MAD76 Installation

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Contents

1 Installation Overview

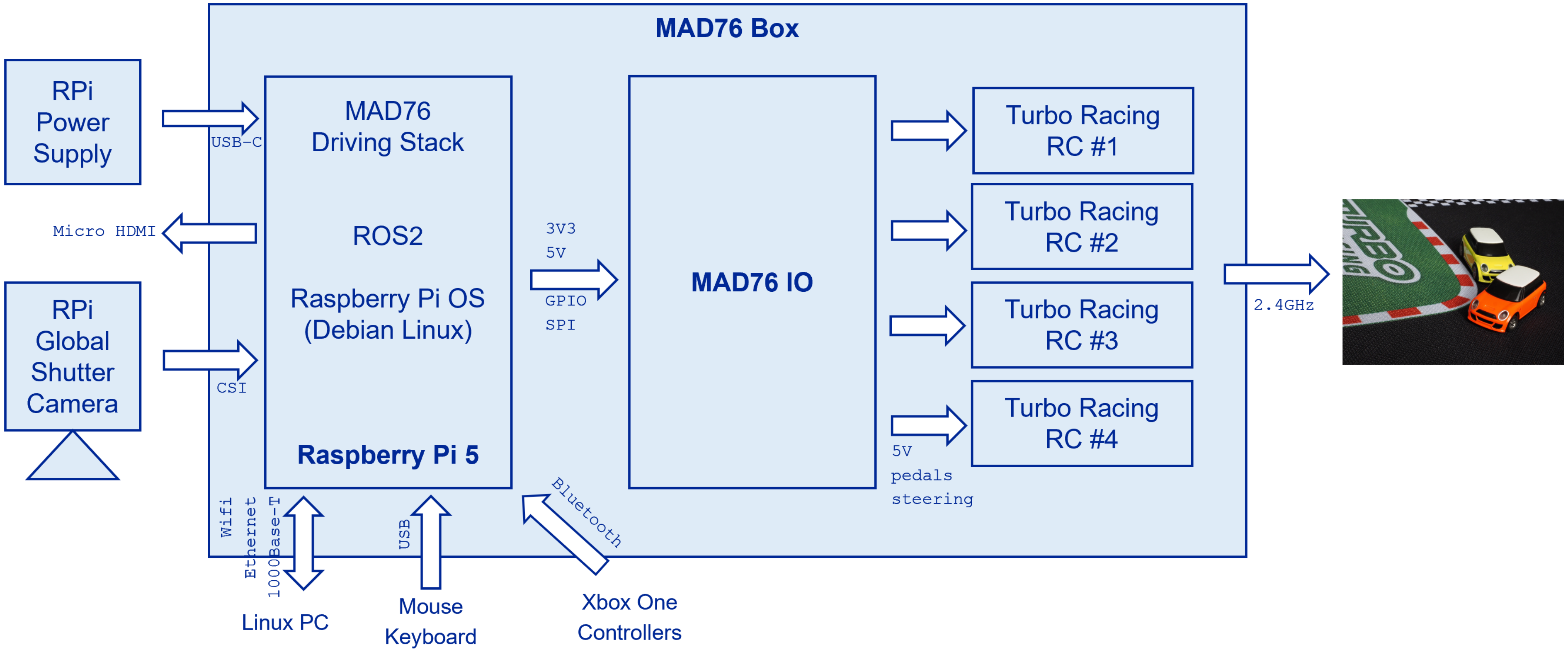


Figure 1: MAD76 System Architecture

The installation steps are:

- Build the MAD76 Box including the MAD76 IO PCB (see Section 2)
- Connect the Turboracing Radio Controllers (RCs) to the MAD76 IO PCB (see Section 3)
- Install Raspberry Pi OS, drivers, and ROS2 (see Section 4)
- Optionally install ROS2 on optional Linux-PC for distributed computing and software-in-the-loop (SiL) simulation (see Section 5)
- Calibrate the Raspberry Pi camera (see Section 6)
- Install AruCo markers for computer vision (see Section **??**)
- Install MAD76 Driving Stack (see Section 8)
- Optionally install MATLAB/Simulink for model-based software engineering (see Section 9)

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

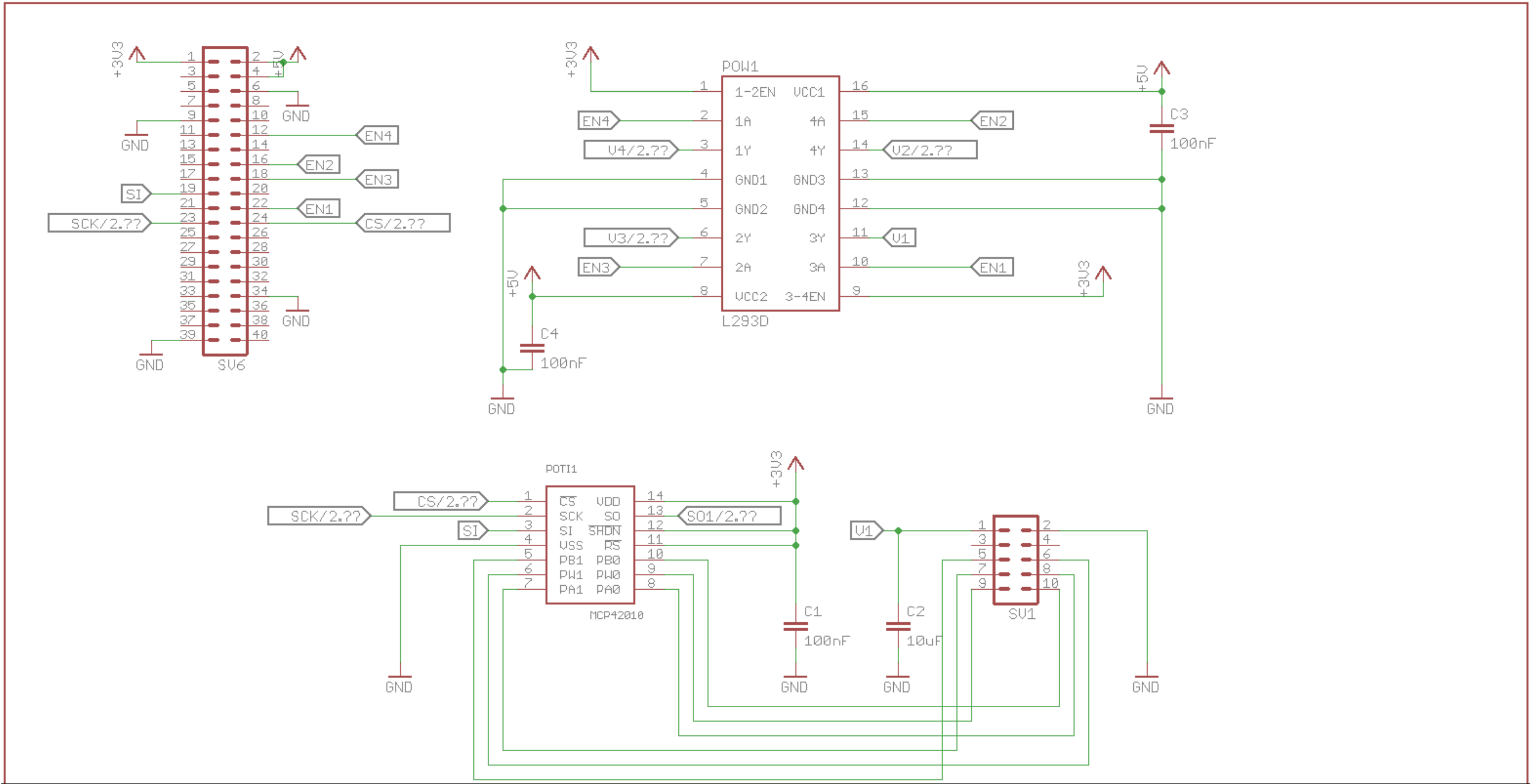
2.1.4 Turbo Racing Cars

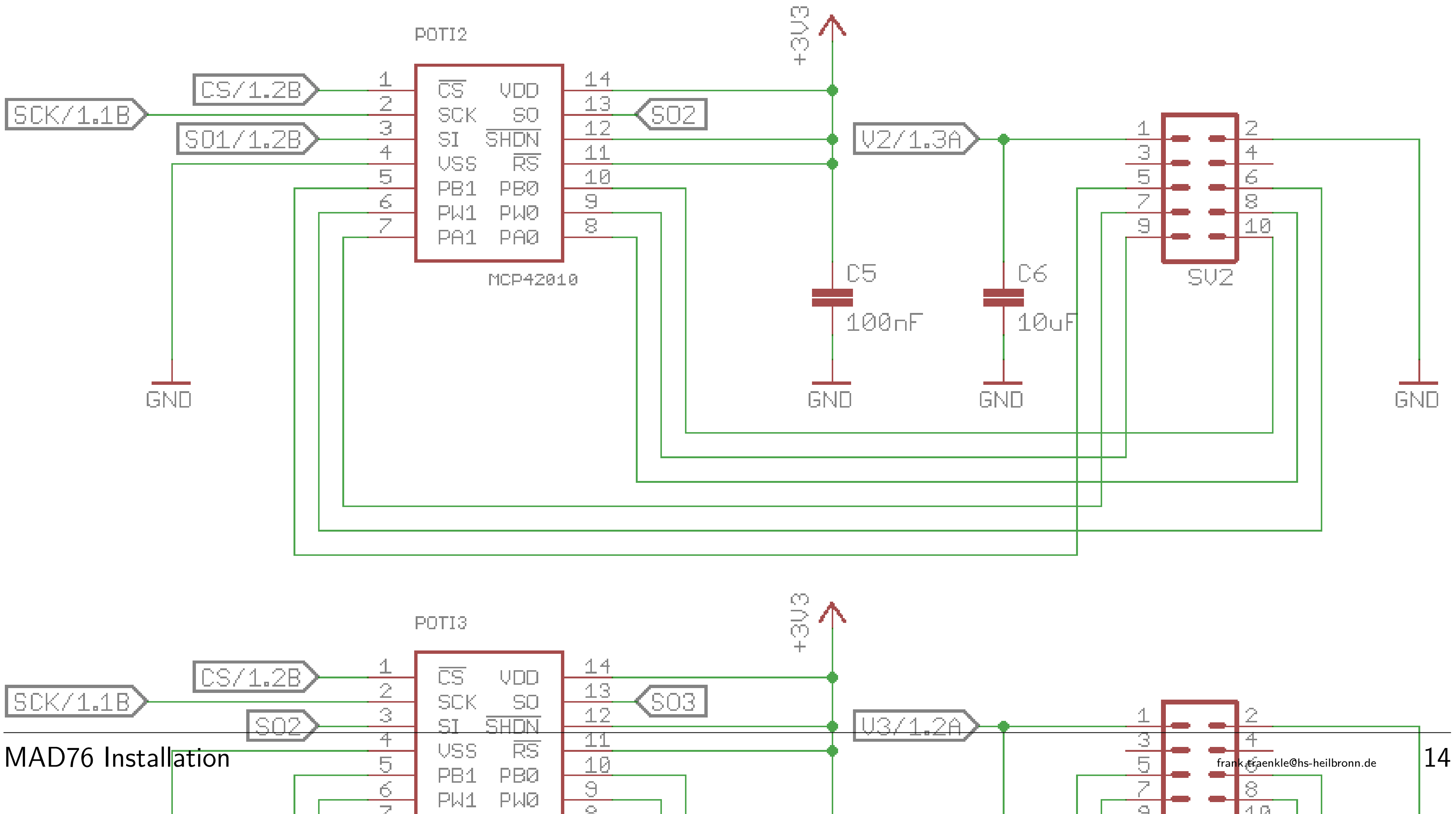
	Description	Part Id	Order Link
1 to 4	Turbo Racing 1:76 Mini Cooper with RC https://www.turboracing.net/		https://www.rcfox.de/TB-TR01-Turbo-Racing-1/76-Micro-Mini-Cooper https://de.aliexpress.com/item/1005001936818767.html
1	Turbo Racing Mat Track 50x95cm		https://www.rcfox.de/TB-760101-Turbo-Racing-Race-Strecke-fuer-Micro-Rally-50x95-cm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

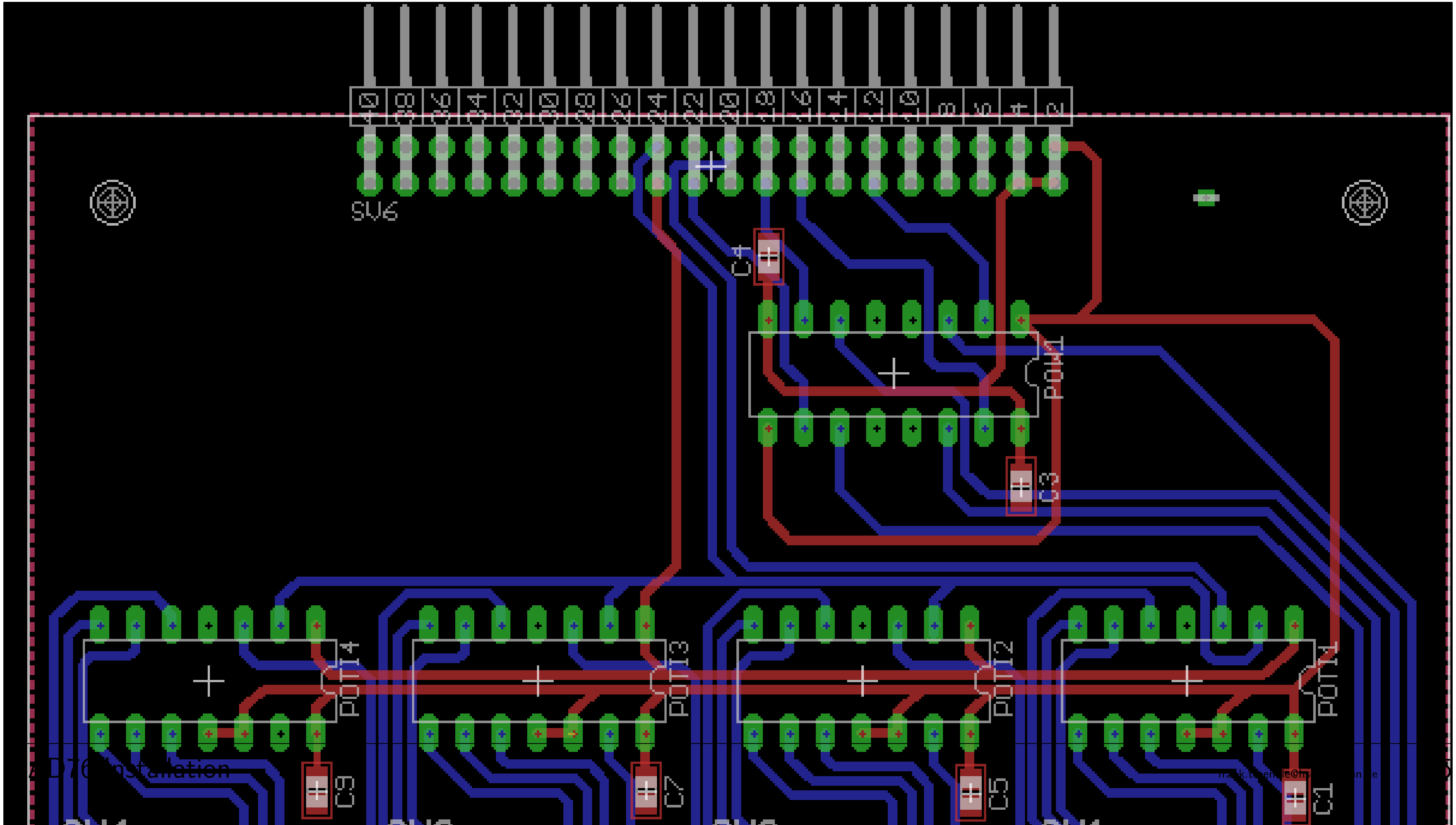
Table 4: BOM of Turbo Racing cars

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.


+3V3
+5V
GND
SV6
EN4
EN2
EN3
SI
EN1
SCK/2.??
CS/2.??
POW1
1-2EN
VCC1
1A
4A
1Y
4Y
GND1
GND3
GND2
GND4
2Y
3Y
2A
3A
VCC2
3-4EN
L293D
V4/2.??
V2/2.??
V3/2.??
V1
C3
100nF
C4
100nF
POTI1
CS
VDD
SCK
SO
SI
SHDN
VSS
RS
PB1
PB0
PW1
PW0
PA1
PA0
MCP42010
SO1/2.??
C1
100nF
C2
10uF
SV1


POTI2
CS/1.2B
SCK/1.1B
SO1/1.2B
CS
SCK
SI
VSS
PB1
PW1
PA1
VDD
SO
SHDN
RS
PB0
PW0
PA0
MCP42010
+3V3
SO2
V2/1.3A
C5
100nF
C6
10uF
SV2
GND
GND
GND
GND
POTI3
CS/1.2B
SCK/1.1B
SO2
SO3
+3V3
V3/1.2A


SV6
C4
POW1
C3
POTI4
POTI3
POTI2
POTI1
C9
C7
C5
C1

3 RC Cabling

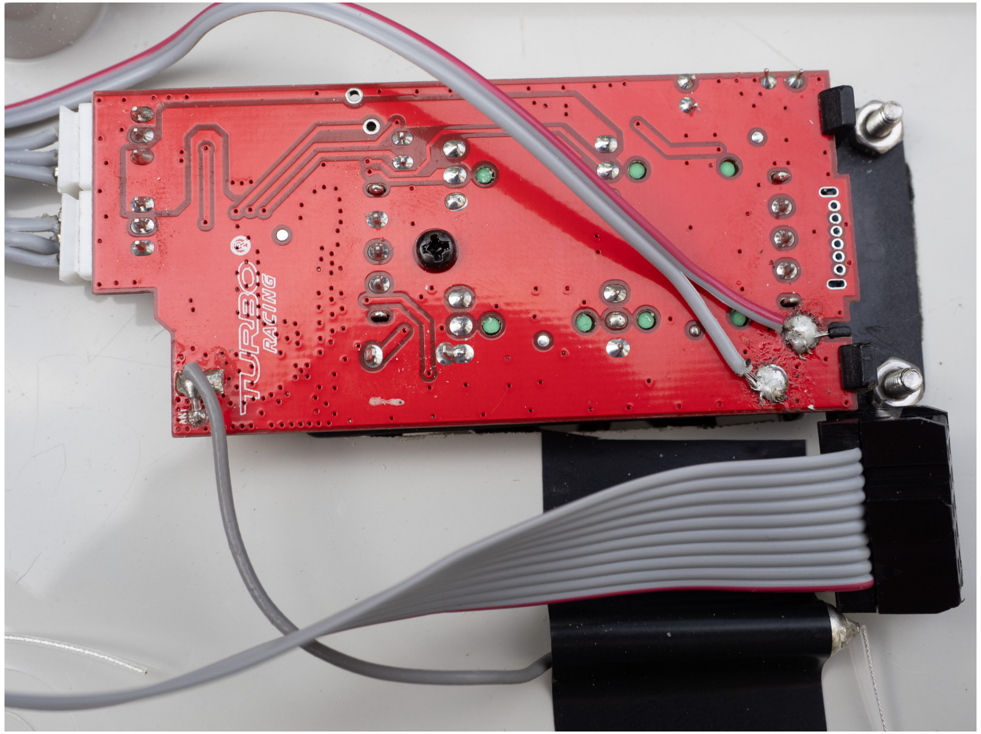


Figure 5: RC Cabling

- Connect the ribbon cables to the 4 RCs and the ports SV1, SV2, SV3, and SV4 on the MAD76 IO board
- Use a length of at least 170mm for the 10-pin ribbon cables
- In Figure 5, the nose of the black SV1 connector is facing upward
- Solder the 5V and GND wires (SV1 pins 1 and 2) to the RC power supply pads
- Pins 3 and 4 are not used and can be cut off
- Crimp steering poti wires (SV1 pins 5, 6, 7) to the upper JST connector (from top to bottom)
- Crimp motor poti wires (SV1 pins 8, 9, 10) to the middle JST connector (from top to bottom)
- Please note that the cabling is designed in such a nice way, such that the individual wires of the ribbon cable do not cross each other
- Connect the cable to SV 1 of MAD76 IO

4 Raspberry Pi Installation

4.1 Raspberry Pi OS

- Download and start installer [3]
  - 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
```

4.2 Raspberry Pi Configuration

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

4.3 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.

4.4 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
```

4.5 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
```

4.6 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 [4, 6]

```
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
```

4.7 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
```

4.8 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/`

5 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 [7]. Make sure to install the following ROS2 packages:

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

6 Camera Calibration

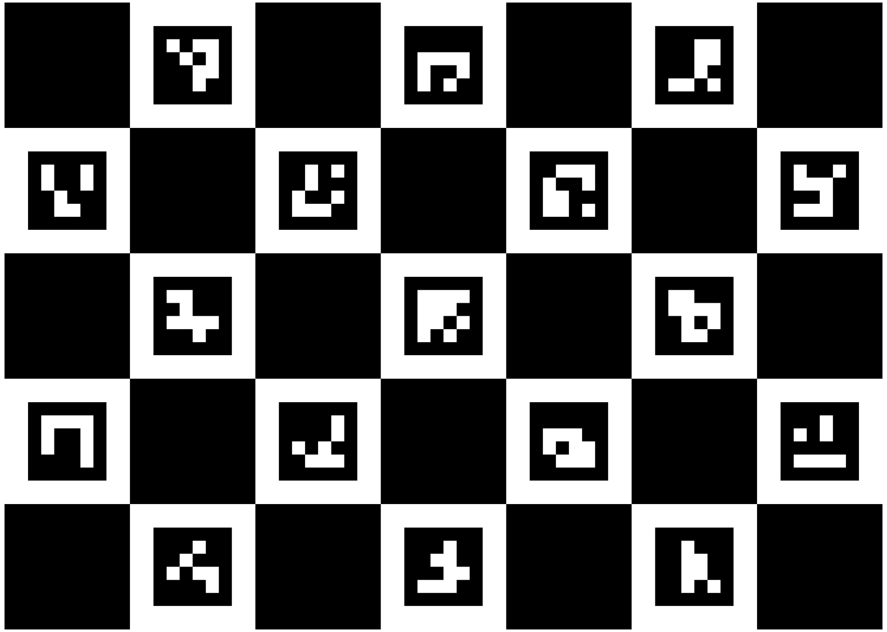


Figure 6: ChArUco board for camera calibration.

The Raspberry Pi camera must be calibrated, so that the MAD76 software can undistort the camera image frames [5]. The calibration is performed applying an ChArUco board, which is an augmentation of a chess board by AruCo markers for higher precision. Follow the following steps for calibrating your camera:

- Print the marker board in Fig. 6 on a snow-white DIN-A4 paper. Use high-quality printer settings.
- Scale the printing such that the black area of the AruCo markers has a height and width of 21mm each.
- This PNG image can optionally be created by

```
cd ~/src/mad2/mad_ws
install/mbmadvisionaruco/lib/mbmadvisionaruco/create_board_charuco -d=0 -w=7 -h=5 -ml=500 -sl=800 charucoboard.
   png
```

- Fix this paper on a cardboard.
- Calibrate the camera by running the following command:

```
ros2 run camera_calibration cameracalibrator --pattern=charuco --size 7x5 --square 0.036 --charuco_marker_size
   0.022 --aruco_dict 4x4_50 image:=/mad/camera/image_raw camera:=/mad/camera camera/set_camera_info:=/mad/
   camera/set_camera_info
```

- After successful calibration the camera matrix and distortion coefficients are stored in the file

```
~/.ros/camera_info/imx296__base_axi_pcie_120000_rp1_i2c_88000_imx296_1a_800x600.yaml
```

```

```

or similar.

- This calibration data file will then be automatically loaded by the MAD76 computer vision for undistorting camera frames.

7 AruCo Markers

MAD76 applies AuUco markers in computer vision for detecting and tracking cars. This section explains

- how to generate and print the markers (see Section 7.1),
- how to place the coordinate frame markers (see Section 7.2),
- how to place the car markers (see Section 7.3),

7.1 Marker Generation

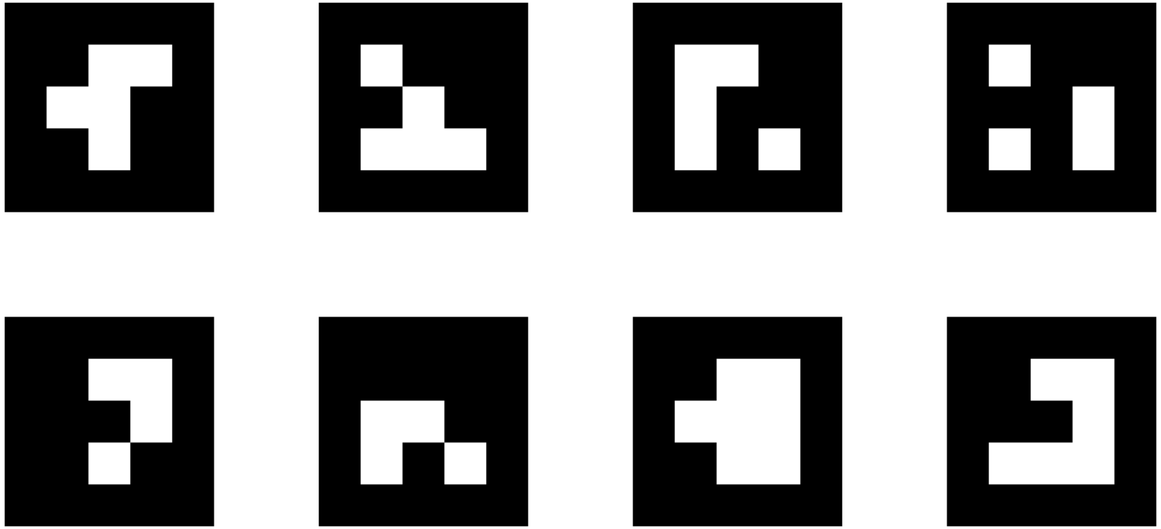


Figure 7: AruCo markers for cars and coordinate frame.

- The cars are tracked by ArUco markers [2].
- Computer vision computes the Cartesian coordinates and the yaw angles of the cars.
- The markers are generated with the OpenCV ArUco library.
- A custom ArUco dictionary of 8 markers with a size of 3x3 bits is used to increase the reliability of computer vision.
- The PNG image of the 8 markers can be optionally created by

```
cd ~/src/mad2/mad_ws
install/mbmadvisionaruco/lib/mbmadvisionaruco/create_board --bb=1 -d=17 -w=4 -h=2 -l=200 -s=100 markers.png
```

- The markers IDs are from 0 to 7, 0 to 3 in the first row from left to right, and 4 to 7 in the second row.
- Print the markers in Fig. 7 on a snow-white, 80 grams paper.
  - Make sure to configure high quality printing.
  - Scale the printing such that the black area of the markers have a height and width of 21mm each.
- Cut the markers as squares including approx. 5mm boundaries.
- Note the marker IDs before cutting with a thin pencil on the boundaries, because you will need these IDs later on.

7.2 Frame Markers

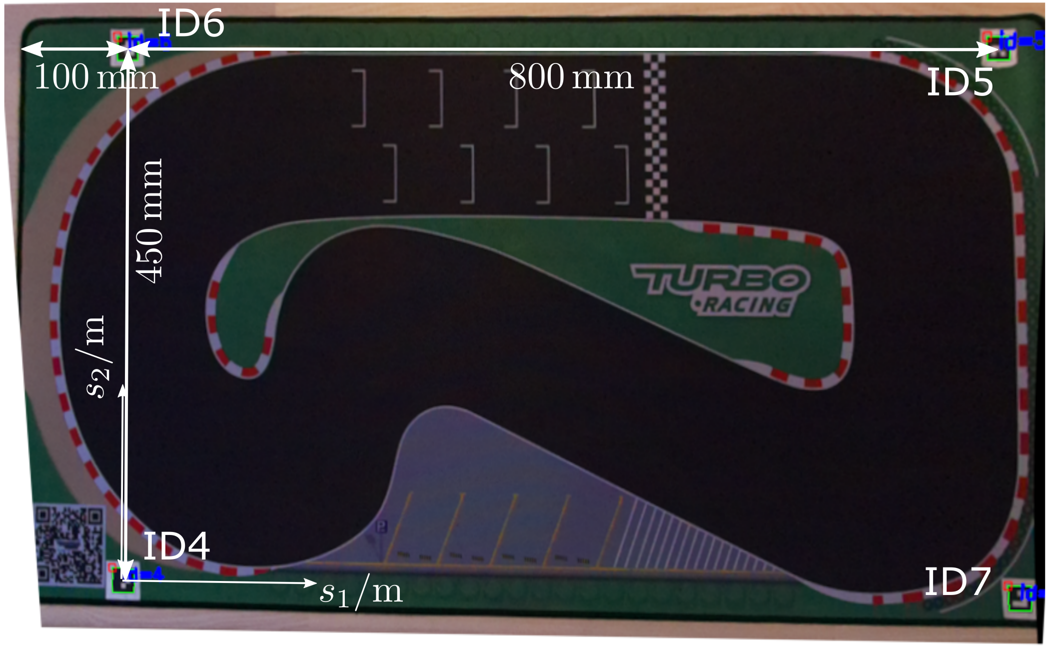


Figure 8: Track with 4 coordinate frame markers.

- 4 frame markers define the coordinate frame of the track.
- All coordinates of cars and track are measured in meters.
- The frame origin $(s_{01}, s_{02}) = (0\mathrm{m}, 0\mathrm{m})$ is at the center point of marker ID4.
- Place frame markers with IDs 4, 5, 6, 7 at corners of board as depicted in figure.
  - It is recommended to place the markers with high accuracy in the 1mm range. Otherwise, the control functions of the MAD76 driving stack will loose precision.
  - Although modified distances may be later configured in the ROS2 package `mbmadvisionaruco`.
  - The distances are measured at the marker center points.
  - The markers must form a rectangle.
  - The sequence of the marker IDs is essential.

7.3 Car Markers

Figure 9: Red car with marker ID 0.

- Each car has its individual marker.
- The following configuration is recommended:

Marker ID	Car
0	orang / red orange
1	green yellow / white
2	blue / white
3	white

- If you have fewer than four cars, please start with ID 0 in any case.
- Each marker's center point must be placed exactly at the car's rear axle center point.
- The horizontal orientation of the marker must match to the forward direction of the car.

8 MAD76 Driving Stack

8.1 Software Architecture

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 $2.4\mathrm{GHz}$ channel via SPI
`tracknode`	track map
`joy_node`	optional node for manual control via joystick

Table 5: ROS2 nodes of MAD76 software

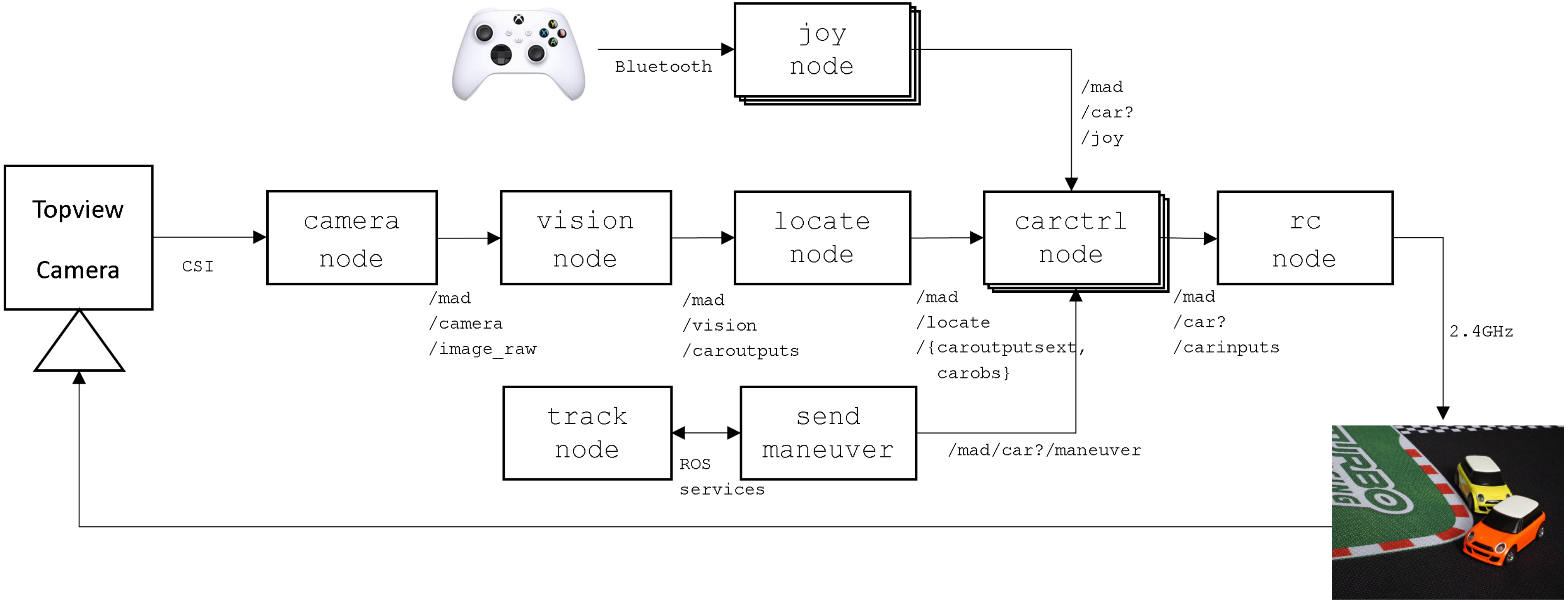


Figure 10: ROS2 nodes of MAD76 Driving Stack

ROS2 Topic	ROS2 Message Type	Description
`/mad/camera/image_raw`	`sensor_msgs::msg::Image`	camera frames with sampling time $25\mathrm{ms}$
`/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 (deprecated)
`/mad/locate/carobs`	`mbmadmsgs::msg::CarObsList`	list of car states and Frenet coordinates w.r.t. center line
`/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

8.2 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 8.3), 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

```
export RMW_IMPLEMENTATION=rmw_fastrtps_cpp
export ROS_DOMAIN_ID=221
source ~/src/ros_ws/install/setup.bash # on Raspberry Pi
#source /opt/ros/jazzy/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
```

8.3 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
  - 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 start all cars in a driverless race

```
ros2 run mbmadcar send_maneuver.py
```

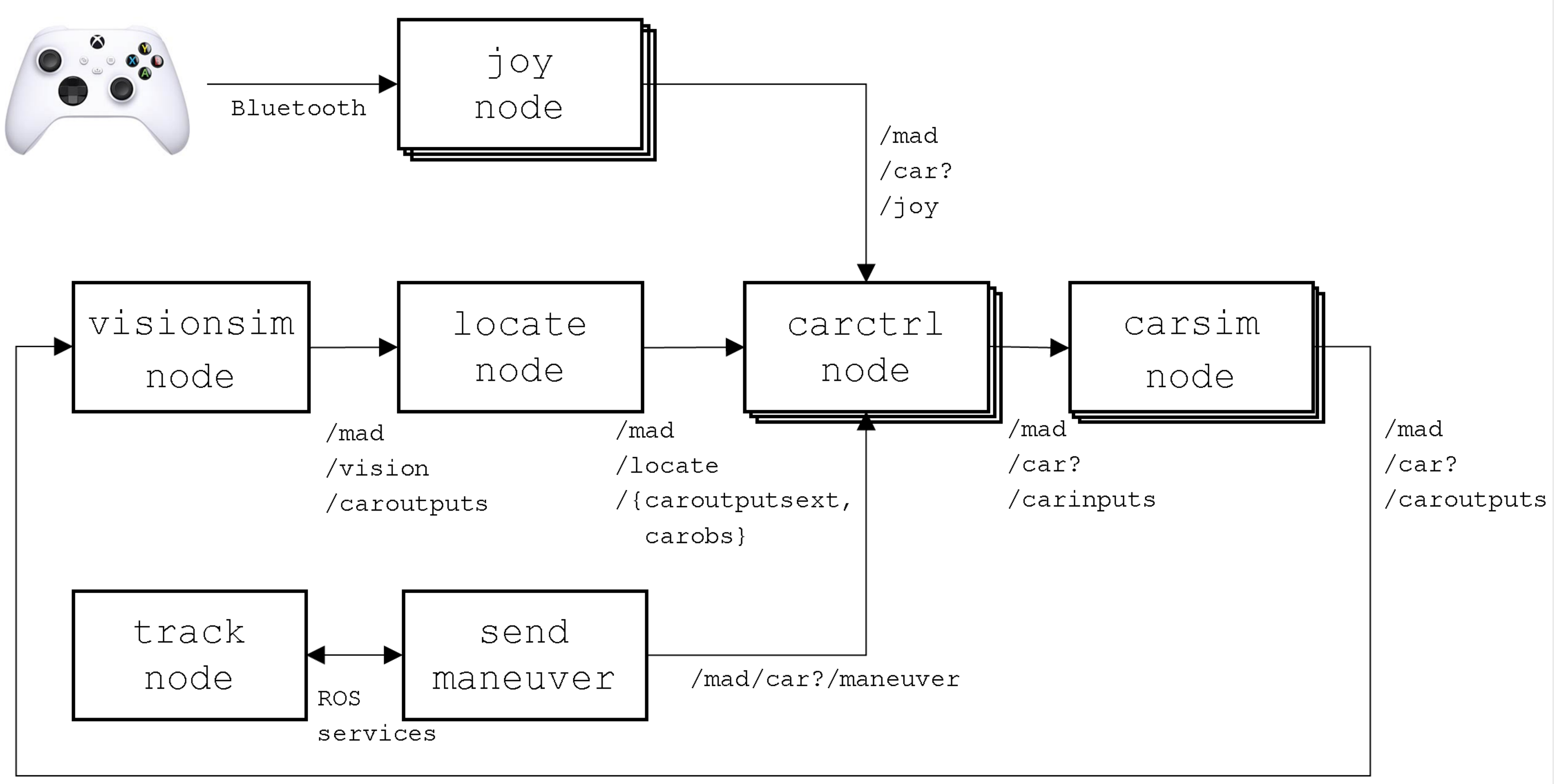


Figure 11: ROS2 nodes in SiL simulation mode

9 MATLAB-Simulink Installation

- MATLAB/Simulink may be optionally installed for model-based software engineering of MAD76 driving stacks.
- 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

9.1 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

9.2 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/*`

9.3 Test Simulink Model in 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. Enter on the MATLAB prompt:

```
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

9.4 Test Simulink Model in SiL Simulation

- 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 ROS2 environment
- `c71_car0_template.slx` runs as a ROS2 node replacing the ROS2 node `carctrlnode` in Figure 11
- All other ROS2 nodes of Figure 11 run as usual
- Start this ROS2 environment in manual simulation mode (without MAD76 driving stack in `carctrlnode`)

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

- Start the simulation of `c71_car0_template.slx`. Enter on the MATLAB prompt:

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

9.5 Test Simulink Model on the Real MAD76 System

- The Simulink model `c71_car0_template.slx` is now simulated on the MAD76 Linux PC to control the real MAD76 cars
- All ROS2 nodes in Figure 10 run on the Raspberry Pi except for `carctrlnode`
- `c71_car0_template.slx` runs as a ROS2 node replacing `carctrlnode` on the Linux PC
- ROS2 runs in a distributed environment consisting of Raspberry Pi and Linux PC
- ROS2 establishes network communication on Ethernet between Raspberry Pi and Linux PC
- Start the ROS2 environment on the Raspberry Pi without `carctrlnode`. Enter on the Raspberry Pi terminal:

```
ros2 launch mbmad madpiman.launch
```

- Start the simulation of `c71_car0_template.slx` on the MAD76 Linux PC. Enter on the MATLAB prompt:

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

  and start the simulation by hitting the `Run` button in toolbar `Simulation`
- Send a maneuver message to the Simulink model, so that the main subsystem is enabled. Enter on the Raspberry Pi:

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

- First argument is the car identifier

0	orange/red car
1	yellow/white car
2	blue car
3	green car

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

- 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
-1	ideal line for low laptimes

- You can now manually control the orange/red car with id 0 by manipulating the sliders in subsystem `Motion Control and carinputs msg/Motion Control/Sliders or Joystick/Sliders`
- You can measure the vehicle states (elements of bussignal `carobs/carobs(1)`) including position, speed, and yaw angle in the Simulink Data Inspector
- Stopping the simulation triggers an emergency stop of the car
- You may now model control functions as part of subsystem `Motion Control and carinputs msg/Motion Control/Sliders or Joystick/Sliders` by replacing the sliders with your control algorithms

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