MAD76 Installation

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Contents

1 Installation Overview

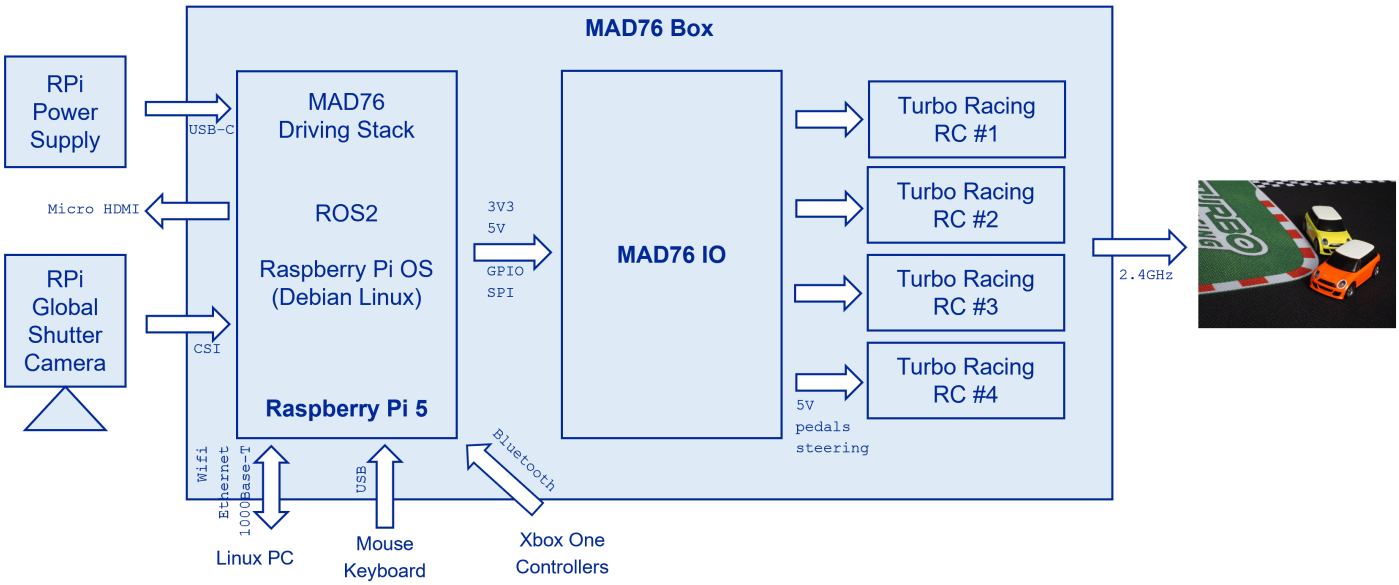

Figure 1: MAD76 System Architecture

The installation steps are:

- Build the MAD76 Box including the MAD76 IO PCB (see Section 2)
- Install Raspberry Pi OS, drivers, and ROS2 (see Section 3)
- Optionally install ROS2 on optional Linux-PC for distributed computing and software-in-the-loop (SiL) simulation (see Section 4)
- Install MAD76 Driving Stack (see Section 5)
- Optionally install MATLAB/Simulink for model-based software engineering (see Section 6)

2 MAD76 Box

The MAD76 Box is a self-built housing for the MAD76 electronics containing

- Raspberry Pi (RPi)
- MAD76 IO: self-built PCB electronics for coupling RPi to remote controllers (RC) for the Turbo Racing cars
- Up to 4 RC cars are supported

This section first lists the bill of materials (BOM) for the MAD76 Box. Then the MAD76 IO is described in more detail.

2.1 Bill of Materials (BOM)

2.1.1 Raspberry Pi and Camera

	Description	Part Id	Order Link
1	Raspberry PI 5 B 8GB Black Bundle	RPI5 BBDL 8GB	https://www.reichelt.de/das-raspberry-pi-5-b-8gb-black-bundle-rpi5-bbdl-8gb-p362348.html
1	microSD-Card 128 GB		https://www.rasppishop.de/Sandisk-microSDHC-UHS-I-128GB-Class10-mit-Raspberry-Pi-OS
1	Raspberry Pi Active Cooler	RASP ACTIVE COOL	https://www.reichelt.de/raspberry-pi-luefter-fuer-raspberry-pi-5-rasp-active-cool-p360116.html
1	Raspberry Pi Global Shutter Camera, 1.6MP, C/CS mount	RASP CAM GS CS	https://www.reichelt.de/raspberry-pi-kamera-1-6mp-shutter-c-cs-fassung-rasp-cam-gs-cs-p345205.html
1	Raspberry Pi Lens, CS mount, 6mm wideangle	RPIZ CAM 6MM WW	https://www.reichelt.de/raspberry-pi-objektiv-fuer-cs-fassung-6mm-weitwinkel-rpiz-cam-6mm-ww-p276922.html
1	AZDelivery Flex Cable 50cm, compatible to Raspberry Pi Zero Camera		https://www.amazon.de/AZDelivery-Flexkabel-Raspberry-Zero-Display/dp/B07SQ3HKNF
1	Joby GorillaPod 3K Kit Tripod		https://www.foto-erhardt.de/stative/joby-gorillapod/joby-gorillapod-3k-kit-black-charcoal.html

Table 1: BOM of Raspberry Pi and camera

2.1.2 MAD76 IO

	Description	Part Id	Order Link
1	Platine, Epoxyd, doppelseitig, 300x200mm	EP2CU 300X200	https://www.reichelt.de/de/de/shop/produkt/platine_epoxyd_doppelseitig_300_x_200_mm-7404
4	MCP42010 10kOhm DIL-14	MCP 42010-I/P	https://www.reichelt.de/digitalpoti-2-kanal-256-schritte-10-kohm-dil-14-mcp-42010-i-p-p90112.html
1	L293B 1A DIP-16	L 293 B	https://www.reichelt.de/push-pull-4-kanal-treiber-1a-dip-16-l-293-b-p9660.html
4	14-poliger DIL-Socket	GS 14P	https://www.reichelt.de/ic-sockel-14-polig-superflach-gedreht-vergold--gs-14p-p8207.html
1	16-poliger DIL-Socket	GS 16P	https://www.reichelt.de/ic-sockel-16-polig-superflach-gedreht-vergold--gs-16p-p8209.html
4	Wannenstecker, 10-polig, gerade	WSL 10G	https://www.reichelt.de/wannenstecker-10-polig-gerade-wsl-10g-p22816.html
1	Wannenstecker, 40-polig, gewinkelt	WSL 40W	https://www.reichelt.de/wannenstecker-40-polig-gewinkelt-wsl-40w-p22836.html
6	SMD-Kondensator 100nF	KEM X7R0805 100N or X7R-G0805 100N or WAL 0805B104K500	https://www.reichelt.de/de/de/shop/produkt/vielschicht-kerko_100nf_50v_125_c-207073
4	SMD-Kondensator 10uF	X5R-G0805 10/16 or KEM 0805 10U-2	https://www.reichelt.de/de/de/shop/produkt/smd-vielschichtkondensator_g0805_-_10_f_16v-89734

Table 2: BOM of MAD76 IO PCB

2.1.3 Housing

	Description	Part Id	Order Link
1	Industriegehäuse, 250x160x90mm, IP65, lichtgrau	5U340000	https://www.reichelt.de/industriegehaeuse-250-x-160-x-90-mm-ip65-lichtgrau-5u340000-p324394.html
1	40-poliges Flachbandkabel 30cm	RPI GPIO40 300	https://www.reichelt.de/raspberry-pi-gpio-kabel-40-pin-30cm-grau-rpi-gpio40-300-p293579.html
4	Pfostenverbinder 2,54mm 2x5 (Flachbandkabel)	BKL 10120668	https://www.reichelt.de/de/de/shop/produkt/pfostenverbinder_2_54mm_2x5-262790
1	sourcing map 20Stk. M2,5x8mm+5mm Stecker Buchse Messing PCB Motherboard Abstandhalter Ständer		https://www.amazon.de/gp/product/B08G1TP68G
1	300 Stück M2.5 Schrauben Set M2.5 Hex Flach-Knopf Schraube Set, A2 Edelstahl Innensechskantschrauben Schraubensortiment		https://www.amazon.de/gp/product/B08B648WWQ
8	JST-Buchsengehäuse, 1x3-polig	JST PH3P BU or 571-440129-3	https://www.reichelt.de/jst-buchsengehaeuse-1x3-polig-ph-jst-ph3p-bu-p185042.html https://www.mouser.de/ProductDetail/571-440129-3
24	JST-Crimpkontakt, Buchse or 2.0mm, Crimp Contact Cut Strip of 100	JST PH CKS or 571-1735801-1-CT	https://www.reichelt.de/de/de/shop/produkt/jst_-_crimpkontakt_buchse_-_ph-185072 https://www.mouser.de/ProductDetail/TE-Connectivity-AMP/1735801-1-Cut-Strip?qs=oXydCMRm13w8Ga1ULORh6A%3D%3D

Table 3: BOM of MAD76 Box housing

2.1.4 Turbo Racing Cars

	Description	Part Id	Order Link
1 to 4	Turbo Racing 1:76 Mini Cooper with RC https://www.turboracing.net/		https://www.rcfox.de/TB-TR01-Turbo-Racing-1/76-Micro-Mini-Cooper https://de.aliexpress.com/item/1005001936818767.html
1	Turbo Racing Mat Track 50x95cm		https://www.rcfox.de/TB-760101-Turbo-Racing-Race-Strecke-fuer-Micro-Rally-50x95-cm https://de.aliexpress.com/item/1005006267808509.html

Table 4: BOM of Turbo Racing cars

2.2 MAD76 IO

- MAD76 IO is the bridge from RPi to the Turbo Racing RCs.
- MAD76 IO controls up to 4 cars.
- MAD76 IO substitutes and emulates the two potentiometers for throttle/braking and steering by digital potis (MCP42010) for each car.
- MAD76 further provides the power supply of 5V for the RCs.
- The power supply is controlled individually for each RC by an L293B.
- The RPi controls the digital potis via SPI.
- The RPi controls the L293B via GPIO.
- The MAD76 IO is connected to the RPi via a standard RPi 40-pin GPIO cable.
- The MAD76 IO is connected to the RCs via 8-pin flat ribbon cables.

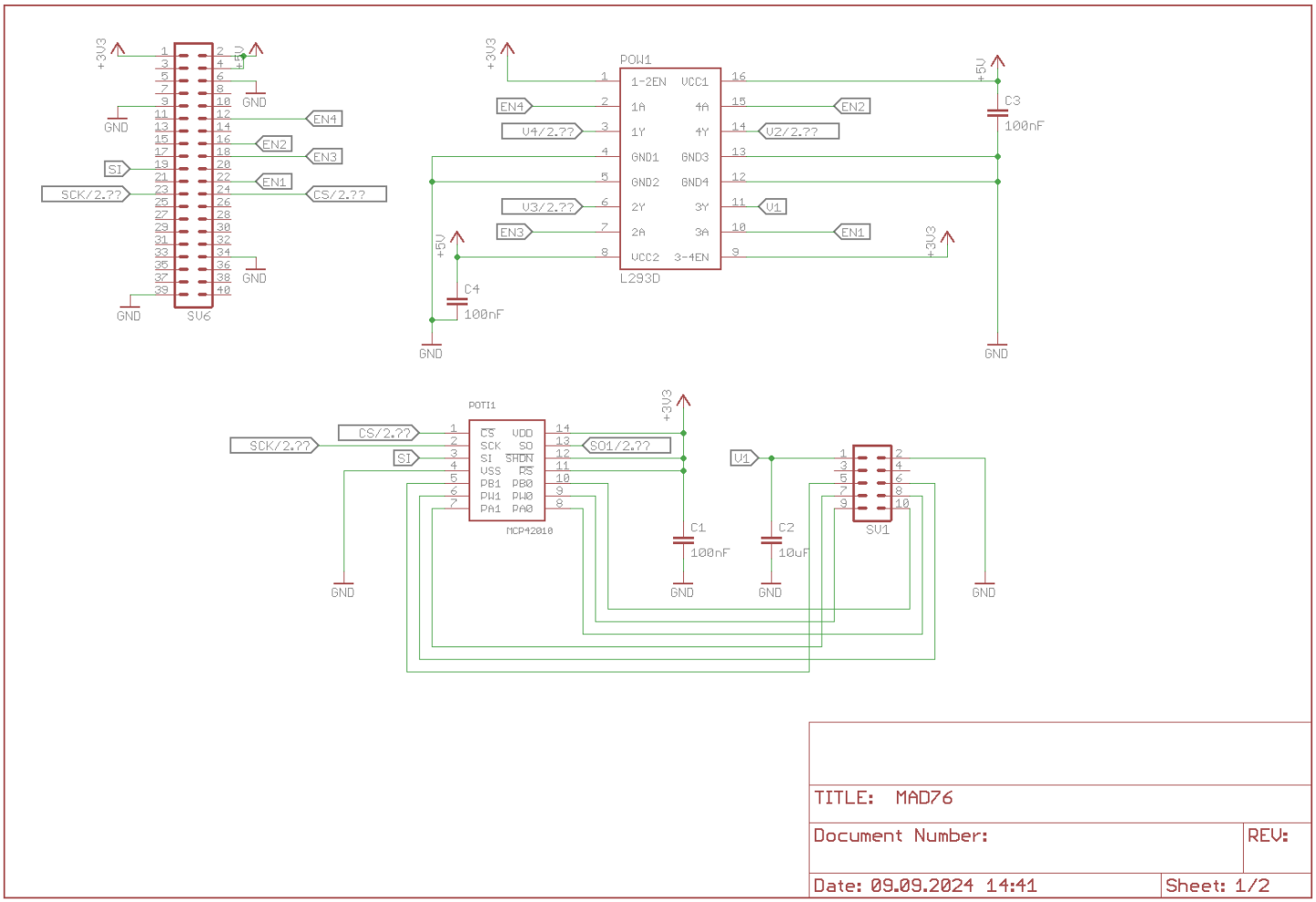

Figure 2: MAD76 IO Schematics Page 1 (Eagle schematics `../../pcb/MAD76.sch`)

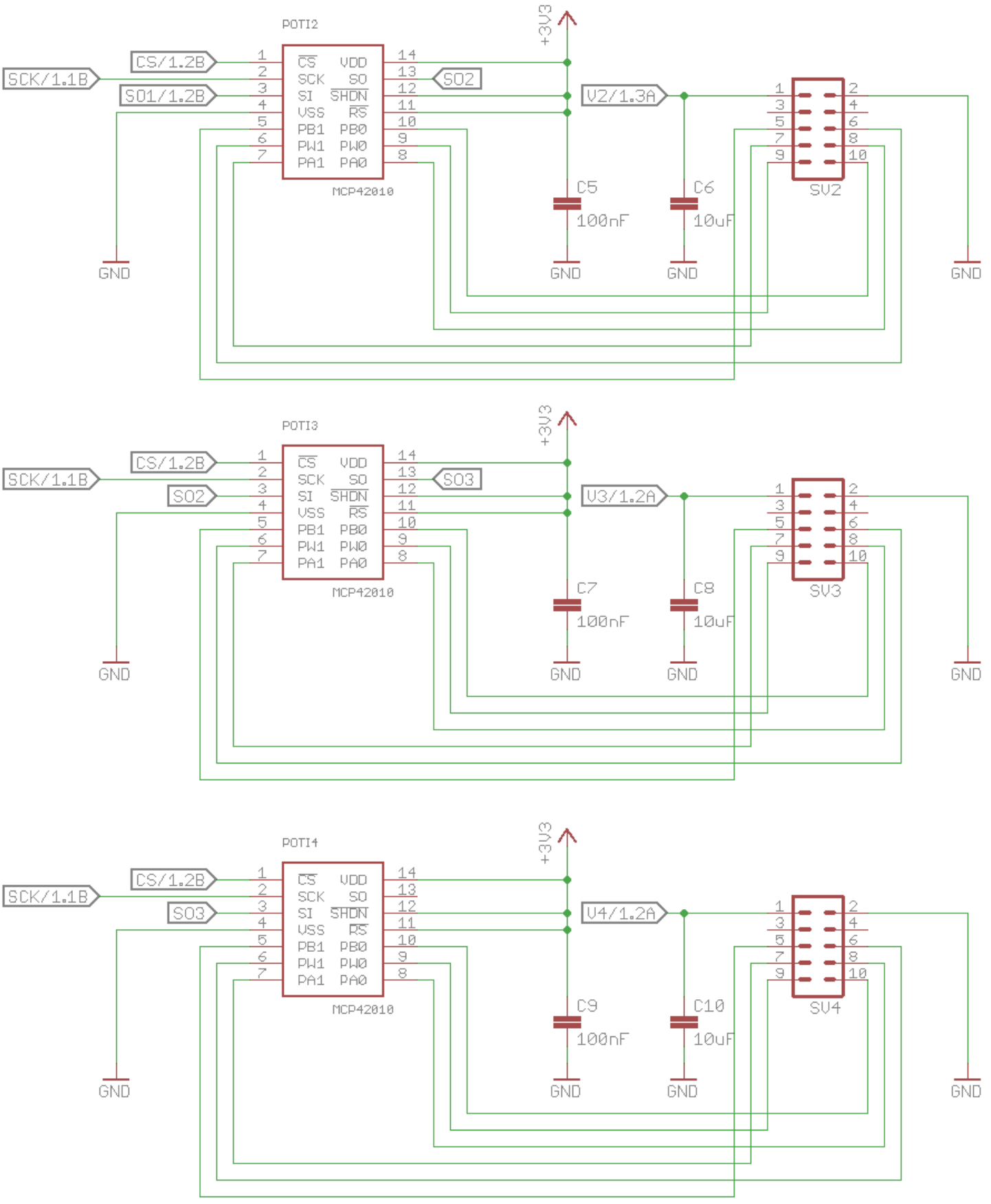

Figure 3: MAD76 IO Schematics Page 2 (Eagle schematics `../../pcb/MAD76.sch`)

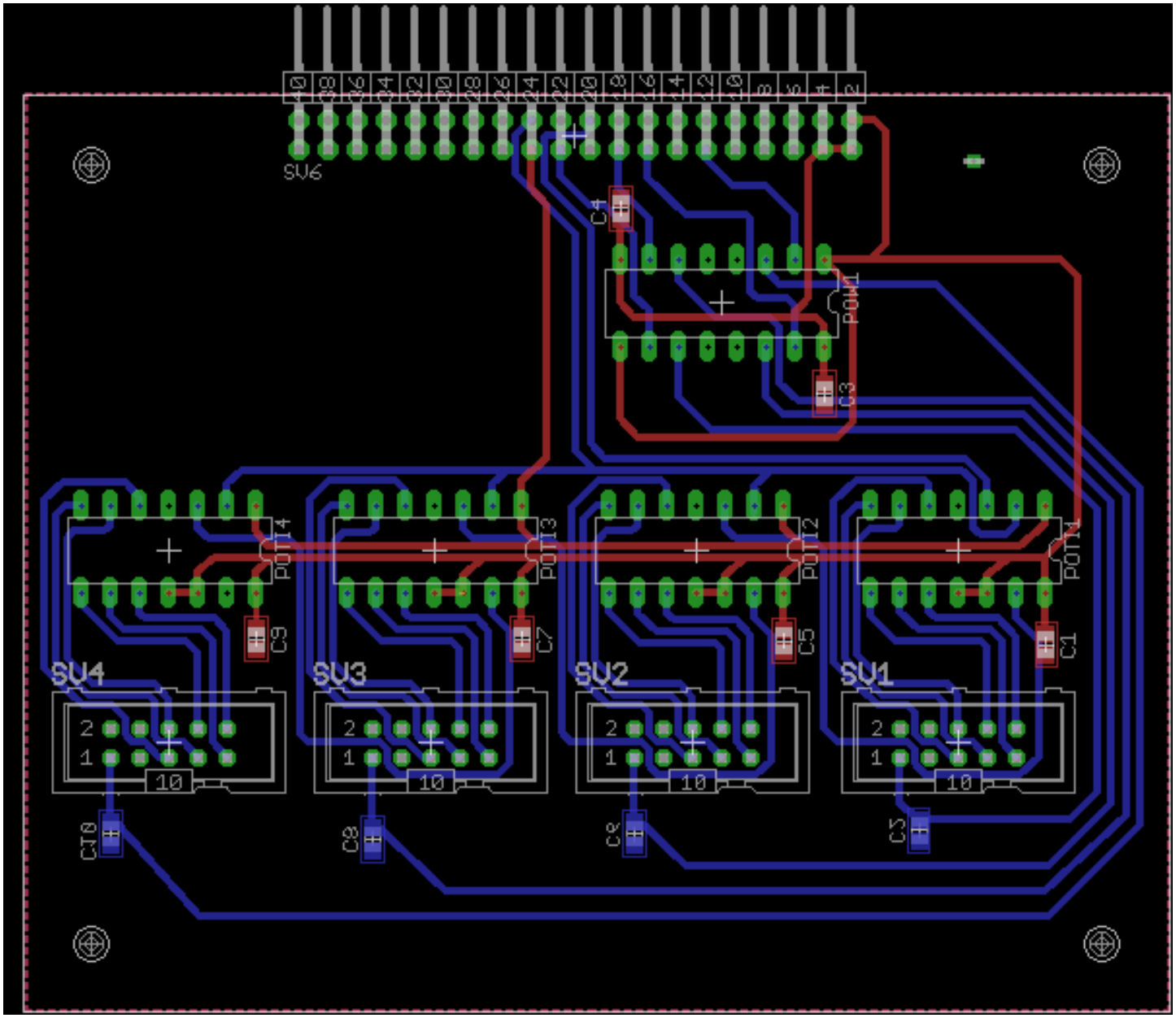

Figure 4: MAD76 IO Board Layout (Eagle layout `../../pcb/MAD76.brd`)

3 Raspberry Pi Installation

3.1 Raspberry Pi OS

- Download and start installer [2]
  - Rasberry Pi OS with desktop (Debian 12 Bookworm 64-bit)
  - Configure `<username>`
  - Configure `<hostname>`
  - Configure WiFi
  - Enable SSH
- Login: `ssh <username>@<hostname>`
- Update Debian

```
sudo apt-get update
sudo apt-get dist-upgrade
# reboot in case of kernel/firmware updates
sudo shutdown -r 0
```

3.2 Raspberry Pi Configuration

- Enable SPI for MAD76 IO
  - `sudo raspi-config`
  - Goto menu `3 Interface Options`
  - Select `I4 SPI`

3.3 VNC Server

VNC Server allows you to remotely connect to the Raspberry Pi from your development PC, either Linux, Windows or MacOS.

- Remove RealVNC

```
sudo apt-get purge realvnc-vnc-server
```

- Install VNC server

```
sudo apt-get install tigervnc-standalone-server
sudo apt-get install tigervnc-xorg-extension
```

- Start VNC server

```
vncserver -localhost no -geometry 2550x1350 -depth 24
```

- Connect to VNC server from your VNC client: `<hostname>:1`
- TightVNC on Windows or Remmina on Linux are popular VNC clients.

3.4 Python Coding

```
sudo apt-get purge python3-rpi.gpio # remove GPIO library for RPi4
sudo apt-get install python3-rpi-lgpio # install GPIO library for RPi5
sudo apt-get install python3-ipykernel # install Jupyter kernel
sudo apt-get install python3-sphinx # install Sphinx for code documentation
```

3.5 WiringPi

WiringPi is a GPIO library for C / C++ programming that is used to access the MAD76 IO board.

- Install WiringPi for MAD76 IO

```
cd
mkdir src
cd src
git clone https://github.com/WiringPi/WiringPi.git
cd WiringPi
./build
```

3.6 ROS2

ROS2 is the middleware for the MAD76 software stack.

- ROS2 Jazzy Jalisco is required. No other ROS2 distribution is supported because of compatibility to both Debian Bookworm and MATLAB/Simulink R2025a.
- Building ROS2 Jazzy Jalisco from source [3, 4]

```
mkdir -p ~/src/ros2_jazzy/src
cd ~/src/ros2_jazzy

locale # check for UTF-8

sudo apt-get install \
  build-essential \
  cmake \
  git \
  python3-colcon-bash \
  python3-pip \
  vcstool \
  wget

sudo apt-get install sqlite3
sudo apt-get install python3-lark python3-netifaces
sudo apt-get install python3-flake8-blind-except python3-flake8-builtins python3-flake8-
    class-newline python3-flake8-comprehensions python3-flake8-deprecated python3-flake8-
    import-order python3-flake8-quotes python3-pytest-repeat python3-pytest-rerunfailures
sudo apt-get install python3-rosdep2 python3-vcstools
sudo apt-get install python3-opencv python3-scipy python3-matplotlib
sudo apt-get install python3-flask python3-peewee
sudo apt-get install libbullet-dev libboost-dev
```

```
sudo apt-get install libasio-dev libtinyxml2-dev
sudo apt-get install qtbase5-dev qtbase5-dev-tools
sudo apt-get install libacl1-dev libcap-dev libssl-dev libxaw7-dev libogre-1.12-dev
    libeigen3-dev
sudo apt-get install libopencv-dev
sudo apt-get install liblttng-ust-dev
sudo apt-get install libboost-python-dev libboost-system-dev libboost-log-dev libgtest-
    dev libjsoncpp-dev
sudo apt-get install netcat-openbsd netcat-openbsd

wget https://raw.githubusercontent.com/ros2/ros2/jazzy/ros2.repos
vcs import src < ros2.repos

rosdep update
rosdep install --from-paths src --ignore-src --rosdistro jazzy -y --skip-keys "rti-
    connext-dds-6.0.1 python3-vcstool"

touch src/eclipse-cyclonedds/COLCON_IGNORE
touch src/eclipse-iceoryx/COLCON_IGNORE
touch src/gazebo-release/COLCON_IGNORE
touch src/ros2/rviz/COLCON_IGNORE
touch src/ros2/rmw_connextdds/COLCON_IGNORE
touch src/ros2/rmw_cyclonedds/COLCON_IGNORE

colcon build --symlink-install --cmake-args -DCMAKE_BUILD_TYPE=Release
```

- Install ROS2 packages for camera, diagnostics, and Xbox controller

```
sudo apt-get install libcamera-dev
source ~/src/ros2_jazzy/install/setup.bash
mkdir -p /src/ros_ws/src
cd ~/src/ros_ws/src
git clone https://github.com/ros/diagnostics.git -b ros2-jazzy
git clone https://github.com/ros-perception/vision_opencv.git -b rolling
git clone https://github.com/christianrauch/camera_ros -b main
git clone https://github.com/ros-drivers/joystick_drivers -b ros2
touch joystick_drivers/ps3joy/COLCON_IGNORE
touch joystick_drivers/spacenav/COLCON_IGNORE
touch joystick_drivers/wiimote/COLCON_IGNORE
touch joystick_drivers/wiimote_msgs/COLCON_IGNORE
cd ..
colcon build --symlink-install --cmake-args -DCMAKE_BUILD_TYPE=Release
```

3.7 Update ROS2

If you want to update ROS2 later on, you can do the following.

- Update ROS2 distribution

```
cd ~/src/ros2_jazzy
vcs custom --args remote update
vcs import src < ros2.repos
```

```
vcs pull src
colcon build --symlink-install --cmake-args -DCMAKE_BUILD_TYPE=Release
```

- Update ROS2 packages for camera and diagnostics

```
cd ~/src/ros_ws/src
cd diagnostics
git pull
cd ../vision_opencv
git pull
cd ../camera_ros
git pull
cd ../joystick_drivers
git pull
cd ../..
source ~/src/ros2_jazzy/install/setup.bash
colcon build --symlink-install --cmake-args -DCMAKE_BUILD_TYPE=Release
```

3.8 Xbox One Controllers

Optionally, Xbox One controllers can be used to manually control the MAD76 cars in car racing mode.

- Enable Bluetooth Low Energy (BLE) privacy, so that Xbox One controllers can be paired to Raspberry Pi
  - Add line `Privacy=device` to the `[General]` section of `/etc/bluetooth/main.conf` according to `https://www.reddit.com/r/linux_gaming/comments/js0trh/comment/gddwyjk/`
- Follow the instructions on `https://pimylifeup.com/xbox-controllers-raspberry-pi/`

4 Linux-PC Installation

Next to the Raspberry Pi installation, MAD76 may be further installed optionally on a Linux PC. The Linux PC allows for more efficient MAD76 software development and debugging. Furthermore, MAD76 may be run in Software-in-the-Loop (SiL) simulation mode on the Linux PC. MATLAB/Simulink may be applied for model-based software engineering of MAD76. For controlling the real MAD76 system, The MAD76 software stack may be run on a distributed ROS2 environment including the Raspberry Pi and the Linux PC.

- Install an Ubuntu Desktop version that supports ROS2 Jazzy Jalisco, such as Ubuntu Noble Numbat 24.04 [1]. ROS2 Jazzy Jalisco (and no other ROS2 version) is required, otherwise distributed computing with PC and Raspberry Pi will not work.
- However, if you only want to run MAD76 in Software-in-the-Loop (SiL) simulation mode only, you may use other ROS2 and Linux distributions.
- Install ROS2 Jazzy Jalisco binary (deb) packages according to [5]. Make sure to install the following ROS2 packages:

```
sudo apt-get install ros-dev-tools ros-jazzy-desktop ros-jazzy-diagnostic-updater
```

5 MAD76 Driving Stack

5.1 Software Architecture

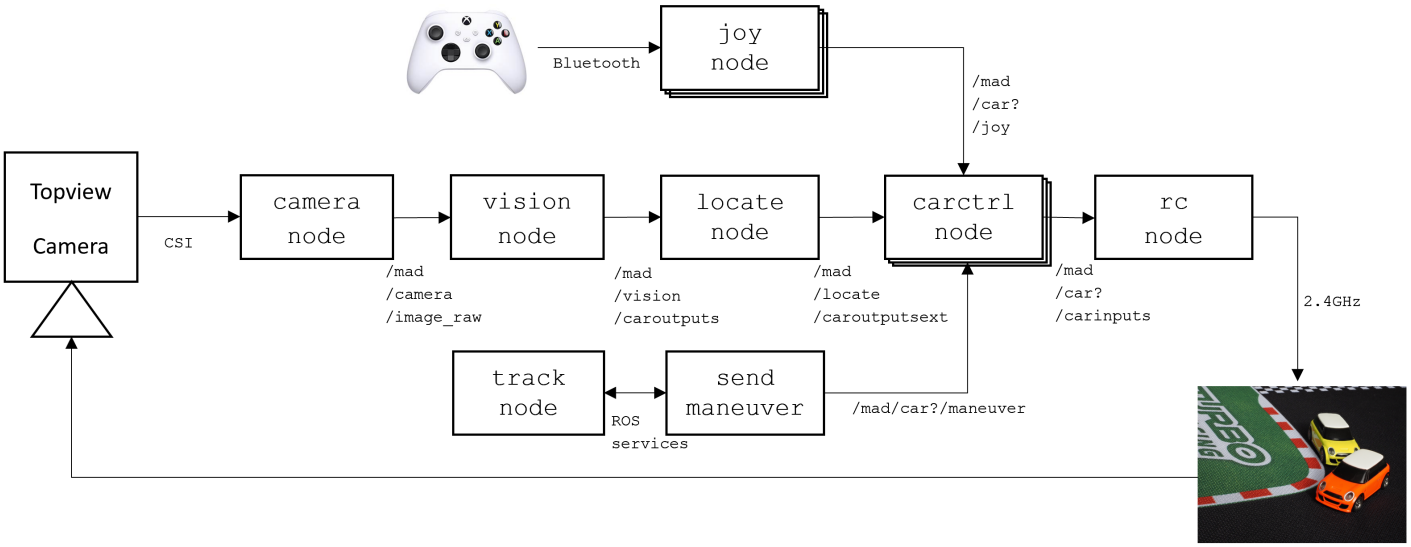

Figure 5: ROS2 nodes of MAD76 Driving Stack

ROS2 Node	Description
`camera_node`	Rasberry Pi camera driver
`visionnode`	computer vision
`locatenode`	multi-object tracking
`carctrlnode`	motion planning and control for each individual car
`rcnode`	remote control signals output to 2.4GHz channel via SPI
`tracknode`	track map
`joy_node`	optional node for manual control via joystick

Table 5: ROS2 nodes of MAD76 software

5.2 Build MAD76

- MAD76 can be built and run on Raspberry Pi and on Ubuntu Linux computers
- ROS2 nodes can run on distributed system with multiple computers
- ROS2 nodes `camera_node` and `rc_node` must run on the Raspberry Pi for interfacing with the camera and Turboracing remote controllers
- All other nodes can run on other computers
- ROS2 supports this distributed computing transparently when setting a common ROS domain ID
- For running MAD76 in Software-in-the-Loop (SiL) simulation mode (see Section 5.3), a build of MAD76 on an Ubuntu Linux-PC is sufficient because SiL mode does not do any input / output, except for optional joystick control
- Clone Git repository and build MAD76 workspace

ROS2 Topic	ROS2 Message Type	Description
/mad/camera/image_raw	sensor_msgs::msg::Image	camera frames with sampling time 25ms
/mad/camera/camera_info	sensor_msgs::msg::CameraInfo	camera calibration info
/mad/vision/caroutputs	mbmadmsgs::msg::CarOutputsList	list of car poses
/mad/locate/caroutputsext	mbmadmsgs::msg::CarOutputsExtList	list of car poses including velocities
/mad/car?/carinputs	mbmadmsgs::msg::CarInputs	control signals for each individual car
/mad/car?/maneuver	mbmadmsgs::msg::DriveManeuver	maneuvers for path following and parking
/mad/car?/joy	sensor_msgs::msg::Joy	standard ROS2 joystick messages

Table 6: ROS2 topics of MAD76 software

```
export RMW_IMPLEMENTATION=rmw_fastrtps_cpp
export ROS_DOMAIN_ID=221
source ~/src/ros_ws/install/setup.bash # on Raspberry Pi
#source /opt/ros/iron/install/setup.bash # on Ubuntu Linux-PC
cd ~/src
git clone https://github.com/modbas/mad76
cd mad76/mad_ws
colcon build --symlink-install --cmake-args -DCMAKE_BUILD_TYPE=Release
```

For building on Raspberry Pi, the `colcon build` command must be extended by `-parallel-workers 1` to avoid out-of-memory problems

```
colcon build --parallel-workers 1 --symlink-install --cmake-args -DCMAKE_BUILD_TYPE=
    Release
```

- Add security limits

```
sudo addgroup mad
sudo adduser <username> mad # where <username> is your username
sudo -i
echo "@mad  - rtprio  98" >> /etc/security/limits.conf
echo "@mad  - memlock unlimited" >> /etc/security/limits.conf
shutdown -r 0 # reboot
```

- Add the following lines to the end of `~/.bashrc` for automatic setup

```
export RMW_IMPLEMENTATION=rmw_fastrtps_cpp
export ROS_DOMAIN_ID=221
source ~/src/mad76/mad_ws/install/setup.bash
```

5.3 Software-in-the-Loop Simulation

- In order to test your MAD76 installation, you may run MAD76 in software-in-the-loop (SiL) simulation mode
  - The real cars, the camera, and the ROS2 nodes `camera_node`, `vision_node` and `rc_node` for computer vision and RC output are replaced by simulation models

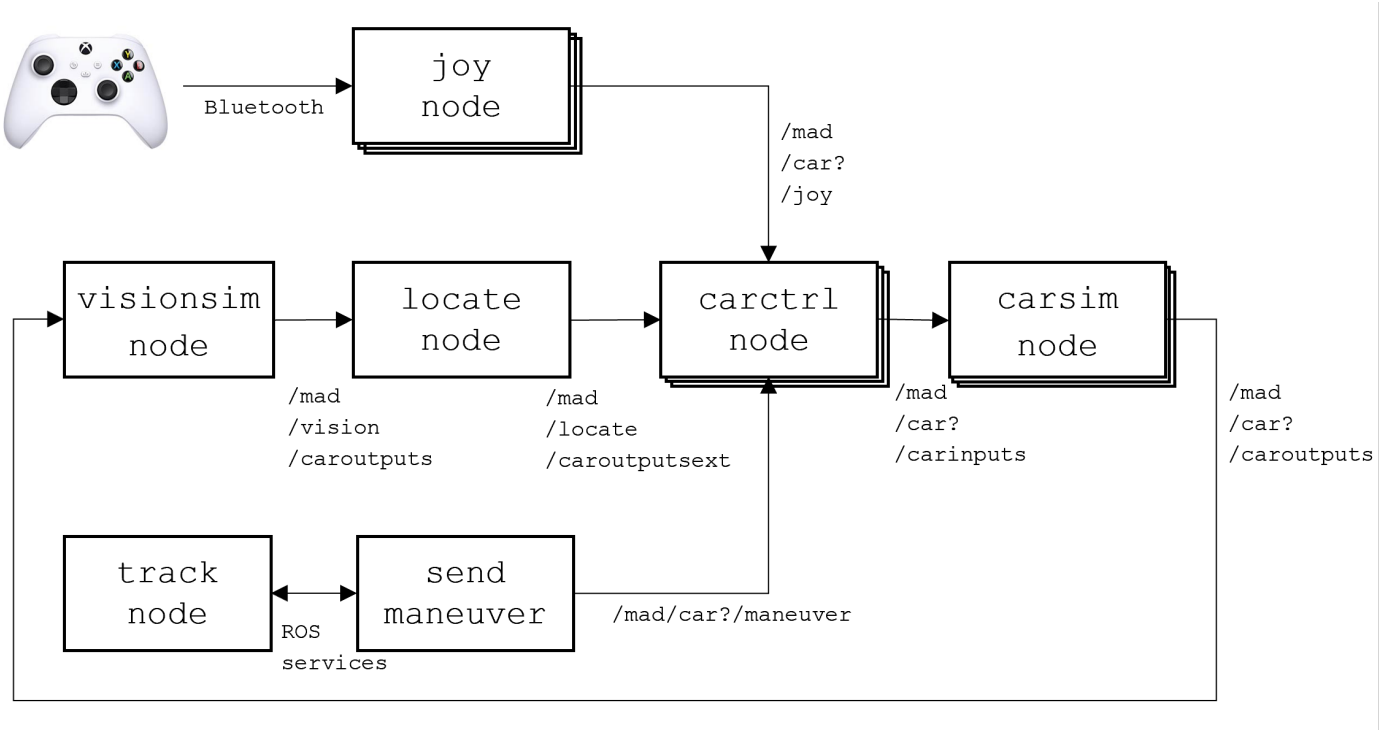

Figure 6: ROS2 nodes in SiL simulation mode

  - The MAD76 Driving Stack runs in the loop with vehicle dynamics simulation models
  - Full operation of the driving stack is supported in SiL simulation mode

- Open a new terminal and start MAD76 in SiL mode

```
ros2 launch mbmad madpisim.launch
```

- Open a further terminal and send a maneuver to car 0 (orange car)

```
ros2 run mbmadcar send_maneuver.py 0 0.3 0.25
```

  - First argument is the car identifier (0 for orange car, 1 for yellow car)

0	orange car
1	yellow car
2	blue car
3	white car

  - Second argument is the car reference speed in $\frac{m}{s}$
  - Third argument is the lateral reference position

0	right curb
0.25	right lane
0.5	center line
0.75	left lane
1	left curb

- Stop `send_maneuver.py` by hitting `Ctrl+c` and send maneuver to car 1 (yellow car)

```
ros2 run mbmadcar send_maneuver.py 1 0.2 0.25
```

- The maximum speed of each car is $0.5\frac{m}{s}$
- You may stop the individual car by sending a maneuver with reference speed $0\frac{m}{s}$
- Reverse driving is possible by setting a negative reference speed

6 MATLAB/Simulink Installation

- The following MATLAB release and toolboxes are required
  - MATLAB R2025a
  - Simulink
  - Stateflow
  - Control-System-Toolbox
  - Curve-Fitting-Toolbox
  - ROS-Toolbox
  - Simulink Coder
  - Embedded Coder
- For model-in-the-loop (MiL) simulation and control design, MATLAB can be installed on any supported platform
- For code generation and MAD76 programming, MATLAB needs to be installed on the MAD76 Linux PC

6.1 Python 3.10 Installation

- MATLAB ROS-Toolbox requires Python 3.10 which is not installed per default on Ubuntu Noble Numbat 24.04
- The default Python 3.12 installation does not work
- Install Python 3.10 on the MAD76 Linux PC from the PPA `Deadsnakes`

```
sudo add-apt-repository ppa:deadsnakes/ppa
sudo apt update
sudo apt install python3.10 python3.10-venv
```

- Activate Python 3.10 in MATLAB ROS-Toolbox
  1. Open MATLAB Settings ROS-Toolbox
  2. Browse for `/usr/bin/python3.10`
  3. Hit pushbutton `Recreate Python Environment`
  4. Select `rmw_fastrtps_cpp` as ROS Middleware

6.2 ROS Custom Messages

- Make custom ROS message types of MAD76 available in MATLAB/Simulink (only needed for code generation)
  1. ROS2 Jazzy Jalisco and MAD76 must be installed on the MAD76 Linux PC running Ubuntu Noble Numbat 24.04 (see `https://github.com/modbas/mad76/blob/main/doc/install/install.md#linux-pc-installation`)

2. At the MATLAB prompt, change to the ROS workspace directory

```
cd ~/src/mad76/mad_ws
```

3. Generate MATLAB/Simulink objects for the custom ROS message types

```
ros2genmsg src
```

4. Test if the message types are available in MATLAB/Simulink

```
ros2 msg list
```

This displayed list must contain message types `mbmadmsgs/*` and `mbsafemsgs/*`

6.3 Test Simulink MiL Simulation

- The Simulink model `s06_sig_template.slx` is the template model for vehicle dynamics modeling and controller design
- Test your new MATLAB/Simulink installation by simulating this model

```
cd ~/src/mad76/matlab/vertical
s06_sig_template
```

- The model should run without errors and display initial positions of the vehicles in the MATLAB figure

6.4 Test Simulink for Code Generation

- The Simulink model `c71_car0_template.slx` is the template model for code generation
- Test your new MATLAB/Simulink installation by simulating this model which communicates with the ROS environment
- Run the ROS environment in manual simulation mode (without MAD76 driving stack)

```
ros2 launch mbmad madpisimman.launch
```

- Start the simulation of `c71_car0_template.slx`

```
cd ~/src/mad76/matlab/vertical
c71_data
c71_car0_template
```

- Send a maneuver message to the Simulink model, so that the main subsystem is enabled

```
ros2 run mbmadcar send_maneuver.py 0 0.2 0.5
```

- You can now manually control the orange car with id 0 by manipulating the sliders in subsystem `Motion Control and carinputs msg/Motion Control/Sliders or Joystick/Sliders`

References

[1] Canonical Ubuntu. *Alternative Downloads*. Accessed: 2025-02-25. 2025. URL: https://ubuntu.com/download/alternative-downloads.

[2] Raspberry Pi Foundation. *Raspberry Pi Software*. Accessed: 2024-12-21. 2024. URL: https://raspberrypi.com/software.

[3] ROS. *Building ROS2 on Linux*. Accessed: 2024-12-21. 2024. URL: https://docs.ros.org/en/eloquent/Installation/Linux-Development-Setup.html.

[4] ROS. *Installation Alternatives Ubuntu (Source)*. Accessed: 2025-02-25. 2025. URL: https://docs.ros.org/en/jazzy/Installation/Alternatives/Ubuntu-Development-Setup.html.

[5] ROS. *Installation Ubuntu (deb packages)*. Accessed: 2025-02-25. 2025. URL: https://docs.ros.org/en/jazzy/Installation/Alternatives/Ubuntu-Install-Binary.html.