AuE-8360
Scaled Autonomous Vehicles

Hardware & Software for Scaled Vehicle Courses

Chinmay Samak
PhD Candidate, CU-ICAR
csamak@clemson.edu

Tanmay Samak
PhD Candidate, CU-ICAR
tsamak@clemson.edu

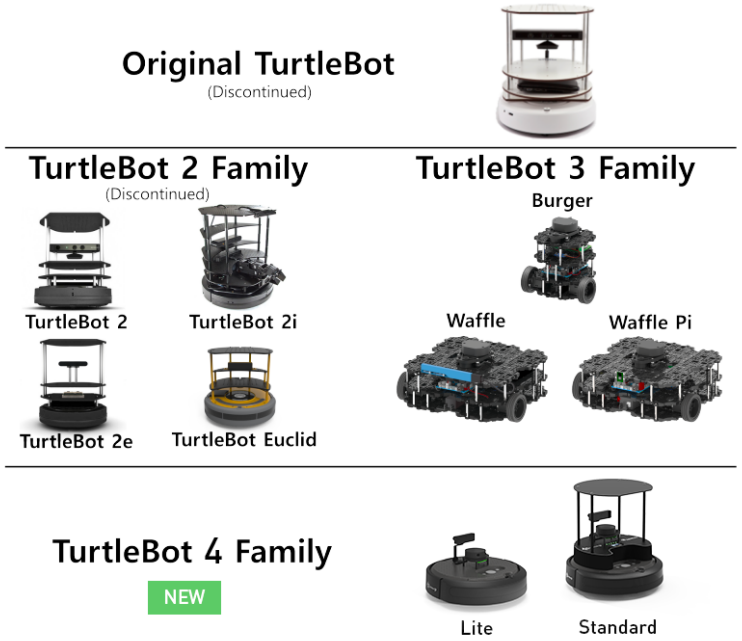
Hardware

Hardware Platforms for Scaled Vehicle Courses

Robot-Like Platforms

- TurtleBot
  - Differential drive (TB1-4)
  - Multi-sensor lineups (TB3-4)
  - Multi-mode actuators (TB3)
  - Small form factor (TB3)
  - Affordable cost (TB3)
  - Open hardware (TB3)
  - Open firmware (TB3)
  - Open software (TB1-4)
  - ROS enabled (TB1-3)
  - ROS2 enabled (TB3-4)

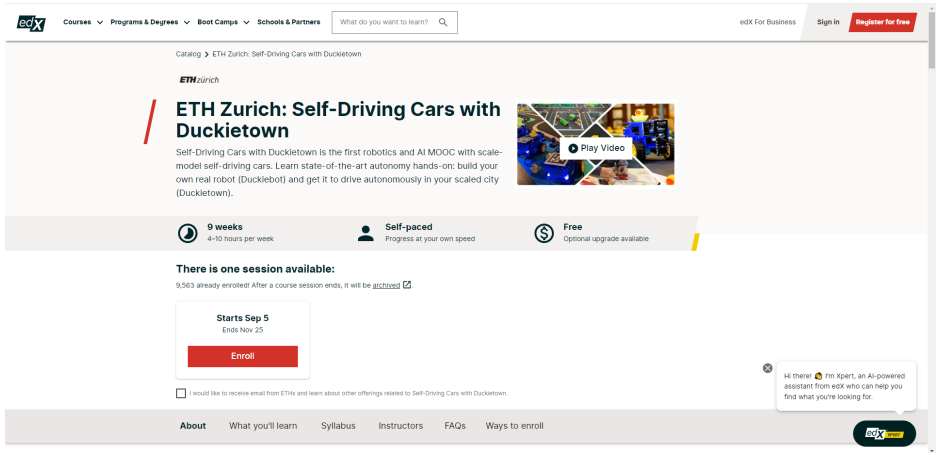
Version	Mobile Base	Battery	Computer(s)	Sensor(s)	Actuator(s)	Developer	Release	Cost
TurtleBot1	iRobot Create	3000 mAh	Asus 1215N Laptop	Gyro, MS Kinect (RGBD-Cam), Encoders	iRobot Create Robot Base Motors	Willow Garage	Nov 2010	$1,400
TurtleBot2	Yujin Kobuki	2200 mAh	Asus 1215N Laptop	Gyro, MS Kinect (RGBD-Cam), Encoders	iClebo Kobuki Robot Base Motors	Yujin Robot	Oct 2012	$1,500
TurtleBot3	Burger, Waffle, Waffle Pi	1800 mAh	Raspberry Pi (or Intel Joule 570x), OpenCR1.0	2D LiDAR, 9-Axis IMU, Encoders, Pi Camera (Mono-Cam), Intel RealSense RGBD-Cam	DYNAMIXEL Servo Motors	ROBOTIS, OSRF	May 2017	$650
TurtleBot4	iRobot Create3	1800 mAh	Raspberry Pi 4B	2D LiDAR, Stereo-Depth Camera, 6-Axis IMU, Encoders, Bumper Zones, IR Cliff and Obstacle Sensors, Optical Flow Sensor	iRobot Create3 Drive Actuators	Clearpath	July 2022	$1,900



Source: TurtleBot.com

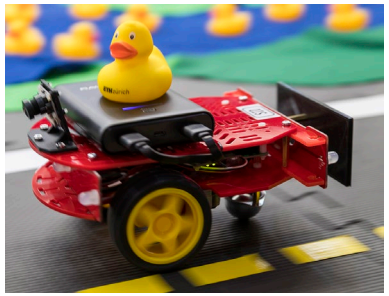
Robot-Like Platforms

- Duckietown
  - Differential drive
  - Scaled robot
  - Scaled infrastructure
  - Small form factor
  - Affordable cost
  - Open hardware
  - Open firmware
  - Open software

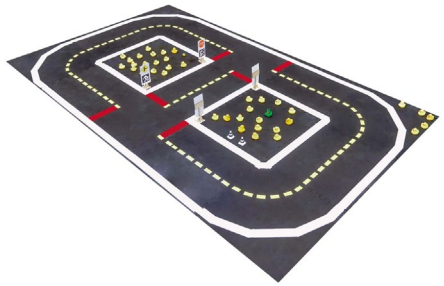


Source: edX.org

Version	Mobile Base	Battery	Computer(s)	Sensor(s)	Actuator(s)	Developer	Release	Cost
Duckiebot	Open-Source	1000 mAh	Raspberry Pi (or Jetson Nano)	Pi Camera (Mono-Cam), IMU*, Encoders*	DC Motors	Duckietown	2016	$450



+



=

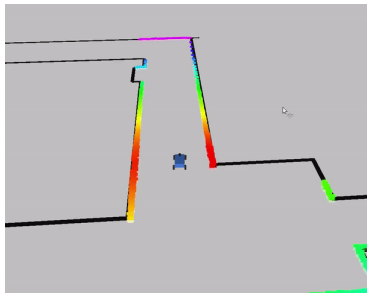
Source: Duckietown.org

Car-Like Platforms

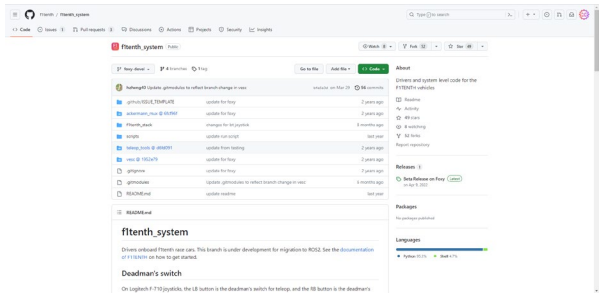
- F1TENTH
  - Ackermann steered
  - 1/10 scale RC-car
  - Open source
  - Moderate form factor
  - Learning resources
  - Build documentation
  - Racing competitions
  - University distribution
  - ROS enabled
  - ROS2 enabled
  - Autoware enabled

Version	Mobile Base	Battery	Computer(s)	Sensor(s)	Actuator(s)	Developer	Release	Cost
F1TENTH	Traxxas Slash	4000 mAh	Jetson Xavier NX	Hokuyo 10LX LIDAR	BLDC Motor, Steering Servo	UPenn	2016	$3,260

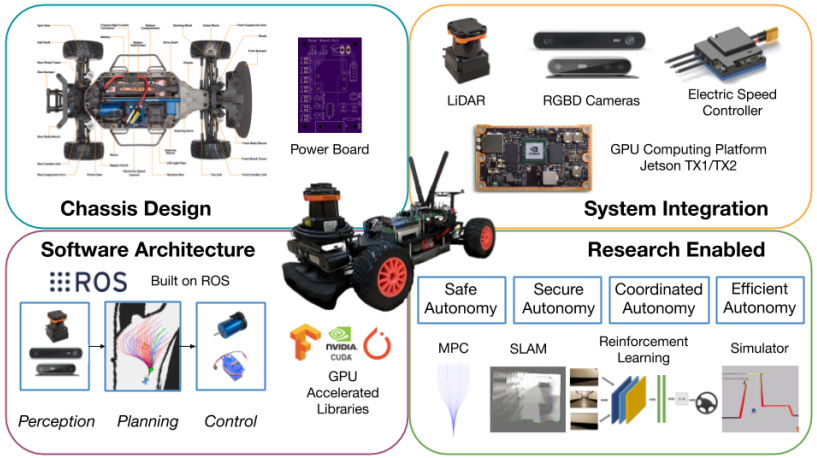
+



+



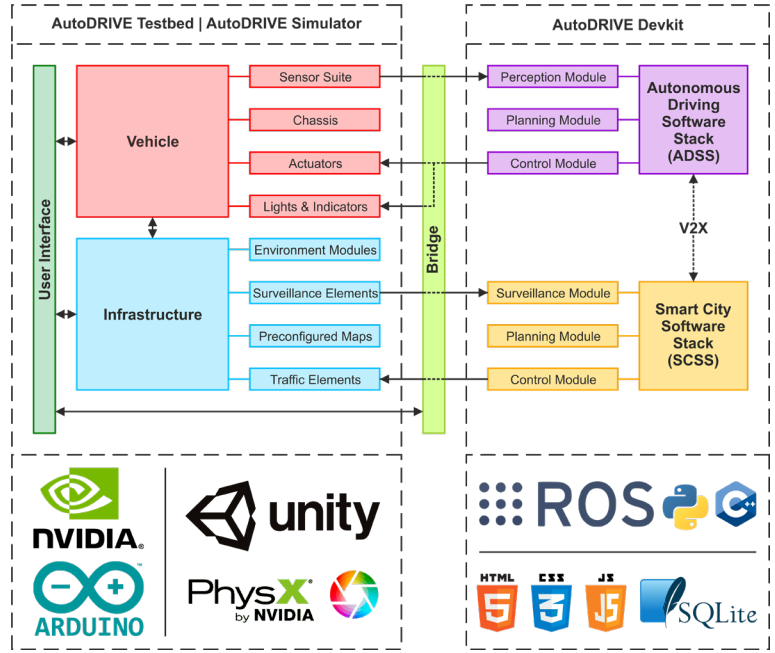
=



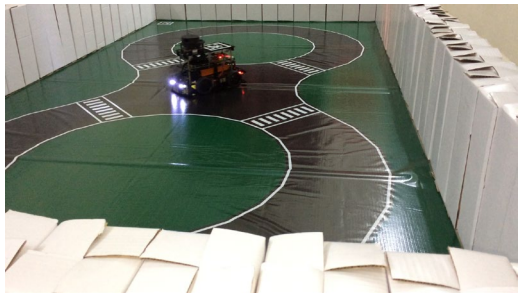
Source: F1TENTH.org

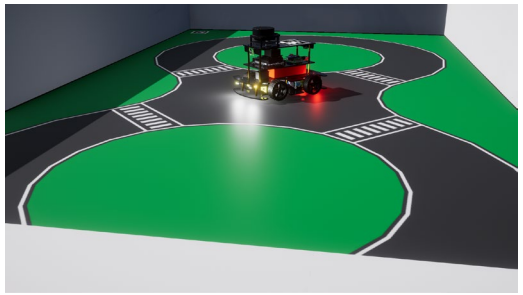
Car-Like Platforms

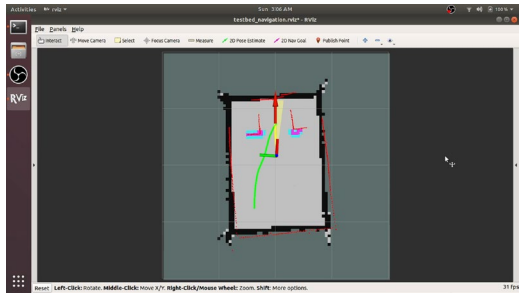
- AutoDRIVE Ecosystem
  - Ackermann-steer, skid-steer, independent 4WD4WS
  - 1/14 scale open chassis
  - Scaled infrastructure
  - Small form factor
  - Flexible APIs
  - High-fidelity simulation
  - Mechatronic testbed
  - AD + SC applications
  - Affordable cost
  - Website
  - GitHub
  - YouTube

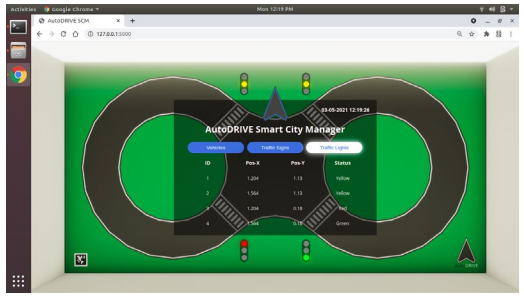


Version	Mobile Base	Battery	Computer(s)	Sensor(s)	Actuator(s)	Developer	Release	Cost
Nigel	Open-Source	5200 mAh	Jetson Nano or Jetson Orin Nano	RPLIDAR A-1, Pi-Cameras, Intel RealSense D435i, 9-Axis IMU, 6-Axis IPS, Encoders, Microphone, Steering Feedback, Throttle Feedback	DC Motors, Steering Servo(s)	CU-ICAR + NTU + SRMIST	2021	$450







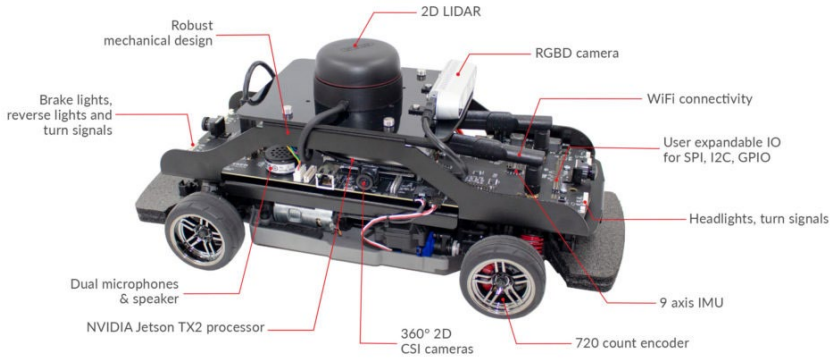


AutoDRIVE

Source: https://autodrive-ecosystem.github.io

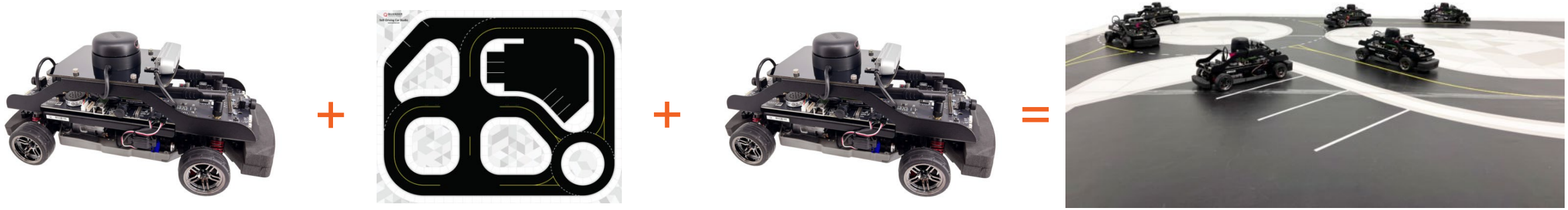
Car-Like Platforms

- QCar
  - Ackermann steered
  - 1/10 scale RC-car
  - Commercial
  - Small form factor
  - Resources
  - Sensor-rich
  - Powerful compute
  - QUARC-Simulink API



Source: Quanser.com

Version	Mobile Base	Battery	Computer(s)	Sensor(s)	Actuator(s)	Developer	Release	Cost
QCar	Traxxas RC Car	3300 mAh	Jetson TX2	Encoders, 9-Axis IMU, Mono-Cams, RGBD-Camera, 2D LIDAR	BLDC Motor, Steering Servo	Quanser	2016	$20,000



Source: Quanser.com

Hardware Platforms – Comparative Analysis

Platform/Ecosystem				Cost *	Sensing Modalities							Computational Resources		Actuation Mechanism		Dedicated Simulator	V2X Support			API Support				
	Scale	Open Hardware	Open Software		Throttle	Steering	Wheel Encoders	GPS/IPS	IMU	LIDAR	Camera	High-Level	Low-Level	Ackermann Steered	Differetial-Drive/ Skid-Steered		Multi-Agent Support	V2V	V2I	C++	Python	ROS	MATLAB/Simulink	Webapp
AutoDRIVE	1:14	✓	✓	$450	✓	✓	✓	✓	✓	✓	✓	Jetson Nano	Arduino Nano	✓	★	✓	✓	✓	✓	✓	✓	✓	★	✓
MIT Racecar	1:10	★	✓	$2600	✗	✗	✗	✗	✓	✓	✓	Jetson TX2	VESC	✓	✗	Gazebo	★	★	✗	✗	✗	✓	✗	✗
AutoRally	1:5	★	✓	$23,300	✗	✗	✓	✓	✓	✓	✓	Custom	Teensy LC/Arduino Micro	✓	✗	Gazebo	★	★	✗	✗	✗	✓	✗	✗
F1TENTH	1:10	★	✓	$3260	✗	✗	✗	✗	✗	✓	✗	Jetson TX2	VESC 6MkV	✓	✗	RViz/Gazebo	✓	✓	✗	✗	✗	✓	✗	✗
DSV	1:10	★	✓	$1000	✗	✗	✓	✗	✓	✓	✓	ODROID-XU4	Arduino (Mega + Uno)	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
MuSHR	1:10	★	✓	$930	✗	✗	✗	✗	✗	✗	✓	Jetson Nano	Turnigy SK8-ESC	✓	✗	RViz	✓	✓	✗	✗	✗	✓	✗	✗
HyphaROS RaceCar	1:10	★	✓	$600	✗	✗	✗	✗	✓	✓	✗	ODROID-XU4	RC ESC TBLE-02S	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
Donkey Car	1:16	★	✓	$370	✗	✗	✗	✗	✗	✗	✓	Raspberry Pi	ESC	✓	✗	Gym	✗	✗	✗	✗	✓	✗	✗	✗
BARC	1:10	★	✓	$1030	✗	✗	✓	✗	✓	✗	✓	ODROID-XU4	Arduino Nano	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
OCRA	1:43	★	✓	$960	✗	✗	✗	✗	✓	✗	✗	None	ARM Cortex M4 μC	✓	✗	✗	✓	✗	✗	✓	✗	✗	✓	✗
QCar	1:10	✗	✗	$20,000	✗	✗	✓	✗	✓	✓	✓	Jetson TX2	Proprietary	✓	✗	Simulink	✓	✓	✗	★	★	★	✓	✗
AWS DeepRacer	1:18	✗	✗	$400	✗	✗	✗	✗	✓	★	✓	Proprietary	Proprietary	✓	✗	Gym	✗	✗	✗	✗	✗	✗	✗	✓
Duckietown	N/A	✓	✓	$450	✗	✗	★	✗	★	✗	✓	Raspberry Pi/Jetson Nano	None	✗	✓	Gym	✓	✗	★	✗	✗	✓	✗	✗
TurtleBot3	N/A	✓	✓	$590	✗	✗	✓	✗	✓	✓	★	Raspberry Pi	OpenCR	✗	✓	Gazebo	★	★	✗	✗	✗	✓	✗	✗
Pheeno	N/A	✓	✓	$350	✗	✗	✓	✗	✓	✗	✓	Raspberry Pi	Arduino Pro Mini	✗	✓	✗	✓	✓	✗	✗	✓	★	✗	✗

✓ indicates complete fulfillment; ★ indicates conditional, unsupported or partial fulfillment; and ✗ indicates non-fulfillment. * All cost values are ceiled to the nearest $10.

T. Samak, C. Samak, S. Kandhasamy, V. Krovi, and M. Xie, "AutoDRIVE: A Comprehensive, Flexible and Integrated Digital Twin Ecosystem for Autonomous Driving Research & Education," Robotics, vol. 12, no. 3, p. 77, May 2023, doi: https://doi.org/10.3390/robotics12030077

Software

Software Frameworks for Scaled Vehicle Courses

Robot Operating System (ROS)

- Robot Operating System (ROS) is a meta-OS
  - **Plumbing:** communication middleware (e.g. nodes, topics, messages, services, etc.)
  - **Tools:** monitor, visualize and debug (e.g. rqt, rviz, etc.)
  - **Capabilities:** out-of-the-box support for robot mobility and manipulation (e.g. perception, planning, control)
  - **Community:** developers and contributors across the globe (e.g. Open Robotics, Autoware, F1Tenth, etc.)

Source: ROS.org

ROS – Overview

- ROS roadmap
  - **ROS-1:** Developed for PR2, extended for academic R&D
  - **ROS-2:** Extension of ROS with new, lightweight middleware
  - **µ-ROS:** Support for embedded and real-time applications
  - **ROS-I:** Extension of ROS to industrial robots and standards

ROS – Resources

ROS

- Documentation
  https://wiki.ros.org/
- Questions & answers
  https://answers.ros.org/questions/
- Support
  http://wiki.ros.org/Support
- Discussion forum
  https://discourse.ros.org/

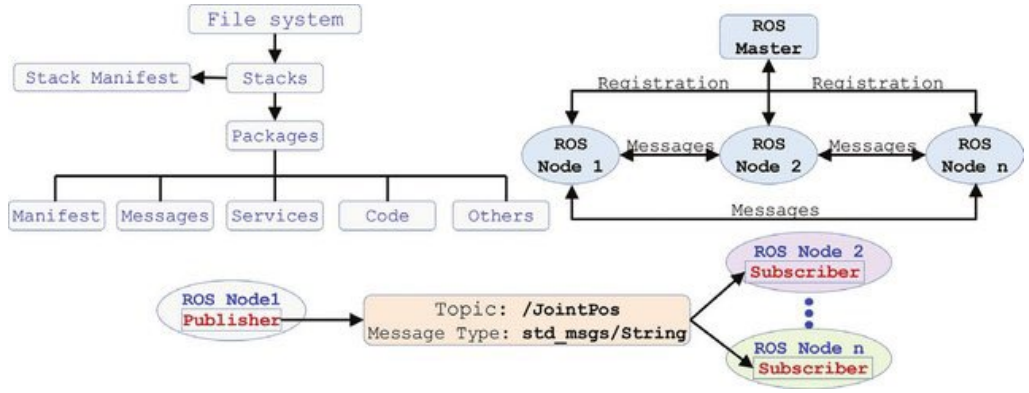
- Documentation
  http://wiki.ros.org/Industrial
- Installation guide
  http://wiki.ros.org/Industrial/Install
- Tutorials
  http://wiki.ros.org/Industrial/Tutorials
- Discussion forum
  https://discourse.ros.org/c/ros-industrial
- Bug/feature tracking
  https://github.com/ros-industrial/ros_industrial_issues

ROS 2™

- Documentation
  https://docs.ros.org/en/foxy/index.html
- Installation guide
  https://docs.ros.org/en/foxy/Installation.html
- Tutorials
  https://docs.ros.org/en/foxy/Tutorials.html
  https://docs.ros.org/en/foxy/How-To-Guides.html
- Concepts
  https://docs.ros.org/en/foxy/Concepts.html
- Support
  https://docs.ros.org/en/foxy/Contact.html

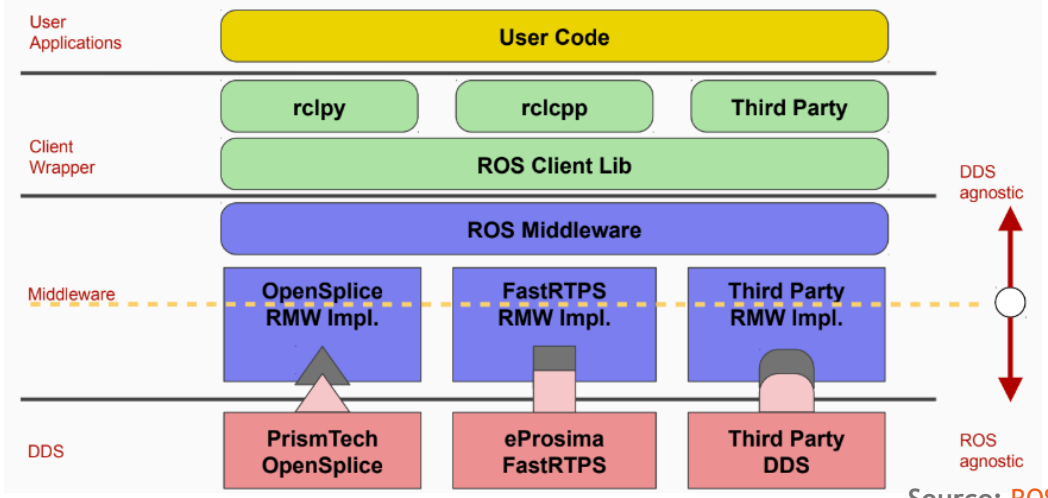
ROS – Deployment Architecture

ROS-1



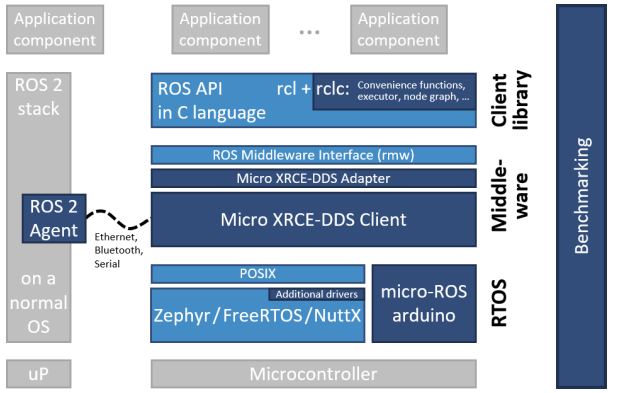
Source: [3]

ROS-2



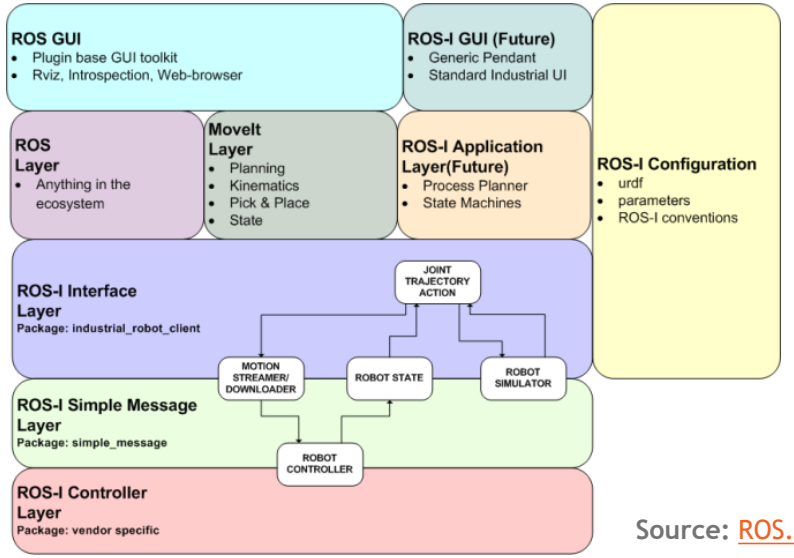
Source: ROS.org

μ-ROS



Source: ROS.org

ROS-I



Source: ROS.org

ROS – Comparative Analysis

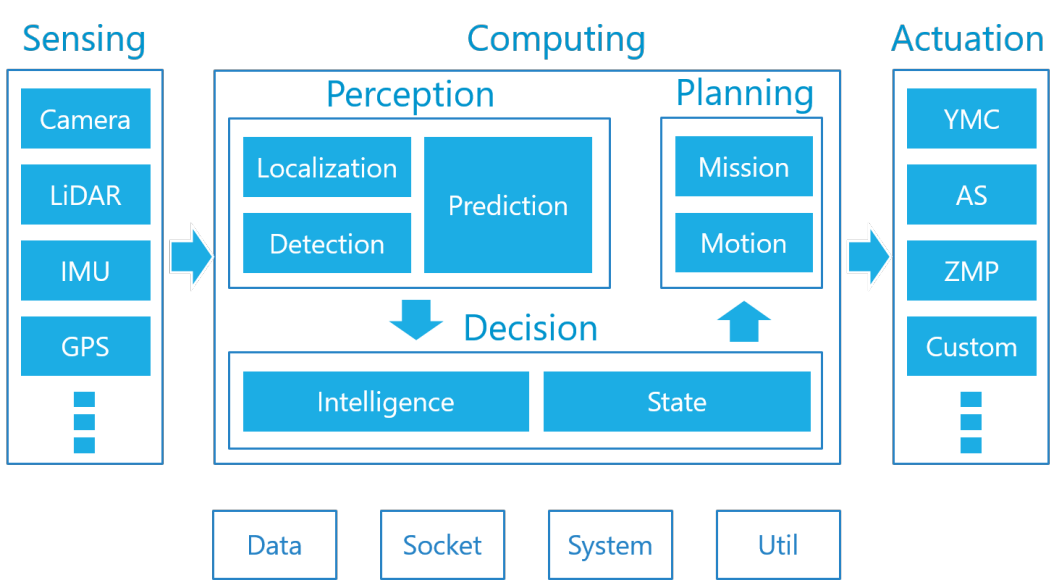
Criteria	ROS-1	ROS-2	ROS-I
Architecture	Centralized Discovery	Distributed Discovery	Centralized Discovery
Multi-Agent Support	Not ideally	Yes	Future
Real-Time Capability	No	Yes	Future
Embedded Platforms	Partially	Yes	Yes
Non-Ideal Networks	No	Yes	Future
Life-Cycle Management	No	Yes	Future
Industrial Support	No	No	Yes
Documentation	Mature	Increasing	Ongoing
Maintenance Support	Nearing EOL	Increasing	Increasing
Language Support	C++03/11, Python2	C++11/14/17, Python3	C++03/11, Python2
OS Support	Linux, macOS	Linux, macOS, Windows, RTOS (μROS)	Linux, macOS
Recommended Scope*	Hobby, Academic	Professional, Real-Time	Industrial

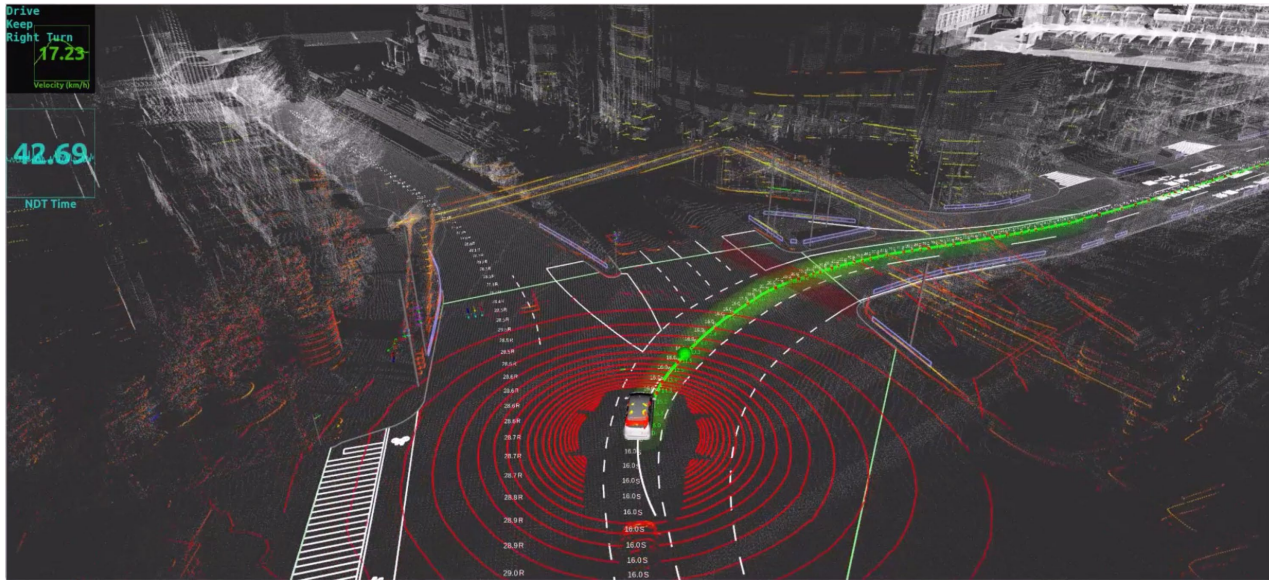
*Recommendation is based on critical analysis presented in rows 1-11

Autoware Stack

AUTOWARE.AI AUTOWARE.AUTO AUTOWARE.IO

- Autoware.AI
  - Started in 2015 by Shinpei Kato (Nagoya University)
  - Autonomous driving software stack (ROS-1)
  - Open source



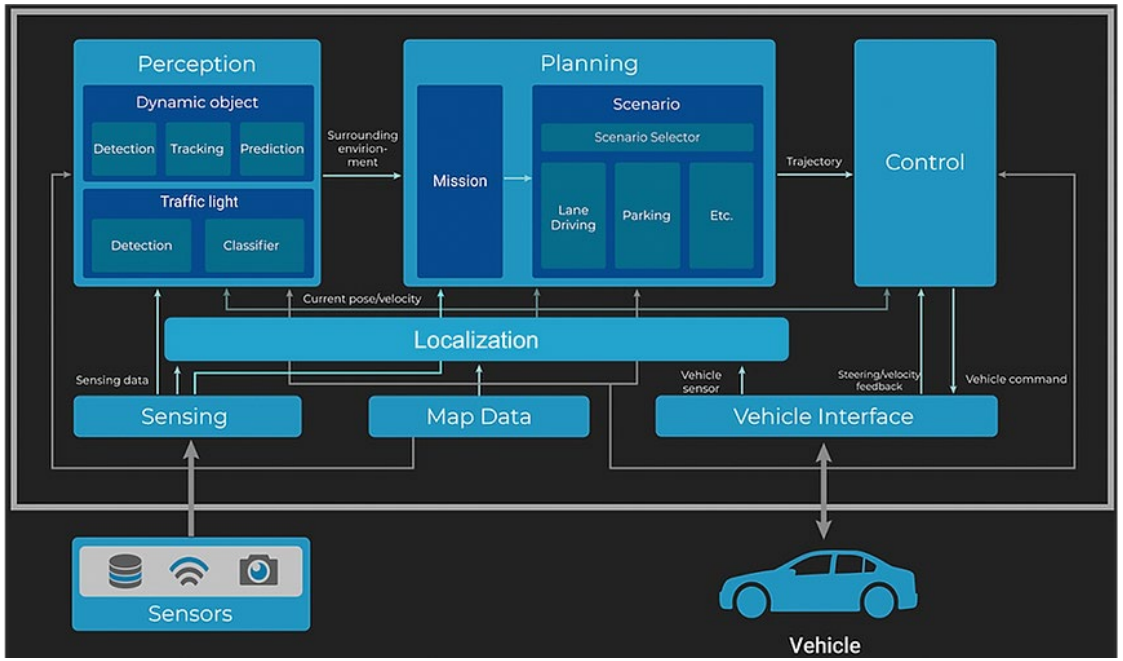


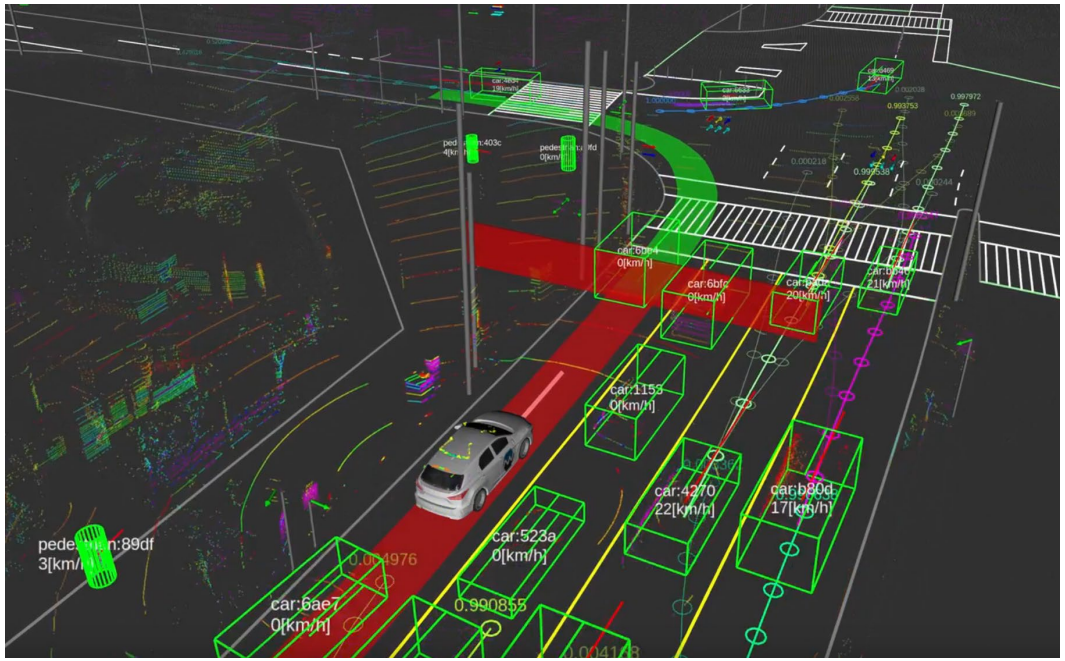
Source: Autoware.org

Autoware Stack

AUTOWARE.AI AUTOWARE.AUTO AUTOWARE.IO

- Autoware.Auto
  - Autonomous driving software stack (ROS-2)
  - Open source

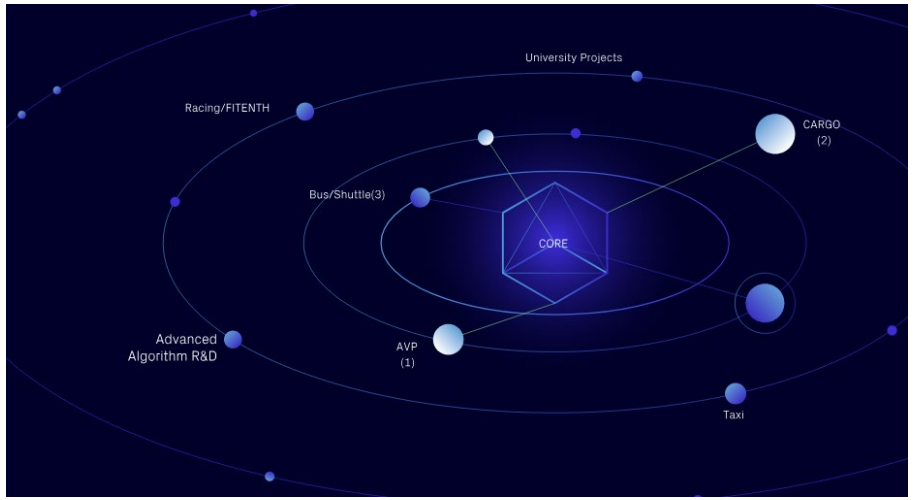




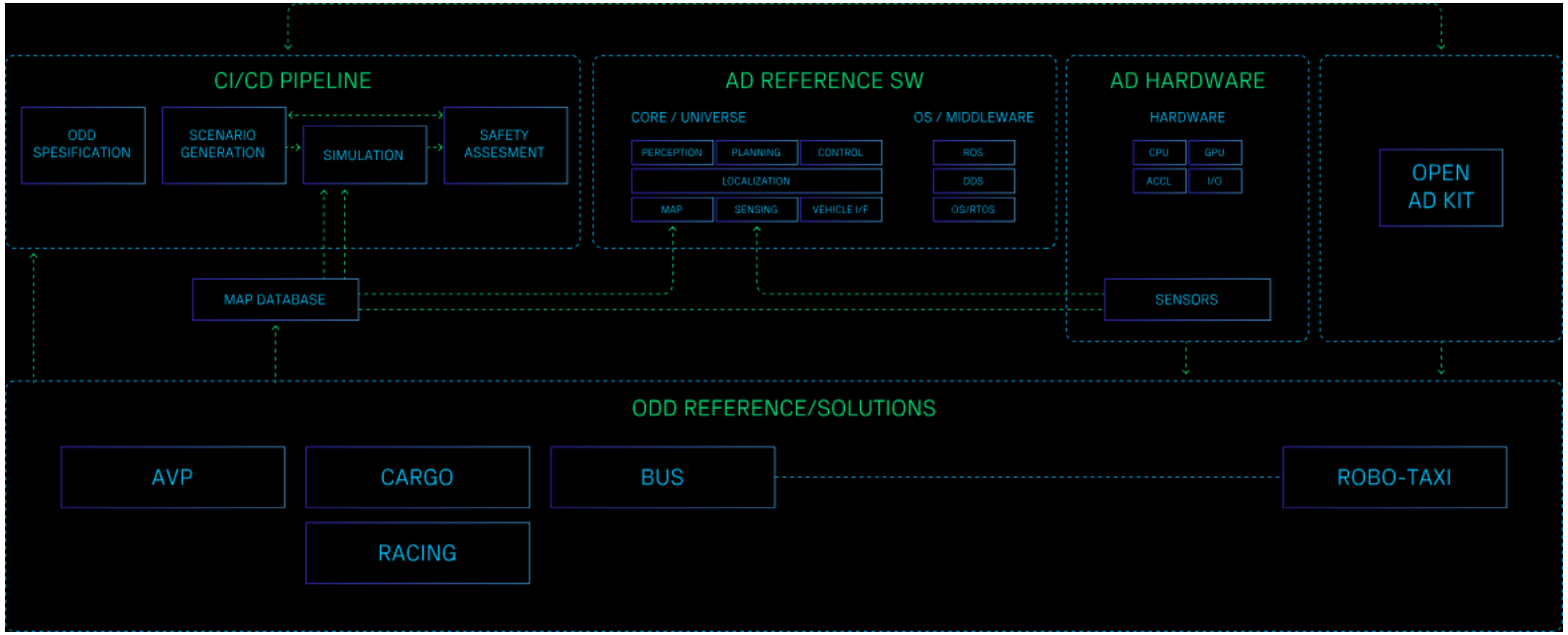
Source: Autoware.org

Autoware Stack

AUTOWARE.AI AUTOWARE.AUTO AUTOWARE.IO



- Autoware Core/Universe
  - Autoware Core: High-quality, stable ROS packages for AVs
  - Autoware Universe: Experimental, cutting-edge ROS packages
  - Autoware I/O
  - OpenAD Kit
  - ODD Reference/Solutions
    - Autonomous Valet Parking
    - Cargo Delivery
    - Racing
    - Robo-Bus/Shuttle
    - Robo-Taxi



Source: Autoware.org

Baidu Apollo Stack

Baidu 百度 | apollo

- AD HW/SW stack
- ROS → Cyber RT
- Open source

Apollo Open Platform

Cloud Service Platform	HD Map	Simulation	Production Components	Security	OTA	DuerOS	V2X
	Fuel Data Service						
Open Software Platform	Map Engine	Localization	Perception	Prediction	Planning	Control	HMI	V2X Adaptor
	Apollo Cyber RT				RTOS			
Hardware Development Platform	Computing Unit	GPS/IMU	Camera	LiDAR	Radar	Ultrasonic Radar	HMI Device	Black Box	ASU	AXU	V2X OBU
Open Vehicle Certificate Platform	Certified Apollo Compatible Drive-by-wire Vehicle				Open Vehicle Interface Standard						

Source: Apollo.auto

Other Frameworks

- MATLAB/Simulink
  - Automated Driving Toolbox
  - Driving Scenario Designer & RoadRunner
- NVIDIA DRIVE SDK
  - DRIVE OS: In-vehicle OS /w acc. comp.
  - DriveWorks: Middleware
  - DRIVE AV: Perception, mapping, planning stacks
  - DRIVE Chauffer: Highway & urban ADAS/AD
  - DRIVE IX: Cockpit sensing and AI
  - DRIVE Concierge: Digital assistant
  - DRIVE Map: Scalable fleet-sourced mapping

Source: Mathworks.com

Source: NVIDIA.com

References

1. M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Ng, “ROS: an open-source Robot Operating System,” in ICRA 2009 Workshop on Open Source Software, vol. 3, Jan 2009. [Online]. Available: http://robotics.stanford.edu/~ang/papers/icraoss09-ROS.pdf
2. S. Macenski, T. Foote, B. Gerkey, C. Lalancette, and W. Woodall, “Robot operating system 2: Design, architecture, and uses in the wild,” Science Robotics, vol. 7, no. 66, p. eabm6074, 2022. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.abm6074
3. R. R. Shamshiri, I. A. Hameed, and M. K. a. Weltzien, "Robotic Harvesting of Fruiting Vegetables: A Simulation Approach in V-REP, ROS and MATLAB", in Automation in Agriculture - Securing Food Supplies for Future Generations. London, United Kingdom: IntechOpen, 2018 [Online]. Available: https://www.intechopen.com/chapters/59402 doi: 10.5772/intechopen.73861
4. T. Samak, C. Samak, S. Kandhasamy, V. Krovi, and M. Xie, “AutoDRIVE: A Comprehensive, Flexible and Integrated Digital Twin Ecosystem for Autonomous Driving Research & Education,” Robotics, vol. 12, no. 3, p. 77, May 2023, doi: https://doi.org/10.3390/robotics12030077