Principles of Robot Autonomy I

Course overview, intro to robotic systems and ROS

Stanford University

Autonomous Systems Lab

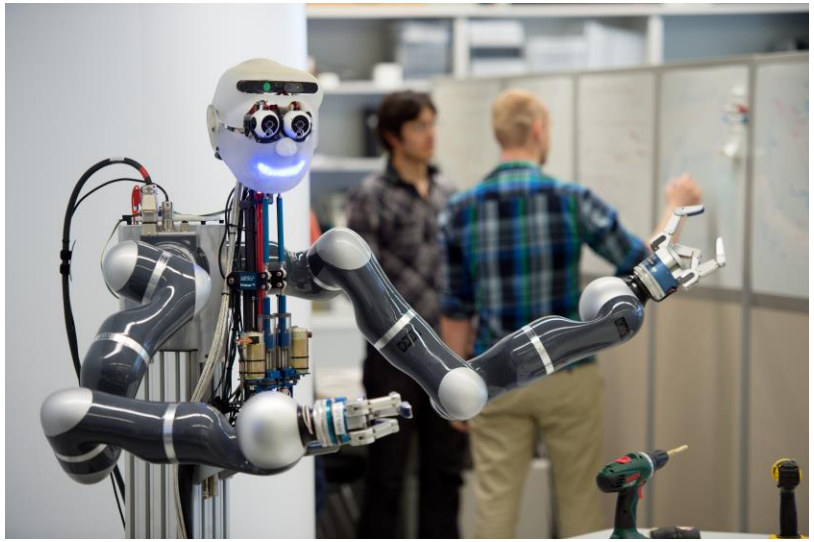
From automation…

…to autonomy

Waymo Self-Driving Car

Intuitive DaVinci Surgical Robot

Apollo Robot at MPI



Astrobee - NASA

Silicon Valley

CBRE

Automotive R&D

April 2016

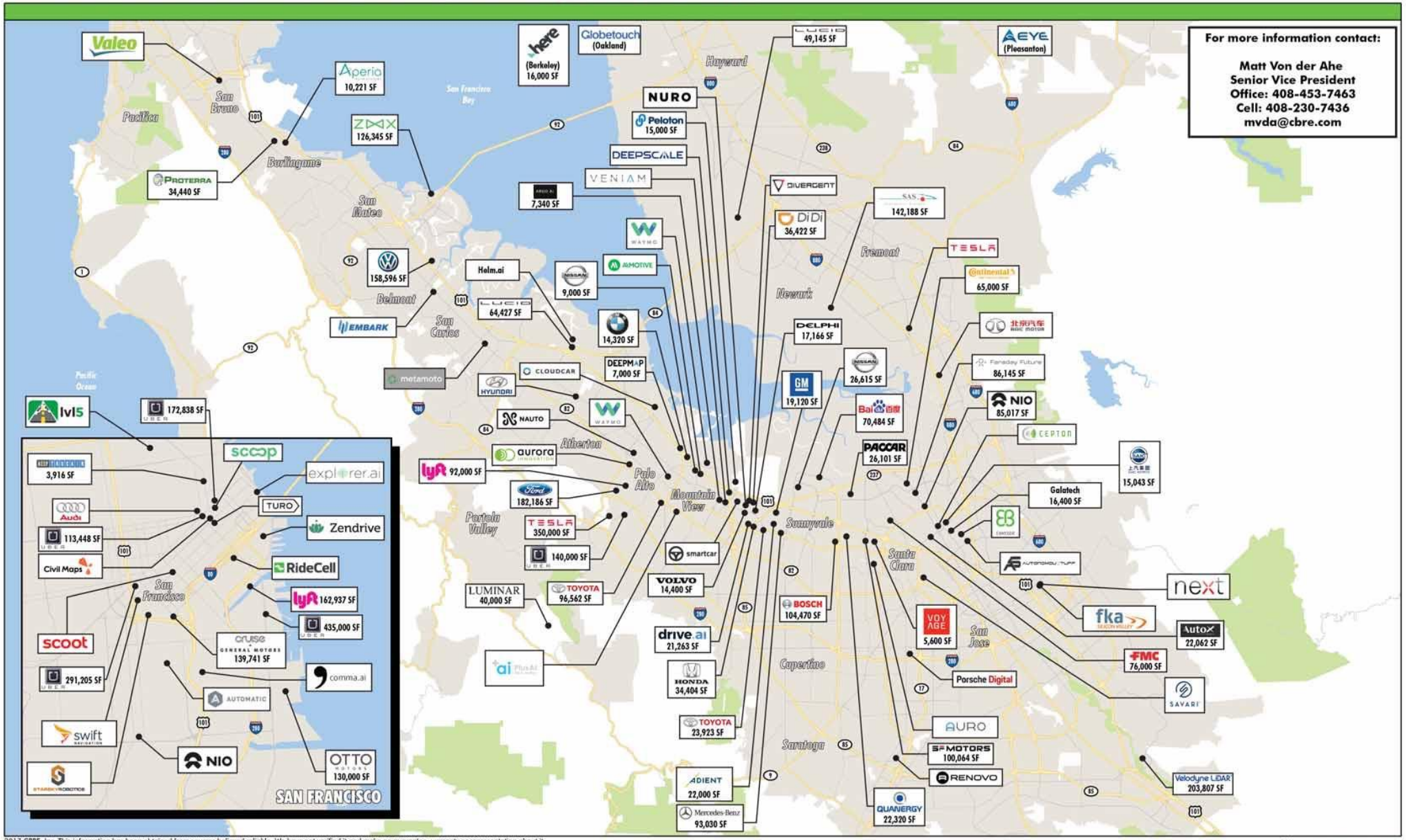
Silicon Valley

CBRE

AUTO LAB MAP APRIL 2017 SILICON VALLEY

CBRE

AUTO LAB MAP SEPTEMBER 2017 SILICON VALLEY



0 1.5 3 6 Miles

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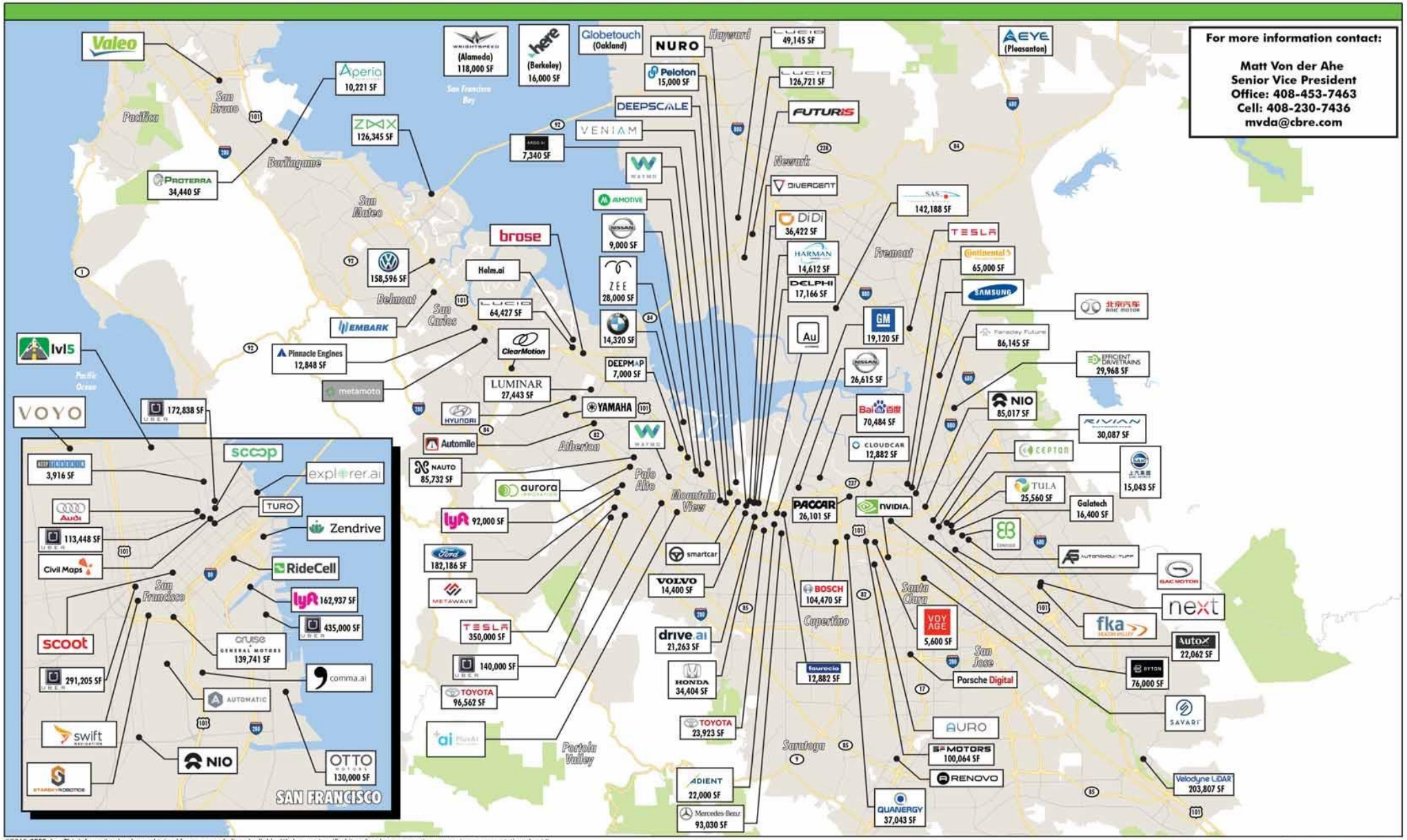
CBRE

AUTO LAB MAP DECEMBER 2017 SILICON VALLEY



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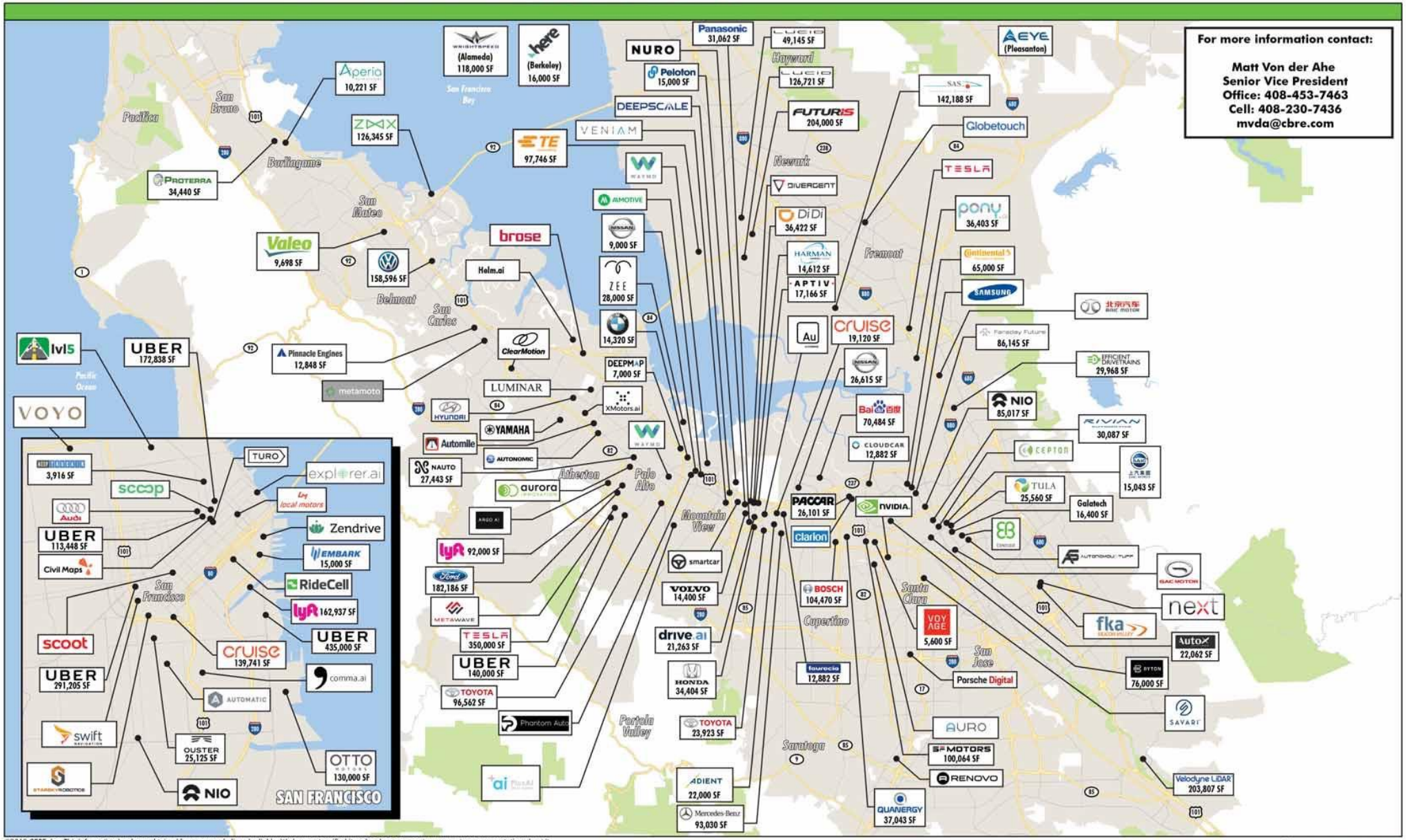
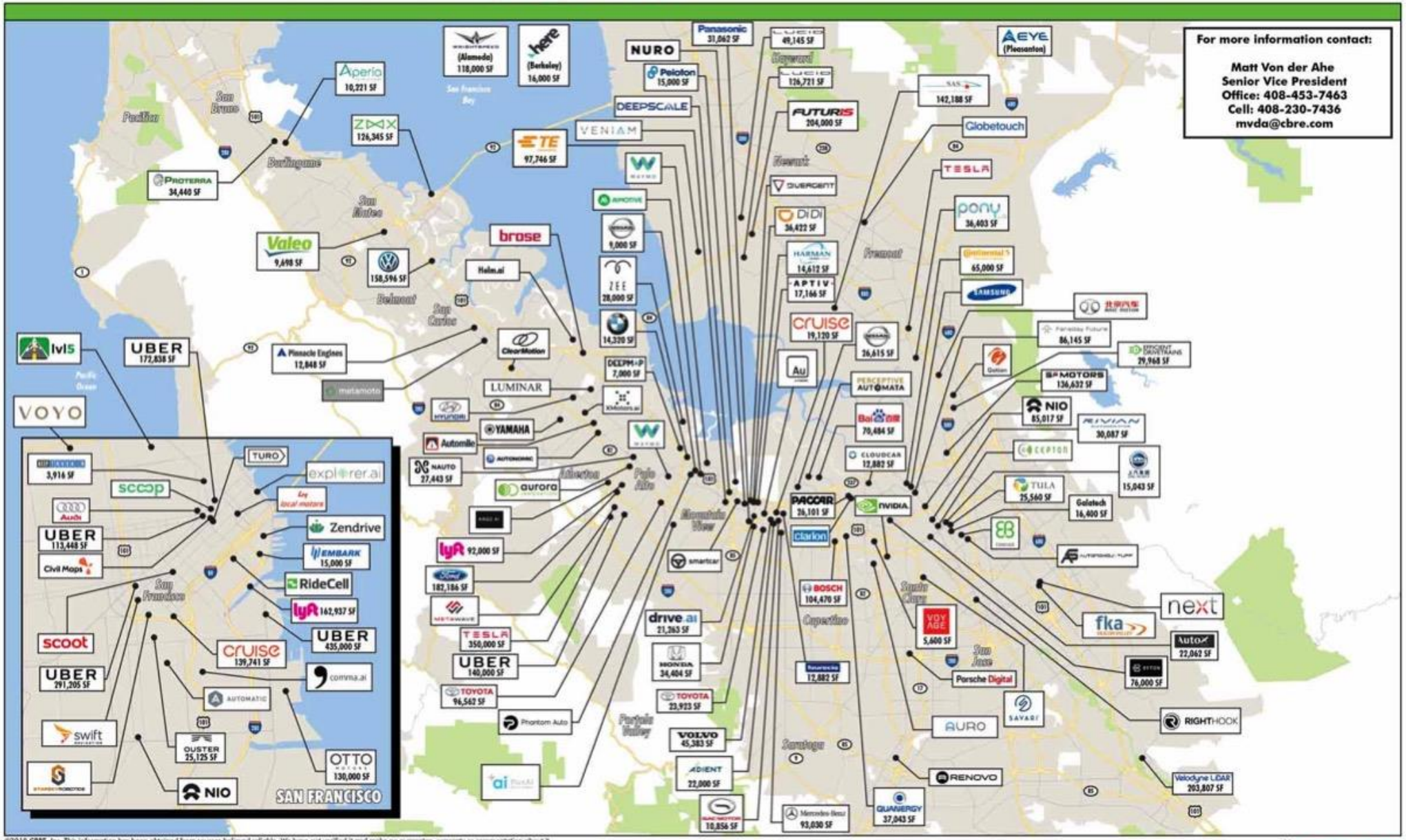
AUTO LAB MAP FEBRUARY 2018 SILICON VALLEY



AUTO LAB MAP MARCH 2018 SILICON VALLEY



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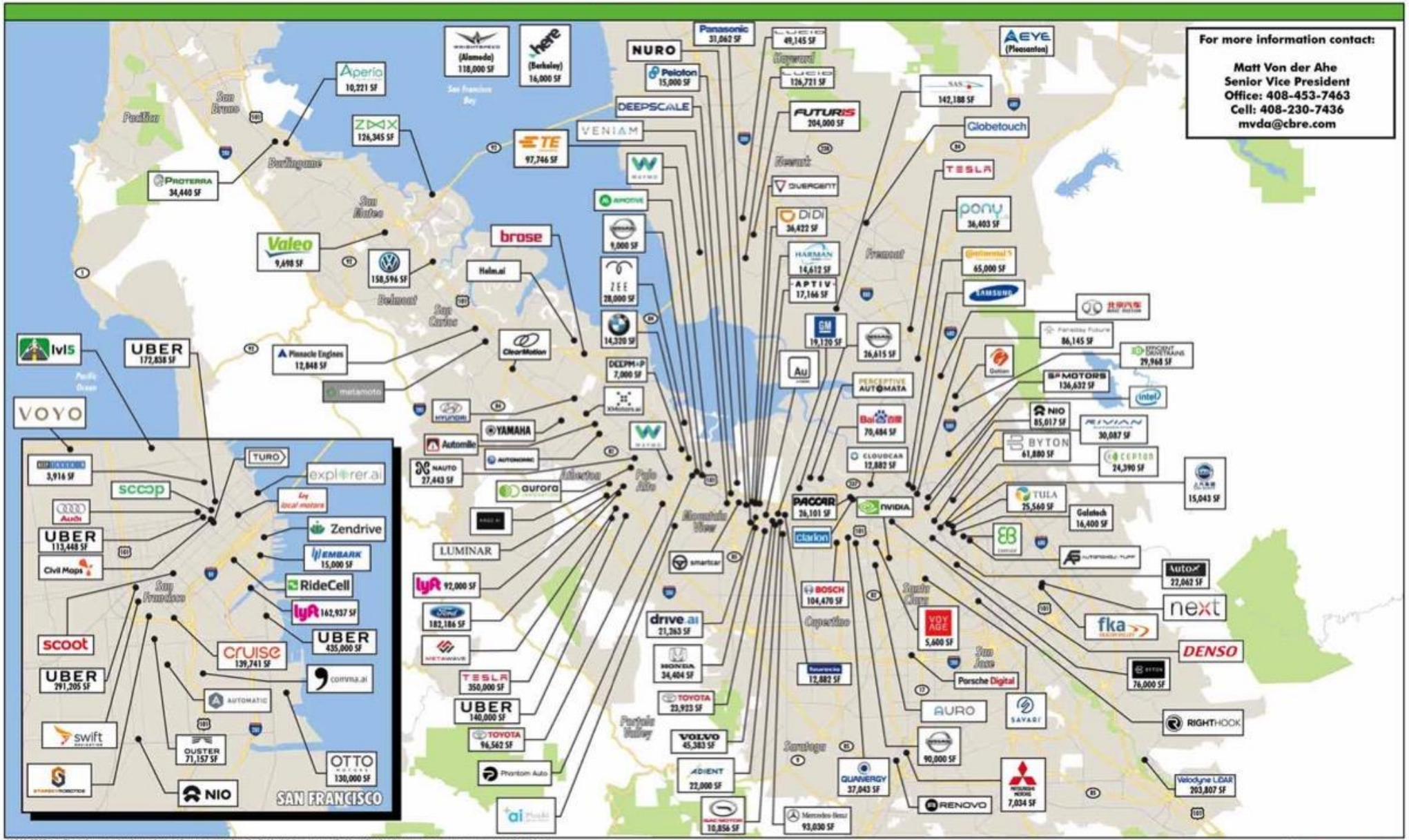
AUTO LAB MAP APRIL 2018 SILICON VALLEY



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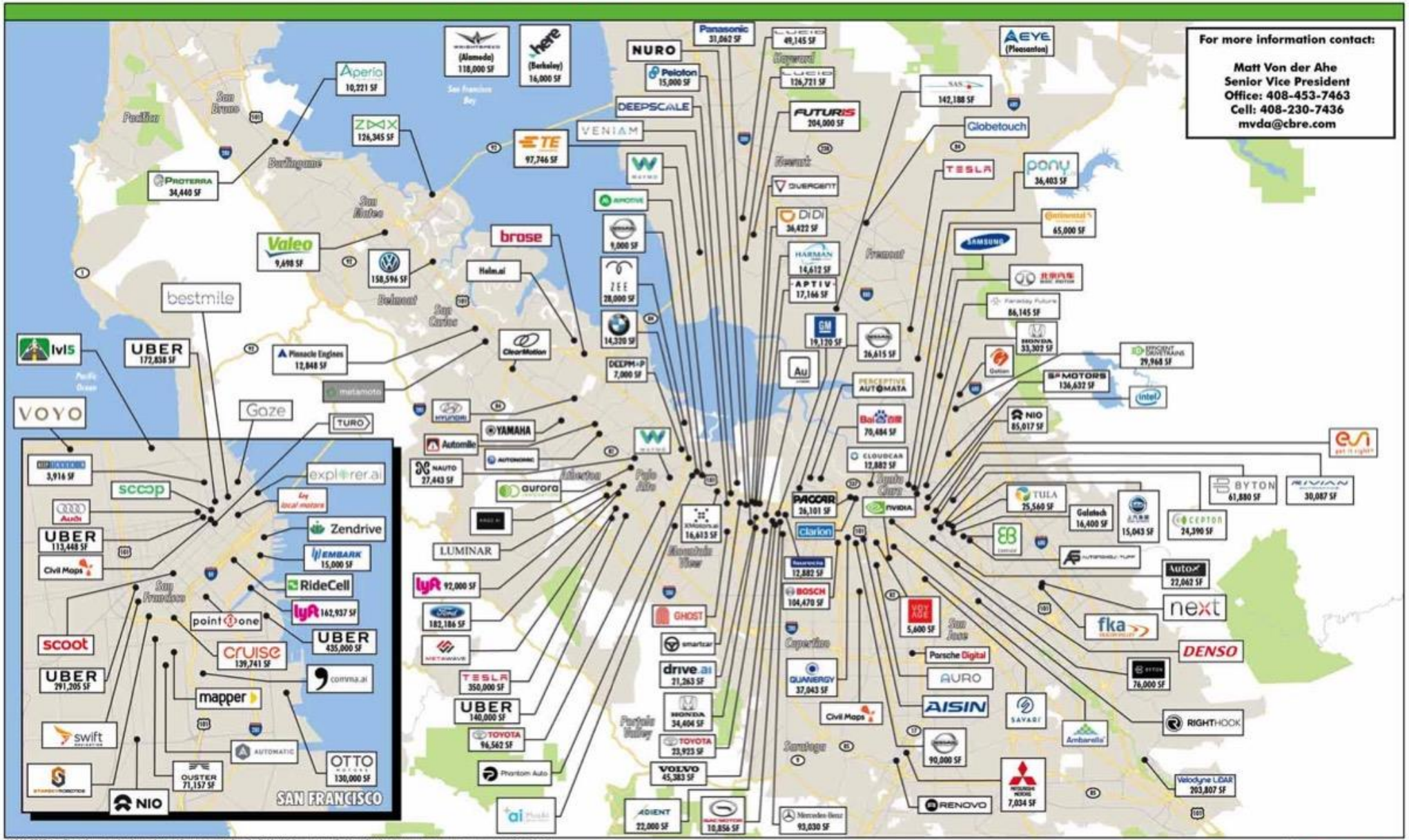

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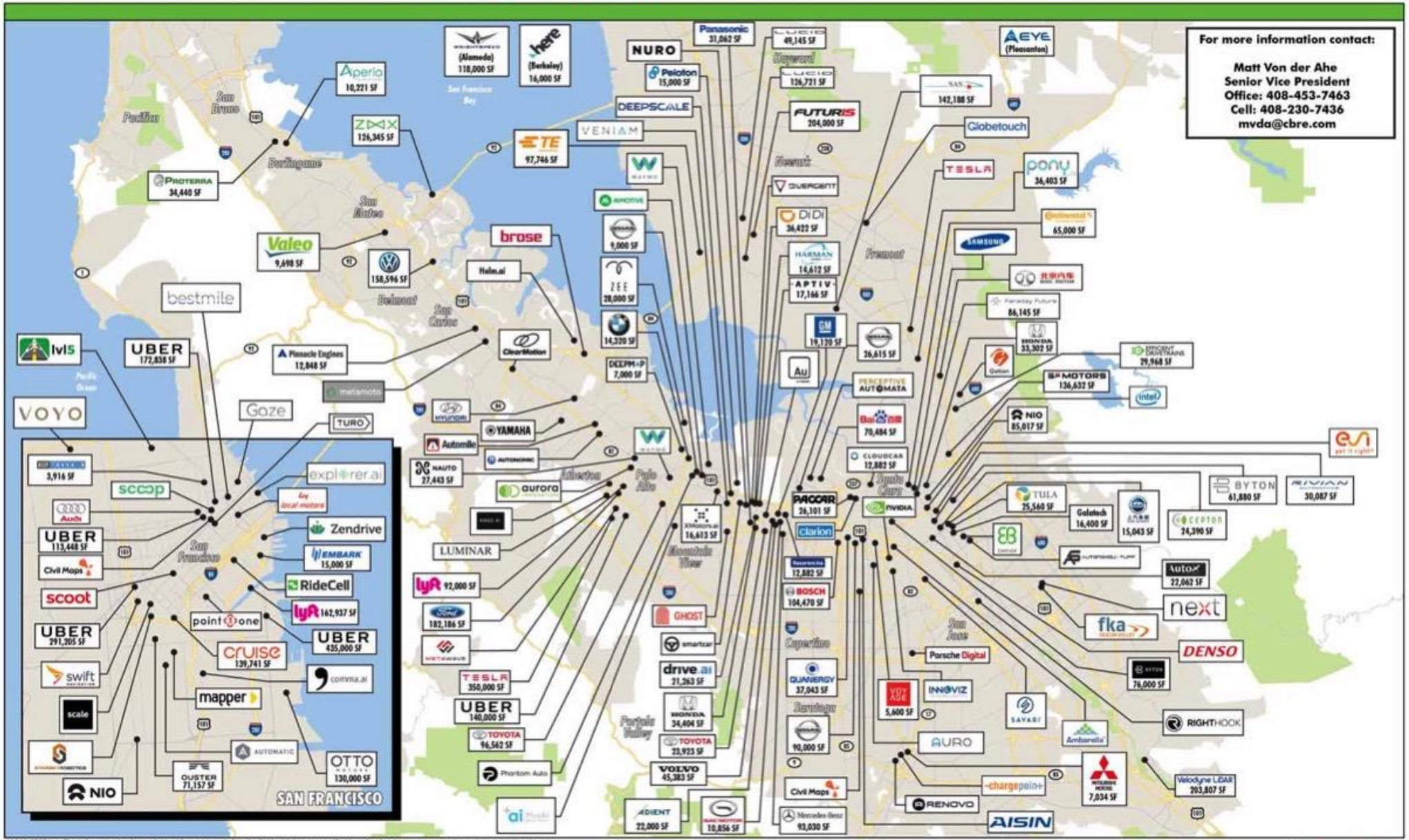

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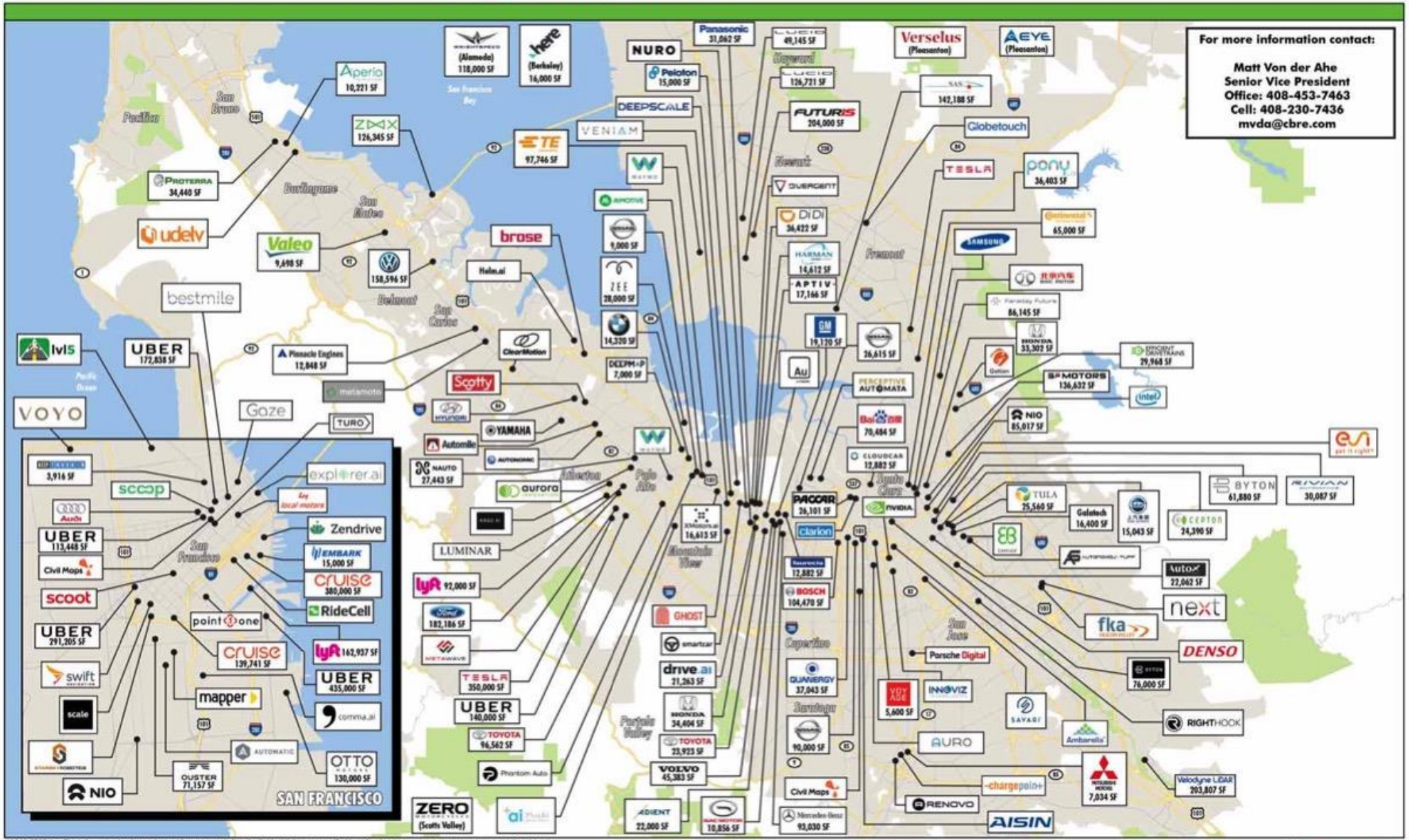

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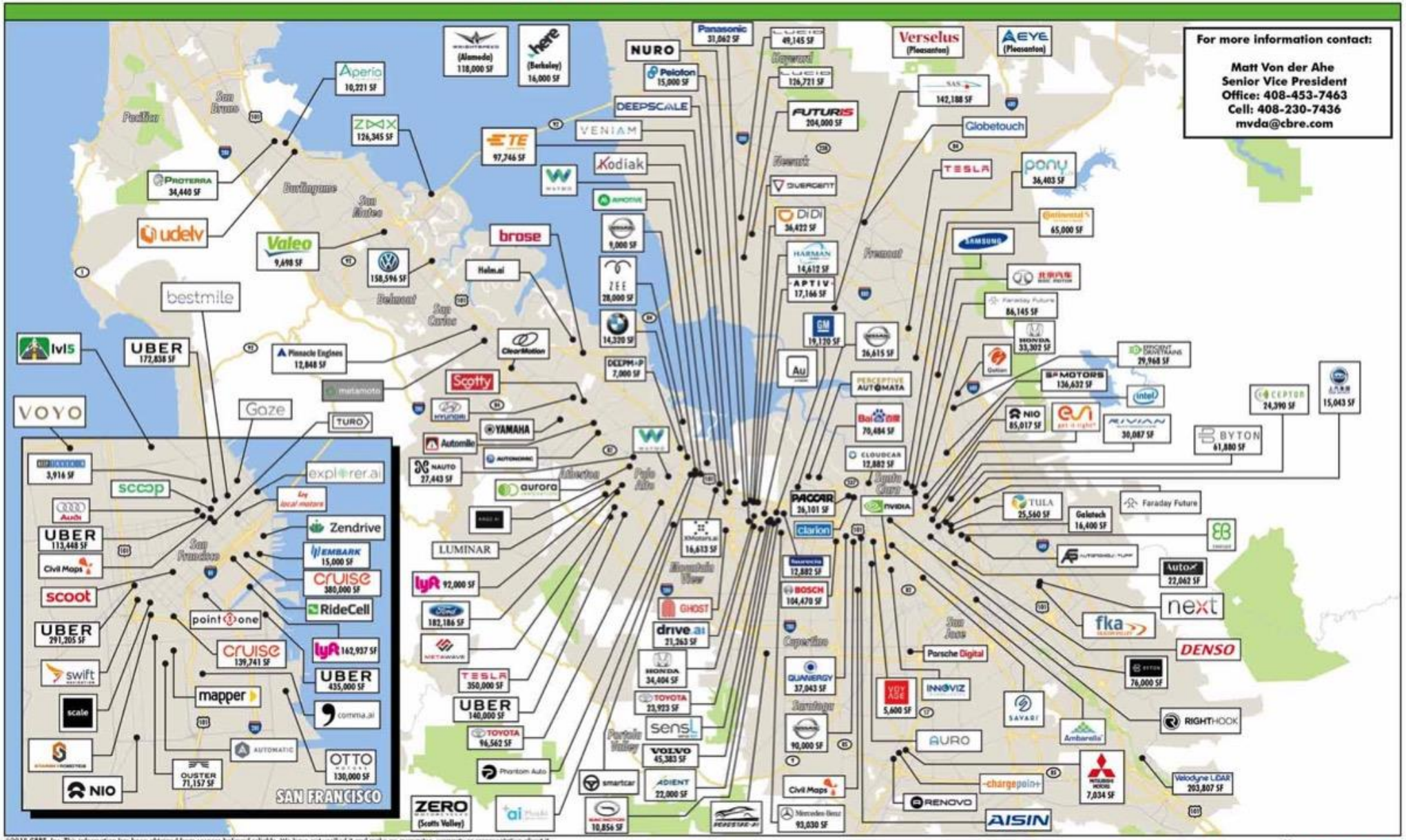
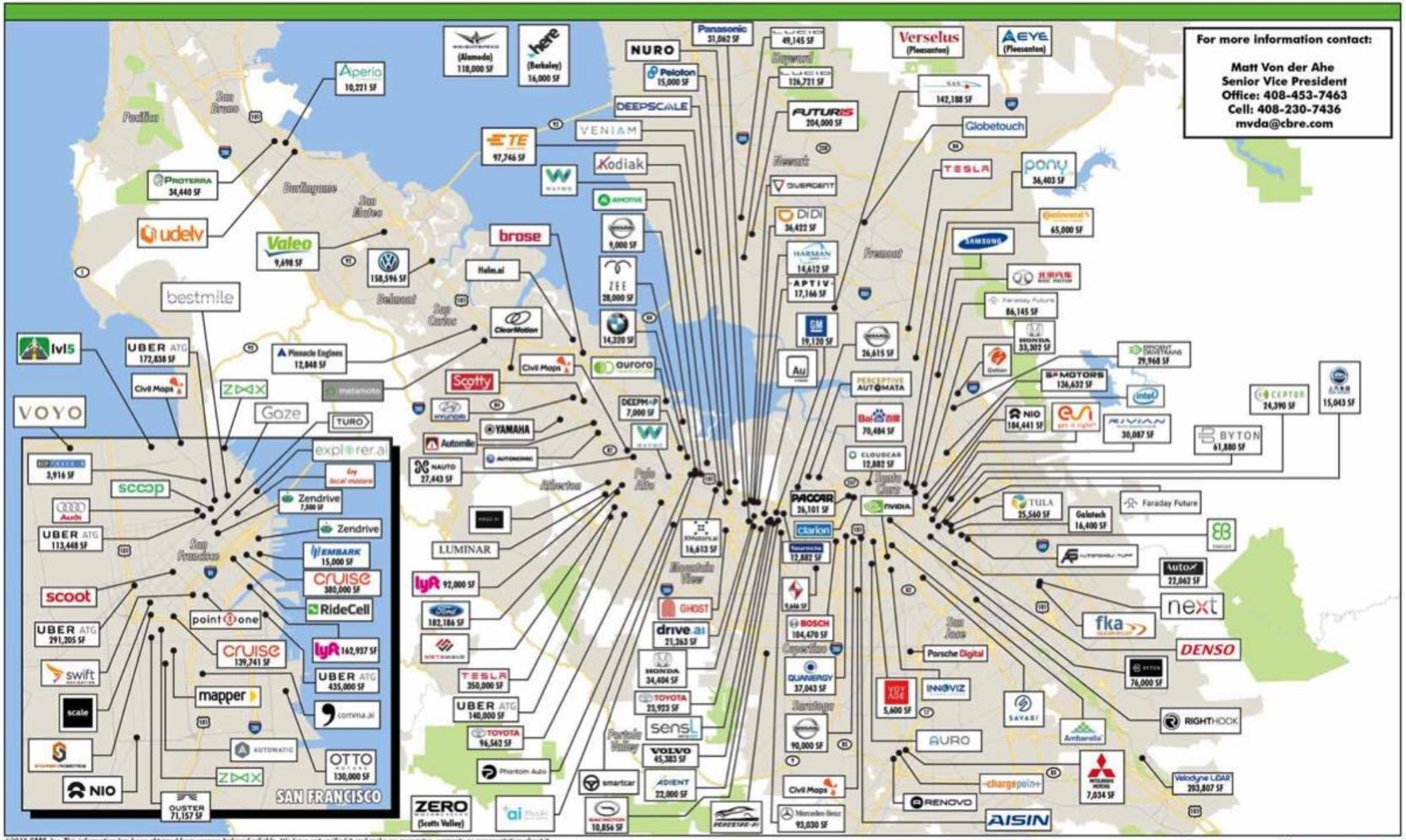
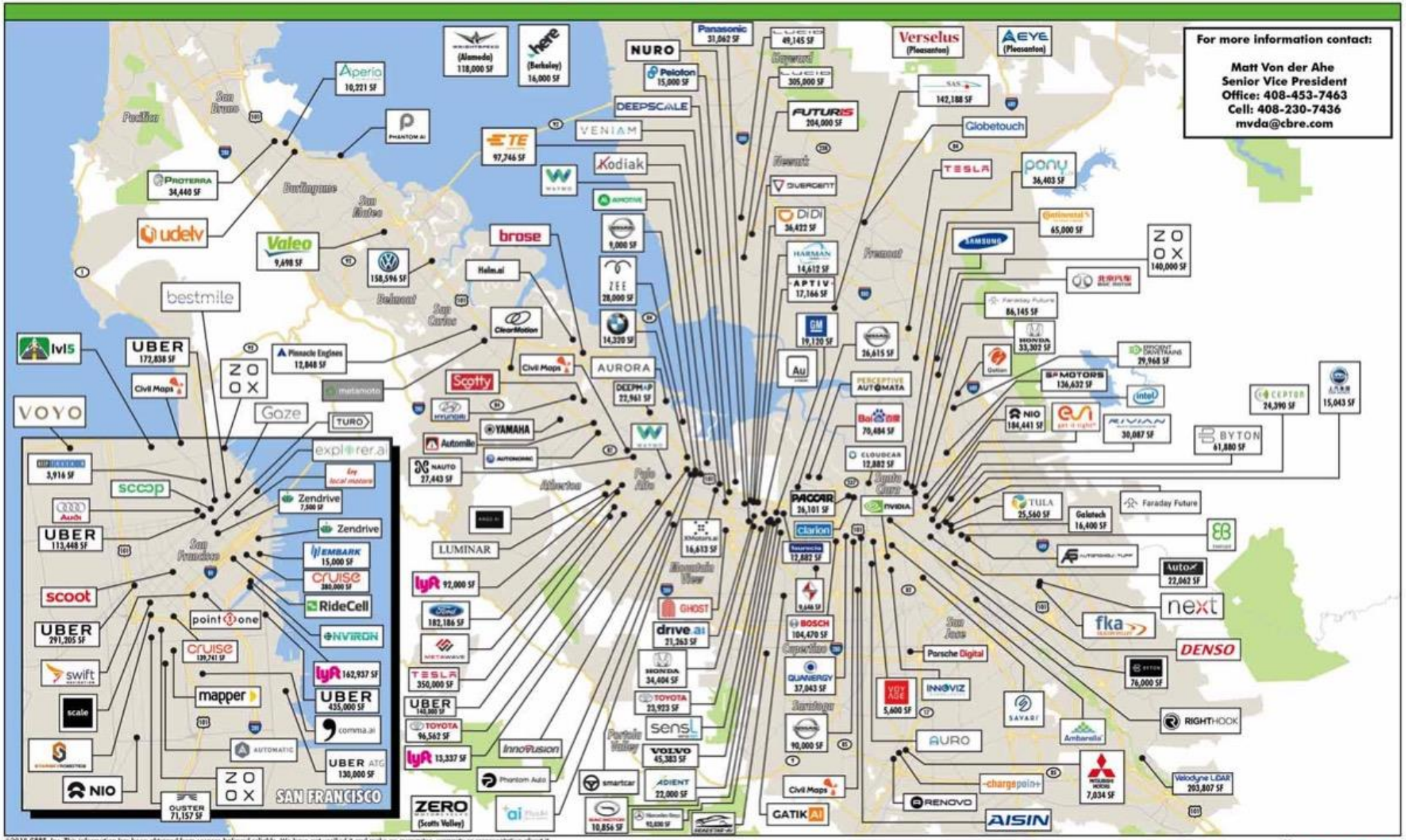


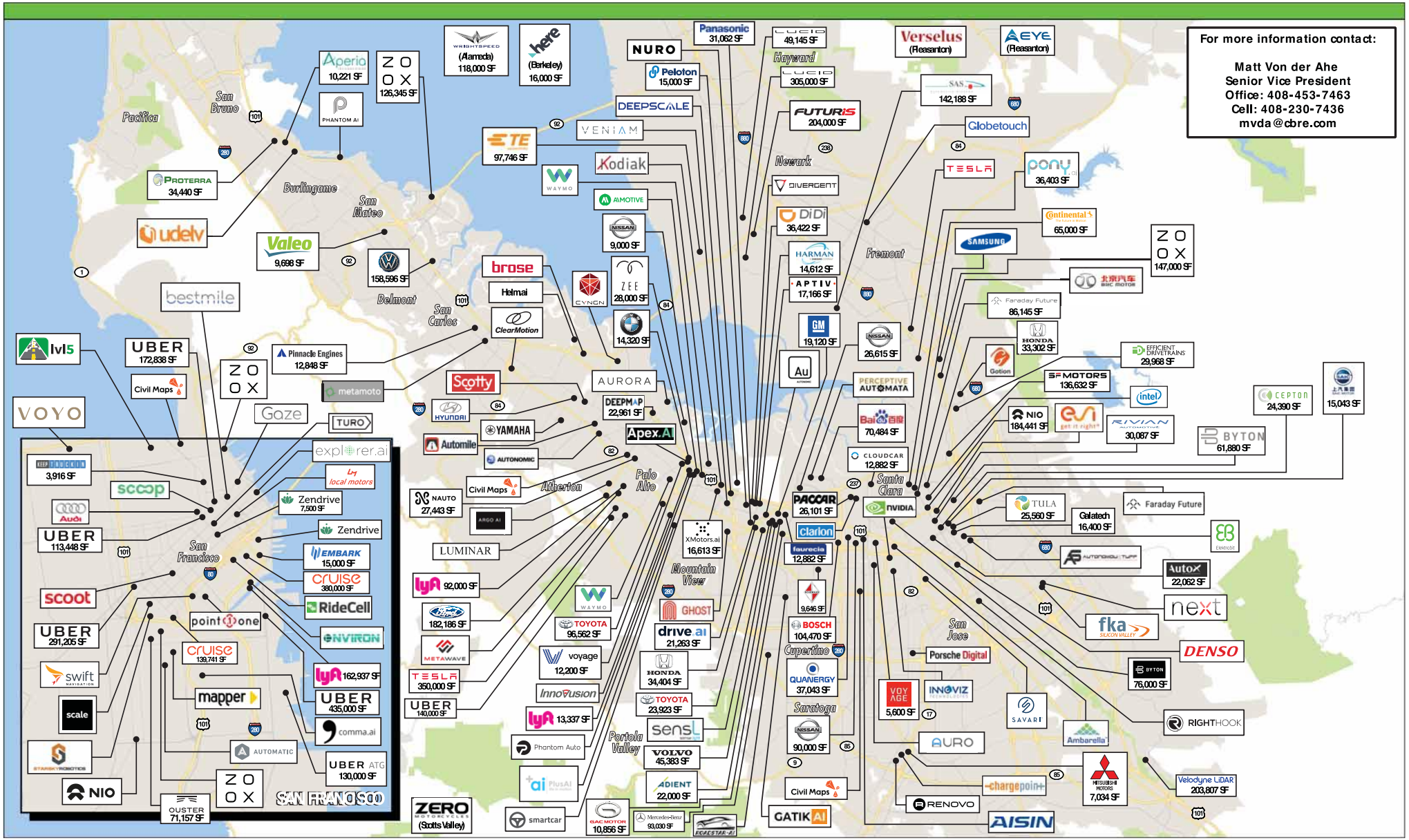
AUTO LAB MAP SEPTEMBER 2018 SILICON VALLEY



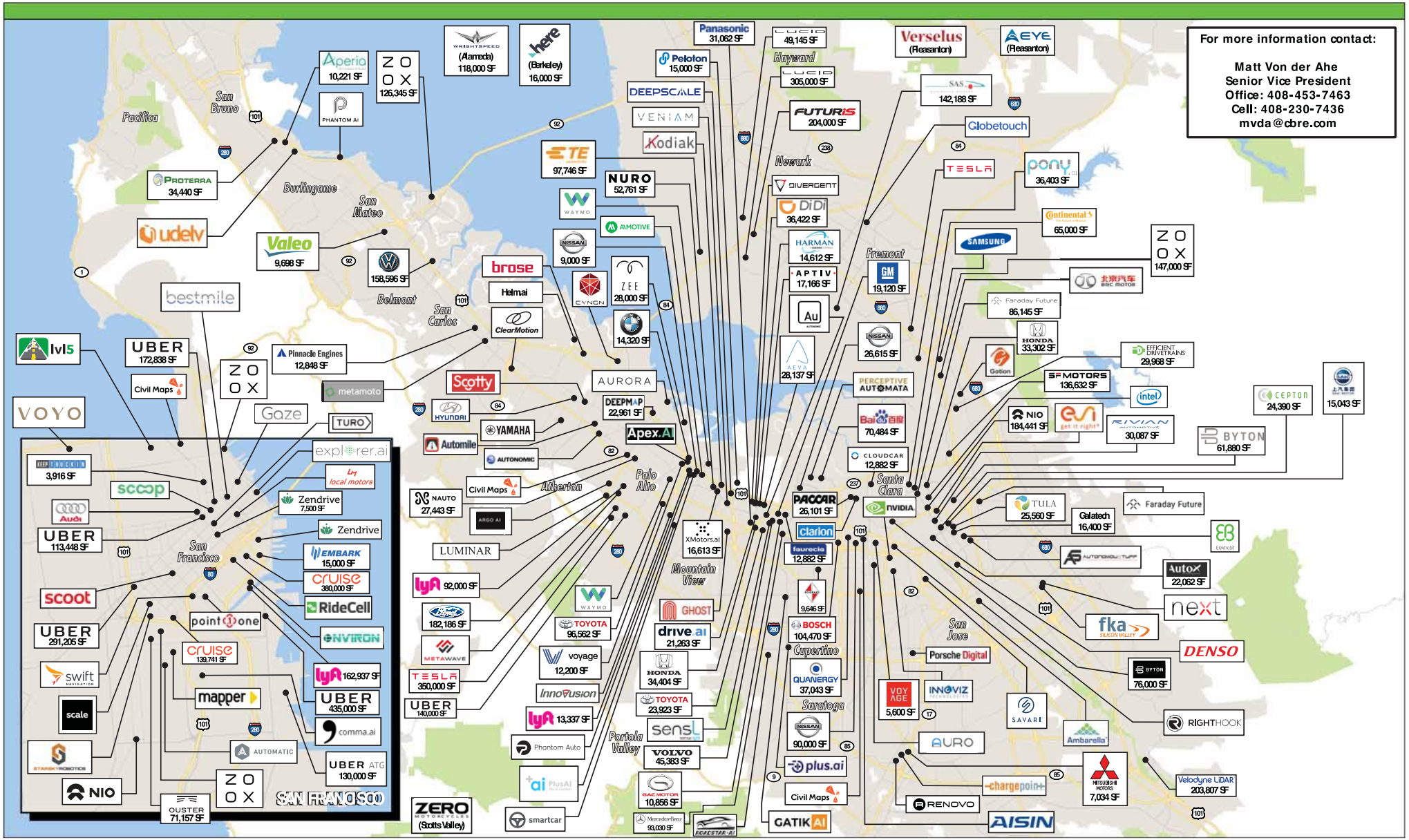
AUTO LAB MAP OCTOBER 2018 SILICON VALLEY



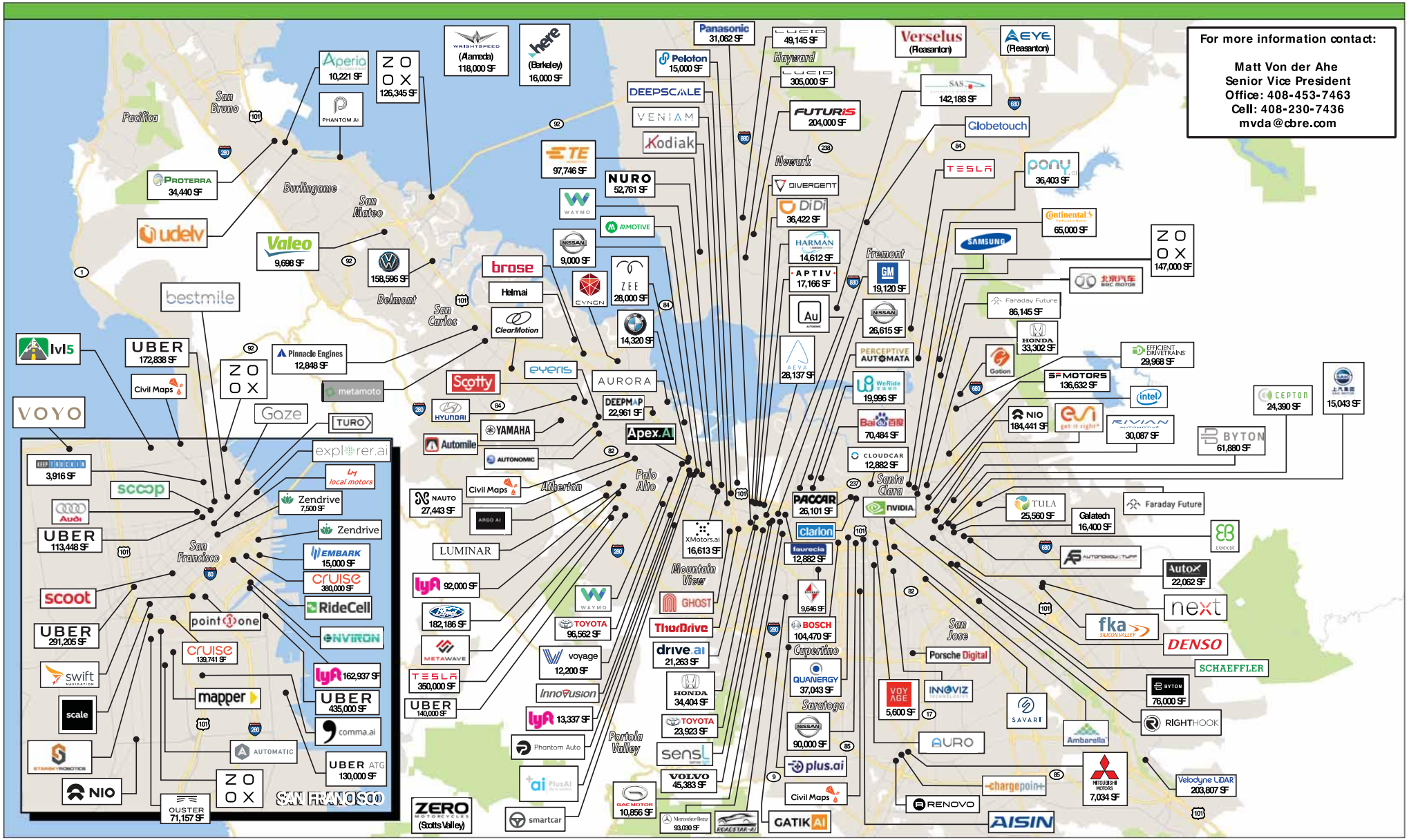
AUTO LAB MAP NOVEMBER 2018 SILICON VALLEY



AUTO LAB MAP DECEMBER 2018 SILICON VALLEY



AUTO LAB MAP JANUARY 2019 SILICON VALLEY



The Drone Market Environment 2019

Hardware

Drone Platforms

Agriculture

Delivery Systems

Safety & Security

Lighter-Than-Air

Drone-in-a-Box

Helicopter

Fixed-Wing

VTOL Fixed-Wing

Recreational

Passenger Drones / eVTOLs / Air Taxis

Counter-Drone Solutions

Components & Systems

Cameras, Imagining and Vision Systems

Launch and Recovery Systems

Navigation & Guidance Systems

Propulsion & Power

Data and Communication

Software

Flight, Fleet & Operation Management

Open Source Infrastructure, SDK

Navigation, CV and AI

UTM, LAANC Suppliers

Data Analytics, Workflow, CV and AI

Services

Drone-as-a-Service Providers

Delivery

Drone Show Providers

Education, Simulation, Training

System Integration, Engineering, Advisory

Maintenance

Market Research & Consulting

User Groups, Networks

Supplier, Retailers

Test Sites

Media, News, Blogs & Magazines

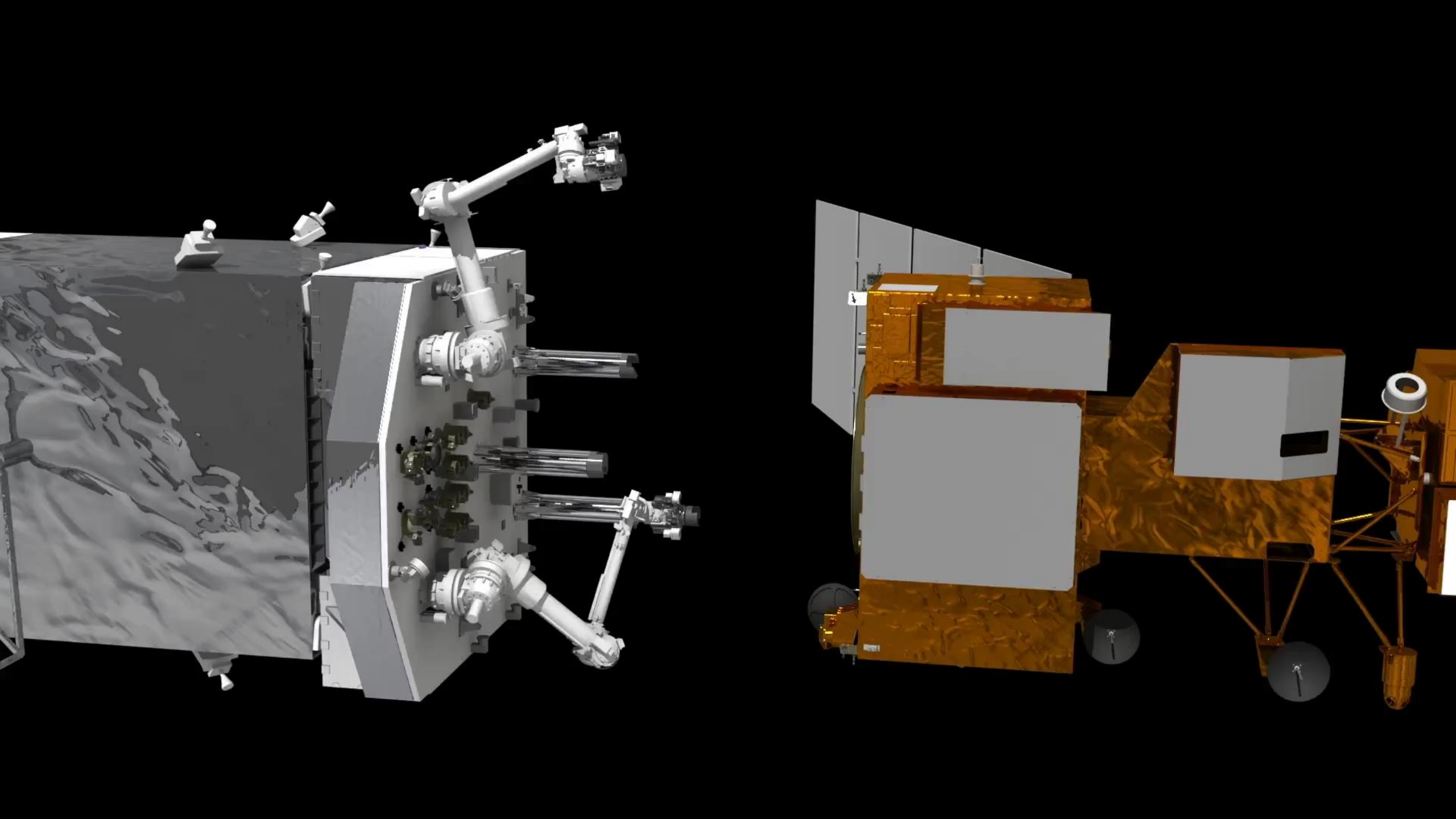
Podcast

Marketplaces

Shows, Conferences, Events

Insurances

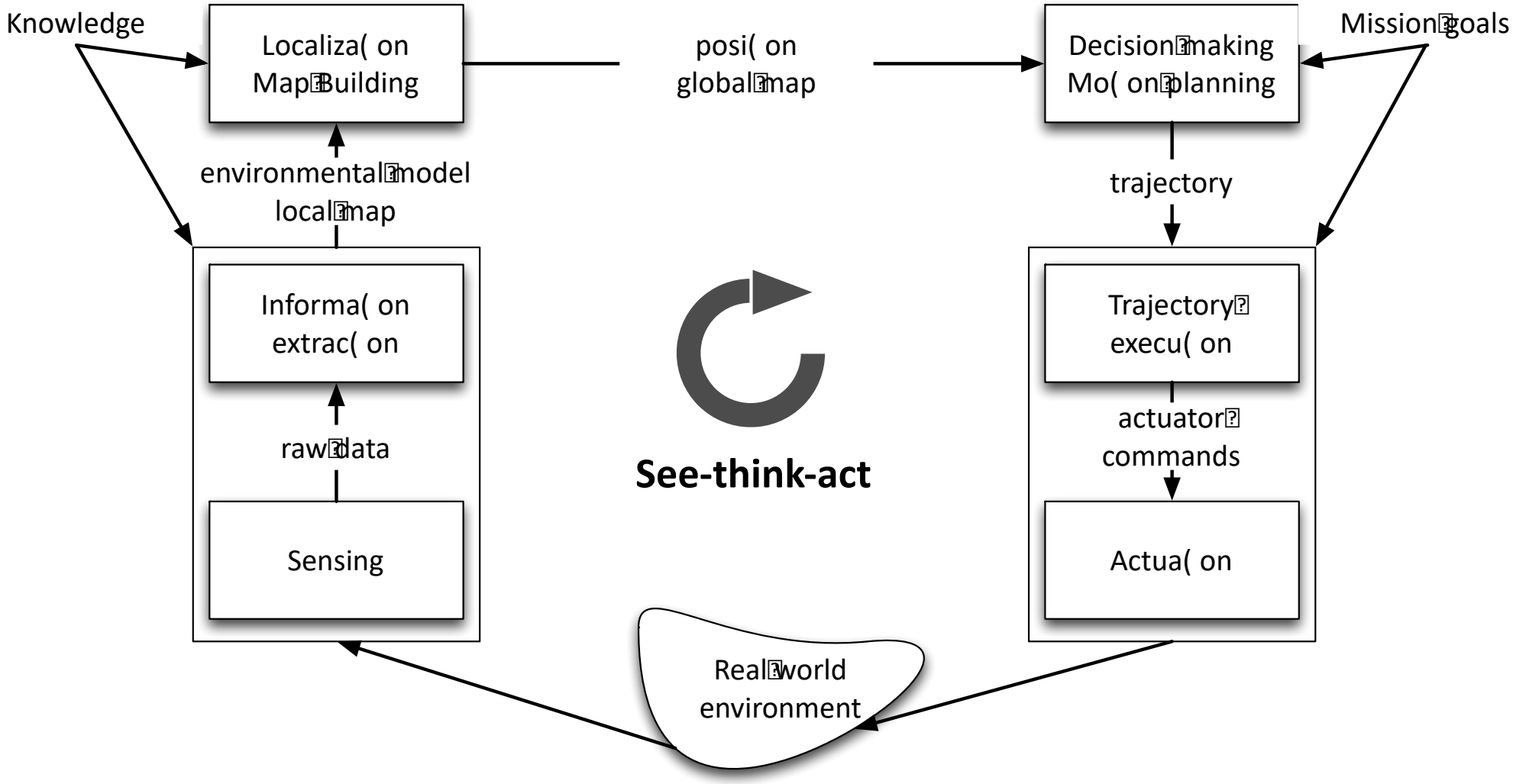
Coalitions, Organizations & Initiatives



Course goals

- To learn the *theoretical*, *algorithmic*, and *implementation* aspects of main techniques for robot autonomy. Specifically, the student will
  1. Gain a fundamental knowledge of the “autonomy stack”
  2. Be able to apply such knowledge in applications using ROS

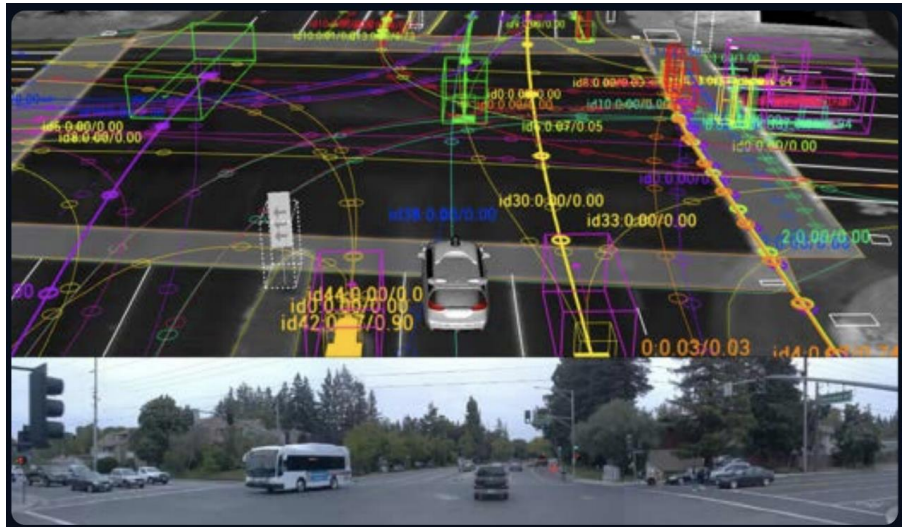
The see-think-act cycle



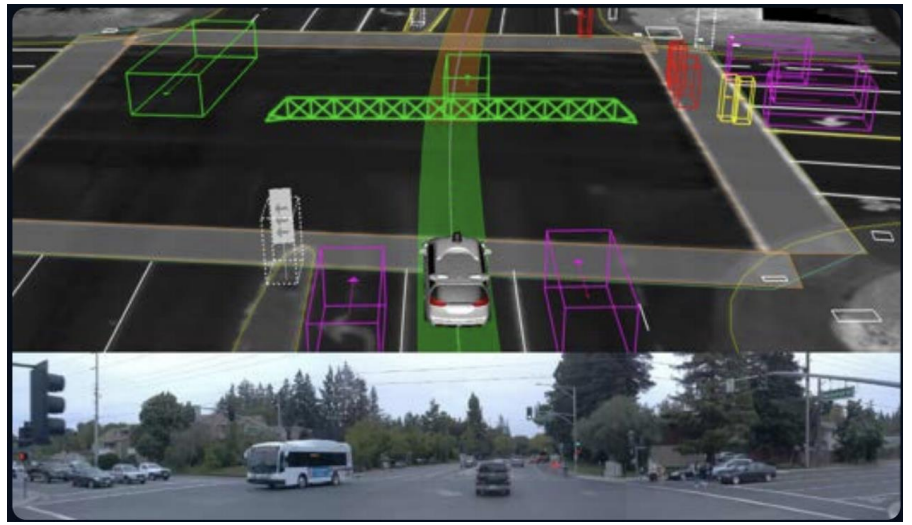
See-think-act cycle for AVs

Note: other architectures are possible and subject of active R&D!

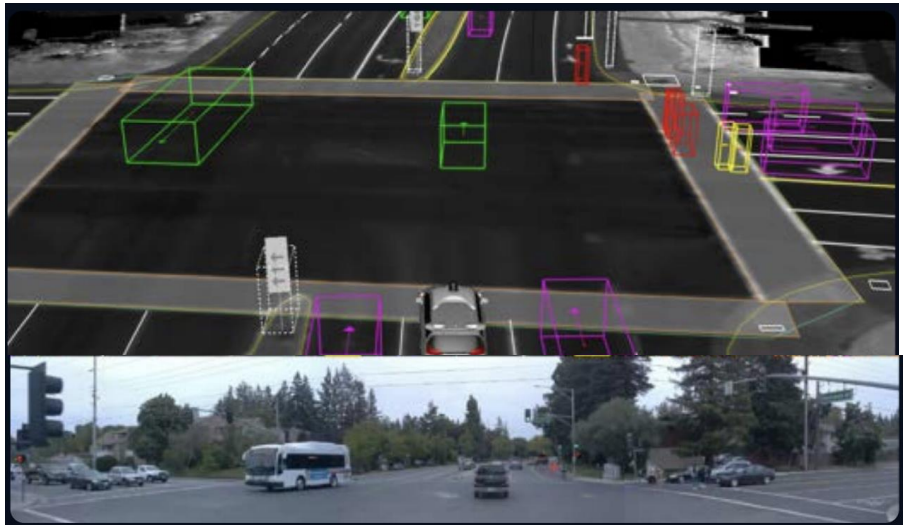
Think



Act



See



Waymo report, 2020

Course structure

- Four main topics:
  1. Robot Operating System (week 1)
  2. Controls & Motion Planning (weeks 2-4) -- *act*
  3. Perception (weeks 5-8) -- *see*
  4. State Estimation, Localization & SLAM (weeks 8-11) -- *think*
- Extensive use of the Robot Operating System (ROS)

- Requirements
  - CS 106A or equivalent
  - CME 100 or equivalent (for calculus, linear algebra)
  - CME 102 or equivalent (for differential equations)
  - CME 106 or equivalent (for probability theory)
  - See also the pre-knowledge quiz on the course website

Logistics

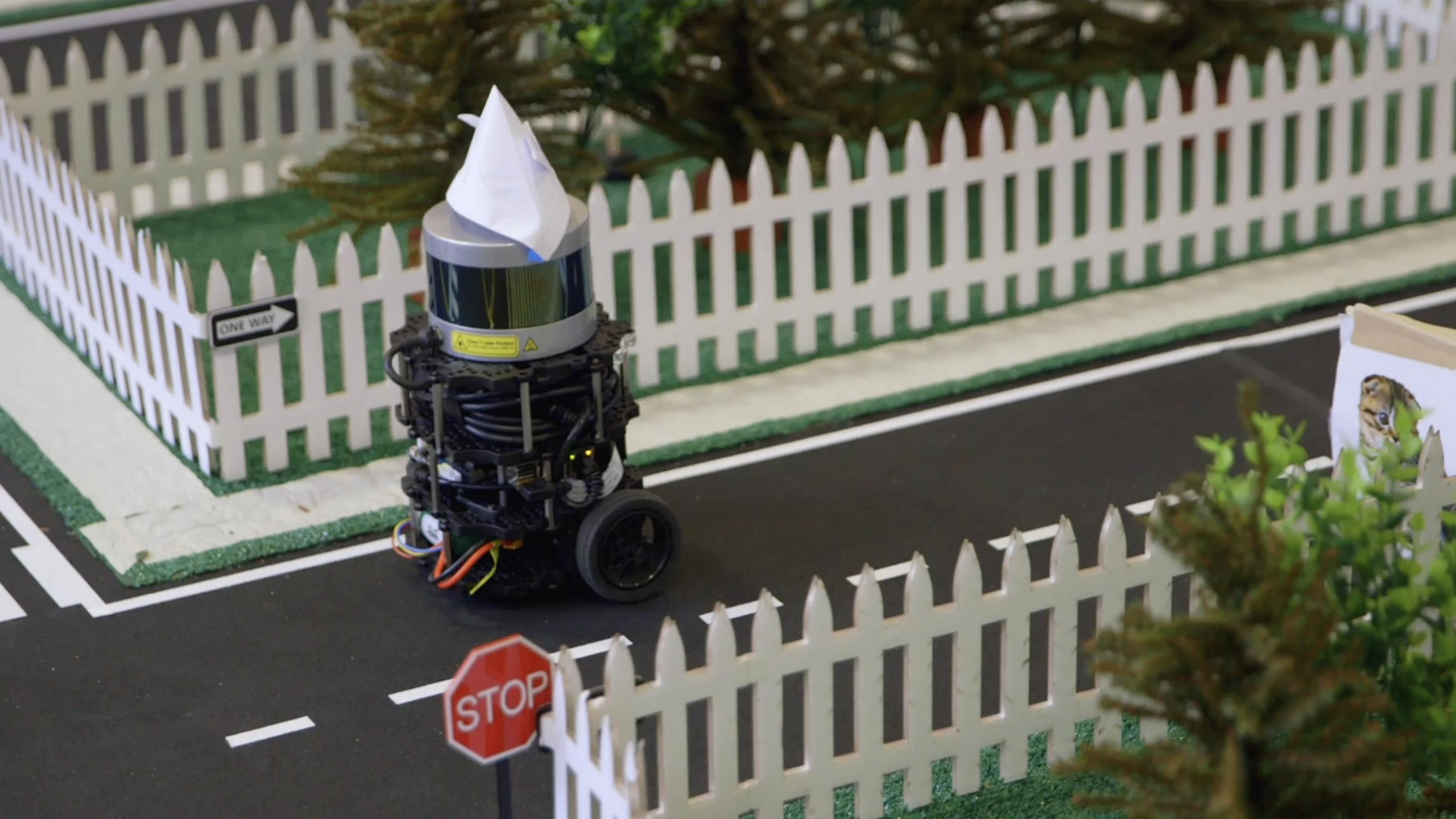
- Lectures:
  - Tuesdays and Thursdays, 10:30am – 11:50am (CODAB60)

- Sections
  - 2-hour, once-a-week on Fridays
  - Hands-on exercises that complement the lecture material, build familiarity with ROS, and develop skills necessary for working with hardware
  - Link to the section sign-up sheet

Logistics

- Office hours:
  - Prof. Pavone: Tuesdays, 1:00 – 2:00pm (Durand 261), after class, and by appointment. Office hours will start during the week of Sep 29.
  - Course assistants: Wednesdays, 4:30 – 6:30pm (Durand 270), and Thursdays, 4:30 – 6:30pm (Durand 270)

- Course websites:
  - For course content: https://stanfordasl.github.io/PoRA-I/aa174a_aut2526/
  - For course announcements: https://canvas.stanford.edu/courses/214652/
  - For course-related questions: https://edstem.org/us/courses/87236/discussion/
  - For homework submissions: https://www.gradescope.com/courses/1137718
  - To contact the AA174A staff: aa174a-aut2526-staff@lists.stanford.edu


ONE WAY
STOP

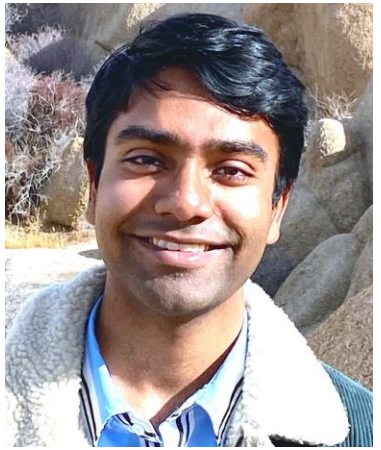
Team

Instructor

Marco Pavone
Associate Professor AA,
and CS/EE (by courtesy)

CAs

Milan Ganai



Yujung Jenny Kim

Jacky Kwok

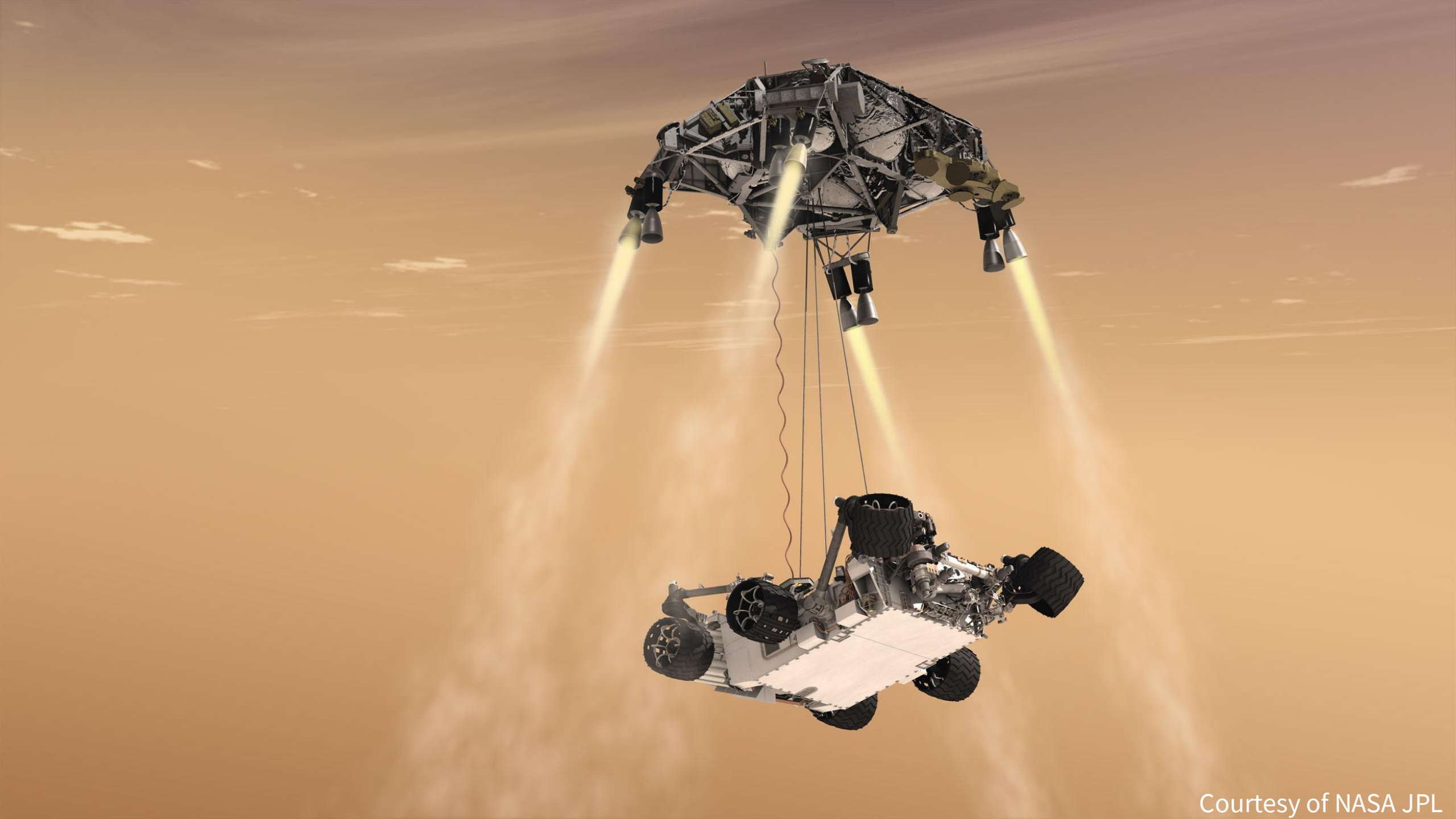
Collaborators

- Daniel Watzenig

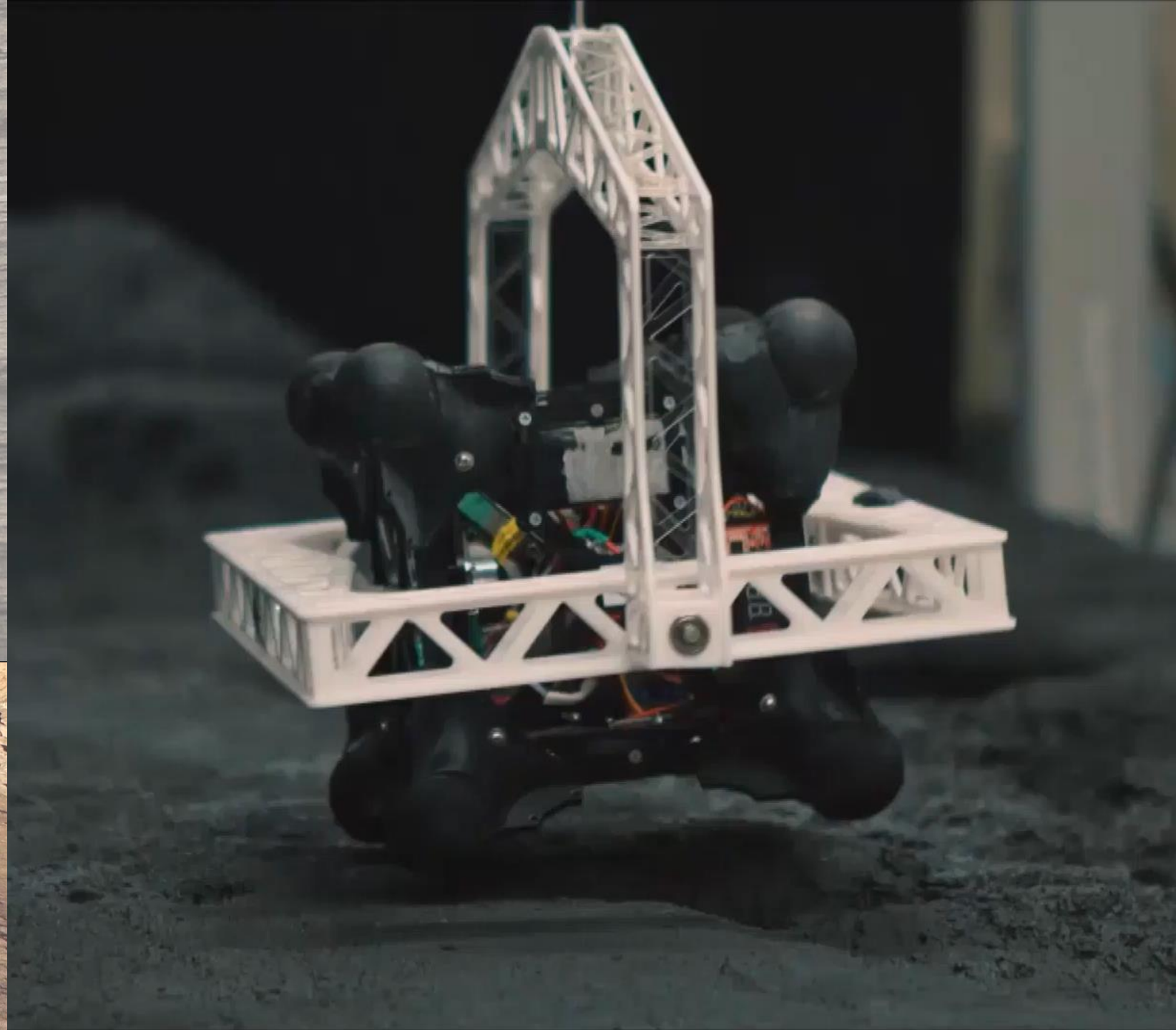
Labs

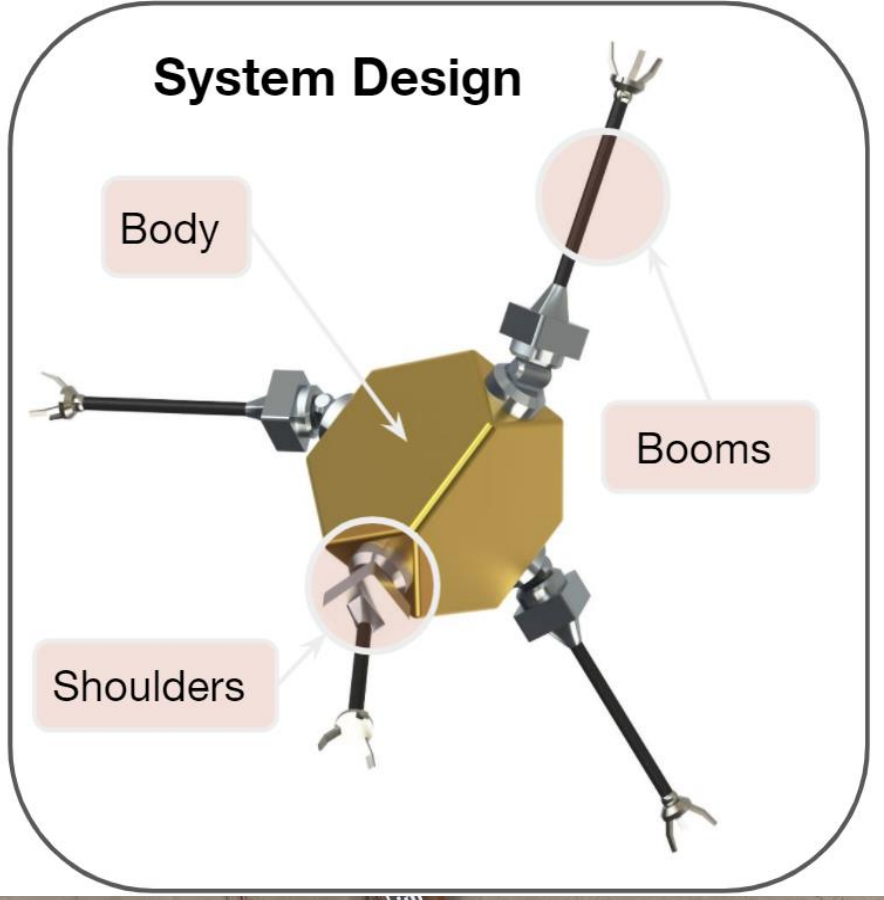
ASL
Autonomous Systems Lab

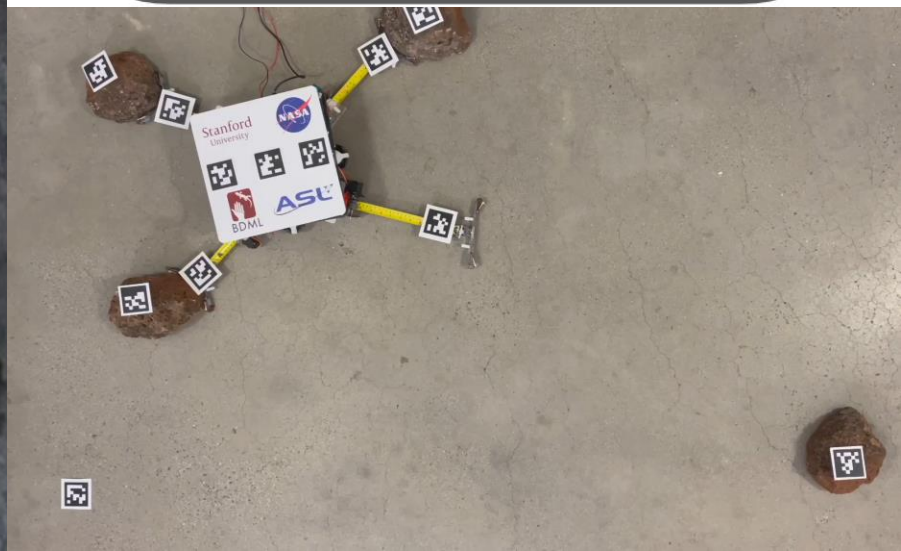
CARS
Center for Automotive
Research at Stanford



Courtesy of NASA JPL




System Design
Body
Booms
Shoulders


Stanford University
NASA
BDML
ASU


SP10

Center for Automotive Research at Stanford

https://cars.stanford.edu/

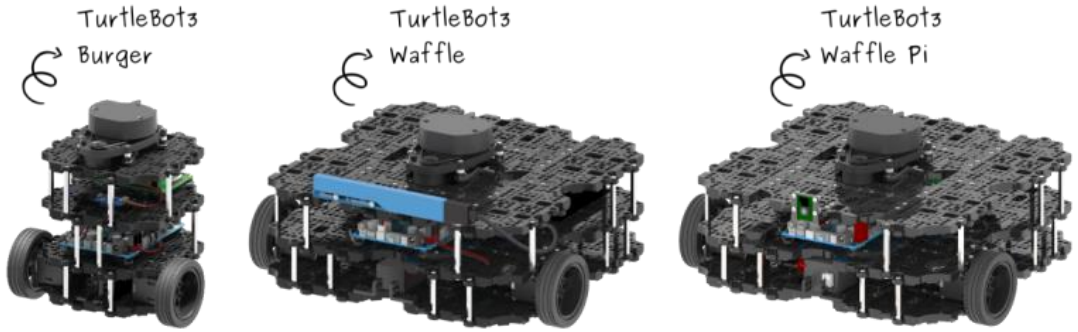
Autonomous Vehicle Research at NVIDIA

https://research.nvidia.com/labs/avg

Schedule

Date	Topic	Assignments
09/23	Course overview, intro to robotic systems and ROS	
09/25	Fundamentals of ROS & vectorized computation in Python	
09/26	⋆ Section 1 – UNIX, Git, and Python	HW1 out
09/30	State space dynamics – definitions and modeling	
10/02	State space dynamics – computation and simulation	
10/03	⋆ Section 2 – ROS, workspaces, packages, nodes	
10/07	Trajectory optimization	HW2 out
10/09	Trajectory tracking	
10/10	⋆ Section 3 – Launch files & RVIZ	HW1 due
10/14	Motion planning I: graph search algorithms	
10/16	Motion planning II: sampling-based methods	
10/17	⋆ Section 4 – Controller gain tuning in hardware	HW2 due
10/21	Robotic sensors & introduction to computer vision	HW3 out
10/23	Camera models and camera calibration	
10/24	⋆ Section 5 – Running a point-to-point navigator	
10/28	Image processing, feature detection, & feature description	
10/30	Information extraction	
10/31	⋆ Section 5 cont. & Section 6 head start	HW3 due, HW4 (part 1) out
11/04	No Lecture – Democracy Day	
11/06	*In-class midterm*	
11/07	⋆ No Section	
11/11	Deep learning for computer vision	
11/13	Intro to state estimation & filtering theory	
11/14	⋆ Section 6 – Object detection	HW4 (part 2) out
11/18	Parametric filtering (KF and EKF)	HW4 (part 1) due
11/20	Markov localization and EKF-localization	
11/21	⋆ Section 7 – Frontier exploration	
11/25		
11/27	*Thanksgiving*	
11/28		
12/02	Multi-sensor perception & sensor fusion	HW4 (part 2) due
12/04	Simultaneous localization and mapping (SLAM)	
12/05	⋆ Section 7 cont.	

Turtlebot3



- Imagine you have a robot with sensors, motors, and AI.
- How do you make all the pieces talk to each other - reliably, in real time, and in a way others can build on?
- That's where ROS comes in!

Velodyne LiDAR

Quadrotor

Manipulation

TurtleBot

The Challenge of Building Robots

- Robots are complex systems
  - Hardware
    - Sensors (IMU, velocity, LiDAR, Camera, Microphone, …)
    - Actuators (wheels, joints, grippers, valves, ...)
    - Structures (Links, frame, …)
  - Software
    - Control
    - Trajectory planning
    - Object detection
    - Localization
    - …

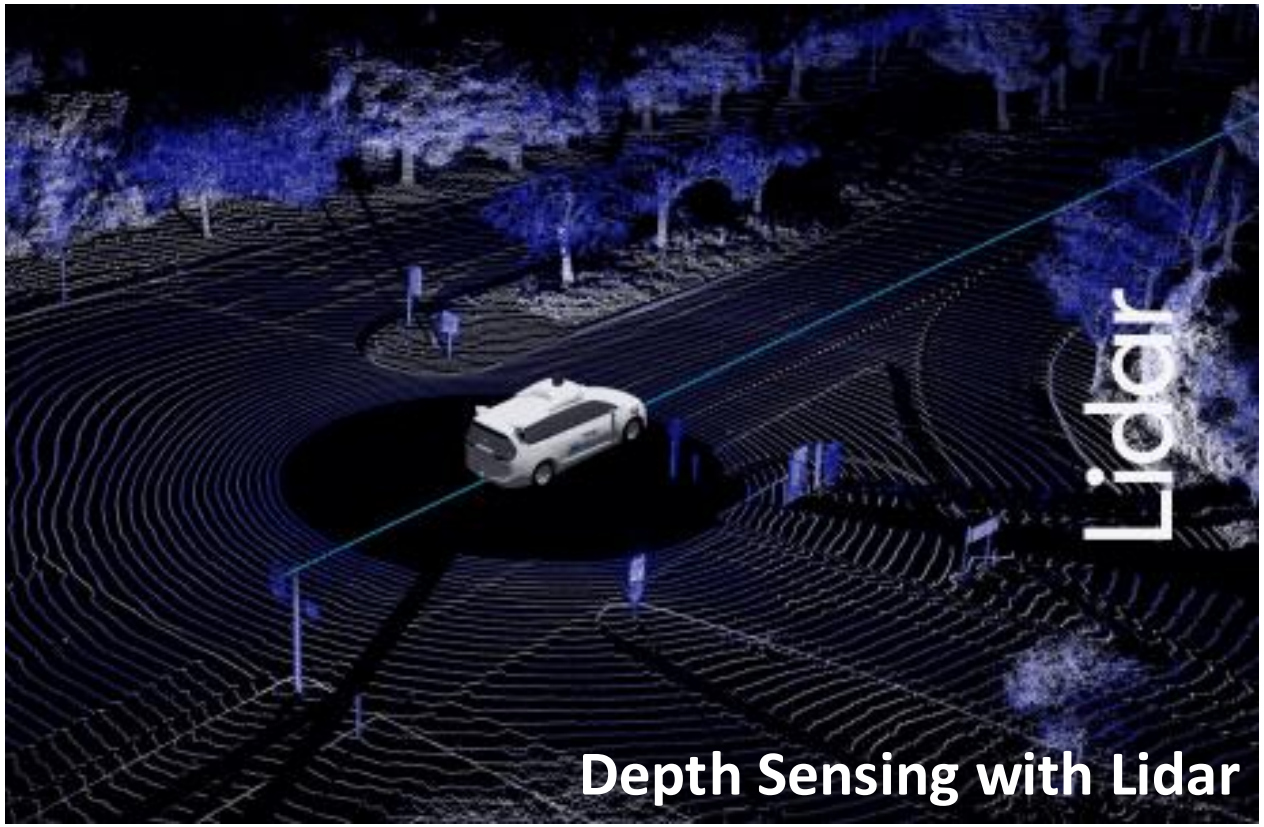
What would we do without ROS?

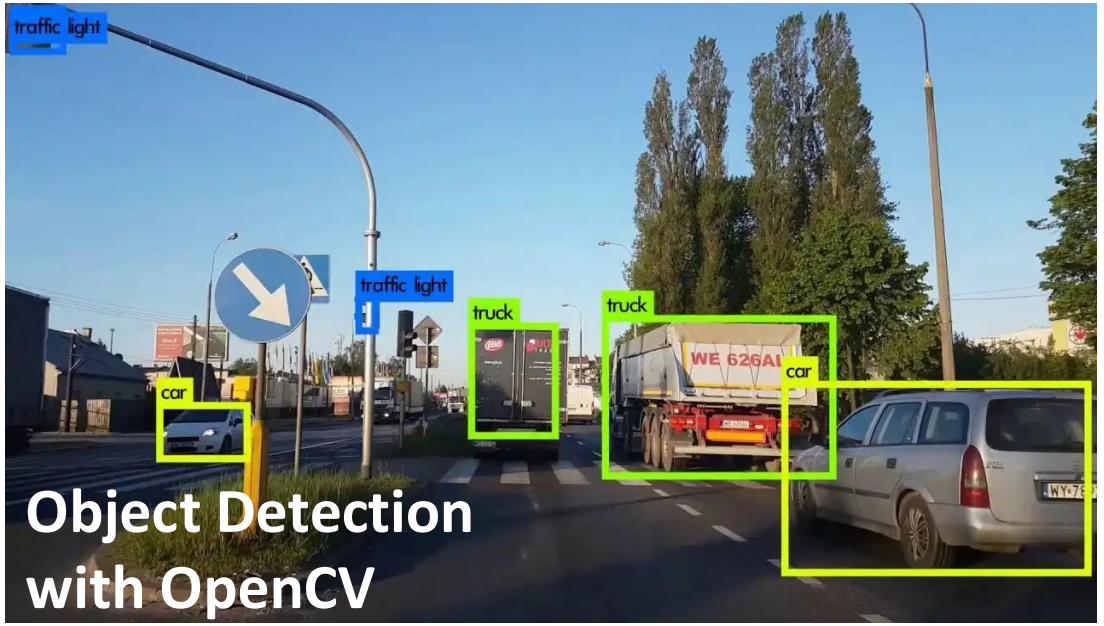
- Write custom code to connect sensors and actuators.
- Reinvent tools for visualization, debugging, and simulation.
- Struggle with versioning, testing, and sharing code.

What is ROS?

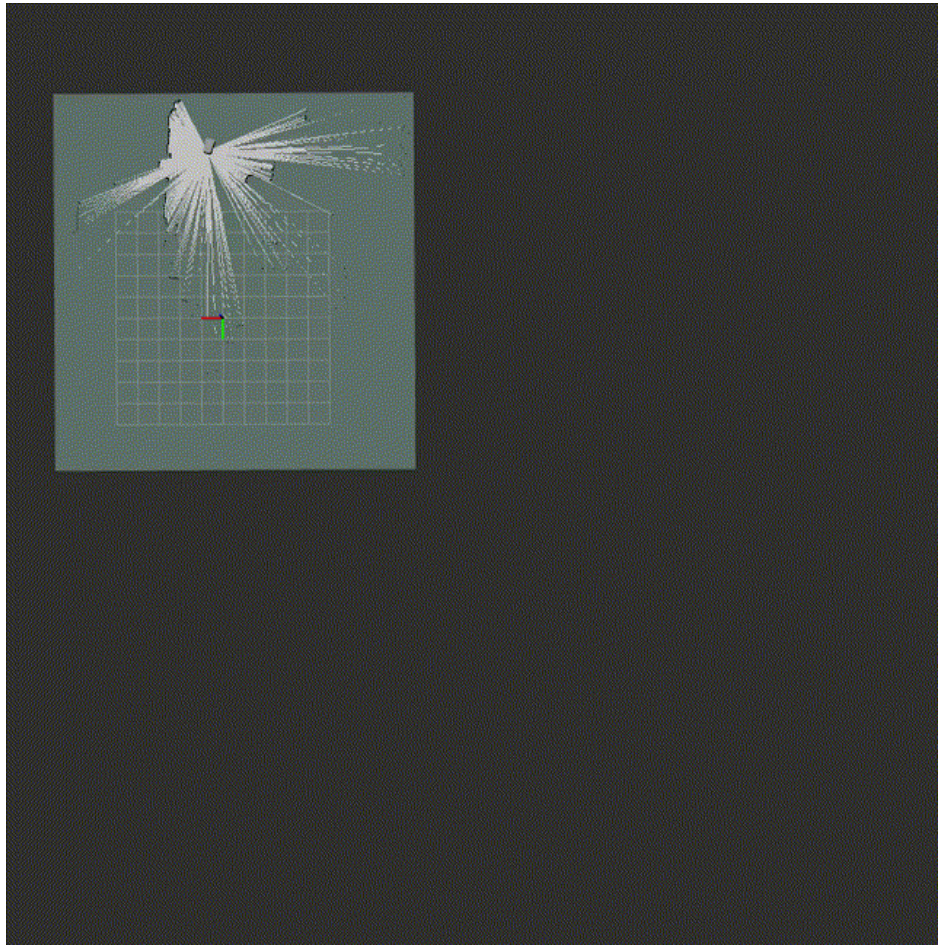
- Middleware (Not an operating system)
- ROS provides:
  - Launching different components
  - Communication between components → Publish/subscribe messaging system.
  - Reusable components → Packages for navigation, vision, motion planning
  - Tools for visualization & debugging → RViz, Gazebo, rqt.
  - Community & ecosystem → Thousands of open-source packages.

Perception


Lidar
Depth Sensing with Lidar


traffic light
traffic light
truck
truck
car
car
Object Detection
with OpenCV

Localization and Mapping



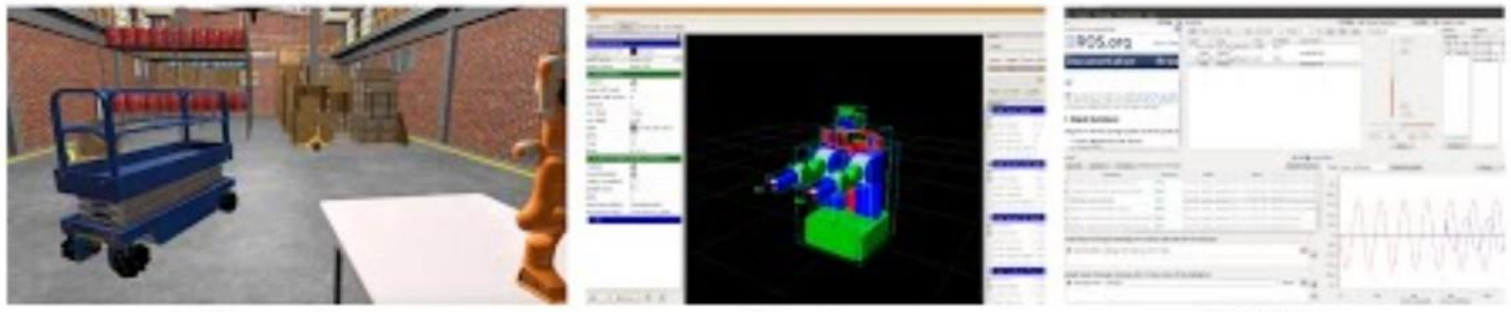
Navigation


Waymo
Navigation
on Freeway


PR2 Navigation around
a Fake Death
MakeAGIF.com

Manipulation

Simulation and Visualization



ROS2 Simulation and Visualization Tools

Multidisciplinary Collaboration

- All disciplines come together
  - Mechanical engineers: Design the robot body and actuators
  - Electrical engineers: Design actuators, sensors, and control
  - Computer scientists / AI researchers: Implement perception and planning
  - Design experts: Build human-robot interfaces via ROS APIs.

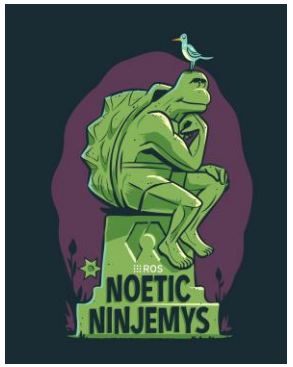
Robot Operating System – History

ROS 1

2014 - 2019

2016 - 2021

2018 - 2023



2020 - 2025

ROS 2

2019 - 2021

2020 - 2023

2022 - 2027

2017 - Present

Key takeaways

ROS2

- ROS is a framework that connects all parts of a robot.
- It saves time, encourages collaboration, and accelerates innovation.
- ROS brings robot autonomy to reality.
- The ROS ecosystem is vast and growing.
- Next lecture: *How ROS actually works* — topics, nodes, packages, ...

Backup

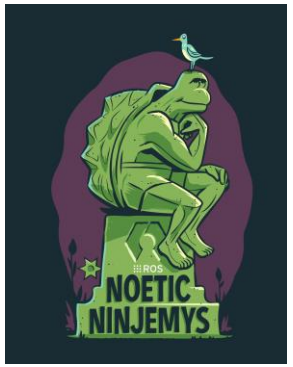
Robot Operating System – History

ROS 1

2014 - 2019

2016 - 2021

2018 - 2023



2020 - 2025

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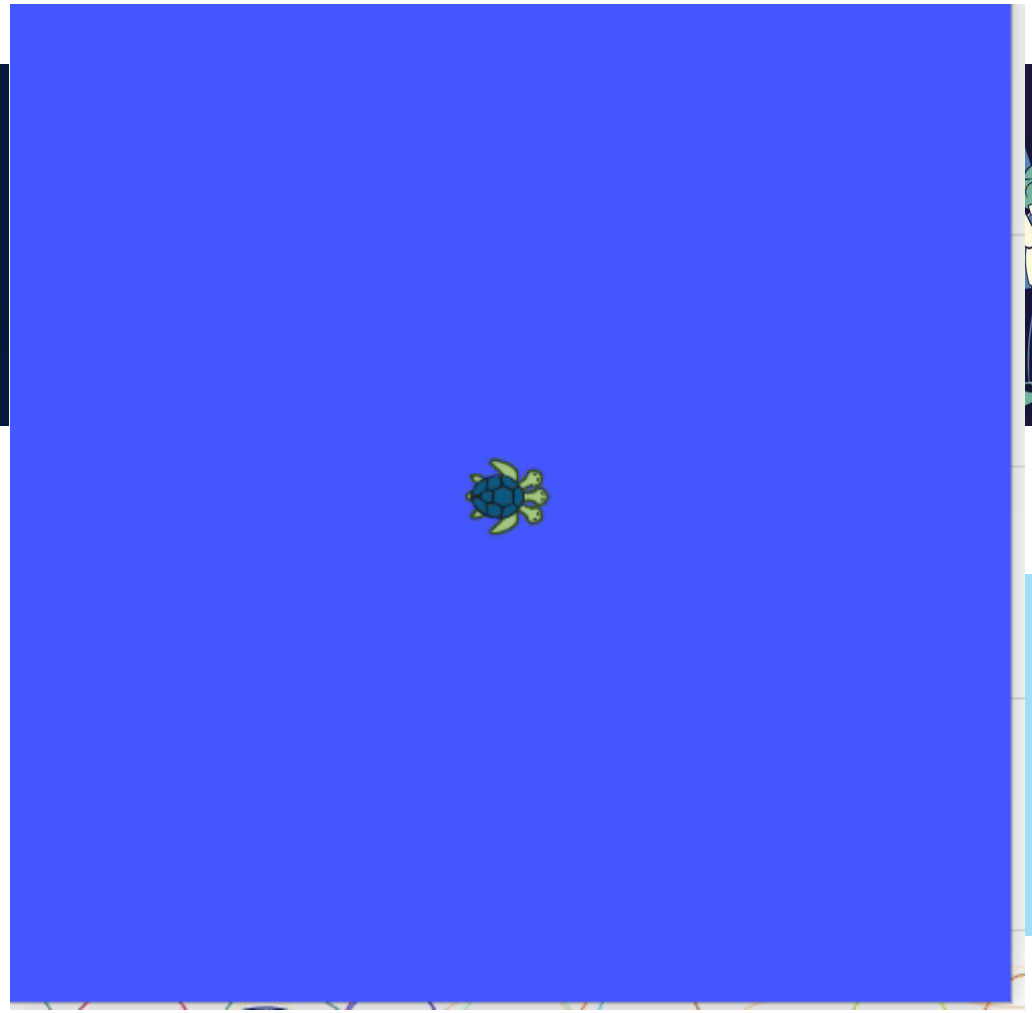
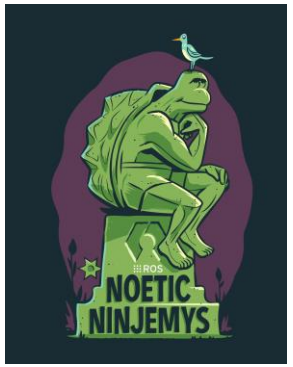
2017 - Present

Robot Operating System – History

ROS 1

2014 - 2019





2020 - 2025

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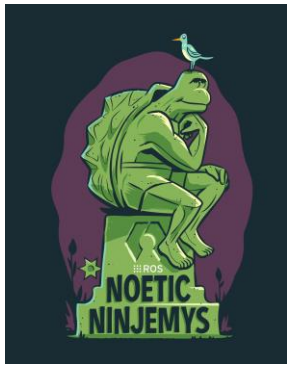


2020 - 2025

ROS 2

2019 - 2021

2020 - 2023

2022 - 2027

2017 - Present

Why is ROS popular in academia?

- Not reinventing the wheel is generally good
- Robotics is hard! It’s great to offload some of the work to smart people
- ROS is now 12 years old and still going strong

Robot Operating System – Overview

- Community & Ecosystem
  - Hardware Drivers
  - Software
- Tooling
  - Visualization
  - Debugging
- Asynchronous Programming Model

Robot Operating System – ROS2

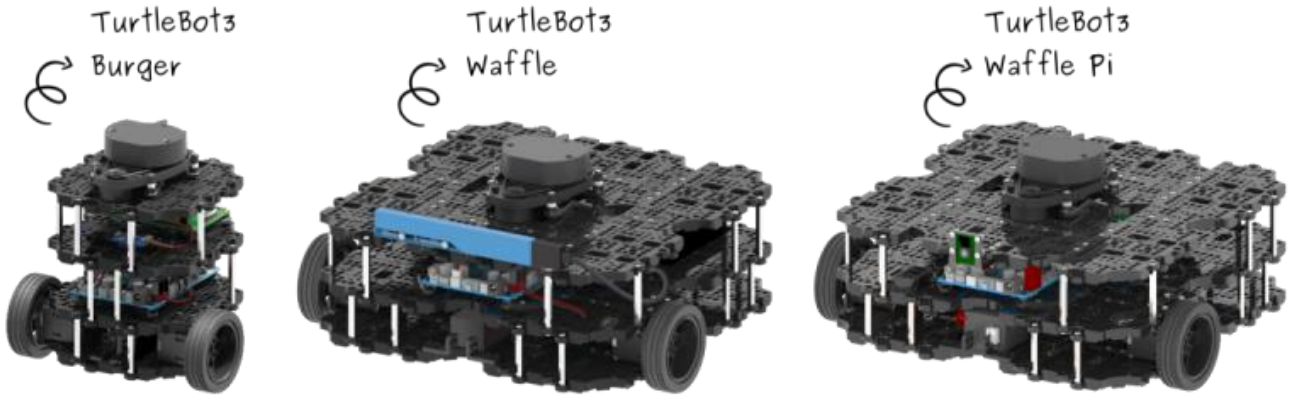
- Community & Ecosystem
  - Hardware Drivers
  - Software

Robot Operating System – ROS2

- Community & Ecosystem
  - Hardware Drivers
  - Software

Crazyflie

Joysticks

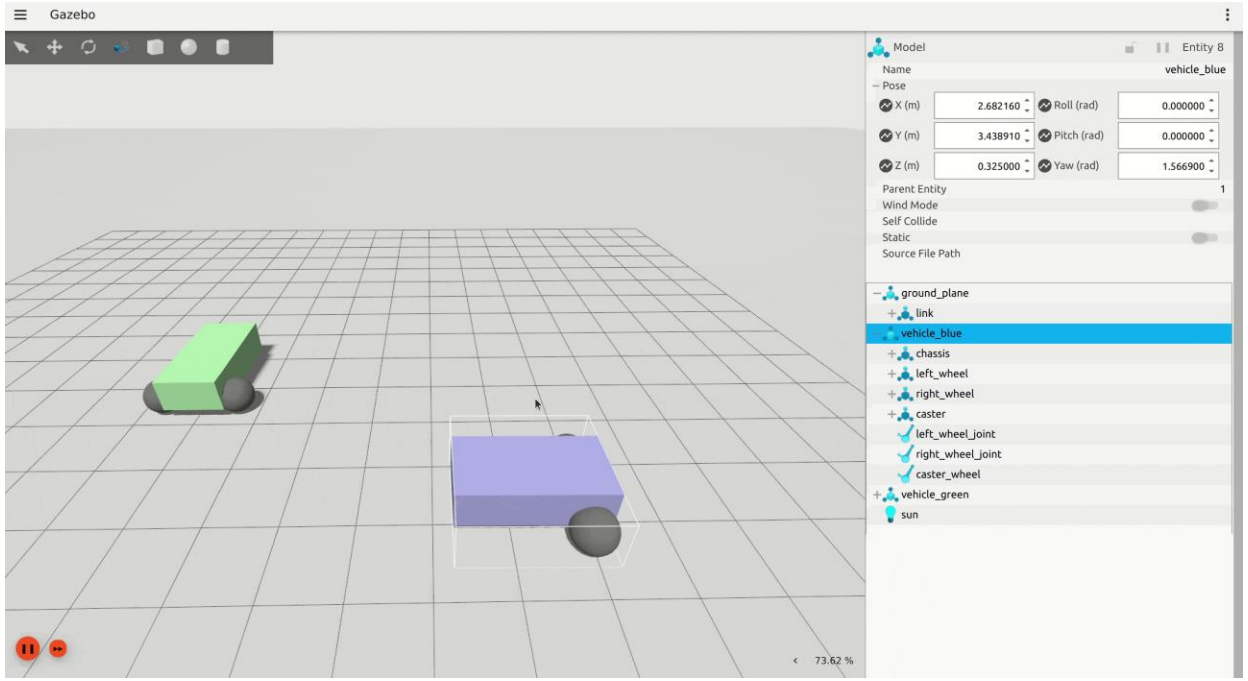


Turtlebot3

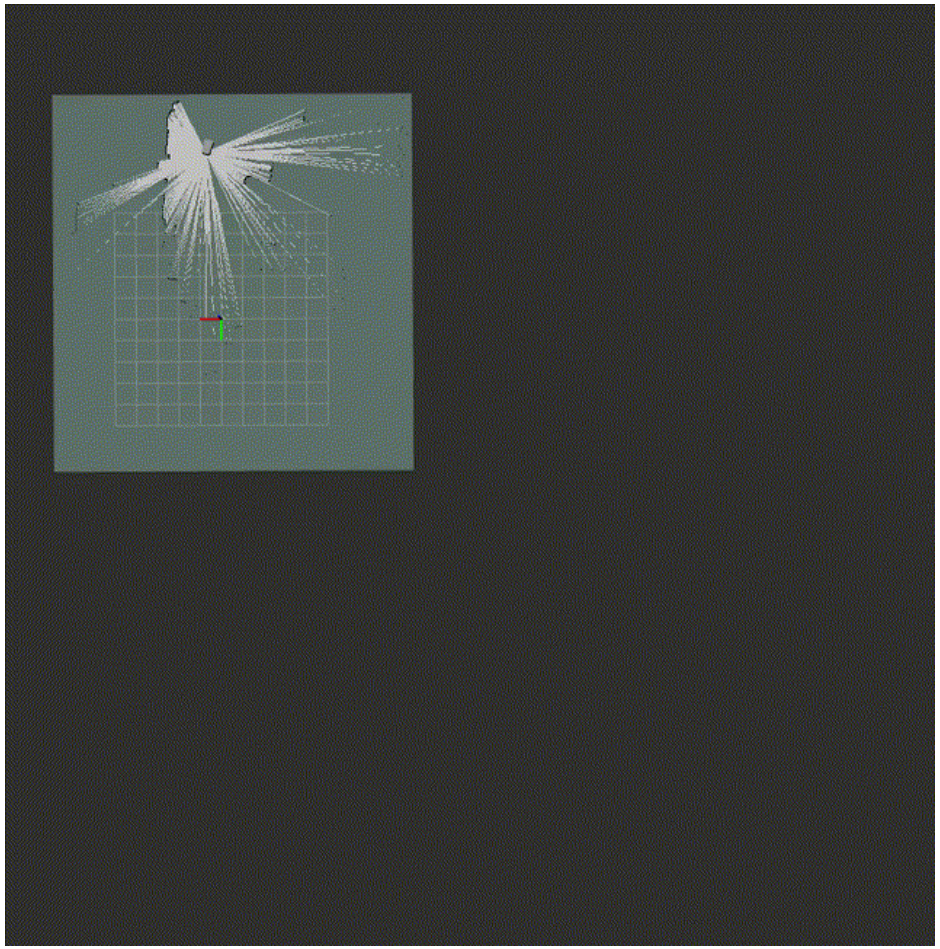
Velodyne LiDAR

Robot Operating System – ROS2

- Community & Ecosystem
  - Hardware Drivers
  - Software



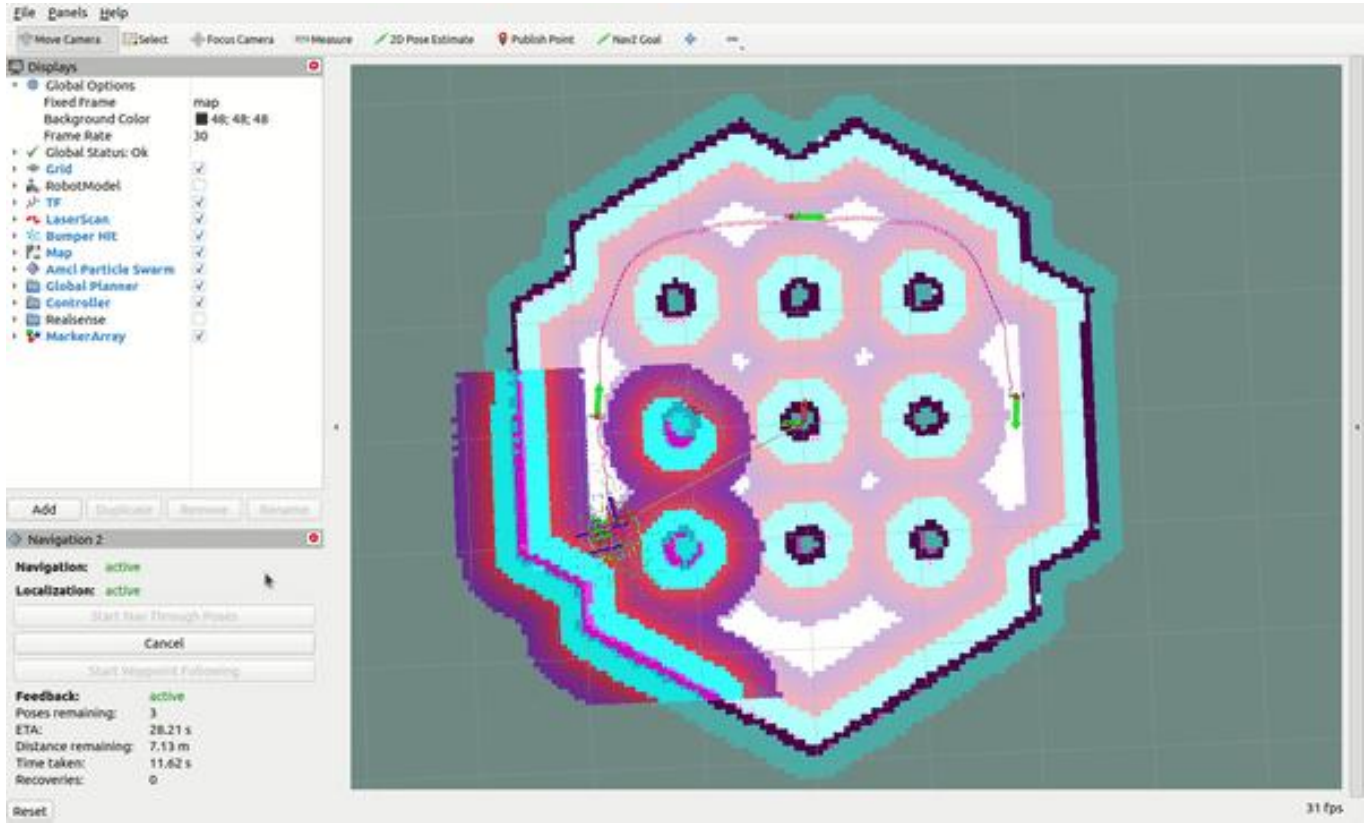
Gazebo Sim



SLAM Toolbox

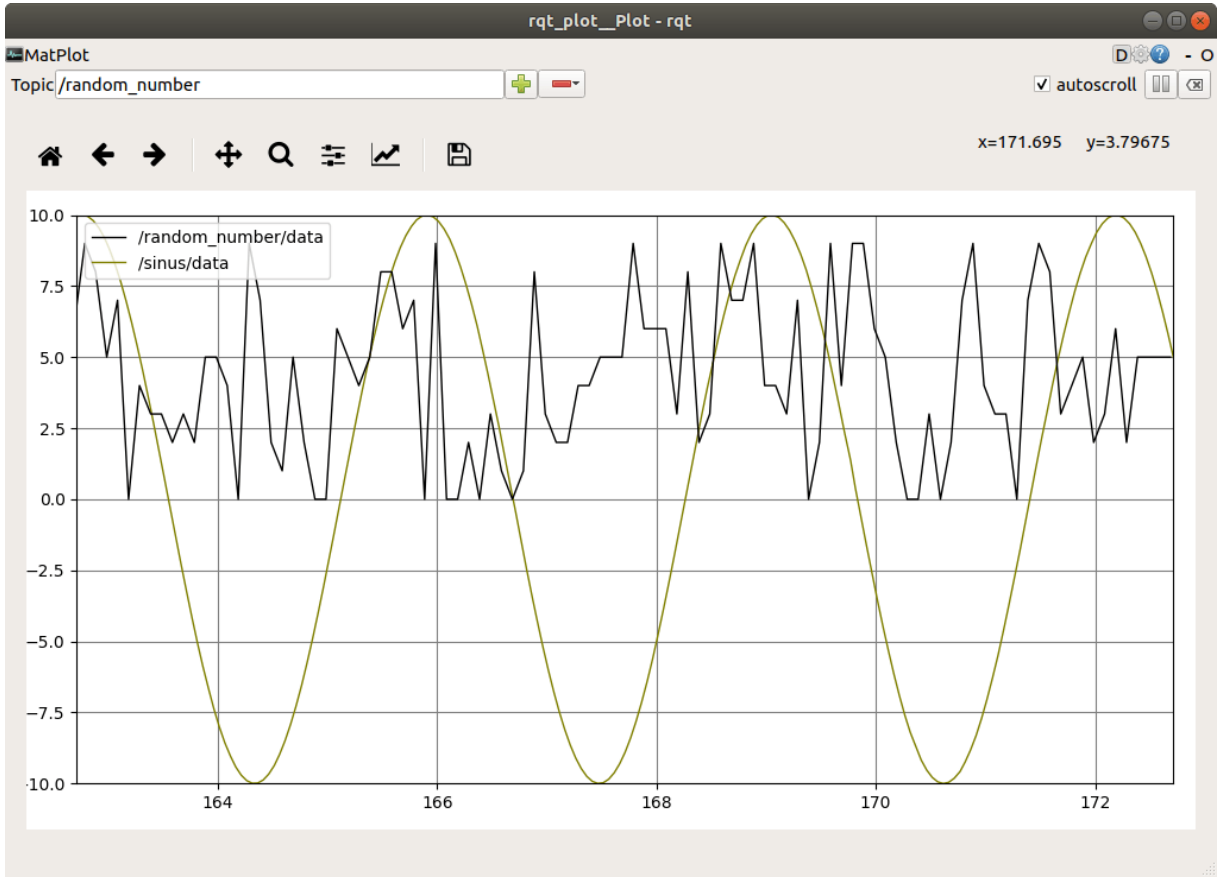
Robot Operating System – ROS2

- Community & Ecosystem
  - Hardware Drivers
  - Software
- Tooling
  - Visualization
  - Debugging



Robot Operating System – ROS2

- Community & Ecosystem
  - Hardware Drivers
  - Software
- Tooling
  - Visualization
  - Debugging



Robot Operating System – ROS2

- Community & Ecosystem
  - Hardware Drivers
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- Asynchronous Programming Model

See-think-act

Robot Operating System – ROS2

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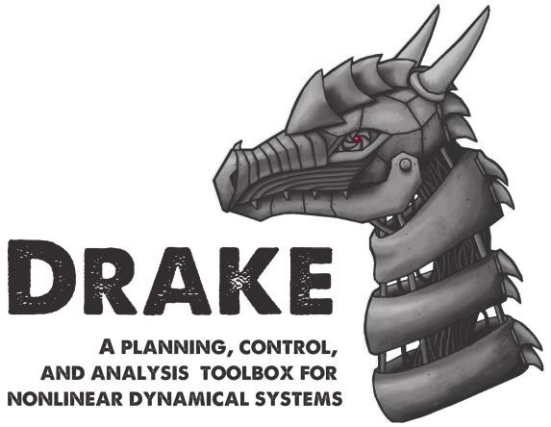
Let’s write some code!

Are there “Alternatives” to ROS?

- LCM
- Drake
- Player
- YARP
- Orocos
- MRPT
- And many others!



Next time: fundamentals of ROS

Robot Operating System