**MyExoMy project 2021-2023**





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# Introduction

All credits for this document go to Maximilian Ehrhardt and Miro Voellmy who created a 3D printable robot ExoMy, a small version of the ExoMars Europe’s Rosalind Franklin ExoMars rover which is scheduled to be launched to Mars in 2028.  
They made a very nice open source hardware and software design. This document describes how I created my own version of the ExoMy, the MyExoMy.

This document can be seen as a notebook with practical information mainly for personal use.  
For a demonstration videos, see <https://www.youtube.com/watch?v=1YoyvSOGMOc> and <https://www.youtube.com/watch?v=Jo6-sg220eQ>.

# From Exomy to MyExoMy

The ESA standard open source hard and software design is a very good basis and suitable for all kinds of additions. See <https://www.esa.int/Enabling_Support/Space_Engineering_Technology/3D_print_your_own_Mars_rover_with_ExoMy>. Below the additions and changes are listed.

## Additions / changes in hardware

* A 20W solar panel is added to the design to charge the batteries. This way the MyExoMy can be 24/7 operational without the need of a separate charging station. Not that ‘operational’ means that for most of the time the MyExoMy will be sleeping and / or charging. Even in winter with dark and short days one should be able to drive a few minutes every day.  
  In summertime this is about 20 minutes every day. This could be higher but the charging current is limited to 60 mA to keep things simple and to be sure the batteries are not overcharged, although charging will stop when the batteries reach a threshold voltage.
* To accommodate the charging with the solar panel a Power Board is designed. This board provides safe charging for the batteries and power to all components like the Raspberry Pi, servo board and the lights. It can also put the MyExoMy in deep sleep.
* Instead of the LiPo accupack 11.1 V 3000 mAh, 5x baby C batteries HR14 NiMH 1.2 V 5500 mAh are used. This because of the following reasons:
  + The charging of NiMH batteries with a solar panel is more straightforward and safer.
  + No voltage converters (buck converters) are needed. Although these can reach a efficiency of > 90%, in practical use efficiency can be as low as 60%. Instead the 5x 1.2V batteries can directly provide 6V for the servo’s. A low drop voltage regulator is used to provide 5.0V for the Raspberry Pi.
  + Using a branch at the fourth battery provides 4.8V. This is needed to power an ATmega328P processor which can put the MyExoMy in deep sleep using as little as 100nA. This cannot be accomplished using a LiPo and an voltage converter.

There is also a disadvantage of the NiMH batteries. Although the energy content is about the same as for the LiPo battery, the weight is about 120 grams more.

* Two headlights are added so MyExoMy can also see at night.
* Microphone (mini USB microphone) and loudspeaker (HK-5002 USB minispeaker) are added for two-way audio.
* External Wifi antenna for Raspberry Pi for better Wifi performance (appr. 5 dBm improvement).
* Rubber 5 mm diameter O-rings are placed around the wheels. This to give MyExoMy a smooth ride on hard surfaces. On soft surfaces like sand the O-rings sink into the ground and the teeth of the wheels will provide the grip.

## A robot with wires and a remote control Description automatically generatedInside view

Figure 1 Inside view

A circuit board with wires and wires

Description automatically generated

Figure 2 Detailed inside view

## Power Board

The Power Board has the following features:

* Provides 5V for the RPi and 6V for the servos and the headlights.
* Can turn the MyExoMy into deep sleep mode, consuming only 100 nA.
* A switch is connected to an ATmega328P input pin to override the sleep mode for testing purposes.
* Can switch on the MyExoMy using an external trigger.
* Has a light sensor to turn on the lights when it is dark.
* Has a charge connection for the batteries.
* Has a trickle charge circuit with voltage protection for the solar panel.
* Measures the battery voltage and solar panel voltage for reporting on the web page.
* Has a trigger input to wake up from deep sleep mode.
* The 5 V provided for the RPi is done using the L4940V5 low drop voltage regulator. However, when the batteries are getting empty current spikes can result in the RPi resetting. Therefore an additional Shottky diode is used to lift the RPi voltage to appr. 5.15 V. Together with a 10000 μF capacitor close to the RPi gives the headroom needed to deal with current spikes.  
  The command vcgencmd get\_throttled can be used to check whether there has been an under-voltage, see <https://forum.libreelec.tv/thread/17860-how-to-interpret-rpi-vcgencmd-get-throttled/>.

## A diagram of a computer Description automatically generatedSchematic and layout

Figure 3 Power Board circuit, created with EasyEDA

A screenshot of a computer

Description automatically generated

Figure 4 Power Board PCB, manufactured at JLPCB

## Adding Audio

### Microphone

A black usb cable with a flexible cord

Description automatically generatedA mini USB microphone is added. The microphone is automatically recognized in Ubuntu 22.04.

Figure 5 Mini USB microphone

### Loudspeaker

A black speaker with holes

Description automatically generatedA HK-5002 USB minispeaker is added.

Figure 6 HK-5002 USB minispeaker

This minispeaker was originally USB-only and could occasionally draw > 1 A causing the Raspberry Pi to reboot. To get around this problem the following modifications were done:

* The USB chip is removed and the USB data wires are cut.
* The USB power lines are connected to the 6V batteries so the speaker does not draw power from the 5V regulated supply to which the Raspberry Pi is connected.
* The Raspberry Pi 3.5 mm stereo audio jack output is connected to the internal MIX2018/1 audio amplifiers.
* To enable audio on the 3.5 mm audio jack, the line  
  dtparam=audio=on  
  is added to /boot/firmware/config.txt.

#### External Antenna connected to RPi Wifi module

A circuit board with wires connected to it

Description automatically generatedAn external antenna to the Raspberry Pi is connected following  
<https://www.youtube.com/watch?v=MTwWnZG8wUY&ab_channel=CalebBeglyFun%26Tech>.  
The results are quite good, the received signal strength improves about 5 dBm.

Figure 7 External antenna with an U.FL connector on the Raspberry Pi board

## Wakeup transmitter

An orange box with wires and a black circuit board

Description automatically generatedFor the wakeup transmitter also a WakeUp Transceiver RC-WuTRx-433 module is used. This one is connected to an ESP32 board. The ESP32 board is always powered on and connected to Wifi. It runs an http or https server, see [https://techtutorialsx.com/2019/04/07/esp32-https-wb-server/](https://techtutorialsx.com/2019/04/07/esp32-https-web-server/)

Figure 8 Wakeup transmitter with ESP32 and RC-WuTRx-433 module

An orange rectangular object with a light on it

Description automatically generated

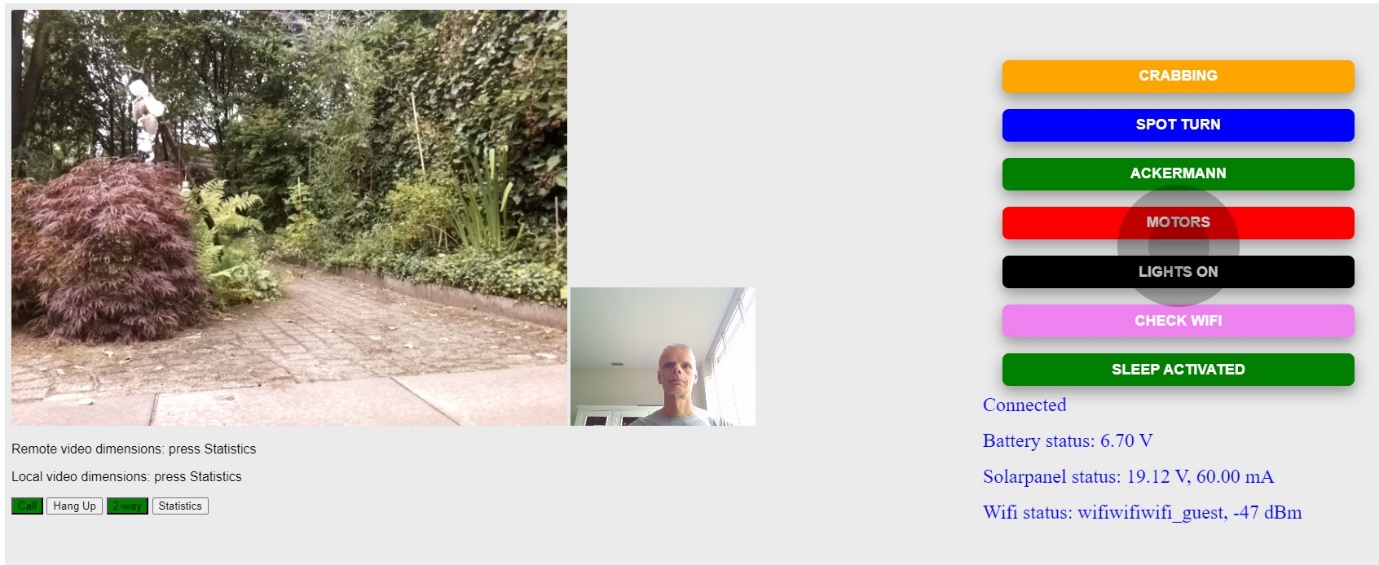
Figure 9 Wakeup transmitter in action

## A computer drawing of a circuit board Description automatically generatedAdditions / changes in software

Figure 10 Wakeup transmitter circuit, created with EasyEda

* The gui/index.html and gui/style.css were adapted to have a bigger video image and to display some statuses like battery, solar panel and wifi status.
* Instead of the original MJPEG video stream, WebRTC is used for streaming, providing low latency, low bandwidth two-way video and audio.
* The MyExoMy webserver port is changed from 8000 to 55555 in docker/run\_exomy.sh and docker/entrypoint.sh, just to have a less obvious port.
* In docker/Dockerfile some additional installations are done:
  + SMBus needed for I2C to communicate with the ATmega328P processor. This script needed smbus to be installed.
  + OpenSSH for communication between the Docker container and the Raspberry Pi host.
* In docker/entrypoint.sh some lines are added to copy the SSH key pair to /root for authentication so SSH can be used without password by a Python script.
* On the Raspberry Pi host the public half of the SSH key pair is installed manually on the Raspberry Pi host. See <https://upcloud.com/community/tutorials/use-ssh-keys-authentication> for a description.
* In src/robot\_node.py additional code was added to publish some statuses like battery status, solar panel status and Wifi status to the ‘/battery\_status’, '/solarpanel\_status' and wifi\_status topic respectively every second.
* In src/robot\_node.py additional code is added to handle the messages published by the Web page (in index.html) on the ‘/own\_button’ topic. These messages are:
  + lights\_on. Through I2C the ATmega328P is instructed to switch on the lights.
  + lights\_off. Through I2C the ATmega328P is instructed to switch on the lights.
  + goto\_sleep. Through I2C the ATmega328P is instructed to go to sleep. This will be acknowledged by the Arduino. Only after the acknowledge the Raspberry Pi will be shut down. The Docker container uses SSH to send the shutdown command to the Raspberry Pi host. The sequence of events:
    - Sleep button is pressed on the web page.
    - In index.html the message ‘goto\_sleep” is published on topic ‘/sleep\_status’.
    - In robot\_node.py the message callback function sends through I2C the instruction to the ATmega328P to go to sleep.
    - The ATmega328P acknowledges the goto\_sleep and goes to sleep after a delay. This delay is needed to enable the Raspberry Pi to shut down in a proper way.
    - robot\_node.py checks for the acknowledge and then sends the shutdown command with SSH to the Raspberry Pi host.
* In src/motor\_node.py the watchdog\_timer for stopping the drive motors is changed from 5 s to 0.5 s. This to make sure that if the Wifi connection drops the MyExoMy stops in 0.5 second. It still is possible that after the MyExoMy stops it starts moving again due to delayed Wifi packet delivery. A way to deal with this is to release the joystick on the web page as soon as the video hangs. Tests show that the MyExoMy then indeed will stop within 0.5 s.
* In src/motor\_node.py the watchdog\_timer also sends an I2C ‘motion’ command to the ATmega328P to indicate that the MyExoMy is in motion, preventing the ATmega328P to put the MyExoMy to sleep. This means that the MyExoMy will be put to sleep when there is no motion for a certain period of time e.g. because of a connection loss. A switch is connected to an ATmega328P input pin to override this for testing purposes.
* In src/motors.py the drive motors are switched off when the speed is very low. This to eliminate the need to calibrate the drive motors to zero speed using the potentiometer every time.
* To prevent Ubuntu to report internal errors where a window pos up and halting the system, the Apport Error Reporting Service is stopped by setting enabled=0 in the file /etc/default/apport.

## Updated web page

Below a screenshot of the updated web page is depicted.

The most important additions:

Figure 11 MyExoMy web page, two-way call enabled

* Button for 2-way video and audio call (WebRTC).
* Continuous status update of Battery, Solar panel and Wifi signal.
* Button to switch to the strongest Wifi access point available.
* Button to put the MyExoMy in deep sleep.

# Tools

## EasyEda PCB settings:

* The track width is chosen to be 0.8 mm with a clearance of 0.4 mm.
* The copper thickness is chosen to be 2 oz = 2x 1.4 mil = 2x 35 μm = 70 μm. Normally it is 1 oz. 2 oz is chosen to allow more current and for robustness. It cannot be set in EasyEda but it can be selected when ordering at JLCPCB.
* According to <https://www.7pcb.com/trace-width-calculator.php> with a track width of 0.8 mm and a thickness of 2 oz the current can be appr. 3A.
* Only the battery tracks have a width of 1.27 mm and with 2 oz thickness can carry appr. 5A.

## Ultimaker Cura settings

The following printer settings were changed from the default for printing the MyExoMy robot with the Creality 3D CR-20 Pro 3D printer.

* Printing Temperature set to 210°.
* Build Plate Temperature set to 60°.
* Layer Height set to 0.15 mm.
* Print speed set to 50 mm/s.
* Initial Layer Speed set to 10 mm/s.
* If support is needed, Support Structure can be set to Tree for easier removal.
* If the first layer is problematic, set Build Plate Adhesion to Raft (i.s.o. Skirt). For small parts this is advisable.
* For the larger parts the Build Plate Adhesion is set to None (i.s.o Skirt).

# Installation of Ubuntu and ROS2 on Raspberry Pi

## Ubuntu on Raspberry Pi

Ubuntu Desktop 22.04.2 LTS (64 bit, codename ‘Jammy Jellyfish’) is installed natively on the Raspberry Pi using the Raspberry Pi Imager. Installation is most convenient with a monitor, keyboard and mouse connected.

After writing the image to the SD card:

* Perform a   
  sudo apt-get update  
  sudo apt-get upgrade
* Install openssh-server following <https://linux.how2shout.com/how-to-enable-ssh-server-on-ubuntu-22-04-jammy-linux/>
* Enable Screen Sharing (VNC) and Remote Login (SSH) via Settings -> Sharing. Note that a VNC server is already available in the standard Ubuntu desktop installation.
* To open a remote desktop you can use RealVNC viewer. Therefore enable ‘Enable Legacy VNC Protocol’ under Ubuntu -> Settings -> Sharing -> Remote Desktop’. In RealVNC viewer, under right click -> ‘Properties… -> Options’ choose another ‘Picture quality’ than ‘Automatic’ otherwise there will be a ‘Protocol error: bad rectangle size’ error message.  
  In addition there is a problem in Ubuntu 22.04 storing the remote desktop password under ‘Settings -> Sharing -> Remote Desktop -> Password’. This can be solved using <https://askubuntu.com/questions/1403943/22-04-remote-desktop-sharing-authentication-password-changes-every-reboot>.
* It is also possible to use the Windows ‘Remote Dektop Connection’ application. In addition there is a problem in Ubuntu 22.04 storing the remote desktop password under ‘Settings -> Sharing -> Remote Desktop -> Password’. This can be solved using <https://askubuntu.com/questions/1403943/22-04-remote-desktop-sharing-authentication-password-changes-every-reboot>. The performance seems to be better than with the RealVNC viewer.
* Install the libcamera library, which is the successor of VideoCore utilities, such as raspistill and raspivid. However, under Ubuntu 22.04 the libcamera library is not available yet. As an alternative, install raspi-config following <https://elbruno.com/2022/09/02/raspberrypi-install-raspi-config-on-ubuntu-22-04-1-lts/>  
  and enable Interface Options -> Legacy Camera Enable/disable legacy camera support .  
  This will enable the camera, make sure the bcm2835-v4l2 module, which is a Video4Linux2 (V4L2) driver is loaded when needed, create the /dev/video0 device representing the camera and enabling the gpu by adding:  
  start\_x=1  
  gpu\_mem=128  
  to /boot/firmware/config.txt. After reboot, the camera will then be available as a mmal service 16.1 camera.
* The camera can be tested using <https://webrtc.github.io/test-pages>.
* On Ubuntu set the display resolution to 1280x720 (16:9) to limit the CPU load when running WebRTC video.
* If needed, raspi-config can be installed following <https://elbruno.com/2022/09/02/raspberrypi-install-raspi-config-on-ubuntu-22-04-1-lts/>
* Add package for I2C communication with ATmega328P.  
  apt-get update && apt-get install python3-smbus -y
* Install i2c-tools with sudo apt-get install i2c-tools
* Create a file called 99-i2c.rules in directory /etc/udev/rules.d with the following content:  
  SUBSYSTEM=="i2c-dev", MODE="0666"  
  This will give all users access to I2C and sudo need not be specified when executing programs using i2c-bus.  
  See <https://github.com/fivdi/i2c-bus/blob/master/doc/raspberry-pi-i2c.md>.
* Finally, in ‘/lib/udev/rules.d/60-i2c-tools.rules’, change  
  KERNEL=="i2c-[0-9]\*", GROUP="i2c", MODE="0660"  
  to  
  KERNEL=="i2c-[0-9]\*", GROUP="i2c", MODE="0666"  
  and then reboot to have the I2C device readable by the i2c group.
* From kernel version 3.18 on (‘uname –a’ shows kernel version): to use GPIO2 (pin 3) and GPIO3 (pin 5) as SDA and SCL respectively, add dtparam=i2c\_arm=on,i2c\_baudrate=32000 at the end of /boot/firmware/config.txt. The last part sets the I2C speed to 32 kbit/s. The default baudrate is 100 kbit/s which seems to be too fast for the Arduino; when using this baudrate an occasional ‘[Errno 5] Input/output error’ is observed when executing the Python ‘bus.read\_byte\_data()’ or ‘bus.write\_byte\_data()’ function. This is probably because the standalone ATmega328P processor runs on 8 MHz. Because the Raspberry Pi does not support I2C clock stretching, slowing down the I2C clock speed is an acceptable solution, see <https://learn.adafruit.com/circuitpython-on-raspberrypi-linux/>.
* Add the exomy user to the i2c group, to do this type sudo adduser exomy i2c.
* Install Adafruit PCA9685 Servo HAT library with pip install adafruit-pca9685
* Enable automatic login (no username / password required) via Settings -> Users -> Automatic Login.
* Disable screen lock via Settings -> Privacy -> Screen -> Automatic Screen Lock
* Set ‘Automatically check for updates’ to ‘Never’ via Software & Updates.
* Install packages for web application.  
  Update repository list for Node.je installation:  
  sudo curl -sL https://deb.nodesource.com/setup\_12.x | sudo bash -  
  Install Node.js:  
  sudo apt-get install nodejs -y  
  Install Node.js http-server:  
  sudo npm install http-server -g
* Install ROS2 generic joystick interface node for ROS2 Galactic. This is only needed when a physical gamepad is used:  
  sudo apt-get install ros-humble-joy -y
* Install rosbridge\_suite for websocket communication between web browser and ROS2  
  sudo apt install ros-humble-rosbridge-suite
* To enable websockets over ssl, add  
  <arg name="ssl" default="true" />  
  <arg name="certfile" default="/home/ubuntu/exomy/ssl/server.crt" />  
  <arg name="keyfile" default="/home/ubuntu/exomy/ssl/server.key" />  
  <arg name="authenticate" default="false" />  
  to /opt/ros/galactic/share/rosbridge\_server/launch/rosbridge\_websocket\_launch.xml
* To enable audio on the 3.5 mm audio jack, the line  
  dtparam=audio=on  
  is added to /boot/firmware/config.txt (in Ubuntu).
* Check the available audio device with aplay -l. There the ‘Headphones’ device should be present.
* If no sound can be heard, check the volume under Settings -> Sound -> System Volume.
* By default, only display resolution 1824x984 is available. To enable multiple screen resolutions, add to /boot/firmware/config.txt:

dtparam=spi=off  
dtoverlay=vc4-fkms-v3d  
hdmi\_drive:0=1  
hdmi\_group:0=2  
hdmi\_mode:0=82  
hdmi\_force\_hotplug=1  
hdmi\_drive:1=1  
hdmi\_group:1=2  
hdmi\_mode:1=82

Set the display resolution to 1280x720 (16:9) to limit the CPU load when running WebRTC video.

## ROS2 on Ubuntu

* Install ROS2 Humble following <https://docs.ros.org/en/humble/Installation.html>
* Don’t forget to source ROS 2 in every new terminal you open!
* Before launching nodes, also source the install/setup.bash so ROS2 can find the packages.

## Additional ROS2 tools

* Install Gazebo with curl -sSL http://get.gazebosim.org | sh
* Run Gazebo with gazebo

## Example ROS2 commands

For many of the example commands the nodes must be running.

* Use colcon build --event-handlers console\_direct+ to show console output while building (can otherwise be found in the log directory).
* Use ros2 pkg list to list the packages.
* Use ros2 node list to list the nodes.
* Use ros2 topic list to list the topics
* Use ros2 topic info /exomy\_pkg/motor\_commands to get the message types
* Use ros2 topic pub --once /exomy\_pkg/motor\_commands messages\_pkg/msg/MotorCommands '{motor\_speeds: [0, 0, 0, 0, 0, 0], motor\_angles: [0, 0, 0, 0, 0, 0]}' to publish once to the messages\_pkg/msg/MotorCommands topic.
* Use ros2 topic echo /exomy\_pkg/motor\_commands messages\_pkg/msg/MotorCommands to listen to the messages on topic /exomy\_pkg/motor\_commands using message type messages\_pkg/msg/MotorCommands.
* Use ros2 param get /exomy\_pkg/motor\_node pin\_drive\_cl to get a parameter from the motor\_node.
* Use rqt\_graph to get a graph of nodes and topics.

# Startup MyExoMy

## Automatic startup

To automatically startup the exomy, the following parts are started:

* Webserver.
* Rosbridge node for websocket communication.
* Exomy nodes.
* WebRTC signaling server and web browser.

A start.sh bash script has been created in $HOME/exomy for this purpose. Make it executable using chmod 755 start.sh.

Because starting up includes starting up a web browser it can only startup after the Gnome desktop is loaded. Therefore in /home/ubuntu/.config/autostart an exomy.desktop file is added.  
This file has the following content:  
[Desktop Entry]  
Type=Application  
Name=conky  
Exec=/home/ubuntu/exomy/start.sh  
StartupNotify=false  
Terminal=false

To write all stdout and stderr of start.sh to a logfile one can use:  
Exec=/bin/bash -c '/home/exomy/exomy/start.sh > /home/exomy/exomy/output.log 2>&1'

## Manual startup

Use the $HOME/exomy/start.sh script as example or with parameters to manually start up.

# Changing code

When a python script is changed, the ROS2 nodes must be rebuilt and installes as follows: /home/ubuntu/exomy use

. /opt/ros/humble/setup.bash  
cd $HOME/exomy  
colcon build  
. ./install/setup.bash

# ROS2 nodes

Using the command rqt\_graph the following graph is shown:

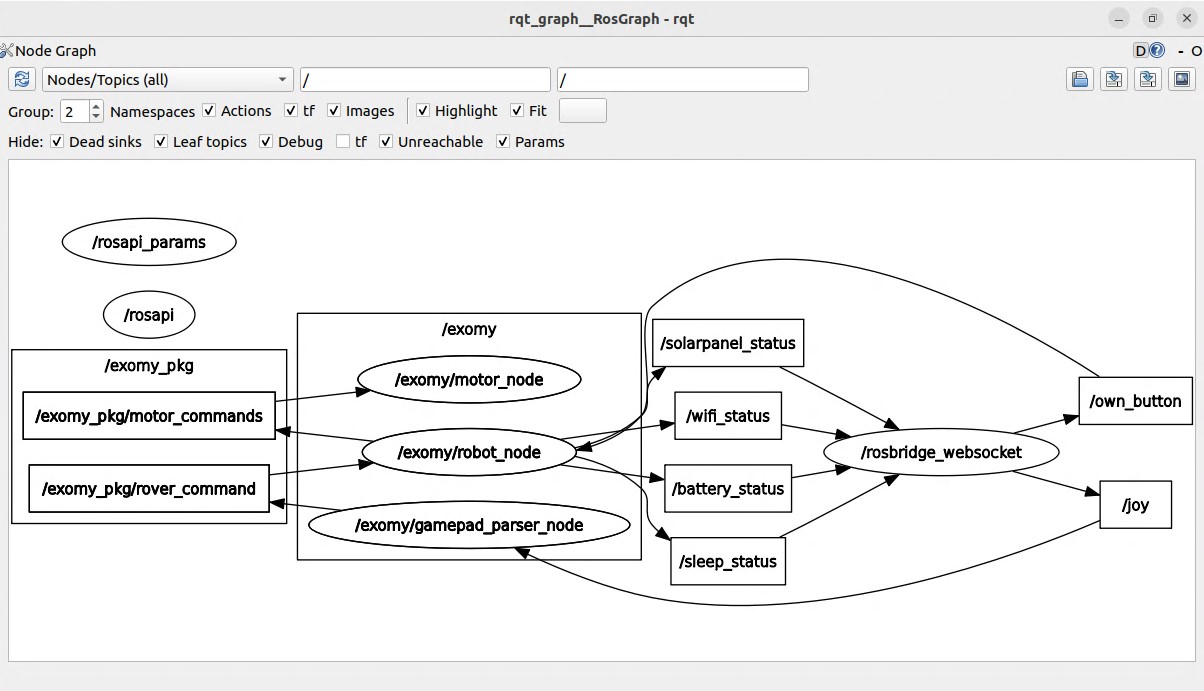
Scenario:

Figure 12 rqt graph showing nodes and topics

* When on the webpage the joystick is moved, a sensor\_msgs/Joy message is published on the /joy topic through the rosbridge. This message contains the joystick axes and the buttons (for the locomotion mode, e.g. ‘Ackermann’).
* The gamepad\_parser\_node transforms this message to a RoverCommand message containing velocity, steering and locomotion mode an publishes this to the exomy\_pkg/rover\_command topic.
* The robot\_node transforms this message to a MotorCommands message containing speeds (6x for the driving servos) and angles (6x for the steering servos) for each servo and publishes this on the /exomy\_pkg/motor\_commands topic.
* The motor\_node sets the actual pwm values on each servo (12 in total).
* When on the webpage the ‘Lights’ or ‘Sleep’ button is pressed, a std\_msgs/String message is published to the /own\_button topic through the rosbridge. This message contains a string indicating the button pressed. The robot\_node handles these messages, e.g. by sending an I2C command to the Arduino to turn on the lights.
* The robot\_node publishes the battery, solarpanel, battery, wifi and sleep status as a std\_msgs/String message on the corresponding topic which are displayed on the webpage through the rosbridge.

# Investigations

Below some investigations are described, just to document things which took some effort to find out.

## Connecting to the Raspberry Pi with SSH and remote desktop (VNC).

## For the first time

This described at <https://github.com/esa-prl/ExoMy/wiki>, but not for headless mode (without a monitor). This is described at <https://desertbot.io/blog/headless-raspberry-pi-4-remote-desktop-vnc-setup>.

## When connection is lost for whatever reason, and no monitor connected to the Raspberry Pi is available.

If for whatever reason connection to the Raspberry Pi is lost, the most obvious thing to do is to attach a monitor to the Raspberry Pi and fix it. If however, no monitor is available, remove the SD memory card from the Raspberry Pi and put it in the laptop. If the SD card is not corrupt, two drives are mounted, one of them is the boot partition and can be read with Windows. Follow again the instructions on <https://desertbot.io/blog/headless-raspberry-pi-4-remote-desktop-vnc-setup>. Make sure all settings are done correctly the first time the SD card is put back in the Raspberry Pi. Note that the empty ‘ssh’ file and the file ‘wpa\_supplicant.conf’ will be removed again after the next reboot. So if things do not work the process has to be repeated.

## Way of working

### For development

* Connect to the RPi using SSH.
* Use sh ~/ExoMy\_Software/docker/run\_exomy.sh -d to start the ExoMy Docker container for development. This will map the Docker container folder /root/exomy\_ws/src/exomy which contains the ExoMy scripts to /home/pi/ExoMy\_Software. This is done by the run\_exomy.sh script by using the ‘-v’ (volume) option with the docker run command.
* On the host computer open FileZilla and connect to the RPi using port 22 for SFTP (SSH FTP). This way files can be transferred between the host computer and /home/pi/ExoMy\_Software. Because this folder is mapped to the ExoMy Docker folder /root/exomy\_ws/src/exomy any change will have immediate effect on the running container. This way the changes will be permanent and not lost when the container is stopped.
* When changing something in a GUI Web Interface .css or .js file, it is necessary to delete the history of the browser before the changes can be seen, as these files are cached by default!
* After logging in to the RPi one can run the Docker exomy\_devel container for development with:  
  sh ~/ExoMy\_Software/docker/run\_exomy.sh -d : starts the exomy\_devel container  
  And then in sequence:  
  source /opt/ros/melodic/setup.bash : does some catkin setup   
  cd /root/exomy\_ws  
  catkin\_make : builds all ROS packages  
  http-server --ssl --cert /root/exomy\_ws/src/exomy/ssl/server.crt --key /root/exomy\_ws/src/exomy/ssl/server.key src/exomy/gui -p 55555 & : starts the web server  
  source devel/setup.bash : does some catkin setup  
  roslaunch exomy exomy.launch : starts the ROS nodes as specified in exomy.launch
* When a python script is changed it is required to quit ROS and to issue roslaunch again.
* In docker/run\_exomy.sh one can see that all Docker containers are based on the same image named ‘exomy’.

### For normal operation

* Use a single sh ~/ExoMy\_Software/docker/run\_exomy.sh -a and ExoMy will become operational, also after a reboot.
* The ExoMy can be operated through its web page at port 55555.

## About Docker

Docker is used on the ExoMy to provide a reliable and reproducable runtime environment. Docker uses a stable read-only image (ros:melodic) and additional installation commands specified in docker/Dockerfile are used to build a container where the software runs. Compare this with using an writable image and manually adding installations to it and letting it grow and grow. This is very hard to maintain or to roll back or repair if somethings goes wrong.

The ExoMy docker containers are based on Ubuntu 18.04.5 LTS (Bionic Beaver).

Advantages Docker

* Provides a reliable and reproducable runtime environment.

Disadvantages Docker

* Some high performance tools do not work inside the Ubuntu Docker environment or with less performance, like MJPG-Streamer (less performance) and UV4L (Raspberry Pi OS only).

## Installing ROS Melodic on Raspberry Pi OS (Debian Buster), no Ubuntu or Docker.

To avoid the Docker / Ubuntu disadvantages one can install ROS on the Raspberry Pi OS (Debian Buster) following <https://www.instructables.com/ROS-Melodic-on-Raspberry-Pi-4-RPLIDAR/>.

## Wifi configuration in /etc/wpa\_supplicant/wpa\_supplicant.conf

On the Raspberry Pi host use sudo nano /etc/wpa\_supplicant/wpa\_supplicant.conf to add the wifi SSID and password of the network to which MyExoMy can connect.

## Communication between the Docker container and the Raspberry host

For some purposes communication between the Docker container and the Raspberry Pi host is needed. For example to shut down the Raspberry Pi host or to get the Wifi status. This is accomplished by using SSH. To enable Python to use SSH, SSH keys must be (one time) manually installed in the Docker container (private and public) and on the Raspberry Pi host (public) with:

mkdir -p ~/.ssh  
chmod 700 ~/.ssh  
ssh-keygen -t rsa

And finally copy the public key to the Raspberry Pi host. On Docker for Linux, the IP address of the gateway between the Docker host and the bridge network is 172.17.0.1 if you are using default networking. So be sure to use that address here.

ssh-copy-id -i ~/.ssh/id\_rsa.pub pi@172.17.0.1

When the container is restarted, the SSH keys in the container will be lost, zo the are copied back by some added lines the docker/entrypoint.sh script. The public SSH key on the Raspberry Pi host will remain.  
The .ssh folder containing the public and private key is added to the .gitignore file.  
See also <https://upcloud.com/community/tutorials/use-ssh-keys-authentication> for a description.

## Start and view RTSP stream

* Start RTSP server on Raspberry Pi:  
  raspivid -o - -t 0 -hf -w 1920 -h 1080 -fps 30 | cvlc -vvv stream:///dev/stdin --sout '#rtp{sdp=rtsp://:8554/x}' :demux=h264
* View in VLC:  
  GUI -> Media -> Open Network Stream -> rtsp://192.168.1.42:8554/x

Note: it is needed to give the stream a name, here ‘x’.

## Improved video streaming to web page

To improve the video streaming several streaming options have been investigated. At the moment the Chrome WebRTC API is used.  
In all cases, when using the Raspberri Pi camera, choose a resolution such that is used so the FoV (Field of View) of the Raspberry Pi camera is full, see <https://picamera.readthedocs.io/en/release-1.12/fov.html>.

When the streaming is done from the Raspberry Pi host, the web\_video\_server and usb\_cam ROS nodes must be removed from the launch/exomy.launch file. Also the port forwarding of port 8080 must be removed from the docker/run\_exomy.sh file.

### Increase resolution in launch/exomy.launch

The most straigthforward way is to increase the resolution of the usb\_cam ROS node as specified in launch/exomy.launch. This can be set to 800x600 and maintaining an acceptable latency (< 0.5 s).

### MJPEG-Streamer

The MJPG-Streamer can be installed in the container following <https://www.sigmdel.ca/michel/ha/rpi/streaming_en.html>. The installation is copied to /root/exomy\_ws/src/exomy which is shared with the host This way the MJPG-Streamer will be available in a new container.  
The following command can be used to stream the video stream to a web page:

/root/exomy\_ws/src/exomy/mjpg-streamer/mjpg\_streamer -i "/root/exomy\_ws/src/exomy/mjpg-streamer/input\_uvc.so -n -f 20 -q 85 -r 1200x900" -o "/root/exomy\_ws/src/exomy/mjpg-streamer/output\_http.so -p 8080 -w /root/exomy\_ws/src/exomy/mjpg-streamer/www"

This command will use /dev/video0 as the video device.

The stream can be viewed via the MJPG-Streamer web page at 192.168.1.42:8080 or directly at 192.168.1.42:8080/stream\_simple.html.

To stop the stream use:

killall mjpg\_streamer > /dev/null 2>&1

On the web page the stream can be picked up using  
stream\_url = '//' + host\_url + ':8080?action=stream'

**Advantages of MJPG-Streamer**

* Reasonable image quality and low latency (< 0.5 s @ 1920x1080).

**Disadvantages of MJPG-Streamer**

* Not maintained anymore.
* When used with input\_uvc.so i.s.o. input\_raspicam.so the image quality and latency are worse.

### GStreamer

Install GStreamer on the Raspberry Pi host following <https://raspberry-projects.com/pi/pi-hardware/raspberry-pi-camera/streaming-video-using-gstreamer>

On Linux it can be installed following <https://gstreamer.freedesktop.org/documentation/installing/on-linux.html>

Basic test when on the desktop (directly or with VNC Viewer):  
gst-launch-1.0 v4l2src device="/dev/video0" ! videoconvert ! autovideosink  
When run on the desktop (not via SSH) one should see a video window.

Start streaming with:  
gst-launch-1.0 v4l2src device=/dev/video0 ! video/x-raw,width=640,height=480,framerate=30/1 ! videoconvert ! jpegenc ! rtpjpegpay ! tcpserversink host=192.168.1.42 port=8080

**Advantaged GStreamer**

* GStreamer is open source and multi-platform.

**Disadvantages GStreamer**

* Most examples show a GStreamer server streaming to a GStreamer client. A working example of streaming to a web page has not been found yet.

### Pi H264 To Browser

A custom H264 streamer making use of Tornado and jMuxer.  
**Advantages Pi H264 To Browser**

* The video is very customizable, the quality setting is useful.

**Disadvantages Pi H264 To Browser**

* The package makes use of python3-picamera, which cannot be installed in the Ubuntu Docker container.
* When running, the video starts at low latency (< 0.5 s), but the latency increases up to a few seconds. This still has to be solved.

See <https://github.com/dans98/pi-h264-to-browser>.

### UV4L

UV4L can be installed on the Raspberry Pi host following  
<https://www.linux-projects.org/uv4l/installation/>

#### MJPEG encoding

A uv4l\_raspicam streaming service can be started with:  
sudo systemctl start uv4l\_raspicam  
It will use then the settings as specified in /etc/uv4l/uv4l-raspicam.conf.

To make it start after reboot:  
sudo systemctl enable uv4l\_raspicam

The service will use the /dev/video0 device.  
The service will be restarted automatically after a reboot.

To stop the service  
sudo systemctl stop uv4l\_raspicam  
To disable the service (so it will not start after the next reboot):  
sudo systemctl disable uv4l\_raspicam  
to check the status:  
sudo systemctl status uv4l\_raspicam

The uv4l streaming can be also started manually with:  
uv4l --auto-video\_nr --driver raspicam --encoding mjpeg --width 1200 --height 900 --framerate 20 –quality 85 --server-option '--port=8080'  
The uv4l process is a process without tty (daemon) and can be listed with  
ps ax  
The stream can be stopped by killing the process.

On the web page the stream can be picked up using  
stream\_url = '//' + host\_url + ':8080/stream/video.mjpeg'

#### H.264 encoding

It is also possible to use H.264 encodeing from the Rasberry Pi by issuing  
uv4l --auto-video\_nr --driver raspicam --encoding h264 --width 1200 --height 900 --framerate 20 –quality 85 --server-option '--port=5000'

The stream can be viewed under Windows with VLC installed by issuing from the command prompt:  
"c:\Program Files (x86)\VideoLAN\VLC\vlc.exe" [http://192.168.1.42:5000/stream/video.h264 --demux h264](http://192.168.1.42:5000/stream/video.h264%20--demux%20h264)

The video is of high quality, the framerate and the bit rate of about 10 Mbit/s instead of 100 Mbit/s when mjpeg is used (all other conditions are the same).  
However, when watching with VLC the latency is about 3 seconds and the processing (probably on the Raspberry Pi) seems to be a problem as sometimes the video freezes.  
To display the stream on a web page it should be packed into mp4 first. This has not been investigated yet.

**Advantages of UV4L**

* UV4L uses WebRTC (Web Real-Time Communications). WebRTC started in 2011, but in 2021 it became an official Web Standard and a World Wide Web Consortium (W3C) recommendation.
* Using WebRTC with H.264 video encoding the video quality is high (when hardware encoding and decoding is enabled) and latency is consistently low (< 0.5 s @ 1920x1080) which gives a great driving experience.
* UV4L uses WebRTC which is designed for low latency connections. WebRTC uses UDP. For comparison, websockets use TCP. While driving UTP gives a better experience; after a connection hiccup the video takes up again fast.

**Disadvantages of UV4L**

* UV4L is closed source. Therefore it is difficult to customize / integrate with own web page.
* Does not seem to work on Android phone or tablet when hardware encoding is used (H.264). When no hardware decoding is selected (VP8) it works but then the resolution is low and cannot be changed.
* The connection for WebRTC must be SSL, meaning on the client device the CA certificate must be added as a trusted root authority.
* UV4L does not install on the ExoMy container Ubuntu version. Therefore it must run on the Raspberry Pi host which is not ideal.
* UV4L gives more CPU load (60%) than Rpi-WebRTC-Streamer (30%) when streaming according to htop. Note that the maximum CPU load for the Raspberry Pi 4 model B is 400% (100% for each core).
* When the streaming service runs, FileZilla is very unresponsive.

See also <https://www.youtube.com/watch?v=5QAHlZoPlgI&ab_channel=ReefNerd>.

### Rpi-WebRTC-Streamer

To start the stream: sudo systemctl start rws  
To stop the stream: sudo systemctl stop rws

**Advantages of Rpi-WebRTC-Streamer**

* WebRTC combination of H.264 encoding and UDP gives low latency and low bandwidth.
* Source code available.
* Works on desktop browser and Android browser.
* Rpi-WebRTC-Streamer gives less CPU load (30%) than Uv4L (60%) when streaming according to htop.

**Disadvantages of Rpi-WebRTC-Streamer**

* Runs only on Raspberry Pi host. Installing in a Ubuntu 18.04.5 LTS (Bionic Beaver) container gives dependency problems with libasound2. Building from source in a container might resolve this.
* There is a bug causing the webrtc-streamer to crash and stopping the stream. The error message when running sudo /opt/rws/webrtc-streamer –verbose:  
  [009:295] [22219] (mmal\_wrapper.cc:150): frame\_buf\_pos : 196657, buffer length: 11943  
  # Fatal error in: mmal\_wrapper.cc, line 153  
  # last system error: 0  
  # Check failed: (int)(frame\_buf\_pos\_ + buffer->length) < size\_  
  # Aborted  
  This seems to be related to the MMAL buffer size according to a posted debug version (<https://github.com/kclyu/rpi-webrtc-streamer/issues/37>) with increased frame buffer size (from 65536\*2 to 65536\*3):  
  (mmal\_wrapper.cc:152): frame\_buf\_pos : 131119, buffer length: 25370  
  One can see that the offset 131119 falls outside the original MMAL frame buffer size.  
  This repaired version of the webrtc\_streamer executable is installed in /opt/rws which fixes the issue.  
  It is not clear why this bug fix is not in the latest release.  
  Fixing and rebuilding from source would be an option, but the WebRTC native-code library has to be cross compiled from Ubuntu. Unfortunately the build recipe is very complicated and lots of errors occur. From the GitHub comments in “Issues” it seems that building does currently not work.

See <http://www.softwaresamurai.org/2017/10/14/uv4l-webrtc-vs-rpi-webrtc-streamer/>  
and  
<https://github.com/kclyu/rpi-webrtc-streamer/>.

### EasyRTC

**Advantages of EasyRTC**

* Runs on any platform that can run node.js.
* Good documentation on how to build your own WebRTC application!

**Disadvantages of EasyRTC**

* Current state / support is not clear as some links at <https://easyrtc.com/> are dead.  
  It seems that the project is continued at <https://github.com/open-easyrtc/open-easyrtc>.
* The demo application executed on the Raspberry Pi works but is not yet convincing; the video quality is not high and the latency is near 0.5 sec, while the bitrate is around 10 Mbit/s @800x600, 20fps. Higher resolution give a distorted image.

See <https://easyrtc.com/> and <https://github.com/open-easyrtc/open-easyrtc>.

### Jitsi on Raspberry Pi

For telepresence two way communication Jitsi can be installed on Raspberry Pi.  
prerequisite is an 64 bit OS is installed fist, like Ubuntu 64 bit and at least 4 GB of RAM is available.

See <https://peppe8o.com/self-host-your-web-meetings-with-jitsi-and-raspberry-pi/>.

### Chrome WebRTC

Chrome implements a well documented WebRTC API. An example WebRTC connection is available at <https://codelabs.developers.google.com/codelabs/webrtc-web>. This repository contains:

* The WebRTC signaling server code using websockets.
* The custom WebRTC client code in which the used media and STUN server can be defined. It includes the index.html page of the WebRTC client serving the video / audio stream and call / hangup buttons.

A node.js server is started (in start.sh) to serve both the index.html page and the webscockets at port 8080.  
For an introduction to the WebRTC protocol: <https://developer.mozilla.org/en-US/docs/Web/API/WebRTC_API/Signaling_and_video_calling>.

|  |
| --- |
| Summary of WebRTC communication on MyExoMy   * For fast communication WebRTC uses UDP peer-to-peer video and audio streaming between two peers (browsers). * There are two peers: the MyExomy peer (Chromium browser) and a remote peer (any browser). This remote peer can be outside the local network. * There is also a node.js signaling server running on the MyExoMy. This signaling server hosts a webpage on port 8080 and contains java scripting (main.js) for doing the WebRTC API calls needed to set up the peer-to-peer connection. * The signaling server makes use of the Socket.IO javascript library for websocket communication (also through port 8080 in this case) with both peers so messages can be sent from one peer to the other through the signaling server. * At startup of the MyExoMy the signaling server will be started (by calling node index.js) up together with the MyExoMy peer which will be the first to log onto the signaling server. * The MyExoMy peer will in sequence call:   + getUserMedia() to get the local media stream with audio and video tracks as requested. For MyExomy this will be one local video track.   + createPeerConnectionAndAddLocalTracks() which will create a peer connection and add the local video track to it.   + createOfferAndSendToPeer() which will create an SDP (Session Description Protocol) offer which is sent over the signaling channel to the remote peer. SDP contains the codec, source address, and timing information of audio and video. In addition the MyExoMy peer will set this as local SDP by calling pc.setLocalDescription. The remote peer receiving the offer will set this as remote SDP by calling pc.setRemoteDescription. After this ICE (Interactive Connectivity Establishment) candidates are retrieved and sent over the signaling channel (by handleIceCandidate() being set as the pc.onicecandidate callback) to the remote peer. These ICE candidates contain information about how to access the peer. For example when the peers are not in the same LAN, ports are exposed through the use of an external STUN server so do not need to be port forwarded. As soon as both peers agree on a ICE candidate (i.e. an acceptable peer-to-peer network route), the media between the peers can start to flow through peer-to-peer UDP. Note: Even after the media is streaming, new candidates may be suggested if the network changes. This can result in changing network routes, media formats or codecs! * If the remote peer (remote browser) is not started yet, the above will obviously not result in a successful peer-to-peer streaming connection. * When the remote peer is started up, it does nothing until the ‘Call’ button is pressed. * When the ‘Call’ button is pressed, it just sends the ‘reload’ message to the MyExoMy. The MyExoMy will reload the page which will result in an offer to be sent to the remote client. Note: Reloading the MyExoMy signaling server page is not strictly necessary but it is a simple and robust way to (re)start MyExoMy signaling. * The ‘offer’ message will trigger a call to createPeerConnectionAndAddLocalTracks(). Because now both peers are present the SDP / ICE negotiation can succeed this time. When the MyExoMy adds the local video track this will result in gotRemoteStream() being called (being set as the pc.ontrack callback) on the remote client resulting in the MyExoMy video track to be shown on the remote client. * When the ‘2-way’ button is pressed to switch to full duplex video and audio, video and audio tracks are added as requested and createOfferAndSendToPeer() is called again. * When the ‘2-way’ button is pressed again to switch back to simplex video, the video and audio tracks are removed from the peer connection as requested. |

**Advantages of Chrome WebRTC**

* Uses only WebRTC functionality in the browser and a standard node.js https server as signaling server.
* Because only browser functionality is used on the Raspberry Pi, no separate programs need to be installed / maintained, besides node.js and JavaScript files. This ensures maximum compatibility with remote browsers.
* Two way video and audio supported out of the box!

**Disadvantages of Chrome WebRTC**

* At both sides a browser instance is needed, so also on the Raspberry Pi.
* On the Raspberry Pi starting Chromium from a Docker container through ssh results in a crash, unless sudo in combination with --no-sandbox is used. Because sudo is used, an additional  
  xhost si:localuser:root;  
  is needed after   
  export DISPLAY=:0 nohup;  
  in the ssh command otherwise Chromium cannot attach to a display.  
  Note that it is not needed that an actual display is attached.
* At the moment a maximum resolution of 1920x1028 (16:9) and 1440x1080 (4:3) seems to be supported in Chromium for the Raspberry Pi camera V2. This can be tested with <https://webrtchacks.github.io/WebRTC-Camera-Resolution/> or <https://test.webrtc.org/> (seems to be <https://test.8x8.vc/> now). Another WebRTC testpage is <https://webrtc.github.io/test-pages>.
* When using this camera with Chromium and MyExoMy the reported local resolution is indeed the configured one. However at higher resolutions (> 800x600) the reported resolution on the remote side varies and the video is blocky and choppy with a high latency (> 1 s) and also the colors are distorted.  
  When testing the Raspberry Pi camera V2 on <https://webrtc.github.io/samples/> the same blockiness and color distortion can be seen. The blockiness and color distortion is not because of the higher CPU load. When ending the call the CPU load is low but the same artifacts can be seen in the local video stream. Also when connecting an USB camera Logitech C930e (Raspberry Pi camera V2 disabled) the video quality is good.  
  When experimenting with <https://webrtc.github.io/samples/src/content/peerconnection/change-codecs/> it turns out that also changing between codec (VP8, VP9 or H264) does not influence the blockiness. It also shows that the CPU load is a little less when using H264 i.s.o. VP8 or VP9 (150..200% versus 200..250% @ 1440x1080, 20fps).  
  Setting the resolution to 640x480 gives reasonable results.
* Chrome Web RTC streaming in Chromium gives a high CPU load, see the measurements in this document. This is due to the streaming itself, not to Chromium. With the higher CPU load one has to realize that it involves two way video streaming.

**Important note:** When changing the resolution as specified in webrtc-web/js/main.js be sure to also clear the browsing data otherwise the previous settings will remain active.

See also  
<https://www.html5rocks.com/en/tutorials/webrtc/basics/>.

## Low Power ATmega328P

For the MyExoMy project the ATmega328P-PU is used with an alternative bootloader which sets the clock to the 8 MHz internal clock. The new board definition (named 'ATmega328 on a breadboard (8 MHz internal clock)') and bootloader is available in the breadboard-1-6-x folder.

See <https://www.arduino.cc/en/Tutorial/BuiltInExamples/ArduinoISP> for how to burn a bootloader on one Arduino board using another Arduino board as ISP.

The 'ATmega328 on a breadboard (8 MHz internal clock)' board is made available to the Arduino IDE by copying the breadboard folder to C:\Program Files (x86)\Arduino\hardware.

See <https://www.arduino.cc/en/Tutorial/BuiltInExamples/ArduinoToBreadboard> for a description of how to connect an ATmega328P on a breadboard and use it.

To make the new board available in Visual Studio Code an Atmega328\_on\_breadboard\_8MHz.json file is added to C:\Users\reneb\.platformio\platforms\atmelavr\boards. This json file is created by copying the uno.json file (which is for the Arduino Uno) and adapted the content with info from boards.txt in breadboard-1-6-x.

## SSL / TLS certificates

See <https://www.youtube.com/watch?v=e8vMTlobW3c&ab_channel=TechForum>, and also the links in the comments.

The generated server.crt and server.key file can be added at the server side on the raspberry pi:

* In docker/entrypoint.sh for the MyExoMy http-server
* In launch/rosbridge\_websocket.launch for the ROS websocket.
* In webrtc-web/index.js for the node.js WebRTC signaling server

The ssl folder containing the public and private key is added to the .gitignore file.  
The generated rootCA.pem can be added in Windows Chrome to the Trusted Root Certification Authorities via Settings -> Privacy and security -> Security -> Manage certificates -> Trusted Root Certification Authorities -> Import.  
In Raspberry Pi Chromium it is something similar.

## Low Power Raspberry Pi

The Raspberry Pi can be put in low power by issuing a ‘sudo halt’. The power of the Raspberrt Pi 4 model B board will go from appr. 700 mA to appr. 16 mA in low power. For this to work the EEPROM bootloader configuration has to be adapted. This will not be used. Instead, low power will be reached using the ATmega328P processor which will completely switch off the power supply to the Raspberry Pi and the servo board.

### Default EEPROM bootloader configuration settings, low power settings in red.

See also <https://www.raspberrypi.org/documentation/hardware/raspberrypi/bcm2711_bootloader_config.md>

BOOT\_UART=0

WAKE\_ON\_GPIO=1 -> 0

POWER\_OFF\_ON\_HALT=0 -> 1

DHCP\_TIMEOUT=45000

DHCP\_REQ\_TIMEOUT=4000

TFTP\_FILE\_TIMEOUT=30000

ENABLE\_SELF\_UPDATE=1

DISABLE\_HDMI=0 (can be set to 1 if HDMI is not used, makes no difference for low power though)

BOOT\_ORDER=0xf41

To view: rpi-eeprom-config  
To edit: sudo -E rpi-eeprom-config –edit

After editing, whether you changed anything or not, always issue a sudo reboot, otherwise the setting does not seem to have any effect.

## Wakeup transceiver RC-WuTRx-433

A close-up of a circuit board

Description automatically generatedA Ultra Low Power WakeUp Transceiver RC-WuTRx-433 module is used to wakeup the MyExoMy, see <https://www.radiocontrolli.com/public/componenti/6061/files/RC-WuTRx-XXX.pdf>.

Figure 13 Wakeup transceiver RC-WuTRx-433

Two identical modules are used. One at the MyExoMy which acts as a receiver and one at a location < 100m to the MyExoMy which is connected to the internet and acts as a transmitter.  
The module on the MyExoMy is put into Ultra Low Power mode in which it consumes appr. 120 μA on average.  
Using the Hercules SETUP utility the module can be configured, see <https://www.hw-group.com/software/hercules-setup-utility>.  
Most of the default configuration is kept.  
The following configurations are changed from the default:

* Local and remote address from 7E7E7E7E to 42424242.  
  This is done using the HEX command: 5E 43 42 42 42 42 42 42 42 42 50 3A.
* Switched from bistable to monostable mode for all 4 channels.  
  This is done using the commands ^M1M, ^M2M, ^M3M and ^M4M. Use ?M to check the monostable states.
* Switched from Low Power mode to Ultra Low Power mode. This is done only for the tranceiver module on the MyExoMy, which acts as a receiver.  
  This is done using the command ^EU.

**NOTES on configuring the RC-WuTRx-433 tranceiver**

* Programming the RC-WuTRx-433 tranceiver can be done using an Arduino Uno with RESET to GND so the Arduino Uno acts as a USB to serial converter. Connext the RX of the RC-WuTRx-433 tranceiver to the RX of the Arduino Uno, similar for TX, so no cross connection!
* For more reliable communication switch to 9600 Baud.
* Using the command ?S one can see the general configuration.
* To store the configuration in FLASH one must use a special programming sequence using the FP (Flash Protection) and RESET pin following the data sheet.
* After switching to Ultra Low Power mode, the module does not communicate through serial anymore. To enable communication again, apply a negative pulse on the TX ENABLE pin (pin 14 labeled W1, shortly connect to ground) to wake up the device after which a command can be given through serial.

## WebRTC on Raspberry Pi Ubuntu

* WebRTC does not seem to work well with Chromium on Ubuntu. The request to ask to use the camera does not come so an ‘getUserMedia() error: NotFoundError’ error appears. Firefox however does work. When Firefox asks the first time for use of the camera and microphone, check ‘Remember this decision’.
* Start Firefox in kiosk mode from the commandline:  
  firefox -kiosk https://localhost:8080
* To stop the kiosk mode, open a terminal (CTRL+ALT+T) and type pkill -f firefox.
* To test the WebRTC:
  + Open a terminal goto /home/ubuntu/exomy/webrtc-web.
  + Start the WebRTC signaling server with node index.js.
  + Open another terminal and start Firefox with  
    firefox https://localhost:8080 (no kiosk mode for easy quitting).
  + On the remote side open <https://192.168.1.42:8080/> in Chrome. After a network change, it can be that the ‘ERR\_CONNECTION\_REFUSED’ error is displayed. It’s possible that the browser stores an outdated cache of the problematic website, triggering the ERR\_CONNECTION\_REFUSED error. Clearing the browser cache will force your browser to fully reload the website’s data, updating the cache to its latest version.

## Accessing the MyExoMy from outside the LAN

For accessing the MyExoMy from outside the LAN it is convenient to give the Raspberry Pi a fixed IP address so port forwarding can be used. At the same time we want DHCP to be used on the MyExoMy so it can also be used in other networks like in a phone’s tethering network. This can be done by letting the router assign a static DHCP IP address (192.168.1.42) to the MyExoMy, using its MAC address.  
For the MyExoMy the following ports must be forwarded:

* MyExoMy main webserver: 55555 (TCP)
* MyExoMy rosbridge websocket: 9090 (TCP)
* MyExoMy WebRTC signaling server: 8080 (TCP)
* MyExoMy Wakeup Transmitter: 55554 (TCP)

Besides these ports UDP ports are used for WebRTC peer-to-peer video and audio streaming. These ports are exposed through the use of an external STUN server so do not need to be port forwarded.  
This STUN server must be specified as a parameter (array of RTCIceServer objects) to RTCPeerConnection. Currently ‘stun.l.google.com’ on port 19302 is used, a free public Google STUN server, but there are many more. If the STUN server cannot be reached, the UDP connection cannot be created and the error “Cannot create RTCPeerConnection object” appears in the remote browser which is initiating the call.  
Note that in typical usecases it is not needed to forward any port for WebRTC. However, because the WebRTC signaling server is now hosted on the MyExoMy and does not have a public IP, port forwarding for the WebRTC signaling is needed.

## Wifi performance

### Video stream buffering

When driving around connection hiccups can occur. Some observations:

* Hiccups occur also when the received signal strength is still good (e.g. -60 dBm).
* Hiccups occur mostly when moving, when standing still the signal mostly is ok.
* The video bitrate does not seem to have a big influence on the hiccups. Even with low video bitrates (e.g. 1 Mbit/s) the hiccups occur.
* Hiccups can be seen in Wireshark as TCP retransmissions. Note that with WebRTC UDP is used which does not care about retransmissions which gives a better video streaming experience.
* It seems that the problem is Adjacent Channel Interference. This happens mainly when the MyExoMy is moving in a location where there are many other Wifi channels and the own Wifi channel does not really standout as it would inside close to its own access point.
* The connection bitrate measured with Windows Task Manager -> Performance -> Wi-Fi shows drops toward 0 Mbit/s during a hiccup.

Measurements using Windows Task Manager -> Performance -> Wi-Fi show that during a connection loss video is buffered at the streaming server side. As soon as the connection is restored the video buffer is sent resulting in a peak in the bitrate as can be seen in the figure below.

A graph with lines and text

Description automatically generated

Figure 14 Video buffering at streaming server side

When the HTML video element is used, the video received is also buffered and thus causing the latency to build up after each connection hiccup.  
When the HTML video element is used, this can be solved at the receiver side in Javascript by setting the video attribute currentTime to its maximum value when the buffer built up gets too large. This will effectively jump the video forward to the current time.  
vid.currentTime = Number.MAX\_VALUE;  
With an MJPEG stream the HTML img element is used and then this is no issue. Also when WebRTC is used this is no issue.

To monitor the network bandwidth from the Raspberry Pi side from the terminal, install vnstat and use vnstat -i wlan0 --live.

### Access points and roaming

When driving around outside there can be quite some hiccups in the connection / video, sometimes up to 5 seconds! Some observations:

* Serious hiccups occur with an Access Point handover. This also is the case with a Wifi Mesh network.
* The best solution found so far is to have one access point at the center of MyExoMy’s playground. This prevents handovers.
* 5 GHz seems to have better performance than 2.4 GHz probably due to the fact that the 5 GHz band is less crowdy.
* For manual roaming a CheckWifi() Python function is created. This function is called when the ‘CHECK WIFI’ button is pressed on the webpage. It checks the signal strengths of a predefined list of Wifi access points (AP) and then switches to the AP with the strongest signal. The CheckWifi() function uses the nmcli command. When running from a ROS node using sudo is required (similar as to running via SSH). To prevent the request for a password, the user ‘exomy’ (The ROS node is running as that user) is added to the sudoers file. This is done by adding the line exomy ALL=(ALL) NOPASSWD: /usr/bin/nmcli to the sudoers file using sudo visudo.

### External antenna for the Raspberry Pi

Because the Raspberry Pi onboard Wifi antenna is low to the ground and covered by the servo board, an external Wifi antenna or USB Wifi dongle can be used.

#### External USB Wifi dongle AWUS036ACM

Figure 15 9.17.3.1. External USB Wifi dongle AWUS036ACM

To disable onboard Wifi and also Bluetooth (to avoid interference) the following lines are added to /boot/firmware/config.txt:  
#dtoverlay=disable-wifi  
#dtoverlay=disable-bt  
The dongle will become wlan0 then.

In case a dongle is used do not forget to change the MAC address in the router for the static DHCP address setting for the MyExoMy. This should be the MAC address of wlan0.

However the results of the AWUS036ACM were disappointing. The received signal strength in dBm was ok but there were many hiccups for no apparent reason.  
Am disadvantage of an external Wifi dongle is the additional power it uses (around 300 mA for the AWUS036ACM).

#### An external Wifi antenna connection

Eventually an external Wifi antenna connection is created as describes earlier in this document.

## Use of 4G i.s.o. Wifi

### General 4G issues

To bypass Wifi roaming problems and to have unlimited range, it is possible to use 4G i.s.o. Wifi. For inspiration, see <https://www.youtube.com/watch?v=aNR4RJQzWS4>. See also <https://store.cloudrc.com/> for 4G remote controlled cars.

In general, to control a robot over the internet by a controlling party, the robot needs to have a routable public IP address / port number. In the case of 4G however the robot has not. Instead it has a public IP address which is shared by many others, a so-called CGNAT (Carrier Grade NAT) IP address. This is to save on the limited amount of IPv4 addresses. So the robot cannot be reached by using an IP address / port number, but the robot can itself reach the internet. The solution is then to set up a reversed tunnel from the robot towards the controlling party after which this tunnel can be used by the controlling party to reach the MyExoMy.

If the controlling party also is behind a CGNAT (like a mobile phone), then an relaying party is required. Two reverse tunnels are set up to the relaying party so the controlling party can still reach the robot via the relaying party. Disadvantage then is that all traffic has to go through the relaying party which adds to the overall complexity and degrades reliability and performance. Typically these services will not be free.

### Practical solutions

To set up a reverse tunnel for example OpenSSL or OpenVPN (which uses OpenSSL and adds an extra layer of encryption) can be used. As a third party server to setup OpenSSL or OpenVPN, a VPS (Virtual Cloud Server) can be used, like with Amazon AWS, Microsoft Azure or Google Cloud Firestore.

A diagram of a computer system

Description automatically generatedIn the case of WebRTC the UDP data relaying party would be a TURN server (next to the STUN server). In addition it would be needed to host a WebRTC signaling server and a WebRTC client page

Figure 16 Example 4G setup from https://www.youtube.com/watch?v=aNR4RJQzWS4

### SIM7600G-H 4G dongle experiences

Figure 17 SIM7600G-H 4G dongle

A SIM7600G-H 4G dongle has been connected to the MyExoMy, and the results were mixed:

* Getting a connection using the SIM7600G-H 4G dongle was not plug-and-play. Ubuntu 22.04 LTS on the Raspberry Pi seemed to recognize the dongle with a KPN SIM card, but most of the times the connection could not be made. With more effort or another dongle this probably can be fixed.
* A SIM card is needed. To prevent a monthly fee or accidental high cost a prepaid card is desired. However, reasonable priced internet-only prepaid SIM cards are hard to find. The mainstream providers(KPN, Vodafone, Tele2, Simyo) only have internet bundles that expire after one month, which is very inconvenient. Example (2023): at Simyo (KPN network) you can buy 150 MB for €5, which expires after one month. For WebRTC using appr. 2 Mbit/s this would mean about 10 minutes of streaming, so €0,50 per minute! There are some providers which seem to be cheaper but it not clear which network they use and if they are reliable.
* Additional power of appr. 150 mA, although about the same amount of power is saved when switching off Wifi.

# Measurements

## Current measurements

|  |  |  |
| --- | --- | --- |
| Current measurements, measured with battery voltage = 6.0 V. | | |
| Measurement | **Value** | **Remark** |
| Sleep mode | Appr. 120 μA | At 6.0V branch: 0 nA. At 4.8V branch: 100 nA used by ATmega328P. At 2.4V branch: 120 μA used by RC-WuTRx-433 wakeup receiver. |
| Fully operational, standing still | 0.90 A |  |
| Fully operational, standing still + lights on | 1.35 A |  |
| Fully operational, driving and steering | 1.5A .. 2.0 A |  |
| Fully operational, driving and steering, lights on | 2.0A .. 2.5 A |  |
| HDMI display | 0.315 A |  |
| Speaker HK-5002 | 0.03A .. 0.3A | Speaker is connected to 6V battery. 0.03A when silent, 0.3A with loud music. With loud acoustic feedback the current can get > 1A. |

## Video bitrate and CPU load measurements

Below the measured video bitrates are shown. Some additional notes:

* Watching an average YouTube video takes a lot less. This is because the encoding is much more efficient as the latency is not an issue. It can also be seen that the bitrate comes in bursts.
* An average Microsoft Teams or Zoom session takes around 3 Mbit/s.
* The ROS usb\_cam node seems to have a bitrate limit around 40 Mbit/s. The actual Wifi limit is at least 100 Mbit/s as can be seen in the table below.
* **Important note:** When measuring the video bitrates, take care not to have the VNC Viewer open, as this will add an additional bitrate!

|  |  |  |
| --- | --- | --- |
| Video bitrate over Wifi and CPU load measurements.  Notes:   * Measurements are done with the onboard with Raspberry Pi camera V2 unless noted otherwise. * The bitrates are measured with Windows Task Manager -> Performance -> Wi-Fi. * The CPU load is measured with htop. * The bitrates are measured with MyExoMy outside on a cloudy day. The bitrate heavily depends on the video content and codec. Inside the scene is calmer and bitrate can be half or less if it gets dark. * The measurements done with Chrome WebRTC involve two way video streaming. * The maximum CPU load for the Raspberry Pi 4 model B is 400% (100% for each core). | | |
| Measurement | **Value** | **Remark** |
| ROS usb\_cam node  640x480 MJPEG, 10 fps, quality 50 | 15 Mbit/s | Framerate is met. |
| ROS usb\_cam node  800x600 MJPEG, 10 fps, quality 50 | 20 Mbit/s | Framerate is met. |
| ROS usb\_cam node  1920x1080 MJPEG, 20 fps, quality 85 | 40 Mbit/s | Framerate is not met, but around 4 fps. |
| Rpi-WebRTC-Streamer 1024x768 H.264, 20 fps, quality ? | 3 Mbit/s | Rpi-WebRTC-Streamer runs on Raspberry Pi host. Framerate is met. |
| Chrome WebRTC 640x480, 20fps | 1..2 Mbit/s CPU load 60..100% | Video quality ok. Remote video resolution also 640x480. Framerate is met. Latency < 0.5 s. |
| Chrome WebRTC 800x600, 20fps | Appr. 2 Mbit/s CPU load 100..150% | Video a bit blocky. Remote video resolution also 640x480. Framerate is met. Latency < 0.5 s. |
| Chrome WebRTC 1440x1080, 20fps | 2..3 Mbit/s CPU load 200..250% | Video very blocky and choppy. Remote video resolution often switches back. Framerate is not met. Latency appr. 1 s. |
| Chrome WebRTC 1920x1080, 20fps with USB camera Logitech C930e | 2..3 Mbit/s CPU load appr. 200% | Video quality ok but choppy. Remote video resolution often switches back. Framerate is not met. Latency > 1 s. |

# Useful links

<https://www.esa.int/Enabling_Support/Space_Engineering_Technology/3D_print_your_own_Mars_rover_with_ExoMy>

<https://github.com/esa-prl/ExoMy/wiki>

<https://github.com/esa-prl/ExoMy_Software>

<https://desertbot.io/blog/headless-raspberry-pi-4-remote-desktop-vnc-setup>

<https://msadowski.github.io/ros-web-tutorial-pt1/>

<https://www.clearpathrobotics.com/assets/guides/kinetic/ros/Practical%20Example.html>

<https://learn.adafruit.com/16-channel-pwm-servo-driver>

<https://upcloud.com/community/tutorials/use-ssh-keys-authentication>

<https://dev.to/natterstefan/docker-tip-how-to-get-host-s-ip-address-inside-a-docker-container-5anh>

<https://www.sigmdel.ca/michel/ha/rpi/streaming_en.html>

<https://picamera.readthedocs.io/en/release-1.12/fov.html>