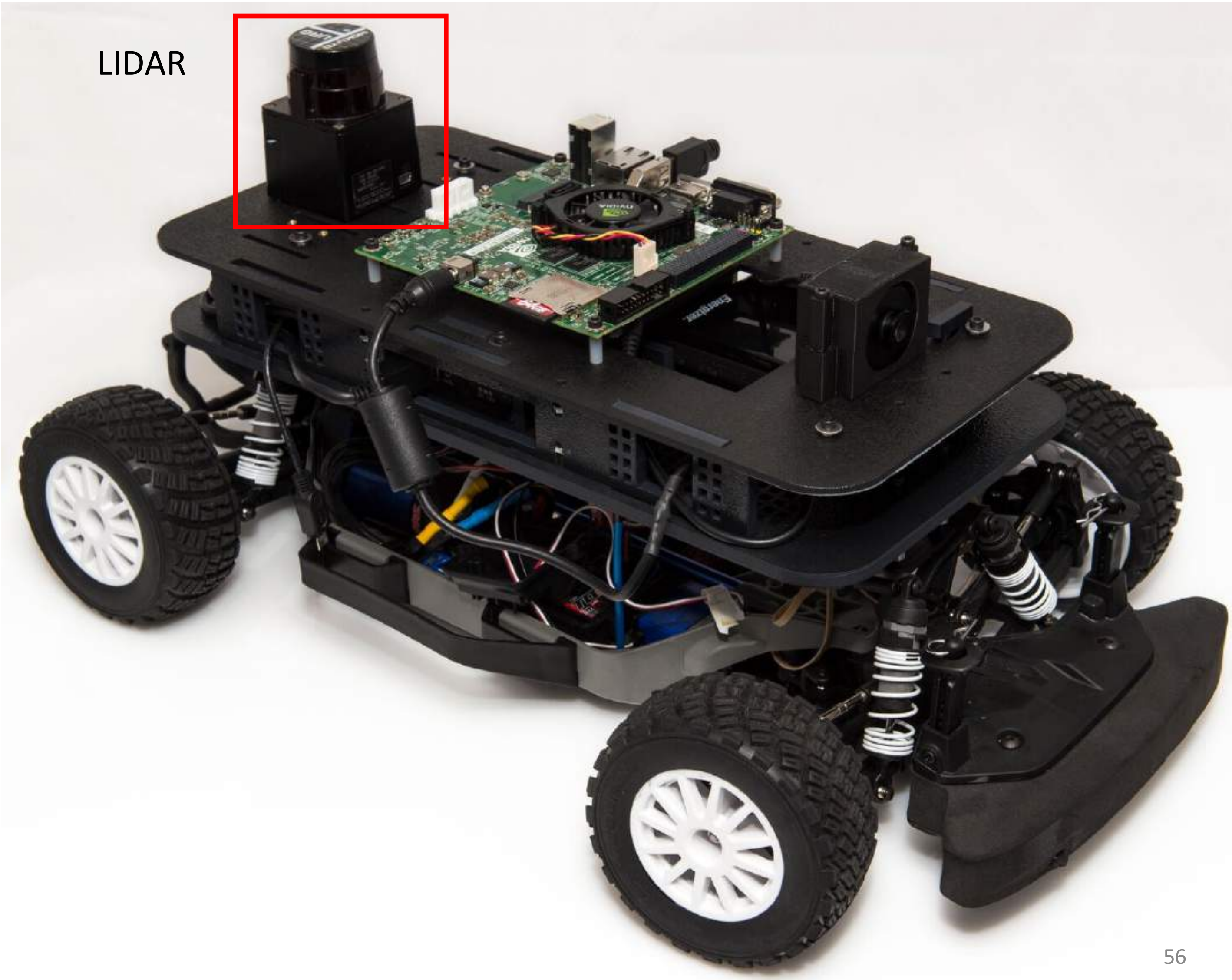
PID Control

Perception

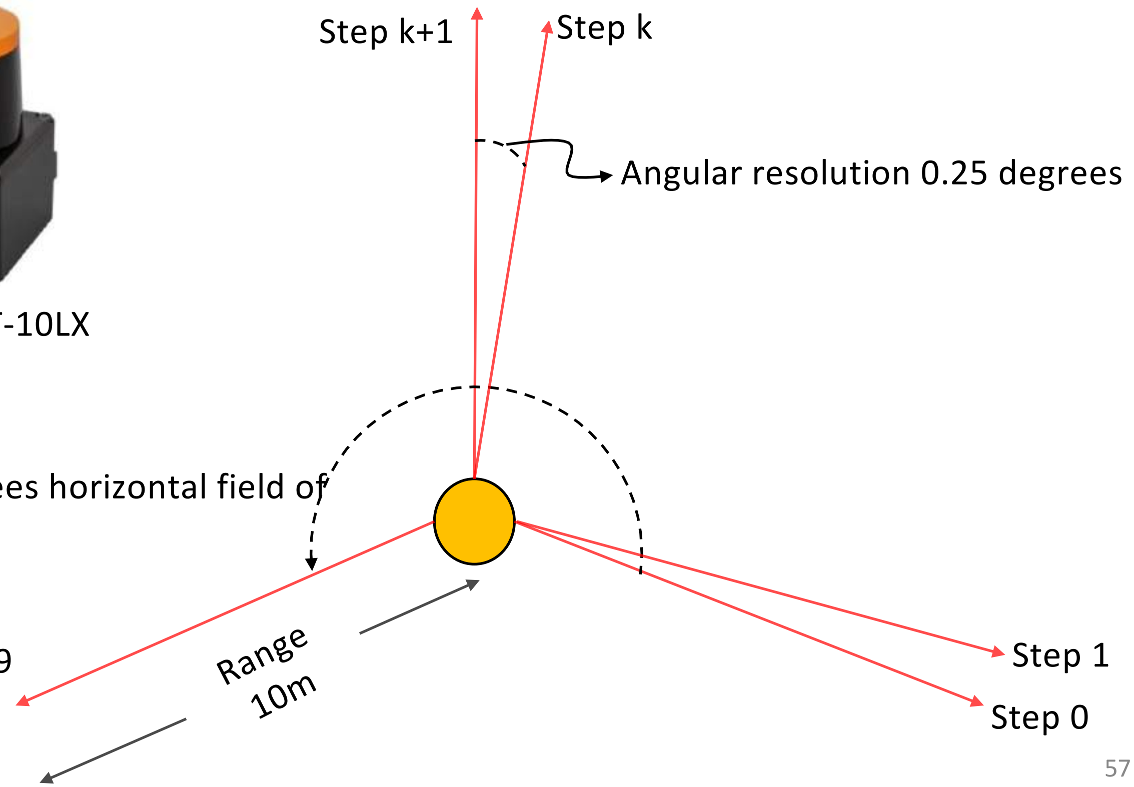
Sensors: specifications, placement and data

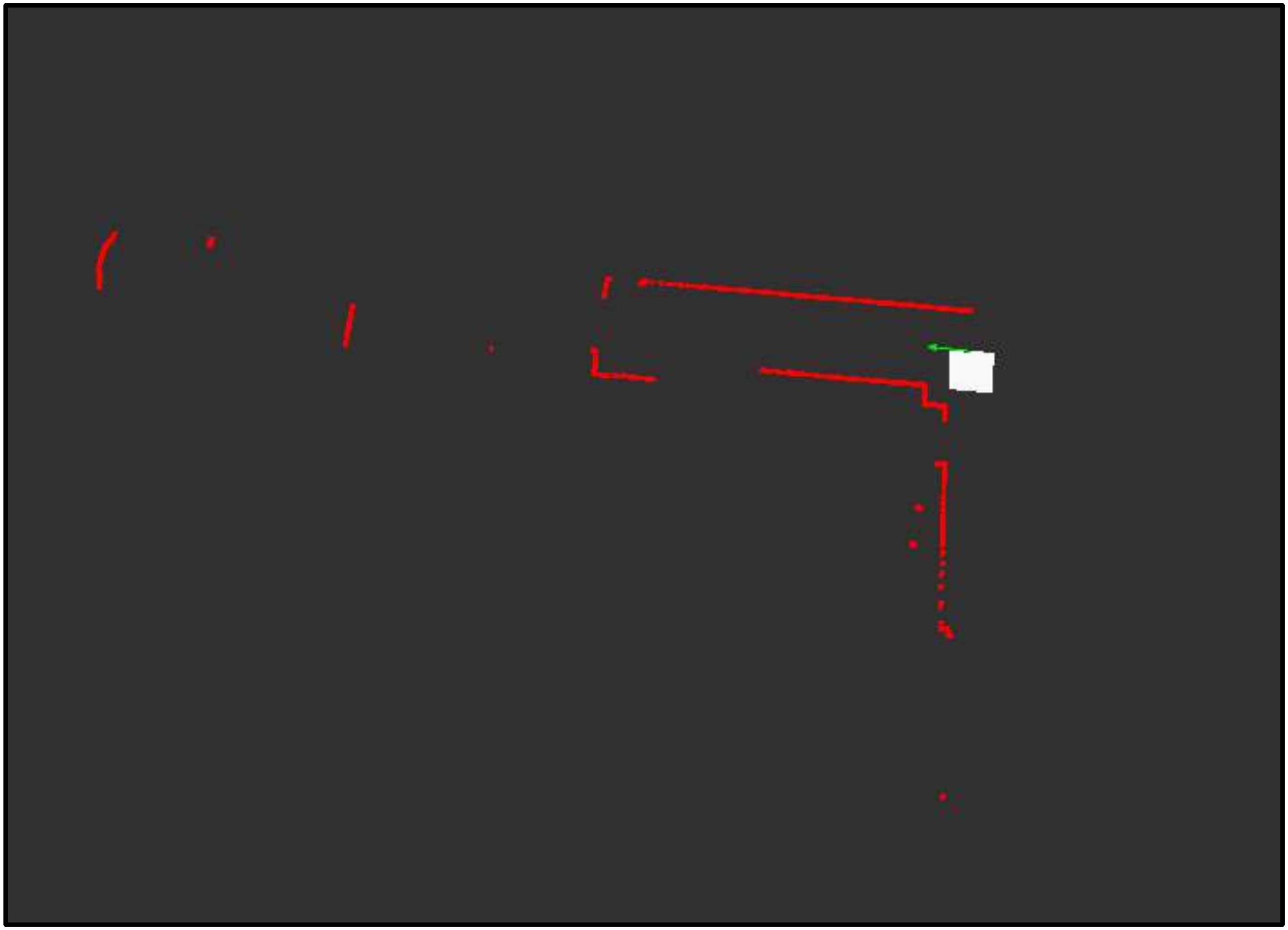
LIDAR

Depth information (how far are objects and obstacles around me)


LIDAR

Hokuyo UST-10LX

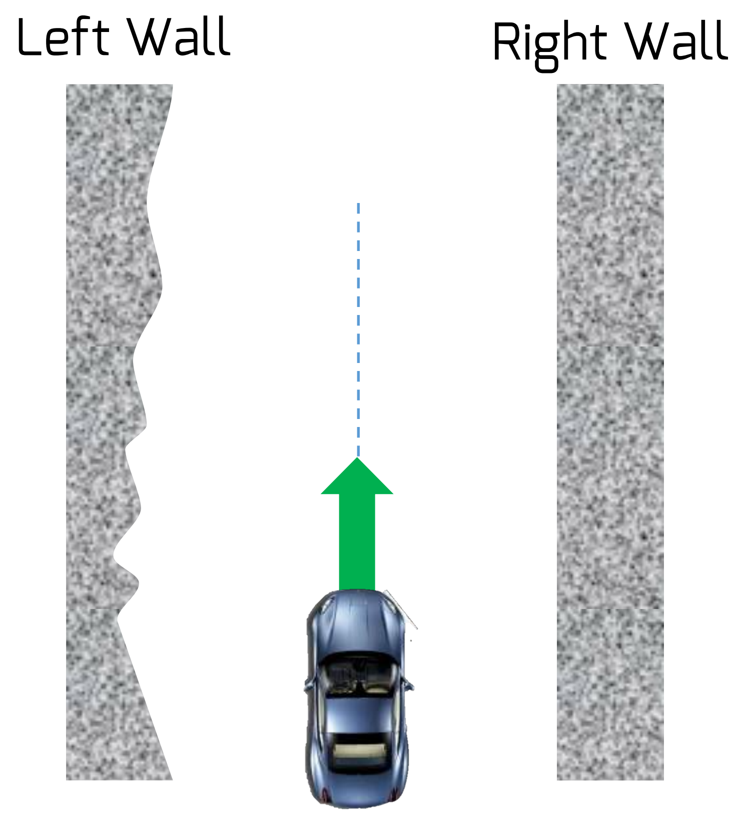




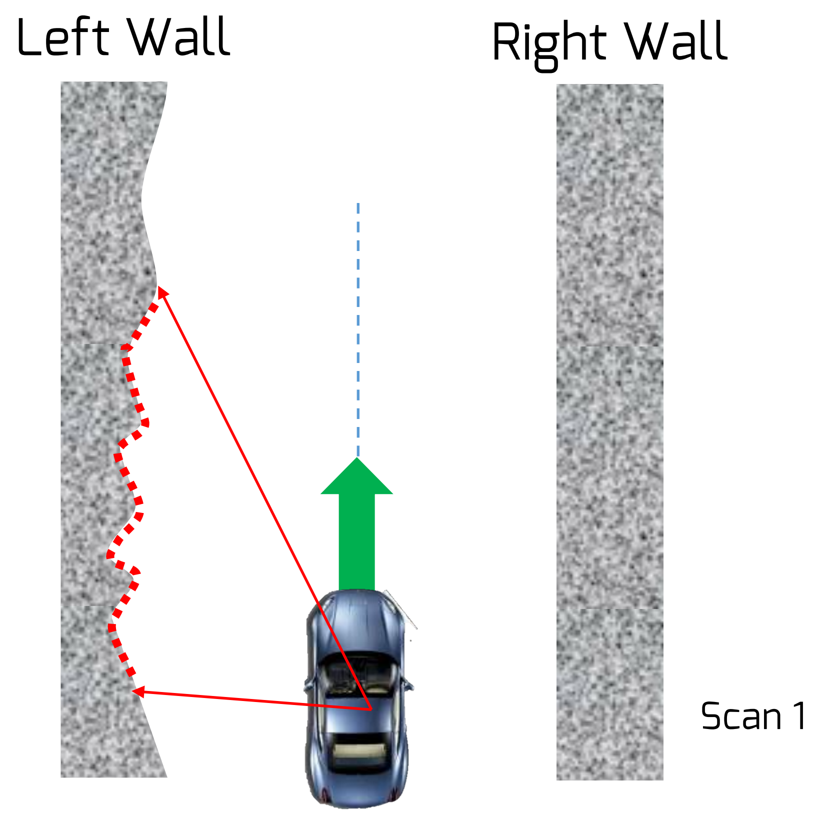
Localization

Know (where is) thyself:

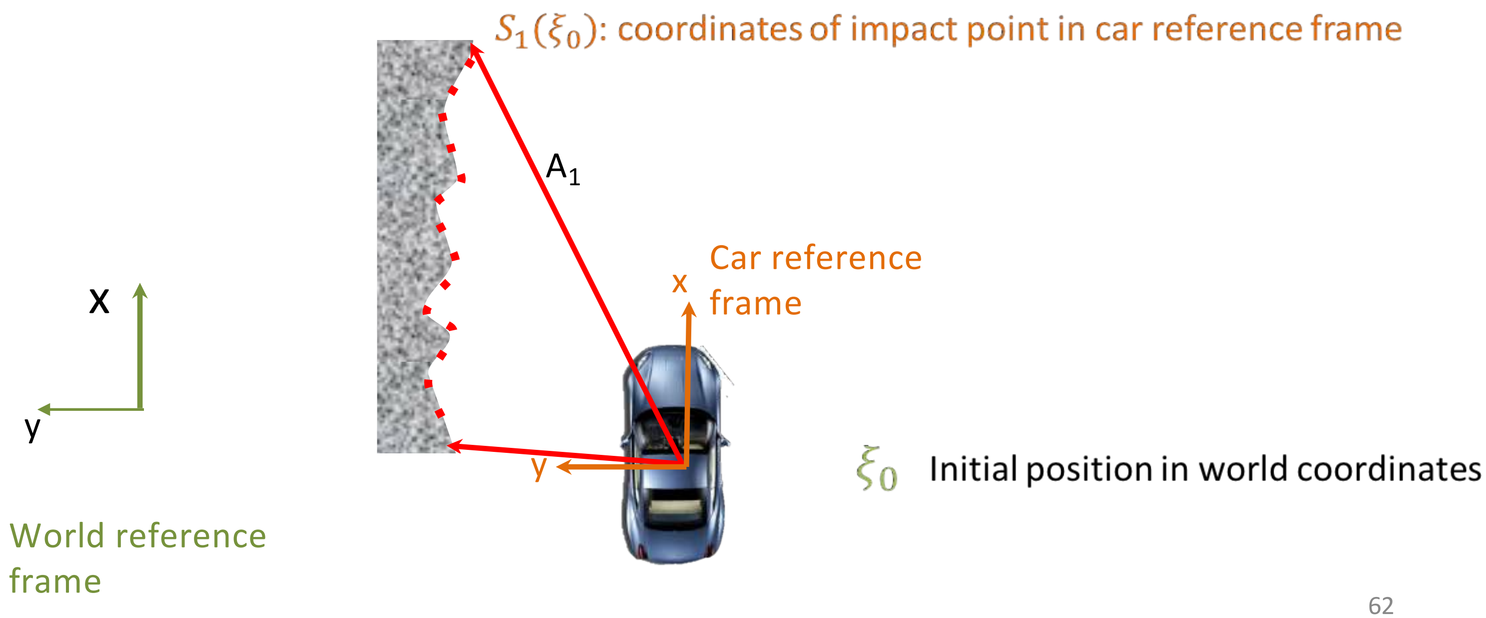
Scan matching



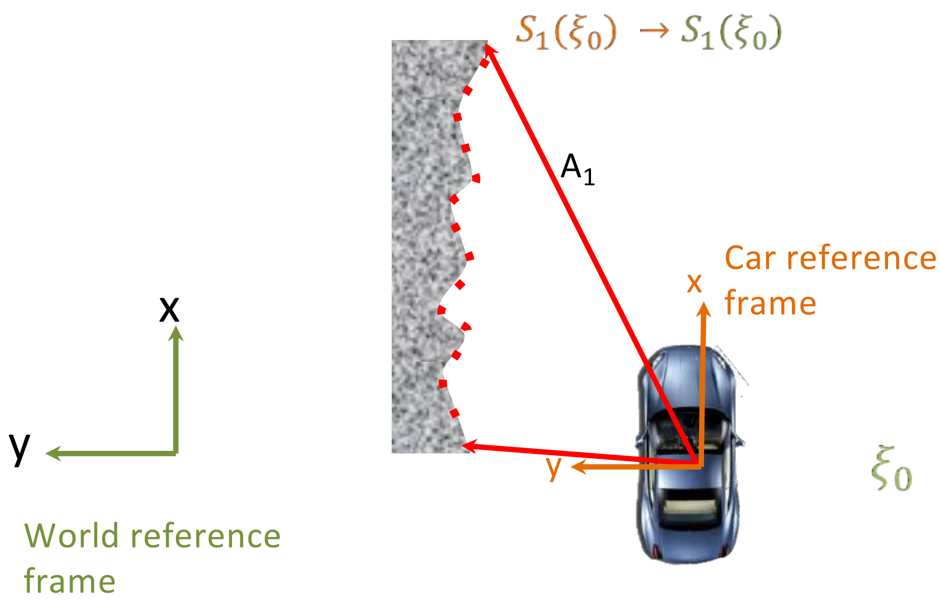
Scan matching



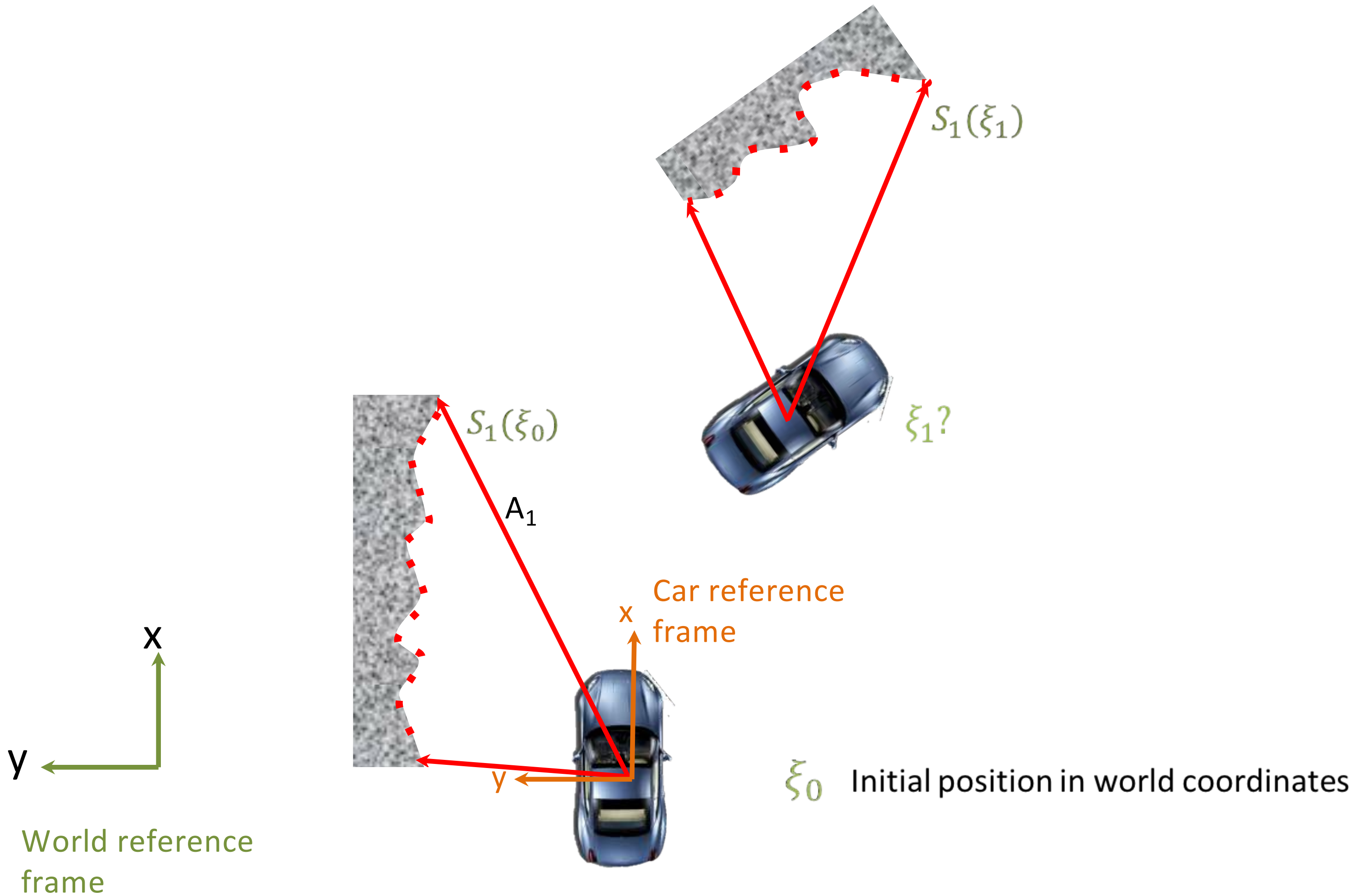
Scan 1

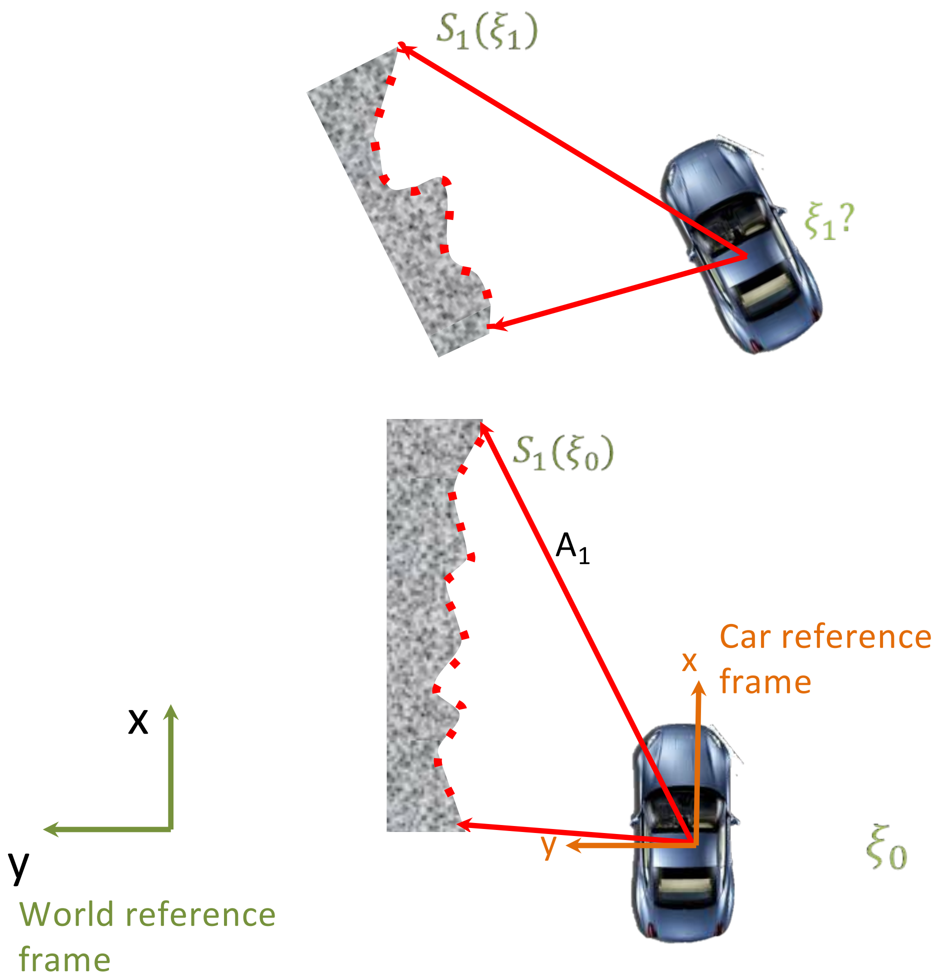

$S_1(\xi_0)$: coordinates of impact point in car reference frame
A_1
Car reference frame
x
y
x
y
World reference frame
ξ_0 Initial position in world coordinates

Scan 1

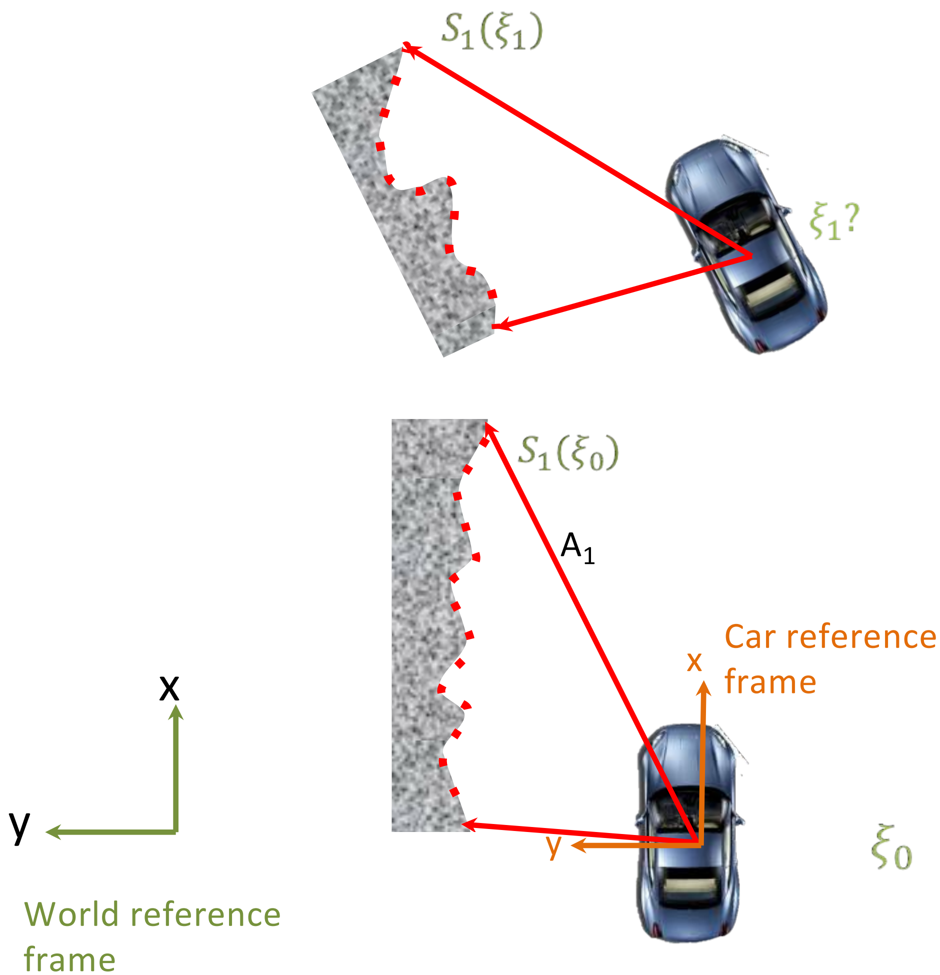


ξ_0 Initial position in world coordinates


$S_1(\xi_1)$
$S_1(\xi_0)$
ξ_1?
A_1
Car reference frame
x
y
x
y
World reference frame
ξ_0 Initial position in world coordinates

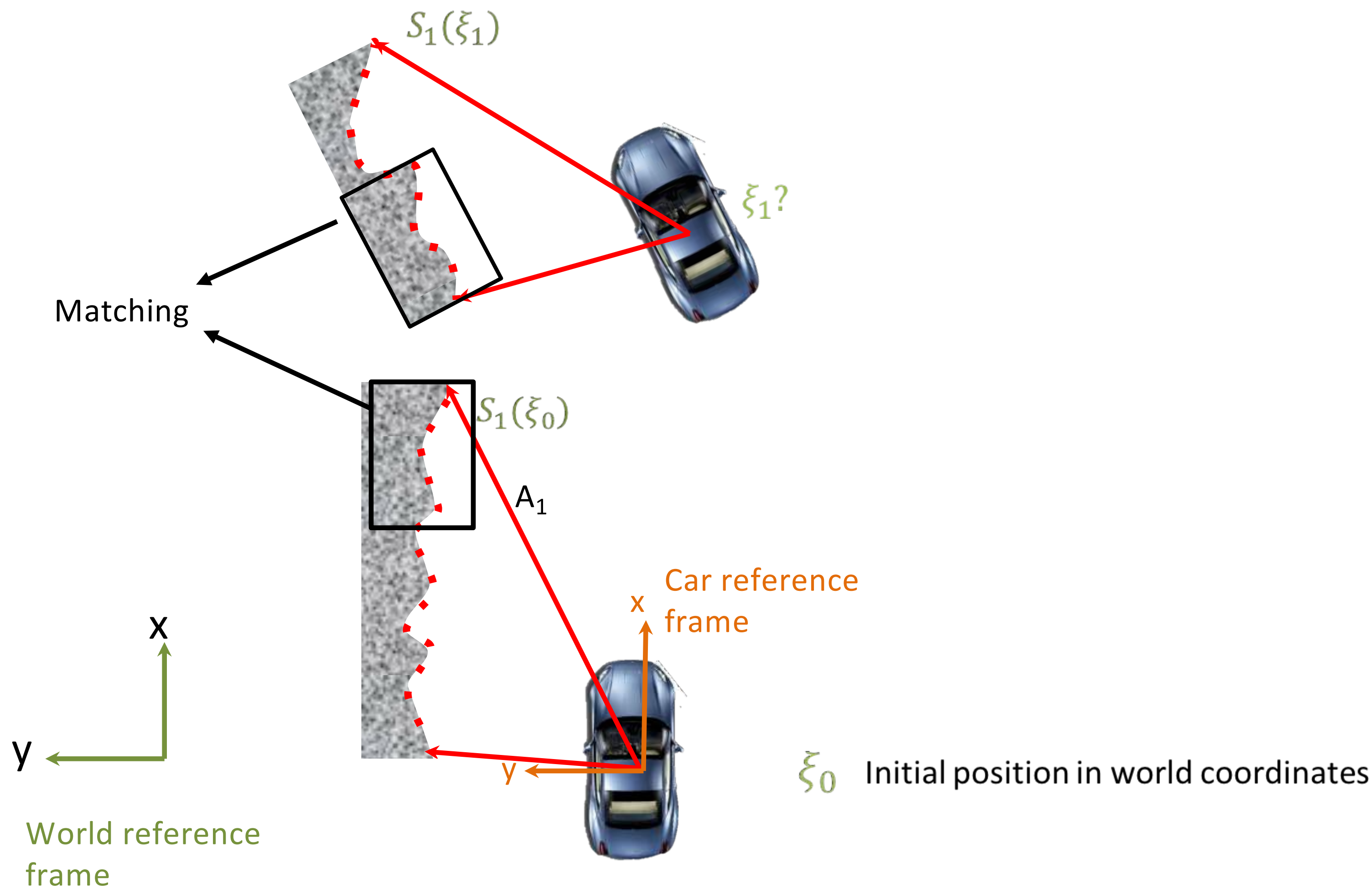


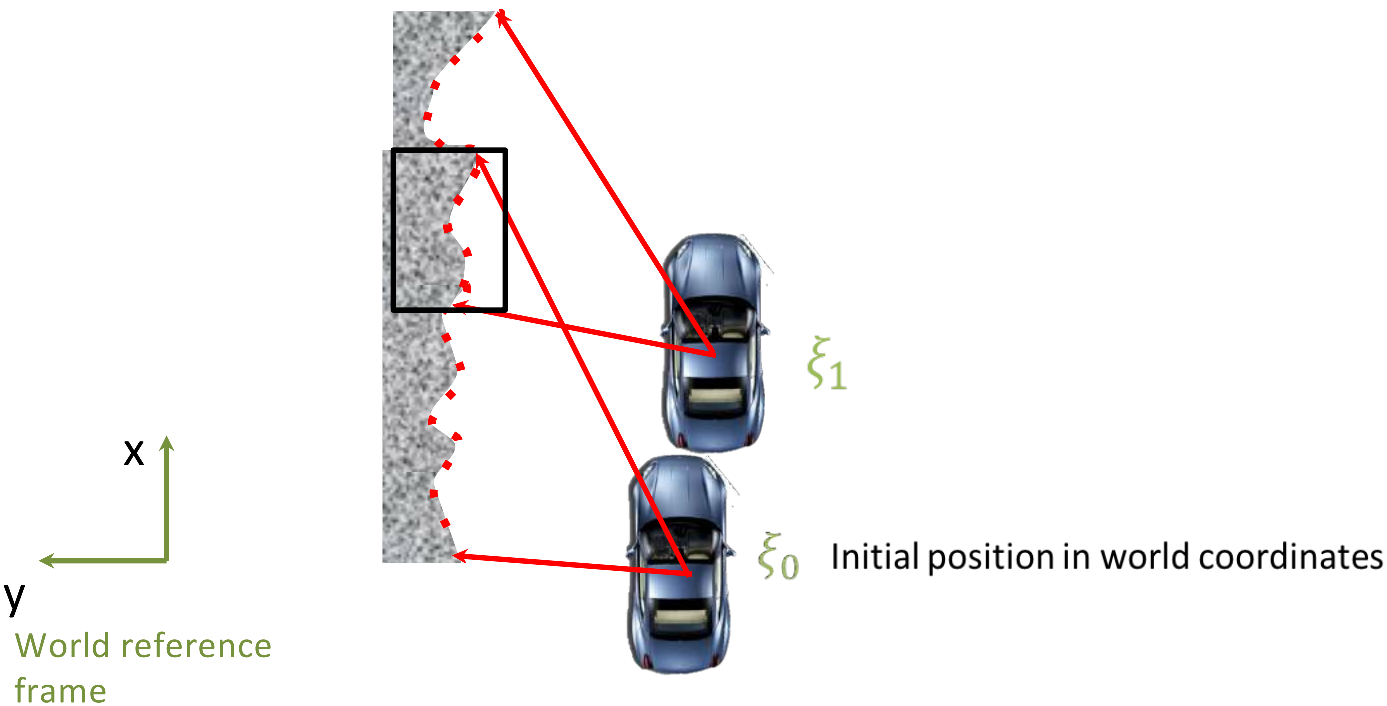
ξ_0 Initial position in world coordinates



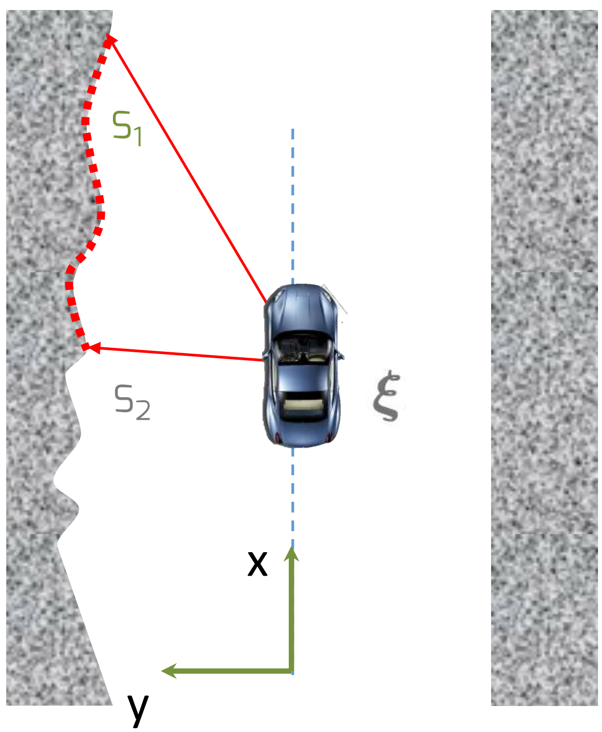
Premise: most likely car position at Scan 2 is the position that gives best overlap between the two scenes

ξ_0 Initial position in world coordinates


$S_1(\xi_1)$
$\xi_1?$
Matching
$S_1(\xi_0)$
A_1
Car reference frame
x
y
x
y
World reference frame
ξ_0 Initial position in world coordinates


x
y
World reference frame
ξ_1
ξ_0
Initial position in world coordinates

Scan matching: optimization



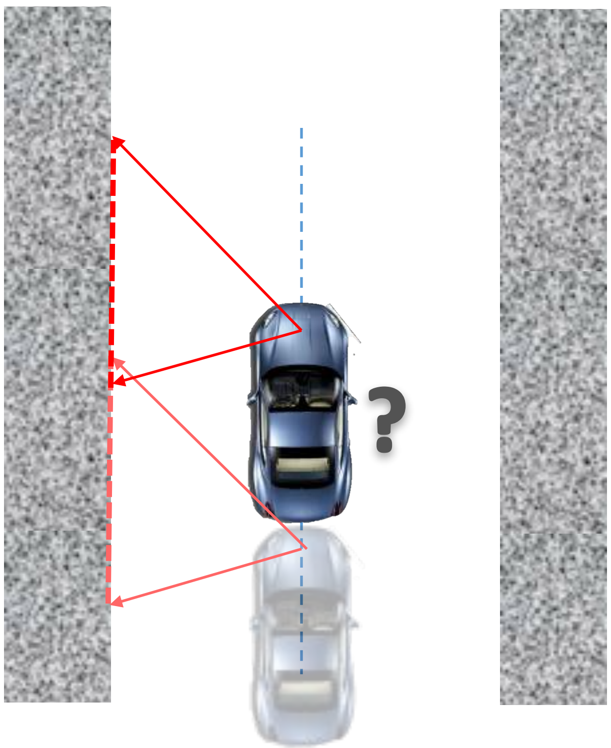
Impact coordinates of ith step in world frame

Total of n steps (n = 1084)

$$\boldsymbol{\xi}^* = \underset{\boldsymbol{\xi}}{\operatorname{argmin}} \sum_{i=1}^{n} \left[1 - M(\mathbf{S}_i(\boldsymbol{\xi}))\right]^2$$

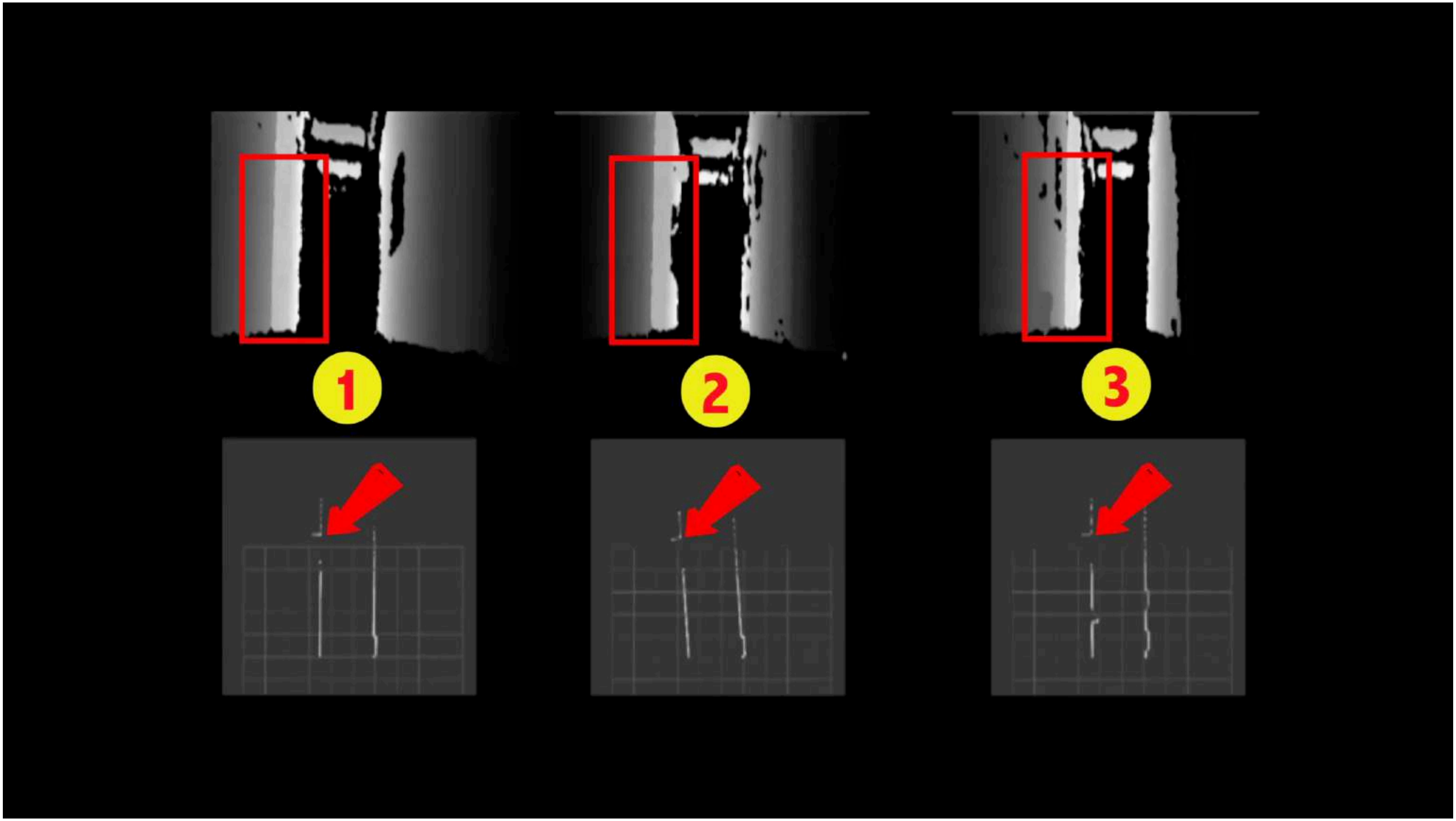
Measure of match

Scan matching : requirements



- Non-smooth, or heterogeneous, surfaces.
- Smooth surfaces all look the same to the matching algorithm.

Door or Turn ?

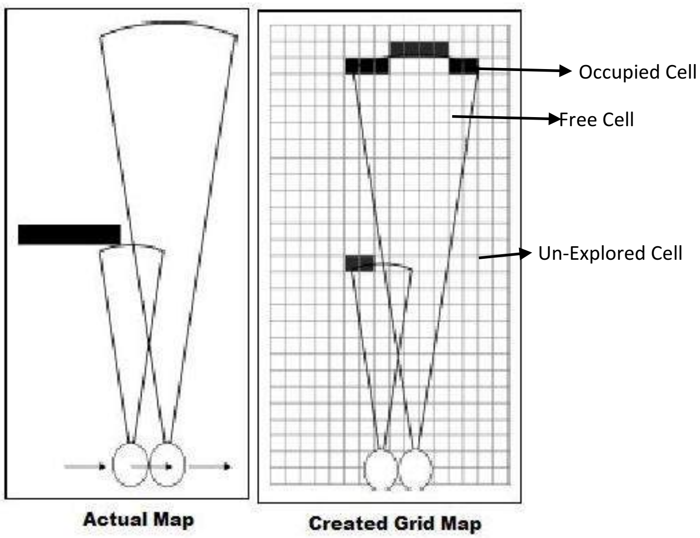


1
2
3

Mapping

Occupancy Grid Mapping

Measurement Model

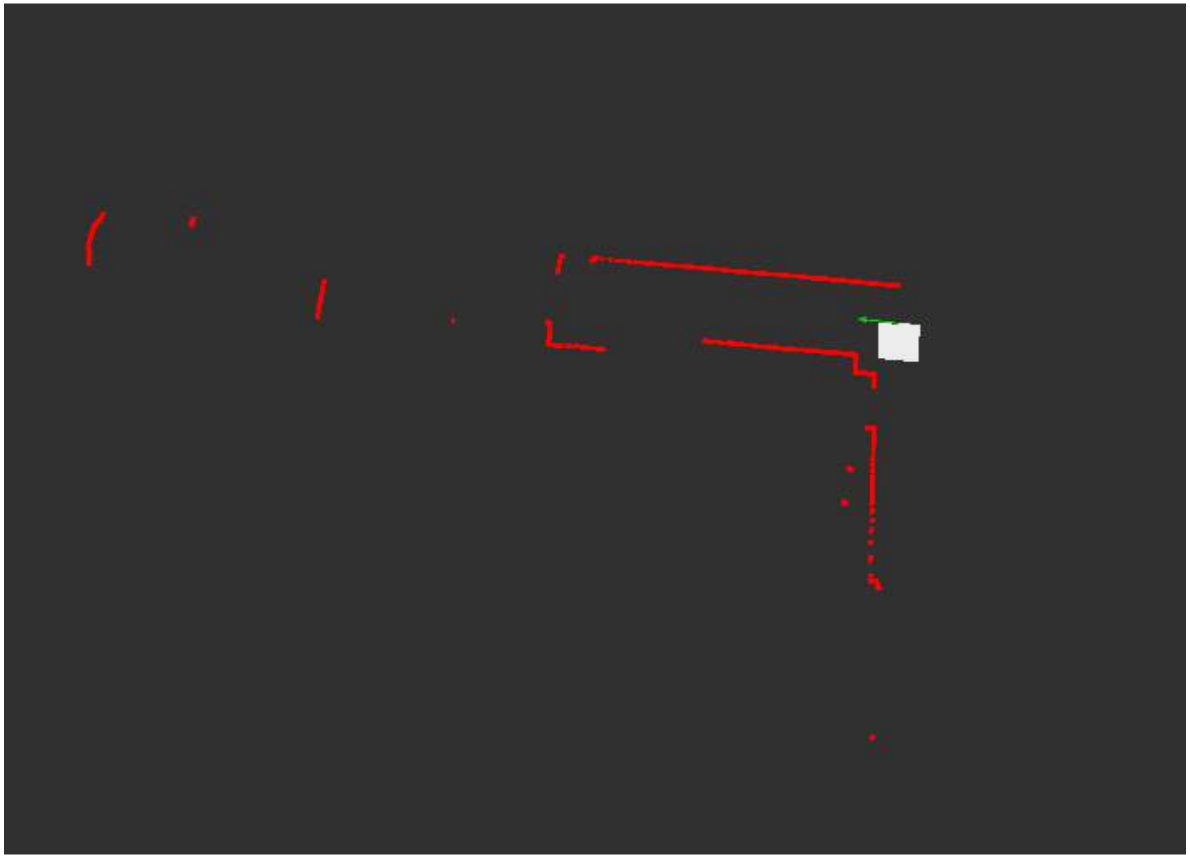


- Measurement :
  - $m_{x,y} = 1$ LiDAR hit
  - $m_{x,y} = 0$ No occlusion
- Map Cell:
  - Z = 1 Occupied
  - Z = 0 UnExplored
  - Z = -1 Free

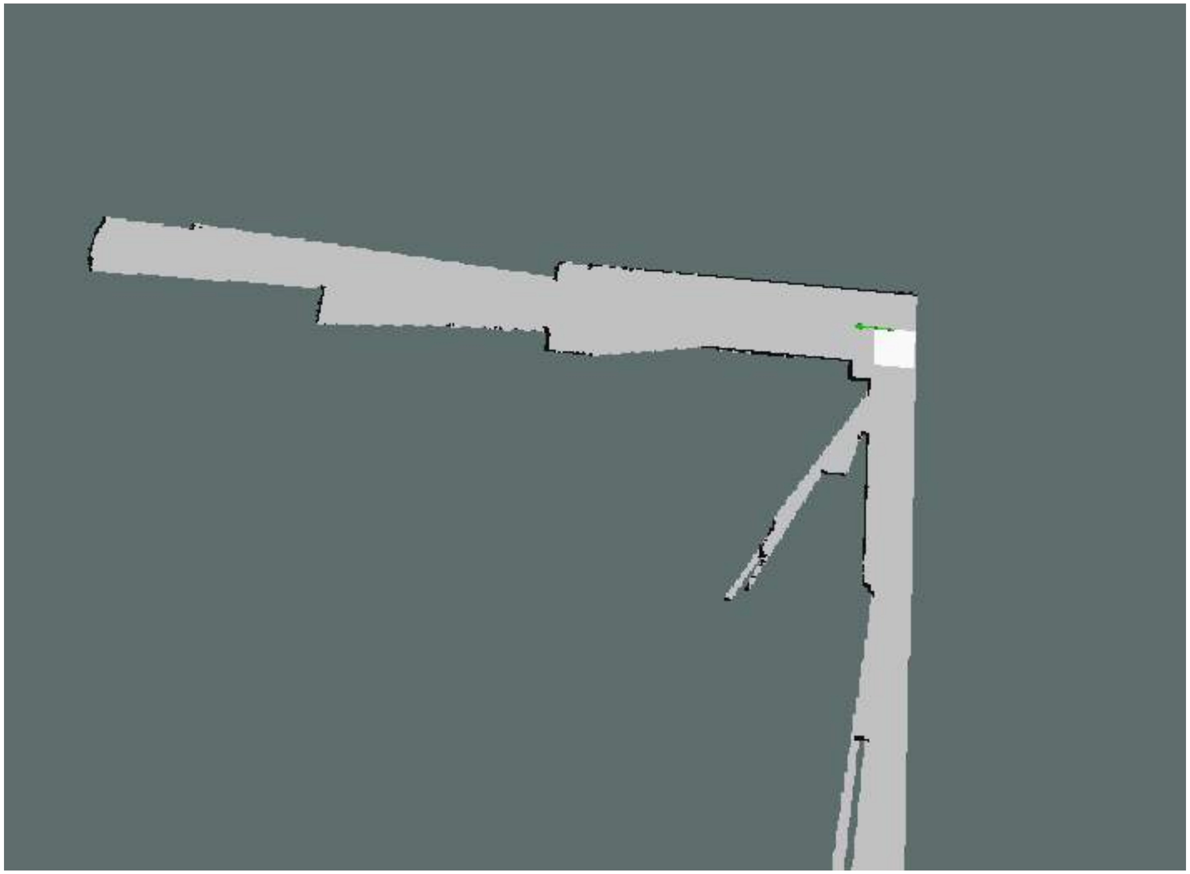
$$p(z|m_{x,y})$$

- Measurement Model :

Registering the first Scan

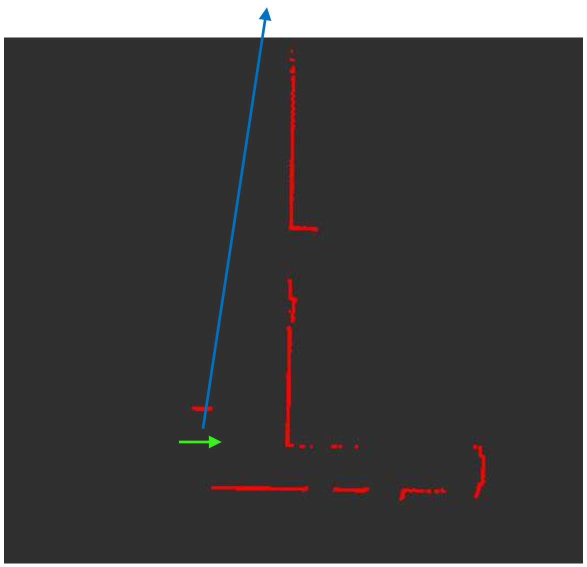


Registering the first Scan

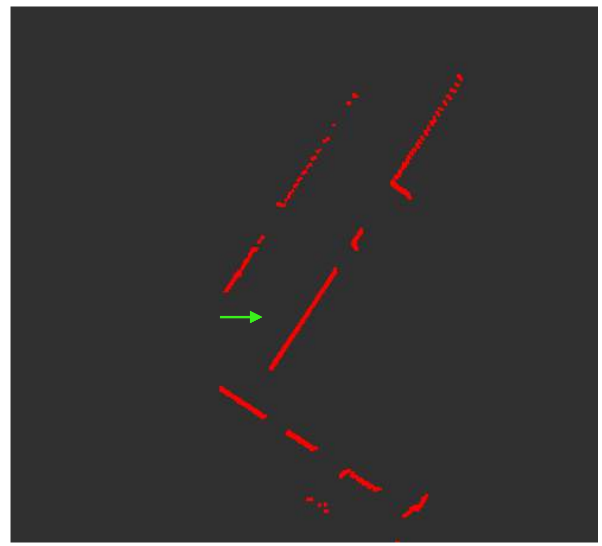


Scan matching

Pose of the Car at t = t1



Laser Scans w.r.t car at Time t = t_1

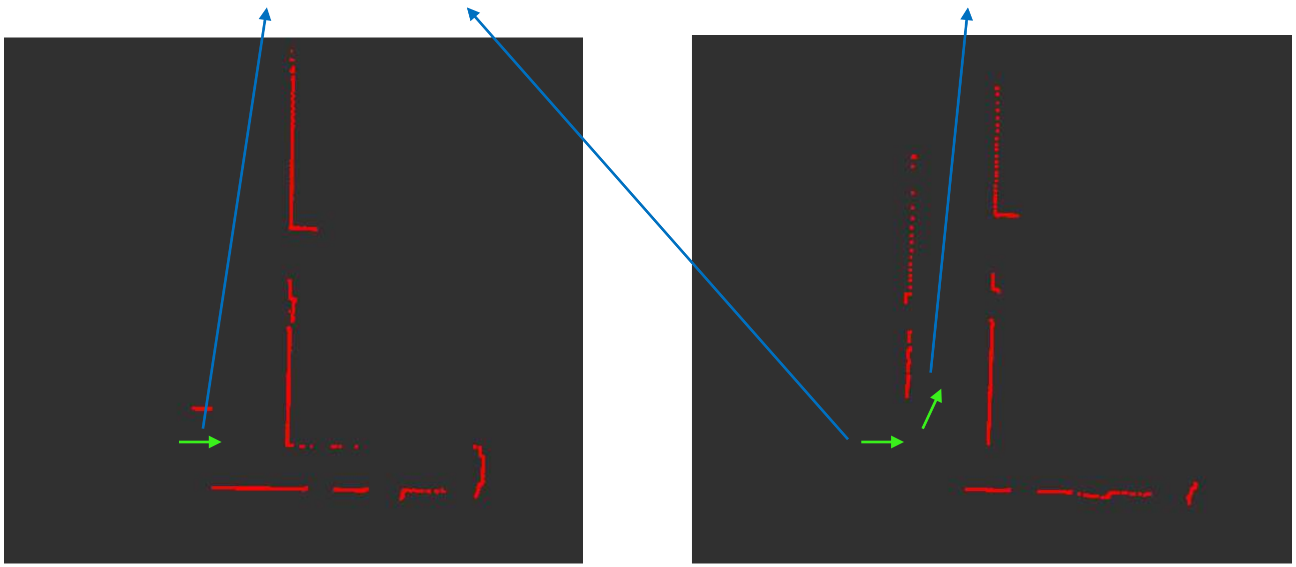


Laser Scans w.r.t car at Time t = t_2

Scan matching

Pose of the Car at t = t1

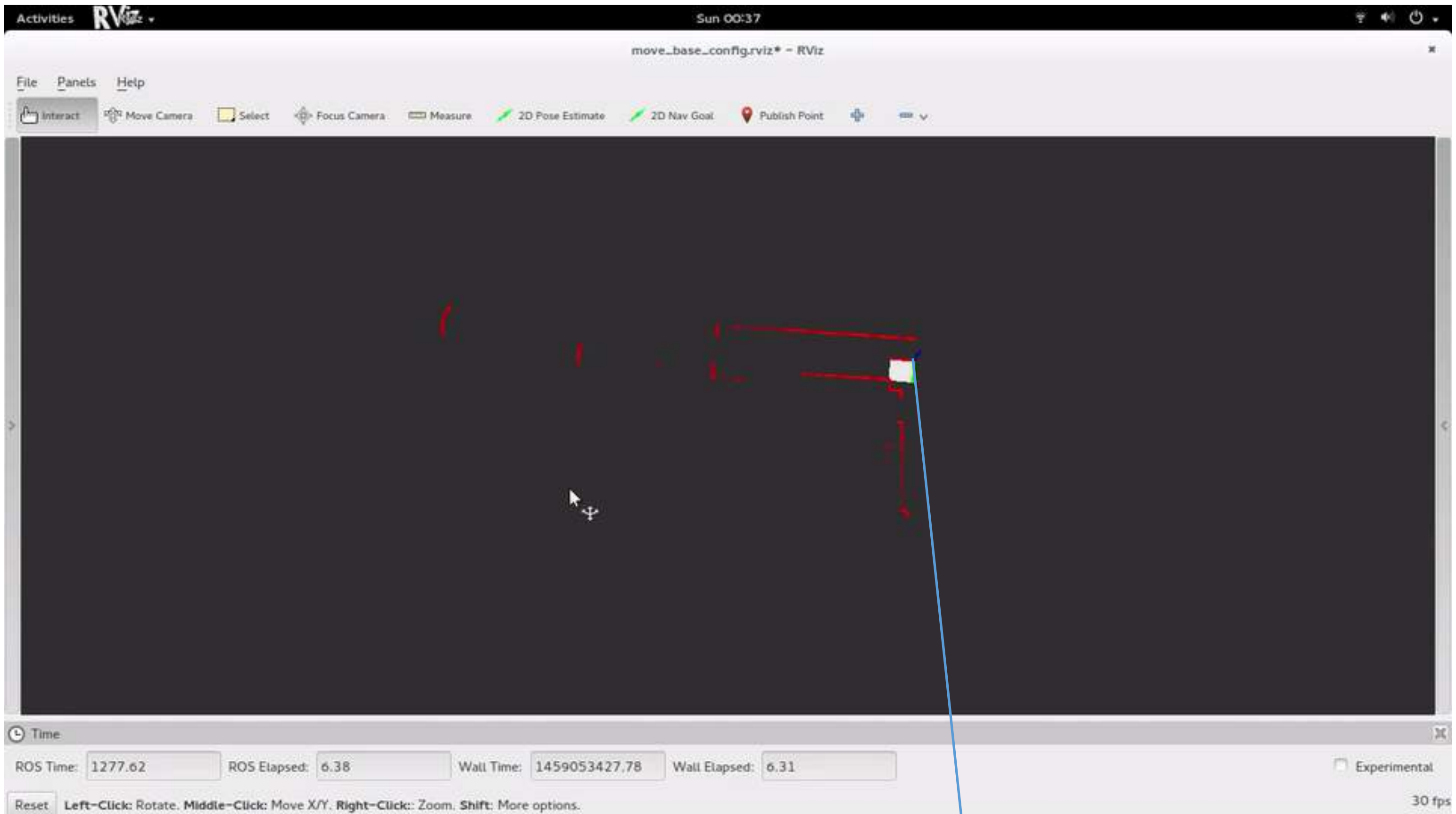
Pose of the Car at t=t2



Laser Scans w.r.t car at Time t = t_1

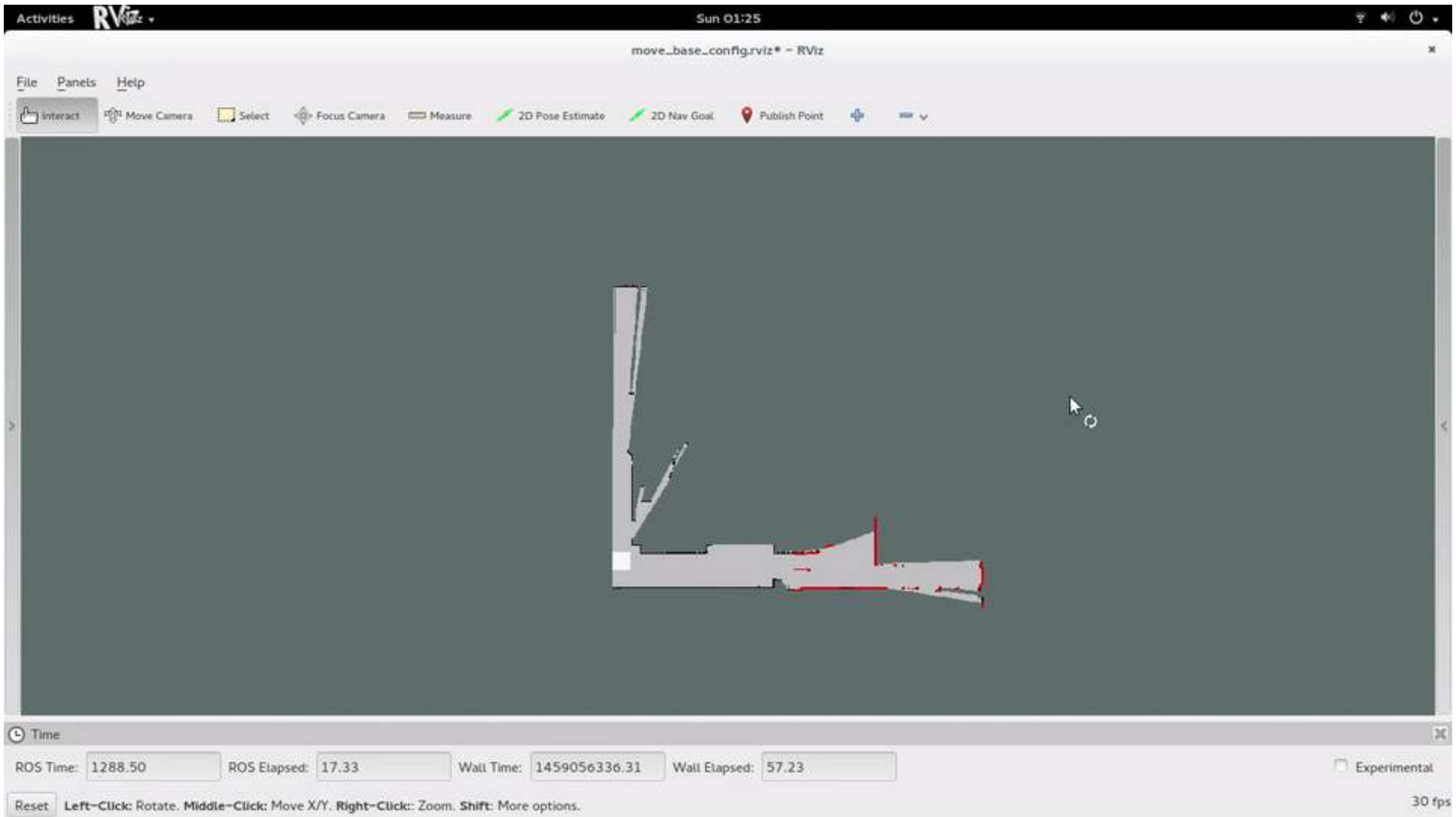
Laser Scans w.r.t car at Time t = t_2

Raw LiDAR Scans

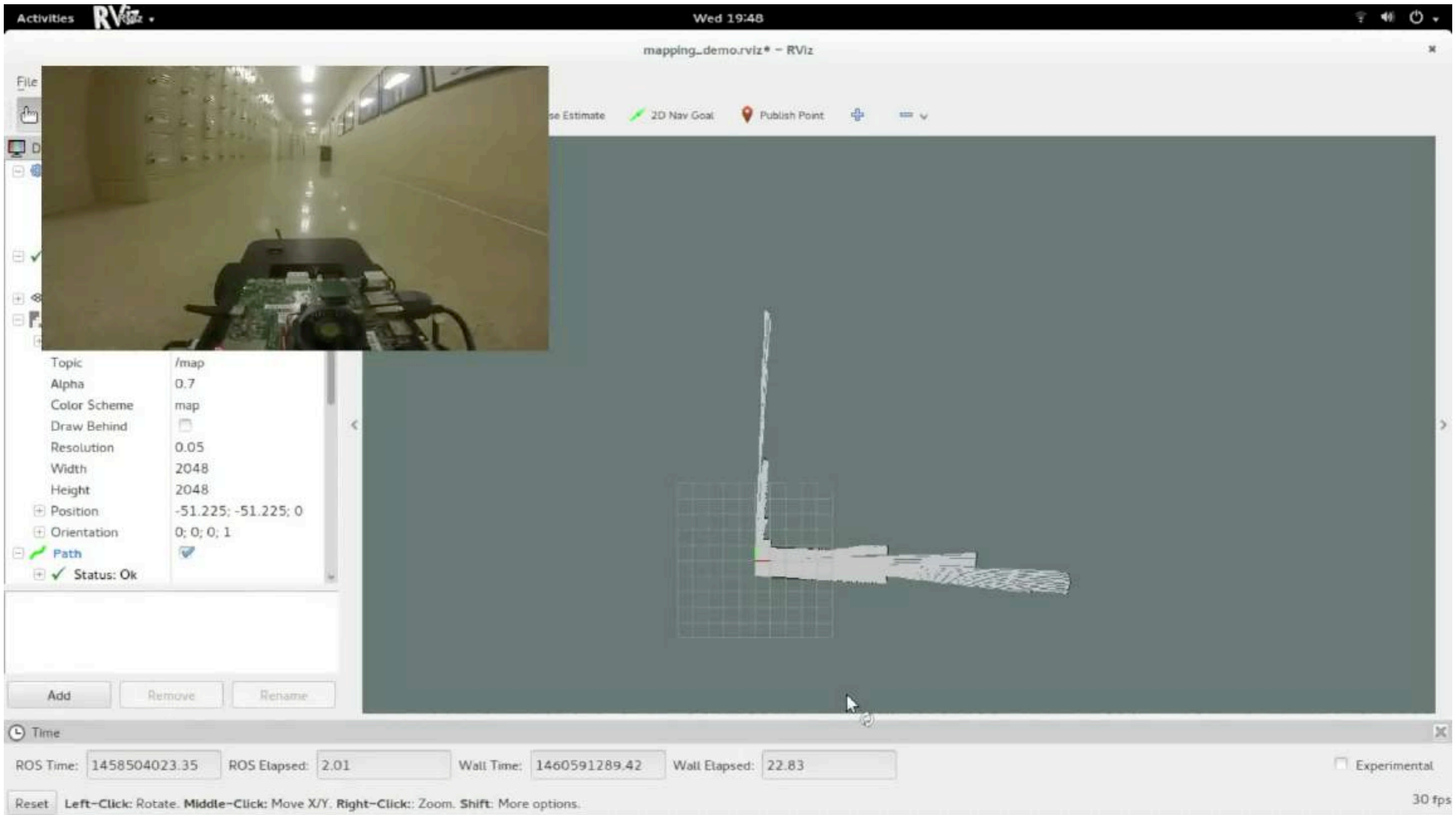


Baseframe Axes

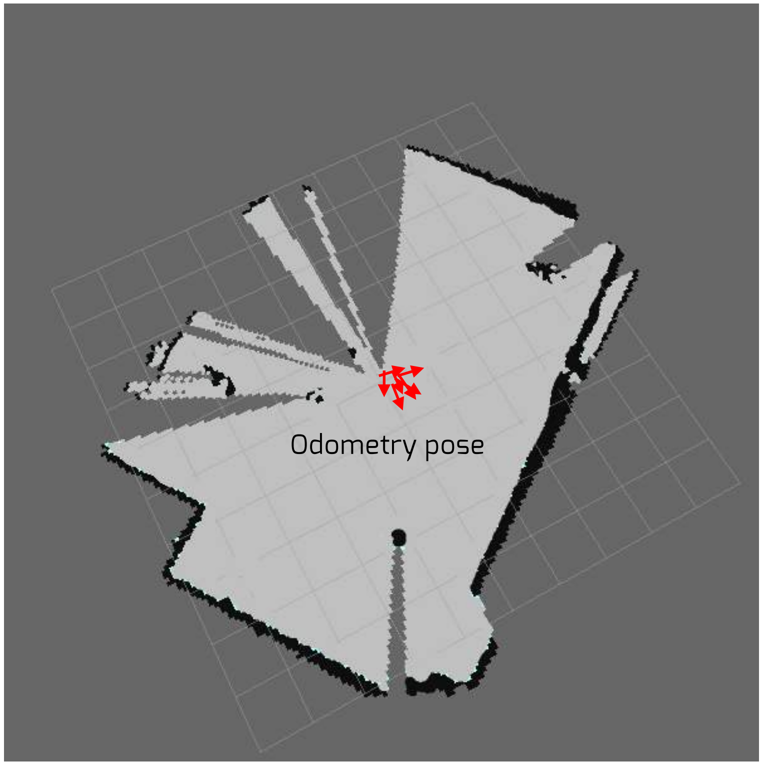
Map Update


Activities
Sun 01:25
move_base_config.rviz* – RViz
File
Panels
Help
Interact
Move Camera
Select
Focus Camera
Measure
2D Pose Estimate
2D Nav Goal
Publish Point
Time
ROS Time: 1288.50
ROS Elapsed: 17.33
Wall Time: 1459056336.31
Wall Elapsed: 57.23
Experimental
Reset
Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click:: Zoom. Shift: More options.
30 fps

Hector SLAM


Activities
Wed 19:48
mapping_demo.rviz* – RViz
File
se Estimate
2D Nav Goal
Publish Point
Topic /map
Alpha 0.7
Color Scheme map
Draw Behind
Resolution 0.05
Width 2048
Height 2048
Position -51.225; -51.225; 0
Orientation 0; 0; 0; 1
Path
Status: Ok
Add
Remove
Rename
Time
ROS Time: 1458504023.35
ROS Elapsed: 2.01
Wall Time: 1460591289.42
Wall Elapsed: 22.83
Experimental
Reset
Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click:: Zoom. Shift: More options.
30 fps

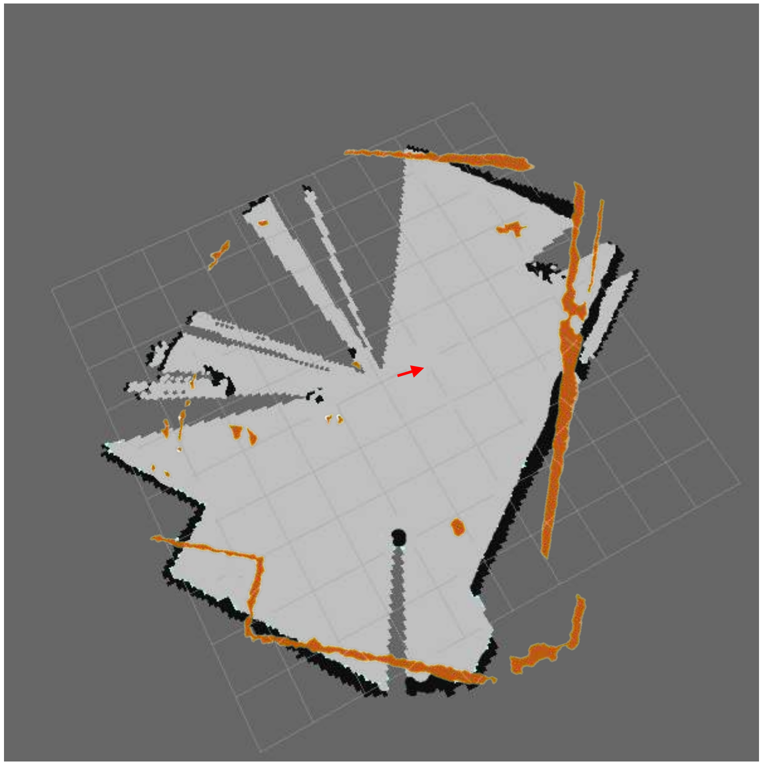
Particle Filter in 2D: Localization



Scan Correlation

$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n \left(A_{mn} - \overline{A}\right)^2\right)\left(\sum_m \sum_n \left(B_{mn} - \overline{B}\right)^2\right)}}$$

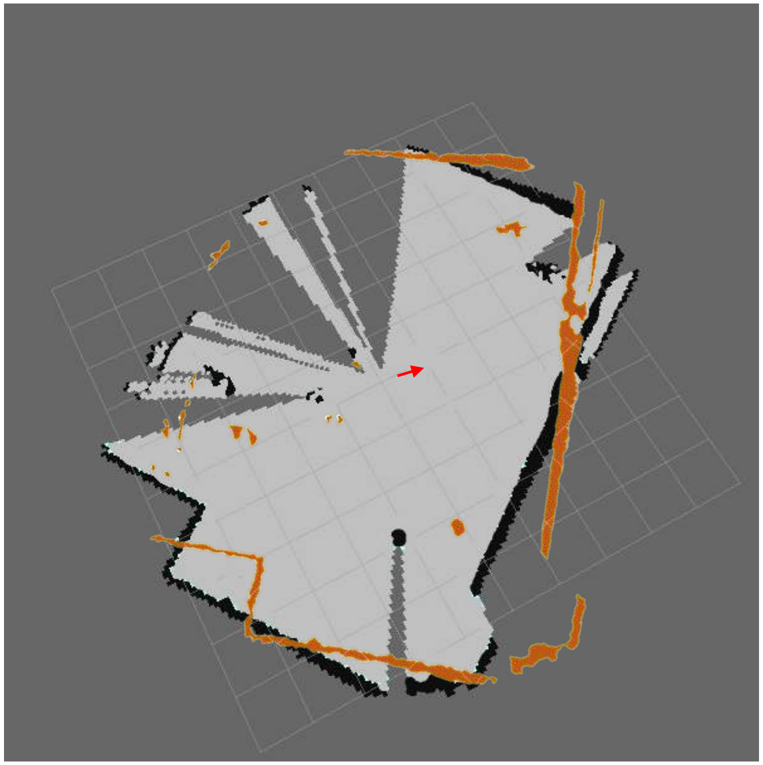
Particle Weight



Scan Correlation

$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \overline{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \overline{B})^2\right)}}$$

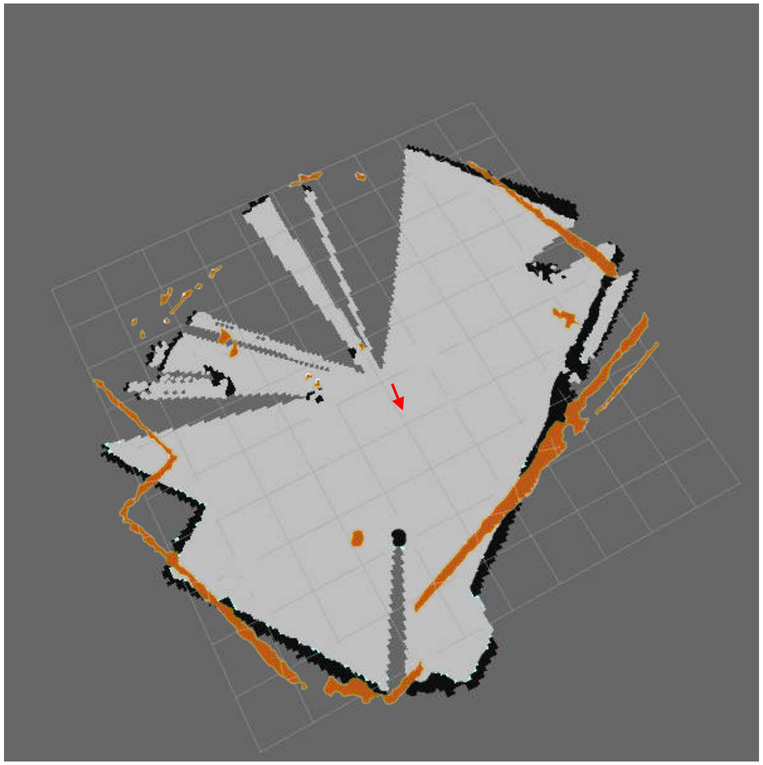
Particle	Weight
Particle 1	W_1



Scan Correlation

$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \overline{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \overline{B})^2\right)}}$$

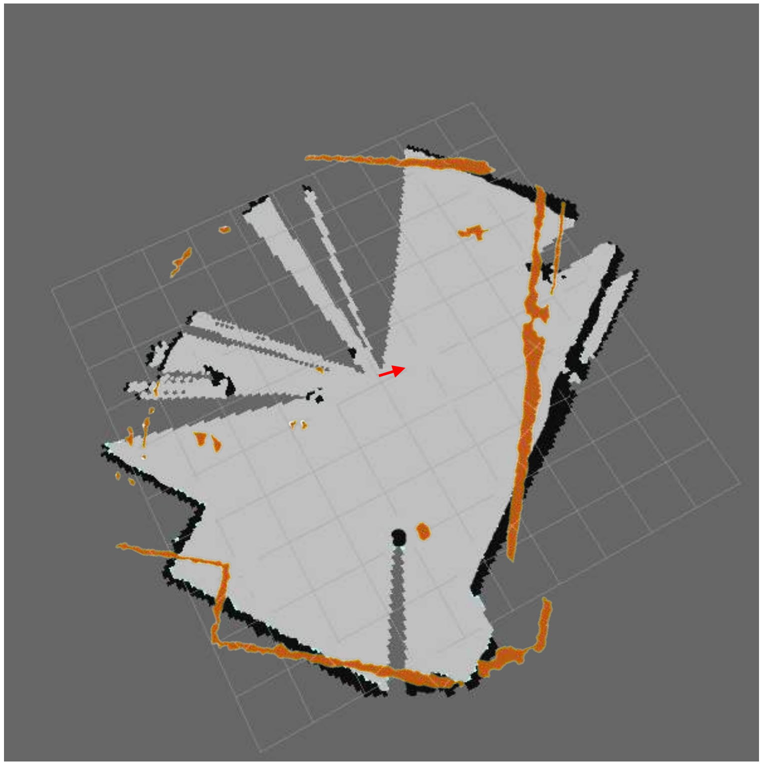
Particle	Weight
Particle 1	W_1
Particle 2	W_2



Scan Correlation

$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \overline{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \overline{B})^2\right)}}$$

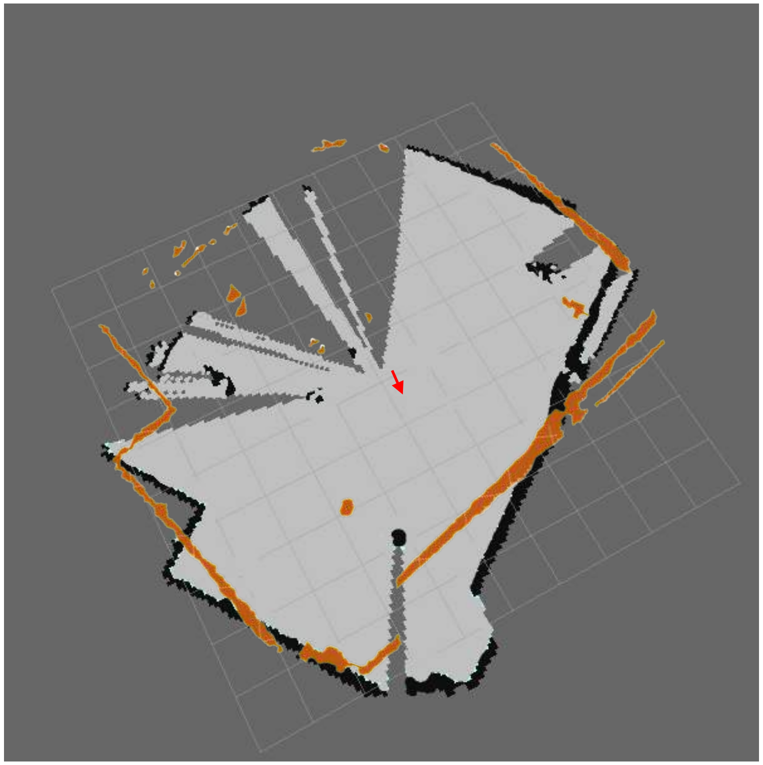
Particle	Weight
Particle 1	W_1
Particle 2	W_2
Particle 3	W_3



Scan Correlation

$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \overline{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \overline{B})^2\right)}}$$

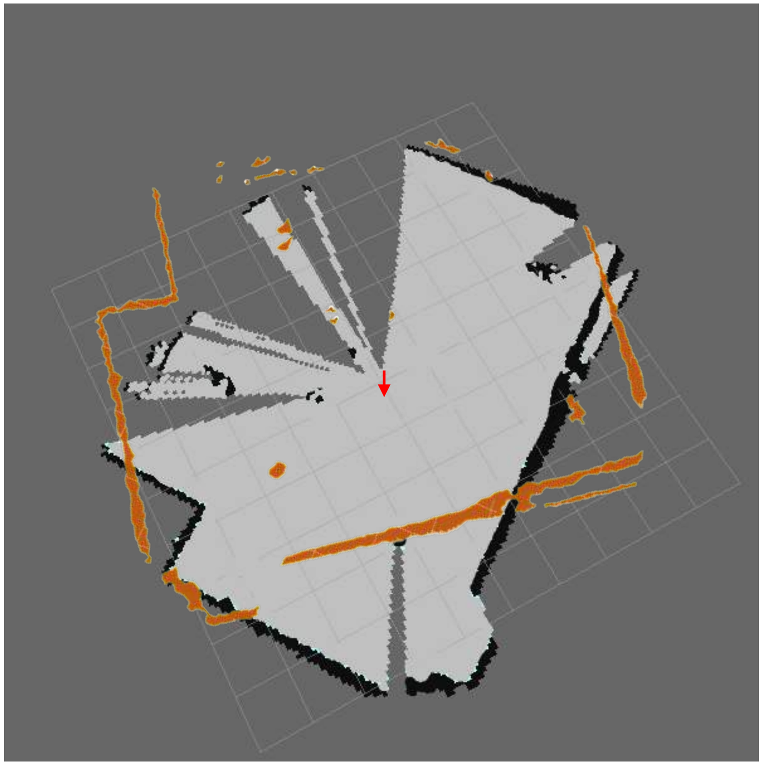
Particle	Weight
Particle 1	W_1
Particle 2	W_2
Particle 3	W_3
Particle 4	W_4



Scan Correlation

$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \overline{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \overline{B})^2\right)}}$$

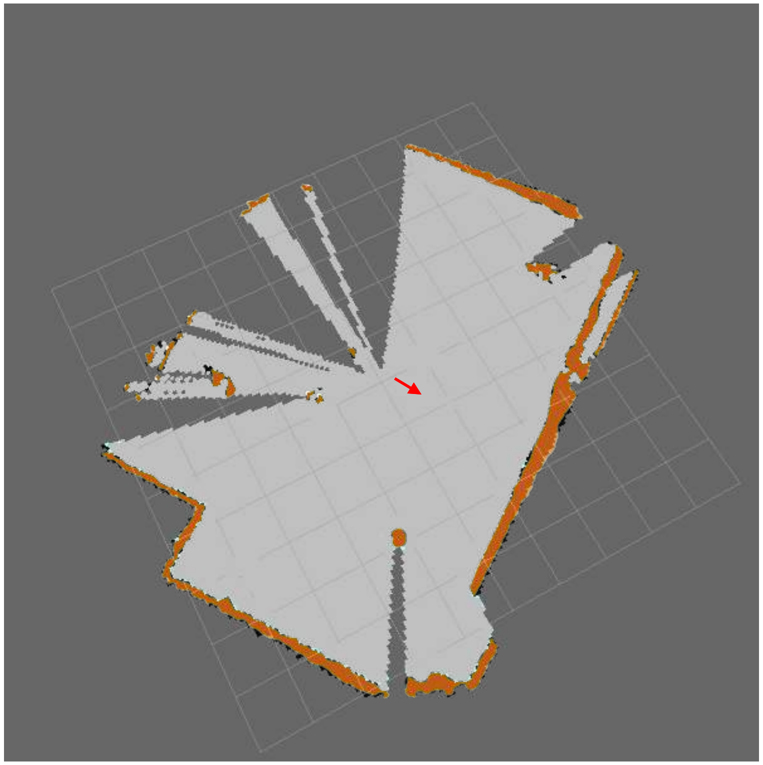
Particle	Weight
Particle 1	W_1
Particle 2	W_2
Particle 3	W_3
Particle 4	W_4
Particle 5	W_5



Scan Correlation

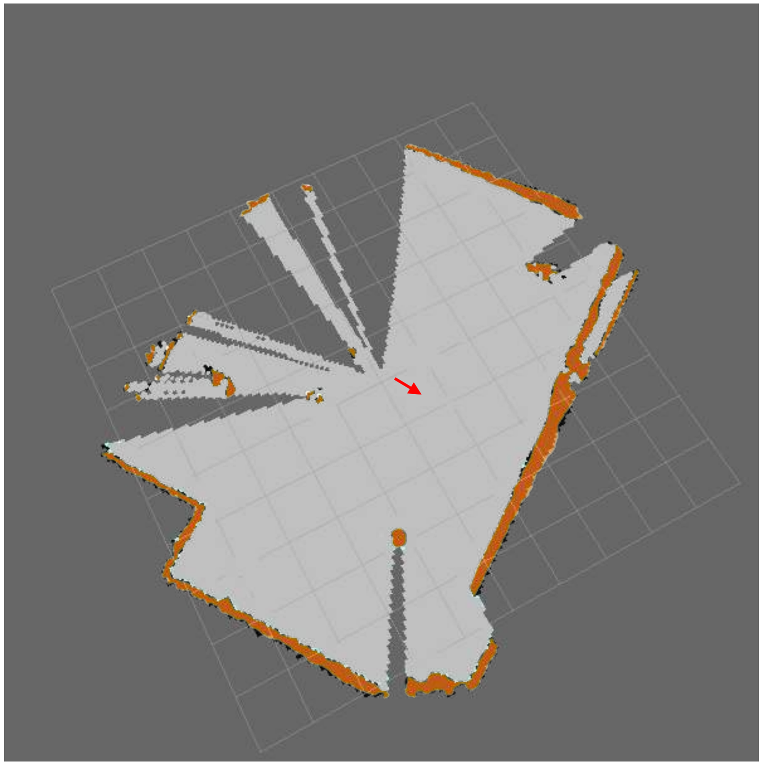
$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \overline{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \overline{B})^2\right)}}$$

Particle	Weight
Particle 1	W_1
Particle 2	W_2
Particle 3	W_3
Particle 4	W_4
Particle 5	W_5
Particle 6	W_6



Scan Correlation

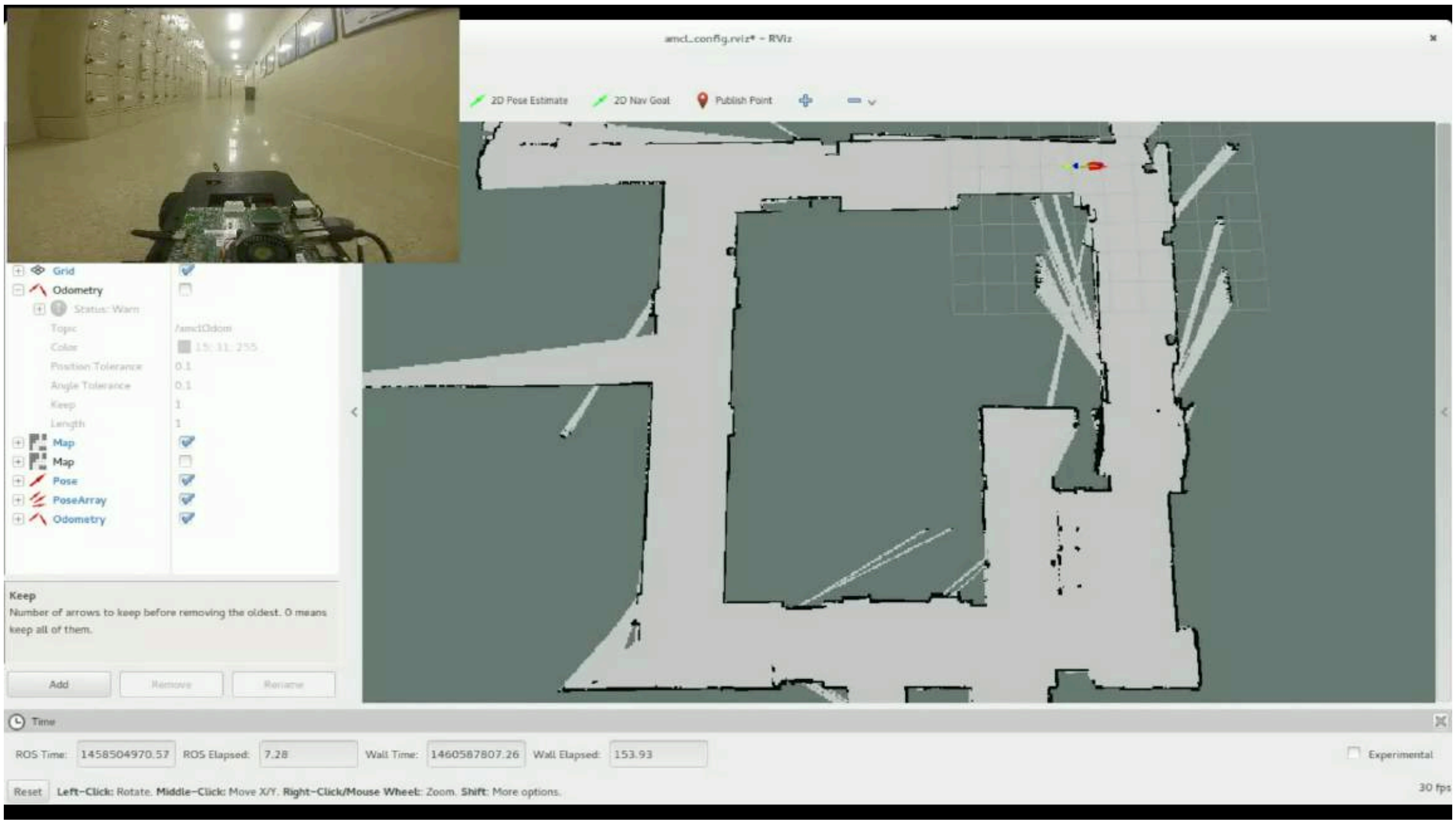
$$W = \frac{\sum_m \sum_n (Amn - \overline{A})(Bmn - \overline{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \overline{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \overline{B})^2\right)}}$$



Particle	Weight
Particle 1	W_1
Particle 2	W_2
Particle 3	W_3
Particle 4	W_4
Particle 5	W_5
Particle 6	W_6

$$W_t \leftarrow W_{t\,-\,1} \times Wt$$

AMCL- Adaptive Monte Carlo Localization



Control

Proportional, **I**ntegral, **D**erivative control

PID control: tuning the gains

- Default set of gains, determined empirically to work well for this car.
  - $K_p = 14$
  - $K_i = 0$
  - $K_d = 0.09$

Nominal gains

PID control: tuning the gains

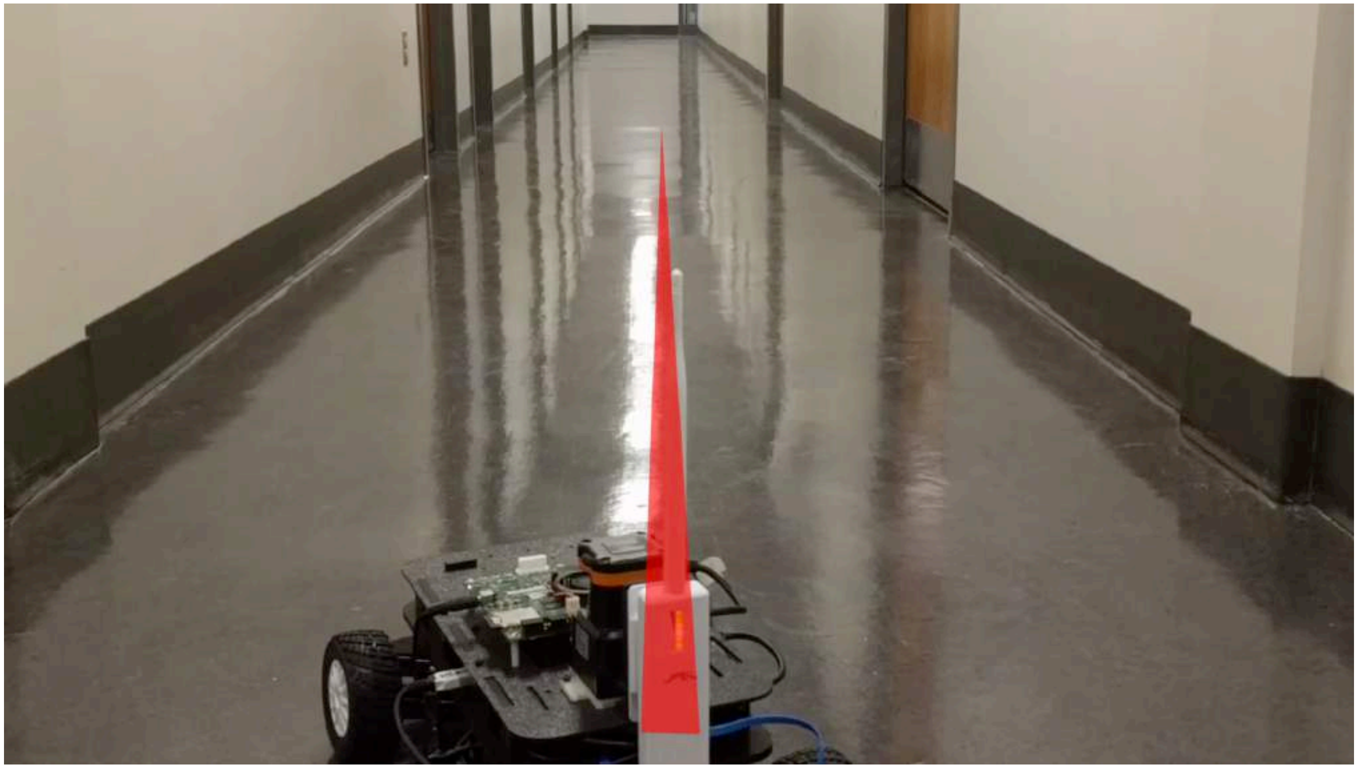
- Reduce K_p → less responsive to error magnitude
  - K_p = 5
  - K_i = 0
  - K_d = 0.09

Smaller Kp

PID control: tuning the gains

- Include K_i → overly sensitive to accumulating error → over-correction
  - $K_p = 14$
  - $K_i = 2$
  - $K_d = 0.09$

Add integral control

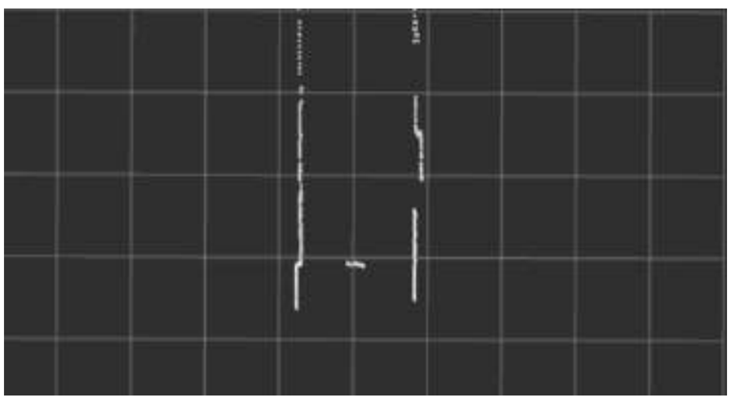


Race

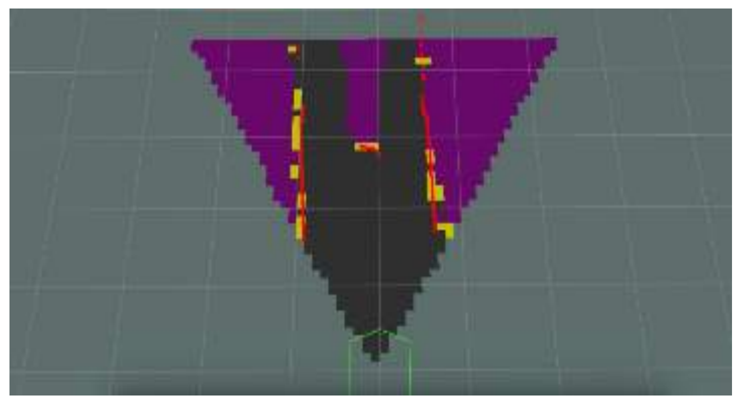
Putting it all together..

RGB Image used to ID dynamic obstacles

Depth image provides 3D pointcloud



Laser scan 3D point cloud to 2D plane



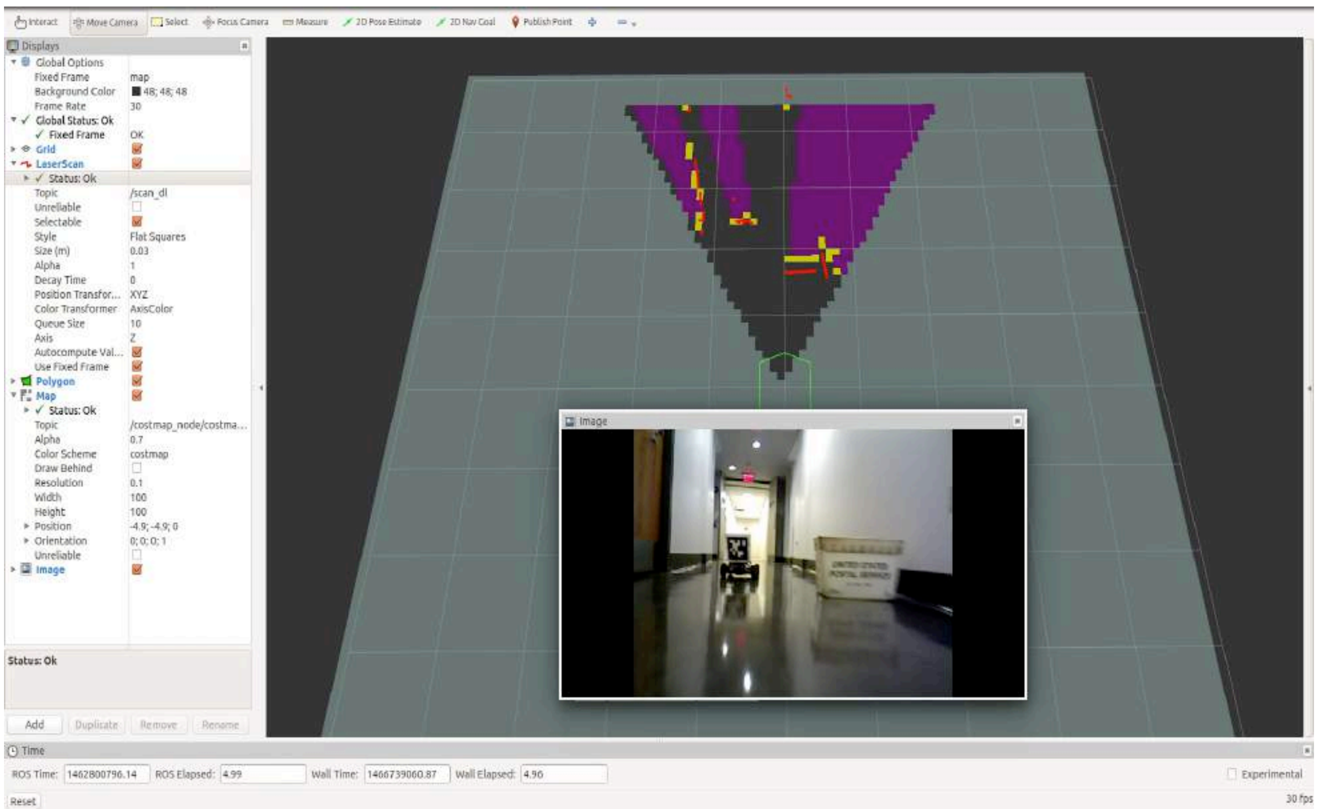
Virtual scan free space, obstacles, and occlusions

Putting it all together..

Estimate the position, orientation, and velocity of other racers?

Local trajectory Planner ?

Overtaking ?

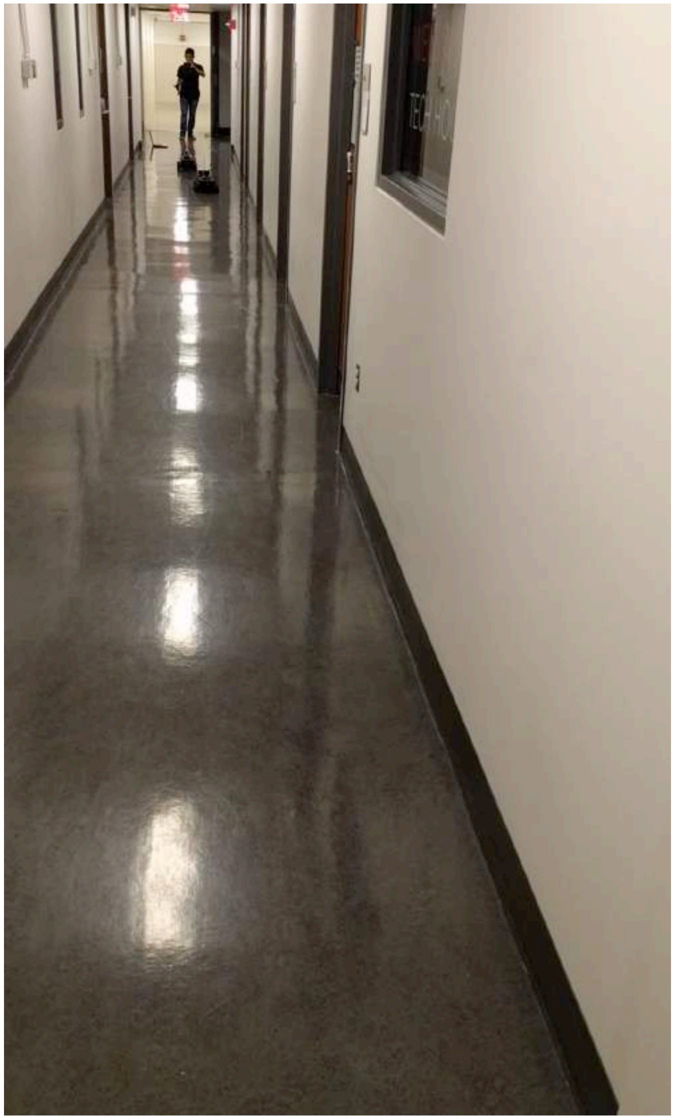


F1/10 Challenges

- **Project Insanity:** Testing the limits of racing control.
- **Optimal racing line** determination.
- **Overtaking** strategies and algorithms.

Overtaking Algorithms ?

Overtaking Algorithms ?



The F1/10 Racing Crew

Paril Jain

Nischal KN

Paritosh Kelkar

Matt Brady

Matthew Kelly

Jake Scherlis

You !!

Carter Sharer

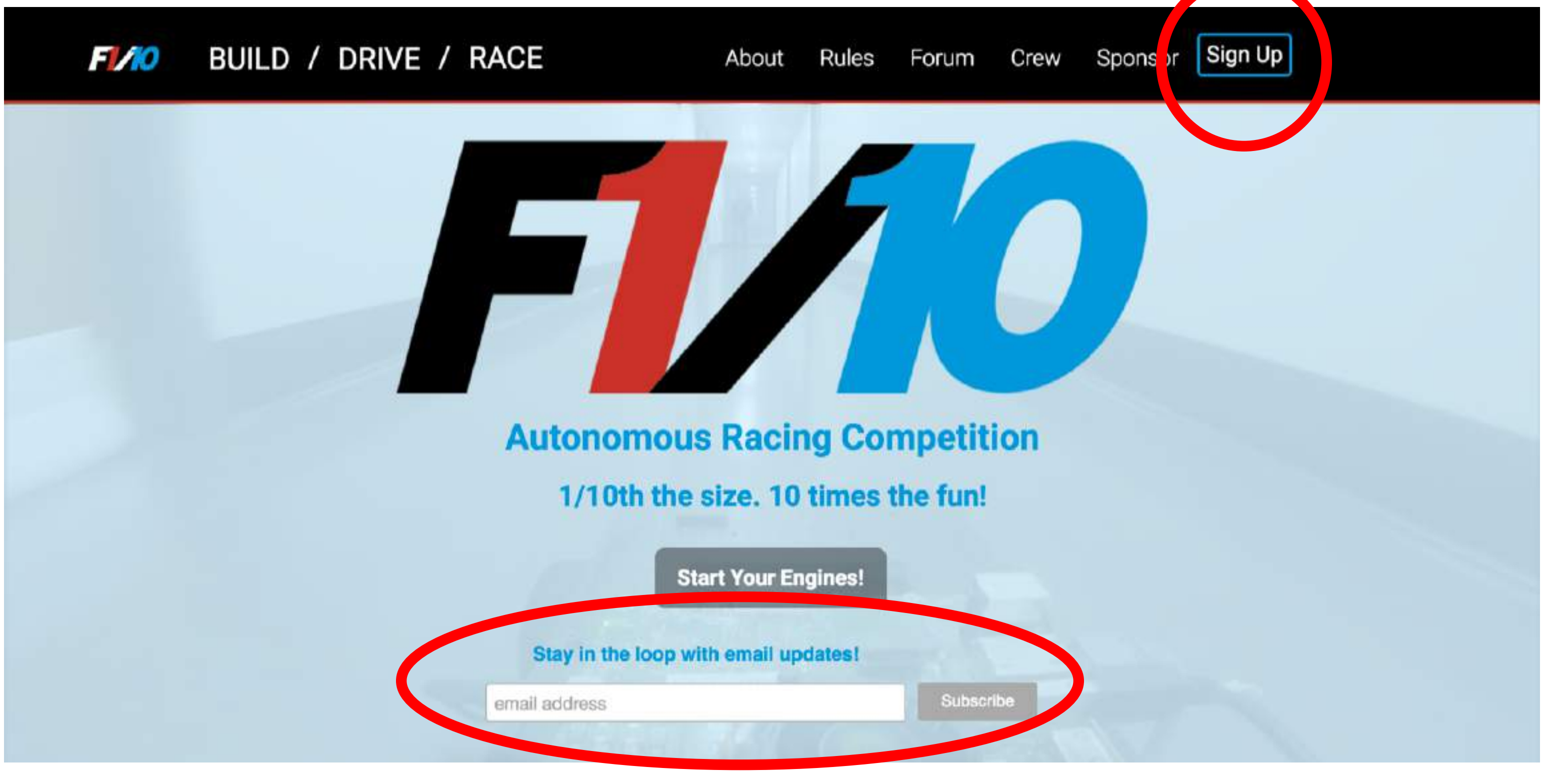
Phil Hu

Houssam Abbas

Madhur Behl

Rahul Mangharam

f1tenth.org



Get Involved !

No drivers were harmed
during the making of this video.

Do you have what it takes to become the fastest autonomous racing driver ?

Do you have what it takes to become the fastest autonomous racing driver ?

Live demo !
Outside Wu & Chen Auditorium to follow