Modular Autonomous Electric Vehicles

AV4EV Platform Zero:
Let's build a self-driving Go-Kart!

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Penn Engineering

April 04, 2025


MIH

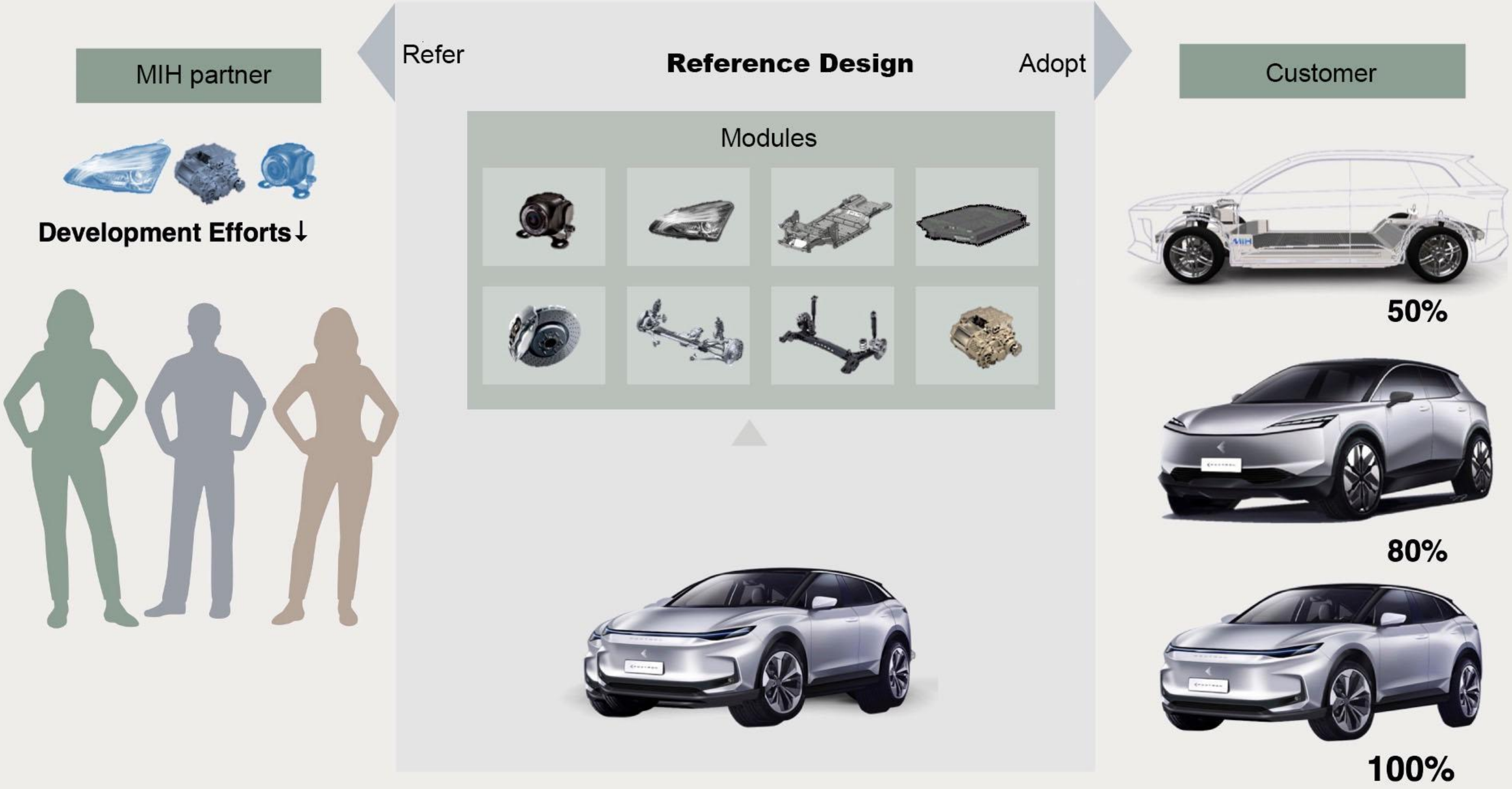
Standardized Electric Vehicle Platforms

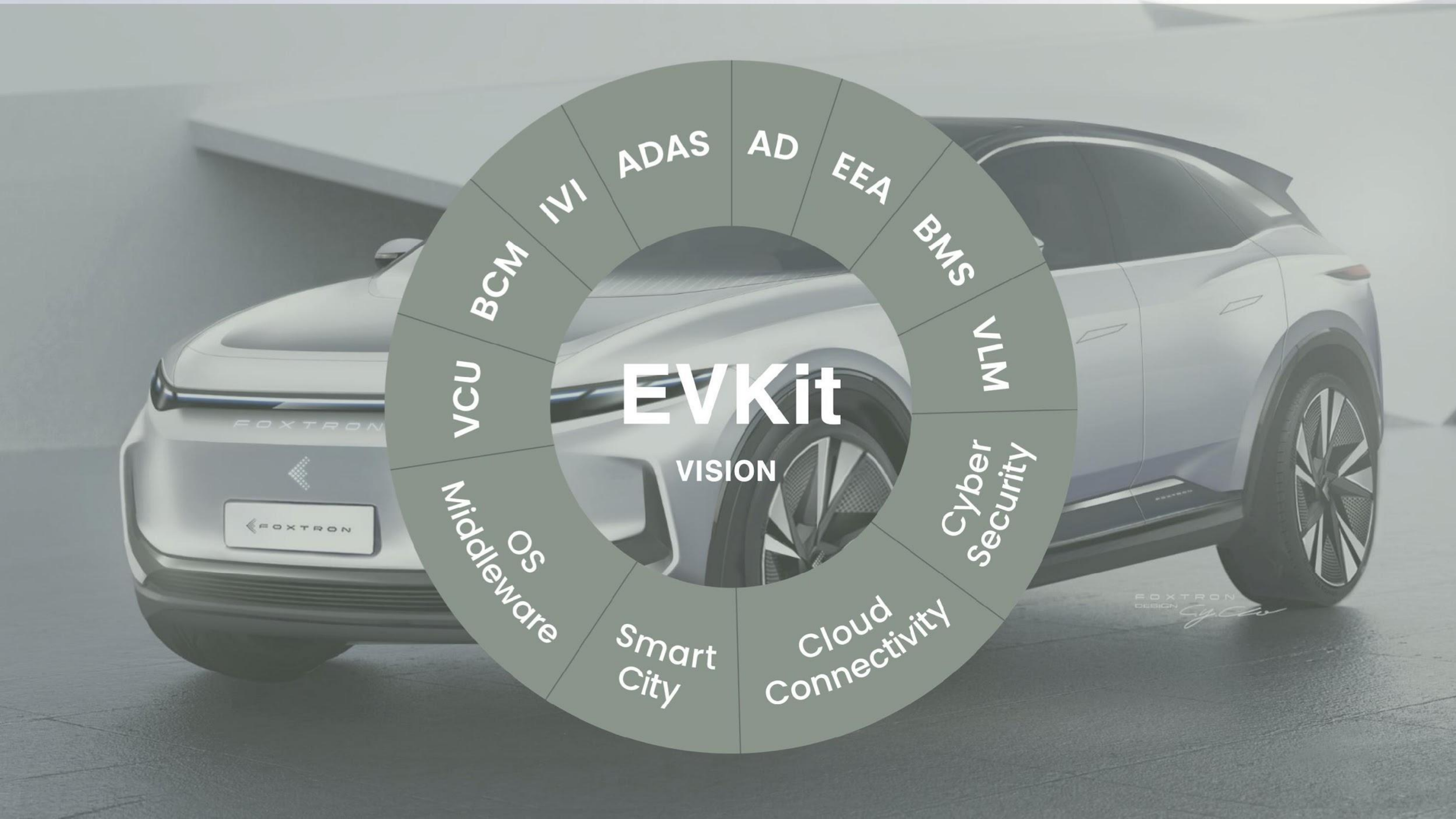
ICE rolling chassis → EV skateboard chassis

2000+ components → 20 components

Open AV for Open EV

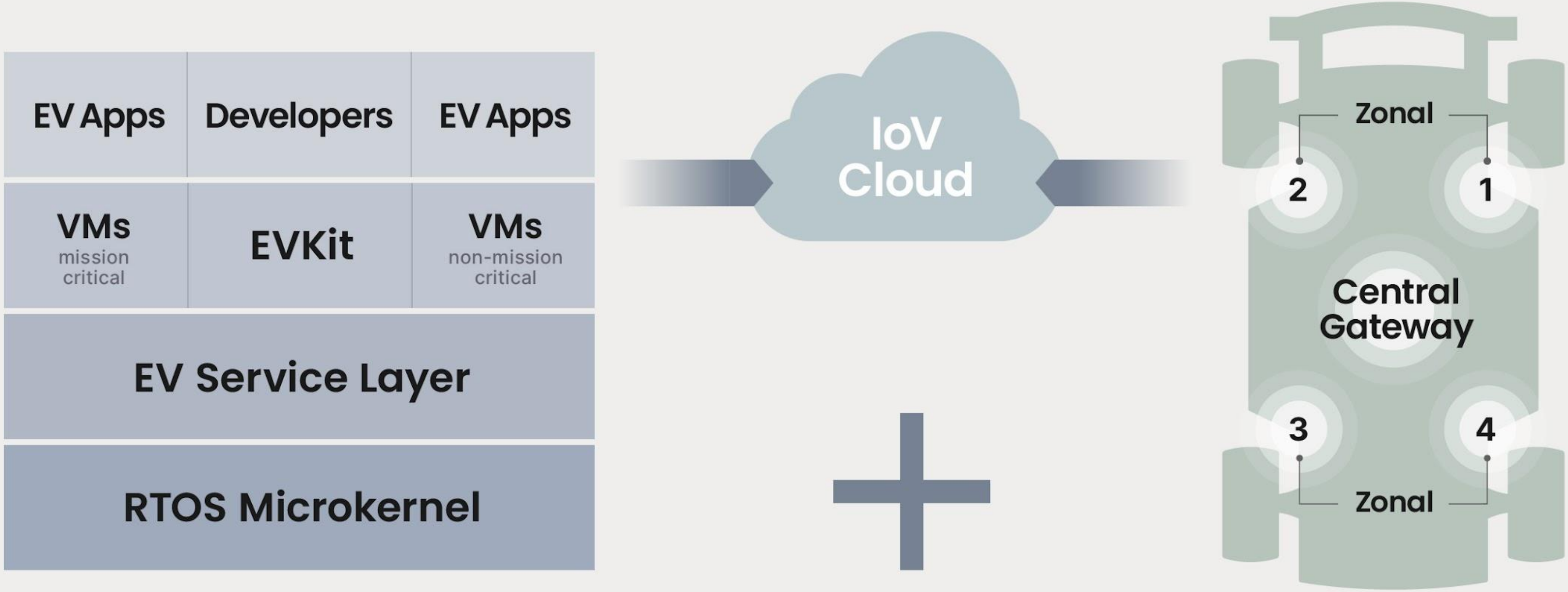
Open-source Autonomous Vehicle Software for Open Standard EV Platforms


MIH partner
Development Efforts↓
Refer
Reference Design
Adopt
Modules
Customer
50%
80%
100%

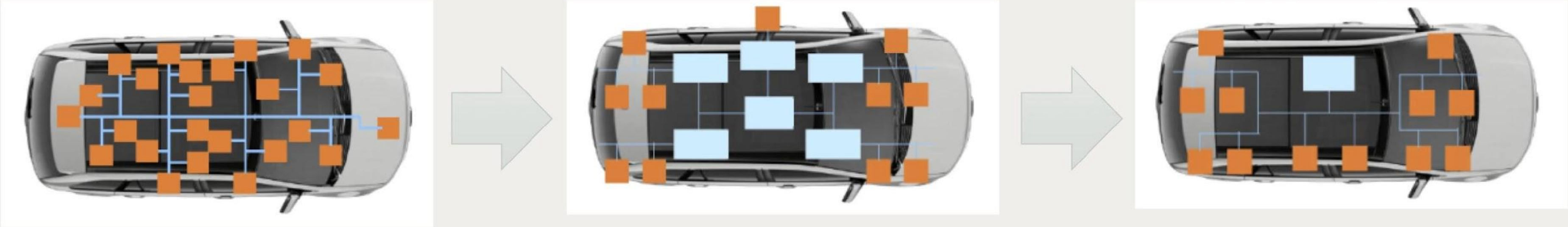

EVKit
VISION
ADAS
AD
EEA
BMS
VLM
Cyber Security
Cloud Connectivity
Smart City
OS Middleware
VCU
BCM
IVI
FOXTRON
FOXTRON DESIGN

Open EV Platform

VISION



Path towards **software defined vehicles (SDV)**



Domain based | Zonal / Centralized | HPC / Cluster

Electrical & Electronic Architecture Evolution

R&D Prototyping + **OpenAD Kit Software** + **OpenEV Platforms**

67 Industry Partners

60+ Academic Partners

Autonomy Stack

Open AV Stack

Autoware OpenAD Kit

Connectivity Stack

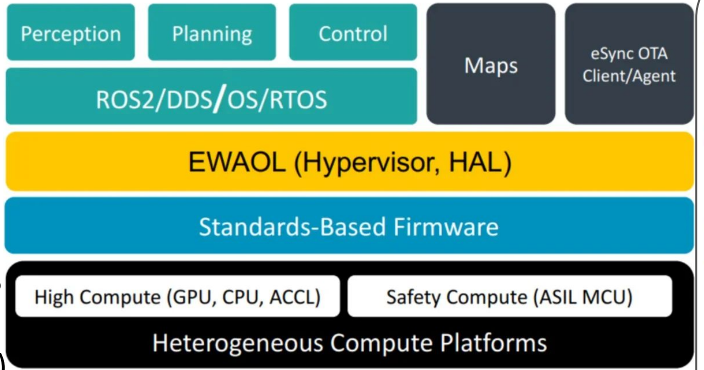
Software Defined Vehicles

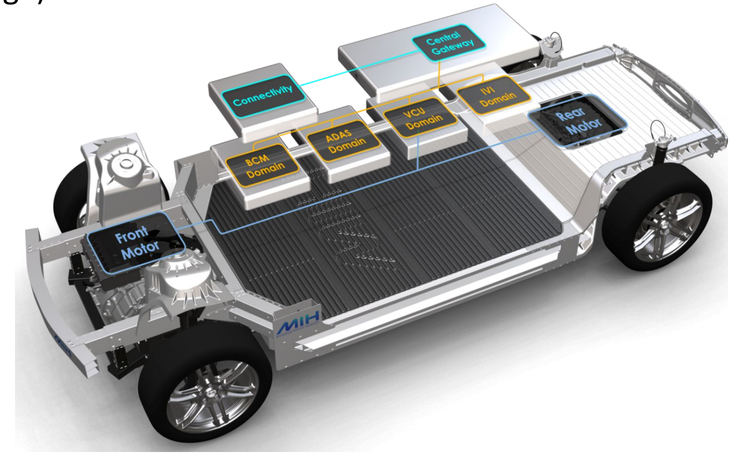
SOAFEE (Scalable Open Architecture for Embedded Edge)

Skateboard EVs

Open EV Platforms

- Prototype: EV Go-kart
- Commercial Deployment: TierIV EV Cargo Platform





Penn Engineering + CLEMSON UNIVERSITY + THE AUTOWARE FOUNDATION + DANLAW + AeroVect

R&D Prototyping | AV Testing | OpenAD Kit Software | OpenEV Platforms | Commercialization

67 Industry Partners

PREMIUM

INDUSTRY & GOVERNMENT

AFFILIATED ORGANIZATIONS

ACADEMIC & NON-PROFIT

Open-source Autonomy Stack

Autonomy Essentials Kit

- Modular perception, planning and control software stack
- Autoware Supported
- Full-stack hardware solution with sensors and compute platform

Cloud-based AV Dev & Test

Software Defined Vehicles

- SOAFEE - Scalable Open Architecture for Embedded Edge
- Firmware over the air updates

Skateboard EVs

Open EV Platforms

- High-precision Drive-by-wire Control on Prototype: EV Go-kart
- Commercial Deployment: Danlaw EV Cargo Platform
- Cost-effective, high-performance, full-openness

Perception | Planning | Control | Maps | eSync OTA Client/Agent

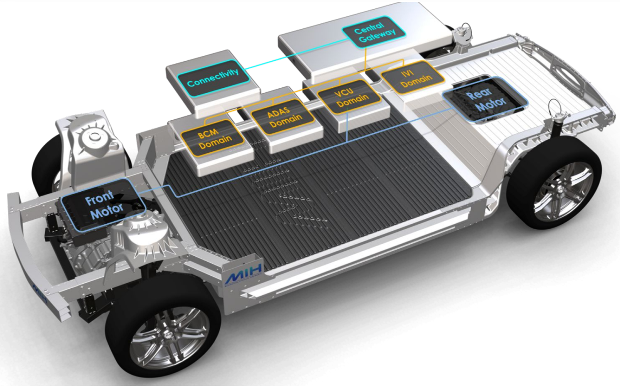
ROS2/DDS/OS/RTOS

EWAOL (Hypervisor, HAL)

Standards-Based Firmware

High Compute (GPU, CPU, ACCL) | Safety Compute (ASIL MCU)

Heterogeneous Compute Platforms



Autonomous Mobile Robots | Mining | Autonomous Logistics | Agriculture | Construction | Autonomous Shuttles

60+ Academic Partners

PREMIUM

ADASTEC Automated, Shared, Connected
ADLINK Leading EDGE COMPUTING
arm
AutoCore Intelligent Vehicle Platform
DANLAW
EPROSIMA The Middleware Experts
eSOL
F1 TENTH
FOXCONN 鴻海科技集團
ITRI Industrial Technology Research Institute
LEO DRIVE
MAP IV
MARVELL
MORAI
ROBOTEC AI
Spring Cloud
TUM
TIER IV
TOMTOM
CAR
whale dynamic 惠尔智能
AMD XILINX
U POWER
Vecow Smarter AIoT Solution Services

INDUSTRY & GOVERNMENT

AISAN TECHNOLOGY
AXELL CORPORATION
cadence
dSPACE
eve auto
embotech
FastLabel
U.S. Department of Transportation Federal Highway Administration
FUTUREWEI Technologies
HESAI
HEXAGON
HITACHI Inspire the Next
HITACHI Inspire the Next 株式会社 日立産業制御ソリューションズ
interplai
KLAS
MACNICA
MINGSHANG
NTT DATA NTT DATA MSE Corporation
NXP
OUSTER
OKAYA & CO.,LTD.
POLYEXPLORE
pix moving
Quanta Computer
robosense

ACADEMIC & NON-PROFIT

CLEMSON
POZNAN UNIVERSITY OF TECHNOLOGY
NAGOYA UNIVERSITY
open robotics
FLORIDA POLYTECHNIC UNIVERSITY
Saitama University 埼玉大学
School of Information Science and Technology The University of Tokyo
JSAE
TAL TECH
utbm

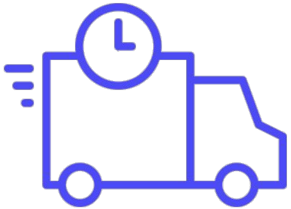
AFFILIATED ORGANIZATIONS

AVC CONSORTIUM
eSync ALLIANCE
eclipse iot
MIH
OpenADx
seL4 FOUNDATION
SOAFEE
Robotiz3d
smartmicro
ThunderSoft
TREND MICRO

Connected Autonomous Machines

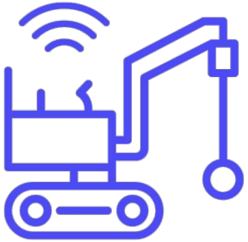
Autonomous Mobile Robots (AMRs)

Mining



Autonomous Logistics

Agriculture



Construction

Shuttle Vehicles

Open Standard EV Chassis for multiple use cases


Advanced
Power

THE AUTOWARE FOUNDATION

MIH

Open AD Kit

- Open-source software
- Autoware-defined architecture
- AD DevOps
- Cloud native

EVKit

Auto-Grade

TierIV

Mobility21 DoT National University Transportation Center ($17MM 2017-2023)

Safety21 DoT National UTC will begin in October 2023 ($20MM 2023-2028)

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Penn Director, Mobility21 DoT UTC

University of Pennsylvania

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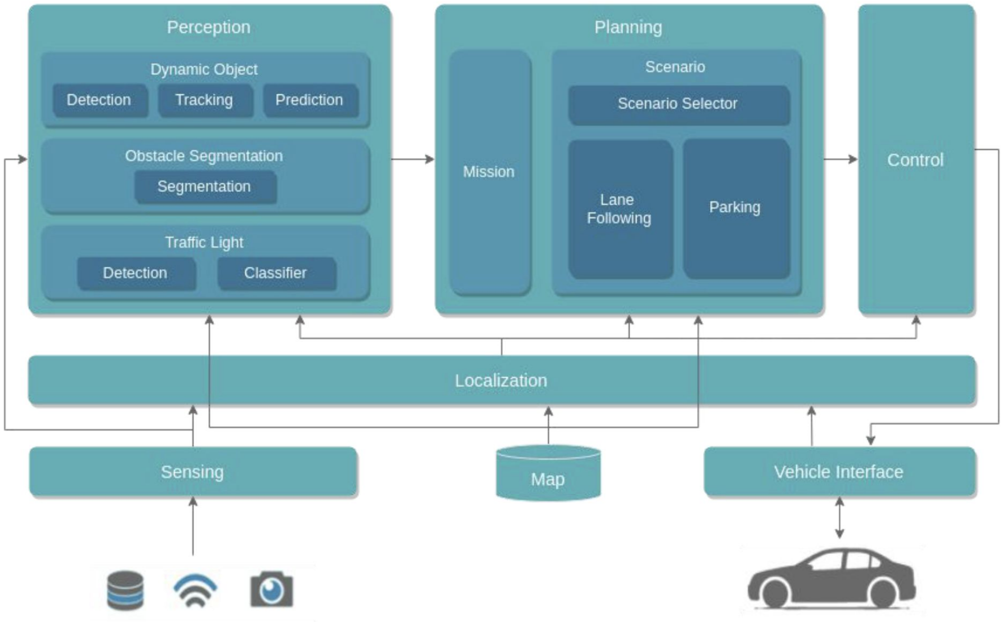
Penn Engineering

Carnegie Mellon University

What is Autoware?



Autoware

The first all-in-one open source software for autonomous driving

- Originally created in 2015 by Shinpei Kato at Nagoya University
- Based on the open-source ROS middleware
- Autoware is:
  - Complete AD software stack
  - Independent of vehicle type or electronic hardware
  - Governed by an independent foundation
  - Completely open-source (licensed under Apache License 2.0)

Autoware Deployments

Autoware: Over a dozen public transit deployments worldwide

AUTOWARE
PROJECT NEWS

[ADASTec]

Istanbul, Turkey

Partnering with Autoware Foundation to deliver the most advanced L4 automated transportation platform for full size commercial vehicle. Watch Video

Autonomous Driving R&D Engagement

AUTOWARE.AUTO

Autoware.Auto

Core Software stack development

Software Modules, Middleware, Open-Source Community

Autoware Core Dev

THE AUTOWARE FOUNDATION

Autoware Partners

Engineer-in-Residence Program

Physical lab for co-development, ODD demonstrations, Support, Know-How, Hardware

PENNOVATION CENTER

12 Research Faculty

Professors, Researchers, New Algorithms, New Hardware

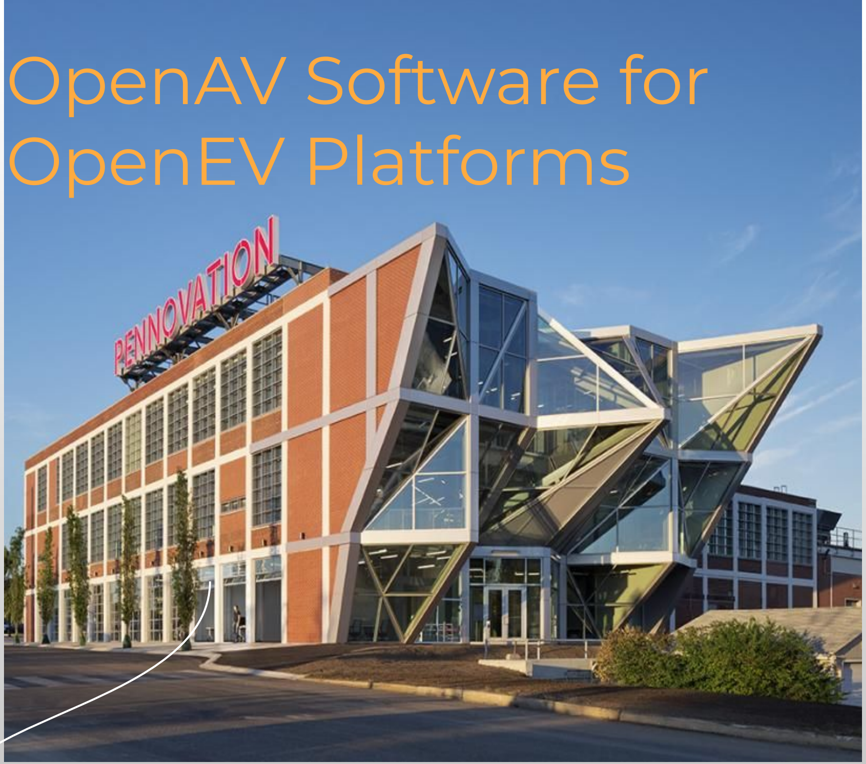
Autoware Universe Dev

Penn Engineering

85 Robotics Students

Master Students, PhD Students Independent Projects, Internships

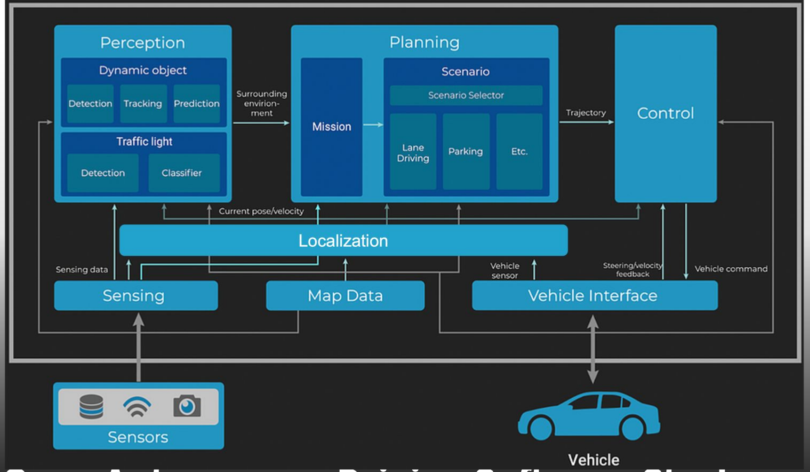
OpenAV Software for OpenEV Platforms



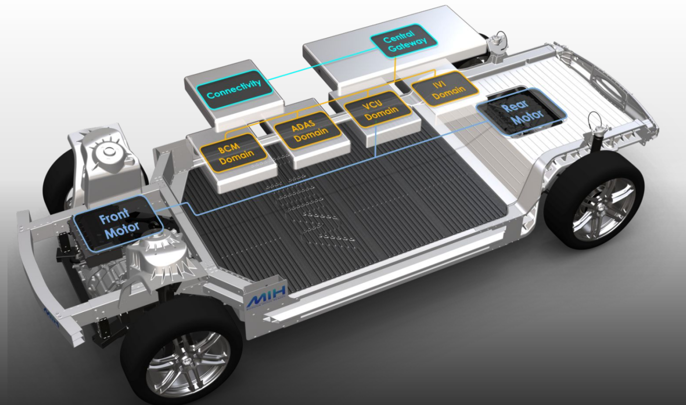
Pennovation Center

800sqft garage lab for hands-on dev & testing

23 acres for R&D demonstrations & deployments



Open Autonomous Driving Software Stack
Perception, planning, control and communication



Standardized EV Skateboard Chassis
Focus on Autonomous Driving Module for OpenEV

Autoware Center of Excellence @ Pennovation Center

www.pennovation.upenn.edu

Launched in Feb 2022

23 acres suitable for AV testing

- AWF Developers → Autoware CoE
- AWF Members → Autoware CoE
- AV Ecosystem & Industry Experts → Autoware CoE

Autoware CoE

- Autoware Core Development & Test
- Autoware Universe Advanced Research

- UPenn GRASP ↔ Autoware CoE
- UPenn GRASP ↕ Univ AD Programs
- Univ AD Programs ⇠ Autoware CoE

THE AUTOWARE FOUNDATION

R&D with Partnerships

THE AUTOWARE FOUNDATION

PENNOVATION CENTER

Penn Engineering
UNIVERSITY of PENNSYLVANIA

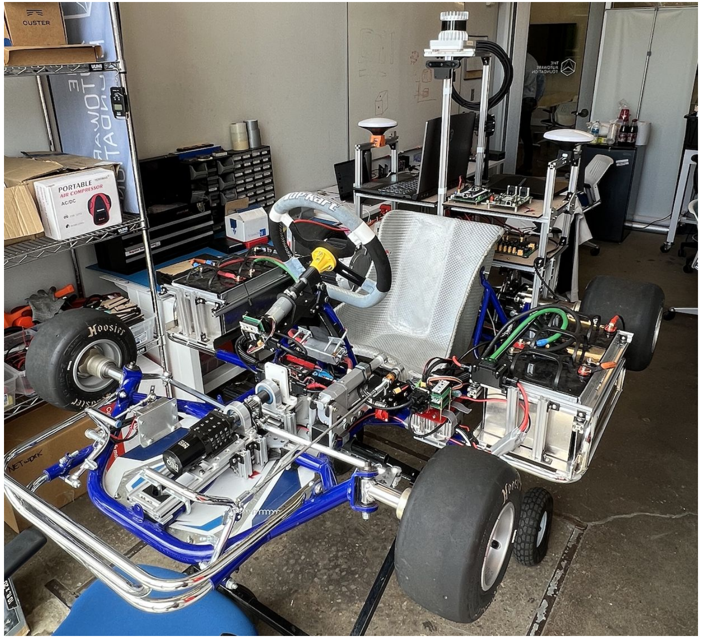
Agile Autonomous Solutions for Passenger cars, shuttle buses, forklifts, material handling, service bots, wheelchairs

ADASTEC Automated, Shared, Connected
ADLINK Leading EDGE COMPUTING
arm
AutoCore Intelligent Vehicle Platform
ALIAS ROBOTICS Robot Cybersecurity
AISAN TECHNOLOGY
AXELL CORPORATION
cadence
embotech
EPROSIMA The Middleware Experts
eSOL
F1 TENTH
dSPACE
DMP
U.S. Department of Transportation Federal Highway Administration
FLIR
HEXAGON
ITRI Industrial Technology Research Institute
LEO DRIVE
LG
FUTUREWEI Technologies
GAIA
HESAI
HITACHI Inspire the Next
navya self-driving made real
ROBOTEC AI
TATA CONSULTANCY SERVICES
Tier IV Intelligent Vehicles For Everyone
intel
ITD Lab Intelligent Stereo Camera
interplai
KALRAY
TOMTOM
woven planet
zing robotics
XILINX
Linaro 96Boards
LSLIDAR
MACNICA
MORAI
Quanta Computer
robosense
rti
SECOND STATE
NXP
OUSTER OKAYA & CO.,LTD.
POLYEXPLORE
pix moving
smartmicro SMART MICROWAVE SENSORS
ThunderSoft
Velodyne LiDAR
wipro

Objective

Converts the Top Kart USA MSTEM3 Go-Kart into an AV Go-kart

Before: Top Kart USA MSTEM3 Go-Kart kit



After: Autoware AV4EV Go-kart

Objective

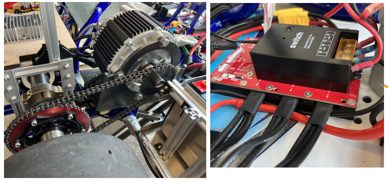
- Convert the base Manual Go-Kart MSTEM3 Chassis into the **Drive-By-Wire** system
  - Mechanical support
  - Power systems design
  - Embedded development
- **Software Stack**
  - Open-source AV software Autoware
  - Robot Operating System (ROS2)
  - Sensors (LiDAR, Camera, GNSS)
  - Mapping and localization
- **Research**
  - Racing at high speeds
  - Imitation learning from humans

Top Kart USA MSTEM3 Go-Kart kit

Penn Engineering

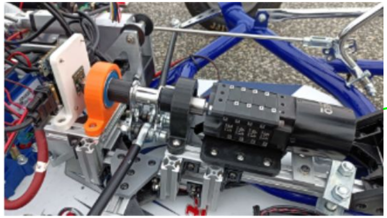
AV4EV Go-kart Mechanical Upgrades

New Drive Motor
+ Throttle-by-wire

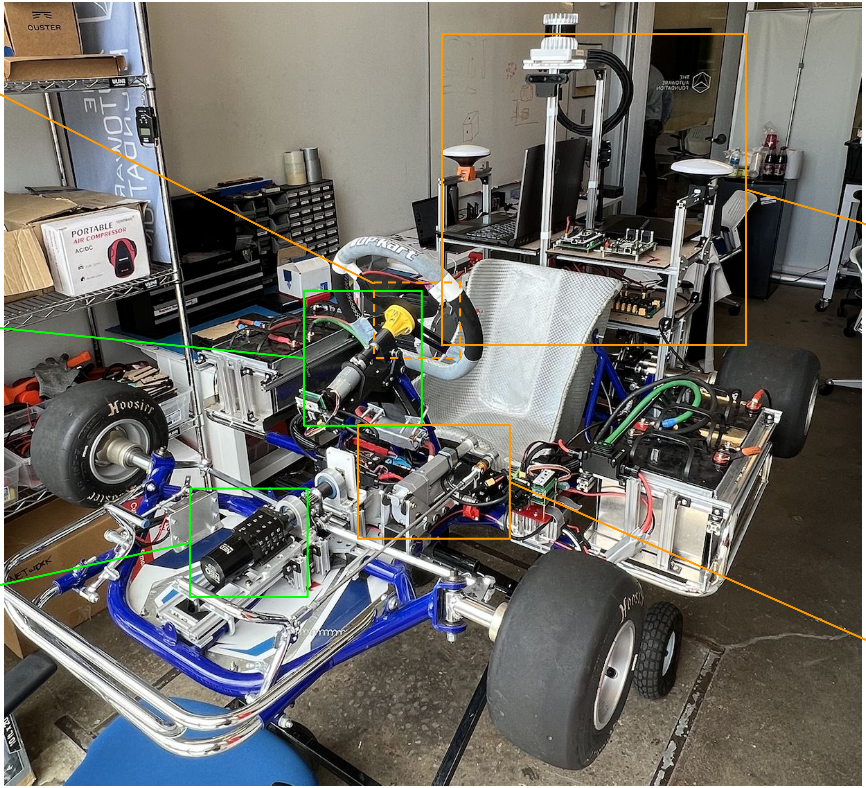


Upper Steer-by-wire

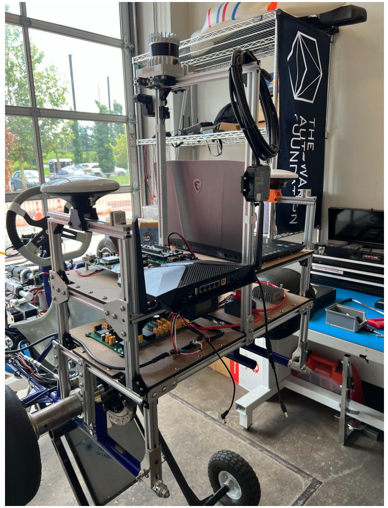
Lower Steer-by-wire



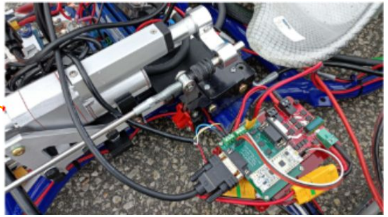
Go-kart Main View



Back Shelf (Redesigned)
+ Main Controller



Brake-by-wire



AV4EV: Let's start with Manual Driving

AV4EV: Joystick Control

Team

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Software & Sensing

Rahul Mangharam
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Team Principal

Autonomous Karting Competition

Purdue University May 2023

Autonomous Karting Competition

Purdue University May 2023

Champions!

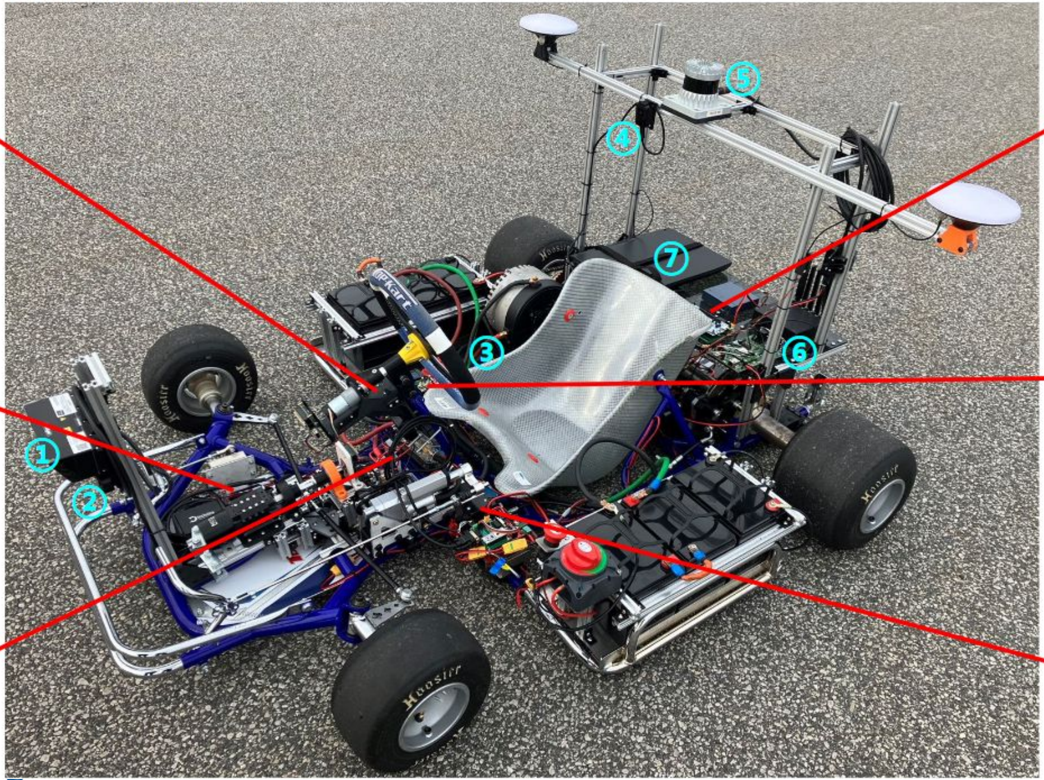
Autoware Team won both categories of racing

- Reactive motion planning
- Open category for motion planning.

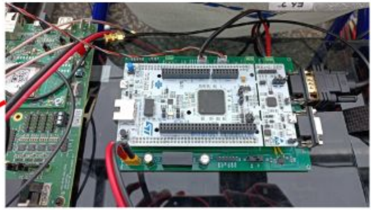
AV4EV Go-kart Overview

Steer-by-Wire (HW)

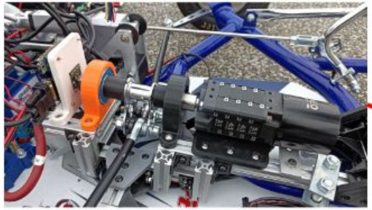
Go-kart Main View



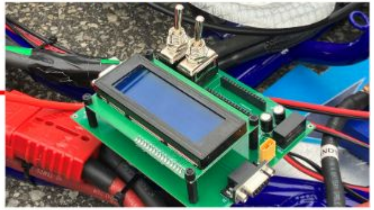
Main Control



Steer-by-Wire (RW)

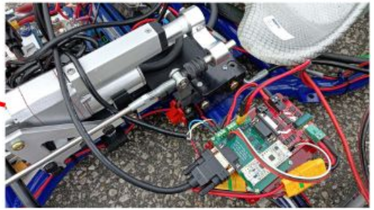


User Interface



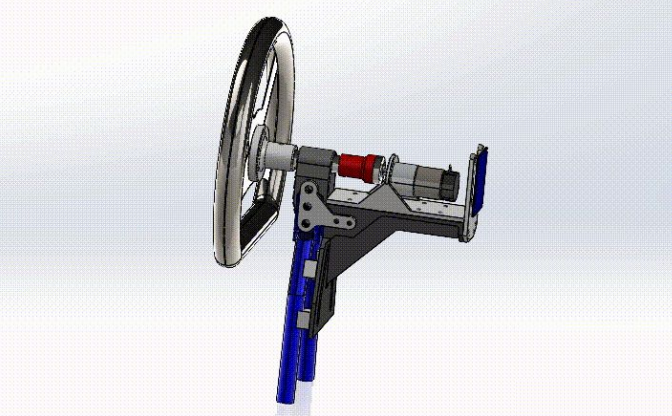
Throttle-by-Wire

Brake-by-Wire

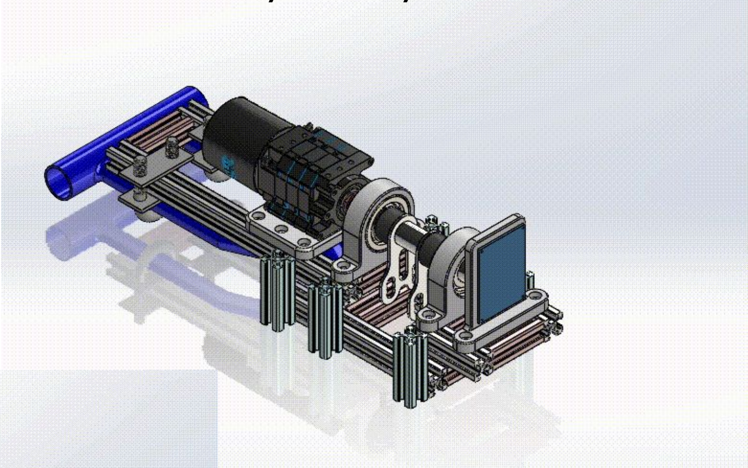


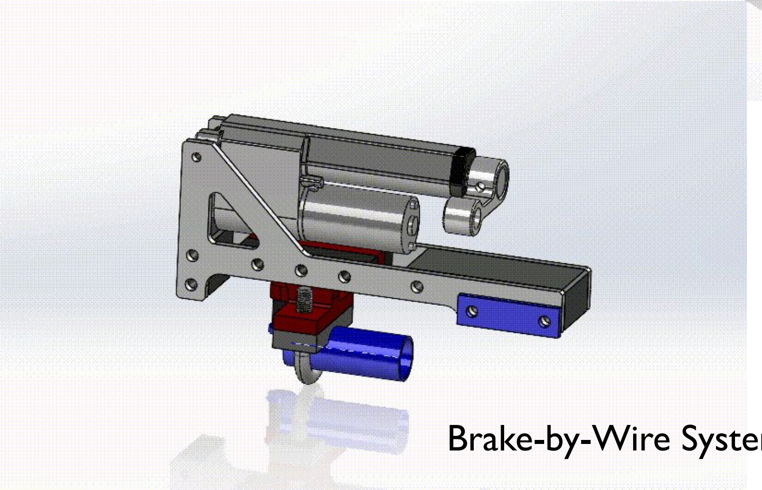
Exploded View

Upper Steer-by-Wire System



Lower Steer-by-Wire System

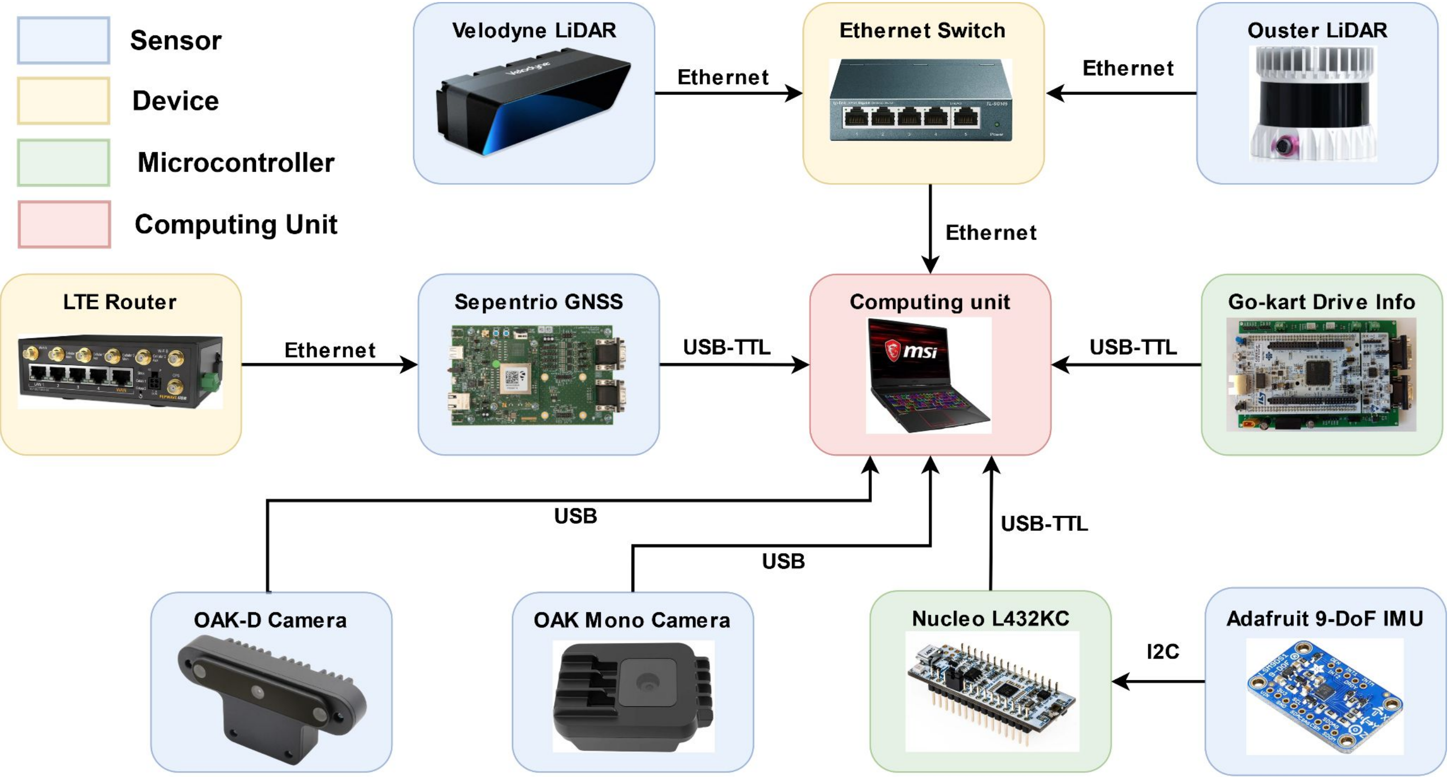




Brake-by-Wire System

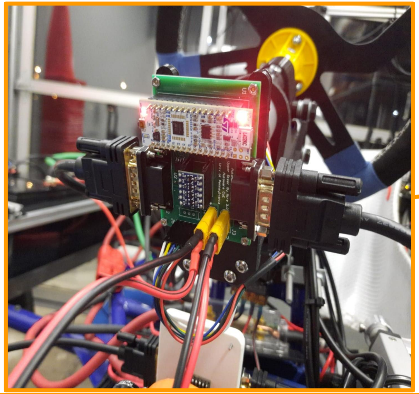
Penn Engineering

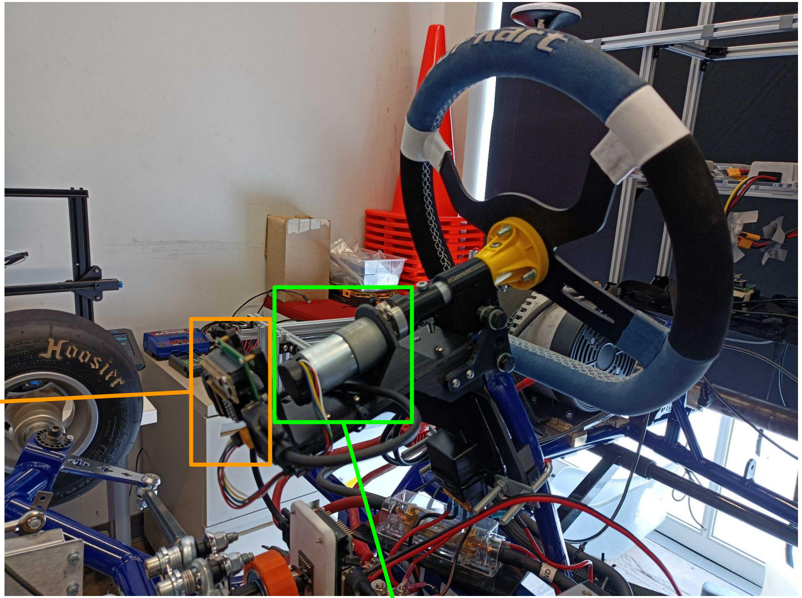
Modular Computing, Control and Sensing

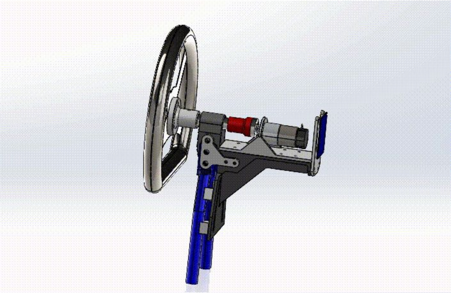


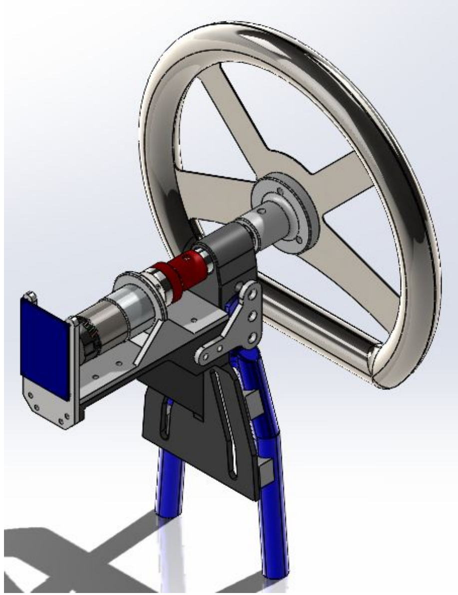
Upper-Steer-by-Wire System

Controls upper steering wheel and reads angle feedback







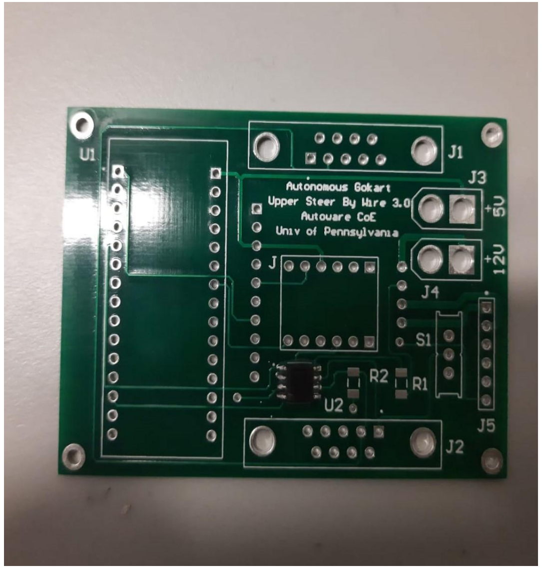


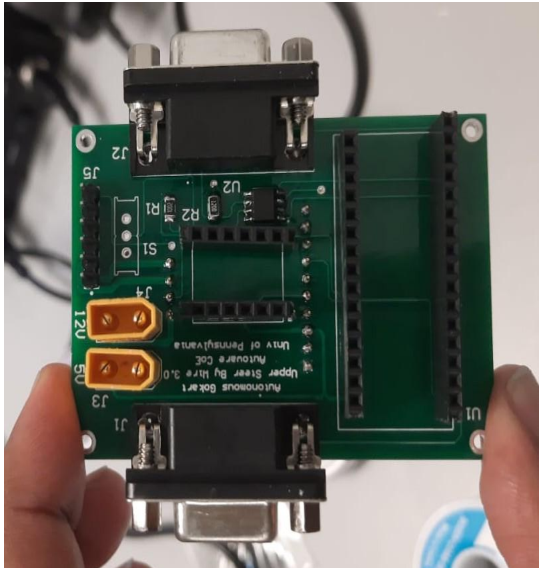
DC Motor Driver +
Nucleo L432KC Microcontroller

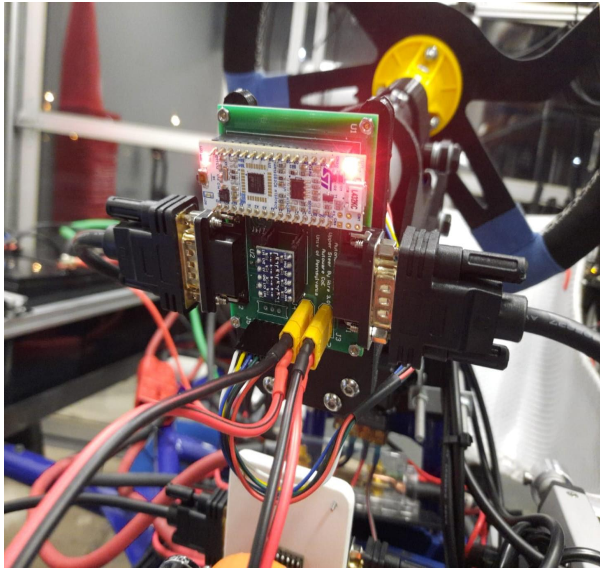
12V Pololu D37 Motor with 100:1 gear
(with built-in Quadrature Encoders)

Upper-Steer-by-Wire System PCB

The new board uses dual channel in-built rotary encoders instead of the previous single channel design. This will give us better resolution (64 counts per revolution).



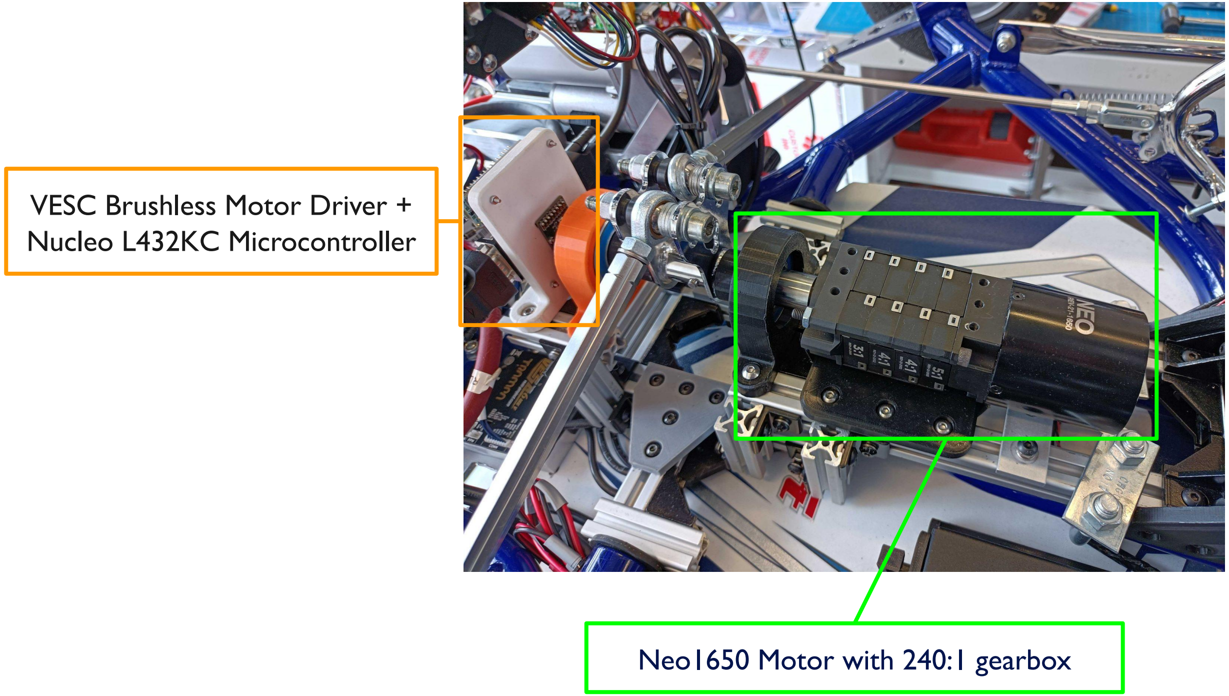


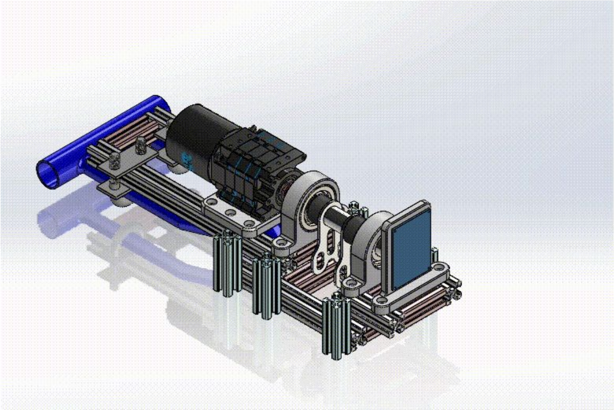


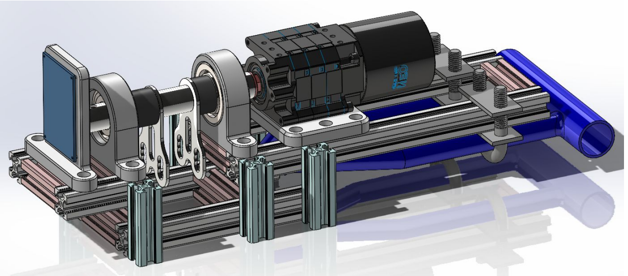
Test on Upper-Steer-by-Wire System

Lower-Steer-by-Wire System

Controls front wheels' steer angle and reads angle feedback







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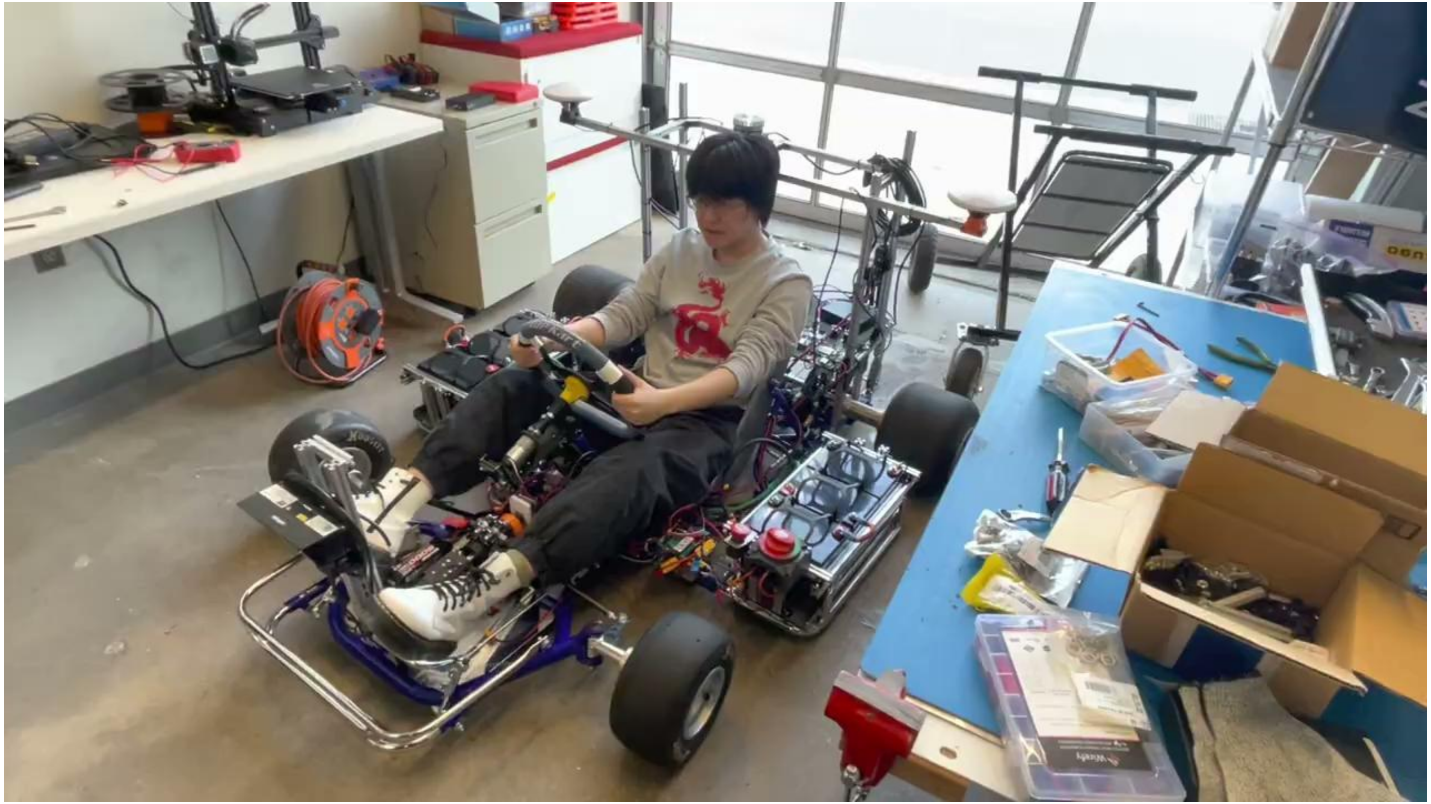
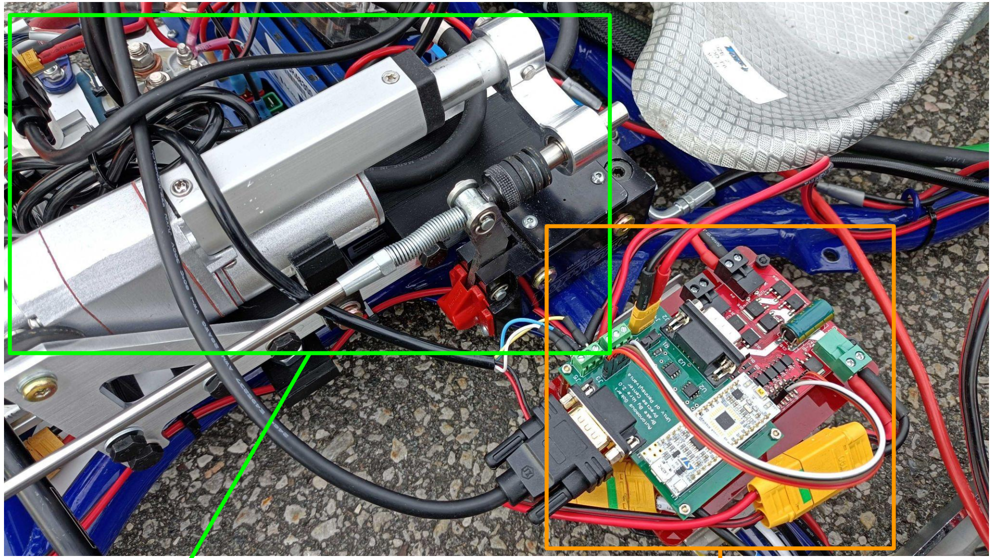
Test on Lower-Steer-by-Wire System

Test on Steer-by-Wire System (w Driver)



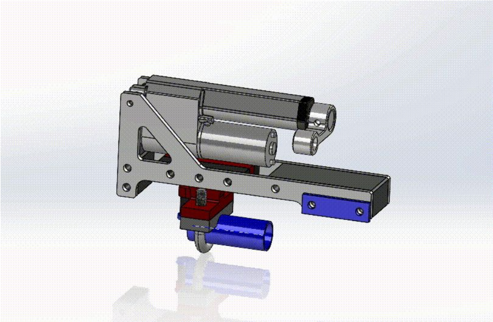
Brake-by-Wire System

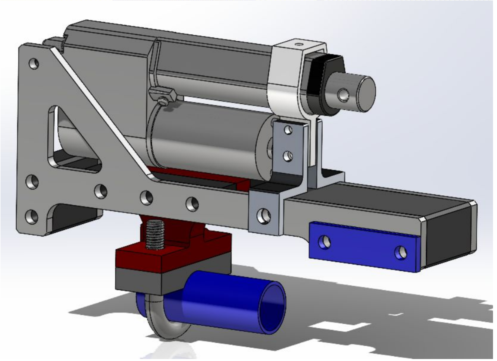
Uses linear actuator to control the brake lever



Progressive Automations 12V Linear Electric Actuator with Feedback (2 in. 50 lbs.)

DC Motor Driver + Nucleo L432KC Microcontroller





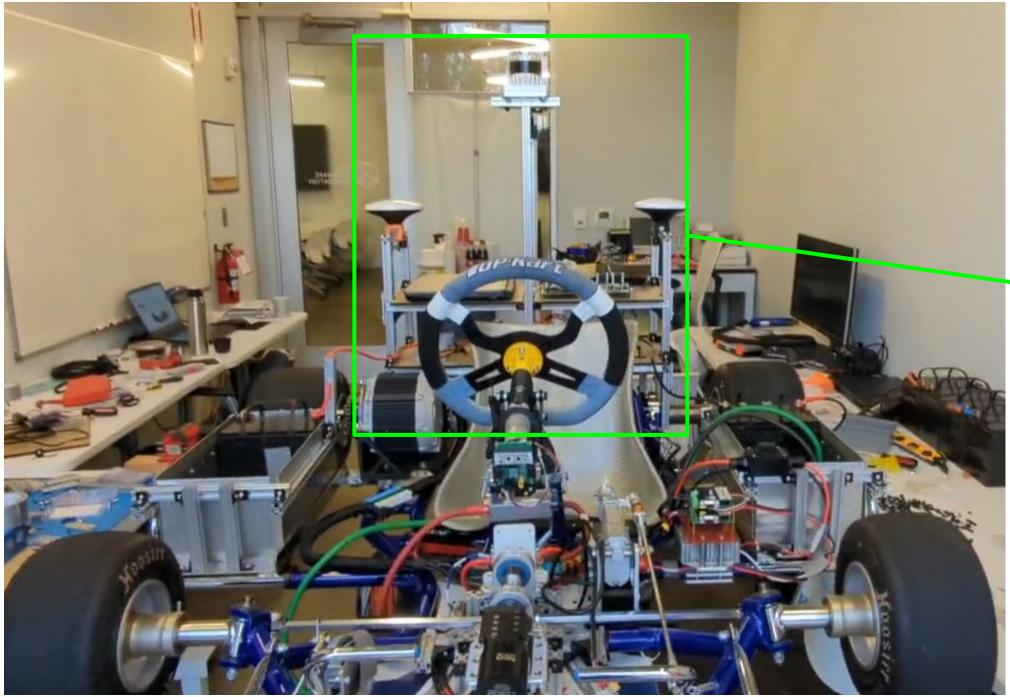
Brake-by-Wire Test

Braking Effect Demo

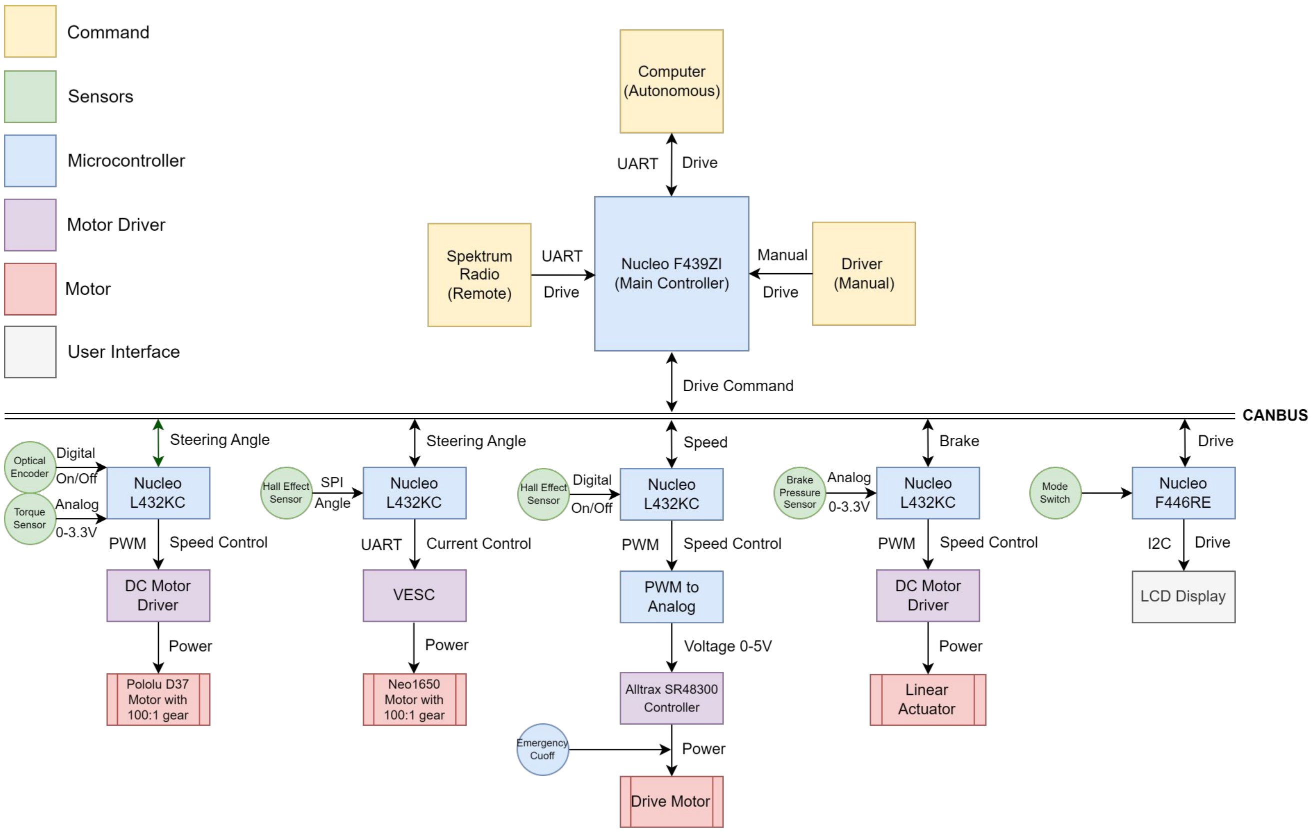
Actual Braking Performance

New Backshelf

The backshelf is being redesigned and reorganized to be more compact



Embedded System Overview

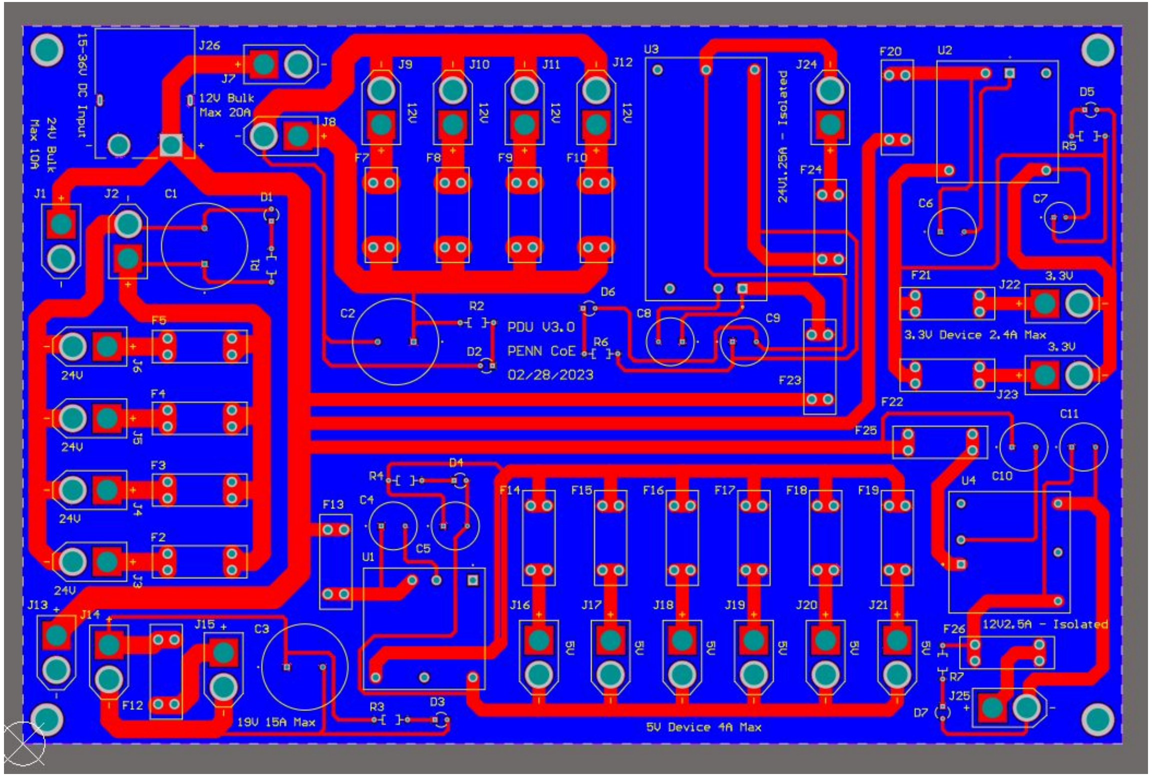


https://app.diagrams.net/#G1PSuZcL5JgvdFQtCdkjqXckcDYqRf3NHm

Power Distribution

Designed using the Altium Schematic and PCB Designer

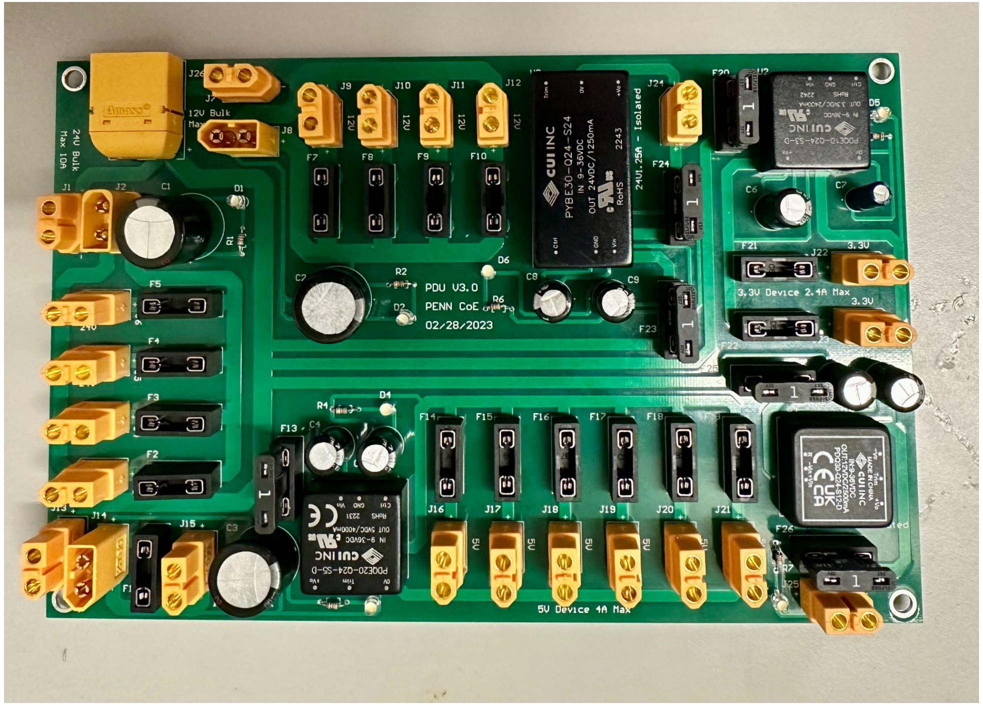
- Two 3.3v port (8w)
- Six 5 volt port (20w)
- Four 24 volt port (120w)
- Four 12 volt port (240w)
- One 19 volt port (280w)
- Isolated 12v Lidar port (30w)
- Isolated 24v Lidar port (30w)



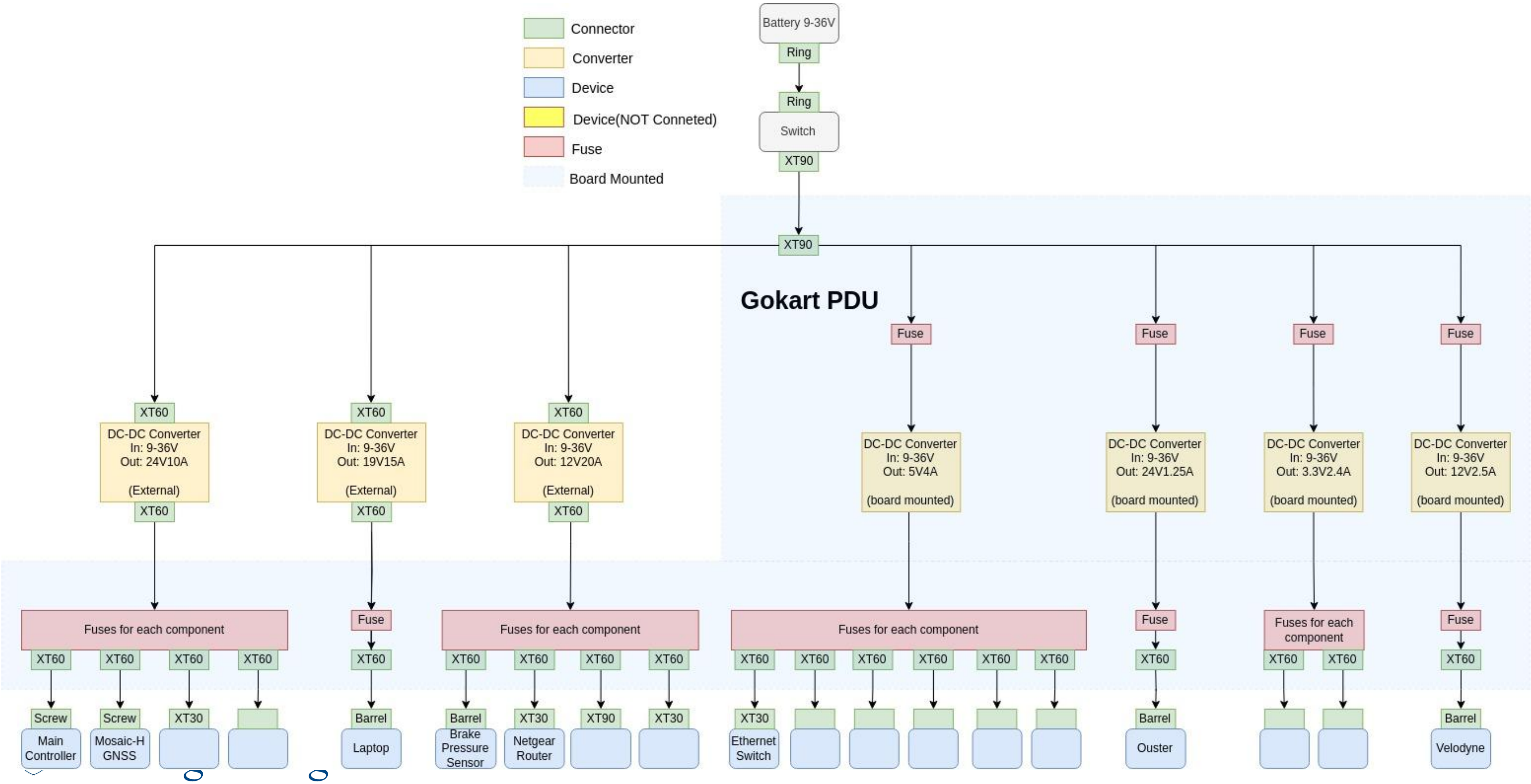
Power Distribution

Built through the manufacture PCBWay and soldered by hand

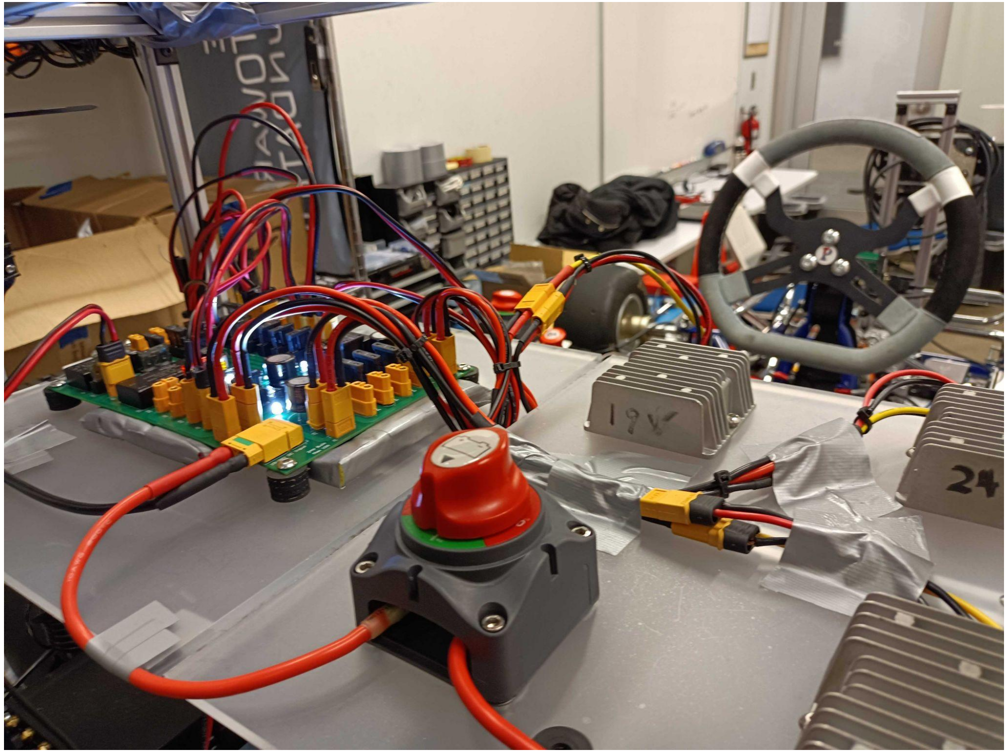
- Two 3.3v port (8w)
- Six 5 volt port (20w)
- Four 24 volt port (120w)
- Four 12 volt port (240w)
- One 19 volt port (280w)
- Isolated 12v Lidar port (30w)
- Isolated 24v Lidar port (30w)



AV4EV Go-kart 24V Power Systems



Power Distribution



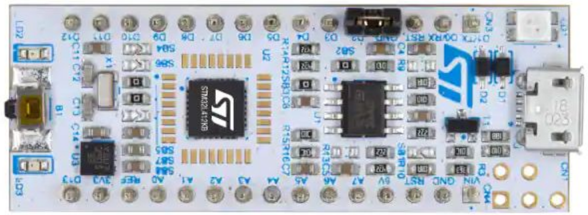
https://app.diagrams.net/#G11VlIgQhHJEyhvAOYIVJNIsCFi_-4VULb

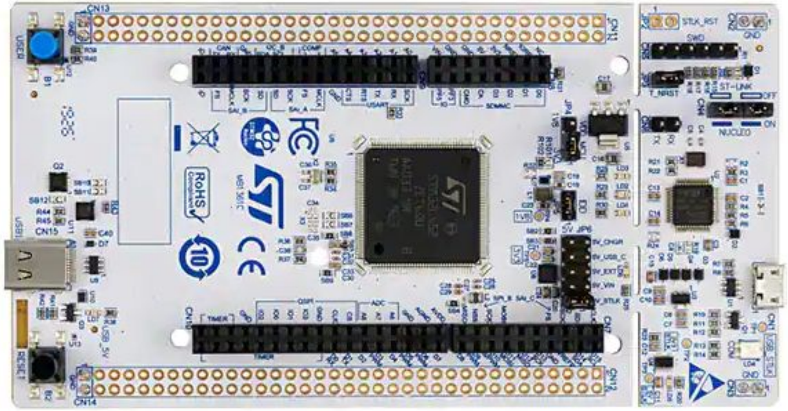
STM32 Microcontrollers (Nucleos)

STM32 is a family of 32-bit microcontroller integrated circuits by STMicroelectronics. The STM32 chips are grouped into related series that are based around the same 32-bit ARM processor core: Cortex-M0, Cortex-M0+, Cortex-M3, Cortex-M4, Cortex-M7, Cortex-M33.

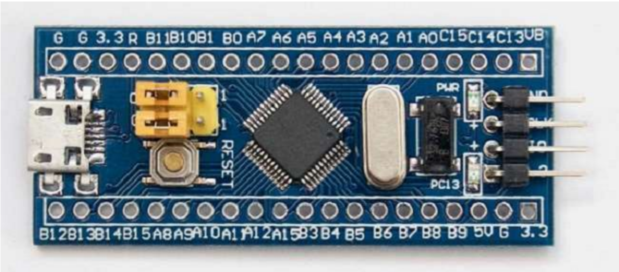
W Wikipedia
https://en.wikipedia.org › wiki › STM32

STM32 - Wikipedia





STM32 v.s. Arduino



		Uno	STM32 Blue Pill
General	Dimensions	2.08¨ x 0.9¨	4¨ x 2.1¨
	Pricing	$20-23	$3-5
Connectivity	I/O Pins	14	37
	PWM Pins	6	15
	Analog In Pins	6	10
	Analog Out Pins (DAC)	-	-
Computing	Processor	ATMega328P	STM32F103C8T6
	Flash Memory	32 kB	64 kB
	SRAM	2 kB	20 kB
	EEPROM	1 kB	-
	Clock speed	16 MHz	72 MHz
	Voltage Level	5V	3.3V
	USB Connectivity	Standard A/B USB	Micro-USB
Communication	Hardware Serial Ports	1	3
	SPI Support	Yes (1x)	Yes (2x)
	CAN Support	No	Yes
	I2C Support	Yes (1x)	Yes (2x)

Controller Area Network (CAN)

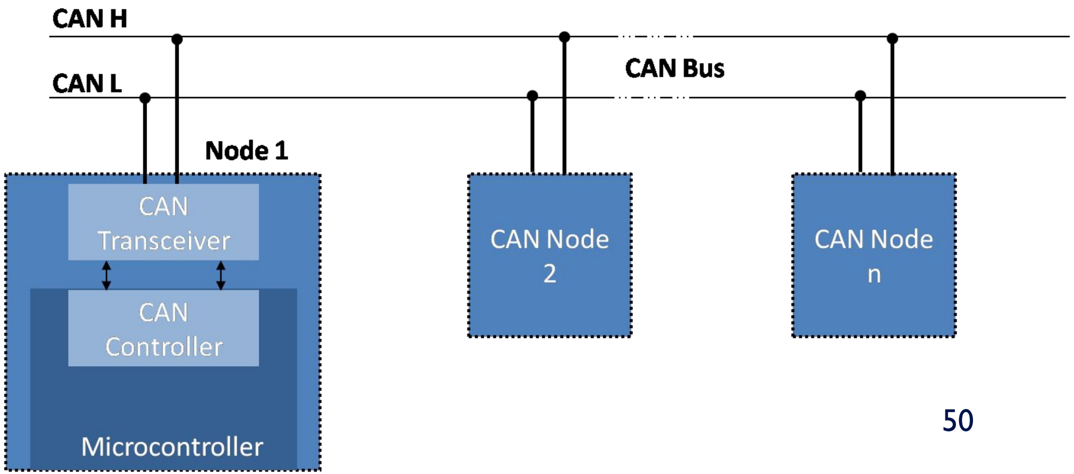
The Controller area network or CAN protocol is a method of communication between electronic devices embedded in a vehicle, such as the engine-management systems, active suspension, central locking, air conditioning, airbags, etc.

EG Engineers Garage
https://www.engineersgarage.com › can-protocol-underst...

CAN protocol: Understanding the controller area network

We use CAN bus as the standard communication proposal for our go-kart. It connects all subsystems and is very reliable.

D-Sub9 Conenctor



Remote Control

In Stock

15 Reviews

DX6e 6-Channel DSMX Transmitter Only

Spektrum - SPMR6655

$249.99

- Virtually unlimited model memory-transmitter stores up to 250 models and only populates the model list with models the user has configured
- Airplane, Helicopter, Sailplane and Multirotor programming
- Built-In Telemetry
- Cross-platform model sharing with other Spektrum transmitters

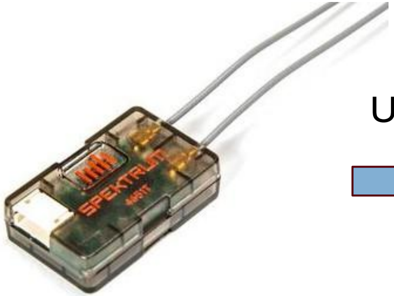
Complete your product

This product may require additional items in order to work out of the box. See below for required items that may be needed to complete.

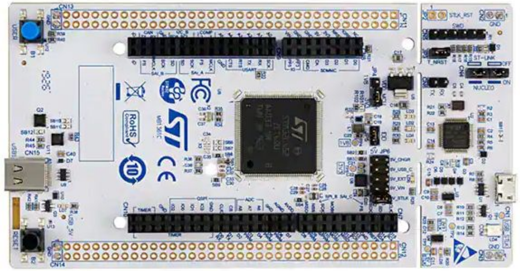
1. Receivers x1

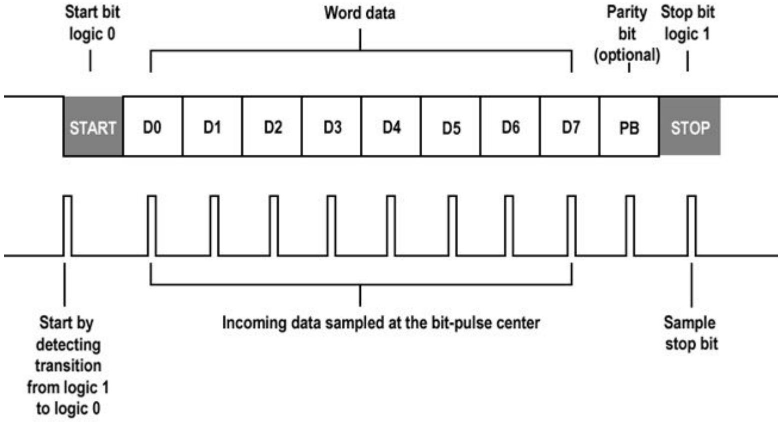
Remote Control

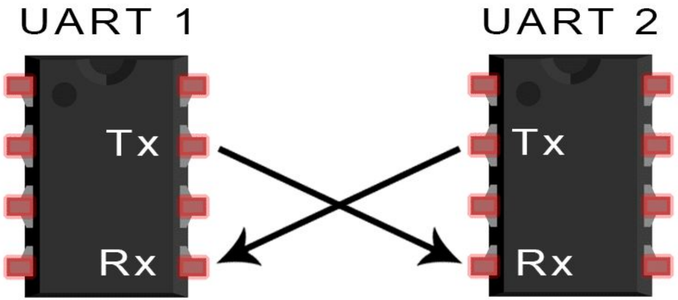
Radio 2.4GHz



UART







User Interface Board

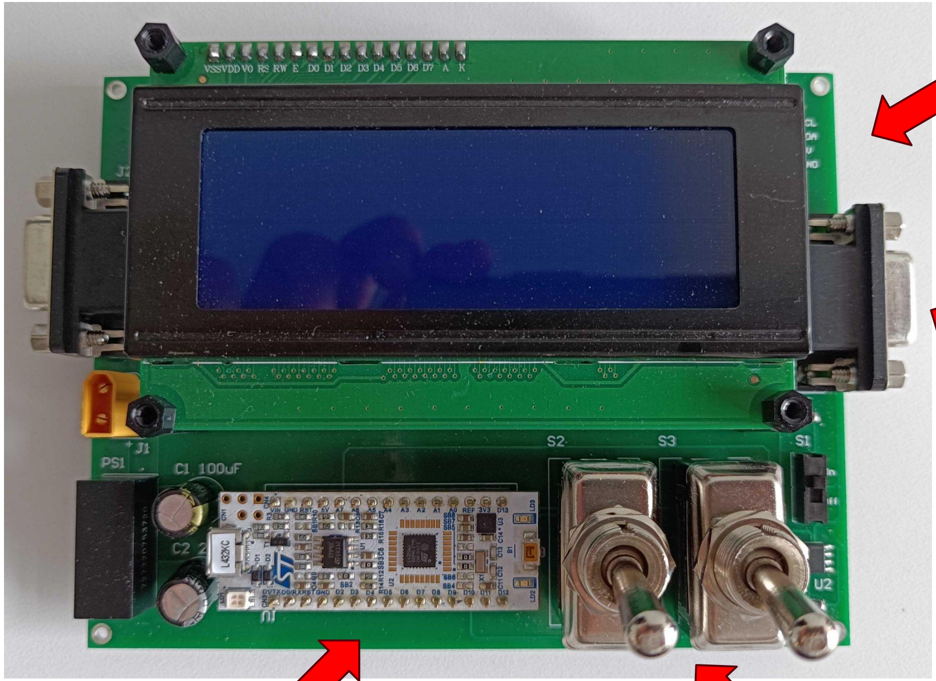
CAN Bus In (D-Sub9)

LCD Display (I2C)

Power In (XT30)

CAN Bus Out (D-Sub9)

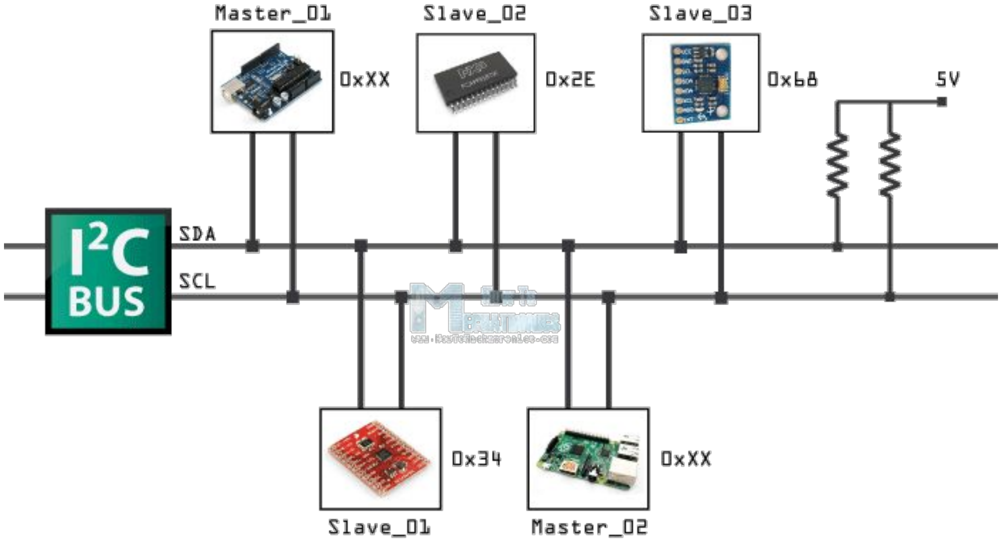
DC-DC Converter



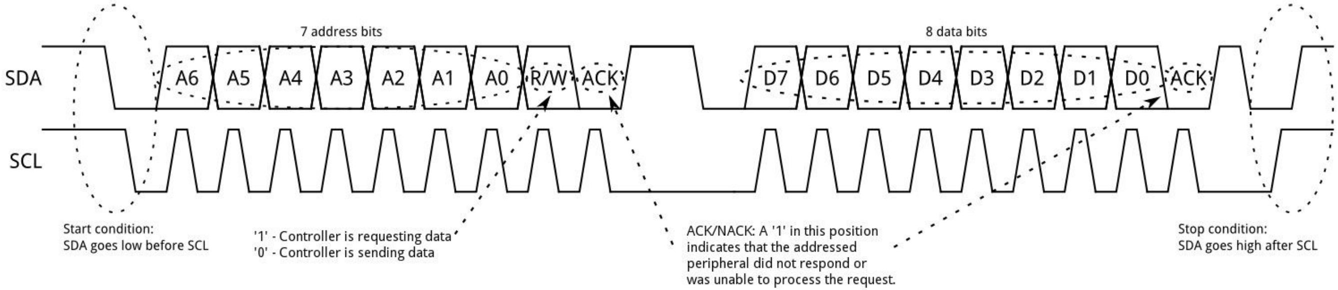
Nucleo L432KC (Controller)

Mode Switch (Digital Input)

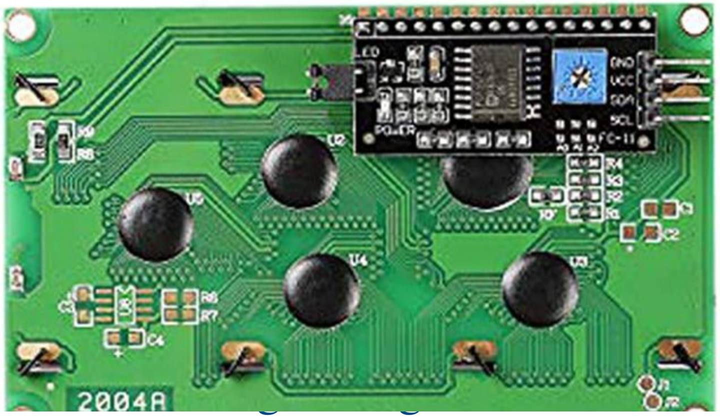
LCD I2C



I2C, alternatively known as I2C or IIC, is a synchronous, multi master /multi slave (controller/target), packet switched, single ended, serial communication bus invented in 1982 by Philips Semiconductors.



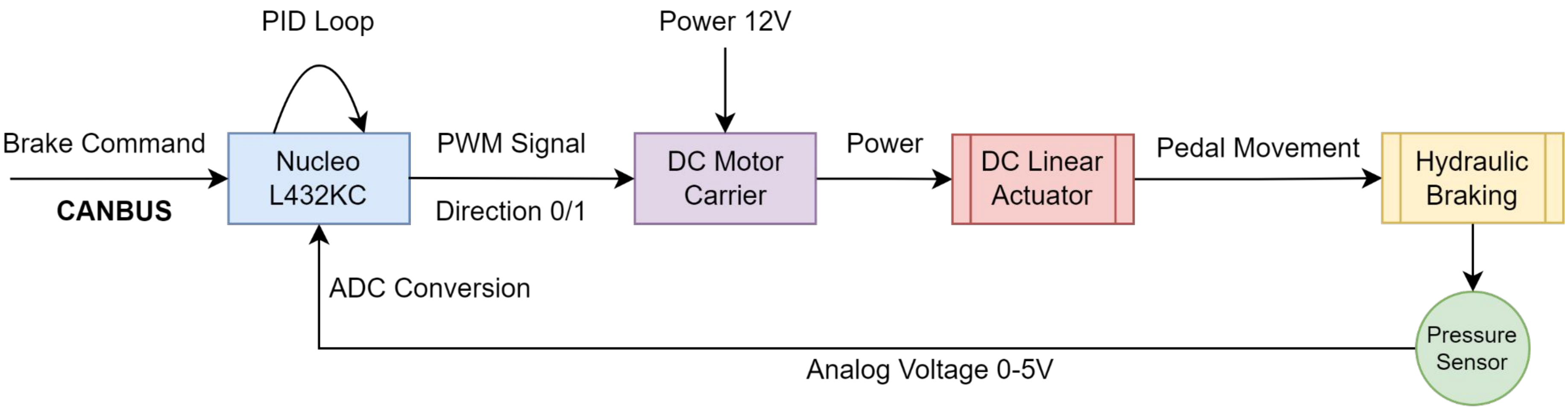
LCD I2C



A standard LCD requires **over ten connections**, which can be a problem if your microcontroller does not have many GPIO pins available. If you happen to have an LCD without an I2C interface incorporated into the design, these can be easily acquired separately.

An I2C LCD advantage is that wiring is straightforward, **requiring only two data pins** to control the LCD.

Motor Control (Brake)

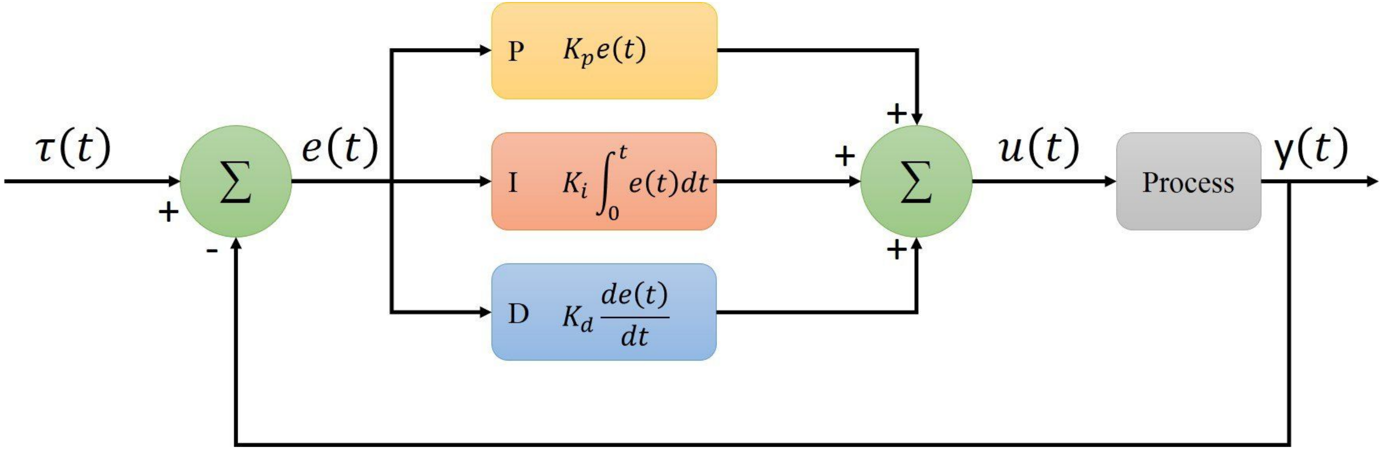


What we used for this subsystem: **CAN Communication, PWM Signal, Analog-Digital Conversion, Digital Output, Closed-Loop PID Control**

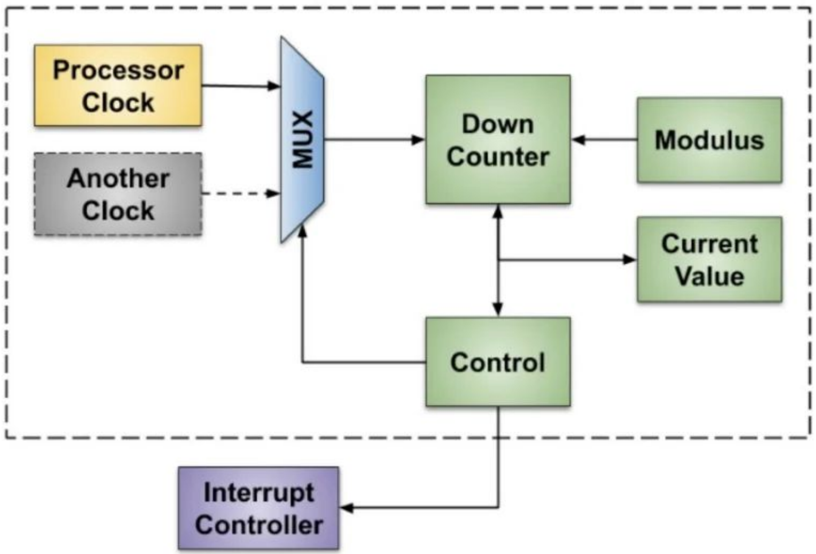
Interrupt

How do I update my system at a fixed frequency (30Hz, 50Hz, 100Hz)? For example, I need to know the exact time elapsed for my PID controller to work.

One way to do it is to use a **Timer Interrupt**



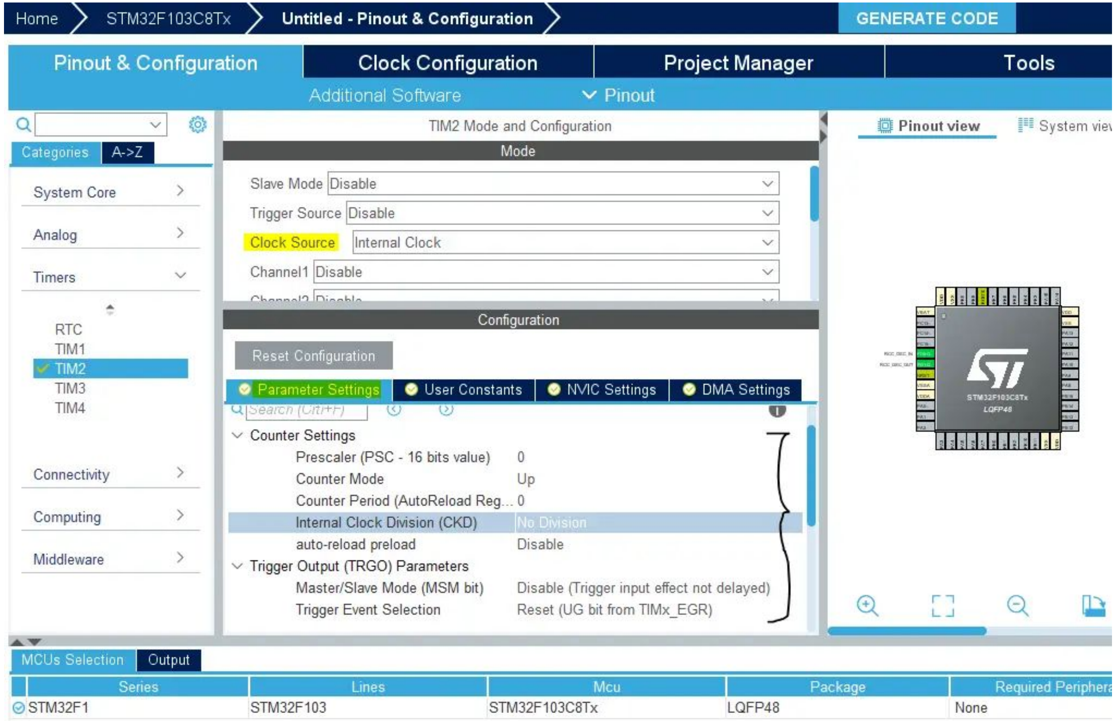
Interrupt



A timer interrupt **occurs when a down counting timer reaches 0 and reloads the modulus in the main counter**. The timer sends a hardware signal to an “interrupt controller” which suspends execution of the main program and makes the processor jump to a software function called an “interrupt service routine” or ISR.

Timer interrupts allow you to perform a task at very specifically timed intervals **regardless of what else is going** on in your code.

Interrupt



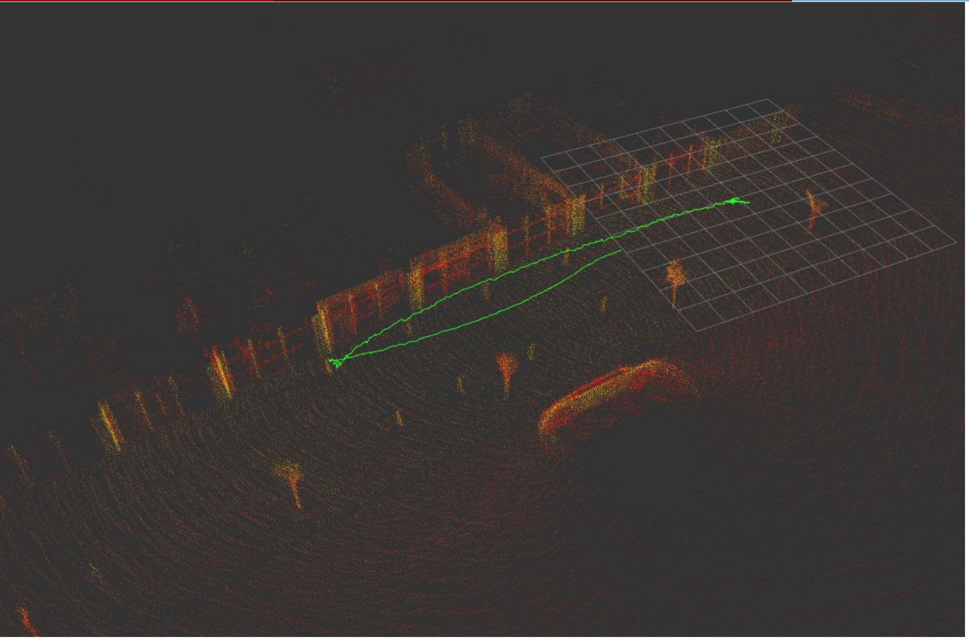
Timer Interrupt for Nucleos

1. Configure the clock speed
2. Set a prescaler to scale down the frequency
3. Set the internal count

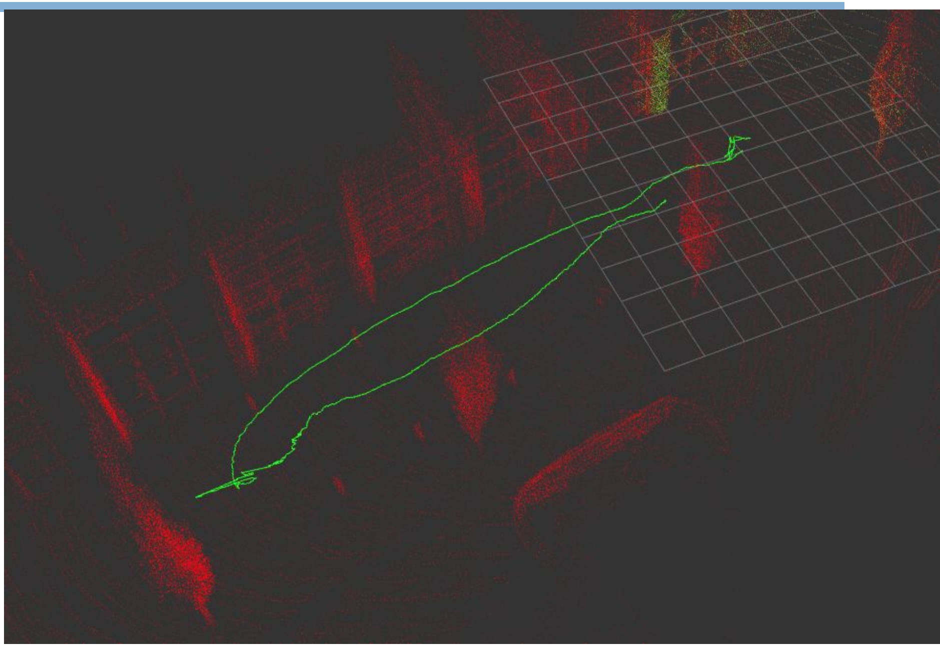
This requires some calculation!

https://www.youtube.com/watch?v=VfbW6nfG4kw

SLAM in ROS2 with NDT

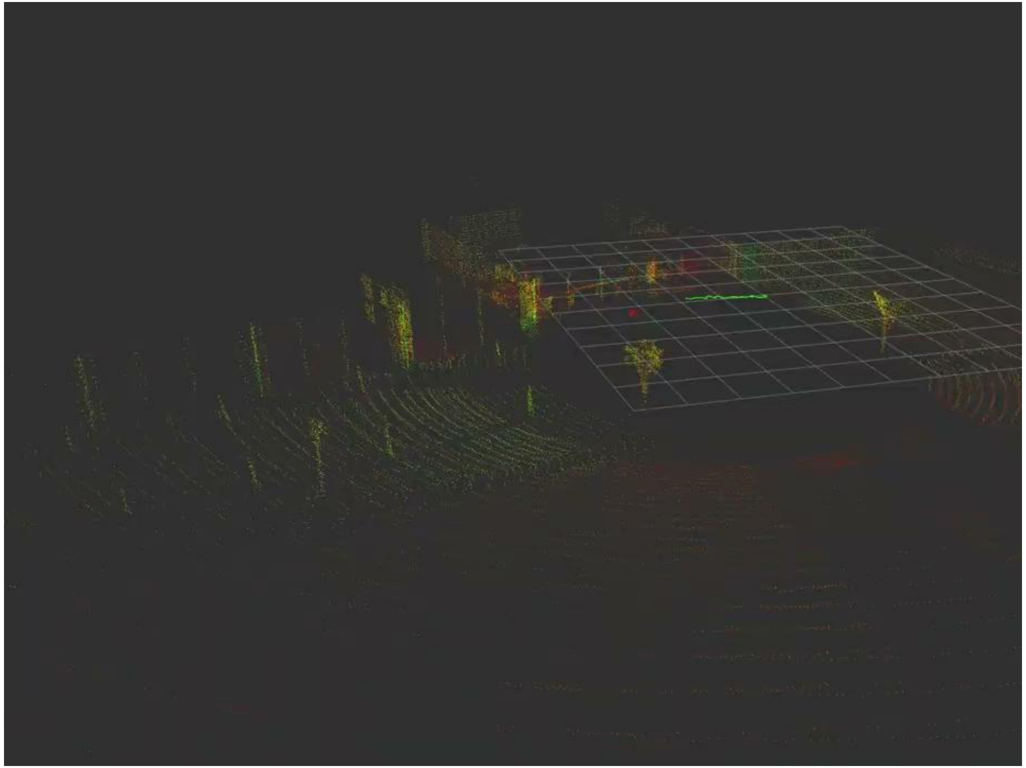


With Ouster



With Velodyne

SLAM in ROS2 with NDT

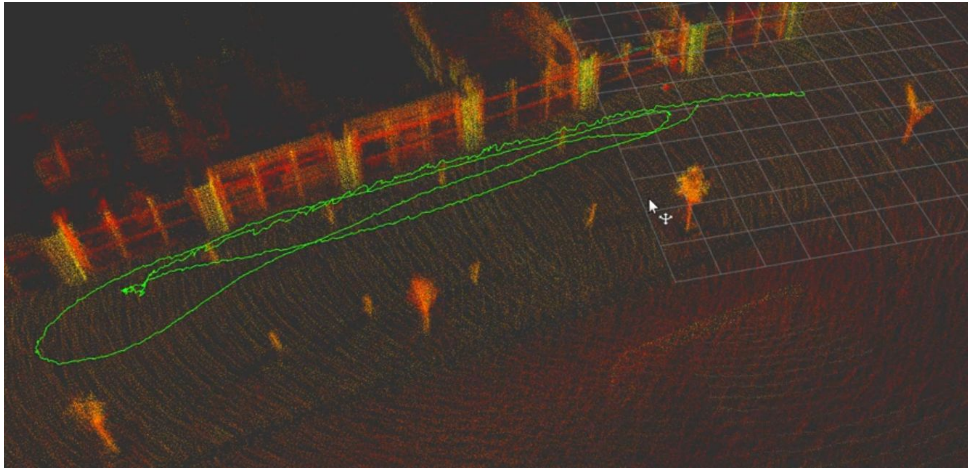


Penn Engineering

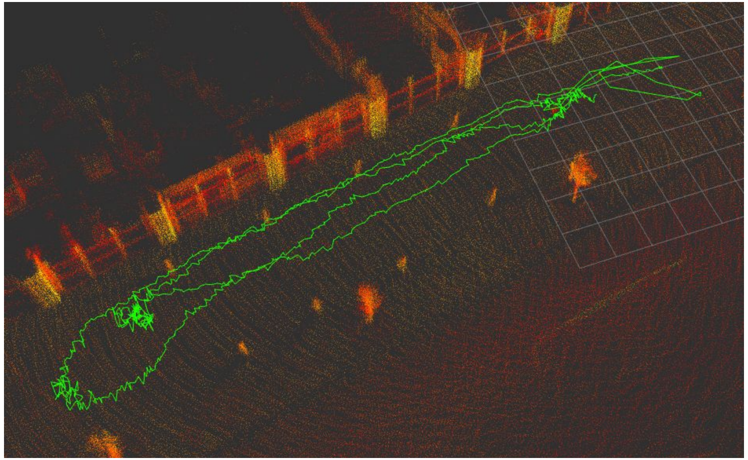
Localization in ROS2

Scan matching

- Pure 3D scan matching(test with open-source lib from Autoware) supports real time dev (roughly test 10~20 hz)
- IMU, Odometry and GNSS can be combined later



SLAM path



PCL localization Path

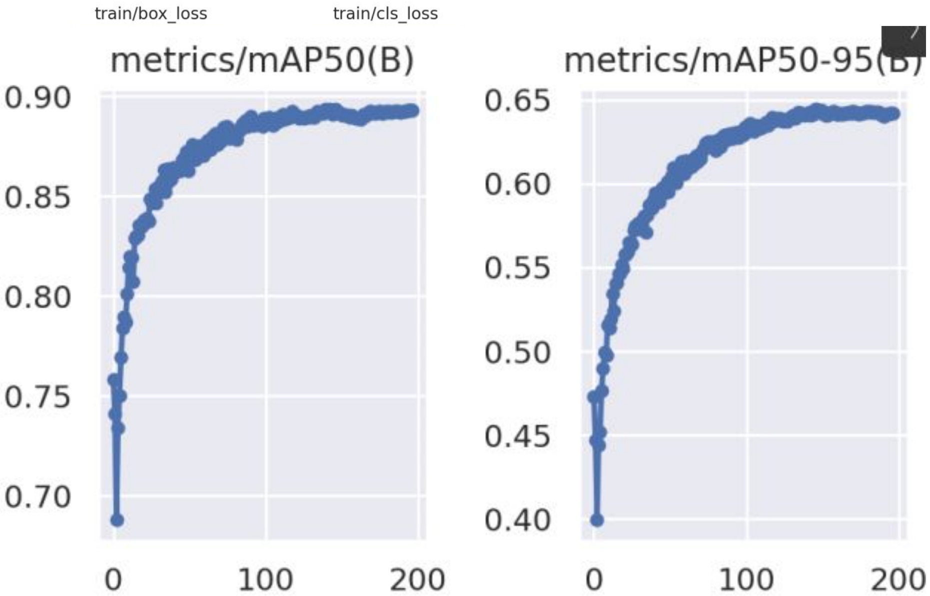
Object detection in Ros2-Yolov8

Model:Yolov8(yolov8-small, 22mb), trained in the roboflow cone dataset

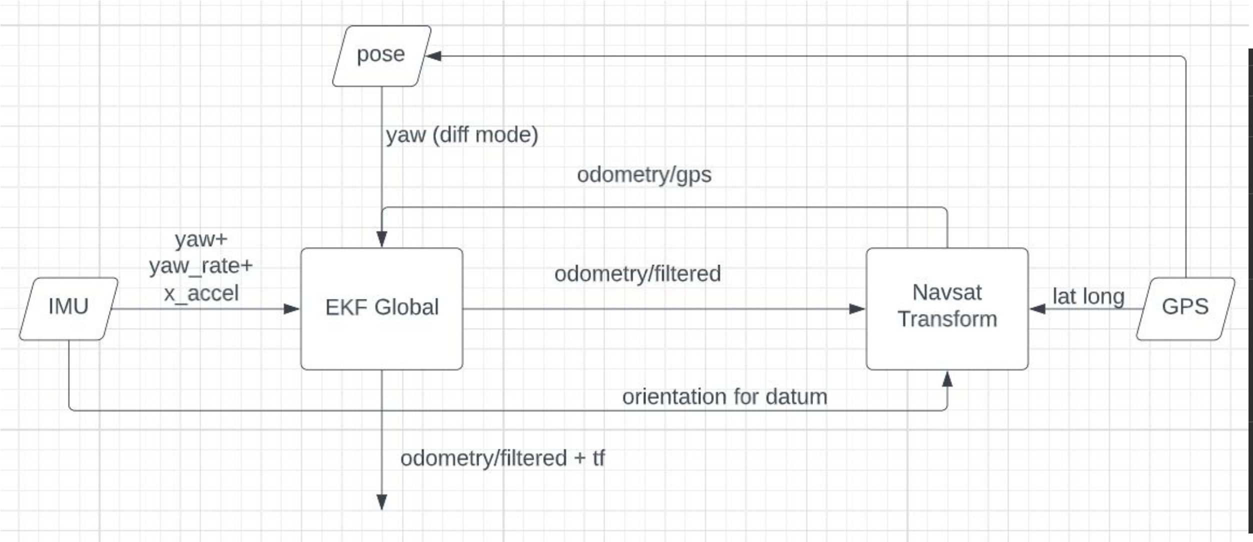
Training: 167 epochs with early stop(50 epochs no improvement), easy to train in server

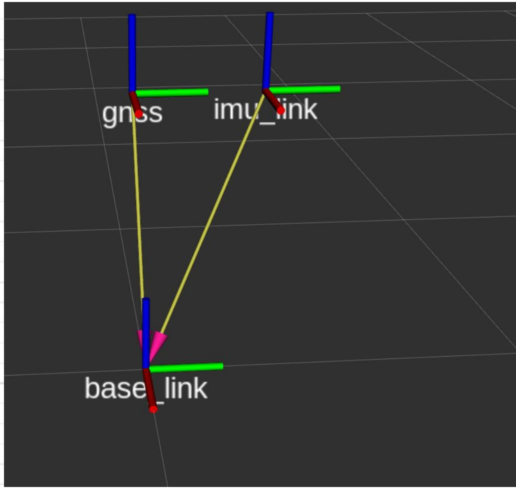
Ros2 node: currently a ros2 wrapper to load the .pt model and inference with python

As quick as the camera published(10~20hz) Can consider further optimization

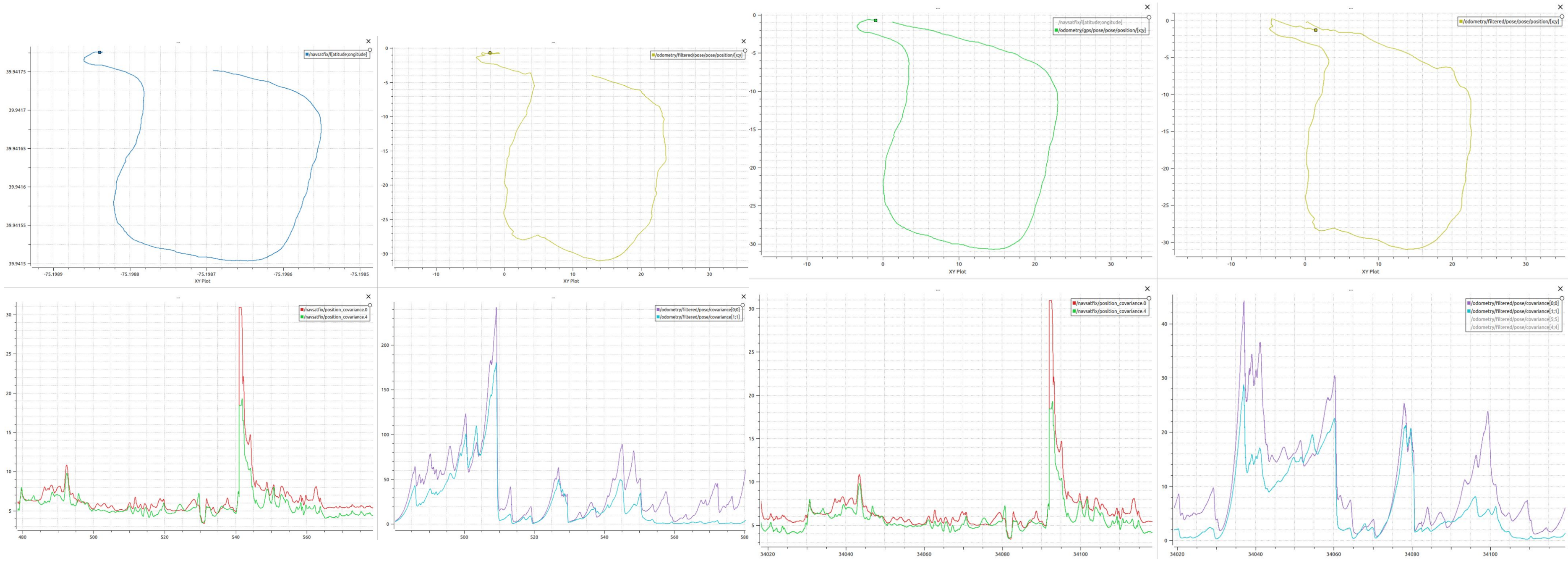


Pose Estimation Architecture

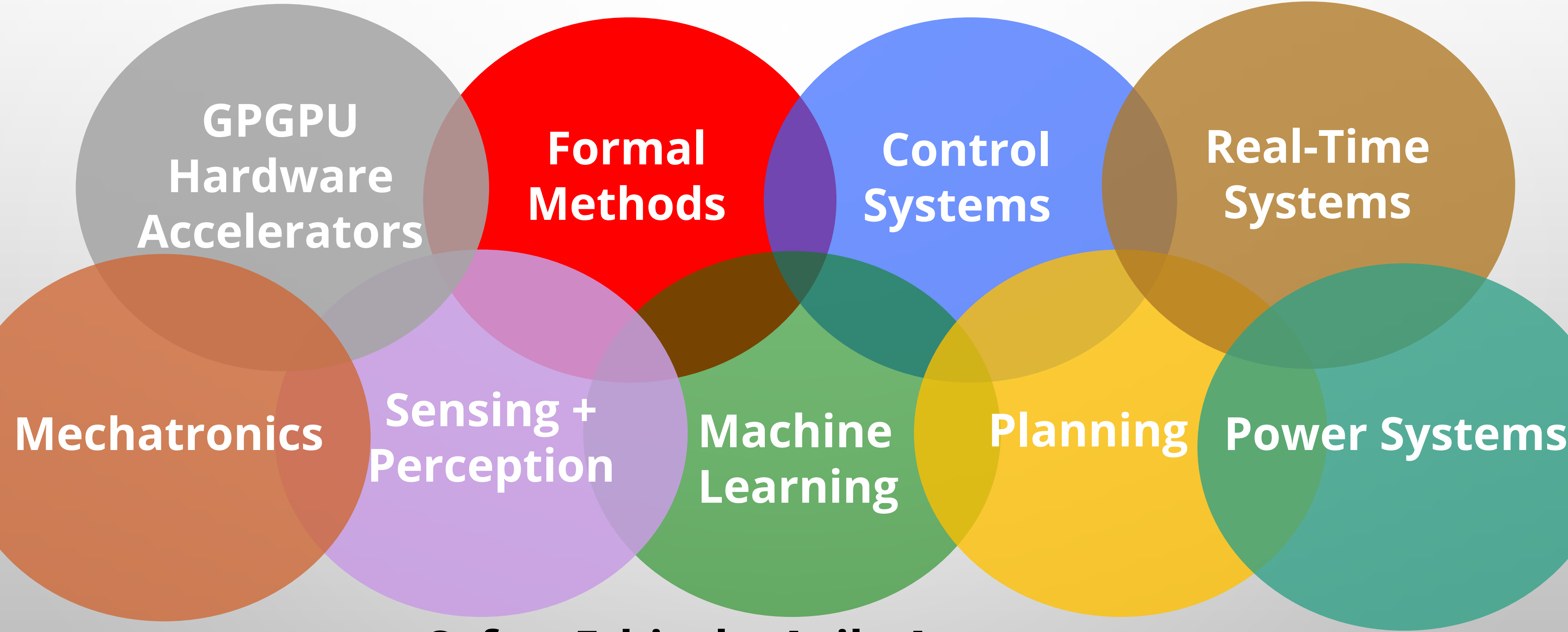




Fusion with GPS + IMU + Pose



Multi-Disciplinary R&D to develop Autonomous Systems



Safe + Ethical + Agile Autonomy

Complex Integrated Systems Engineering with well-defined modules

AV4EV Summary

A successful go-kart requires innovative ideas and relentless effort. It is also a great project and research opportunity.

Join the AV4EV Team!

Building Safe Autonomous Systems

ESE3500 Past Project Highlights:

Prof. Rahul Mangharam
Director, Autoware Center of Excellence
Penn Director, Mobility21 DoT UTC
rahulm@seas.upenn.edu

April 04, 2023

Penn Engineering

ESE3500 Legacy

PivotBoard

Hawkin Hockey

Shadow Hand

RC Paraglider