

Principles of Robot Autonomy I

Course overview, intro to robotic systems and ROS



Stanford
University



From automation...



...to autonomy

Waymo Self-Driving Car



Intuitive DaVinci Surgical Robot



Apollo Robot at MPI



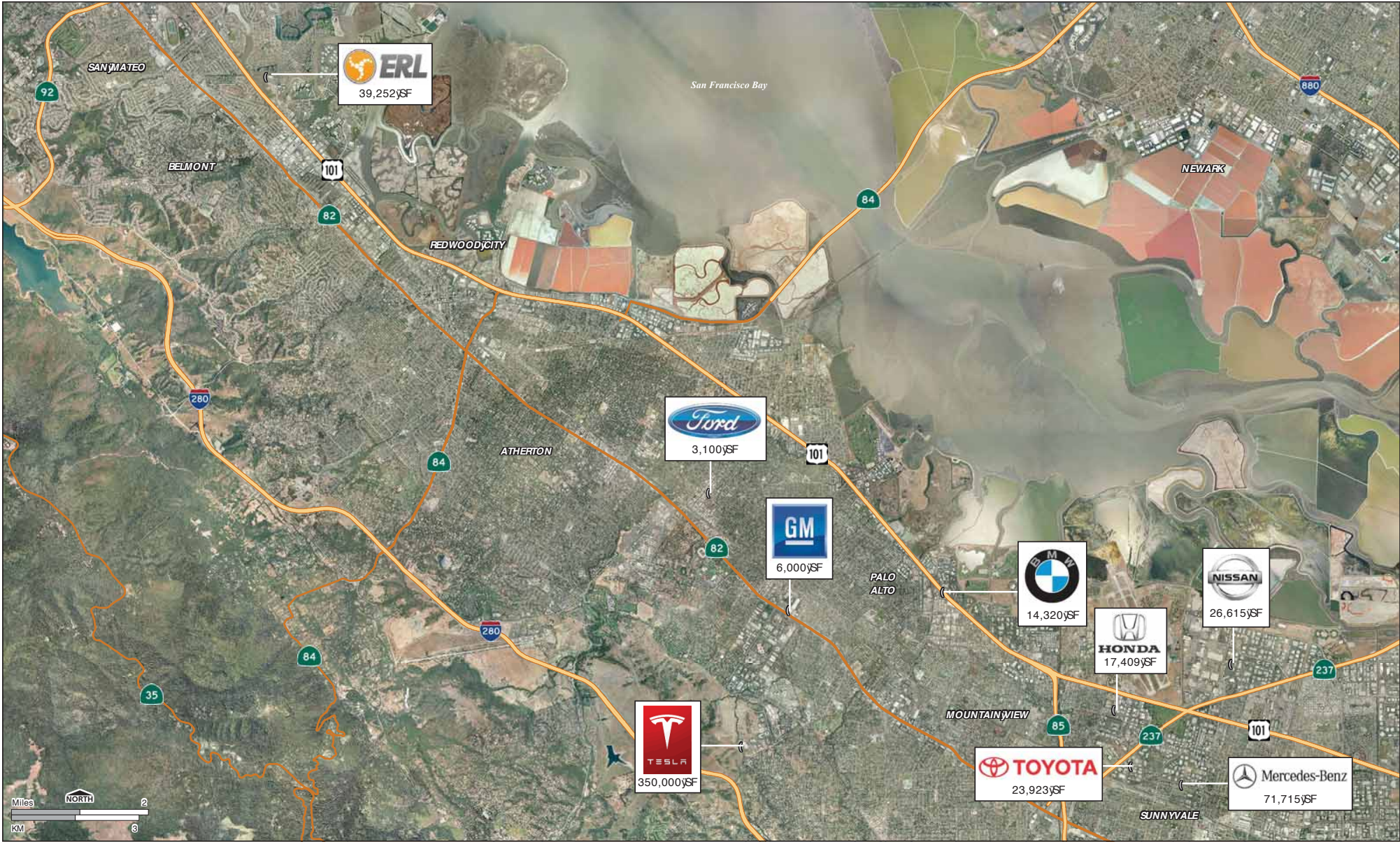
Boston Dynamics – Spot Mini

Astrobee - NASA



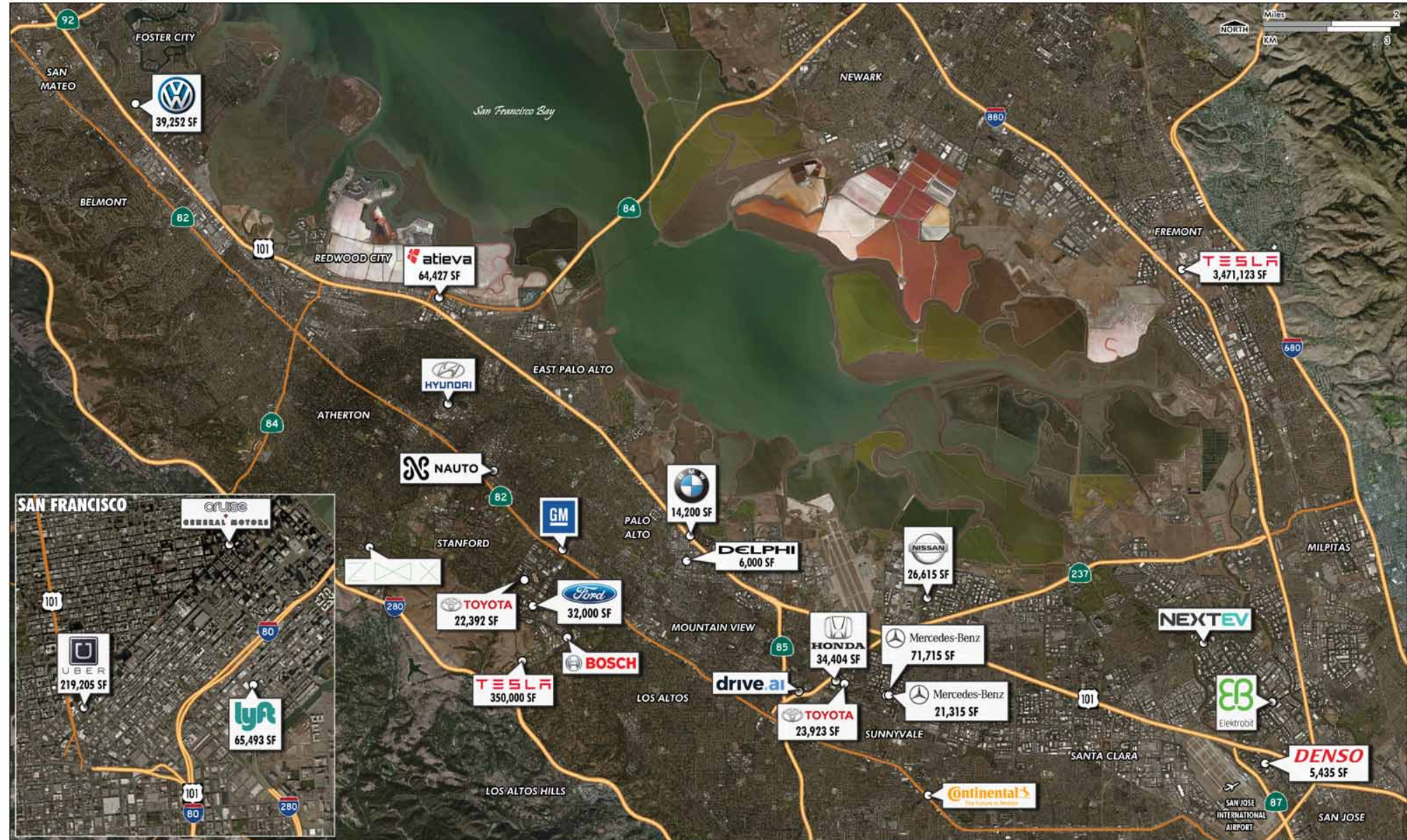
Zipline

Silicon Valley



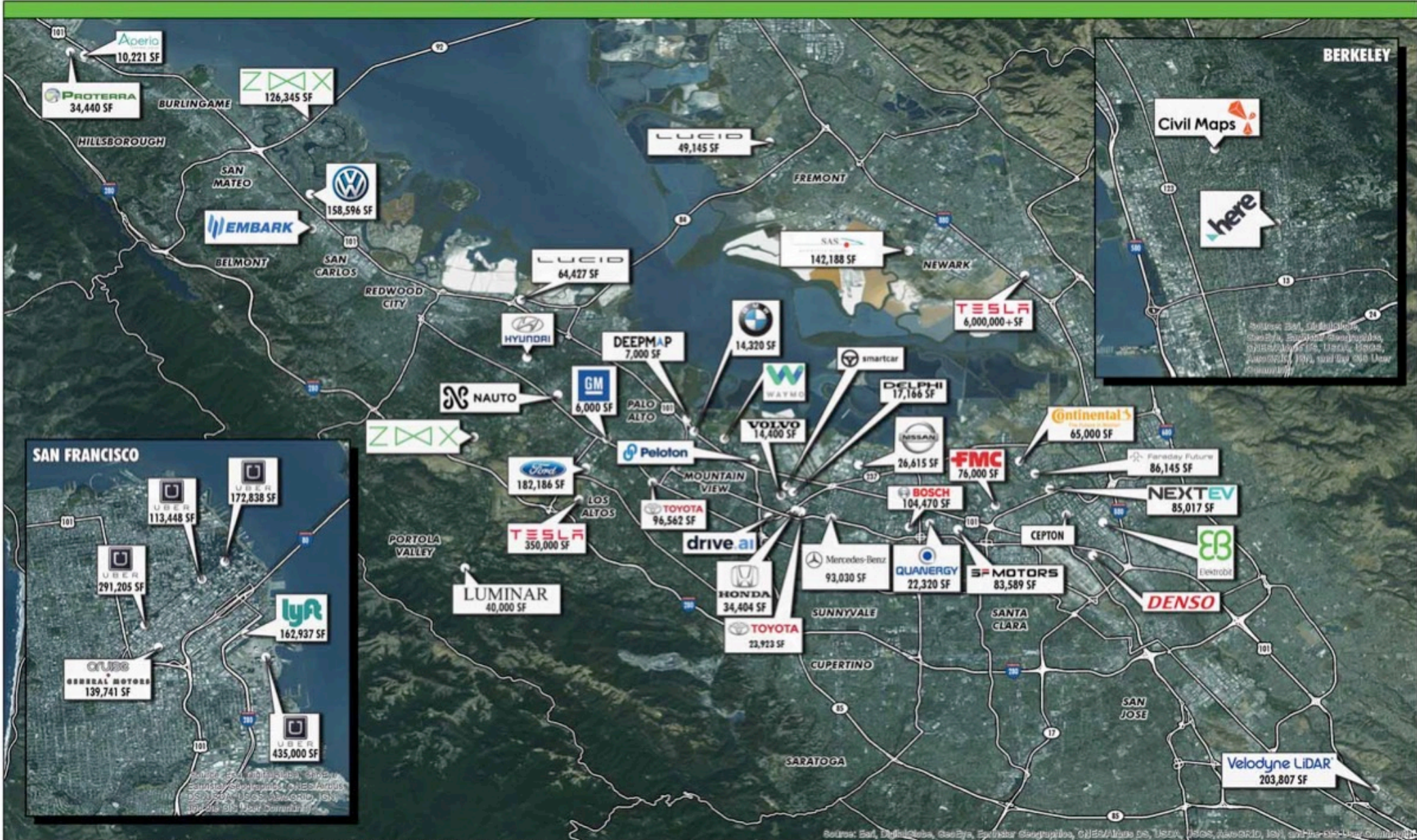
This map contains information from sources whose accuracy is not guaranteed. It is not intended to be used for any purpose other than general information. All rights reserved. Sources: ESRI, Mapping Services, 171880-4674, Kroll, Inc., and other third parties. MapInfo Work 2014.298837.1, work 12/20/14

Silicon Valley



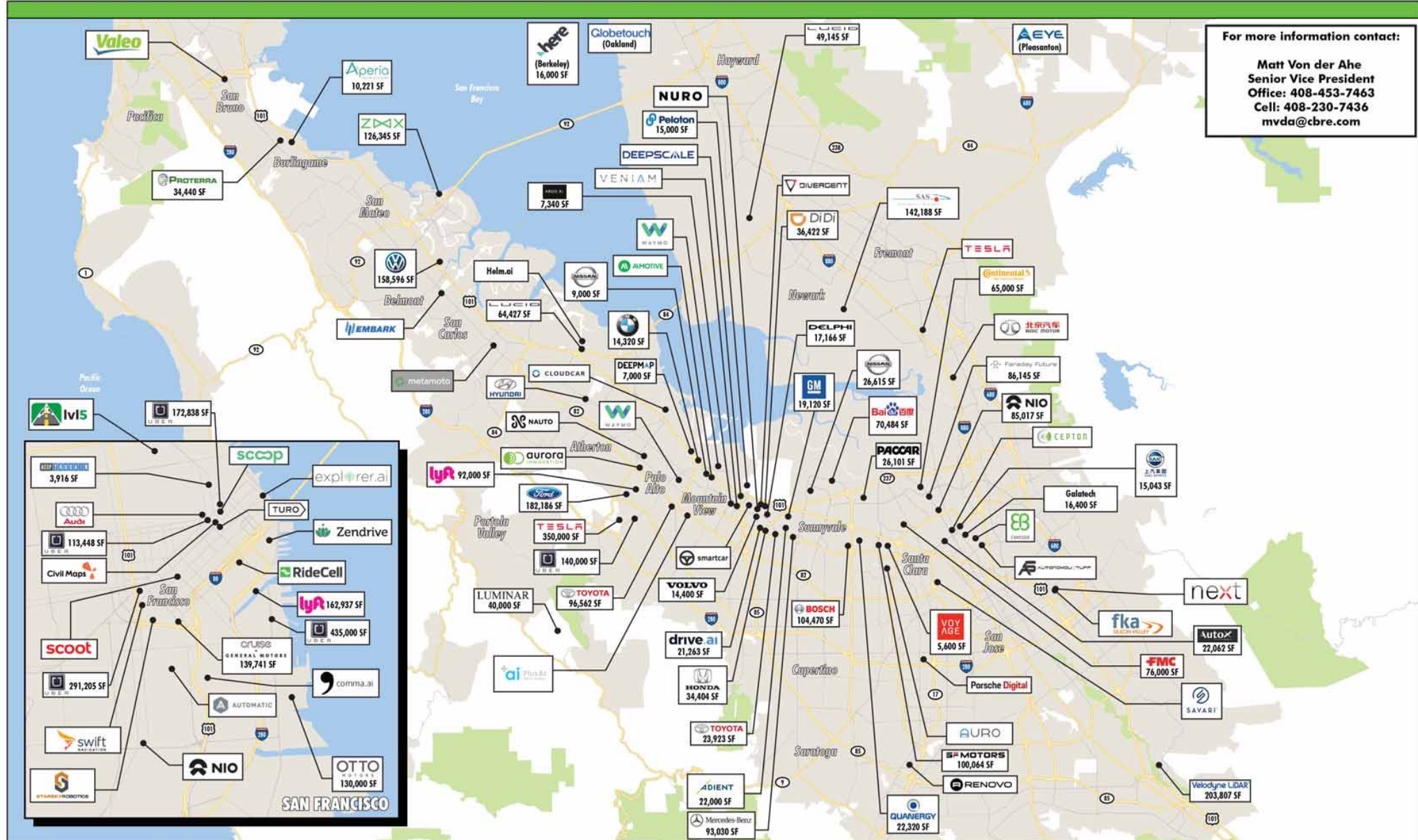
This map contains information from sources we believe to be reliable, but we make no representation, warranty or guarantee of its accuracy. This map is published for the use of CBRE and its clients only. Redistribution in whole or part to any third party without the prior written consent of CBRE is strictly prohibited. All logos displayed on this map are the property of their respective owners. Small icons indicate that businesses associated with these marks are located in buildings displayed on the map. All Rights Reserved. Sources: CBRE Mapping Services (877) 585-6674, Nielsen, StreetView, Microsoft Bing. MapData/MapData2/16/333911 user: 4/5/2016.

AUTO LAB MAP APRIL 2017 SILICON VALLEY



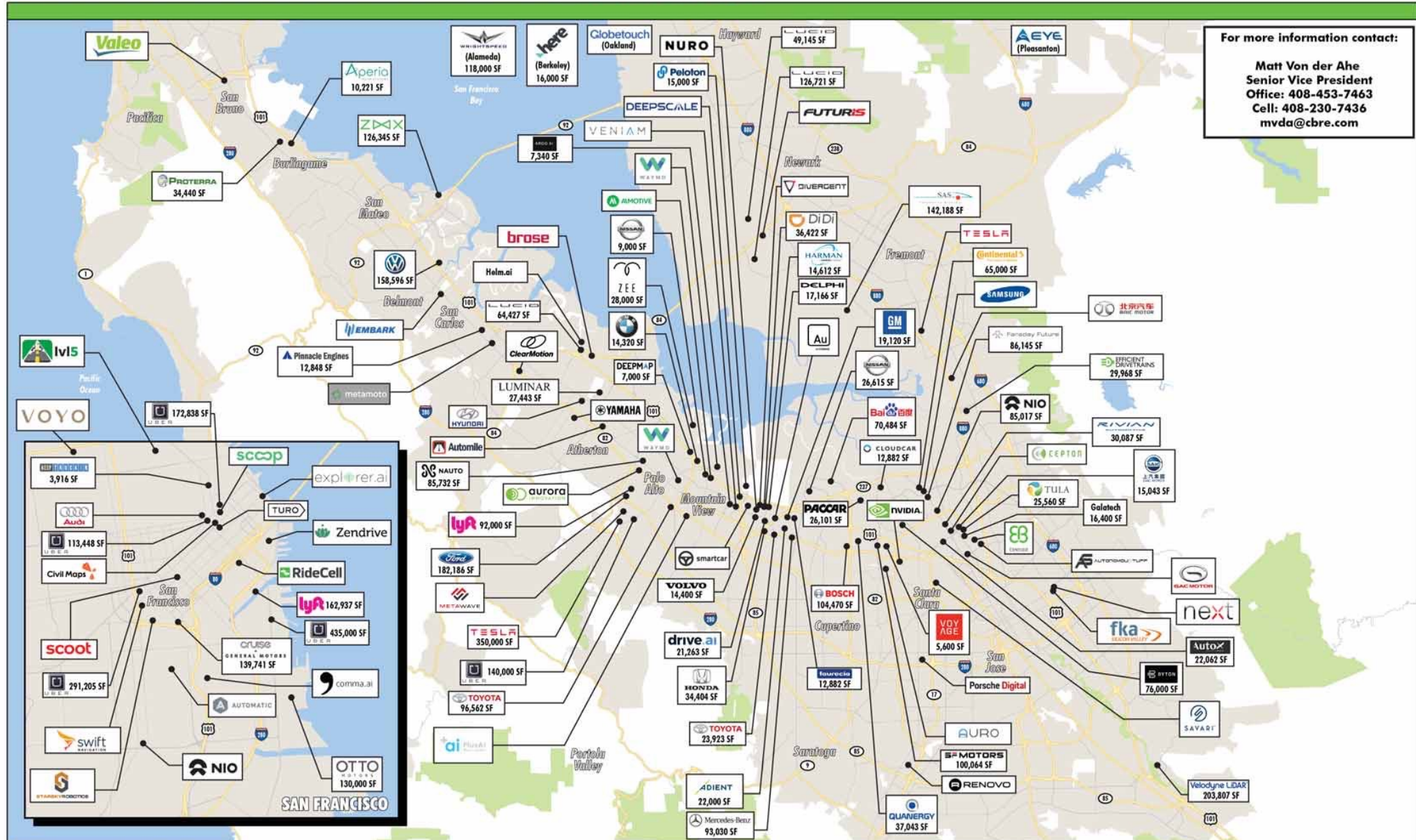
© 2017 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. \\Team-GSD\Projects\Phoenix\2017\2ndQtr\336633\336633.mxd

AUTO LAB MAP SEPTEMBER 2017 SILICON VALLEY



For more information contact:
Matt Von der Ahe
 Senior Vice President
 Office: 408-453-7463
 Cell: 408-230-7436
 mvda@cbre.com

AUTO LAB MAP DECEMBER 2017 SILICON VALLEY

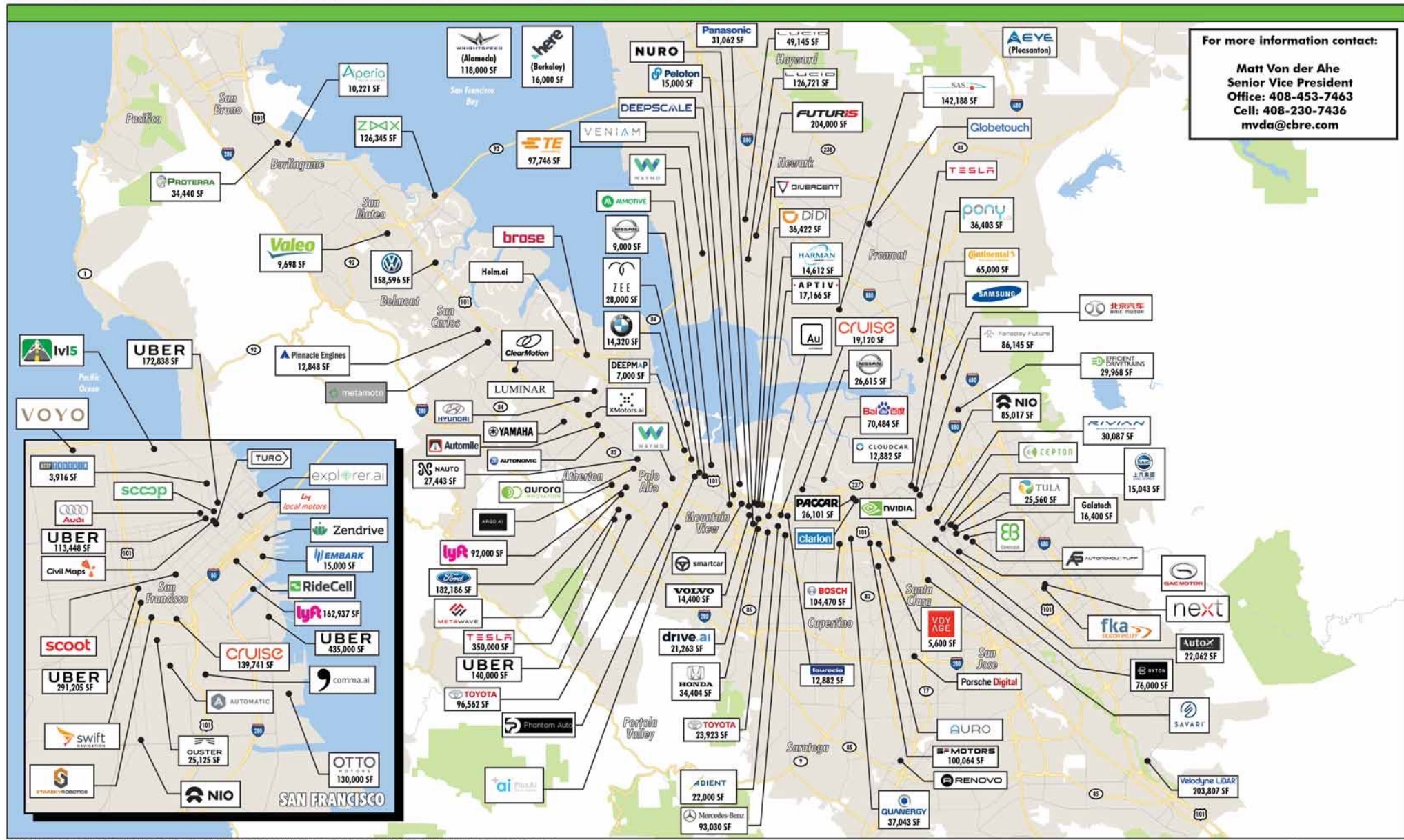


For more information contact:

Matt Von der Ahe
 Senior Vice President
 Office: 408-453-7463
 Cell: 408-230-7436
 mvda@cbre.com

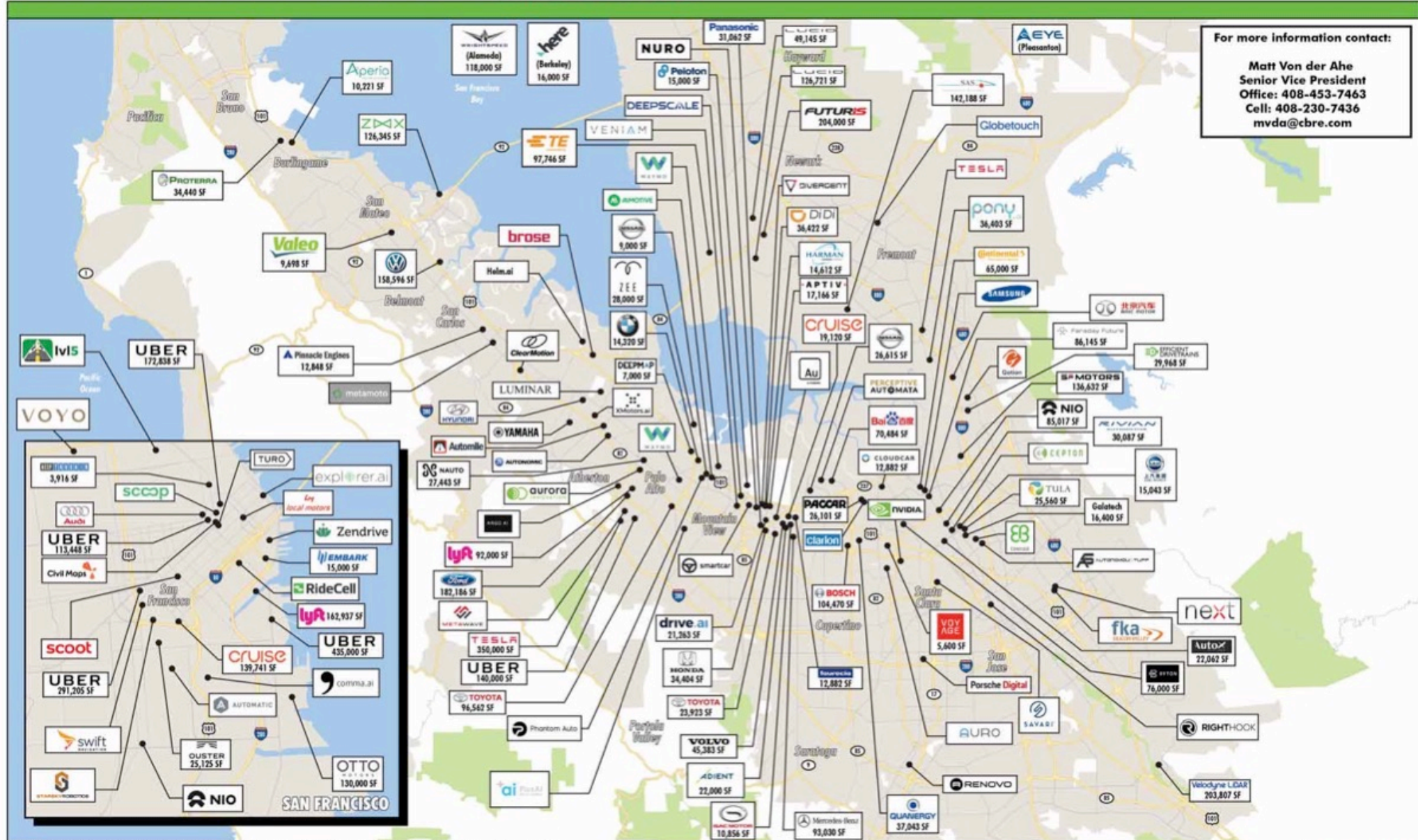
©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team-GISData\Projects\Phoenix\2017\4thQtr\345660\345660.mxd

AUTO LAB MAP FEBRUARY 2018 SILICON VALLEY



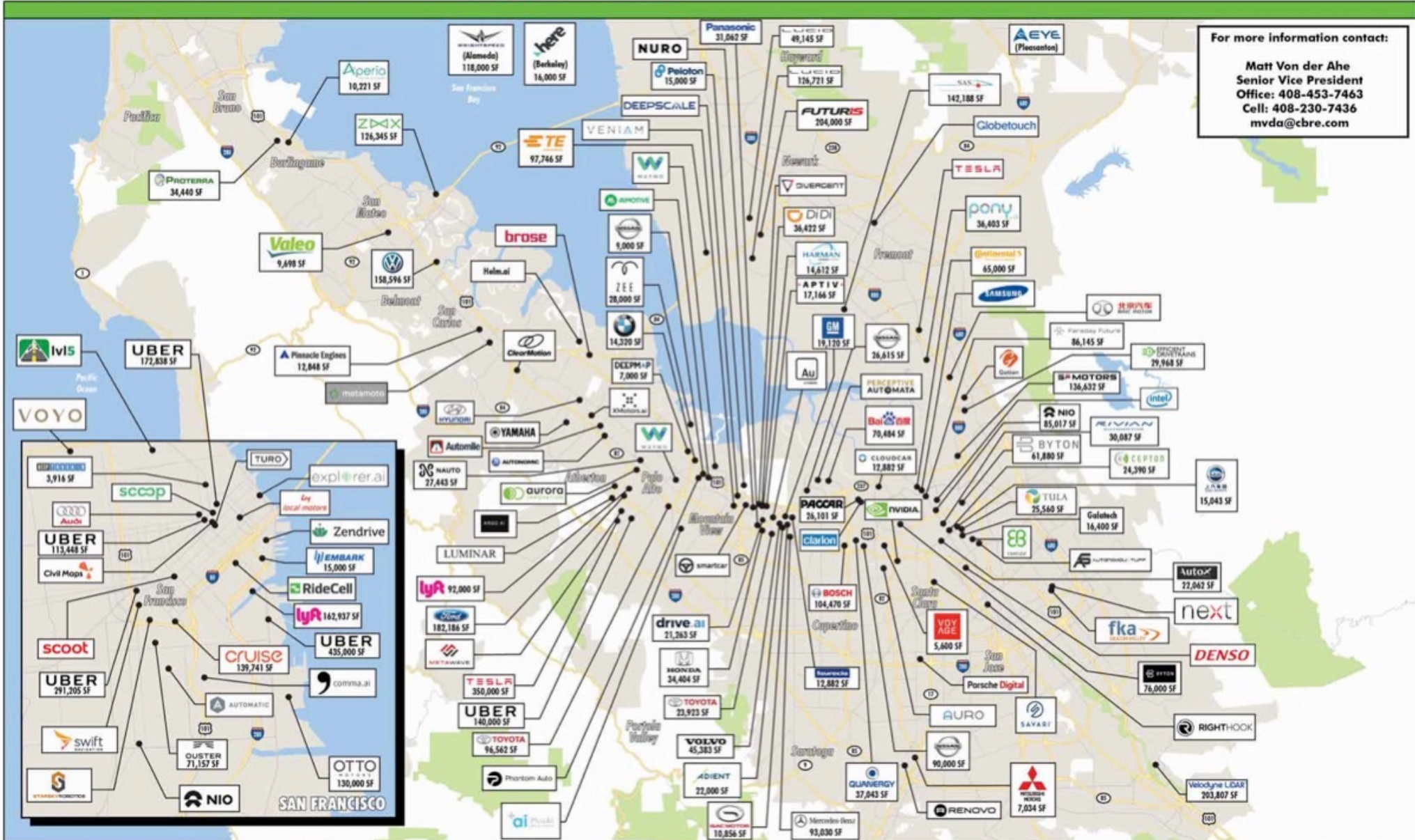
For more information contact:
Matt Von der Ahe
 Senior Vice President
 Office: 408-453-7463
 Cell: 408-230-7436
 mnda@cbre.com

AUTO LAB MAP MARCH 2018 SILICON VALLEY



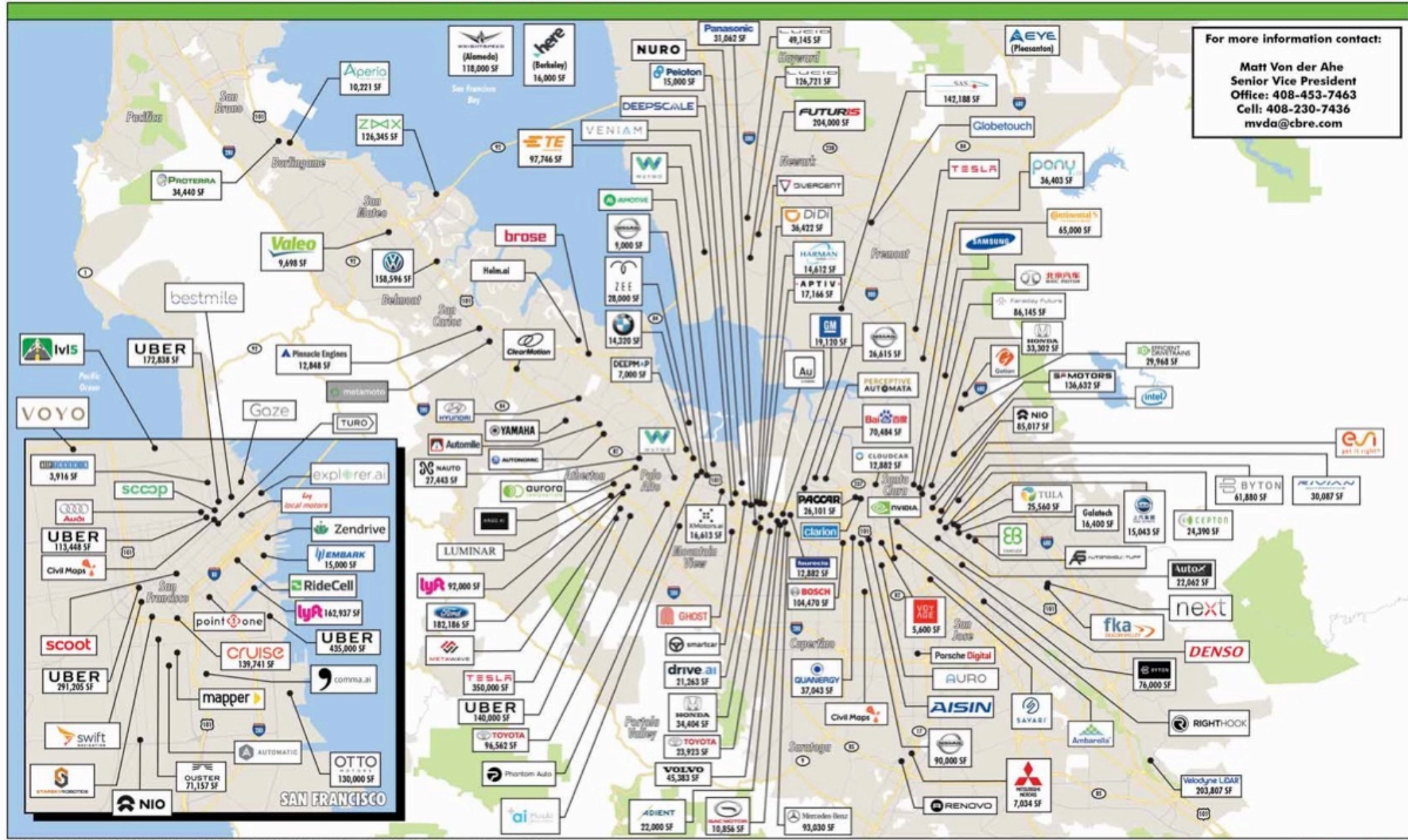
©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team-GISData\Projects\Phoenix\2018\2ndQtr\350079\350076.mxd

AUTO LAB MAP APRIL 2018 SILICON VALLEY



©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team-GISData\Projects\Phoenix\2018\2ndQtr\350965\350965.mxd

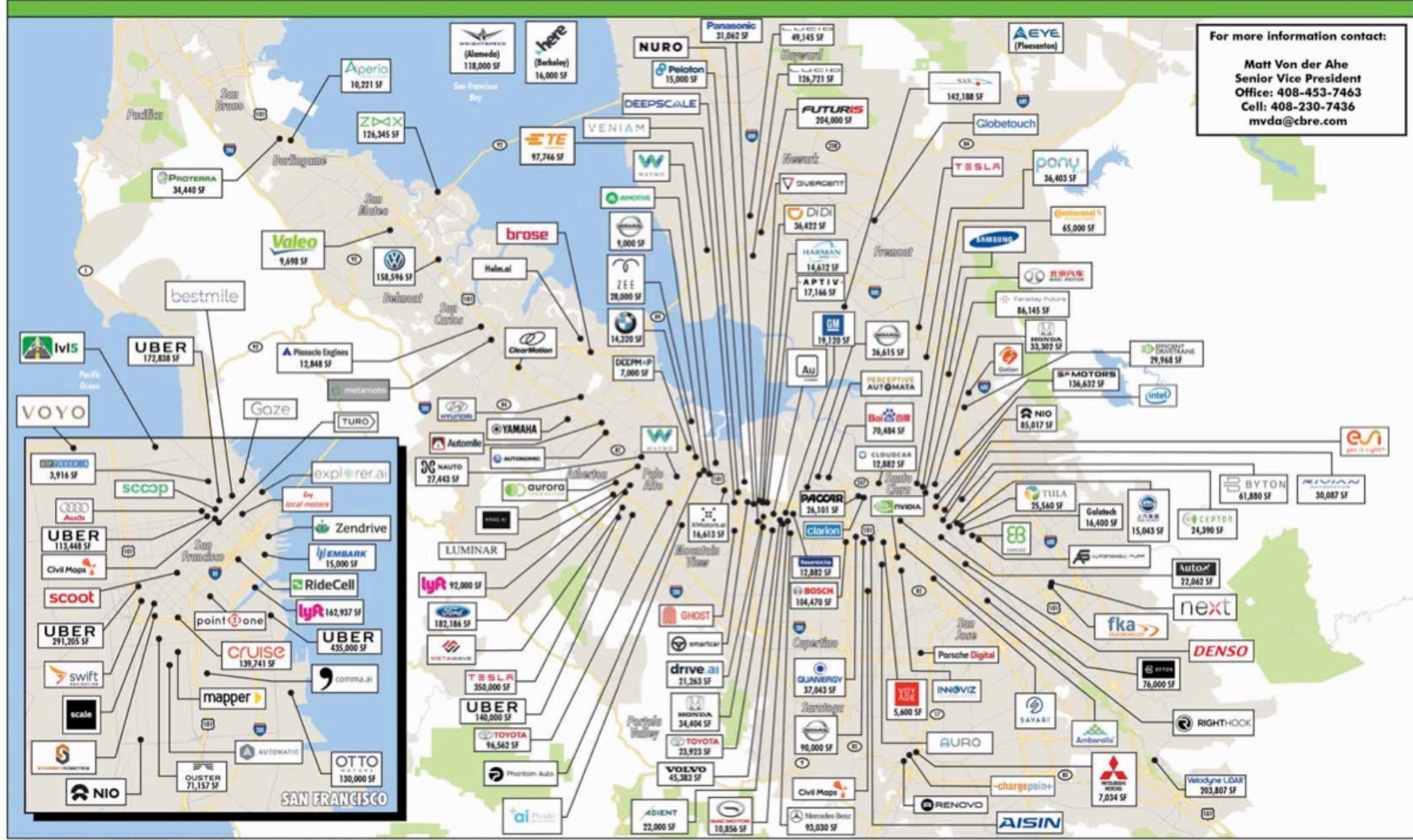
AUTO LAB MAP MAY 2018 SILICON VALLEY



For more information contact:
Matt Von der Ahe
 Senior Vice President
 Office: 408-453-7463
 Cell: 408-230-7436
 mvda@cbre.com

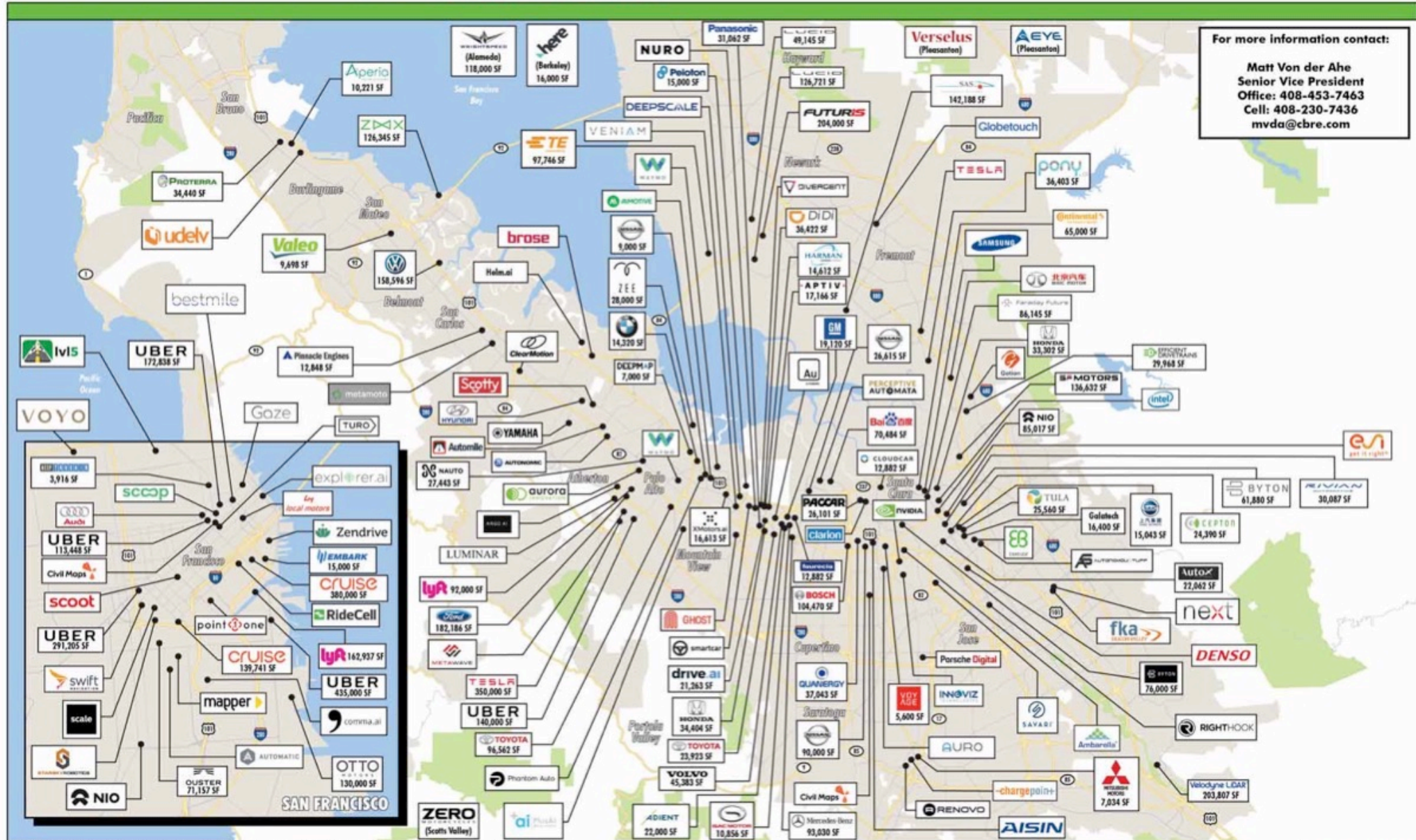
©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team-GISData\Projects\Phoenix\2018\2ndQtr\351950\351950.mxd

AUTO LAB MAP JUNE 2018 SILICON VALLEY



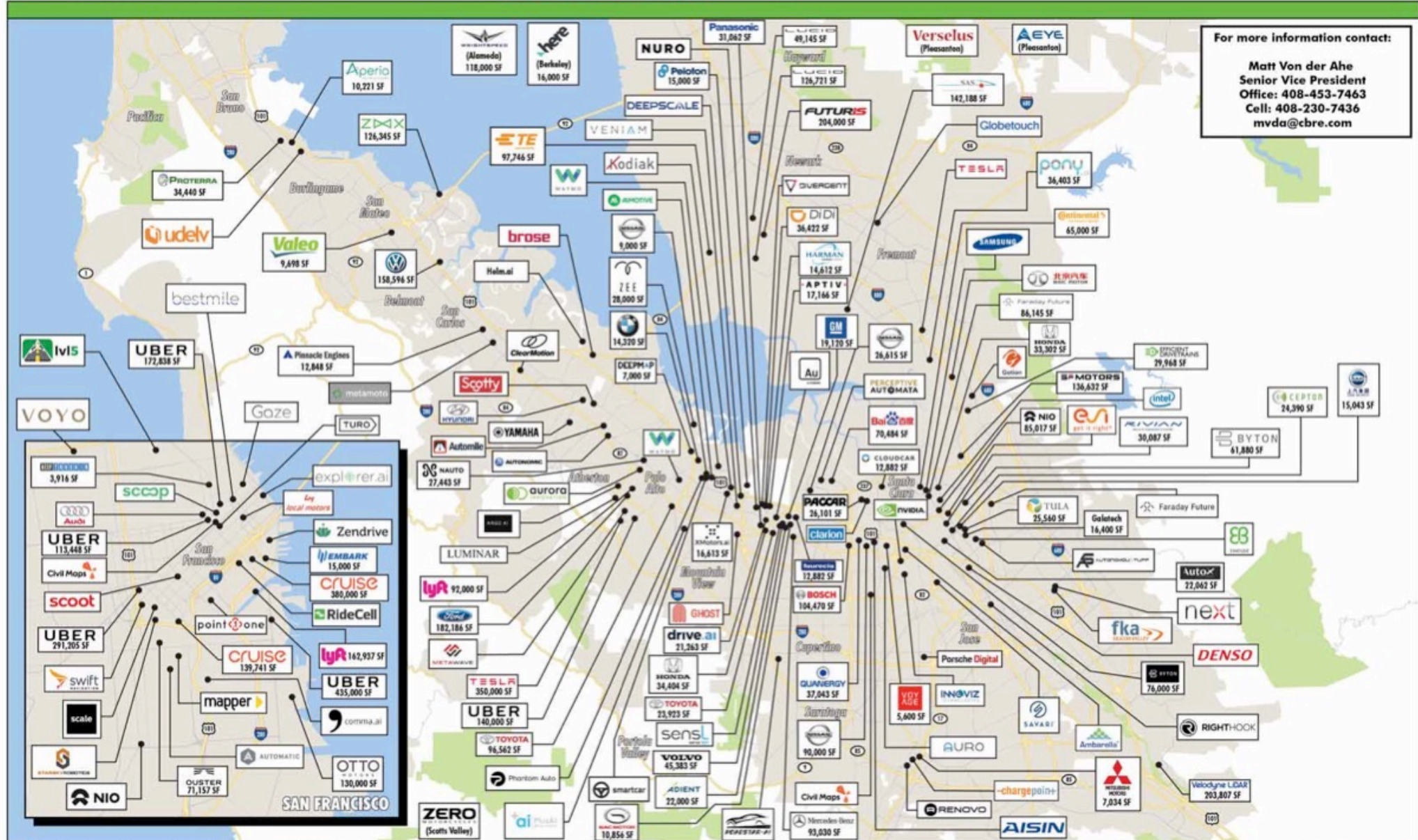
©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team-GISData\Projects\Phoenix\2018\2ndQtr\352852\352852.mxd

AUTO LAB MAP JULY 2018 SILICON VALLEY



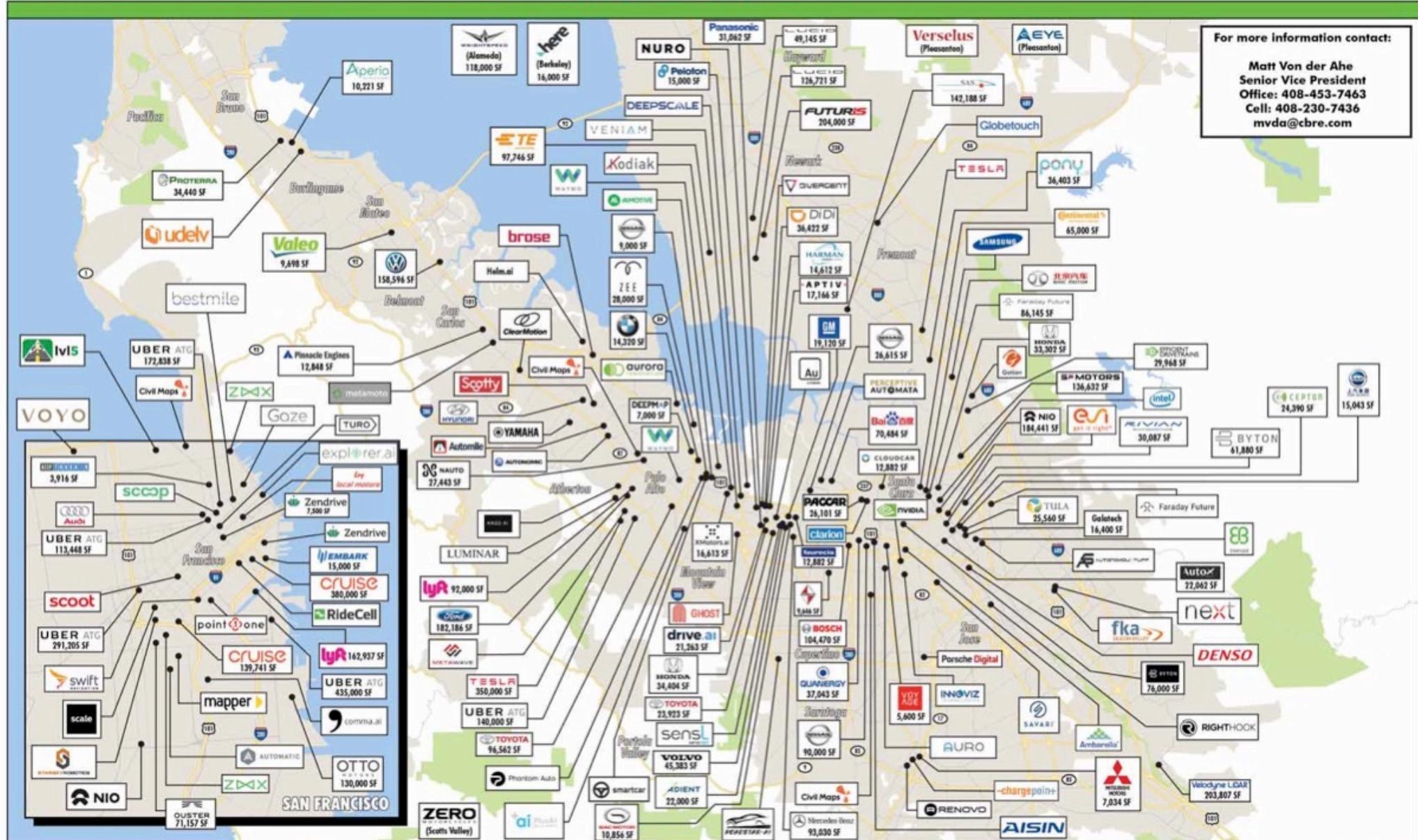
©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team-GISData\Projects\Phoenix\2018\3rdQtr\354306\354306.mxd

AUTO LAB MAP AUGUST 2018 SILICON VALLEY



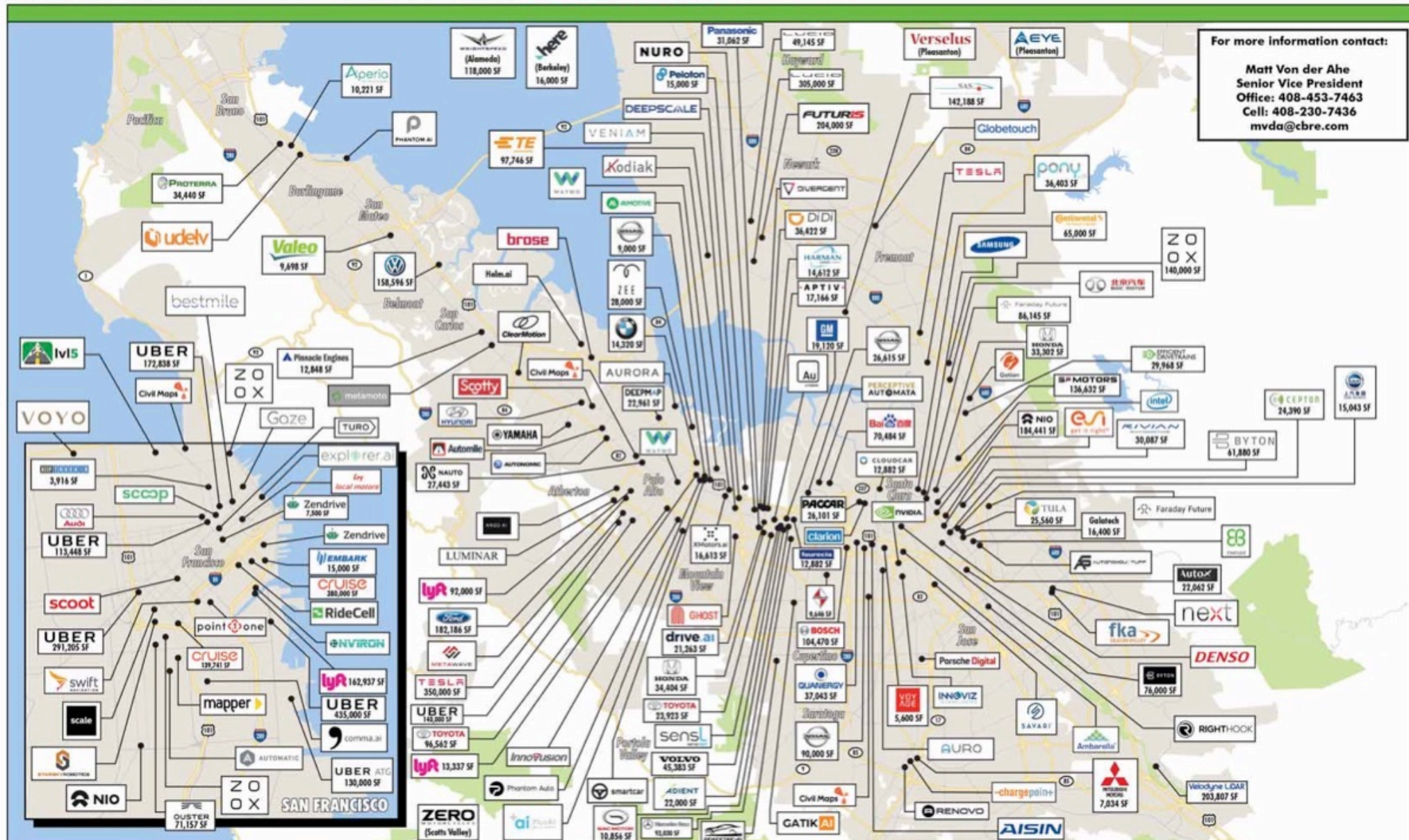
©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or valuations used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team\GISData\Projects\Phoenix\2018\3rdQ\355552\355552.aprx

AUTO LAB MAP SEPTEMBER 2018 SILICON VALLEY

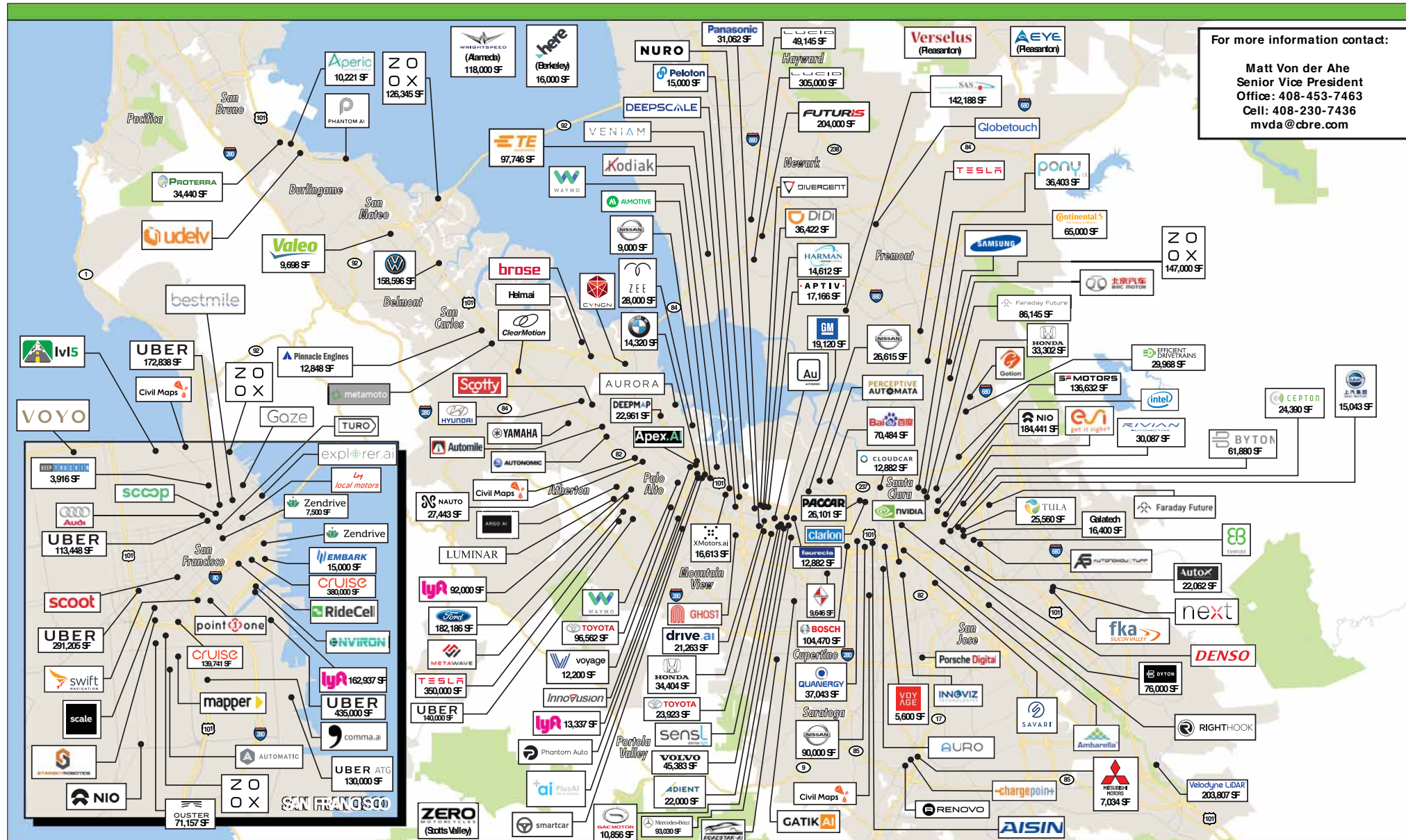


©2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliated or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. N:\Team-GISData\Projects\Phoenix\2018\4thQtr\356870\356870.aprx

AUTO LAB MAP OCTOBER 2018 SILICON VALLEY

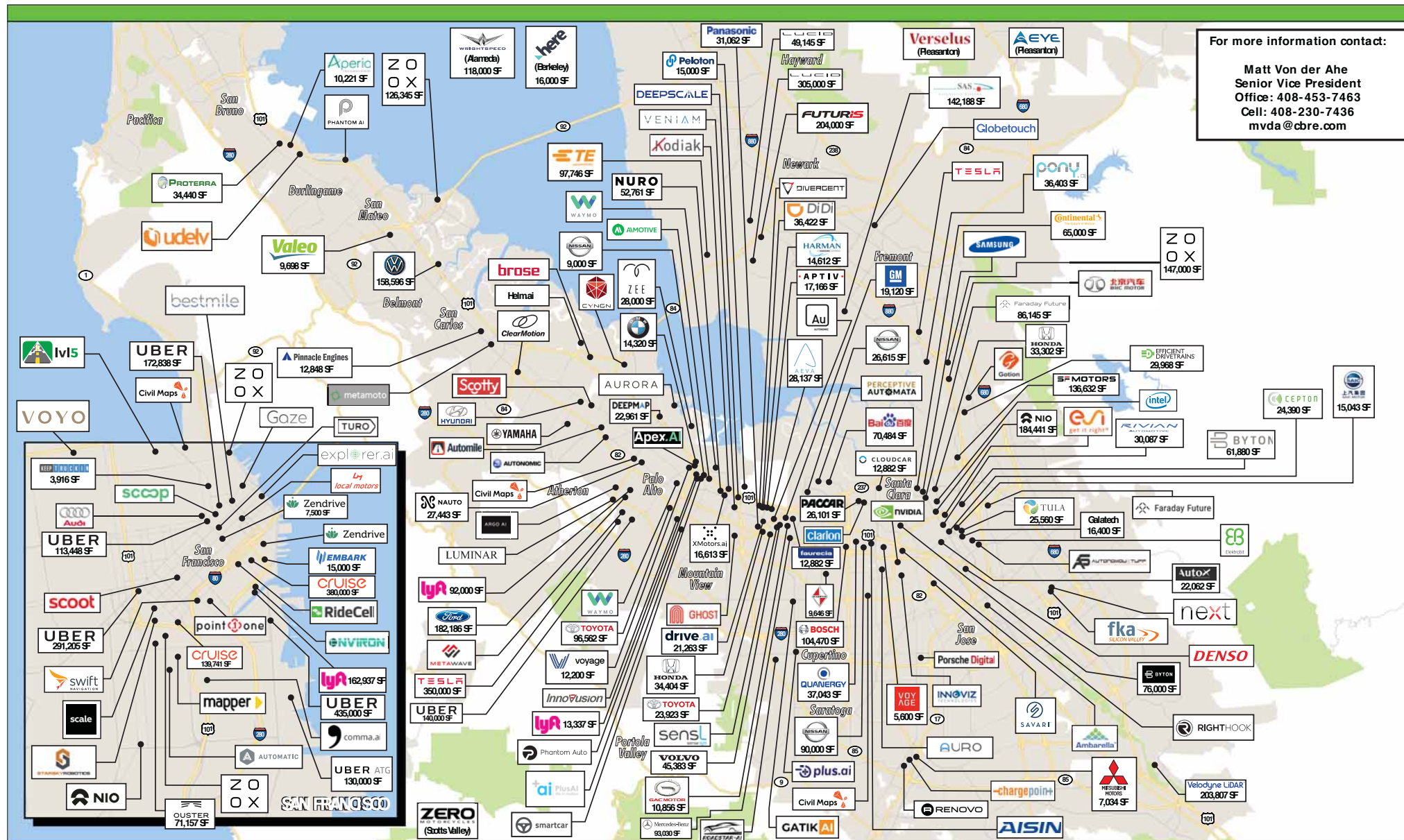


AUTO LAB MAP NOVEMBER 2018 SILICON VALLEY



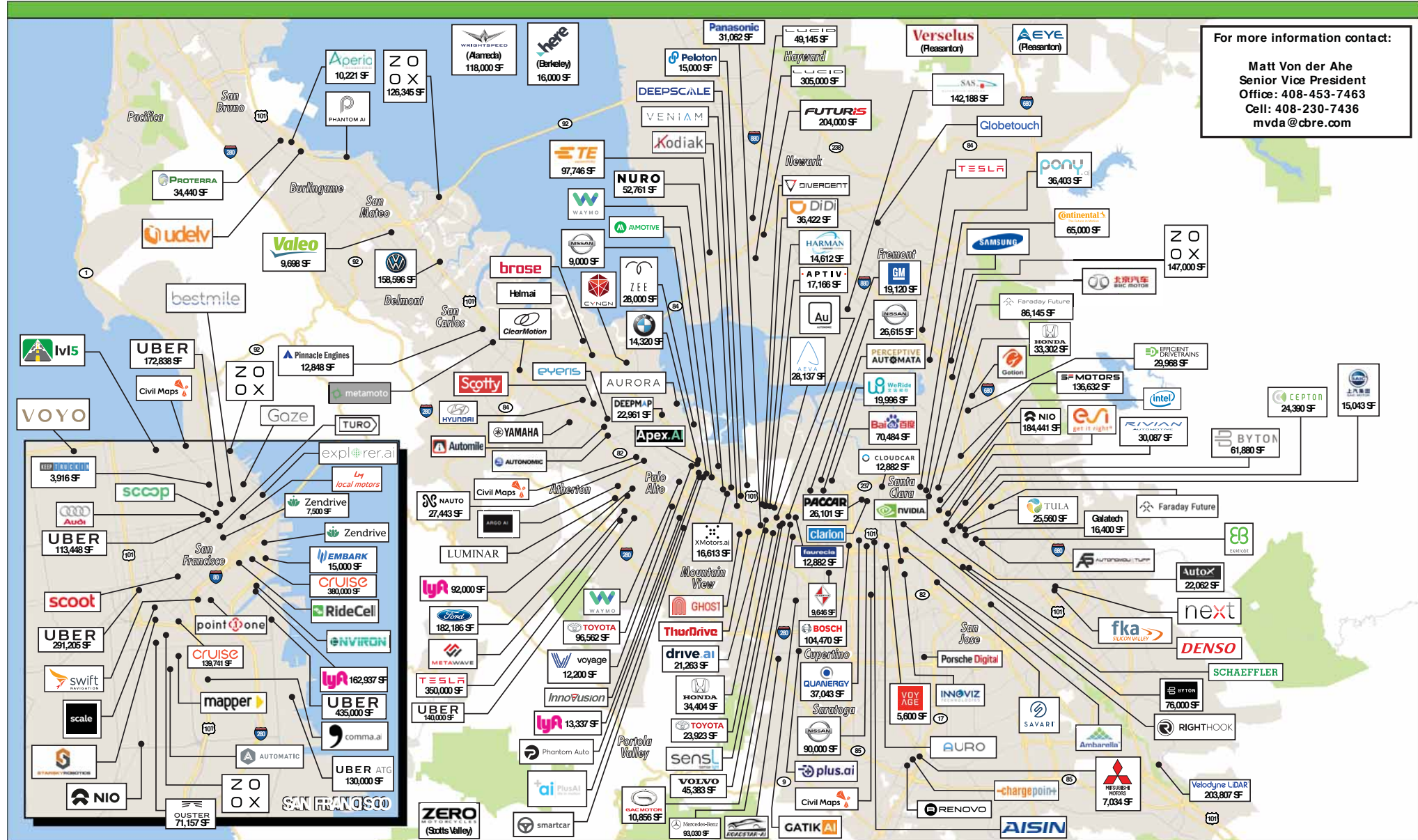
For more information contact:
Matt Von der Ahe
Senior Vice President
Office: 408-453-7463
Cell: 408-230-7436
mvda@cbre.com

AUTO LAB MAP DECEMBER 2018 SILICON VALLEY



© 2018 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine its suitability for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliate or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. All Rights Reserved. Source: CBRE Mapping Services (877) 580-4674; StreetView: 360624

AUTO LAB MAP JANUARY 2019 SILICON VALLEY



© 2019 CBRE, Inc. This information has been obtained from sources believed reliable. We have not verified it and make no guarantee, warranty or representation about it. Any projections, opinions, assumptions or estimates used are for example only and do not represent the current or future performance of the property. You and your advisors should conduct a careful, independent investigation of the property to determine to your satisfaction the suitability of the property for your needs. CBRE and the CBRE logo are service marks of CBRE, Inc. and/or its affiliate or related companies in the United States and other countries. All other marks displayed on this document are the property of their respective owners. All Rights Reserved. Source: CBRE Mapping Services (877) 580-4674; StreetView: 360674

The Drone Market Environment 2019

Hardware

Drone Platforms

Agriculture
Aerodrone, AgEagle, DROPCOPTER, AgEagle, HONEYCOMB, HSE, FTEC, AgEagle, YAMAHA, RANTIZO, SkyMax, YAMAHA

Delivery Systems
DROGNAMICS, AERONEXT, GRUFF, AVIADROME, KAITE-VTOL, RIGITECH, UVIONIX, SWOOP AERO, VAVU

Safety & Security
Aeronaautics, ACTURUS UAV, Bluebird, DPS, DRONE, EVOLVE, ESIG, GLOBEFLY, INSITU, LEONARDO, Raytheon, UAS SPEC, SHELBY, SCHIEBEL, THREED, WINCHENSE AEROSPACE, ANSE, AEROTAIN, h-aero, LOON, solarship

Fixed-Wing
Aeromoo, Aeromapper, AeroTerraScan, ALLIANCE DRONES, Altamav, ATLAS, BAYON, BYE PERSPECTIVE, C-ASTRAL, CAT UAV, DELAIR, flyHz, JEBTON, MARQUES, PASSERINE, PRIMCO UAV, ROBOT AVIATION, senseFly, Skyeye, UASUSA, UAVE, uavision, VANILLA, xrobots

VTOL Fixed-Wing
AEROVEL, AEROVINCI, ALTI, ATMOS UAV, WING, FuWx, Helico, J UAV, KRAY, OLEX, MARTIUS, QUANTUM, SKYX OO, SMD, VERTICAL, VENTURI, WINGSCOPTER, wingtra, Wing, X-CRAFT, ZEPOTECH

Recreational
AIR, AIRDOG, DreamHeli, HOVER CARACAS, SKYdio, SYMA, t.ie, UMG, TREAL, VANTAGE ROBOTICS, XIRO

Drone Platforms
AUS, AERONES, ACSL, ACTOR DRONES, AEE, AERIALTRONICS, APPELLIX, AERONEXUS, AEROTOLS, AERUDON, AERONIX, AIRCONIX, AIRK, AIRMAP, APELLIX, Apollo Robotics, AUTEL, bluejay, CHALLENGER, CLEAR FLIGHT SOLUTIONS, DAR, delatadrome, DJI, DRONAVIA, DRONE AMERICA, DRONE AZURE, DRONEMATRIX

Drone-in-a-Box
DRONE DELIVERY SYSTEMS, Airscort, AIRBOTICS, COEX, EASY AERIAL, H Dynamics, GREENSIGHT, NIGHTINGALE, PERCEPTO

Helicopter
AEROSCOUL, ALIGN, ALPHA, ALTUS, AVIX, FLYING-CAM, HELIPE, INNOVATION IN AVIATION, LAPLAPPE, PULSE, SWISS DRONES, TECTANG, UAVOV, ZIYAN

Software

Flight, Fleet & Operation Management

Aerosense, AirHub, AIRNEST, AIRWAYZ, Botlink, CAPE, DREAMHAMMER, DRONESAR, DRONE HARMONY, DroneLogbook, DroneSense, EVERDRONE, FlyFreely, KITTYHAWK, PrenaV, Skyward, simulyze, UGCS, vHive, VIGILANT AEROSPACE SYSTEMS

Open Source Infrastructure, SDK
AUTORIO, DRONEKIT, flybase, SKYFISH

Navigation, CV and AI
ARCDPILOT, ansur, Hionos, SHIELD AI, SIGTEC, Third Insight

UTM, LAANC Suppliers
AIRMAP, AIRMARKET, AirMatrix, airpalette, airspaceLink, AIRXDS, ALTITUDE, FLYNEK, INVOLI, SkyGrid, UFLYTE, UNIFLY

Services

Drone-as-a-Service Providers

Aerial Robotics, Aerial Solutions, Aerial Vision, Aerialworks, Aerobotics, AeroSpectre, AeroWorks, aridrones, ARIA, AIRINGOV, Airmap3D, AERONIX, AIRTEAM, AKER, ALTAMETRIS, ArchAerial, auav, AVIAN UAS, AVISIGHT, Betterview, BIV, Bit Ner, C4D, CANAD, CAESTES, CLOUD, ConnectLife, CTRERAWK, DEXERON, DIO DRONE, DJM, DONECLE, Dronak, DRONE BASE, PRONE, DRONEHIVE, DRONE ORBITAL, Drones-Tech, drone.reed, EXO DRONE, FALCONVIZ, FLYWHEEL, GEOMAPPER, GLOBEFLY, HAWK AERIAL, LEVITAR, lufttronix, market, MEASURE, NATIONAL DRONES, J-SRTHLB, NORDIC LEAPWING, SHARPER SHAPE, sitsaware, SKT AERO, SkyEye, SKY-FUTURES, SKYLARK, SKYMATICS, SkySkopes, SPECTRA, SPECTRA, TALON, XTEAMUAV, TERRADONE, TEKNO Drone, THE BOYS, UAVONIC, WANYKA, XIM2, XPRIME, VERGE AERO, verity

Delivery
Amazon, Amazon Prime Air, DHL, DORON, FLUG, Flirley, FLYTREX, GoPilot, JD, Matternet, Robodub, SKYWAYS, UPS, VBLAN-3, zipline

Drone Show Providers
ARROWONICS, ARS ELECTRONICA, CAULIN, Dronis, PIXEL GROUP, hubgamatika, SKYMAGIC, VERGE AERO, verity

Passenger Drones / eVTOLs / Air Taxis

AIRBUS HELICOPTERS, Aurora, ASX, astro, AUTONOMOUS FLIGHT, CARTIVATOR, DELTA RACE, DELTA RACE AERONAUTICS, EHANG, EVA, ESASERO, EVIATION, HOP, JAUNT, JETOPTERA, JETPACK, JOBY, KAREM, KH, LIFT, LIUM, MAXWELL, METRO SKYWAYS, METRO, NEUV, OPENER, PALV, PHIBISTREL, SPARK RACING, SKYDRIVE, SureFly, URBAN, VERTICAL, VIMANA, VOLOCOPTER, XTI, ZAPATA

Counter-Drone Solutions

AERONAUTICS, AeroDefense, AIRBUS, APOLLO SHIELD, aselsan, AVTC, BATTILE, Black Sage, Brighter, CERBAIR, CIRA, DEFENSE, Convexum, ctrl+sky, D-FEND, DEDRONE, Delfi Dynamics, departmen, Defect, DSS, DRONE DEFENSE, DRONE, DRONESHIELD, elt, GeoDome, LITVIVE, MADIA, MBDA, MYBEENCE, sesp, SkySafe, Spatter, SQUAREHEAD, Tarsier, TELESPRO, NORPAL, WHITEFOX

Data Analytics, Workflow, CV and AI

SDR, Aerial Applications, AGERPOINT, agremo, Agrosout, AIRBUS, Airfusion, AIRMA, Bentley, Birds.ai, central systems, Clobotics, Datumate, DroneDeploy, DroneLab, DroneMapp, Dronifi, eagleview, esri, EZ3D, GAMAYA, Geown, HANGAR, HEMAV, hivemapper, Identified, Indshine, intelinair, Kongsberg Geospatial, Leica, LOVELAND, MAPS, MEDIC SOFTWARE, neuroia, OPTILOS, picterra, PIXIO, PIX, PRO, PRECISION, prodrone, propeller, RAZOR, scopito, senterla, simactive, Sitemark, SKYCATCH, SKYCSIXN, SKYSPECS, Sterblue, Strayos, Terravision, TRACEAIR, UAVA, vineview, Wildlife Drones

Cameras, Imaging and Vision Systems

Amarella, cubed, DROPTERRA, oment, FAT SHARK, FLIR, HASSELBLAD, Headwall, inUAV, LIDAR LISA, LUCINT, MAPII, Micasense, NextVision, optris, PHASE ONE INDUSTRIAL, PHENIX, RIEGL, SABRE, SHOT OVER, SLANSTRANGE, TERABEEL, TETRACAP, thirdEye, Velodyne, WORKSWELL, YellowScan

Components & Systems

AGILE, AIRBOT, AIRROW, BLUE VIGIL, COBALT, DRONECAGE, DRONERAFTS, DRONE TERMINUS, EAGLE TREE, FISHER, FISH, OPEN, HARRIS, InfiniDome, KLAUPFK, Lykus, MEMS, MOBILICOM, polarpop, SightLine, SKYSENSE, TERN BLUESPEED, UAS, UAV COMPONENTS, VIZ, WINGFOOT, XES

Propulsion & Power
AEROMANA, AVADVICES, BALLARD, BHPower, ENERGYOR, GET, Intelligent Energy, LAUNCHPOINT, HARTWELL UAV

Navigation & Guidance Systems

AdaPilot, Aerotenna, ZINSTEIN, APLUM, AutoModality, ARA, BARCOLEAN, ECHOBYNE, EXE, FLARM, Fitec, IMAR, Iris Automation, LedgerTECH, lightware, MicroPilot, PIXIT, SageTech, SBG SYSTEMS, SKYSDRONE, SKY-ORONES, SKYSENSE, swift, TRIG, ublox, UAV, uaventure, uAvionix, VECTORNAV, HELI CENTER

Data and Communication
Aerobee Innovations, AMIMON, BERTEN, DOODLE, e2E, PARALINX, RAJANT, SKY HOPPER

Education, Simulation, Training

aero/cameras, AEROSIM, AVISIGHT, Drone Academy, GLOBE, DARTDRONES, DRONEBLOCKS, DRONE CLASS, DRONEFLY, KoptR, Sea Mass, Simlat, SKYOP, TECHNIDRONE, UUAIR, Zephyr

System Integration, Engineering, Advisory

AREAL, AlphaLink, ARGUS, BLACK WING, BLUE BEAR, CONSORTIO, DRONE USA, DRONEXPERT.NL, DRONEXPERTS, EMPOWENT, FLY TECH, FRANK FUCHS CONSULTING, GO, MIRRAGIN, MULTIROTOR, SAFRAN, SPH, TZX, UNMANNED EXPERTS

Maintenance

DRONEDOCTOR, DRONESHIELD, FORTRESS UAV, Robotic Sites

Supplier, Retailers

AHIGATOR, COPTRZI, DRONE, DRONEFLY, DRONENERS, DRONER.DK, DRONES DIRECT, DSLR PRO, FOXTECH, HELIGUY, HELIGUY, MAVERICK, OCULUS, Position, QUACKCOPTER.COM, rise above, sphere drones, tecniTop

Test Sites

ACUASI, ATLAS, BCN, DRONES, GRANDSKY, SPACE 53, WindShape

Market Research & Consulting

DRONE ANALYST, DRONE STUDE, DRONEII.COM

User Groups, Networks

ALASKA UAV, SKYDRONES, SKYPIXEL

Media, News, Blogs & Magazines

DRONE, droneblog, drone life, DRONE, DRONE, ELIAS NEWS, TODRONE, UAS MAGAZINE, UTMANNED AERIAL, UST, UST, UST, Podcast, Drone Radio Show, THE TPN SHOW

Marketplaces

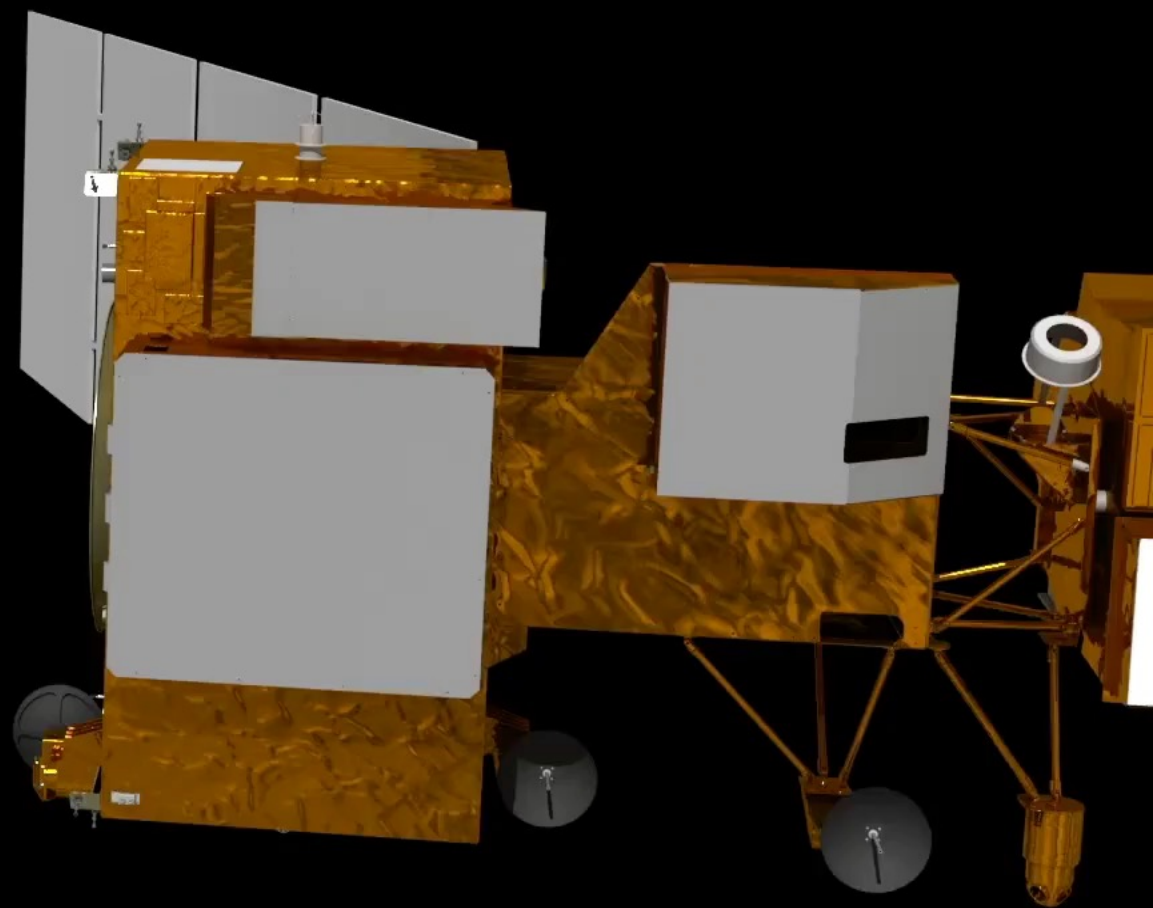
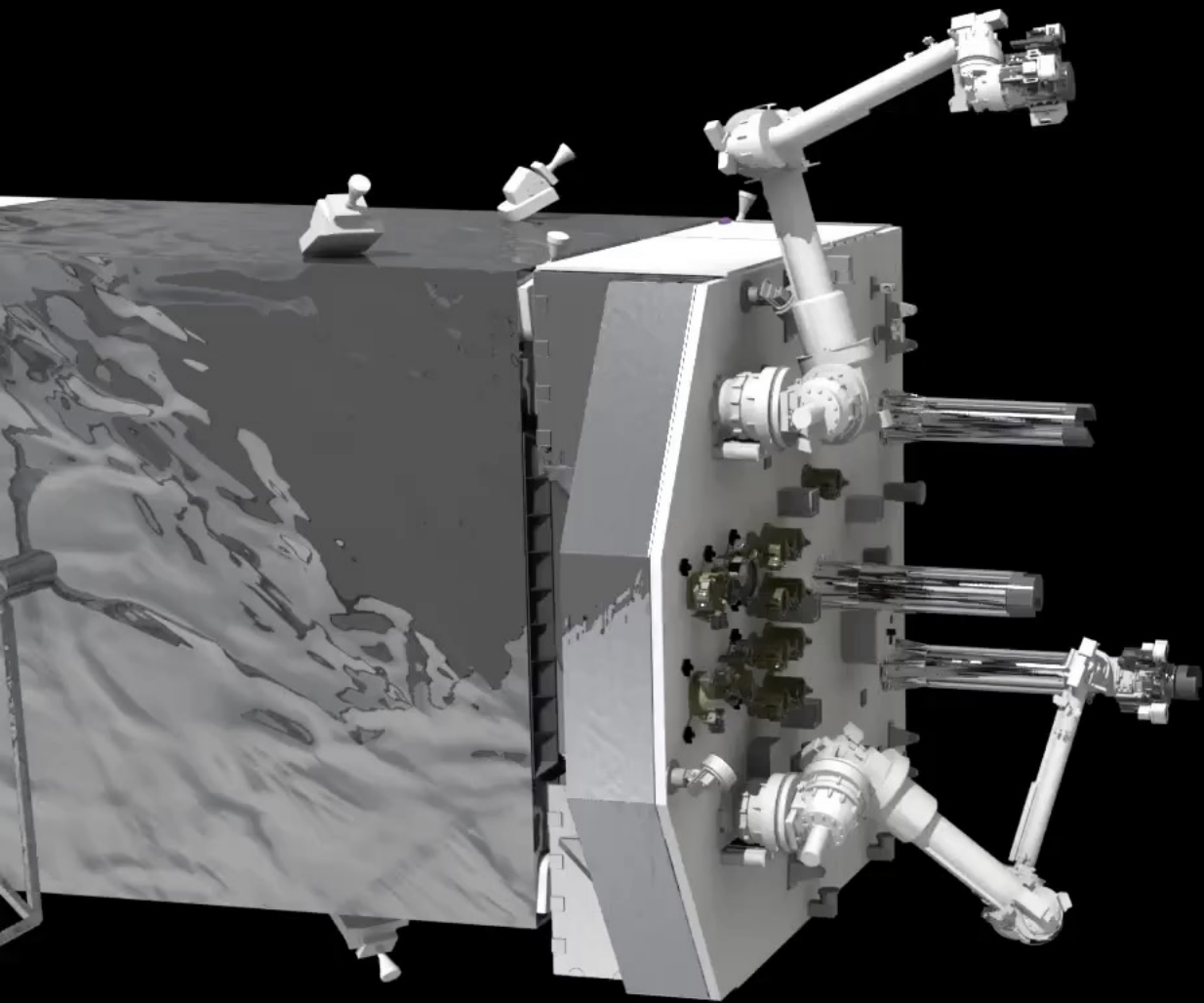
AIRVID, AIRVIZ, ArcadiaSky, BEE JOB, DRONE ENTRY, DRONE LIST, DRONEJOB, DRONESTOCK, GETADRONE, HIREDRONE.COM, JOBS FOR DRONES, skytango, up, Sonder

Shows, Conferences, Events

DRONE WEEK, COMMERCIAL UAV EXPO, DRL, DRONE, DRONETECH, FAT, IDE, InterDrone, Japan Drone, UAS EXPO, UAS EXPO, UAS EXPO

Coalitions, Organizations & Initiatives

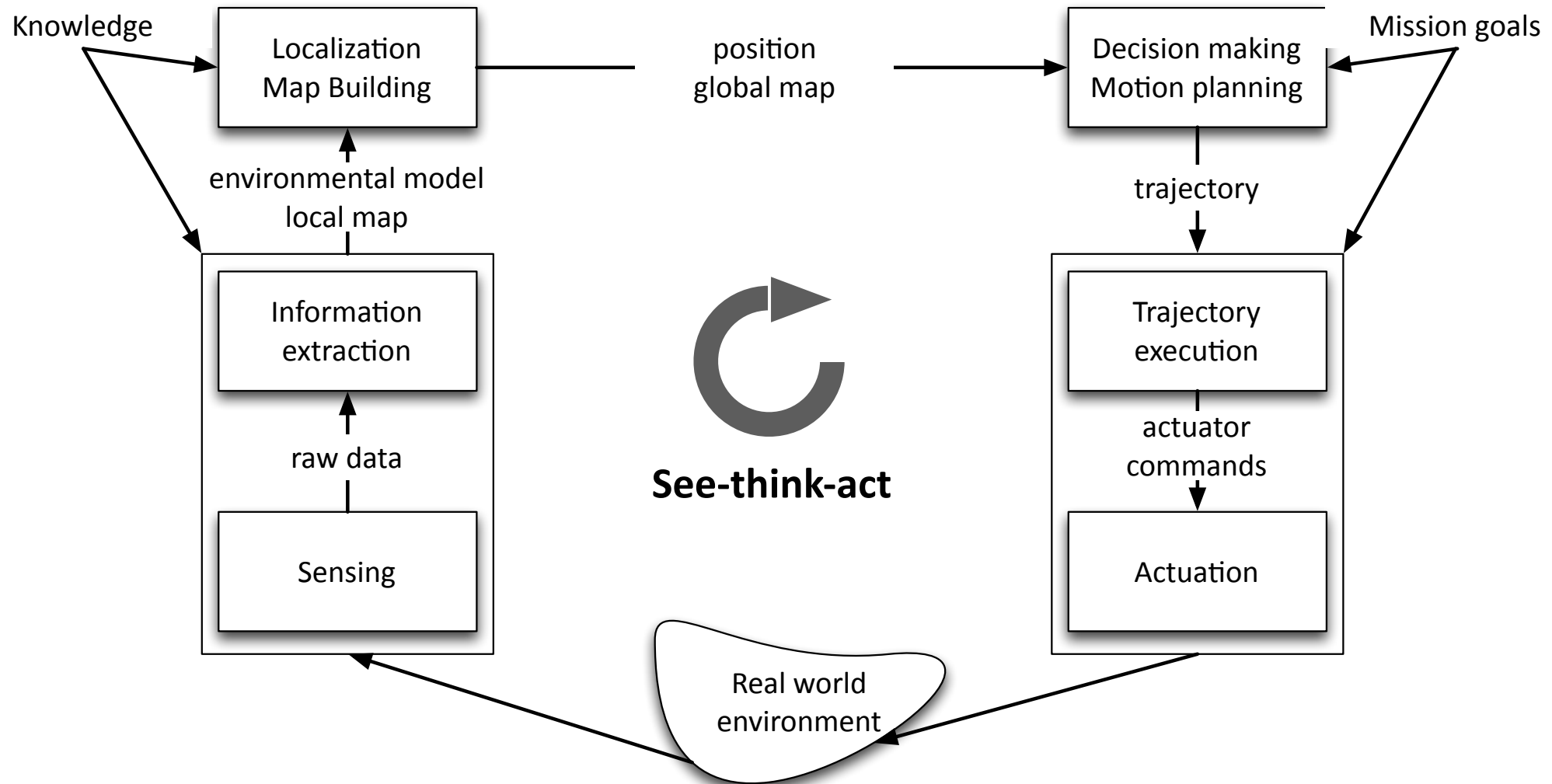
AUAS, AEA, ARPAS-UK, ASSURE, AUVSI, DRONE ALLIANCE EUROPE, Drone Industry Alliance Europe, Dronecode, DRA, IATA, MAPPS, NUAIR, SESAR, SMALL UAV, UAV, UAV, UAV, windrove



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



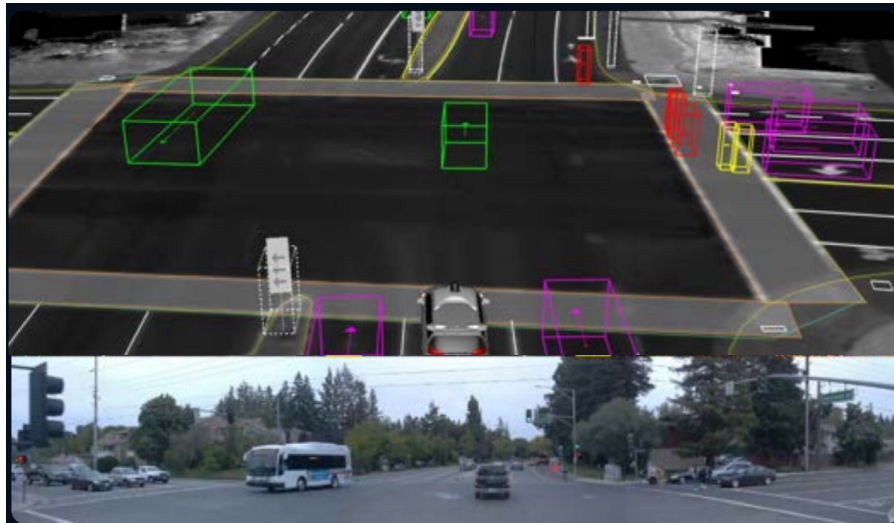
See-think-act cycle for AVs

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

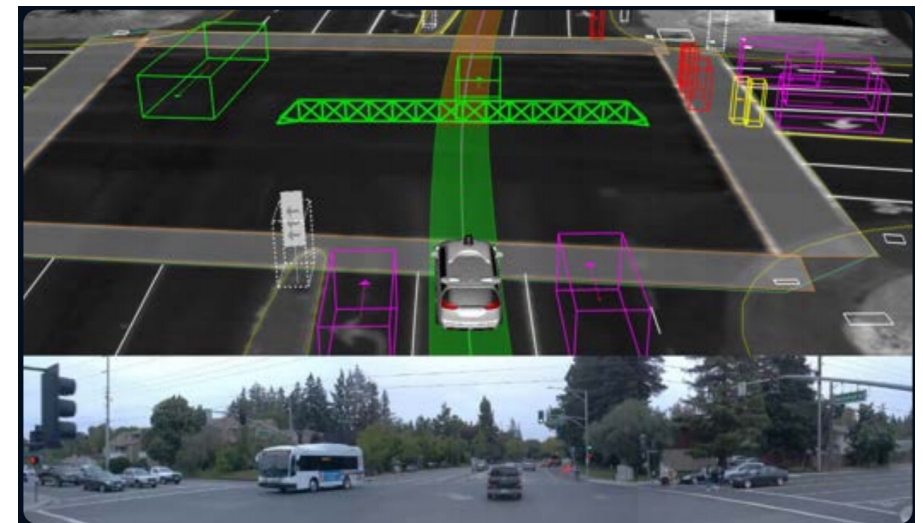
Think



See



Act



Course structure

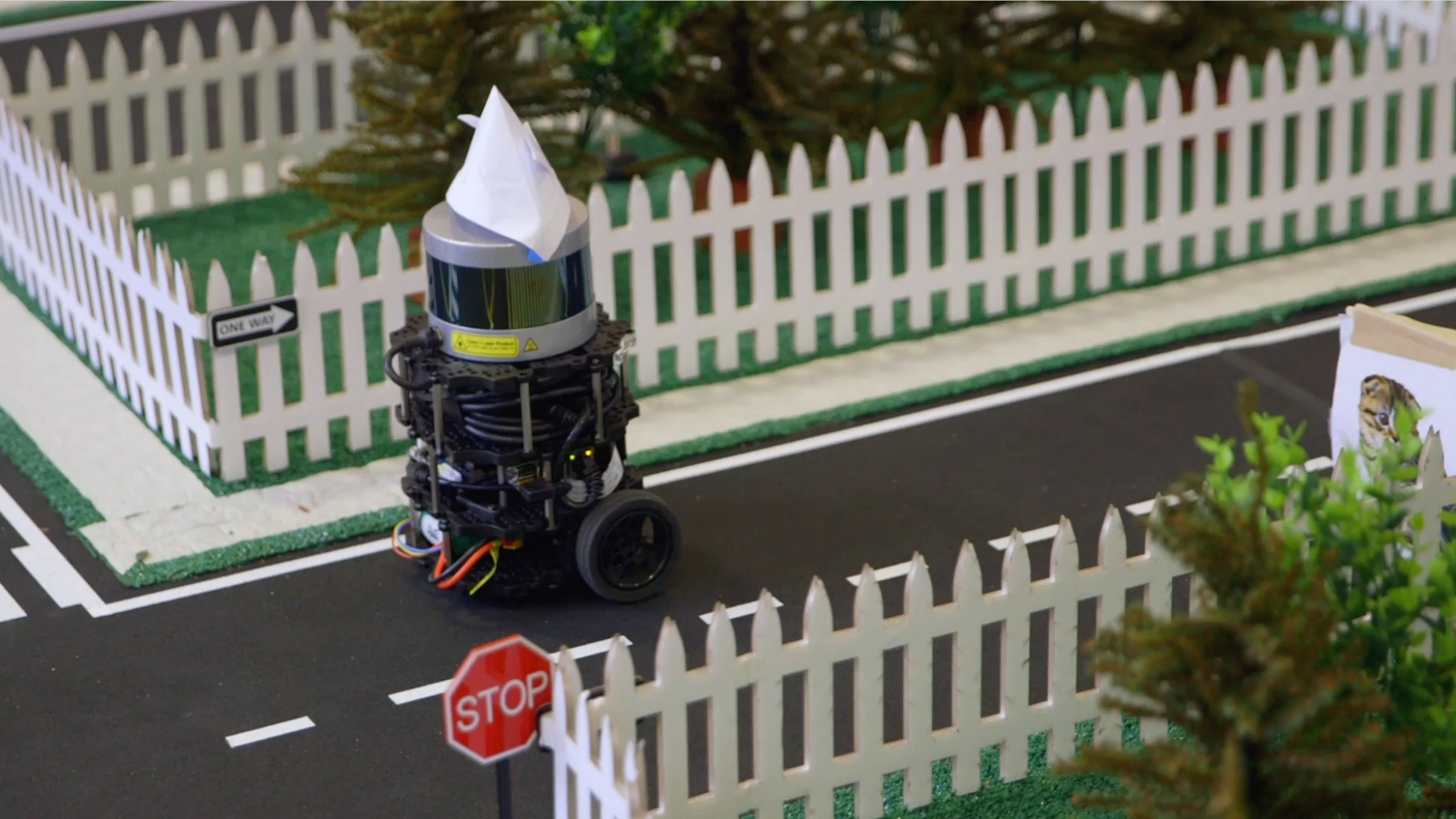
- Four main topics:
 1. Robot Operating System (week 1)
 2. Controls & Motion Planning (weeks 2-4) -- *act*
 3. Perception (weeks 5-8) -- *see*
 4. State Estimation, Localization & SLAM (weeks 8-11) -- *think*
- Extensive use of the Robot Operating System (ROS)
- Requirements
 - CS 106A or equivalent
 - 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 (Shriram 104)
- 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.
 - Course assistants: Tuesdays, 2:00 – 4:00pm, and Thursdays, 4:00 – 6:00pm, room TBD.
- Course websites:
 - For course content: <https://asl.stanford.edu/aa174a>
 - For course announcements: <https://canvas.stanford.edu/courses/180672>
 - For course-related questions: <https://edstem.org/us/courses/47593/discussion/>
 - For homework submissions: <https://www.gradescope.com/courses/623415>
 - To contact the AA174A staff: aa174a-aut2324-staff@lists.stanford.edu



ONE WAY

STOP



Team

Instructor



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

Collaborators

- Daniel Watzenig

Labs



CAs

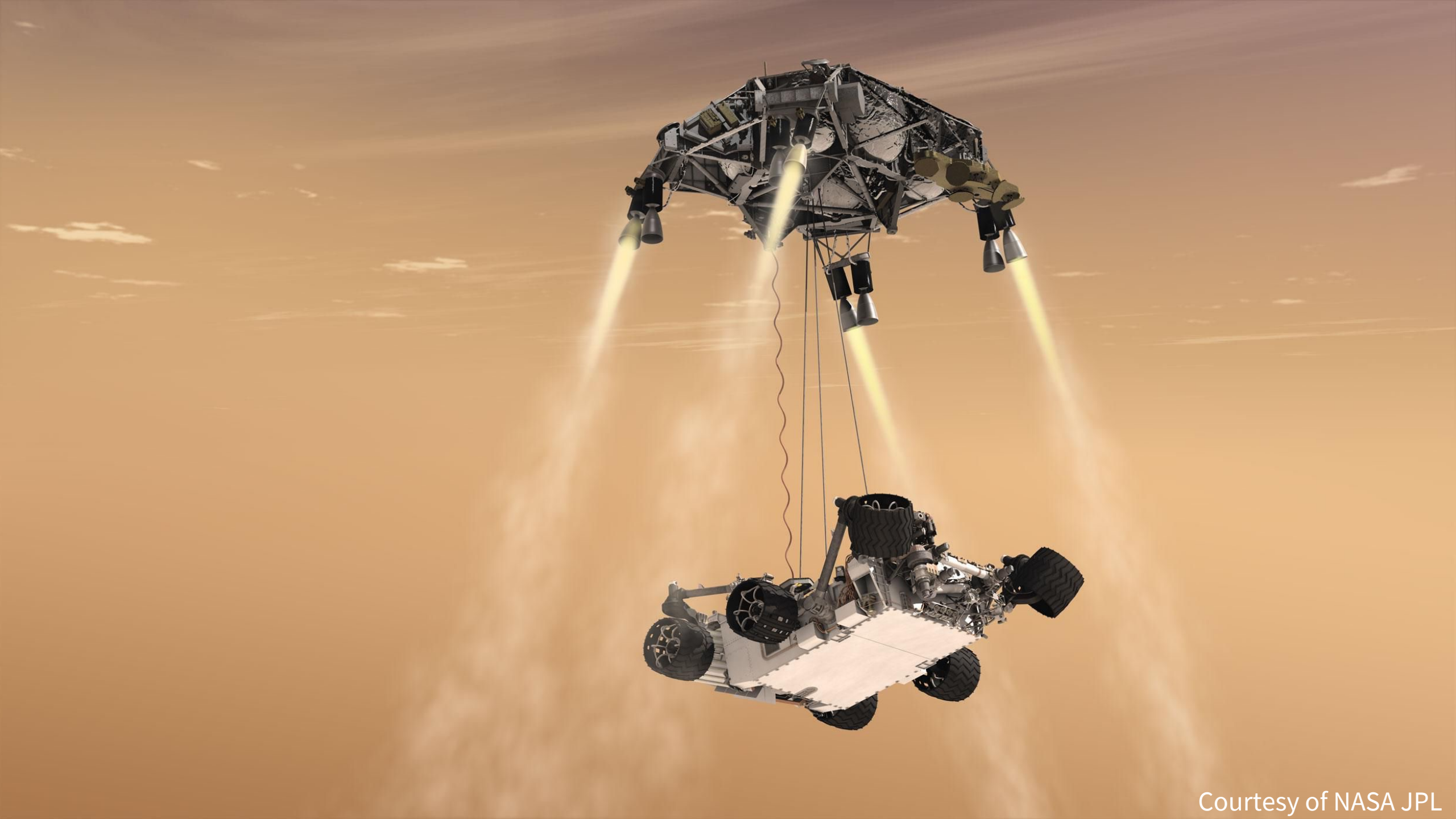
Chris Agia

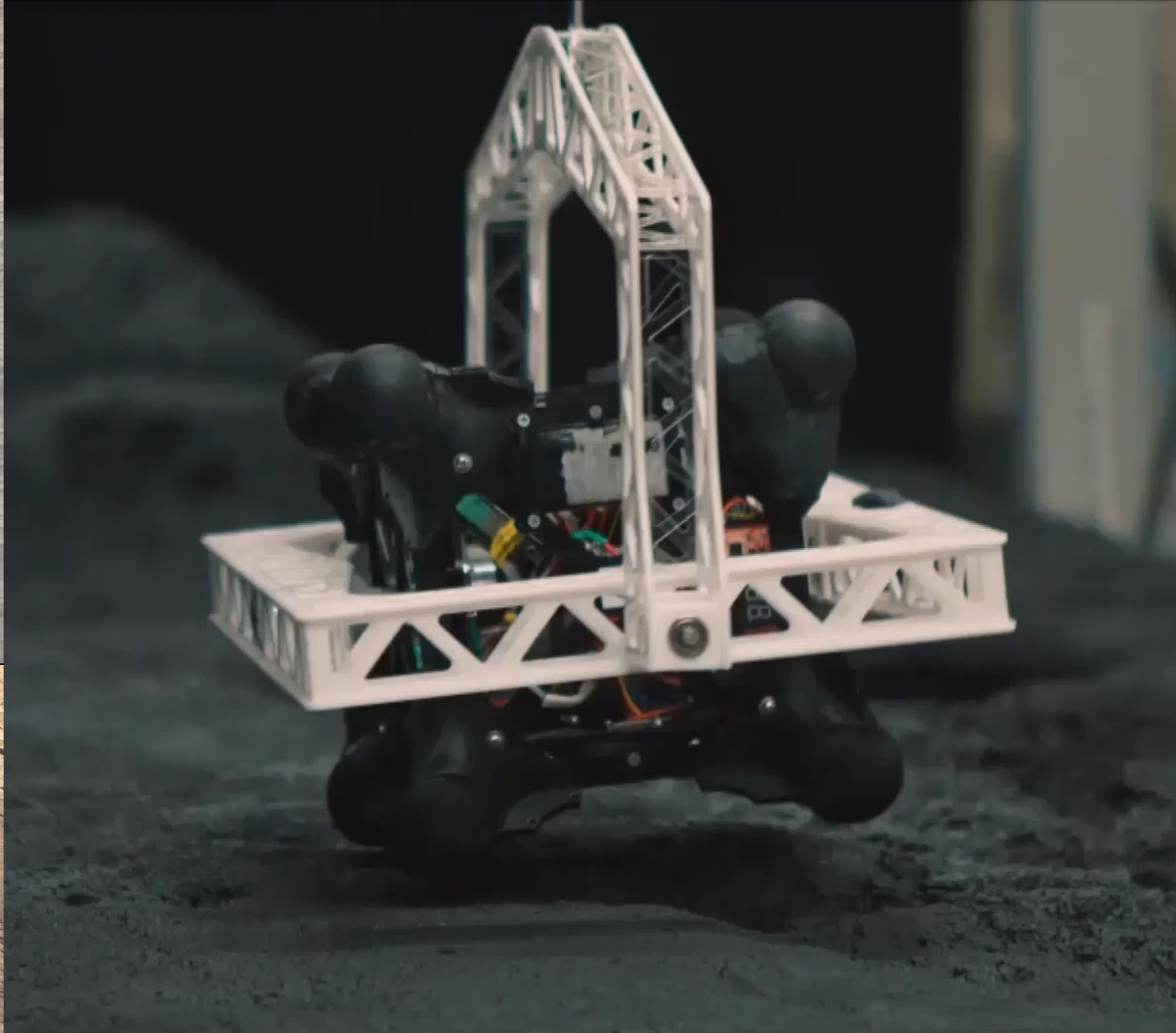


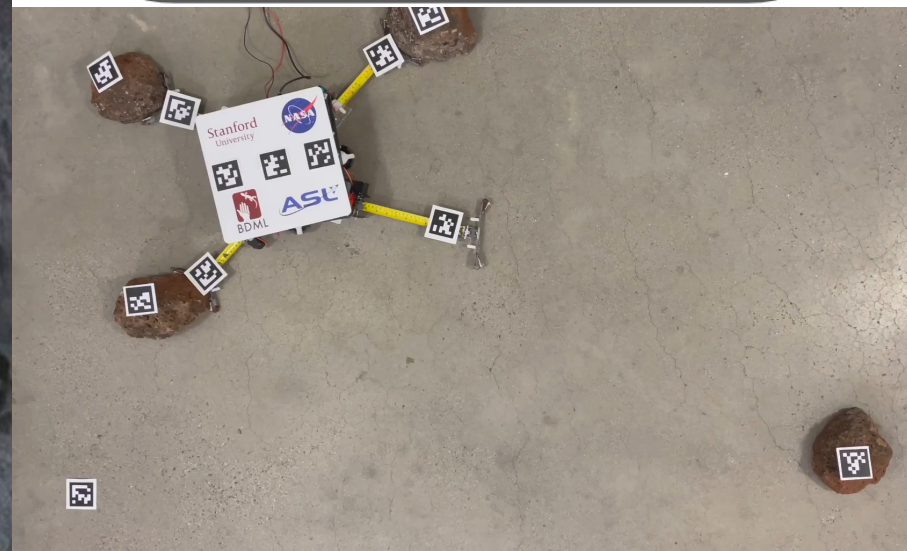
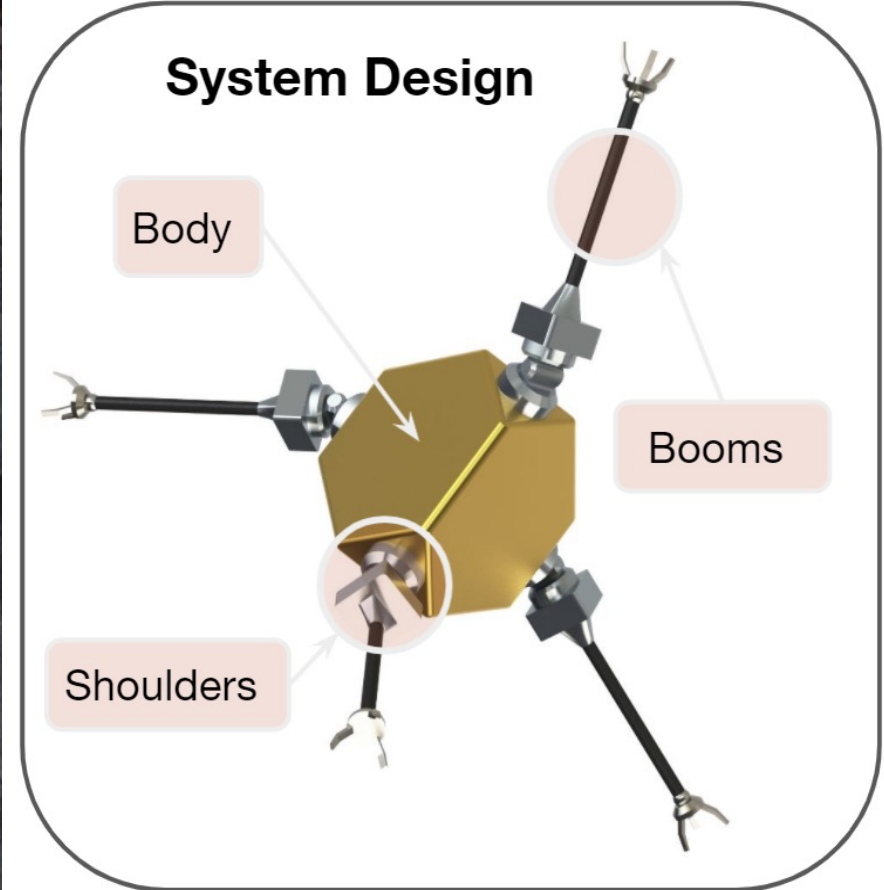
Luis Pabon



Alvin Sun









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
09/26	Course overview, intro to robotic systems and ROS	
09/28	Fundamentals of ROS	
09/29	★ Section 1 – intro to UNIX environment	
10/03	State space dynamics – definitions and modeling	HW1 out
10/05	State space dynamics – computation and simulation	
10/06	★ Section 2 – ROS2 packages, publication, and subscription	
10/10	Trajectory optimization	
10/12	Trajectory tracking & closed-loop control	
10/13	★ Section 3 – ROS2 launch files & RVIZ	
10/17	Graph search algorithms	HW1 due, HW2 out
10/19	Sampling-based motion planning	
10/20	★ Section 4 – heading control	
10/24	Robotic sensors & introduction to computer vision	
10/26	Camera models & coordinate frames	
10/27	★ Section 5 – point-to-point navigation 1	
10/31	Image processing & information extraction	HW2 due, HW3 out
11/02	Visual camera tracking & control	
11/03	★ Section 6 – point-to-point navigation 2	

11/07	No Lecture – Democracy Day	
11/09	<i>In-class midterm</i>	
11/10	★ No Section	
11/14	Deep learning for computer vision	
11/16	Intro to state estimation & filtering theory	
11/17	★ Section 7 – object detection	HW3 due, HW4 out
11/21		
11/23	<i>Thanksgiving</i>	
11/24		
11/28	Parametric filtering (KF and EKF)	
11/30	Object tracking and EKF localization	
12/01	★ Section 8 – frontier exploration	
12/05	Multi-sensor perception & sensor fusion	
12/07	Simultaneous localization and mapping (SLAM)	
12/08	★ Section 9 (optional) – extra credit work	HW4 due

Robot Operating System – History

ROS 1



2014 - 2019



2016 - 2021



2018 - 2023



2020 - 2025

ROS 2



2019 - 2021



2020 - 2023



2022 - 2027



2017 - Present

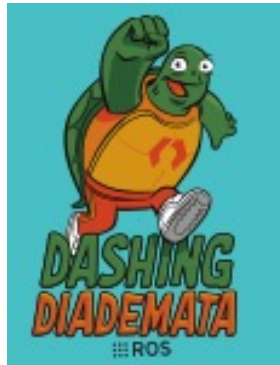
Robot Operating System – History

ROS 1

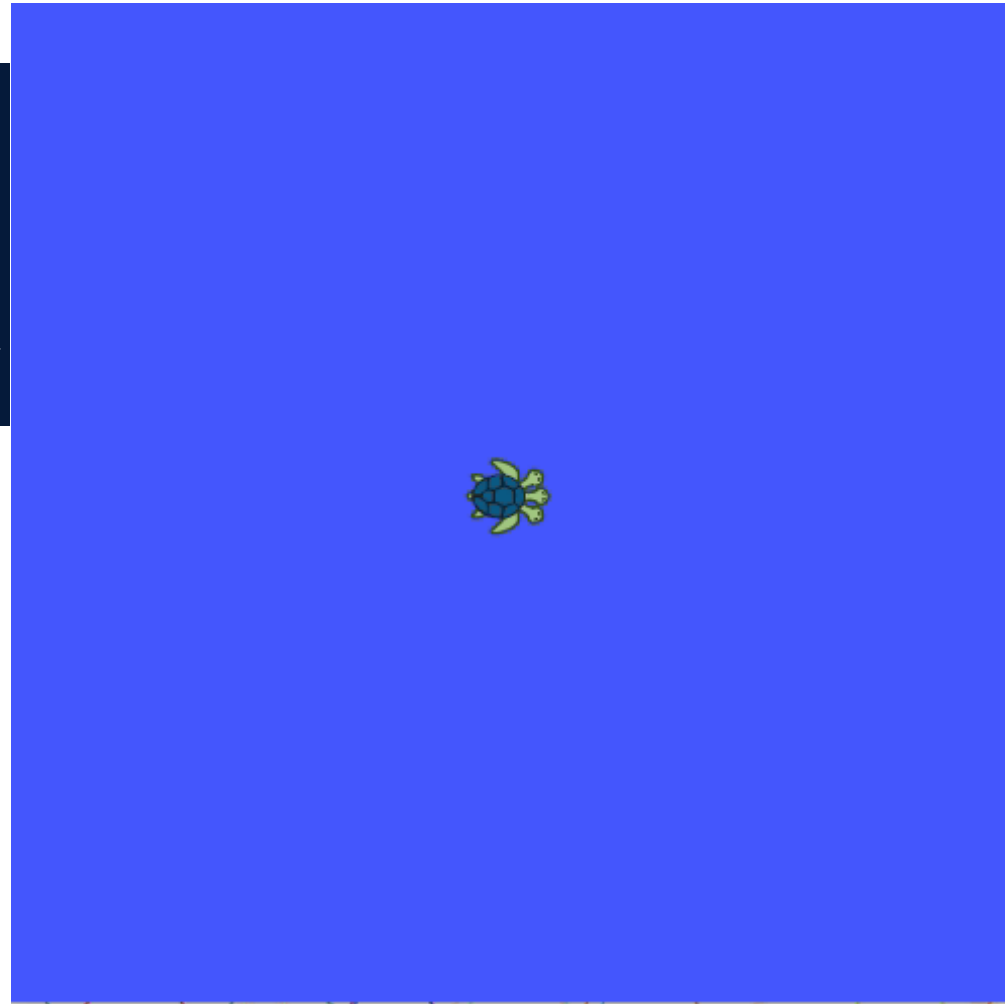


2014 - 2019

ROS 2



2019 - 2021



2020 - 2025



2017 - Present

Robot Operating System – History

ROS 1



2014 - 2019



2016 - 2021



2018 - 2023



2020 - 2025

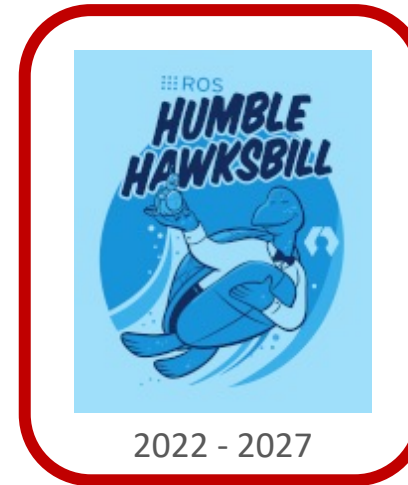
ROS 2



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

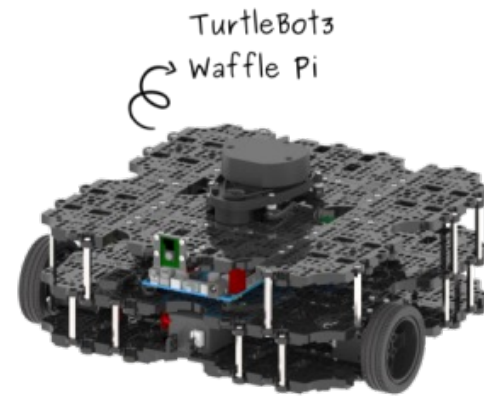
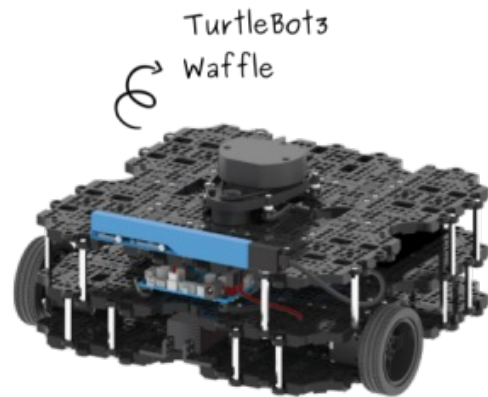
- Community & Ecosystem
 - **Hardware Drivers**
 - Software



[Crazyflie](#)



[Joysticks](#)



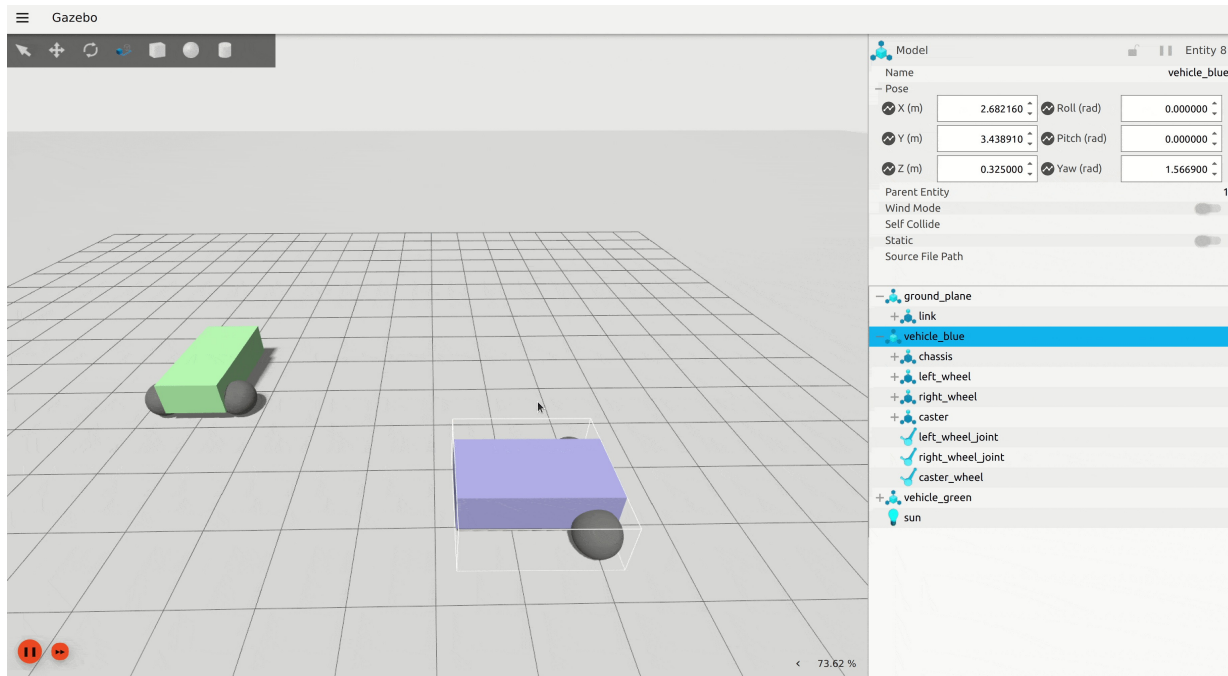
[Turtlebot3](#)



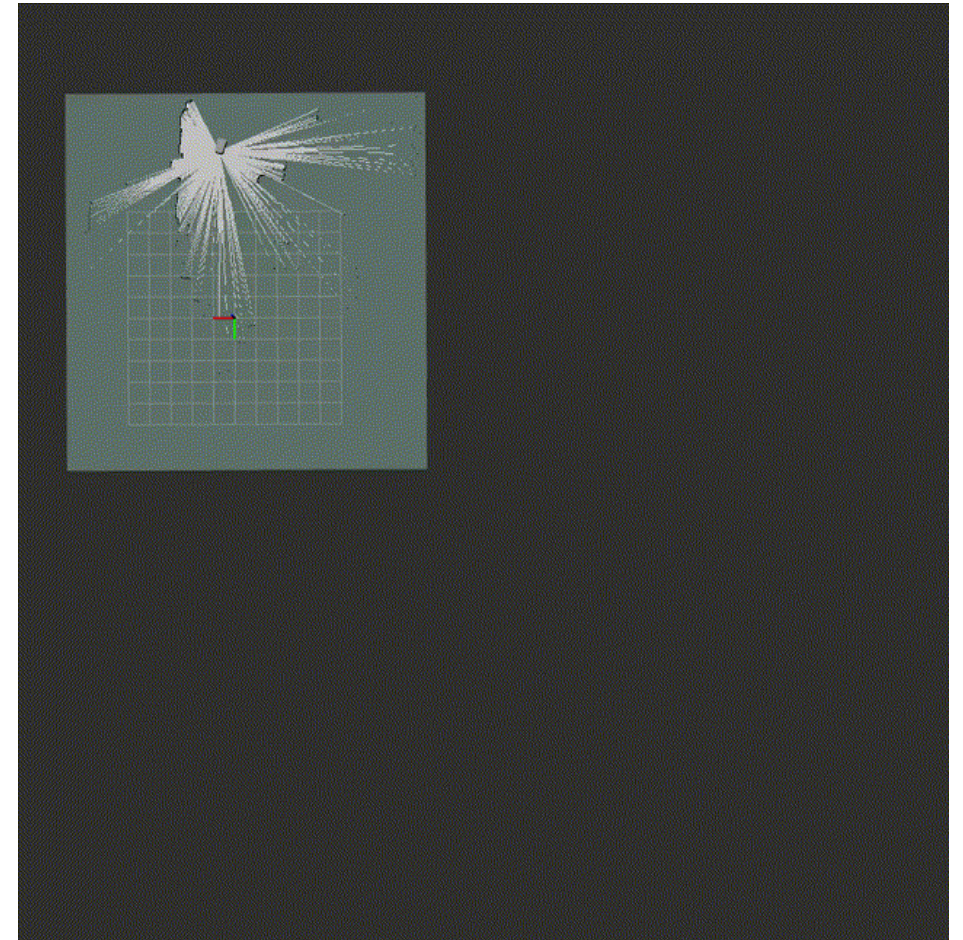
[Velodyne LiDAR](#)

Robot Operating System – ROS2

- Community & Ecosystem
 - Hardware Drivers
 - **Software**



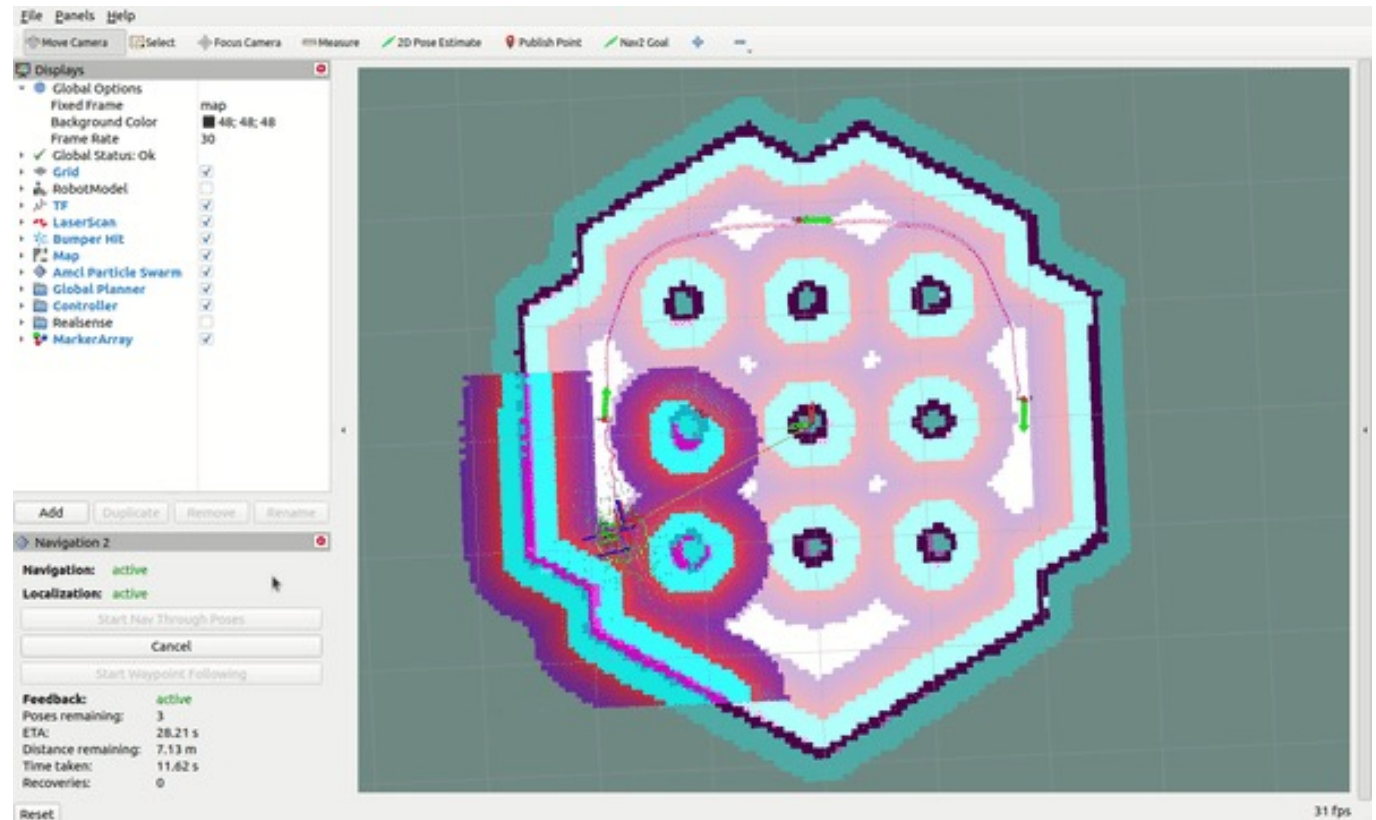
[Gazebo Sim](#)



[SLAM Toolbox](#)

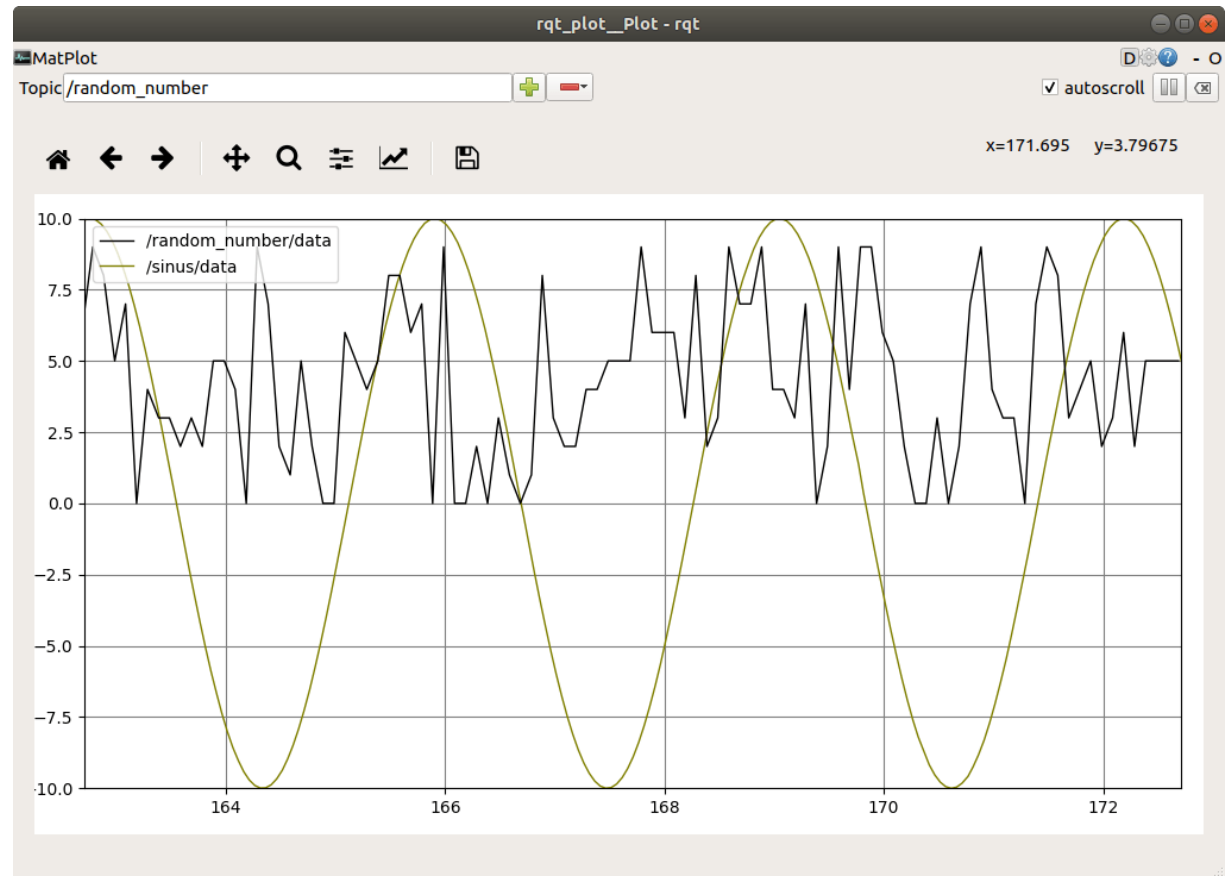
Robot Operating System – ROS2

- 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
 - Software
- Tooling
 - Visualization
 - Debugging

Turtlebot Autonomy Demo

Robot Operating System – ROS2

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



See-think-act

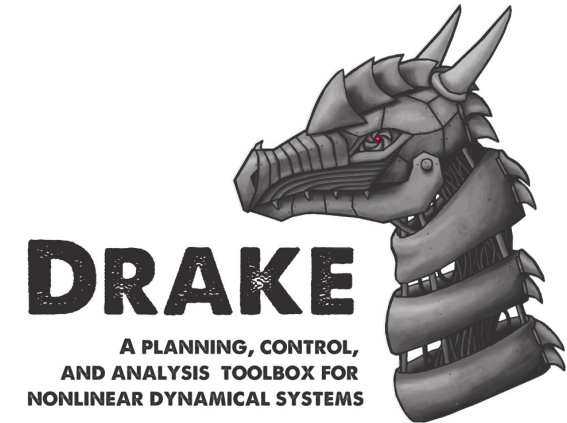
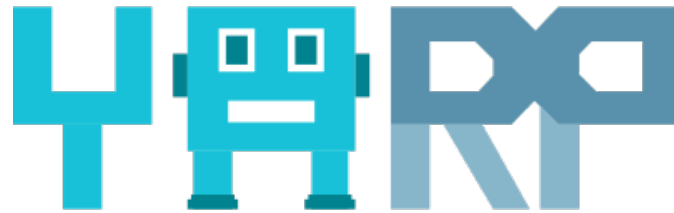
Robot Operating System – ROS2

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

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