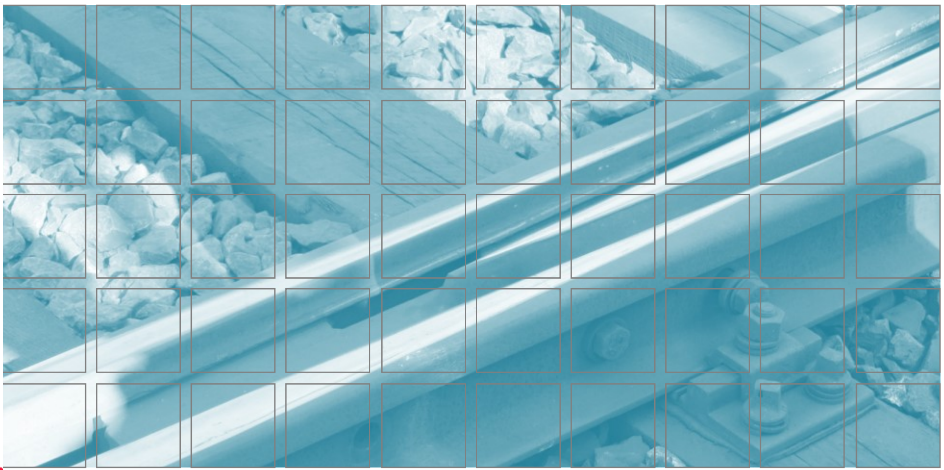
COMET-Projekt Rail4Future
Resilient Digital Railway Systems to enhance performance



D2.2.4 Report on Data Quality and Generation Concept

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Preface

Turnouts are one of the most stressed and safety-critical components of the railway infrastructure. The assessment, regarding necessary maintenance or renewal is made based on visual inspections of qualified employees. One of the aims of this project is to aid this time and cost intensive approach by utilising measured data and advanced algorithms to reduce time and cost.

To this end, additional sensor modalities are installed on the measurement locomotive EM100VT of Plasser & Theurer. The new sensor modalities are a linescan-camera-system measuring with a near-infrared wavelength, and a vibration sensor system by HBK. These systems are combined with highly precise time and spatial information via a GNSS sensor and the ptp-v2 protocol. This document highlights the installation of said systems onto the EM100VT by Plasser & Theurer, introduces the necessary software components to measure data and presents an initial analysis of recorded data.

Content

1 Data Generation Concept

This section describes the hardware concept of the proposed track recording car mounted multi-sensor platform. It provides a combination of non-invasive measurement methods for recording and monitoring rail infrastructure such as turnouts, rail joints, etc. The measured vibration and visual data of the rail tracks are combined with highly precise time and spatial (geo-reference) synchronisation data. This enables the recording and annotation of ground truth (training) data, needed for subsequent evaluation and monitoring.

The figure below shows the block diagram of the overall hardware concept of the measurement system including all sub components and its communication channels.

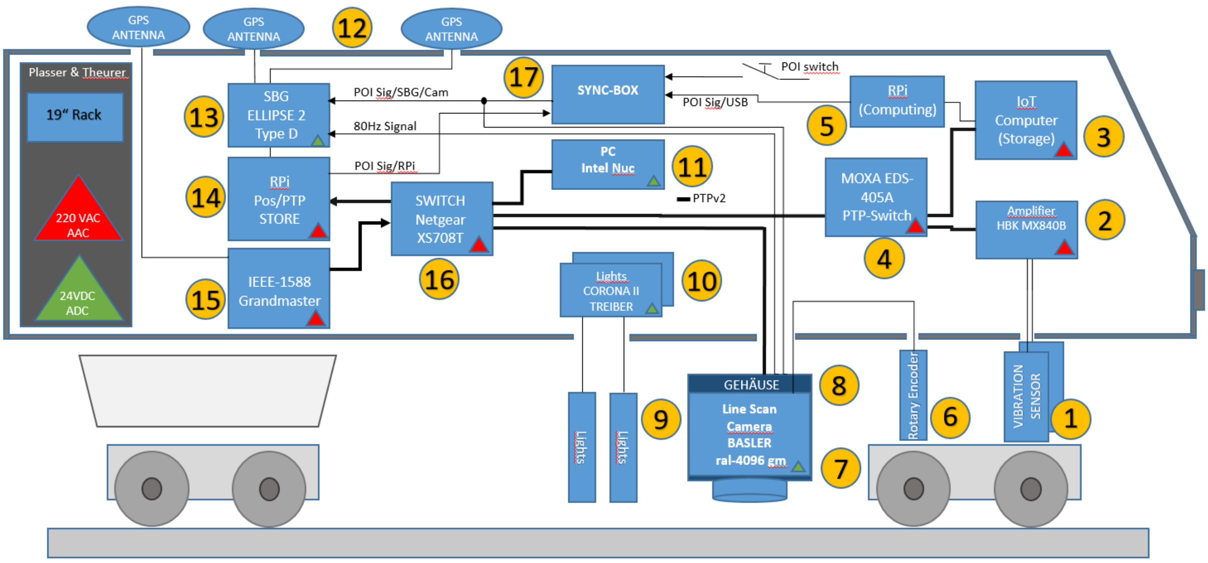


Figure 1: Hardware concept of the measurement system

The concept is developed by Joanneum Research in collaboration with the project partners Plasser & Theurer and HBK. The measurement system is installed on a track recording car by the project partner Plasser & Theurer. HBK provides the vibration sensors and the vibration signal recording hardware.

The main sensors for data acquisition are two vibration sensors (1-5) and a line-scan camera (6-11). While the vibration sensor data are time encoded, the line-scan camera data is rotary (distance) encoded. For time and geo-synchronicity of the recorded data, we utilize the Precise Timing Protocol v2 (PTPv2) (15, 16) and a high-end GNSS receiver (12-14). As the data from the line-scan camera cannot be recorded continuously due to its high data-rate, we utilize a self-built synchronization box (17) to trigger the storing of the camera data.

1.1 Sub Components

The following chapters list the subcomponents of the measurement system and defines their specifications.

1.1.1 Vibration Sensors (1)

Analysing a dataset of acceleration data recorded on a moving rail car resulted in the selection of the **Bruel & Kjaer Triaxial CCLD Accelerometer Type 4529-B/4529-B-001**, depicted in Figure 2a. It has a sensitivity of ~100 mV/g / 10 mV/g and a maximum operation level of 71 g / 710 g, respectively. The two sensors are mounted on the left and right axle boxes. As the 4529-B and the 4529-B-001 have the same mechanical specifications, it is possible to interchange the two sensors for different measurement campaigns.

a) (© HBK) b) (© HBK) c) (© Vecow)

Figure 2: Vibration Sensor Measurement System

1.1.2 Vibration Sensors Amplifier (2)

The **HBK QuantumX MX840B** module, depicted in Figure 2b, is a universal measuring amplifier. The amplifier provides a constant current supply to the vibration sensors as well as amplifying the signals to operational level. Furthermore, a temperature sensor is attached to one of the inputs of this amplifier to log air temperature during recording.

1.1.3 IoT Computer (Storage) (3)

An **ECX-1000**-IoT Computer, shown in Figure 2c, is used to record the data generated by the two vibration sensors at a sampling rate of 9600Hz. To this end, it is connected to the Vibration Sensor Amplifier (2) via the MOXA EDS-405A PTP-Switch. Furthermore, the Catman-Software (see Sec. 2.2) is used to record data only if a viable ptp-timestamp is available. This ensures that the ptp-link is established before any measurements are recorded to enable time synchronicity with the other measurement components.

1.1.4 MOXA EDS-405A PTP-Switch (4)

The **MOXA EDS-405A-ptp** is a 5-port switch capable of supporting ptp-v2. It is used to connect the Vibration Sensor Amplifier (2) with the IoT Computer (Storage) (3) and the Netgear XS708T Switch (16).

1.1.5 Vibration Computing Engine (5)

Compared to the system concept proposed in [1] we included the optionally vibration computing engine. This enables to trigger the storage of the camera data, combined with the Synchronization box (17).

We utilize a **Raspberry Pi 4** with **4GB RAM** and connect it with a point-to-point Ethernet connection to the IoT Storage Computer (3). The Catman Software running on (3) transmits the recorded data directly via a UDP port to the Raspberry Pi. The storage of the camera data is currently triggered by comparing the averaged mean-square value obtained with a moving average filter with a threshold. Please note that it is easily possible to adapt this algorithm in a future version of the measurement system.

1.1.6 Rotary Encoder (6)

The rotary encoder of the type **Lenord & Bauer GEL293/10000 differential** is installed on the track recording car by Plasser & Theurer and is used to trigger the recording of single video frames of the camera.

1.1.7 Camera (7, 8)

The **Basler raL4096-24gm**, depicted in Figure 3, is a GigE line-scan camera with a maximum line rate of 26 kHz for using all 4096 Pixels. Limiting the number of pixels to 1024 pixels allows to speed up the line rate to the maximum readout speed of the sensor of 80 kHz. This enables a recording of reliable vision data up to a rail car speed of 80 km/h with a resolution of approximately 0.33 mm/line in traveling direction and a comparable resolution along the height of the rail. The housing of the camera and lens as well as for the LED illumination is provided by Plasser & Theurer and described in Sec. 1.2.1.

Figure 3: Basler raL4096-24gm

1.1.8 Lights (9, 10)

To guarantee perfect light conditions for visual recording, the **Corona II lights** and **LED-Control Units of the type XLC4-1 by chromasens** are installed. Since visible light is not allowed for this rail vehicle, we selected a LED version with a central wavelength of 850 nm – a wavelength, where the corresponding camera still has a good sensitivity. The light beam is focused to an approximately parallel sheet of light, which allows us to illuminate a stripe on the rail of approximately 2 cm with high intensity and high uniformity.

1.1.9 Industrial Computer (11)

The previously selected fanless embedded computer Advantech ARK-3530 (cmp. [1]) has been replaced by the smaller but equally powerful computer **Minisforum EliteMini X500-5700G**. The originally required additional high performance GigE-Framegrabber Matrox Concord 1G was replaced by directly using one of the computer's built-in GigE-Interfaces along with a software dongle. This setup allows the data acquisition at a linerate of 80kHz – resulting in a datarate of about 100MB per second.

1.1.10 Antennas (12)

For the GNSS Sensor (13) the **TyrAnt** antennas, depicted in Figure 4, by JAVAD are used. These multifrequency-antennas are mounted on a flat ground plane and have a low height, making it ideal for mounting on the track recording car.

Figure 4: TyrAnt antenna

1.1.11 GNSS Sensor (13)

The **SBG Ellipse 2 Type D** is a versatile miniature inertial navigation system (INS) integrating a dual-band-antenna and a multi-band GNSS receiver. The Sensor provides highly precise navigation data to the embedded computer (14). It is directly connected to the line scan camera (7, 8) to receive trigger signals from the camera and provide the navigation data to the embedded computer (14) for each camera-recorded frame. Furthermore, the INS is connected to the SyncBox (17) to receive trigger signals generated by the three different options described in Sec. 1.1.15. The GNSS receiver features 0.05° Roll and Pitch (RTK), 0.2° Heading (Dual Antenna RTK GNSS), is immune to magnetic distortions and provides a spatial resolution of up to 1 cm in RTK Mode and up to 1.2 m in Single Point Mode. Its output rate is up to 200 Hz for the precise Extended Kalman Filter navigation and attitude data or 1000 Hz for raw IMU data.

1.1.12 Embedded Computer (14)

An embedded computer of the type **Raspberry Pi 4** is used to connect to the GNSS-System (13). It is responsible for managing the received geo data from the GNSS System, storing the data and providing it to the local network in a synchronized way. Additionally, the embedded computer is connected to the line scan camera via a hardware trigger. It is used for sending store commands after the camera requests geo data for each recorded camera frame from the GNSS System via an additional hardware trigger (13). Additionally a location based triggering of the camera can be provided over the SyncBox (17) via the embedded computer.

1.1.13 Masterclock / GNSS Grandmaster (15)

The grandmaster generates a time-stamp for synchronizing the whole measurement system. Plasser & Theurer provides a **Trimble GM200** system that fulfils the PTPv2 Standard, tolerates harsh environmental conditions, and provides 15ns (1-sigma) time accuracy relative to the GNSS reference.

1.1.14 Network Switch (16)

The network switch is the core of communication of the measurement system. It ensures system wide time synchronisation as well as data exchange. The selected model **Netgear XS708T** is an 8-port 10-gigabit smart managed switch that fulfils the systems requirements in terms of reaction times and switching capacity.

1.1.15 Synchronization Box (17)

The synchronization box triggers the storage of a buffer of the line scan camera. Note that a predefined distance of the track before the triggering and a predefined distance of the track after the triggering are stored, e.g., 100m before the triggering and 200m after the triggering. This ensures that the interesting parts are included in the recorded data.

Three mechanism are implemented to trigger the storing of a buffer:

a) A manual point-of-interest button that can be used by the operator.
b) A signal coming from the vibration computing engine (5).
c) A signal coming from the GNSS embedded computer (14).

Option b) and c) are triggered by the vibration computing engine described in Section 1.1.5 and the embedded computer described in Section 0.

1.2 Mounting on the EM100VT

1.2.1 Camera System

The camera is mounted at a distance of roughly 870 mm from the rail at an angle of about 30° (see Figure 5).

The two corona II lights are mounted in the same plane as the line of the line-scan camera. The exact positions within this plane are determined at the time of the assembly of the system in a way to ensure optimum illumination of the inspected area of the rail.

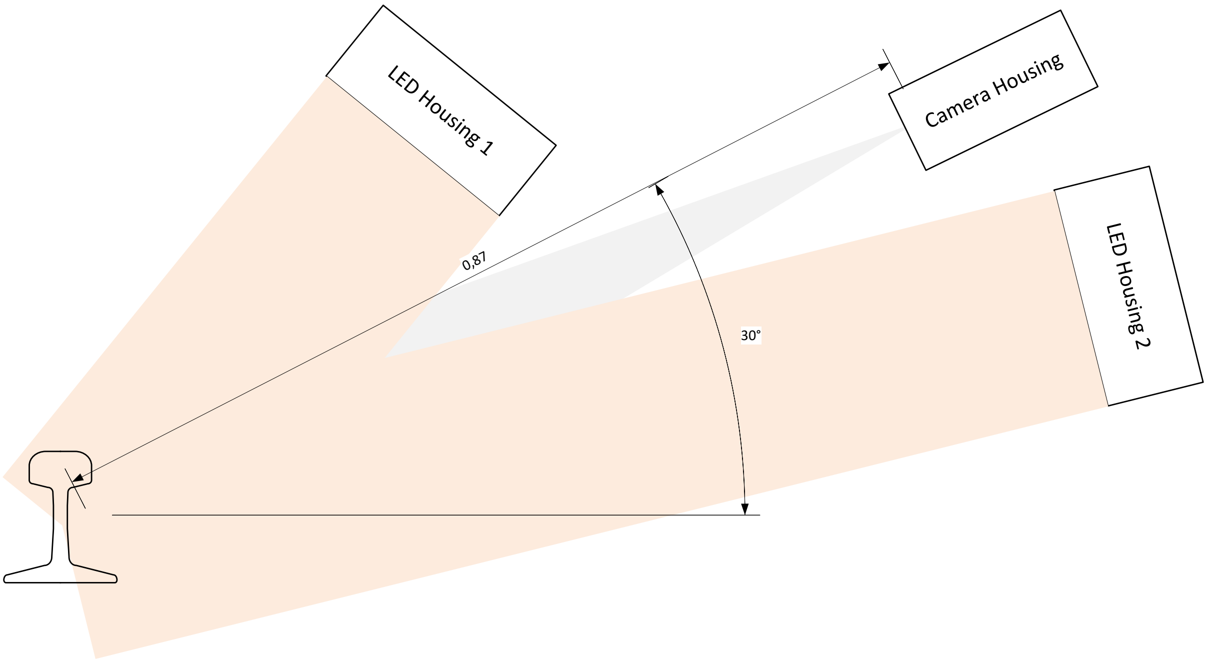
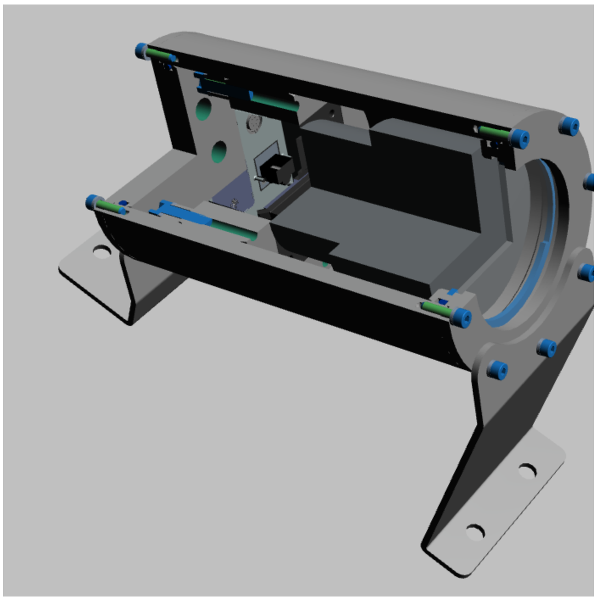


Figure 5: Positions of Camera and LEDs with reference to the rail

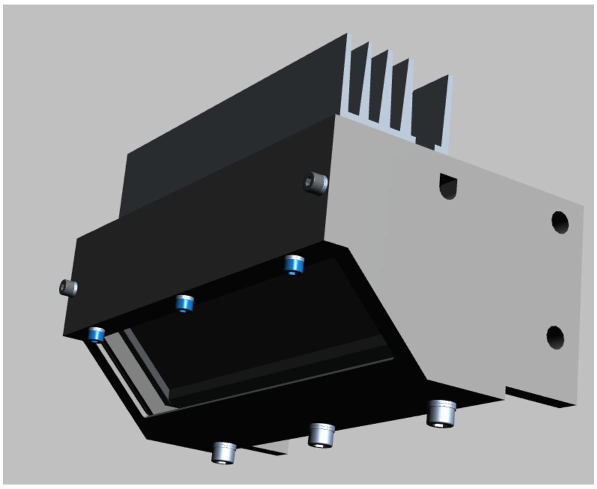
An aluminum housing to avoid possible damage to the sensitive electronics and lenses will cover the camera (see Figure 6) as well as the LED-Units (see Figure 7).

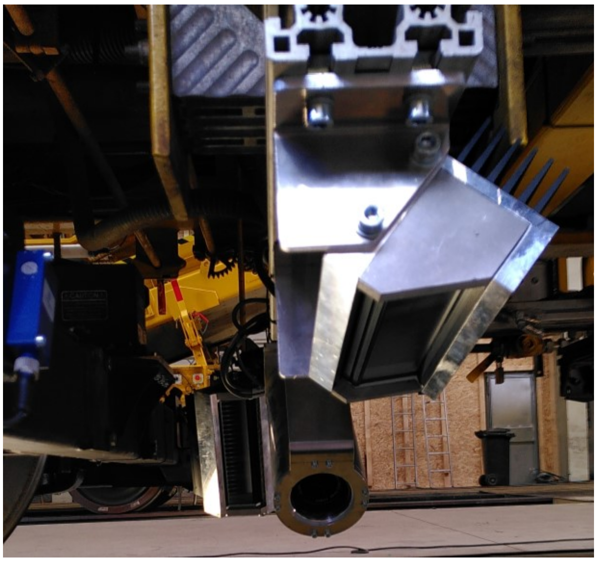


a) © (P&T)

b) © (JR)

Figure 6: Mouting of the camera



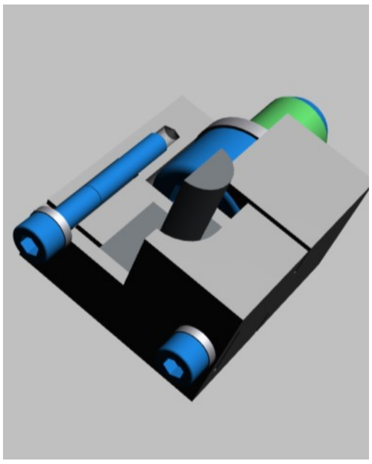


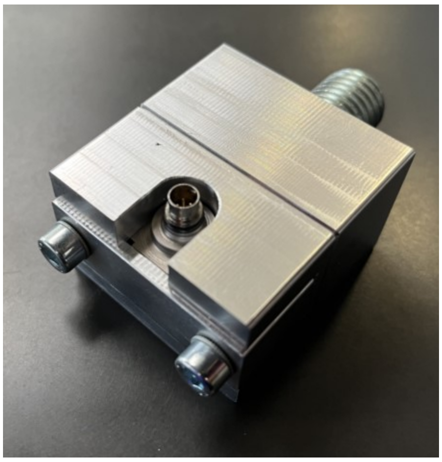
a) © (P&T) b) © (JR)

Figure 7: Mouting of the LED lights

1.2.2 Vibration System

For the mounting of the vibration sensors on the axle boxes of the EM100VT, Plasser & Theurer developed and manufactured enclosures for the vibration sensors, depicted in Figure 8.





a) (© P&T) b) (© P&T) c) (© JR)

Figure 8: Mounting enclosure for the Vibration Sensors

Figure 9 shows the mounting of the vibration sensors on the axle boxes of the EM100VT. At the moment, the 4529-B sensor is mounted on the right side and the 4529-B-001 sensor is mounted on the left side. Please note that left and right are defined with respect to driver's cab 1 (see also Figure 10).

a) left side (© JR)   b) right side (© JR)

Figure 9: Mounting of the Vibration Sensors on the EM100VT

Figure 10 depicts the mounting positions of the two vibration sensors, the local coordinate systems of the triaxial sensors and the installed equipment in the server rack of the EM100VT.

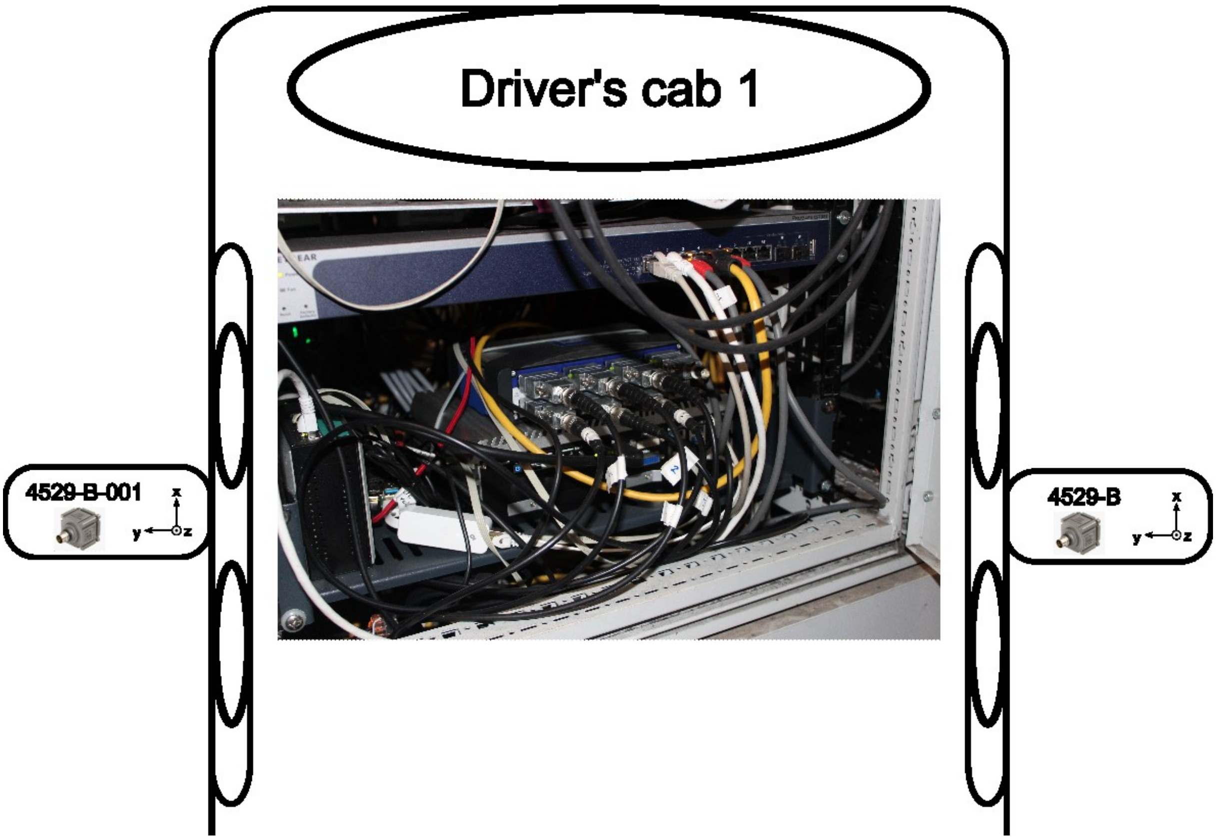


Figure 10: Mounting positions of the two vibration sensors

1.2.3 GNSS System

The mounting of the GNSS antennas is essential for the precise calculation of the position of the train. Therefore, the antennas are mounted pointing in the same direction. Furthermore, the lever arms in regards to the centre of the INS unit have been measured within an accuracy of below 5 cm. It is also required to provide the installation direction of the INS unit to itself. With this information, the INS is configured properly via a configuration interface.

2 Initial Data Analysis and Assessment

2.1 Line Scan Camera

Due to the required high resolution of the images, the line-scan camera acquires images of the size 1000 x 1000 pixels at a maximum data rate of about 100MB per second (resolution of 0.3 x 0.3mm per Pixel). This high amount of data cannot be stored permanently on harddisks without adding a huge storage system. Additionally most of the images will not contain data necessary for the ground truth classification of the vibration sensor system. On the other hand, it is not useful to start the image acquisition only when the vibration data or the GNSS system report a possible point of interest or an operator triggers the system manually at a point of interest, since the vehicle may already have passed the potentially interesting range of the track by then.

To solve these problems, the line-scan camera will acquire images permanently and store them in a ring-buffer in the computer's memory. The size of the ring buffer is adjustable to allow a suitable length of track to be stored (several hundreds of meters). After some adjustable delay whenever a trigger is generated by any of the mentioned systems (vibration analysis, GNSS position, operator) the current ring buffer is saved into a separate directory. To avoid losing data for further points of interest while saving a ring buffer, the camera system continues to acquire data into a second (and optionally a third) ring-buffer. As soon as the saving process is finished, the ring-buffer will be available again for storing image data for the next possible points of interest.

To be able to synchronize the acquired images with the data acquired by the vibration sensor system and the positions recorded by the GNSS system, each grabbed image will be labelled using its acquisition time. Additionally, for every image, a file containing its recording time and ring buffer information will be generated.

One additional file is generated every time a ring buffer is saved. This file contains information about the time when the saving process has been triggered.

Example of the informational file stored for every ring buffer:

```
[Grab Info]
Trigger Data Valid = true
Trigger Time Stamp PTP = 1668597205170159
Trigger Time Stamp Corrected = 1668597168170159
Trigger PTP Valid = true
Trigger Ring Buffer Index = 354
```

Example of the information file stored for every image:

```
[Grab Info]
Time Stamp = 1668597158270157
PTP Valid = true
Ring Buffer Index = 358
```

The acquisition times of all data recording systems synchronize permanently using the Precision Time Protocol (PTP V2).

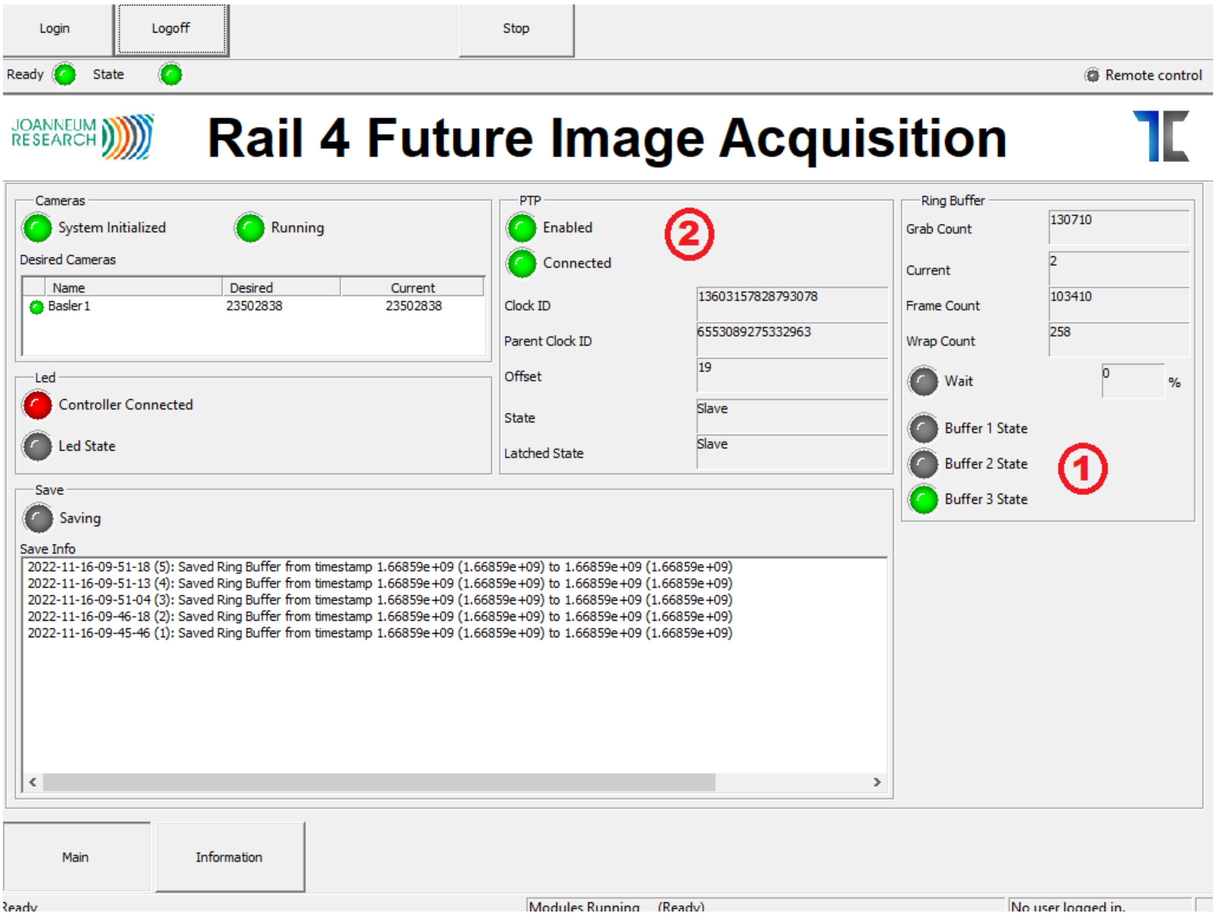


Figure 11: Camera system with connected PTP Grandmaster (2) acquring data using ring buffer 3 (1)

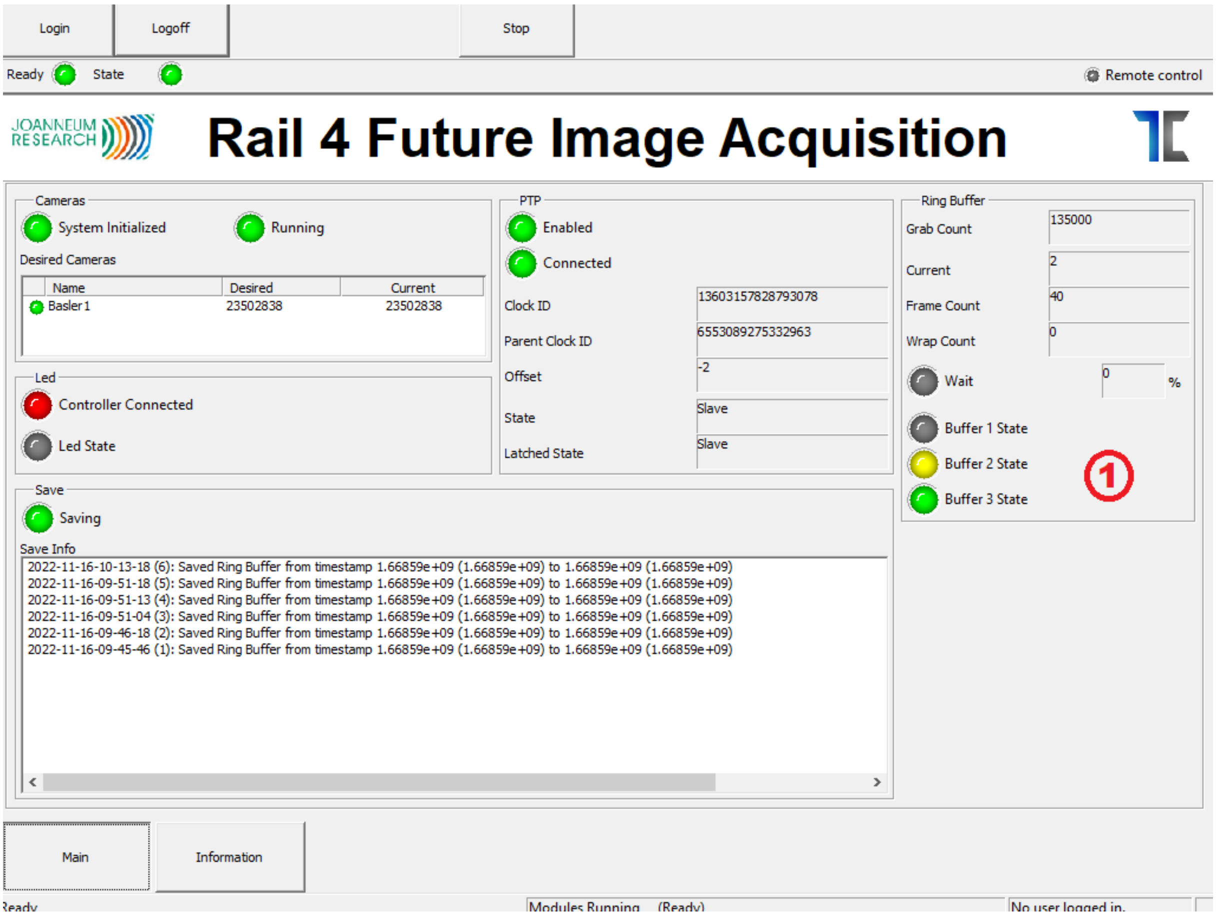


Figure 12: Camera system acquiring images into ring buffer 3 while ring buffer 2 being saved

2.2 Vibration Data

Within this section, we highlight the software storing and processing the vibration data in Sec. 2.2.1 and Sec. 2.2.2, respectively. Furthermore, Sec. 2.2.3 presents an initial analysis of collected data, including the comparison to an ad-hoc measurement with a second measurement system.

2.2.1 Storage of the Data

The data from the vibration sensors is digitized utilizing the MX840-B measurement amplifier. The data is processed and stored with the data collection software “catman” by HBK. Figure 13 shows an overview of the “catman” software. To make an automatic start of the software possible it is included in the windows autostart. Note that for starting of the measurement an “EasyScript” in Visual Basic is processed. This script monitors two variables: (i) the masterId of the connected ptp-device to ensure that the grandmaster is connected and (ii) the current value of the ptp-time-value to make sure that the value is in a plausible region. Only of both conditions are met, a measurement is started. Furthermore, if due to any reason a measurement is cancelled, the script ensures that it is restarted.

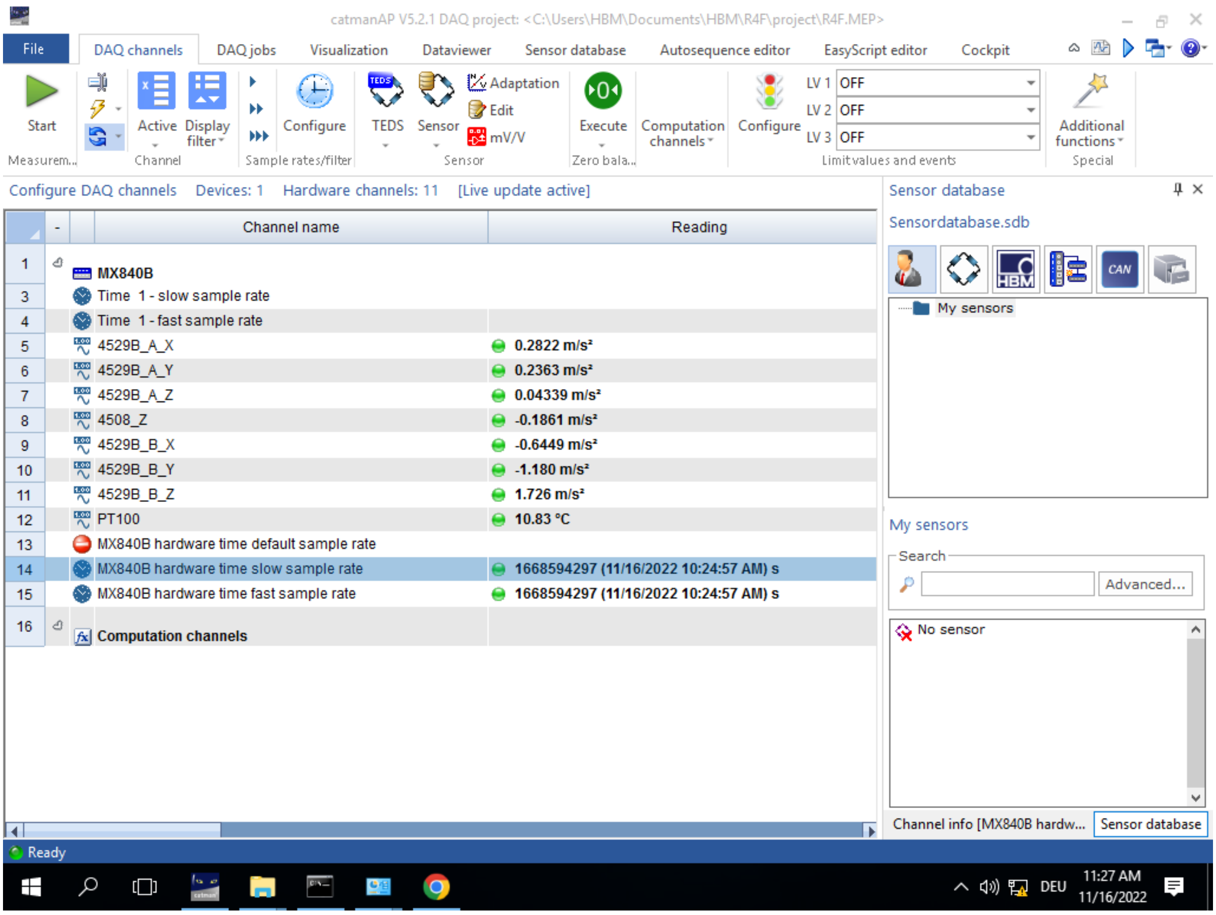


Figure 13: Overview of "catman" software

After a measurement is started, the software receives the following channels from the measurement amplifier:

- Local time slow (@ 10 Hz) in s
- Local time fast (@ 9600Hz) in s
- x, y, z of sensor 4529-B (@ 9600Hz) in m/s²
- x, y, z of sensor 4529-B-001 (@ 9600Hz) m/s²
- temperature (@ 10Hz) in °C
- ptp-time-stamp slow (@ 10Hz) in s since 1.1.1970
- ptp-time-stamp fast (@ 9600Hz) in s since 1.1.1970

To have reasonable sized files, the software stores the values in mat-files in 10min chunks.

2.2.2 Processing of the vibration data

In Sec. 1.1.15 three different possibilities to trigger the storage of a camera buffer are described. This section describes the option to trigger the storage by the vibration computing engine.

To get the data from the "catman" software to the computing engine, we utilize the option to live stream the received data via a UDP port. We use a point to point connection from the storage computer to the computing engine. Figure 14 depicts the UDP options.

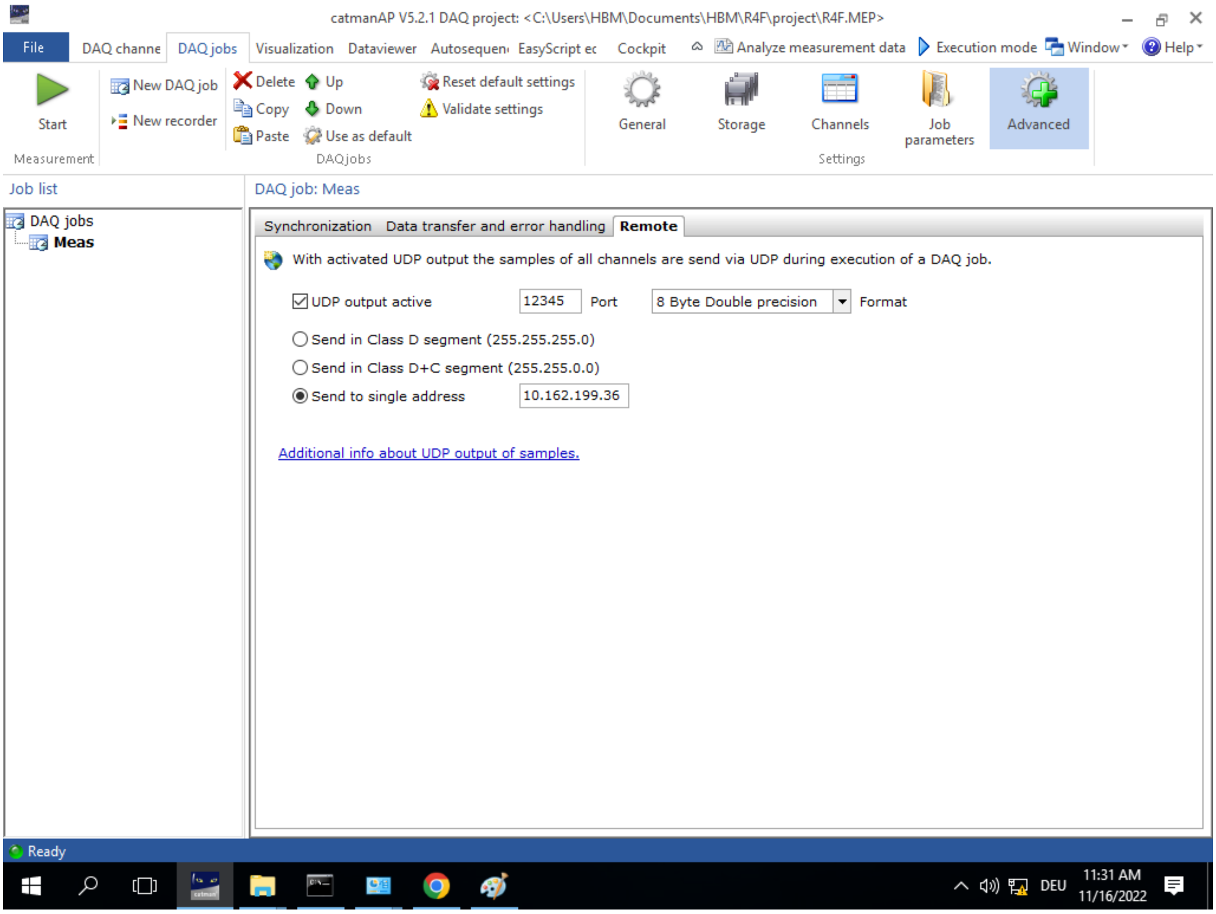


Figure 14: UDP connection settings

On the vibration-computing engine, a python program is used to receive and process the data. While python is not the fastest programming language, it has several advantages including the possibility of rapid prototyping and an abundance of open source libraries. Currently, a very simple formula is employed to trigger the storage of a camera buffer:

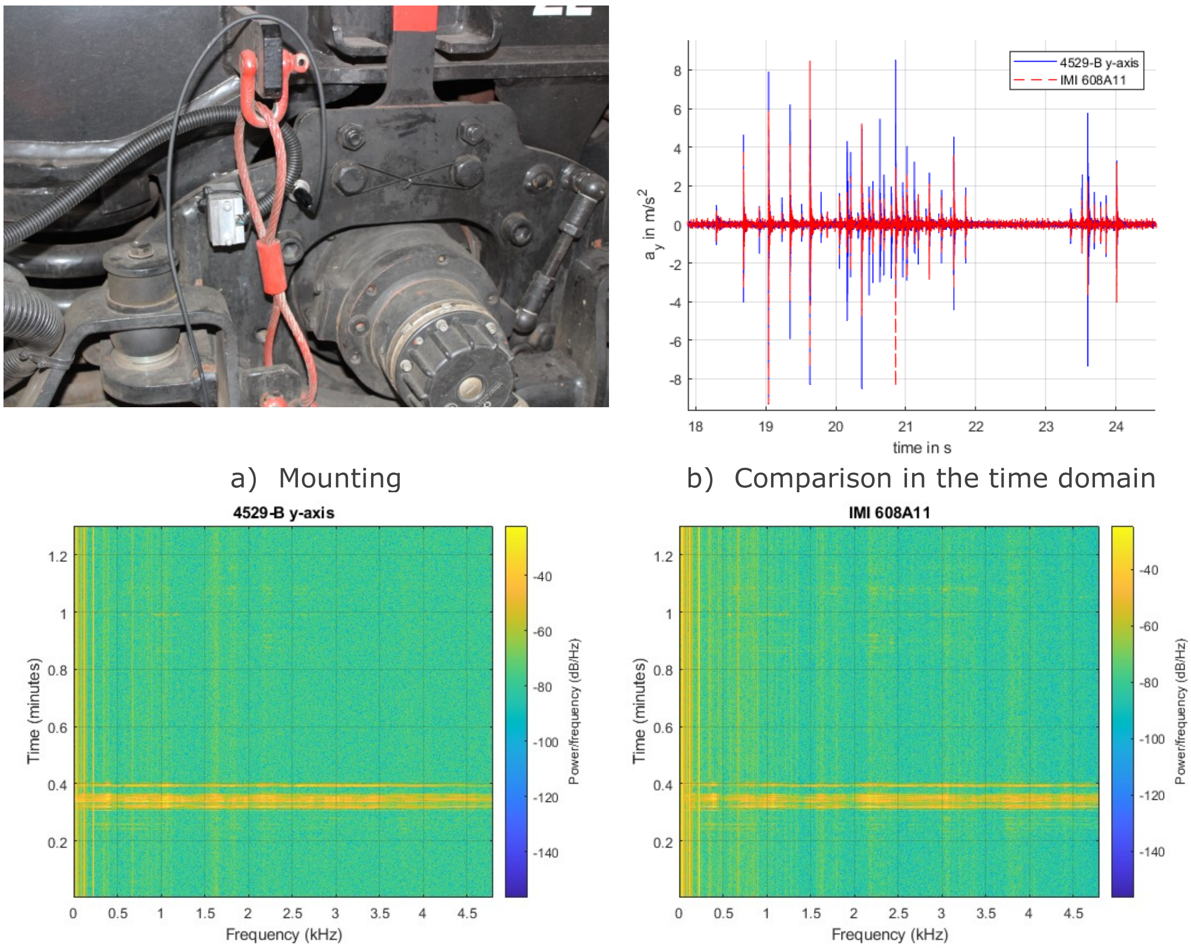
$$\sum_{l=0}^{L} \left|a_{z,4529-B}[n-l]\right|^2 > th \qquad (1)$$

Eq (1) descibes a moving average filter of the last L samples of the squared absolute value of the acceleration in z-direction for the 4529-B vibration sensor. The algorithm has two parameters, namely the length of the moving average filter L and the threshold th. These two parameters will be optimized during the project duration. Depending on the success (false alarm rate, true positives, etc.) of this simple algorithm, ones that are more elaborate will be proposed over the course of the project.

If (1) returns true, a trigger command is sent via a serial connection at a baudrate of 115200bps with the following hex message ("AA5501010000000A"). This command triggers the syncbox, which in turn triggers the storage of the camera data.

2.2.3 Initial Analysis of the data

First, we compare the data of the sensor mounted on the right axle box to the 'IMI 608A11' sensor, an industrial ICP-vibration sensor from PCB piezotronics. This sensor can be mounted with a magnet, which is depicted in Figure 15a.

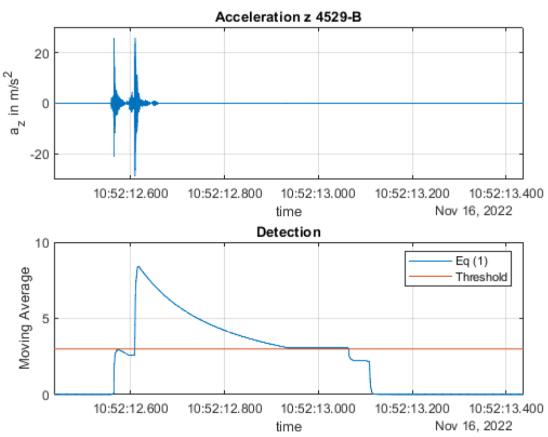


a) Mounting
b) Comparison in the time domain
c) Spectrogram 4529-B
d) Spectrogram IMI 608A11

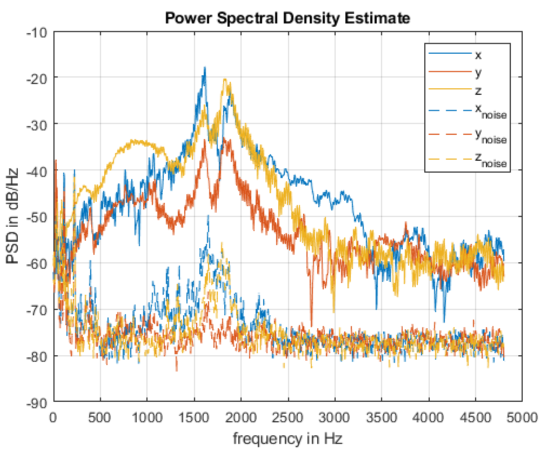
Figure 15: Comparison to IMI-608A11 vibration sensor

To compare some 'impulse' like sequences, both sensors have been excited by knocking on the metal plate onto which the sensors are mounted. As we digitized the signal of the IMI 608A11 sensor with an off-the-shelf sound card (Focusrite Scarlett 4i4) and a signal-converter (iSEMcon SA-P48/CCP-C), the measured amplitudes are not calibrated. To compare the data of the two sensors, it is assumed that the maximum absolute value is the same for both sensors. Figure 15b shows the measured data for both sensors when knocking occurred. The peaks are clearly occurring at the same time and show comparable acceleration values. Figure 15c and d depict the spectrogram of the two sensors. Both sensors show the peaks from approximately 0.3 minutes to 0.4 minutes with comparable frequency content and similar noise levels.

In Section 1.1.15 three mechanisms are described to trigger the storage of the line-camera data. To test the triggering utilizing the vibration data, we knocked on the mounting of the vibration sensor. The upper plot in Figure 16a shows the acceleration data of the z-axis. The lower plot depicts the moving average computed by (1) and a chosen threshold. Note that we knocked twice onto the housing to highlight an important property of the algorithm described by (1). While the first excitation would not suffice to trigger the synchronization box, the cumulative effect of the two knocks triggers the storing of the camera data. Figure 16b shows the power spectral density during the knocking as well as for a duration, where only noise is present. Clearly, the knocking influences the medium to high frequency range (above 500Hz) more than the lower frequency range. The three peaks in the lower frequency region occur during both, the noise-only and the 'knocking' time duration. While the locomotive was standing still during these measurements, the diesel generator was working, leading to some vibrations on the axle boxes.



a) Knocking on Sensor Mounting



b) Power Spectral Density

Figure 16: Triggering of the synchronization box

2.3 GNSS Data

The GNSS data is send to the Embedded Computer every 5ms. The embedded computer generates three different log files:

- GNSS-Log: The embedded computer directly logs the received data to this log-file
- Trigger-Log-Camera: If the camera sends a trigger signal, the INS generates a log message which is received by the Embedded Computer, holding a timestamp of the trigger event. With this information the navigation data can be computed by interpolation between two positions. This interpolated data is stored in the trigger-log-camera file, holding the navigation data for all trigger events.
- Trigger-Log-POI: This log file stores the UTC-timestamps if a trigger due to a POI event occurs.

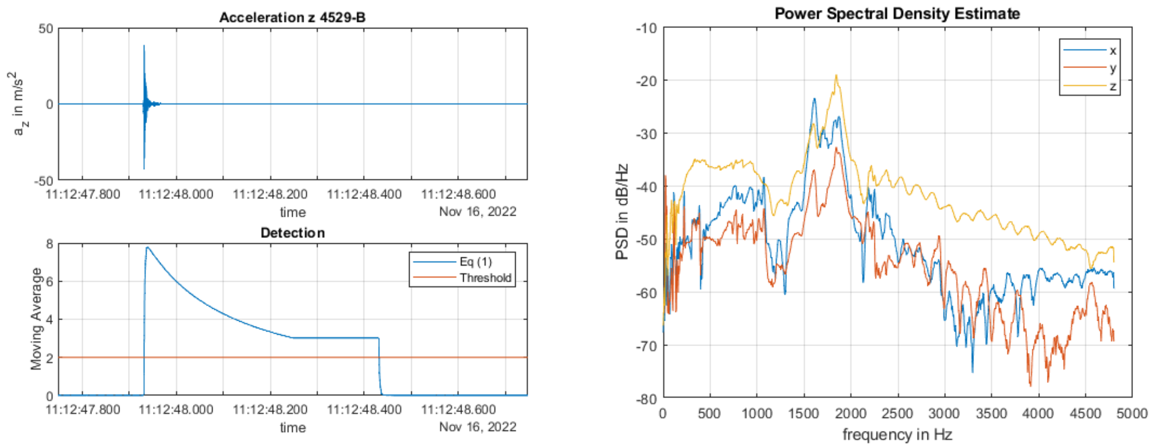
To control the recording software, a REST interface was established. With this interface, it is possible to start and stop the recording or get spatial information. Furthermore, the software can detect POIs, which are provided as ellipsoidal coordinates. Then the Software commands the Embedded Computer to send a trigger signal to the Synchronization box.

Figure 17: Position recorded during static tests

The first static tests after the integration on the train show a position accuracy of ±3m as shown in Figure 17. Clearly, the position is not very accurate. The reason for this offset is due to the close by hangar, which blocks the satellites north to it. A cleaner view of the sky will result in a more accurate position.

2.4 Time Synchronicity

To analyse the time synchronicity between the different sensor modalities, we used the following setup: The vibration sensor was chosen to deliver the input to the synchronization box, by knocking on the sensor (see also Sec. 2.2.2 and 2.2.3).



a) Knocking on Sensor Mounting b) Power Spectral Density

Figure 18: Triggering via the vibration-computing engine

Figure 18 shows the excitation of the vibration sensor. The vibration-computing engine triggers the synchronization box at approximately `11:12:47.93 (UTC)`. This timestamp can be converted to a unix time stamp as `1668597167.9327474`. One has to be careful when evaluating the different time stamps, as the catman-Software delivers a UTC-timestamp, while the camera uses the raw ptp-values which are given in international atomic time (TAI). Note that due to the introduction of leap seconds UTC is currently 37s behind TAI.

Table 1: Triggering Time Stamps

Time stamp Vibration	1668597167.9327474
Time stamp Camera	1668597168.170159

In Table 1 the three logged time stamps generated during triggering are shown. These time stamps are within a quarter of a second. This time difference stems from the latency generated by the sync box and the logging. As the camera system (depending on its settings) can store data starting up to 300m before triggering and 300m after triggering this latency is easily low enough. Please note that the synchronization of the data is still as accurate as the ptp time-stamps (in the range of ns).

3 Outlook

3.1 Planned Data Acquisition Trips

During the next few months, several data acquisition trips are planned. Most importantly, the measurement system will run whenever P&T will make measurement trips. Of course, it will be important to make several trips over the same turnouts to compare different measurement runs and develop the algorithms.

At least one measurement trip is planned to measure the chosen project turnouts. This data shall be used to compare the new measurements to the already existing data presented in the documents D2.2.3.

Furthermore, in spring next year (April 2023), we want to use the EM100VT to measure the 'Sensorkonzept Weiche' developed by the project partner virtual vehicle.

The data generated during these measurement trips will be evaluated on a continuous basis, meaning that the algorithms will be developed incrementally.

3.2 Planned Annotation Tool

The development of a tool for visualization and annotation of sensor data is planned for the remaining project duration. For this purpose, a prototype of an existing web-based geographic information system will be extended, which can retrieve a variety of sensor data via different interfaces through a database and display them within a map or a diagram.

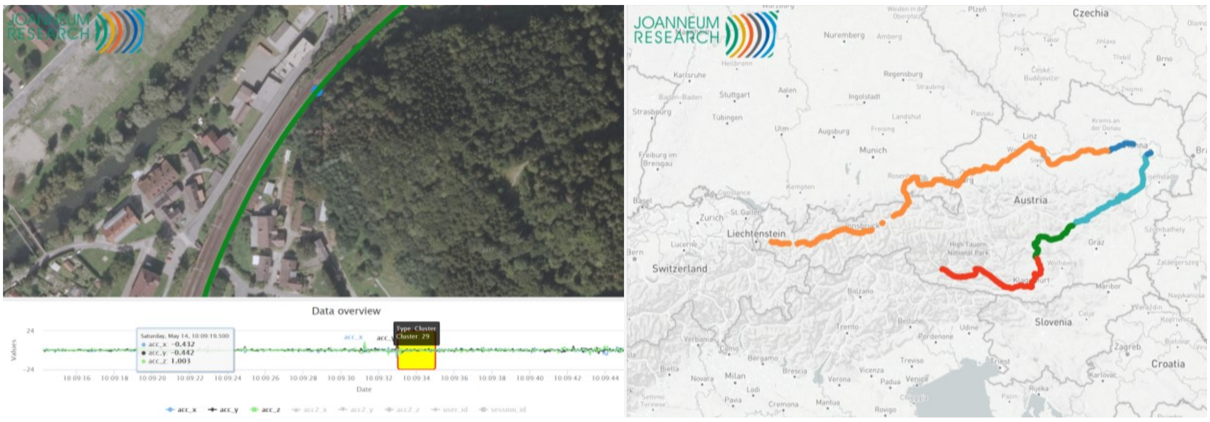


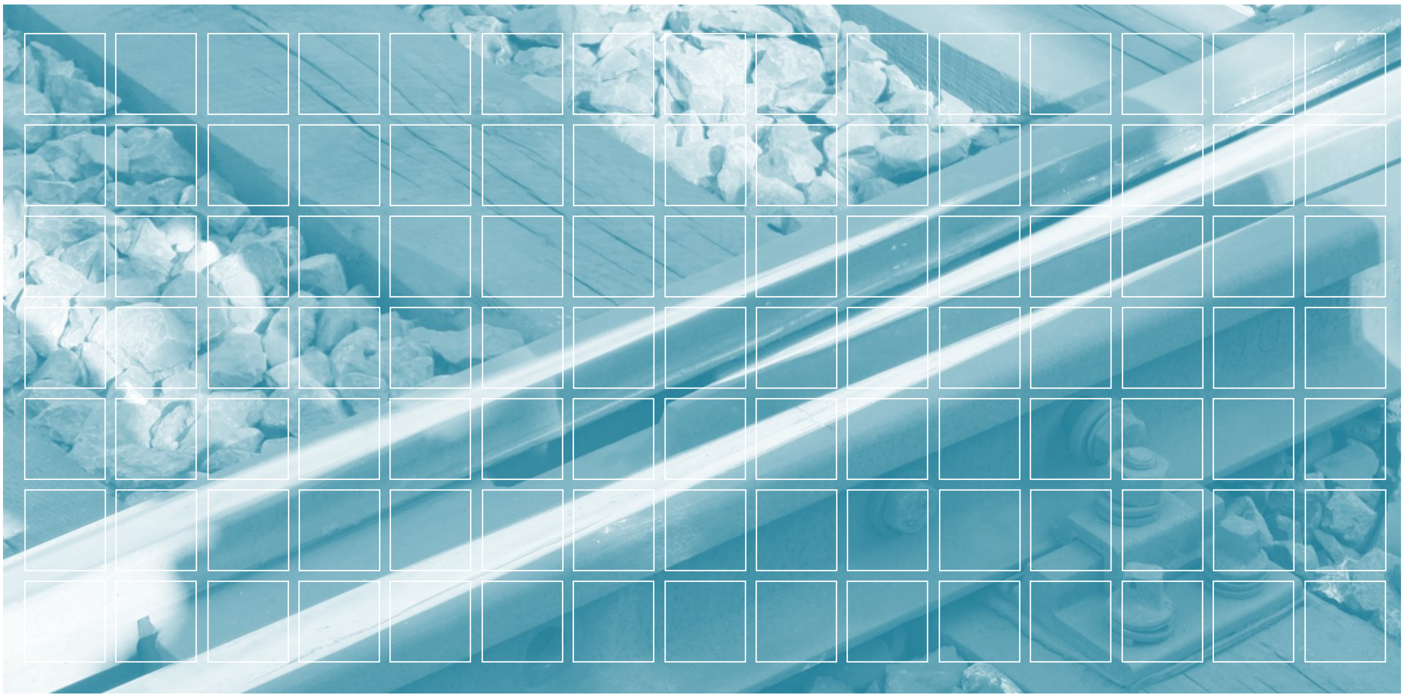
Figure 19: Rail4Future Visualization and Annotation Tool

The interface shall consist of (i) a map view supporting different layers (e.g. aerial images, route network, etc.) showing the recorded route in a georeferenced way, (ii) a sensor data view in form of a diagram showing vibration data, line-scan camera data and corresponding metadata e.g. timestamps, IDs, referenced ground truth images and (iii) an annotation and control interface.

The tool will on the one hand provide an overview of all recorded tracks and on the other hand a detailed view of a track for inspection and annotation of areas of interest. The annotation of areas of interest in the signal can be used for documentation purposes and especially for the improvement of the analysis algorithms (labelling). For an additional visual comparison, the current position of the measurement point in the map is synchronized with the vibration signal and the line-scan camera data in the diagram. In addition to the possibility of visualizing measurement data and annotations, it should also be possible to display processing results from the data analysis.

References

[1] S. Marschnig, M. Loidolt, F. Graf and J. Fuchs, D2.2.2 Report of Requirements, Project R4F, 2021.



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