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Master Thesis

Development of a hardware and software framework for the automated characterization of permanent magnets for low-field MRI systems

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Abstract

In the construction of low-field MRI devices based on permanent magnets, a large number of magnets are used. In order to realize a homogeneous B0 field with these magnets, which is necessary for many setups, the magnetic properties of these magnets have to be **as** similar to a certain degree. Due to the complex manufacturing process of neodymium magnets, the different properties, the direction of magnetization, can deviate from each other, which affects the homogeneity of the field. To adjust the field afterwards, a passive shimming process is typically performed, which is complex and time-consuming and requires manual corrections to the magnets used. To avoid this process, magnets can be systematically measured in advance. In this methodology, the recording, data storage and subsequent evaluation of the data play an important role. Various existing open-source solutions implement individual parts, but do not provide a complete data processing pipeline from **aquisition** to analysis and the data storage formats of these are not compatible to each other. For this use case, the MagneticReadoutProcessing library was created, which implements all major aspects of acquisition, storage, analysis, and each intermediate step can be customized by the user without having to create everything from scratch, favoring an exchange between different user groups. Complete documentation, tutorials and tests enable users to use and adapt the Framework as quickly as possible. The framework for the characterization of different magnets, which requires the integration of magnetic field sensors, was used for the evaluation.

List of abbreviations

CAD Computer Aided Design. 8

CDC Communication Device Class. 11

CLI Command Line Interface. 11, 12, 16, 27, 28, 35–38, 44, 48

GPIO General Purpose Input/Output. 9, 19

GUI Graphical User Interface. 36

HAL Hardware Abstraction Layer. 25

HTML Hypertext Markup Language. 45, 46

I2C Inter-Integrated Circuit. 7, 11

IC Integrated Circuit. 7

ID Identification Number. 27–29, 31

IDE Integrated Development Environment. 41, 45

IP Internet Protocol. 26

JSON JavaScript Object Notation. 30

LUT Lookup Table. 11, 27, 28

MRP MagneticReadoutProcessing. 6, 12, 14, 16, 17, 19, 23, 27, 29, 32, 36–38, 41–44, 46, 47, 54

PC Personal Computer. 9, 11, 13, 19, 20, 23–26, 30, 37, 42

PDF Portable Document Format. 45

PIP Python Package Installer. 43

PPS Puls Per Second. 26

PTP Precision Time Protocol. 26

REST Representational State Transfer. 24, 25

SBC Single Board Computer. 14, 19, 24, 26

UART Universal Asynchronous Receiver / Transmitter. 11, 19

USB Universal Serial Bus. 11, 13, 14, 26

Contents

1	Introduction	1
1.1	Background and Motivation	1
1.1.1	Low-Field MRI	1
1.1.2	Shimming procedure	1
1.2	Aim of this Thesis	1
1.3	Structure	1
2	State of the art	3
2.1	Opensource projects	3
2.2	Conceptual design	3
3	Use cases	4
4	Unified Sensor	6
4.1	Sensor selection	6
4.2	Mechanical S tructure	7
4.3	Electrical Interface	8
4.4	Firmware	9
4.4.1	Communication interface	11
4.4.2	Sensor syncronisation interface	13
4.5	Example sensors	16
4.5.1	1D: Single S ensor	17
4.5.2	3D: Fullsphere	18
4.5.3	Integration of an industry teslameter	19
5	Software readout framework	22
5.1	Library requirements	22
5.1.1	Concepts	22
5.1.2	User interaction points	22
5.2	Extension M odules	22
5.2.1	HAL	22
5.2.2	Visualisation	23

5.2.3 Storage	23
5.2.4 Export	23
5.3 Multible sensor setup	23
5.3.1 Network-Proxy	25
5.3.2 Sensor Synchronisation	26
5.3.3 Command-Router	27
5.4 Examples	29
5.4.1 MRPReading	29
5.4.2 MRPHal	30
5.4.3 MRPSimulation	31
5.4.4 MRPAnalysis	32
5.4.5 MRPVisualisation	32
5.4.6 MRPHallbachArrayGenerator	34
6 Usability improvements	36
6.1 Command Line Interface	36
6.2 Programmable data processing pipeline	38
6.3 Tests	41
6.4 Package distribution	43
6.4.1 Documentation	45
7 Evaluation	47
7.1 Hardware preperation	48
7.2 Configuration of the measurement	48
7.3 Custom algorithm implementation	49
7.4 Execution of analysis pipeline	50
8 Conclusion and dicussion	53
8.1 Conclusion	53
8.2 Outlook	53
Bibliography	55
List of Figures	57
List of Tables	59
Listings	60

1 Introduction

1.1 Background and Motivation

1.1.1 Low-Field MRI

1.1.2 Shimming procedure

1.2 Aim of this Thesis

1.3 Structure

This work is divided into six main chapters, which deal with the approach and implementation. The techniques and concepts used are explained in detail. Specific examples provide an overview of the possible use of the developed solution by the user.

2. **State of the art** describes the current state of technology and forms the basis for further development. Existing measurement methods and findings are shown here in order to define the context for the current project.

3. **Usecases** are the application cases in which the project is to be used. They illustrate the practical scenarios and define how the product can be used in the real world. This is crucial for understanding the needs of the target group and designing the end result accordingly.

4. **Unified Sensor** refers to the integration of different sensors into a standardised solution. This enables simple data acquisition and serves as a basic hardware system

on which the subsequent data processing library can be applied.

5. **Software readout framework** chapter describes the implementation of the data readout framework. This includes an explanation of the various modules and specific application examples.

6. **Usability improvements** refers to measures to improve user-friendliness. This involves optimising interfaces, interactions and processes to ensure intuitive and efficient use of the product. This includes, code documentation or the distribution of source code to users.

7. **Evaluation** comprises the systematic review and assessment of the overall system. This includes the demonstration of the implemented capabilities of the overall system against the previously defined use cases.

2 State of the art

2.1 Opensource projects

2.2 Conceptual design

- Entwicklung eines hardware und software framework zur einfachen Aquirierung von Magnetfelddaten
- Analysetools und Funktionen

3 Usecases

The following section defines some use cases that the future project should be able to cover. They illustrate practical situations and help to understand the functionality and added value of the implemented project for the user. These were defined in the course of project planning and provide an overview of how the user interacts with the project and what functionalities can be expected. In the later evaluation7 process, the defined usecases are also used as a reference to demonstrate the implemented capabilities of the solution.

1. **Ready to use hardware sensor designs** A universal, easy-to-integrate Hall sensor design allows users to evaluate the framework quickly and cost-effectively. The pre-built hardware sensors provide an optimal solution for research, reducing development time and achieving repeatable measurement results. Once successfully evaluated, the Hall sensor design should be easily adaptable to other sensors without the need for major firmware changes.
2. **Taking automatic measurements from sensors** The purpose of the framework is to enable the automated acquisition of measurement data from various connected hardware sensors. The user should be able to configure various measurement series, which should then be carried out by the framework without further user interaction.
3. **Open storage formats for data export** The use of open storage formats for the export of data enables an interoperable data exchange environment. The implementation of standardized formats improves the portability and long-term availability of data. This encourages the exchange and further processing of measurement data in other software tools.
4. **Ready to integrate data analysis functions** Once it is possible to record and store measured values, it should be possible for the user to analyse and visualize this data using various algorithms. The focus here should be on extending the

framework with user-created algorithms.

5. **User programmable data processing pipelines** User-programmable data processing pipelines enable the flexible design of data processing sequences by users. The framework should enable users to create their own Analyse pipelines with the previously defined data analysis functions.

4 Unified Sensor

A defined main objective of this project is the development of a cost-effective Hall sensor interface that is also universally expandable. The focus is on mapping different sensors and being compatible with different magnet types and shapes. This ensures broad applicability in different scenarios. Another goal is reproducibility to ensure consistent results. Easy communication with standard PC hardware maximises the user-friendliness of the interface. The flexibility to support different sensors and magnets makes the system versatile and opens up possibilities for different applications. A low-cost Hall sensor interface will therefore not only be economically attractive, but also facilitate the integration of Hall sensors in different contexts. In addition, the low-cost Hall sensor interface will serve as a development platform for the data evaluation MagneticReadoutProcessing (MRP) library and provide real measurement data from magnets. In addition, the interface firmware creates a basis for the development of a data protocol for exchanging measured values. This makes it easy to integrate your own measuring devices into the MRP ecosystem at a later date. This is only possible with a minimal functional hardware and firmware setup and was developed for this purpose first.

4.1 Sensor selection

The selection process for possible magnetic field sensors initially focussed on the most common and cost-effective ones, especially those that are already used in smartphones and are therefore widely available. A key aspect of this selection was the preference for sensors with digital interfaces to facilitate implementation in the circuit layout. The integration of integrated temperature sensors represents a significant enhancement that will later enable precise temperature compensation.

Linear analogue Hall sensors were deliberately omitted, although they are suitable for more precise measurements and extended measuring ranges. They were excluded due to the more complex circuit layouts required and more complex power management. In

the context of the desired goal of developing a cost-efficient and universally expandable Hall sensor interface, the decision in favour of digital sensors seems appropriate.

Tabelle 4.1: Implemented digital **halleffect** sensors

	TLV493D-A1B6	HMC5883L	MMC5603NJ	AS5510
Readout-Axis	3D	3D	3D	1D
Temperature-Sensor	yes	no	yes	no
Resolution [uT]	98	0.2	0.007	48
Range [mT]	±130.0	±0.8	±3	±50
Interface	Inter-Integrated Circuit (I2C)	I2C	I2C	I2C

Focussing on digital **interfaces not only facilitates** implementation, but also contributes to overall cost efficiency. At the same time, the integration of temperature sensors enables precise measurements under varying environmental conditions. This strategic choice forms the basis for a flexible, universally applicable Hall sensor interface that can be seamlessly integrated into various existing systems.

The table4.1 shows a selection of sensors for which hardware and software support has been implemented. The resolution of the selected sensors covers the expected range of values required by the various magnets to be tested.

4.2 Mechanical Structure

The mechanical structure of a sensor is kept **very simple** for the following tests. The focus was on providing a stable foundation for the sensor Integrated Circuit (IC) and an exchangeable holder for different magnets.

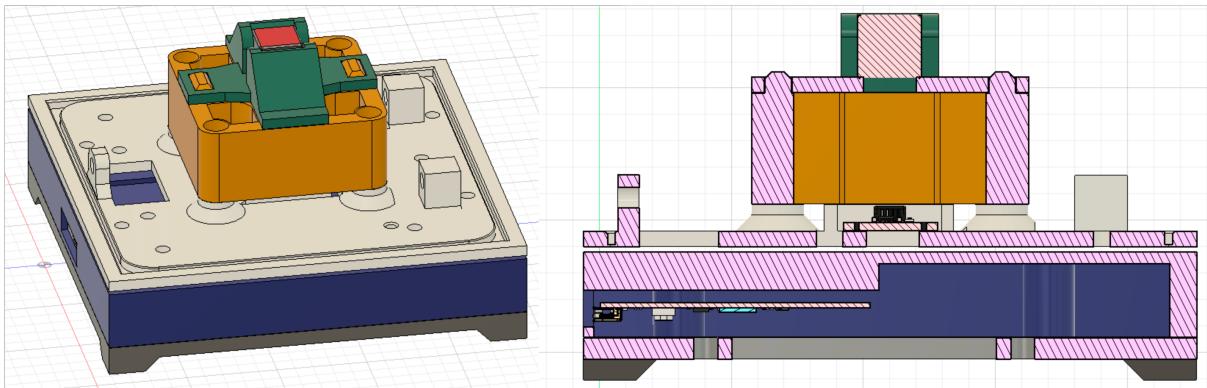


Figure 4-1: 1D sensor mechanical 3D printed structure

The following figure 4-1, shows a sectional view of the Computer Aided Design (CAD) drawing of the 1D: Single sensor 4.5.1.

All parts were produced using the 3D printing process. The sensor circuit board was glued underneath the magnet holder. This is interchangeable, so different distances between sensor and magnet can be realised.

The exchangeable magnetic holder (shown in green) can be adapted to different magnets. It can be produced quickly due to the small amount of material used. The two recesses lock the holder with the inserted magnet over the sensor. Due to predetermined tolerances, the magnet can be inserted into the holder with repeat accuracy and without play. This is important if several magnets have to be measured, where the positioning over the sensor must always be the same.

4.3 Electrical Interface

As with the mechanical design, the electronics should be kept as simple as possible so that it is possible to use the microcontroller and a magnetic field sensor.

The focus here was on utilising existing microcontroller development and evaluation boards, which already integrate all the components required for smooth operation. This not only enabled a time-saving implementation, but also ensured a cost-efficient realisation.

A decisive step in my work was the in-house PCB design 4-2, which leads out all the

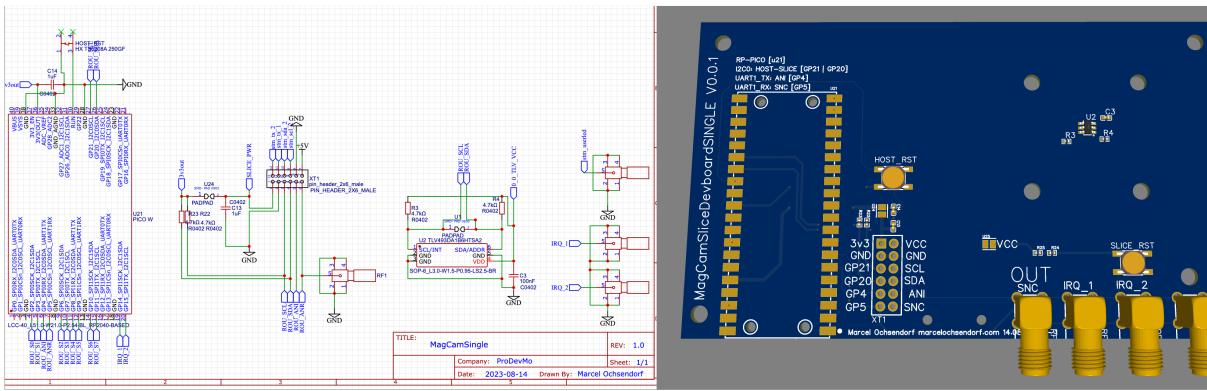


Figure 4-2: 1D sensor schematic and circuit board

important connections. The placement and alignment of components optimised the wiring, which in turn improved the reliability of the sensor tests. Particular attention was paid to the implementation of a SYNC-General Purpose Input/Output (GPIO), which enables subsequent multi-sensor synchronisation. This functionality opens up the possibility of synchronising data from different sensors to achieve precise and coherent measurement results. Overall, this integrated approach represents an effective solution for the flexible evaluation of sensors and helps to optimise the development process.

4.4 Firmware

Microcontroller firmware is software that is executed on a microcontroller in embedded systems. It controls the hardware and enables the execution of predefined functions. The firmware is used to process input data, control output devices and fulfil specific tasks according to the program code. It handles communication with sensors, actuators and other peripheral devices, processing data and making decisions. Firmware is critical to the functioning of devices.

The firmware is responsible for detecting the possible connected sensors and reading them out. This measured data can be forwarded to a host Personal Computer (PC) via a user interface and can then be further processed there.

An important component is that as many common sensors as possible can be easily connected without having to adapt the firmware. This modularity was implemented using abstract class design. These are initiated according to the sensors found at startup. If new hardware is to be integrated, only the required functions need to be implemented.

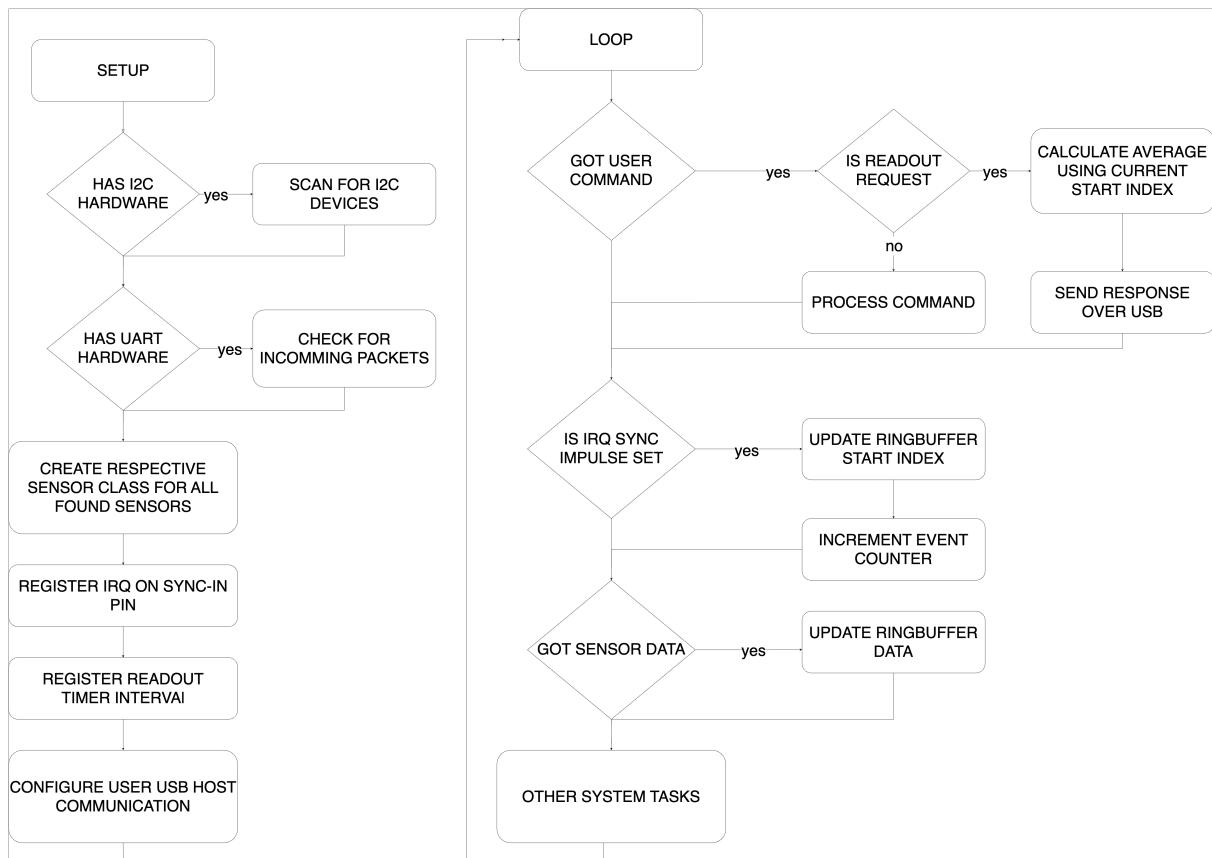


Figure 4-3: Unified sensor firmware simplified program structure

```

1 #ifndef __CustomSensor_h__
2 #define __CustomSensor_h__
3 // register your custom sensor in implemented_sensors.h also
4 class CustomSensor: public baseSensor
5 {
6 public:
7     CustomSensor();
8     ~CustomSensor();
9     // implement depending sensor communication interface
10    bool begin(TwoWire& _wire_instance); // I2C
11    bool begin(HardwareSerial& _serial_instance); // UART
12    bool begin(Pin& _pin_instance); // ANALOG or DIGITAL PIN like onewire
13    // FUNCTIONS USED BY READOUT LOGIC
14    bool is_valid() override;
15    String capabilities() override;
16    String get_sensor_name() override;
17    bool query_sensor() override;
18    sensor_result get_result() override;
19 };
20 #endif

```

Listing 4.1: CustomSensor-Class for adding new sensor hardware support

The flow chart 4-3 shows the start process and the subsequent main loop for processing the user commands and sensor results. When the microcontroller is started, the software checks whether known sensors are connected to I2C or Universal Asynchronous Receiver / Transmitter (UART) interfaces. If any are found (using a dedicated Lookup Table (LUT) with sensor address information), the appropriate class instances are created and these can later be used to read out measurement results.

Next, the subsystem for multi-sensor synchronisation 4.4.2 is set up. The last step in the setup is to set up communication with the host or connected PC. All microcontroller platforms used here have a Universal Serial Bus (USB) slave port. The used USB descriptor is `Serial over (+usb)-((+usb))Communication Device Class (CDC)`. This is used to emulate a virtual RS232 communication port using a USB port on a PC and usually no additional driver is needed on modern systems.

Now that the setup process is complete, the system switches to an infinite loop, which processes several possible actions. One task is, to react to user commands which can be sent to the system by the user via the integrated Command Line Interface (CLI). All sensors are read out via a timer interval set in the setup procedure and their values are stored in a ringbuffer. Ring buffers, offer efficient data management in limited memory. Its cyclic structure enables continuous overwriting of older data, saves memory space and facilitates seamless processing of real-time data.

Ring buffers are well suited for applications with variable data rates and minimise the need for complex memory management. The buffer can be read out by command and the result of the measurement is sent to the host. Each sensor measurement result is transmitted from the buffer to the host together with a time stamp and a sequential number. This ensures that in a multi-sensor setup with several sensors. The measurements are synchronized 4.4.2 in time and are not out of sequence or drift.

4.4.1 Communication interface

Each sensor that has been loaded with the firmware, registers on to the host PC as a serial interface. There are several ways for the user to interact with the sensor:

```

help
=====
> help                      shows this message
> version                   prints version information
> id                        sensor serial number for identification purposes
> sysstate                  returns current system state machine state
> opmode                     returns 1 if in single mode
> sensorcnt                returns found sensorcount
> readsensor x <0-senorcount> returns the readout result for a given sensor index for X axis
> readsensor y <0-senorcount> returns the readout result for a given sensor index for Y axis
> readsensor z <0-senorcount> returns the readout result for a given sensor index for Z axis
> readsensor b <0-senorcount> returns the readout result for a given sensor index for B axis
> temp                       returns the system temperature
> anc <base_id>             perform a autonumbering sequence manually
> ancid                      returns the current set autonumbering base id (-1 in singlemode)
> reset                      performs reset of the system
> info                        logs sensor capabilities
> commands                   lists sensor implemented commamnds which can be used by hal
=====

```

Figure 4-4: Sensors CLI

```

readsensor b 0
3279.99

```

Figure 4-5: Query sensors b value using CLI

- Use with MRP-library5
- Stand-alone mode via sending commands using built-in CLI

The CLI mode is a simple text-based interface with which it is possible to read out current measured values, obtain debug information and set operating parameters. This allows to quickly determine whether the hardware is working properly after installation. The CLI behaves like terminal programmes, displaying a detailed command reference⁴⁻⁴ to the user after connecting. The current measured value can be output using the [readout](#) command⁴⁻⁵.

The other option is to use the MRP-library. The serial interface is also used here. However, after a connection attempt by the [MRPHal](#) module^{5.2.1} of the MRP-library, the system switches to binary mode, which is initiated using the [sbm](#) command. The same commands are available as for CLI-based communication.

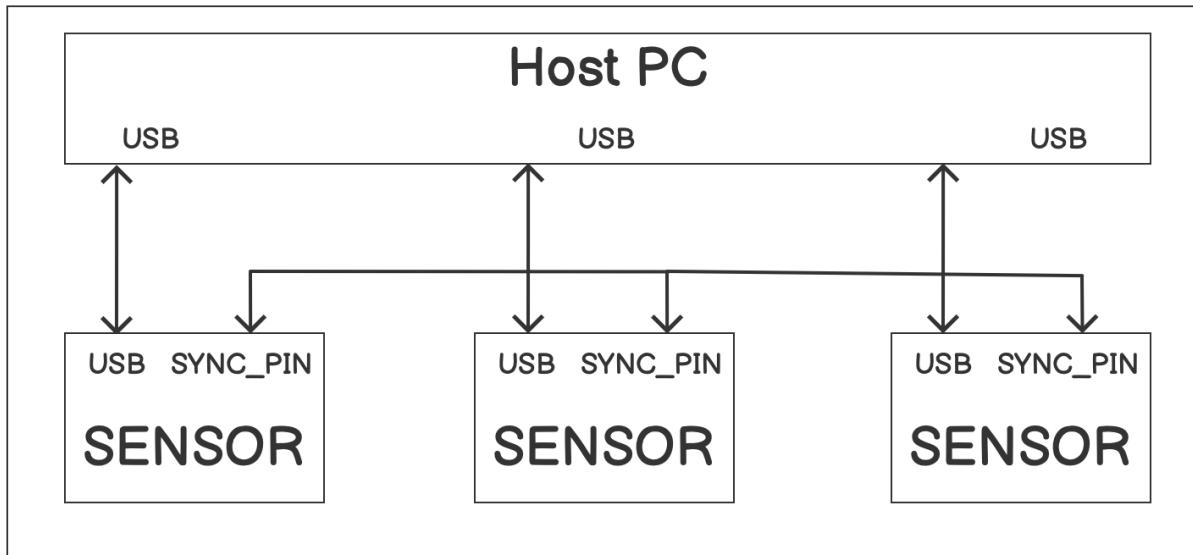


Figure 4-6: Multi sensor synchronisation wiring example

4.4.2 Sensor synchronisation interface

One problem with the use of several sensors on one readout host PC is that the measurements may drift over time. On the one hand, USB latencies can occur. This can occur due to various factors, including device drivers, data transfer speed and system resources. High-quality USB devices and modern drivers often minimise latencies. Nevertheless, complex data processing tasks and overloaded USB ports can lead to delays.

Tabelle 4.2: Measured sensor readout to processing using host software

RunPoints	runtime [ms]	Average Sensor		Communication jitter time [ms]	Comment
		Host software	communication time per reading [ms]		
1 1	9453		1.44	0	
2 1	9864		1.5	0	
3 10	12984		1.22	0.9	
4 10	12673		1.13	1.1	

RunPoints	Host software runtime [ms]	Average Sensor communication time per reading [ms]	Communication jitter time [ms]	Comment
5 10	43264	2.19	8.2	96% system load

The table shows various jitter measurements. These were performed on a Raspberry Pi 4 4GB-Single Board Computer (SBC) together with an [1D: Single Sensor](#) [4.5.1](#) and the following software settings:

- Raspberry Pi OS Lite - debian bookworm x64,
- MRP5-library - version 1.4.1
- Unified Sensor Firmware [4](#) - version 1.0.1

It can be seen that a jitter time of up to an additional [1ms](#) is added between the triggering of the measurements by the host system and the receipt of the command by the sensor hardware. If the host system is still under load, this value increases many times over. This means that synchronising several sensors via the USB connection alone is not sufficient.

The other issue is sending the trigger signal from the readout software [5](#). Here too, unpredictable latencies can occur, depending on which other tasks are also executed on this port.

In order to enable the most stable possible synchronisation between several sensors, an option has already been created to establish an electrical connection between sensors. This is used together with the firmware to synchronise the readout intervals. The schematic [4-6](#) shows how several sensors must be wired together in order to implement this form of synchronisation.

Once the hardware has been prepared, the task of the firmware of the various sensors is to find a common synchronisation clock. To do this, the register [irq on sync pin](#) is overwritten. To set one [primary](#) and several [secondary](#) sensors, each sensor waits for an initial pulse on the sync-pin [4-7](#). Each sensor starts a random timer beforehand, which sends a pulse on the sync line. All others receive this and switch to [secondary](#) mode and synchronise the measurements based on each sync pulse received. Since

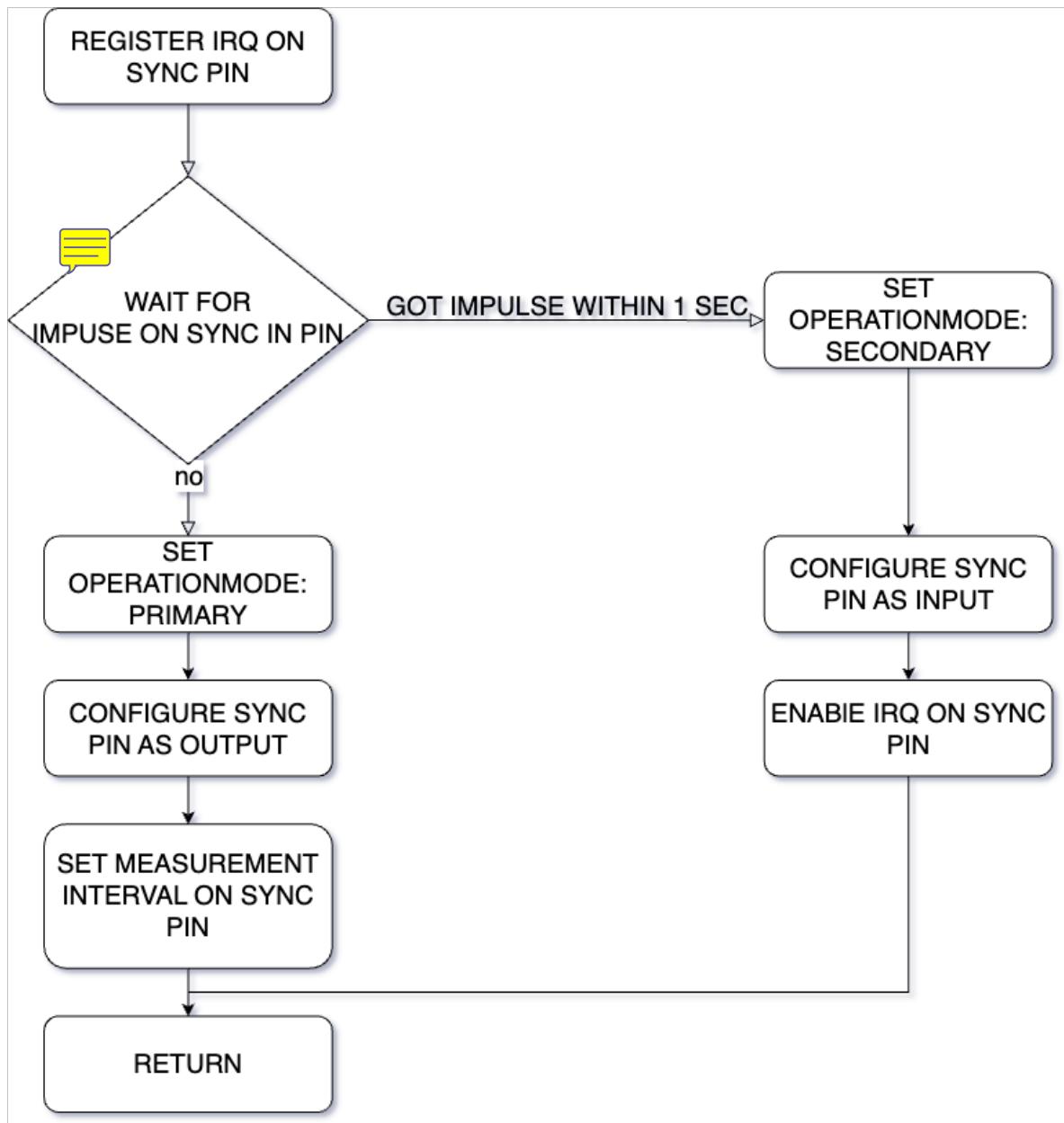


Figure 4-7: Unified sensor firmware multi sensor synchronisation procedure

```
opmode
SECONDARY (got sync after 823ms)
```

Figure 4-8: Query opmode using CLI

the presumed [primary](#) sensor cannot register its own sync pulse (because the pin is switched to output), there is a timeout [got pulse within 1000ms](#) and this becomes the [primary](#) sensor. This means that in a chain of sensors there is exactly one [primary](#) and many [secondary](#) sensors. In single-sensor operation, this automatically jumps to [primary](#) sensor operation through the [got impulse within 1000ms](#) query. The synchronisation status can be queried via the user interface^{4.4.1} using the [opmode](#)⁴⁻⁸ command. An important aspect of the implementation [here was](#) that there is no numbering or sequence of the individual sensors. This means that for the subsequent readout of the measurements, it is only important that they are taken at the same interval across all sensors. The sensor differentiation takes place later in the readout software⁵ by using the sensor identification number.

4.5 Example sensors

Two functional sensor platforms^{4.3} were built in order to create a solid test platform for later tests and for the development of the MRP library with the previously developed sensor concepts.

Tabelle 4.3: Build sensors with different capabilities

	1D ^{4.5.1}	1D: dual sensor	3D: Fullsphere ^{4.5.2}
Maximal magnet size	Cubic 30x30x30	Cubic 30x30x30	Cubic 20x20x20
Sensor type	MMC5603NJ	TLV493D	TLV493D
Sensor count	1	2	1
Scanmode	static (1 point)	static (2 points)	dynamic (fullsphere)

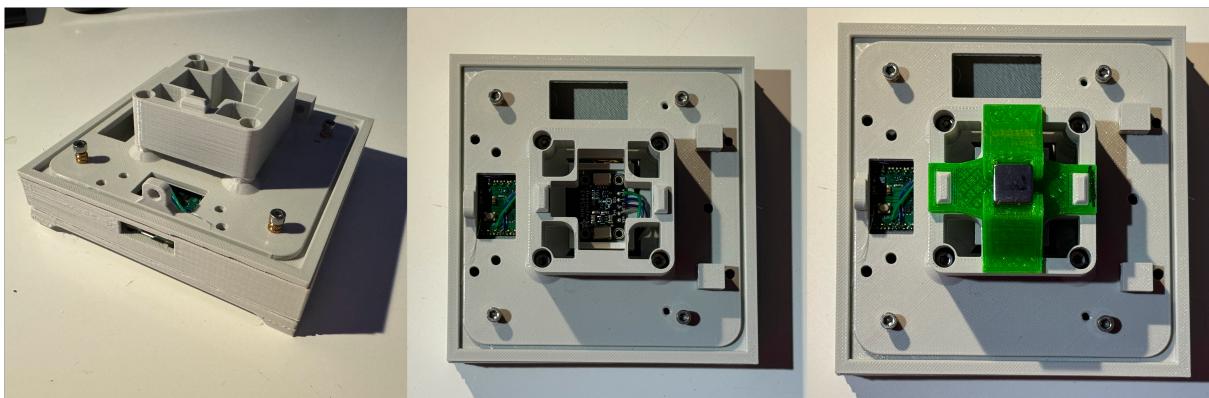


Figure 4-9: 1D sensor construction with universal magnet mount

These cover all the required functions described in the [Usecases3](#). The most important difference, apart from the sensor used, is the [scan mode](#). In this context, this describes whether the sensor can measure a [static](#) fixed point on the magnet or if the sensor can move [dynamically](#) around the magnet using a controllable manipulator.

In the following, the hardware structure of a [static](#) and [dynamic](#) sensor is described. For the [static](#) sensor, only the [1D](#) variant is shown, as this does not differ significantly from the structure of the [1D: dual sensor](#), except it uses two [TLV493D](#) sensors, mounted above and on top of the magnet.

4.5.1 1D: Single Sensor

The [1D sensor4-9](#) is the simplest possible sensor that is compatible with the [Unified Sensor Firmware4.4](#) platform and also with the [MRP-library5](#).

The electrical level here is based on a [Raspberry-Pi Pico](#) together with the [MMC5603NJ](#) [magnetic](#) sensor. The mechanical setup consists of four [3D-printed](#) components, which are fixed together with nylon screws to minimise possible influences on the measurement.

Since the [MMC5603NJ](#) only has very limited measuring range, even small neodymium magnets already saturate its range, it is possible to use [3D-printed](#) spacers above the sensor.

The standard magnet holder can be adapted for different magnet shapes and can be placed on the spacer without [play in order](#) to be able to perform a repeatable

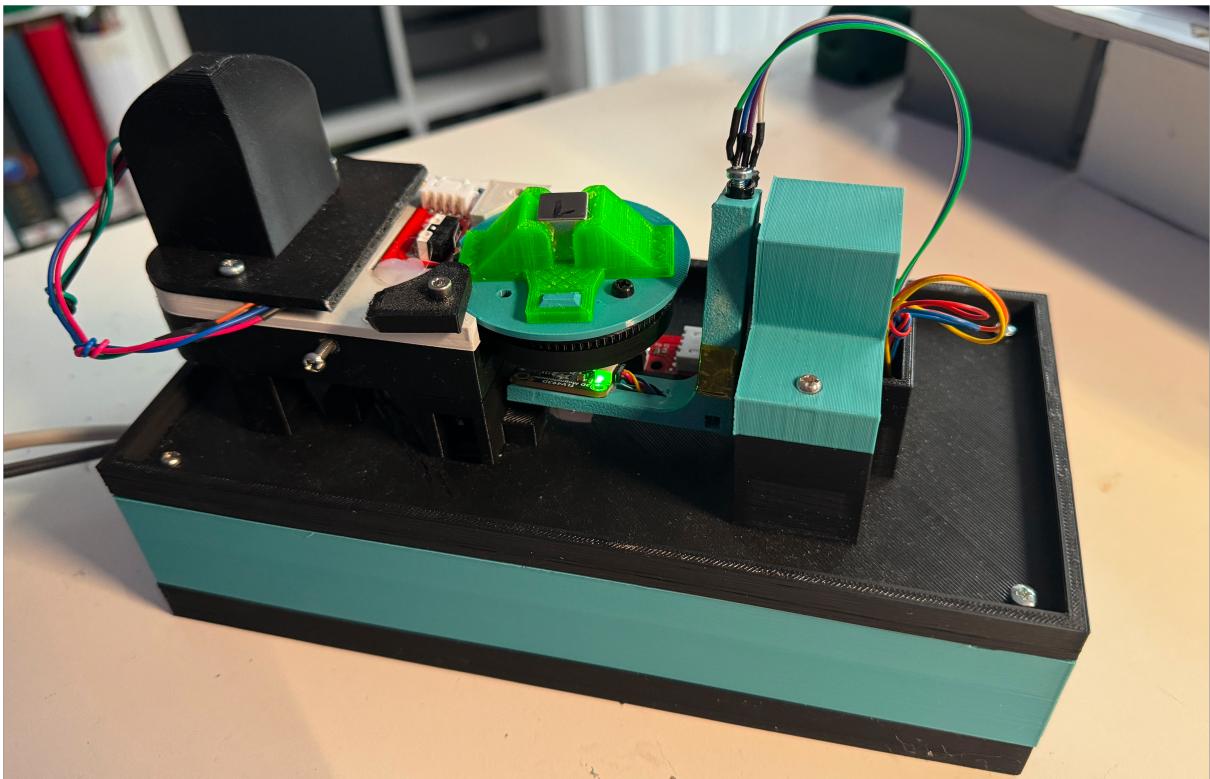


Figure 4-10: Full-Sphere sensor implementation using two Nema17 stepper motors in a polar coordinate system

measurement without introducing measurement irregularities by mechanically changing the magnet.

4.5.2 3D: Fullsphere

The 3D [Fullsphere](#) 4-10 sensor offers the possibility to create a 3D map 4-11 of the magnets. The magnet sensor is mounted on a movable arm, which can move 180 degrees around the magnet on one axis. In order to be able to map the full sphere, the magnet is mounted on a turntable. This permits the manipulator to move a polar coordinate system.

As the magnets in the motors, as with the screws used in the 1D sensor, can influence the measurements of the magnetic field sensor, the distance between these components and the sensor or magnets was increased. The turntable and its drive motor are connected to each other via a belt.

On the electrical side, it also consists of a [SKR Pico](#) stepper motor controller, together with the [TLV493D](#) magnetic field sensor. This was chosen because of its larger measuring range and can therefore be used more universally without having to change the sensor

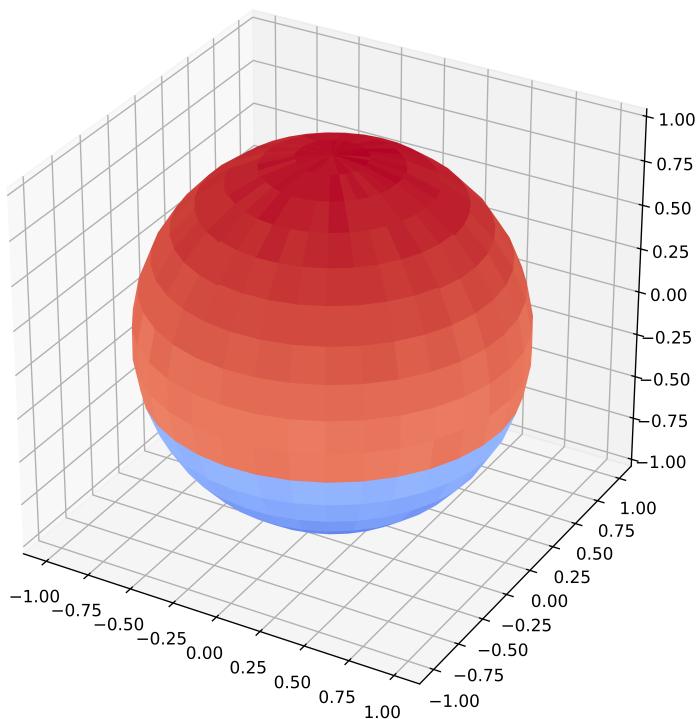


Figure 4-11: 3D plot of an N45 12x12x12 magnet using the 3D fullsphere sensor

of the arm.

4.5.3 Integration of an industry teslameter

As the sensors shown so far relate exclusively to self-built, low-cost hardware, the following section shows how existing hardware can be integrated into the system. This is shown here using a temperature-compensated Voltcraft GM-70 teslameter⁴⁻¹², which has a measuring range of 0–3T with a resolution of 0.1mT. It offers an RS232 interface with a documented protocol⁴⁻⁴ for connection to a PC. This connectivity makes it possible to make the device compatible with the MRP library using interface software [13] executable on the host PC. However, it does not offer the range of functions that the Unified Sensor Firmware⁴⁻⁴ offers.

Another option is a custom interface board between the meter and the PC. This is a good option as many modern PCs or SBCs no longer offer an RS232 interface. As with the other sensors, this interface consists of your RaspberryPi Pico with an additional level shifter. The Teslameter is connected to the microcontroller using two free GPIOs in UART mode. The Unified Sensor Firmware⁴⁻⁴ was adapted using a separate build configuration and the protocol of the measuring device was implemented.

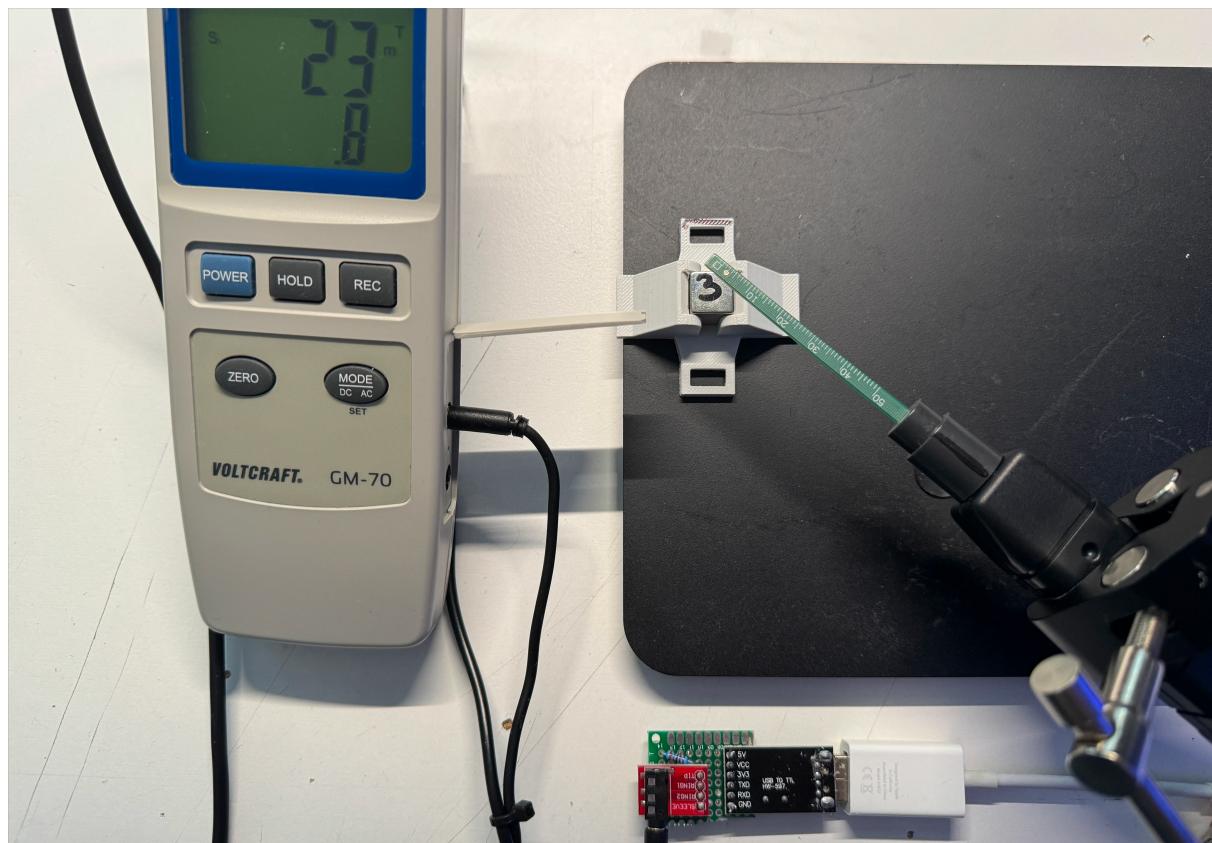


Figure 4-12: Voltcraft GM70 teslameter with custom PC interface board

Tabelle 4.4: Voltcraft GM70 serial protocol

BYTE-INDEX	REPRESENTATION	VALUE
0	PREAMBLE	0x2
1		0x1
2		0x4
3	UNIT	'B' => Gauss 'E' => mT
5	POLARITY	'1' => 0.1 '2' => 0.01
6	value MSB	0x-0xFF
13	value LSB	0x-0xFF

BYTE-INDEX	REPRESENTATION	VALUE
14	STOP	0x3

This software or hardware integration can be carried out on any other measuring device with a suitable communication interface and a known protocol thanks to the modular design.

5 Software readout framework

5.1 Library requirements

5.1.1 Concepts

- beispiele für projekte welche nur einzelne schnritte implementieren
- so kann man sich auf die implementierung

5.1.2 User interaction points

5.2 Extension Modules

Im folgenden werden die einzelnen module, welche vom user modifiziert und ersetzt werden können im details erläutert.

5.2.1 HAL

- aufbau hal im grunde wird nur ein die commandos an das sensor cli weitergegeben
- alle sensoren implementieren mehr oder weniger die gleichen befehle
- hal gibt nur weiter und ist “dumm”

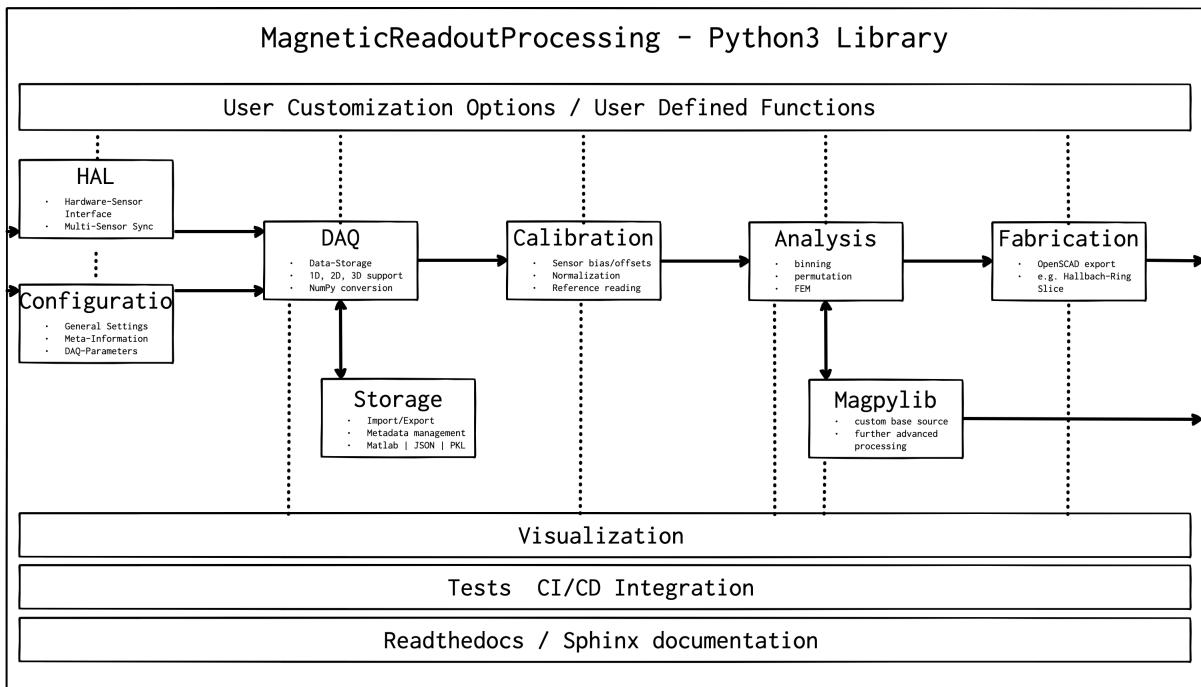


Figure 5-1: MRPlib COMPLETE FLOW

5.2.2 Visualisation

5.2.3 Storage

- metadata management

5.2.4 Export

- format import export
- matlab

5.3 Multible sensor setup

At the current state of implementation, it is only possible to detect and use sensors that are directly connected to the PC with the MRP-library. It has the disadvantage that there must always be a physical connection. This can make it difficult to install

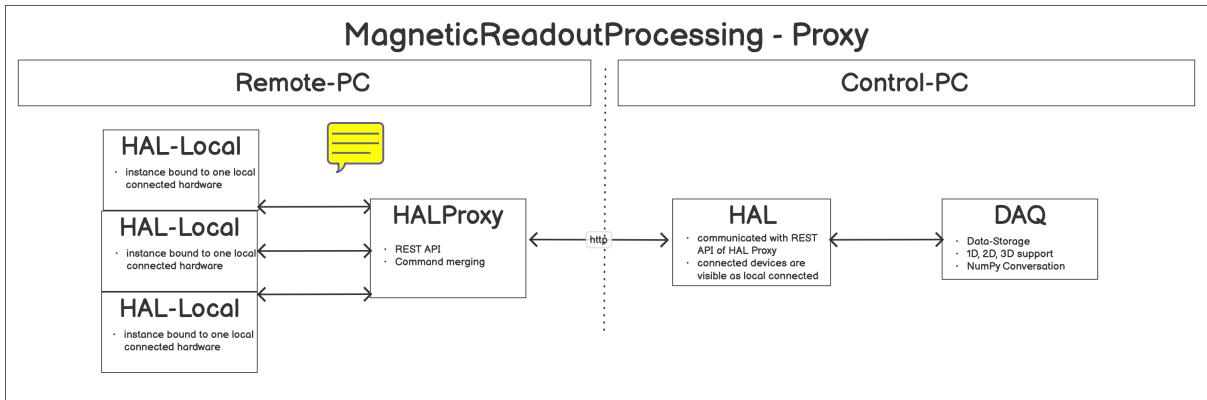


Figure 5-2: MRPlib Proxy Module

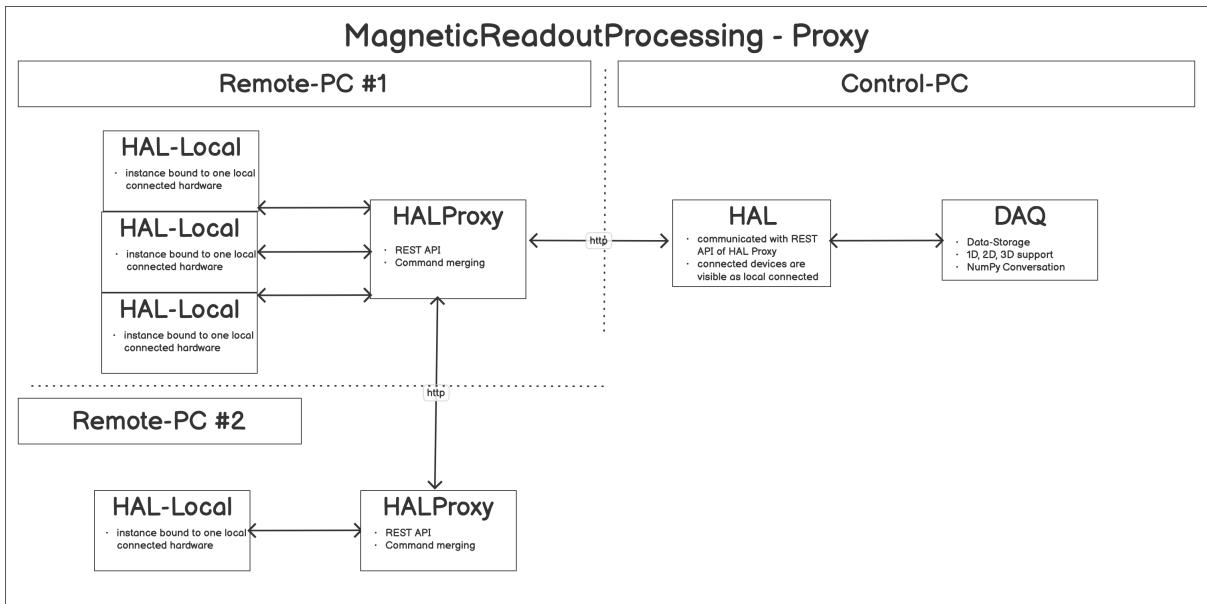


Figure 5-3: mrp proxy multi

multiple sensors in measurement setups where space or cable routing options are limited. To make sensors connected to a small [remote](#) PC available on the network, the [Proxy](#) module has been developed. This can be a SBC (e.g. a Raspberry Pi). The small footprint and low power consumption make it a good choice. It can also be used in a temperature chamber. The approach of implementing this via a Representational State Transfer (REST) interface also offers the advantage that several measurements or experiments can be recorded at the same time with the sensors.

Another application example is when sensors are physically separated or there are long distances between them. By connecting several sensors via the proxy module, it is possible to link several instances and all sensors available in the network are available to the [control](#) PC.

The figure 5-3 shows the modified multi-proxy – multi-sensor topology. Here, both proxy instances do not communicate directly with the control PC, but remotePC#2 is connected to remotePC#1. This is then visible as a sensor opposite the Control PC, even if there are several proxy instances behind it.

5.3.1 Network-Proxy

The figure 5-2 shows the separation of the various Hardware Abstraction Layer (HAL) instances, which communicate with the physically connected sensors on the remote PC and the control PC side, which communicates with the remote side via the network. For the user, nothing changes in the procedure for setting up a measurement. The proxy application must always be started^{5.1} on the remote PC side.

```
1 # START PROXY INSTANCE WITH TWO LOCALLY CONNECTED SENSORS
2 $ python3 mrpproxy.py proxy launch /dev/ttySENSOR_A /dev/ttySENSOR_B #
   add another proxy instance http://proxyinstance_2.local for multi-
   sensor, multi-proxy chain
3 Proxy started. http://remotePC.local:5556/
4 PRECHECK: SENSOR_HAL: 1337 # SENSOR A FOUND
5 PRECHECK: SENSOR_HAL: 4242 # SENSOR B FOUND
6 Terminate Proxy instance [y/N] [n]:
```

Listing 5.1: MRPproxy usage to enable local sensor usage over network

After the proxy instance has been successfully started, it is optionally possible to check the status via the REST interface^{5.2}:

```
1 # GET PROXY STATUS
2 $ wget http://proxyinstance.local:5556/proxy/status
3 {
4 "capabilities": [
5   "static",
6   "axis_b",
7   "axis_x",
8   "axis_y",
9   "axis_z",
10  "axis_temp",
11  "axis_stimestamp"
12 ],
13 "commands": [
14   "status",
15   "initialize",
16   "disconnect",
```

```
17 "combinedsensorcnt",
18 "sensorcnt",
19 "readsensor",
20 "temp"
21 ]}
22 # RUN A SENSOR COMMAND AND GET THE TOTAL SENSOR COUNT
23 $ wget http://proxyinstance.local:5556/proxy/command?cmd=
    combinedsensorcnt
24 {
25 "output": [
26   "2"
27 ]}
```

Listing 5.2: MRProxy REST endpoint query examples

The query result shows that the sensors are connected correctly and that their capabilities have also been recognised correctly. To be able to configure a measurement on the other, only the Internet Protocol (IP) address or host name of the remote PC is required.

```
1 # CONFIGURE MEASUREMENT JOB USING A PROXY INSTANCE
2 $ MRPcli config setsensor testcfg --path http://proxyinstance.local
   :5556
3 > remote sensor connected: True using proxy connection:
4 > http://proxyinstance.local:5556 with 1 local sensor connected
```

Listing 5.3: MRPcli usage example to connect with a network sensor

5.3.2 Sensor Synchronisation

Another important aspect when using several sensors via the proxy system is the synchronisation of the measurement intervals between the sensors. Individual sensor setups do not require any additional synchronisation information, as this is communicated via the USB interface. If several sensors are connected locally, they can be connected to each other via their sync input using short cables. One sensor acts as the central clock as described in?. This no longer works for long distances and the synchronisation must be made via the network connection.

If time-critical synchronisation over the network is required, Precision Time Protocol (PTP) and Puls Per Second (PPS) output functionality[9] can be used on many SBC, such as the Raspberry-Pi Compute Module 4.

5.3.3 Command-Router

As it is possible to connect many identical sensors to one host using the [Network–Proxy](#) 5.3.1, it must be possible to address them separately. This separation is done by the [MRPProxy.proxy](#) module and is therefore not part of the core MRP library.

Each connected sensor is addressed via the text-based CLI or the binary interface, this is initially the same for each sensor. The only identification feature is the sensor Identification Number (ID).

The [Network–Proxy](#) 5.3.1 instance pretends to be a sensor to the MRP host, so the multiple sensors must be combined into one. This is done in several steps, in the [Network–Proxy](#) 5.3.1 start procedure:

1. Construct the Sensor ID LookUp-Table

Immediately after starting the [network–proxy](#) 5.3.1, the IDs of all locally connected sensors are read out. These are stored together with the instance of the [MRPHal](#) module in a LUT. This makes it possible to address a sensor directly using its ID.

2. Merging the sensor capabilities

Tabelle 5.1: Sensor capabilities merging

SENSOR A	SENSOR B	MERGED CAPABILITIES	CAPABLE SENSORS ID LUT
static	static		A
	dynamic	dynamic	B
axis_temp	axis_temp	axis_temp	A B
axis_x	axis_x	axis_x	A B

When using sensors with different capabilities, these must be combined. These are used to select the appropriate measurement mode for a measurement. For this purpose, the

`info` command of each sensor is queried. This information is added to the previously created LUT. Duplicate entries are summarized (see Table 5.1) and returned to the host when the `info` command is received over network.

```
1 # QUERY Network-Proxy capabilities
2 $ wget http://proxyinstance.local:5556/proxy/status
3 {"capabilities": [
4   "static",
5   "dynamic",
6   "axis_temp",
7   "axis_x"
8 ]}
```

Listing 5.4: MRProxy REST endpoint query examples



The same procedure is performed for the `commands` CLI-command of each sensor, to merge to available commands of connected sensors into the LUT.

3. **Dynamic extension of the available network proxy commands** In order for the host to be able to send a command to the network multi-sensor setup, the command received must be forwarded to the correct sensor. In addition, there are commands such as the previously used `info` or `status` command, which must be intercepted by the `MRProxy` module so that it can be handled differently (see example 5.4).

To realize this, a LUT was created in the previous steps, which contains information regarding requested capability -> sensor-ID -> physical sensor and allows the commands to be routed.

For commands where there are several entries for CAPABLE SENSORS ID LUT 5.1, there are two possible approaches to how the command is processed:

- redirect to each capable sensor
- extend commands using an id parameter

These two methods have been implemented and are applied automatically. The decision is based on which hardware sensors are connected. In a setup where only the same sensor variants are connected, redirect to each capable sensor is applied. This offers a time advantage as fewer commands need to be sent from the host. Thus, with a `readsensor` command, all sensors are read out via one command and the summarized result is transmitted to the host.

The `extend` commands using an `id` parameter strategy is used for different sensors. Each command is extended on the `network-proxy` by another `ID` parameter, according to the following scheme:

- `readsensor <axis> <sensor number>-> readsensor <axis> <ID>`
- `opmode-> opmode <ID>`

This allows the host to address individual sensors directly via their specific ID.

5.4 Examples

The following shows some examples of how the MRP library can be used. These examples are limited to a functional minimum for selected modules of the MRP library. The documentation6.4.1 contains further and more detailed examples. Many basic examples are also supplied in the form of test cases6.3.

5.4.1 MRPRADING

The `MRPRADING` module is the cornerstone of the MRP library. It is used to manage the measurement data and can be imported and exported. The following example5.5 shows how a measurement is created and measurement points are added in the form of `MRPRADINGEntry` instances. An important point is the management of the meta data, which further describes the measurement. This is realised in the example using the `set_additional_data` function.

```
1 from MRP import MRPRADING, MRPMeasurementConfig
2 # [OPTIONAL] CONFIGURE READING USING MEASUREMENT CONFIG INSTANCE
3 config : MRPMeasurementConfig = MRPMeasurementConfig
4 config .sensor_distance_radius(40) # 40mm DISTANCE BETWEEN MAGNET AND
      SENSOR
5 config .magnet_type(N45_CUBIC_12x12x12) # CHECK MRPMagnetTypes.py FOR
      IMPLEMENTED TYPES
6 # CREATE READING
7 reading : MRPRADING = MRPRADING(config)
8 # ADD METADATA
9 reading.set_name("example reading")
10 ## ADD FURTHER DETAILS
```

```
11 reading.set_additional_data("description", "abc")
12 reading.set_additional_data("test-number", 1)
13 # INSERT A DATAPOINT
14 measurement = MRPReadingEntry.MRPReadingEntry()
15 measurement.value = random.random()
16 reading.insert_reading_instance(measurement, False)
17 # USE MEASURED VALUES IN OTHER FRAMEWORKS / DATAFORMATS
18 ## NUMPY
19 npmatrix: np.ndarray = reading.to_numpy_matrix()
20 ## CSV
21 csv: [] = reading.to_value_array()
22 ## JSON
23 js: dict = reading.dump()
24 # EXPORT READING TO FILE
25 reading.dump_to_file("exported_reading.mag.json")
26 # IMPORT READING
27 imported_reading: MRPReading = MRPReading()
28 imported_reading.load_from_file("exported_reading.mag.json")
```

Listing 5.5: MRPReading example for setting up an basic measurement

Finally, the measurement is exported for archiving and further processing; various export formats are available. Using the `dump_to_file` function, the measurement can be converted into an open JavaScript Object Notation (JSON) format. This file can then be imported again at a later date using `load_from_file`.

5.4.2 MRPHal

After generating simple measurements with random values in the previous example5.4.1, the next step is to record real sensor data. For this purpose, the `MRPHal` module was developed, which can interact with all `Unified Sensor4`-compatible sensors. In the following example5.6, an `1D: Single Sensor4.5.1` is connected locally to the host-PC.

```
1 from MRP import MRPHalSerialPortInformation, MRPHal, MRPBaseSensor,
    MRPReadingSource
2 # SEARCH FOR CONNECTED SENSORS
3 ## LISTS LOCAL CONNECTED OR NETWORK SENSORS
4 system_ports = MRPHalSerialPortInformation.list_sensors()
5 sensor = MRPHal(system_ports[0])
6 # OR USE SPECIFIED SENSOR DEVICE
7 device_path = MRPHalSerialPortInformation("UNFSensor1")
8 sensor = MRPHal(device_path)
9 # RAW SENSOR INTERACTION MODE
```

```

10 sensor.connect()
11 basesensor = MRPBaseSensor.MRPBaseSensor(sensor)
12 basesensor.query_readout()
13 print(basesensor.get_b()) # GET RAW MEASUREMENT
14 print(basesensor.get_b(1)) # GET RAW DATA FROM SENSOR WITH ID 1
15 # TO GENERATE A READING THE perform_measurement FUNCTION CAN BE USED
16 reading_source = MRPRReadingSourceHelper.createReadingSourceInstance(
    sensor)
17 result_readings: [MRPRReading] = reading_source.perform_measurement(
    _readings=1, _hwavg=1)

```

Listing 5.6: MRPHal example to use an connected hardware sensor to store readings inside of an measurement

In general, a sensor can be connected using its specific system path or the sensor-ID via the `MRPHalSerialPortInformation` function. Locally connected or network sensors can also be automatically recognised using the `list_sensors` function. Once connected, these are then converted into a usable data source using the `MRPRReadingSource` module. This automatically recognises the type of sensor and generated an `MRPRReading` instance with the measured values of the sensor.

5.4.3 MRPSimulation

If no hardware sensor is available or for the generation of test data, the `MRPSimulation` module is available. This contains a series of functions that simulate various magnets and their fields. The result is a complete `MRPRReading` measurement with a wide range of set meta data. The example 5.7 illustrated the basic usage. Different variations of the `generate_reading` function offers the user additional parameterisation options, such as random polarisation direction or a defined centre-of-gravity vector. The data is generated in the background using the `magpylib`[14] library according to the specified parameters.

```

1 from MRP import MRPSimulation, MRPPolarVisualization, MRPRReading
2 # GENERATE SIMULATED READING USING A SIMULATED HALLSENSOR FROM magpy
    LIBRARY
3 reading = MRPSimulation.generate_reading(MagnetType.N45_CUBIC_12x12x12,
    _add_random_polarisation=True)
4 # GENERATE A FULLSPHERE MAP READING
5 reading_fullsphere = MRPSimulation.generate_random_full_sphere_reading(
    ())
6 # RENDER READING TO FILE IN 3D
7 visu = MRPPolarVisualization(reading)
8 visu.plot3d(None)

```

```
9 visu.plot3d("simulated_reading.png")
10 # EXPORT READING
11 reading.dump_to_file("simulated_reading.mag.json")
```

Listing 5.7: MRPSimulation example illustrates the usage of several data analysis functions

5.4.4 MRPAnalysis

Once data can be acquired using hardware or software sensors, the next step is to analyse this data. The MRP library provides some simple analysis functions for this purpose. The code example shows the basic use of the module. The [Evaluation](#)⁷ chapter shows how the user can implement their own algorithms and add them to the library.

```
1 from MRP import MRPAnalysis, MRPReading
2 # CREATE A SAMPLE MEASUREMENT WITH SIMULATED DATA
3 reading = MRPSimulation.generate_reading(MagnetType.N45_CUBIC_10x10x10)
4 # CALCULATE MEAN
5 print(MRPAnalysis.calculate_mean(reading))
6 # CALCULATE STD DEVIATION ON TEMPERATURE AXIS
7 print(MRPAnalysis.calculate_std_deviation(reading, _temperature_axis=
    True))
8 # CALCULATE CENTER OF GRAVITY
9 (x, y, z) = MRPAnalysis.calculate_center_of_gravity(reading)
10 # APPLY CALIBRATION READING TO REMOVE BACKGROUND NOISE
11 calibration_reading = MRPSimulation.generate_reading(MagnetType.
    N45_CUBIC_10x10x10, _ideal = True)
12 MRPAnalysis.apply_calibration_data_inplace(calibration_reading, reading
    )
```

Listing 5.8: MRPAnalysis example code performs several data analysis steps

5.4.5 MRPVisualisation

This final example shows the use of the MRP Visualisation module, which provides general functions for visualising measurements. This makes it possible to visually assess the results of a measurement. This is particularly helpful for full-sphere measurements recorded with the [3D: Fullsphere](#)^{4.5.2} sensor. The sub-module ‘[MRPPolarVisualisation](#)’ is specially designed for these. The figure⁵⁻⁴ shows a plot of a fullsphere measurement.

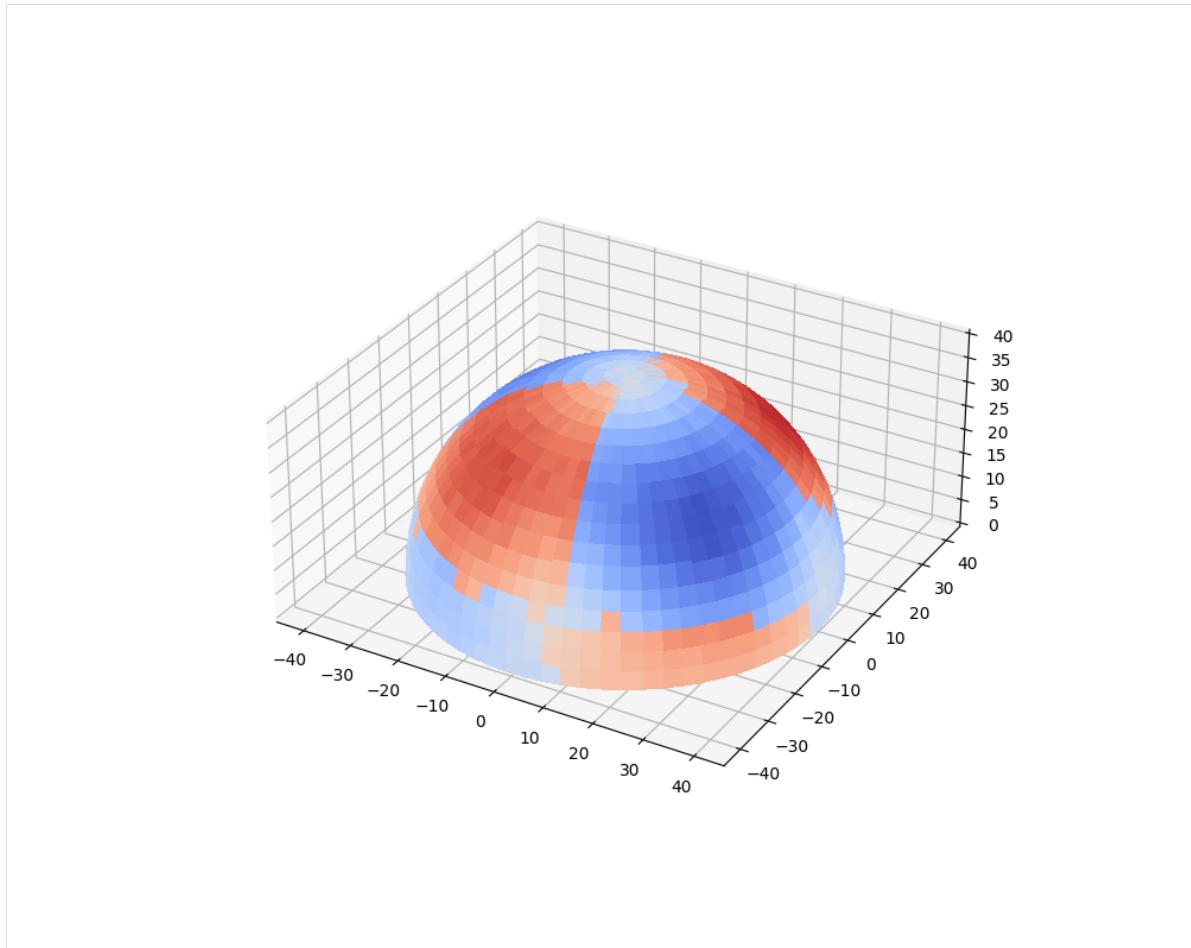


Figure 5-4: Example full sphere plot of an measurement using the MRPVisualisation module

It is also possible to export the data from the MRPAAnalysis module graphically as diagrams. The [MRPVisualisation](#) modules are used here. The following example5.9 shows the [use of both modules](#).

```
1 from MRP import MRPPolarVisualization
2 # CREATE MRPPolarVisualization INSTANCE
3 ## IT CAN BE REUSED CALLING plot2d AGAIN, AFTER LINKED READING DATA
4 ## WERE MODIFIED
5 visu = MRPPolarVisualization.MRPPolarVisualization(reading)
6 # 2D PLOT INTO A WINDOW
7 visu.plot2d_top(None)
8 visu.plot2d_side(None)
9 visu.plot3d(os.path.join('./plot3d_3d.png'))
10
11 # PLOT ANALYSIS RESULTS
12 from MRP import MRPDataVisualization
13 MRPDataVisualization.MRPDataVisualization.plot_error([reading_a,
14 reading_b, reading_c])
```

Listing 5.9: MRPVisualisation example which plots a fullsphere to an image file

5.4.6 MRPHallbachArrayGenerator

The following example code5.10, shows how a simple [Hallbach magnetic ring](#) can be generated. Eight random measurements are generated here. It is important that the magnet type (here [N45_CUBIC_15x15x15](#)) is specified. This is necessary so that the correct magnet cutouts can be generated when creating the 3D model. After the measurements have been generated, they are provided with a position and rotation offset according to the Hallbach design and calucation scheme[15] using the [MRPHallbachArrayGenerator](#) module.

```
1 readings = []
2 for idx in range(8):
3     # GENERATE EXAMPLE READINGS USING N45 CUBIC 15x15x15 MAGNETS
4     readings.append(MRPSimulation.MRPSimulation.generate_reading(
5         MRPMagnetTypes.MagnetType.N45_CUBIC_15x15x15))
6 ## GENERATE HALLBACH
7 hallbach_array: MRPHallbachArrayGenerator.MRPHallbachArrayResult =
8     MRPHallbachArrayGenerator.MRPHallbachArrayGenerator.
9     generate_1k_hallbach_using_polarisation_direction(readings)
10 # EXPORT TO OPENSCAD
11 ## 2D MODE DXF e.g. for lasercutting
```

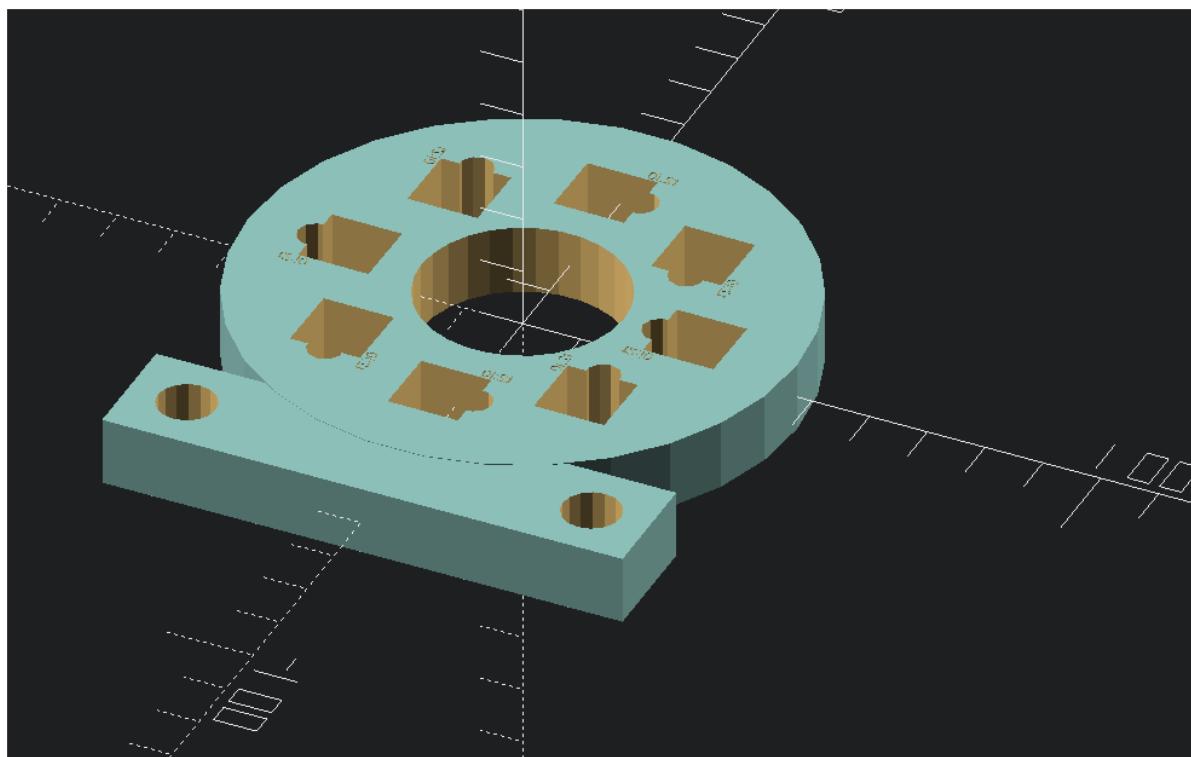


Figure 5-5: Generated hallbach array with generated cutouts for eight magnets

```
9 MRPHallbachArrayGenerator.MRPHallbachArrayGenerator.  
    generate_openscad_model([ hallbach_array ], "./2 d_test.scad",  
    _2d_object_code=True)  
10 ## 3D MODE e.g. for 3D printing  
11 MRPHallbachArrayGenerator.MRPHallbachArrayGenerator.  
    generate_openscad_model([ hallbach_array ], "./3 d_test.scad",  
    _2d_object=False)
```

Listing 5.10: MRPHallbachArrayGenerator example for generating an OpenSCAD based hallbach ring

In the last step, a 3D model with the dimensions of the magnet type set is generated from the generated magnet positions. The result is an [OpenSCAD\[11\]](#) file, which contains the module generated. After computing the model using the [OpenSCAD-CLI](#) utility, the following model rendering 5-5 can be generated.

6 Usability improvements

Usability improvements in software libraries are crucial for efficient and user-friendly development. Intuitive API documentation, clearly structured code examples and improved error messages promote a smooth developer experience. Standardised naming conventions and well thought-out default values simplify the application. A Graphical User Interface (GUI) or CLI application for complex libraries can make it easier to use, especially for developers with less experience. Continuous feedback through automated tests and comprehensive error logs enable faster bug fixing. The integration of community feedback and regular updates promotes the adaptability of the MRP-library to changing needs. Effective usability improvements help to speed up development processes and increase the satisfaction of the developer community. In the following, some of these have been added in and around the MRP-library, but they are only optional components for the intended use.

6.1 Command Line Interface

In the first version of this MRP-library, the user had to write his own Python scripts even for short measurement and visualisation tasks. However, this was already time-consuming for reading out a sensor and configuring the measurement parameters and metadata and quickly required more than 100 lines of new Python code. Although such

```
CONFIGURE READING
READING-NAME: [read_dualsensor_normal]: >? new_measurement
OUTPUT-FOLDER [./readings/tlv493d_N45_12x12x12/]: >? ./
final output path for reading /Users/marcelochsendorf/Downloads/MagneticReadoutProcessing/src/MagneticReadoutProcessing
SUPPORTED MAGNET TYPES
0 > NOT_SPECIFIED
1 > RANDOM_MAGNET
2 > N45_CUBIC_12x12x12
3 > N45_CUBIC_15x15x15
4 > N45_CUBIC_9x9x9
5 > N45_CYLINDER_5x10
6 > N45_SPHERE_10
Please select one of the listed magnet types [0-6] [2]:
>? 3
```

Figure 6-1: MRP CLI output to configure a new measurement

examples are provided in the documentation, it must be possible for programming beginners in particular to use them. To simplify these tasks, a CLI6-2 was implemented around this MRP-library. The (+mrp)-library-CLI implements the following functionalities:

- Detection of connected sensors
- Configuration of measurement series
- Recording of measured values from stored measurement series
- Simple commands for checking recorded measurement series and their data.

Thanks to this functionality of the CLI, it is now possible to connect a sensor to the PC, configure a measurement series with it and run it at the end. The result is then an exported file with the measured values. These can then be read in again with the MRP-library and processed further. The following bash code6.1 shows the setup procedure in detail:

```
1 # CLI EXAMPLE FOR CONFIGURING A MEASUREMENT RUN
2 ## CONFIGURE THE SENSOR TO USE
3 $ MRPcli config setupsensor testcfg
4 > 0 - Unified Sensor 386731533439 - /dev/cu.usbmodem3867315334391
5 > Please select one of the found sensors [0]:
6 > sensor connected: True 1243455
7 ## CONFIGURE THE MEASUREMENT
8 $ MRPcli config setup testcfg
9 > CONFIGURE testcfg
10 > READING-NAME: [testreading]: testreading
11 > OUTPUT-FOLDER [/cli/reading]: /tmp/reading_folder_path
12 > NUMBER DATAPOINTS: [1]: 10
13 > NUMBER AVERAGE READINGS PER DATAPOINT: [1]: 100
14 # RUN THE CONFIGURED MEASUREMENT
15 $ MRPcli measure run
16 > STARTING MEASUREMENT RUN WITH FOLLOWING CONFIGS: [ 'testcfg' ]
17 > config-test: OK
18 > sensor-connection-test: OK
19 > START MEASUREMENT CYCLE
20 > sampling 10 datapoints with 100 average readings
21 > SID:0 DP:0 B:47.359mT TEMP:23.56
22 > ....
23 > dump_to_file testreading_ID:525771256544952_SID:0_MAG:
N45_CUBIC_12x12x12.mag.json
```

Listing 6.1: CLI example for configuring a measurement run

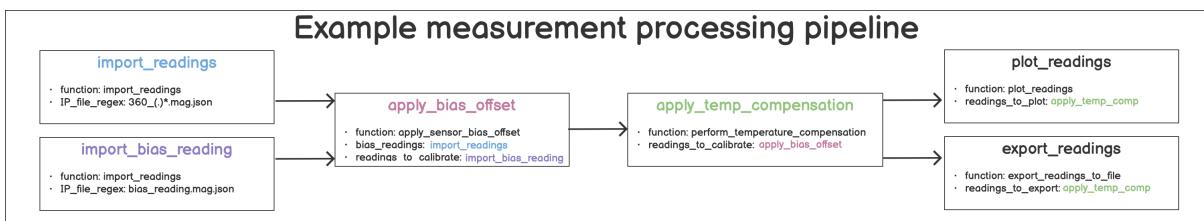


Figure 6-2: example measurement analysis pipeline

6.2 Programmable data processing pipeline

After it is **very** easy for users to carry out measurements using the CLI, the next logical step is to analyse the recorded data. This can involve one or several hundred data records. Again, the procedure for the user is to write their own evaluation scripts using the MRP-library. This is particularly useful for complex analyses or custom algorithms, but not necessarily for simple standard tasks such as bias compensation or graphical plot outputs.

For this purpose, a further CLI application was created, which enables the user to create and execute complex evaluation pipelines for measurement data without programming. The example6-2 shows a typical measurement data analysis pipeline, which consists of the following steps:

- Import the measurements
- Determine sensor bias value from imported measurements using a reference measurement
- Apply linear temperature compensation
- Export the modified measurements
- Create a graphical plot of all measurements with standard deviation

In order to implement such a pipeline, the `yaml` file format was chosen for the definition of the pipeline, as this is **easy** to understand and can also be easily edited with a text editor. Detailed examples can be found in the documentation[2]. The pipeline definition consists of sections which execute the appropriate Python commands in the background. The signatures in the `yaml` file are called using `reflection` and a real-time search of the loaded `global()` symbol table[6]. This system makes almost all Python functions available to the user. To simplify use, a pre-defined list of tested MRP library functions for use in pipelines is listed in the documentation[2]. The following pipeline definition6.2 shows the previously defined steps6-2 as `yaml` syntax.

6 Usability improvements

```
1 stage import_readings:
2   function: import_readings
3   parameters:
4     IP_input_folder: ./readings/fullsphere/
5     IP_file_regex: 360_(.)*.mag.json
6
7 stage import_bias_reading:
8   function: import_readings
9   parameters:
10    IP_input_folder: ./readings/fullsphere/
11    IP_file_regex: bias_reading.mag.json
12
13 stage apply_bias_offset:
14   function: apply_sensor_bias_offset
15   parameters:
16     bias_readings: stage import_bias_reading # USE RESULT FROM FUNCTION
17       import_bias_reading
17     readings_to_calibrate: stage import_readings
18
19 stage apply_temp_compensation:
20   function: apply_temperature_compensation
21   parameters:
22     readings_to_calibrate: stage import_readings # USE RESULT FROM
23       FUNCTION import_readings
24
24 stage plot_normal_bias_offset:
25   function: plot_readings
26   parameters:
27     readings_to_plot: stage apply_temp_compensation
28     IP_export_folder: ./readings/fullsphere/plots/
29     IP_plot_headline_prefix: Sample N45 12x12x12 magnets calibrated
30
31 stage export_readings:
32   function: export_readings
33   parameters:
34     readings_to_plot: stage apply_temp_compensation
35     IP_export_folder: ./readings/fullsphere/plots/
```

Listing 6.2: Example User Defined Processing Pipeline

Each pipeline step is divided into `stages`, which contain a name, the function to be executed and its parameters. The various steps are then linked by using the `stage <name>` as the input parameter of the next function to be executed (see comments in 6.2). It is therefore also possible to use the results of one function in several others without them directly following each other. The disadvantages of this system are the following:

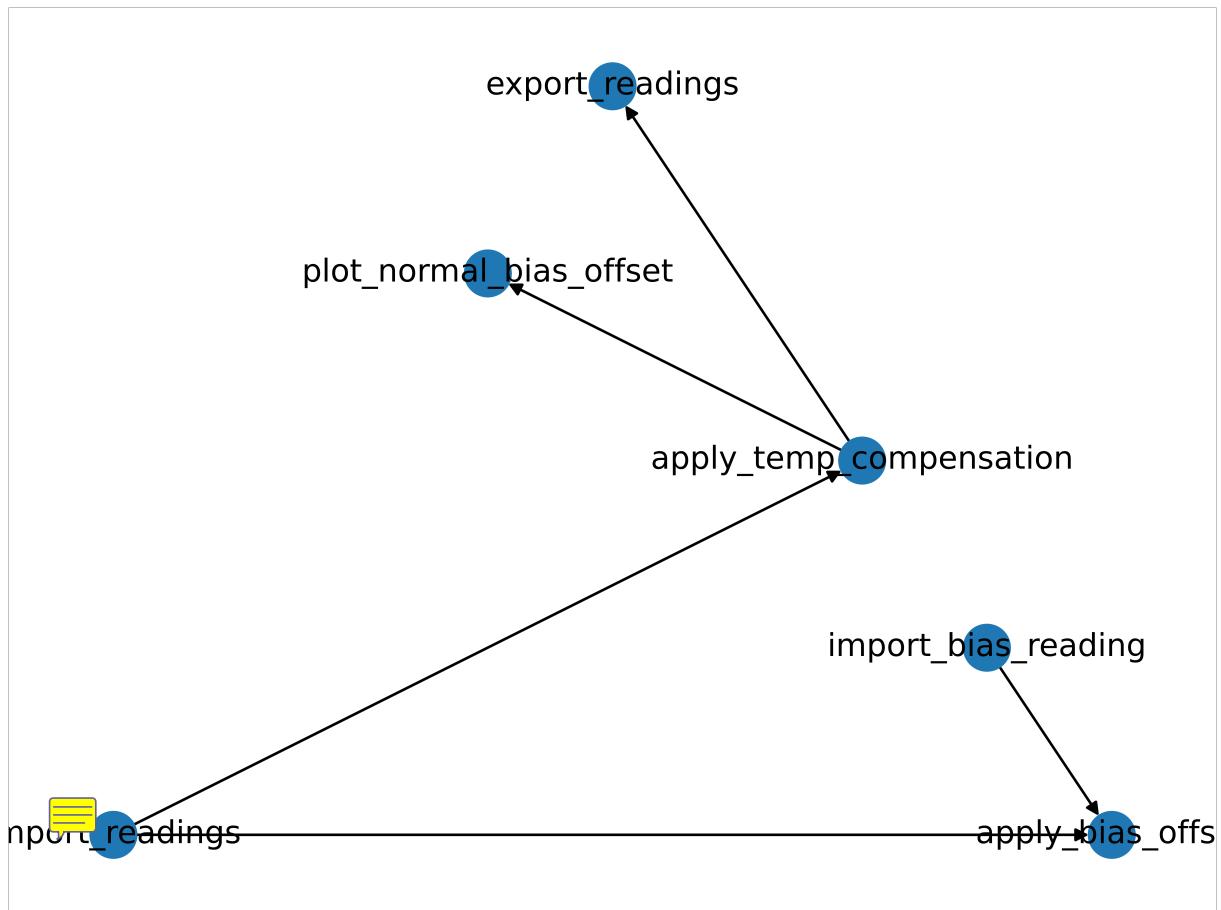


Figure 6-3: Result step execution tree from user defined processing pipeline example

- No circular parameter dependencies
- Complex determination of the execution sequence of the steps

To determine the order of the pipeline steps, the parser script creates converts them into one problem of the graph theories. Each step represents a node in the graph and the steps referred to by the input parameter form the edges.

After several simplification steps, determination of possible start steps and repeated traversal, the final execution sequence can be determined in the form of a call tree⁶⁻³. The individual steps are then executed along the graph. The intermediate results and the final results⁶⁻⁴ are saved for optional later use.

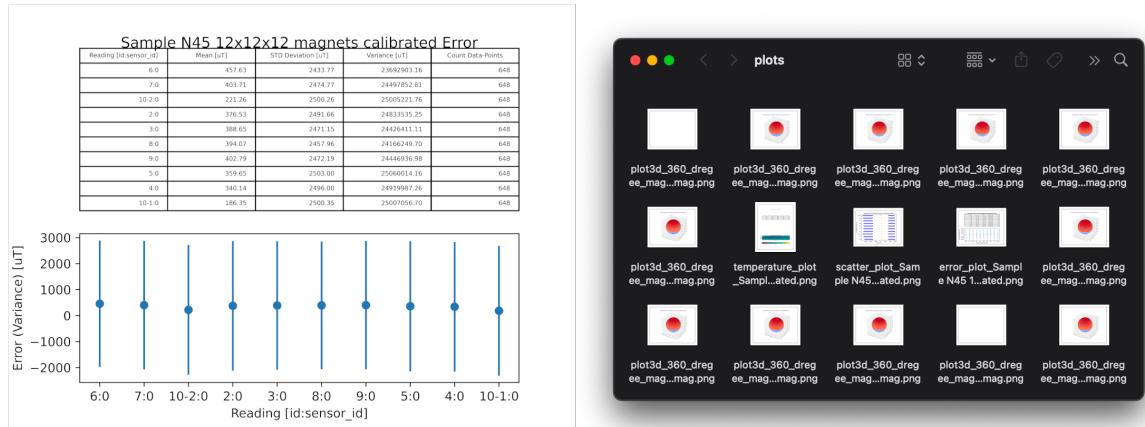


Figure 6-4: pipeline output files after running example pipeline on a set of readings

```

test_MPRReading
  ✓ TestMPRReading           381 ms
    ✓ test_cartesian_reading  0 ms
    ✓ test_export_reading     7 ms
    ✓ test_import_reading    0 ms
    ✓ test_matrix_init       372 ms
    ✓ test_reading_init      2 ms
  > ✘ test_MPReadoutSource   0 ms
> Ø test_MRPSimulation     0 ms
  ✓ test_SensorAnalysis      15 sec 850 ms
    ✓ TestMRPDataVisualization 15 sec 850 ms
      ✓ test_error_visualisation 3 sec 72 ms
      ✓ test_mean               0 ms
      ✘ test_scatter_visualisation 2 sec 876 ms
      ✓ test_std_deviation      0 ms
      ✓ test_temperature_visualisation 9 sec 902 ms
Skipped
SKIPPED [ 7%]
Skipped
SKIPPED [ 8%]
Skipped

test_SensorAnalysis.py::TestMRPDataVisualization::test_mean
test_SensorAnalysis.py::TestMRPDataVisualization::test_scatter_visualisation
test_SensorAnalysis.py::TestMRPDataVisualization::test_std_deviation
test_SensorAnalysis.py::TestMRPDataVisualization::test_temperature_visualisation
test_SensorAnalysis.py::TestMRPDataVisualization::test_variance
test_misc.py::TestMPRReading::test_full_sphere_reading PASSED [ 84%]PASSED [ 89%]PASSED [ 92%]PASSED [ 94%]

=====
===== 2 failed, 22 passed, 15 skipped, 13 warnings in 49.36s =====
PASSED [100%]
Process finished with exit code 1

```

Figure 6-5: MRP library test results for different submodules executed in PyCharm IDE

6.3 Tests

Software tests in libraries offer numerous advantages for improving quality and efficiency. Firstly, they enable the identification of errors and vulnerabilities before software is published as a new version. This significantly improves the reliability of MRP-library applications. Tests also ensure consistent and reliable performance, which is particularly important when libraries are used by different users and for different use cases.

During the development of the MRP-library, test cases were also created for all important functionalities and **use cases**. The test framework [PyTest](#)[12] was used for this purpose, as it offers direct integration in most IDEs (see 6-5) and also because it provides detailed and easy-to-understand test reports as output in order to quickly identify and correct errors. It also allows to tag tests, which is useful for grouping tests or excluding certain tests in certain build environment scenarios. Since all intended use cases were mapped using the test cases created, the code of the test cases could later be used in slightly simplified variants as examples for the documentation.

6 Usability improvements

```
1 class TestMPRReading(unittest.TestCase):
2     # PREPARE A INITIAL CONFIGURATION FILE FOR ALL FOLLOWING TEST CASES
3     # IN THIS FILE
4     def setUp(self) -> None:
5         self.test_folder: str = os.path.join(os.path.dirname(os.path.
6             abspath(__file__)), "tmp")
7         self.test_file:str = os.path.join(self.
8             import_export_test_folderpath , "tmp")
9
10    def test_matrix(self):
11        reading: MRPReading = MRPSimulation.generate_reading()
12        matrix: np.ndarray = reading.to_numpy_matrix()
13        n_phi: float = reading.measurement_config.n_phi
14        n_theta: float = reading.measurement_config.n_theta
15        # CHECK MATRIX SHAPE
16        self.assertTrue(matrix.shape != (n_theta,))
17        self.assertTrue(len(matrix.shape) <= n_phi)
18
19    def test_export_reading(self) -> None:
20        reading: MRPReading = MRPSimulation.generate_reading()
21        self.assertIsNotNone(reading)
22        # EXPORT READING TO A FILE
23        reading.dump_to_file(self.test_file)
24
25    def test_import_reading(self):
26        # CREATE EMPTY READING AND LOAD FROM FILE
27        reading_imported:MRPReading = MRPReading.MRPReading(None)
28        reading_imported.load_from_file(self.test_file)
29        # COMPARE
30        self.assertIsNotNone(reading_imported.compare(MRPSimulation.
31            generate_reading()))
```

Listing 6.3: Example pytest class for testing MRPReading module functions

One problem, however, is the parts of the MRP-library that require direct access to external hardware. These are, for example, the `MRPHal` and `MRPHalRest` modules, which are required to read out sensors connected via the network. Two different approaches were used here. In the case of local development, the test runs were carried out on a PC that can reach the network hardware and thus the test run could be carried out with real data.

In the other scenario, the tests are to be carried out before a new release in the repository on the basis of [Github Actions](#)[10]. Here there is the possibility to host local runner software, which then has access to the hardware, but then a PC must be permanently available for this task. Instead, the hardware sensors were simulated by

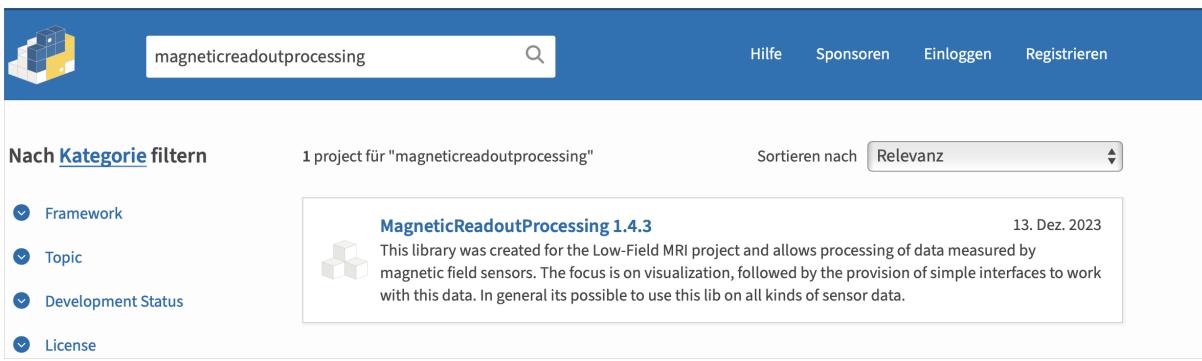


Figure 6-6: MagneticReadoutProcessing library hosted on PyPi

software and executed via virtualisation on the systems provided by [Github Actions](#)[10].

6.4 Package distribution

One important point that improves usability for users is the simple installation of the MRP-library. As it was created in the Python programming language, there are several public package registry where users can provide their software modules. Here, [PyPi](#) [5]6-6[4] is the most commonly used package registry and offers direct support for the package installation programm Python Package Installer (PIP)6.4.

In doing so, PIP not only manages possible package dependencies, but also manages the installation of different versions of a package. In addition, the version compatibility is also checked during the installation of a new package, which can be resolved manually by the user in the event of conflicts.

```
1 # https://pypi.org/project/MagneticReadoutProcessing/
2 # install the latest version
3 $ pip3 install MagneticReadoutProcessing
4 # install the specific version 1.4.0
5 $ pip3 install MagneticReadoutProcessing==1.4.0
```

Listing 6.4: Bash commands to install the MagneticReadoutProcessing (+mrp)-library using pip

To make the MRP-library compatible with the package registry, Python provides separate installation routines that build a package in an isolated environment and then provide an installation [wheel](#) archive. This can then be uploaded to the package registry.

6 Usability improvements

Since the MRP-library requires additional dependencies (e.g. `numpy`, `matplotlib`), which cannot be assumed to be already installed on the target system, these must be installed prior to the actual installation. These can be specified in the MRP-library installation configuration `setup.py` for this purpose.

```
1 # dynamic requirement loading using 'requirements.txt'
2 req_path = './requirements.txt'
3 with pathlib.Path(req_path).open() as requirements_txt:
4     install_requires = [str(requirement) for requirement in pkg_resources
5                         .parse_requirements(requirements_txt)]
6
7 setup(name='MagneticReadoutProcessing',
8       version='1.4.3',
9       url='https://github.com/LFB-MRI/MagnetCharacterization/',
10      packages=[ 'MRP', 'MRPcli', 'MRPUDpp', 'MRPproxy'],
11      install_requires=install_requires,
12      entry_points={
13          'console_scripts': [
14              'MRPcli = MRPcli.cli:run',
15              'MRPUDpp = MRPUDpp.udpp:run',
16              'MRPproxy = MRPproxy.mrpproxy:run'
17          ]
18      }
19 )
```

Listing 6.5: `setup.py` with dynamic requirement parsing used given `requirements.txt`

To make the CLI scripts written in Python easier for the user to execute without having to use the `python3` prefix. This has been configured in the installation configuration using the `entry_points` option, and the following commands are available to the user:

- `MRPcli --help` instead of `python3 cli.py --help`
- `MRPUDpp --help` instead of `python3 udpp.py --help`
- `MRPproxy --help` instead of `python3 proxy.py --help`

In addition, these commands are available globally in the system without the terminal shell being located in the MRP-library folder.

6.4.1 Documentation

In order to provide comprehensive documentation for the enduser, the source code was documented using Python-[docstrings](#)[8] and the Python3.5 type annotations:

- Function description
- Input parameters - using `param` and `type`
- Return value - using `returns`, `rtype`

The use of type annotations also simplifies further development, as modern IDEs can more reliably display possible methods to the user as an assistance.[??](#)

```
1 # MRPDataVisualisation.py – example docstring
2 def plot_temperature(_readings: [MRPReading.MRPReading], _title: str =
3     '', _filename: str = None, _unit: str = "degree C") -> str:
4     """
5         Plots a temperature bar graph of the reading data entries as figure
6         :param _readings: readings to plot
7         :type _readings: list(MRPReading.MRPReading)
8         :param _title: Title text of the figure , embedded into the head
9         :type _title: str
10        :param _filename: export graphic to an given absolute filepath with .
11            png
12        :type _filename: str
13        :returns: returns the abs filepath of the generated file
14        :rtype: str
15        """
16        if _readings is None or len(_readings) <= 0:
17            raise MRPDataVisualizationException("no readings in _reading
18                given")
19        num_readings = len(_readings)
20        # ...
```

Listing 6.6: Python docstring example

Since ‘docstrings’ only document the source code, but do not provide simple how-to-use instructions, the documentation framework [Sphinx](#)[1] was used for this purpose. This framework makes it possible to generate Hypertext Markup Language (HTML) or Portable Document Format (PDF) documentation from various source code documentation formats, such as the used [docstrings](#). These are converted into a Markdown format in an intermediate step and this also allows to add further user documentation such as examples or installation instructions. In order to make the documentation created by [Sphinx](#) accessible to the user, there are, as with the package management by [PyPi](#)

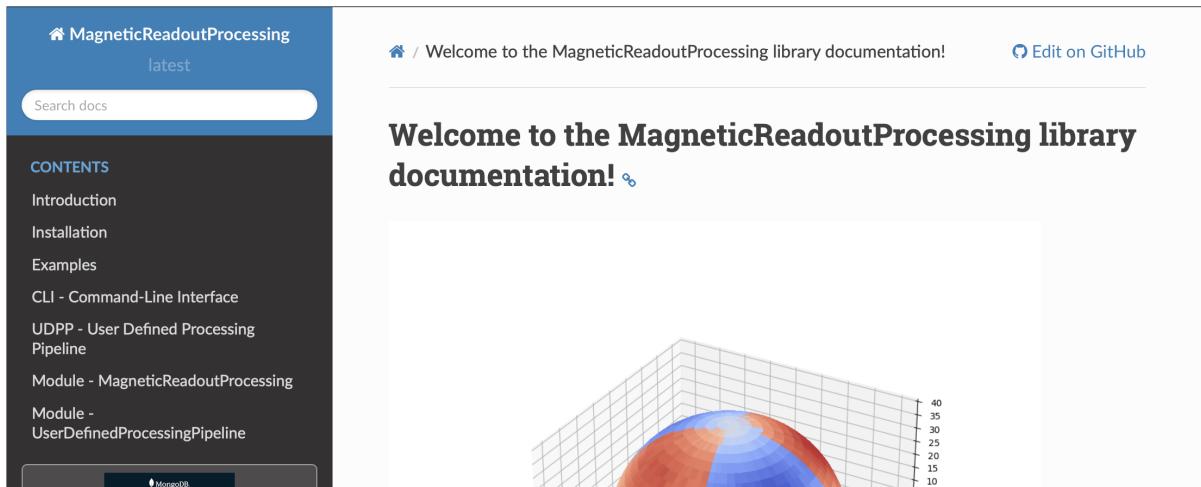


Figure 6-7: MagneticReadoutProcessing documentation hosted on ReadTheDocs

services, which provide Python MRP-library documentation online.

Once the finished documentation has been generated from static HTML files, it is stored in the project repository. Another publication option is to host the documentation via online services such as [ReadTheDocs](#)[3], where users can make documentation for typical software projects available to others.

The documentation has also been uploaded for [ReadTheDocs](#)[2] and linked in the repository and on the overview page [6-7](#) on [PyPi](#).

The process of creating and publishing the documentation has been automated using [GitHub Actions](#)[10], so that it is always automatically kept up to date with new features.

7 Evaluation

This work successfully implemented a universal hardware and software framework for the automated characterisation of permanent magnets. This framework consists of a low-cost hardware interface that supports various magnetic field sensors and a library for automating and analysing the measurement data. The process of this framework comprises several steps, which I will explain below:

1. **Hardware preparation** Users can prepare measurements using the implemented framework. This includes the placement of the sensors and the selection of the relevant parameters for the characterisation of the permanent magnets.
2. **Configuration of the measurement** The software provides a user-friendly interface for configuring the measurement parameters. Users can make the desired settings here and customise the framework to their specific requirements.
3. **Custom algorithm implementation** An important contribution of the MRP echo-system is the possibility for users to implement their own algorithm for data analysis. This allows customisation to specific research questions or experimental requirements.
4. **Execution of analysis pipeline** The analysis pipeline can then be executed with the implemented algorithm. The collected measurement data is automatically processed and analysed to extract characteristic parameters of the permanent magnets.

This process covers all the essential functionalities required for a comprehensive characterisation of permanent magnets³. The developed framework not only offers a cost-effective and flexible hardware solution, but also enables customisation of the analysis algorithms to meet the requirements of different research projects.

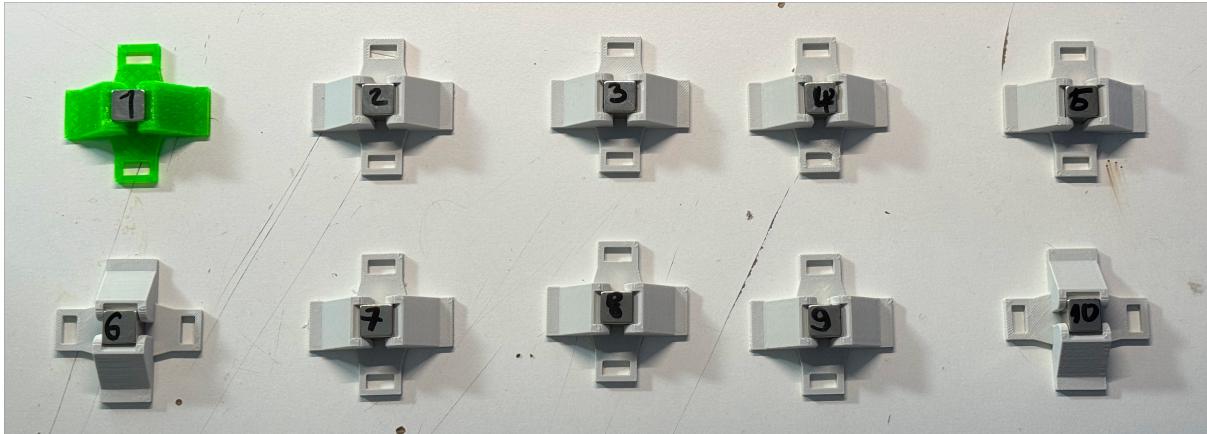


Figure 7-1: testmagnets in holder

7.1 Hardware preparation

For the hardware setup, the 3D: Fullsphere4.5.2 sensor was used for the evaluation of the framework. As this is equipped with an exchangeable magnetic holder mount, suitable holders are required for the magnets to be measured. Ten random N45 12x12x12mm neodymium magnets were used here. These were placed in modified 3D printed holders7-1 and then numbered. This allows them to be matched to the measurement results later.

7.2 Configuration of the measurement

The configured hardware was then connected and connected to the host system using the MRPcli config setupsensor eval_measurement_config-CLI command. The measurement was then configured7.1.

```

1 ## CONFIGURE THE MEASUREMENT
2 $ MRPcli config setup eval_measurement_config
3 > READING-NAME: 360_eval_magnet_<id>
4 > OUTPUT-FOLDER: ./readings/evaluation/
5 > NUMBER DATAPOINTS: 18 # FOR A FULLSPHERE READING USE MULTIPLE OF 18
6 > NUMBER AVERAGE READINGS PER DATAPOINT: 10

```

Listing 7.1: Measurement configuration for evaluation measurement

The MRPcli measure run command was then called up for each individual magnet to carry out a measurement. After each run, the READING-NAME parameter was filled with the

id of the next magnet so that all measurements could be assigned to the physical magnets.

7.3 Custom algorithm implementation

The next step for the user is the implementation of the filter algorithm7.2. This can have any function signature and is implemented in the file [UDPPFunctionCollection.py](#). This Python file is loaded when the pipeline is started and all functions that are imported here as a module or implemented directly can be called via the pipeline. As this is a short algorithm, it was inserted directly into the file. The parameter `_readings` should later receive the imported measurements from the stage `import` and the optional `IP_return_count` parameter specifies the number of best measurements that are returned. The return parameter is a list of measurements and should contain the measurements that are closest to the mean value of all measurements after the function has been executed.

```

1 @staticmethod
2 def FindSimilarValuesAlgorithm(_readings: [MRPReading.MRPReading],
3                                 IP_return_count: int = -1) -> [MRPReading.MRPReading]:
4     import heapq
5     heap = []
6     # SET RESULT VALUE COUNT
7     IP_return_count = max([int(IP_return_count), len(_readings)])
8     if IP_return_count < 0:
9         IP_return_count = len(_readings) / 5
10    # CALCULATE TARGET VALUE: MEAN FROM ALL VALUES
11    target_value = 0.0
12    for idx, r in enumerate(_readings):
13        mean: float = MRPAnalysis.MRPAnalysis.calculate_mean(r)
14        target_value = target_value + mean
15    target_value = target_value / len(_readings)
16    # PUSH READINGS TO HEAP
17    for value in _readings:
18        # USE DIFF AS PRIORITY VALUE IN MIN-HEAP
19        diff = abs(value - target_value)
20        heapq.heappush(heap, (diff, value))
21    # RETURN X BEST ITEMS FROM HEAP
22    similar_values = [item[1] for item in heapq.nsmallest(IP_return_count,
23                                                          heap)]
24    # CLEAN UP USED LIBRARIES AND RETURN RESULT
25    del heapq
26    return similar_values

```

Listing 7.2: User implemented custom find most similar readings algorithm

The python `heapq`[7] module, which implements a priority queue, is used for this purpose. The calculated distances from the mean value of the measurements to the global mean value are inserted into this queue. Subsequently, as many elements of the queue are returned as defined by the `IP_return_count` parameter. The actual sorting was carried out by the queue in the background.

7.4 Execution of analysis pipeline

Once the filter function has been implemented, it still needs to be integrated into the analysis pipeline^{7.3}. Here, the example pipeline 6-2 is simplified and an additional stage `find_similar_values` has been added, which has set `FindSimilarValuesAlgorithm` as the function to be called. As a final step, the result is used in the `plot_filtered` stage for visualisation.

```
1 settings:
2   enabled: true
3   export_intermediate_results: false
4   name: pipeline_mrp_evaluation
5
6 stage import:
7   function: import_readings
8   parameters:
9     IP_input_folder: ./readings/evaluation/
10    IP_file_regex: 360_(.)*.mag.json
11
12 stage find_similar_values:
13   function: custom_find_similar_values_algorithm
14   parameters:
15     _readings: stage import # USE RESULTS FROM import STAGE
16     IP_return_count: 4 # RETURN BEST 4 of 10 READINGS
17
18 stage plot_filtered:
19   function: plot_readings
20   parameters:
21     readings_to_plot: stage find_similar_values # USE RESULTS FROM
22       find_similar_values STAGE
23     IP_export_folder: ./readings/evaluation/plots/plot_filtered/
24     IP_plot_headline_prefix: MRP evaluation - filtered
```

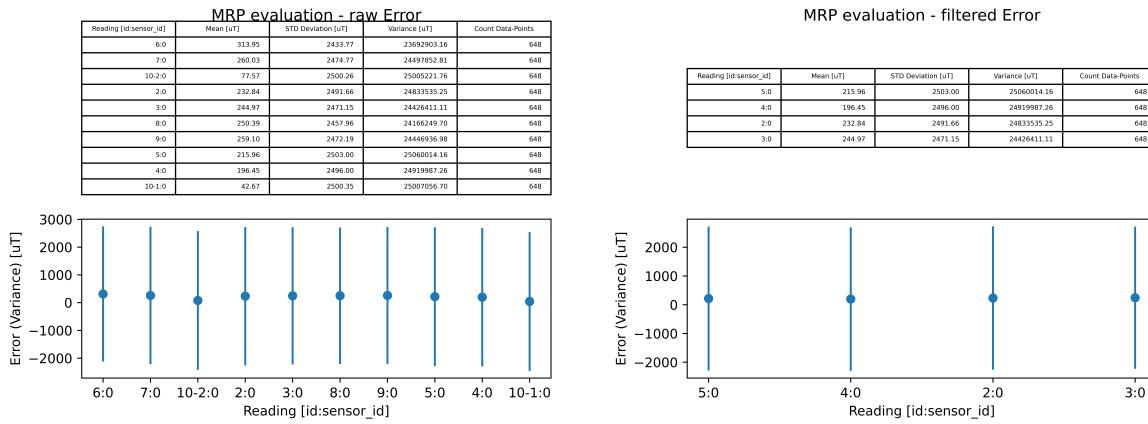


Figure 7-2: MRP evaluation result

Listing 7.3: User defined processing pipeline using custom implemented filter algorithm

The final pipeline has been saved in the pipeline directory as `pipeline_mrp_evaluation.yaml` file and is ready for execution. This is carried out using the `MRPudpp-(cli)7.4`. After the run has been successfully completed, the results are saved in the result folder specified in the pipeline using the `IP_export_folder` parameter.

```

1 # LIST ACTIVE PIPELINES IN PIPELINE DIRECTORY
2 $ MRPudpp pipeline listenabledpipelines
3 > Found enabled pipelines:
4 > 1. pipeline_mrp_evaluation.yaml
5 # EXECUTE THE EVALUATION PIPELINE
6 $ MRPudpp pipeline run
7 > loading pipeline pipeline_mrp_evaluation.yaml
8 > stage nodes: ['import', 'find_similar_values', 'plot_raw', '
    plot_filtered']
9 > =====> stage: import
10 > =====> stage: find_similar_values
11 > =====> stage plot_filtered
12 > Process finished with exit code 0

```

Listing 7.4: Bash result log of evaluation pipeline run

The figure 7-2 shows this result. The plot of the raw measured values is shown on the left. The variance of the determined `Mean [uT]` mean values is plotted on ten individual measured values. Here you can see that there are measured values with larger deviations (see measurement 7:0,10-2:0,10-1:0).

On the right-hand side 7-2, the measured values are plotted as a result of the filter algorithm. As the `IP_return_count` parameter was set to four, only the four most similar measurements were exported here. It can be seen from the plotted mean values `Mean [uT]` that these are closest to the global mean value 208.8 μT . The algorithm was thus successfully executed using the pipeline and the results could be validated.

8 Conclusion and discussion

8.1 Conclusion

This work describes the development of a universal Python library that is used to efficiently process data from magnetic field sensors from acquisition to analysis. In order to ensure a practical application and to give users the opportunity to directly acquire their own magnetic field data, cost-effective and easily reproducible hardware was also developed.

The hardware is based on widely used magnetic field sensors and low-cost microcontrollers, which enables an easily expandable and applicable solution for measuring magnets with repeatable accuracy. A particular focus was placed on expandability by the user. Interchangeable modules allow the user to develop their own analysis algorithms without having to redesign everything from scratch.

This extensibility and customisability was successfully demonstrated during the evaluation. This underlines the performance of the developed framework and shows that it is not only effective in the processing of magnetic field sensor data, but also offers a flexible platform for the implementation of user-specific analyses.

8.2 Outlook

In this version of the framework, a solid foundation has been laid that includes all the necessary features and is ready for use. During development, particular emphasis was placed on comprehensive documentation to make it easier to get started. Together with examples for various use cases, a user can quickly evaluate the framework.

However, it should be noted that the framework is still in its infancy. The stable version

distributed via the package registry is well suited for the intended purpose. All tests and evaluations took place under normal conditions, especially for the developed hardware sensors, as the MRP library works successfully with the measurement data.

On the software side, the focus is on integration for the support of more professional measuring devices. Only in this way is it possible to evaluate and improve the sensor hardware and quantify the measurement results.

To summarise, it can be said that a solid software framework has been created that can be used directly for the intended purpose. It provides a good foundation, but can be further developed by integrating professional measurement devices to enable a more comprehensive evaluation and improvement of the sensor hardware.

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List of Figures

4-1	1D sensor mechanical 3D printed structure	8
4-2	1D sensor schematic and circuit board	9
4-3	Unified sensor firmware simplified program strucutre	10
4-4	Sensors CLI	12
4-5	Query sensors b value using CLI	12
4-6	Multi sensor synchronisation wiring example	13
4-7	Unified sensor firmware multi sensor synchronisation procedure	15
4-8	Query opmode using CLI	16
4-9	1D sensor construction with universal magnet mount	17
4-10	Full-Sphere sensor implementation using two Nema17 stepper motors in a polar coordinate system	18
4-11	3D plot of an N45 12x12x12 magnet using the 3D fullsphere sensor . .	19
4-12	Voltcraft GM70 teslameter with custom PC interface board	20
5-1	MRPlib COMPLETE FLOW	23
5-2	MRPlib Proxy Module	24
5-3	mrp proxy multi	24
5-4	Example full sphere plot of an measurement using the MRPVisualisation module	33
5-5	Generated hallbach array with generated cutouts for eight magnets . .	35
6-1	MRP CLI output to configure a new measurement	36
6-2	example measurement analysis pipeline	38
6-3	Result step execution tree from user defined processing pipeline example	40
6-4	pipeline output files after running example pipeline on a set of readings	41
6-5	MRP library test results for different submodules executed in PyCharm IDE	41
6-6	MagneticReadoutProcessing library hosted on PyPi	43
6-7	MagneticReadoutProcessing documentation hosted on ReadTheDocs	46
7-1	testmagnets in holder	48

List of Figures

7-2 MRP evaluation result	51
-------------------------------------	----

List of Tables

4.1	Implemented digital haloeffect sensors	7
4.2	Measured sensor readout to processing using host software	13
4.3	Build sensors with different capabilities	16
4.4	Voltcraft GM70 serial protocol	20
5.1	Sensor capabilities merging	27

Listings

4.1	CustomSensor-Class for adding new sensor hardware support	10
5.1	MRPproxy usage to enable local sensor usage over network	25
5.2	MRPproxy REST enpoiint query examples	25
5.3	MRPcli usage example to connect with a network sensor	26
5.4	MRPproxy REST enpoiint query examples	28
5.5	MRPReading example for setting up an basic measurement	29
5.6	MRPHal example to use an connected hardware sensor to store readings inside of an measurement	30
5.7	MRPSimulation example illustrates the usage of several data analysis functions	31
5.8	MRPAnalysis example code performs several data analysis steps	32
5.9	MRPVisualisation example which plots a fullsphere to an image file	34
5.10	MRPHallbachArrayGenerator example for generating an OpenSCAD based hallbach ring	34
6.1	CLI example for configuring a measurement run	37
6.2	Example User Defined Processing Pipeline	38
6.3	Example pytest class for testing MRPRReading module functions	41
6.4	Bash commands to install the MagneticReadoutProcessing (+mrp)-library using pip	43
6.5	setup.py with dynamic requirement parsing used given requirements.txt	44
6.6	Python docstring example	45
7.1	Measurement configuration for evaluation measurement	48
7.2	User implemented custom find most similar readings algorithm	49
7.3	User defined processing pipeline using custom implemented filter algorithm	50
7.4	Bash result log of evaluation pipeline run	51