# MAD76 Installation

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# Contents

# 1 Installation Overview

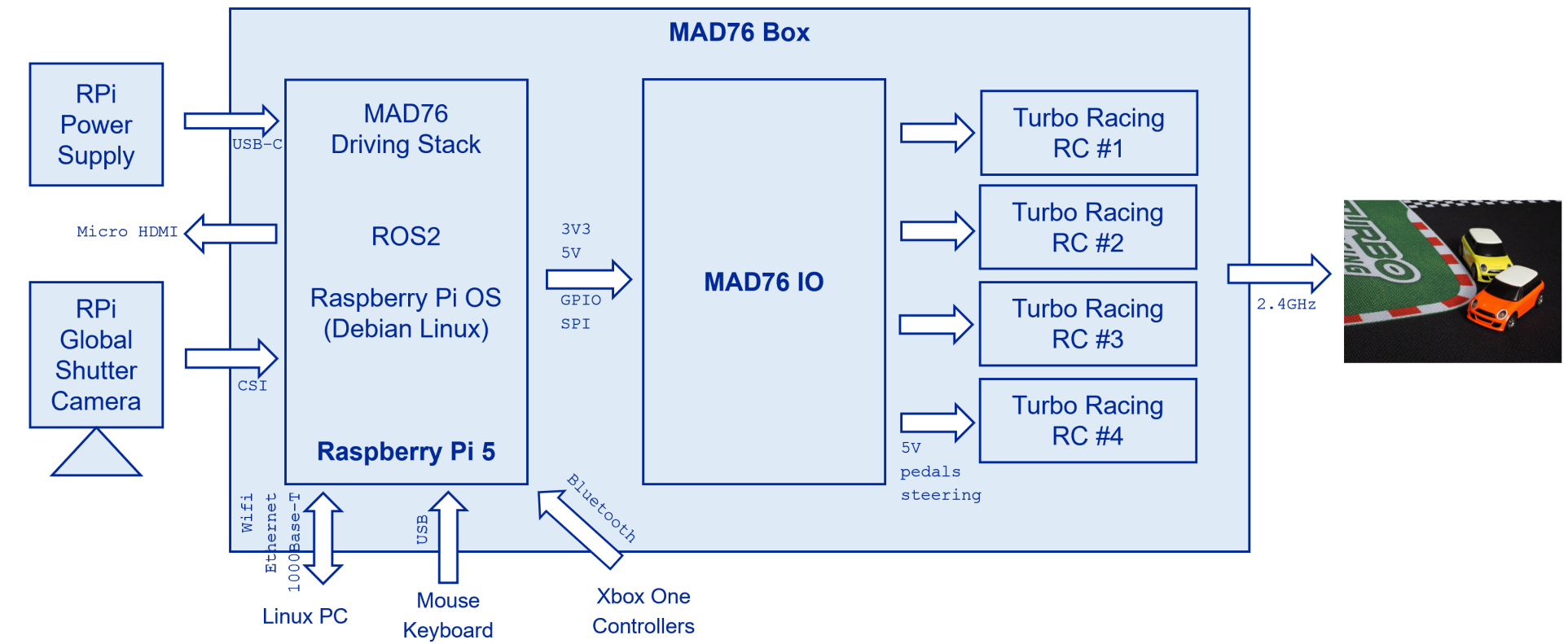



Figure 1: MAD76 System Architecture

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 7)
- 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

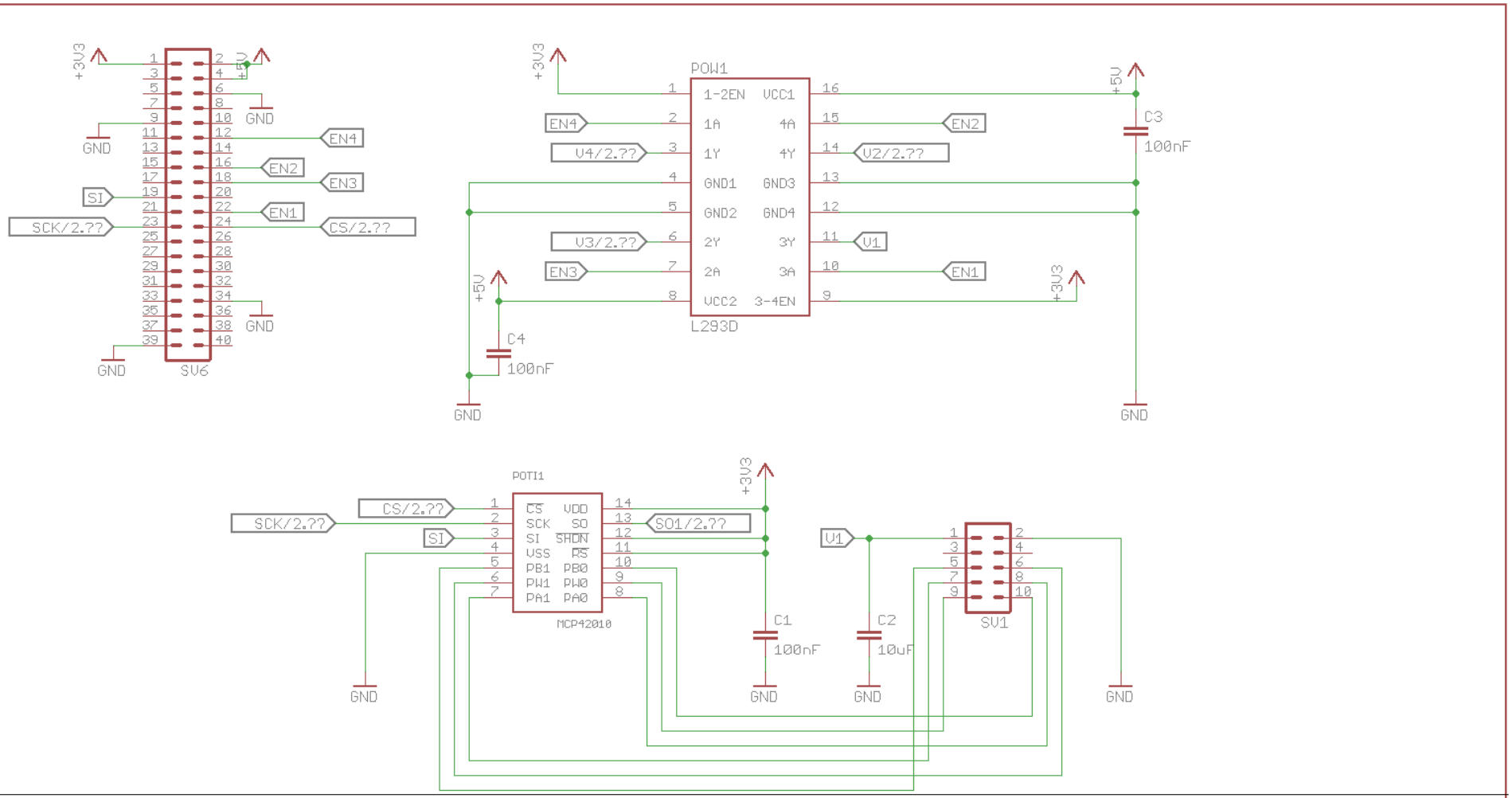
### 2.1.4 Turbo Racing Cars

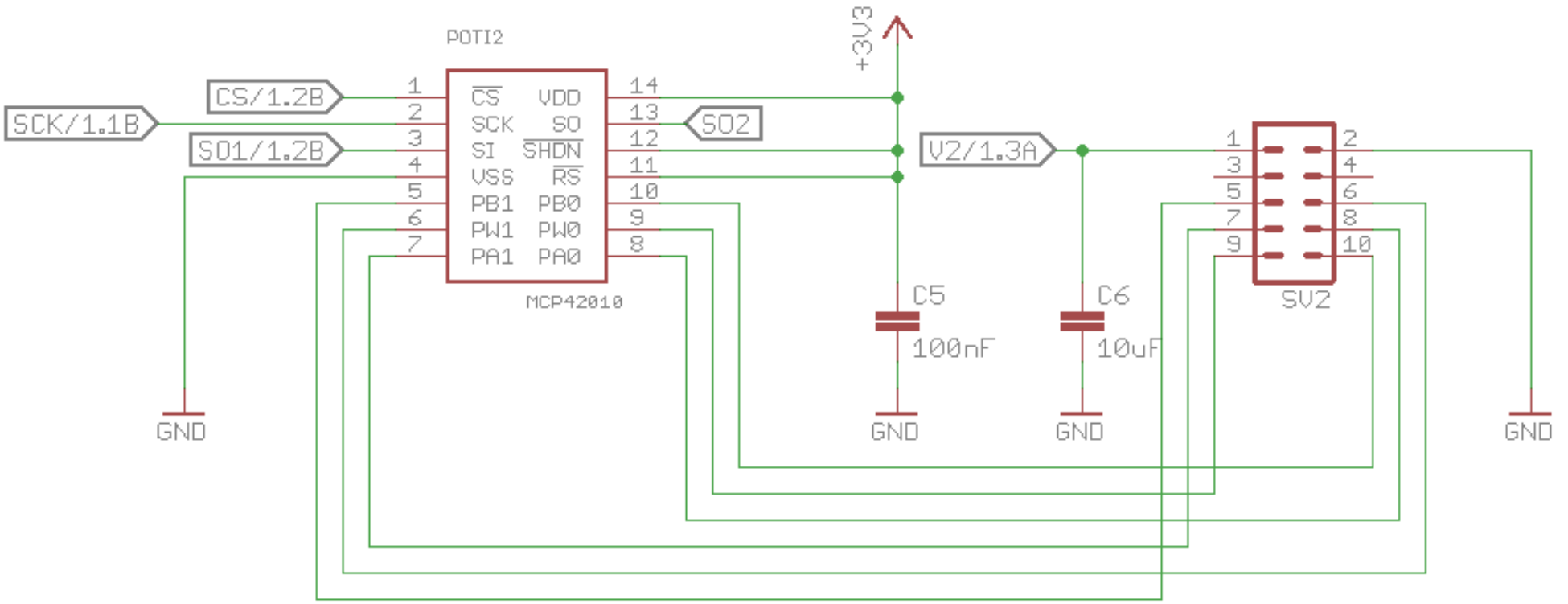
| | Description | Part Id | Order Link |
|---|---|---|---|
| 1 to 4 | Turbo Racing 1:76 Mini Cooper with RC https://www.turboracing.net/ | | https://www.rcfox.de/TB-TR01-Turbo-Racing-1/76-Micro-Mini-Cooper https://de.aliexpress.com/item/1005001936818767.html |
| 1 | Turbo Racing Mat Track 50x95cm | |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

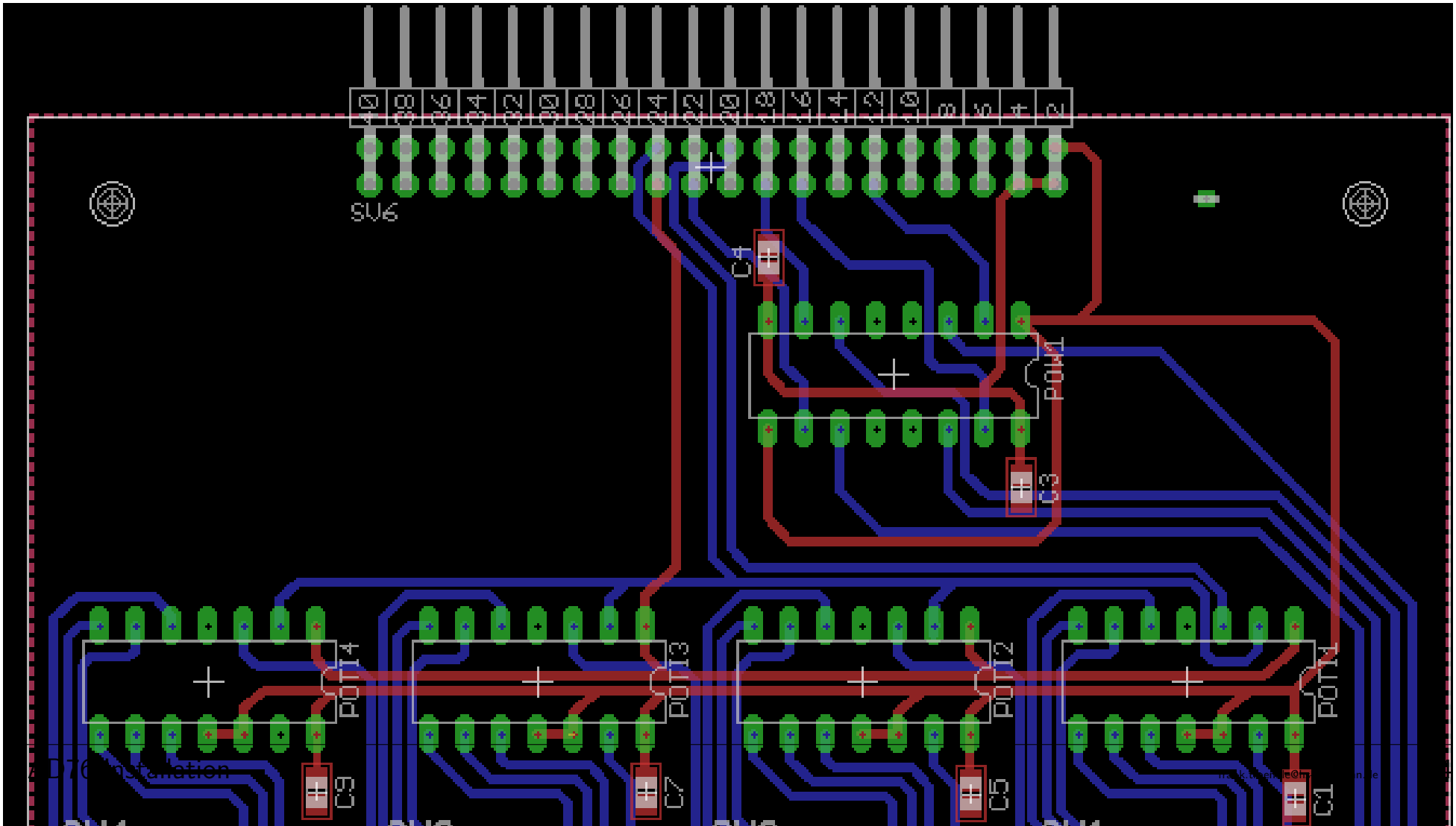
Table 4: BOM of Turbo Racing cars

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


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


SV6
C9
C7
C5
C3
C1
POW1
POW2
POW3
POW4

# 3 RC Cabling

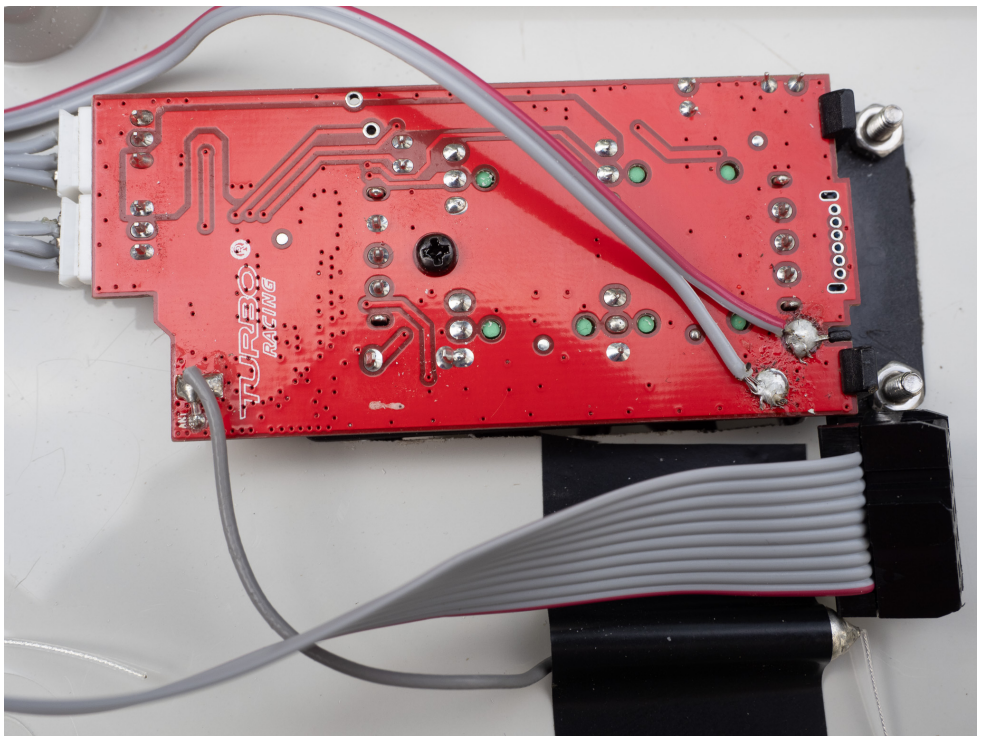



Figure 5: RC Cabling

- 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

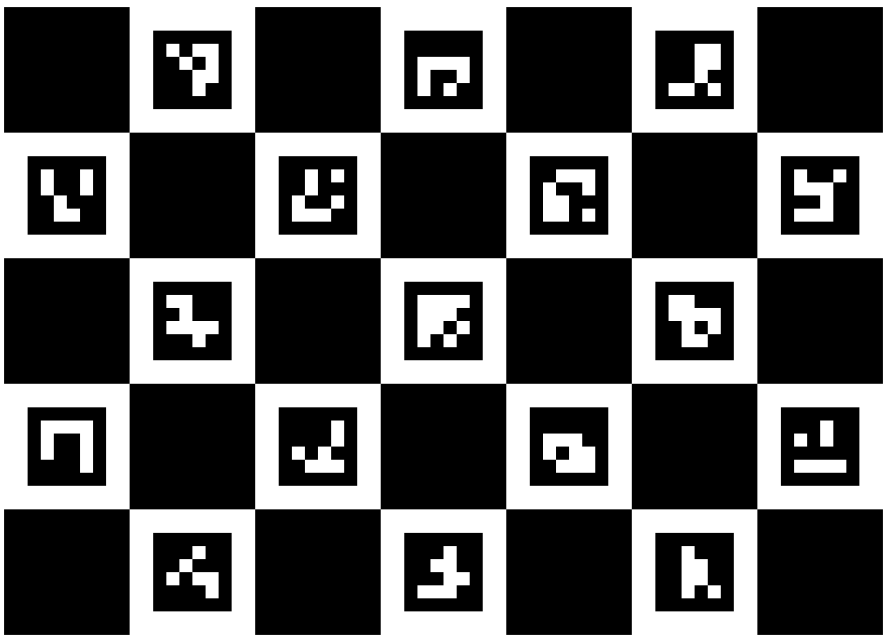


Figure 6: ChArUco board for camera calibration.

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

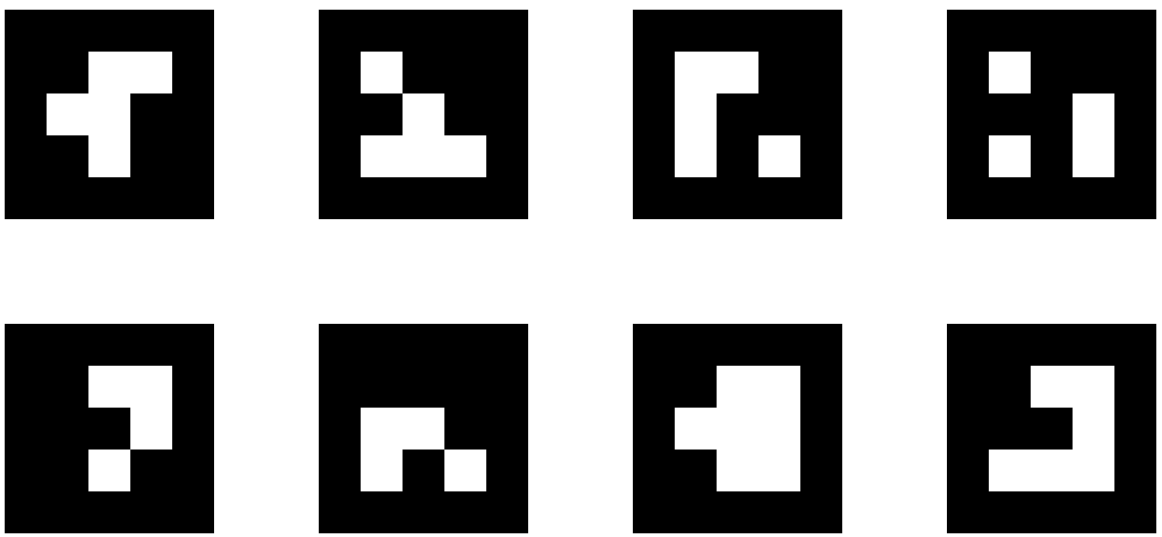


Figure 7: AruCo markers for cars and coordinate frame.

- 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

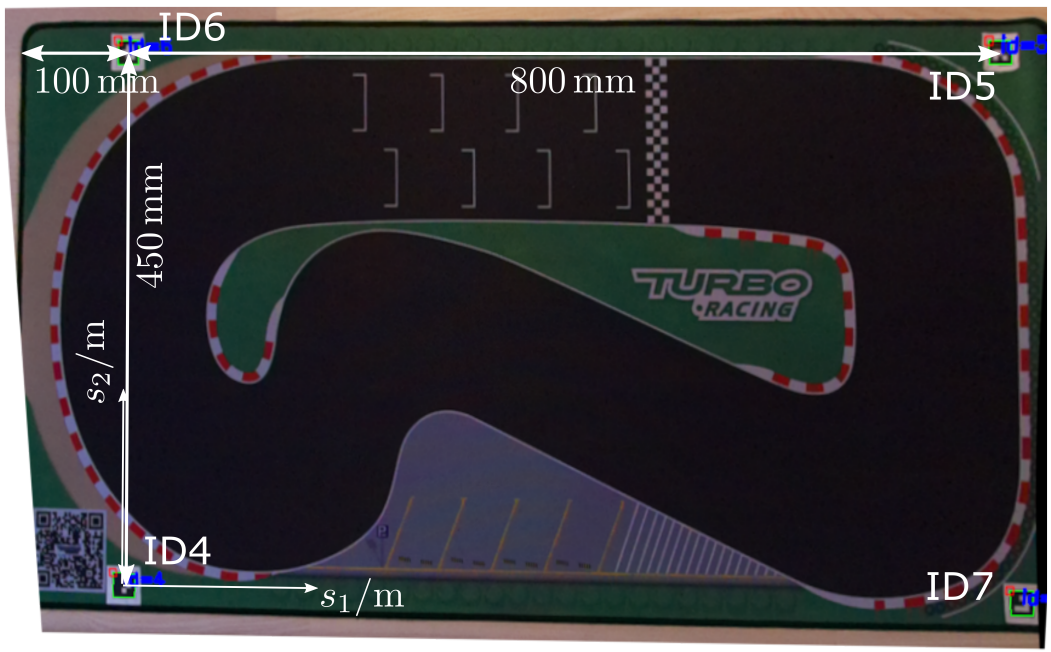



Figure 8: Track with 4 coordinate frame markers.

- 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

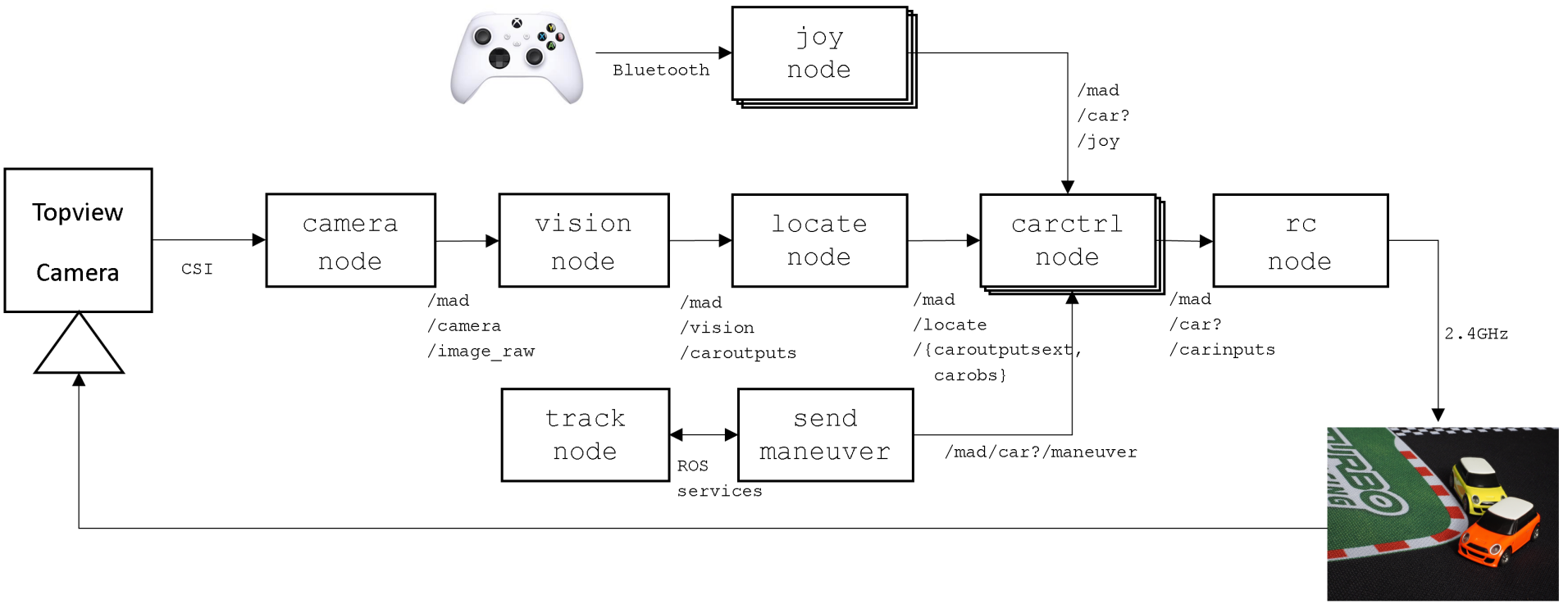



Figure 10: ROS2 nodes of MAD76 Driving Stack

| 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
```

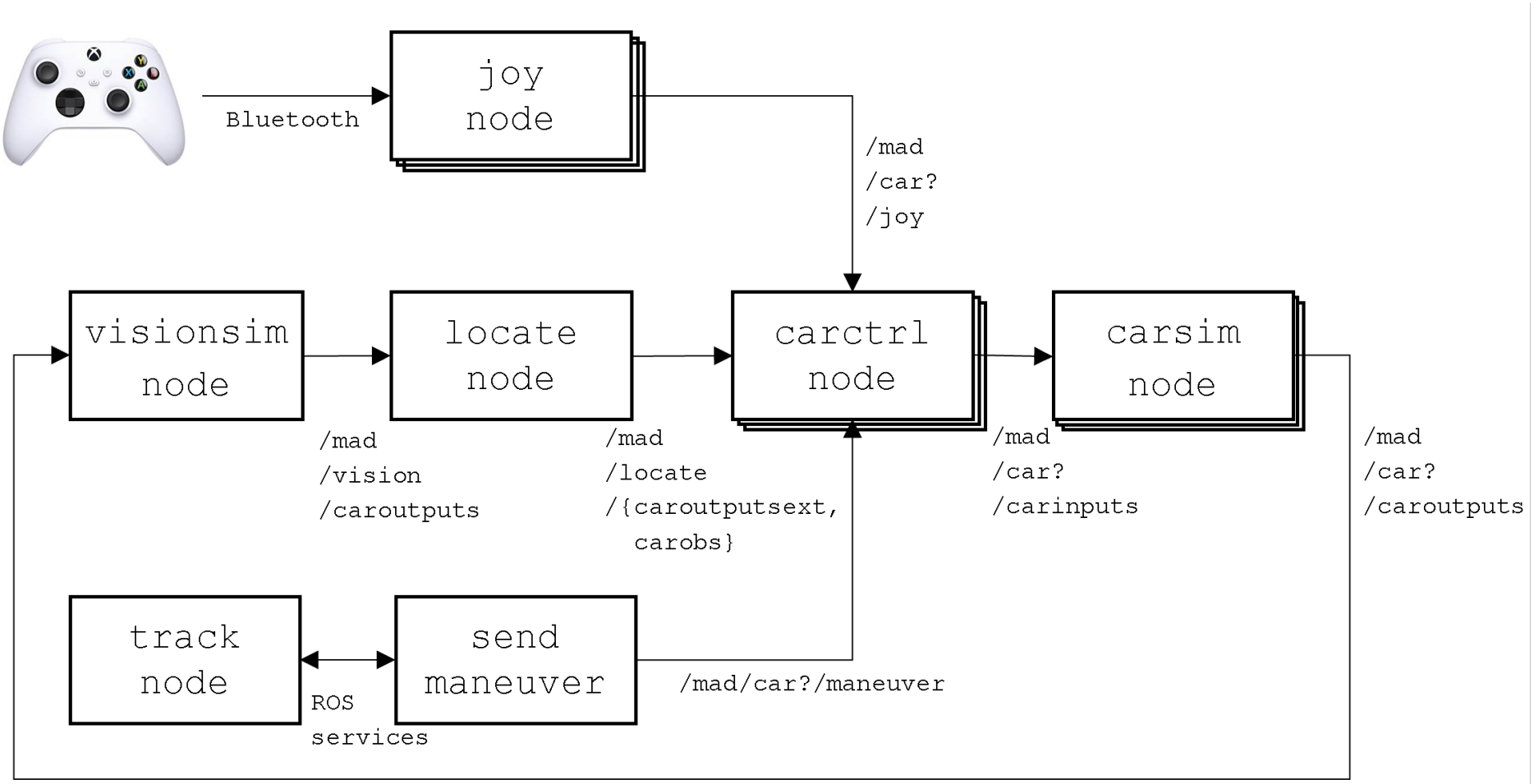





Figure 11: ROS2 nodes in SiL simulation mode

# 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/*`

# References

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

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

[5] ROS. *How to Calibrate a Monocular Camera*. Accessed: 2025-02-05. 2025. URL: https://wiki.ros.org/camera_calibration/Tutorials/MonocularCalibration.

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