

# FH Aachen

## Faculty Electrical Engineering and Information Technology

### Information Systems Engineering

Master Thesis

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

Submitted by

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# **Erklärung**

I hereby declare that I have prepared this thesis independently and without outside assistance. Text passages, which are based literally or in the sense on publications or lectures of other authors, are marked as such. The work has not yet been submitted to any other examination authority and has not yet been published.

Aachen, \_\_\_\_\_, \_\_\_\_\_

# **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 aquation 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 characterisation of different magnets, which requires the integration of magnetic field sensors, was used for the evaluation.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
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
<b>2</b>	<b>State of the art</b>	<b>2</b>
2.1	Opensource projects . . . . .	2
2.2	Conceptual design . . . . .	2
<b>3</b>	<b>Use cases</b>	<b>3</b>
<b>4</b>	<b>Unified Sensor</b>	<b>4</b>
4.1	Sensor selection . . . . .	4
4.2	Mechanical Structure . . . . .	5
4.3	Electrical Interface . . . . .	5
4.4	Firmware . . . . .	5
4.4.1	Command Line Interface (CLI)) Interface . . . . .	6
4.5	Sensor Syncronisation . . . . .	7
4.6	Example Sensors . . . . .	7
4.6.1	1D: Single Sensor . . . . .	7
4.6.2	1D: Dual Sensor . . . . .	7
4.6.3	Full-Sphere . . . . .	7
4.6.4	Integration of an Professional Teslameter . . . . .	8
<b>5</b>	<b>Software readout framework</b>	<b>9</b>
5.1	Library requirements . . . . .	9
5.1.1	Concepts . . . . .	9
5.1.2	User interaction points . . . . .	9
5.1.3	Export . . . . .	9
5.1.4	Multi-Sensor setup . . . . .	10

5.1.5 Examples . . . . .	13
<b>6 Usability improvements</b>	<b>14</b>
6.1 Commandline interface . . . . .	14
6.2 Programmable data processing pipeline . . . . .	14
6.3 Tests . . . . .	15
6.4 Package distribution . . . . .	17
6.4.1 Documentation . . . . .	19
<b>7 Evaluation</b>	<b>22</b>
7.1 Prequesites for evaluation . . . . .	22
7.2 Evaluation confiugration . . . . .	22
7.2.1 Sensor readout . . . . .	22
7.2.2 Processing pipeline . . . . .	22
7.3 Test scenarios . . . . .	22
7.4 Results . . . . .	22
<b>8 Conclusion and dicussion</b>	<b>23</b>
8.1 Conclusion . . . . .	23
8.2 Problems . . . . .	23
8.3 Outlook . . . . .	23
<b>Literaturverzeichnis</b>	<b>24</b>
<b>Abbildungsverzeichnis</b>	<b>26</b>
<b>Tabellenverzeichnis</b>	<b>27</b>

# **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**

## **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**

# 4 Unified Sensor

- ziel ist es einen low cost hallsensor-interface zu entwickeln welcher möglichst universell
- verschiedene sensoren abbilden kann
- mit verschiedenen magneten typen und formen nutzbar
- reproduzierbar
- 1d, 2d, 3d
- integration

## 4.1 Sensor selection

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

- for higher ranges analog sensoren nutzen welche jedoch eine aufwändigeren schaltung erfordern
- datenblätter links ergänzen
- alle i2c in der regel, welches eine einfache integration ermöglicht
- eingebauter temperatursensor ermöglicht temperaturkompensation
- conrad teslameter mit separaten temperatursensor

## **4.2 Mechanical Structure**

- 3d druck toleranztest
- magnet halterung mit kraftloser arretierung
- motoren und andere unter umständen magnetische teile in der nähe des sensors
- nylon schrauben, 3d druck, 3d gedruckte klemmverbindungen
- später rausrechnen durch kalibrierung

## **4.3 Electrical Interface**

- usb, ethernet
- pps input output
- multiplexer for i2c sensors already implemented

## **4.4 Firmware**

- automatic sensor detection ablaufdiagramm erst nach i2c geräte scannen dann analog versuchen
- serial cli support for manual mode
- sync impulse => 1 mastersensor als taktquelle
- interne mittelung und speichern der werte im buffer ringbuffer welcher bei jedem sync impuls neu belegt wird

```
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 4-1: Sensors CL-Interface

```
readsensor b 0
3279.99
```

Figure 4-2: Query sensors b value using CLI

- 2. core übernimmt mittelung und auswertung
- was durch den user implementiert werden muss klasse

#### 4.4.1 CLI) Interface

- einfache bedienung durch nutzer auch ohne weitere software
- configuration
- debugging

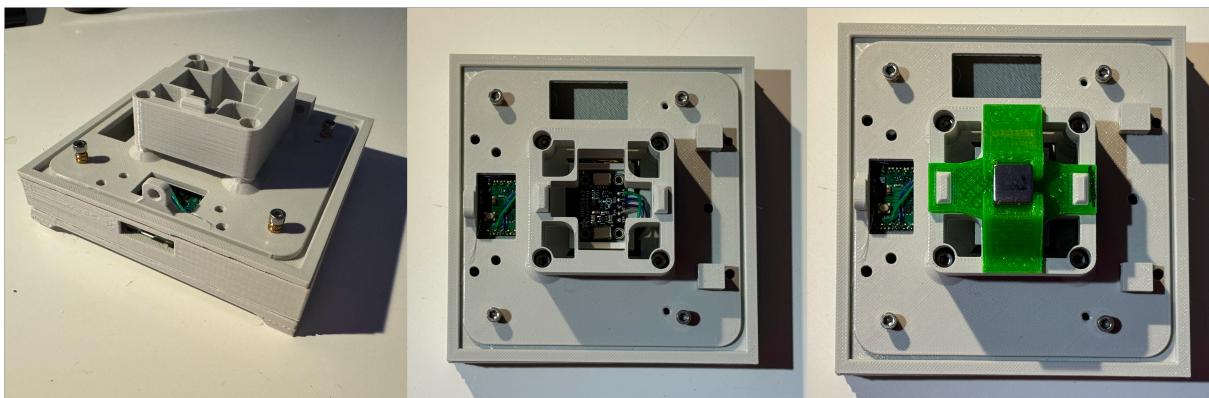


Figure 4-3: 1D sensor contrsuction with universal magnet mount

## 4.5 Sensor Syncronisation

## 4.6 Example Sensors

anbei werden drei erschienee sensoren für unterschiedliche anwendungfälle tablle statisch dynamisch

### 4.6.1 1D: Single Sensor

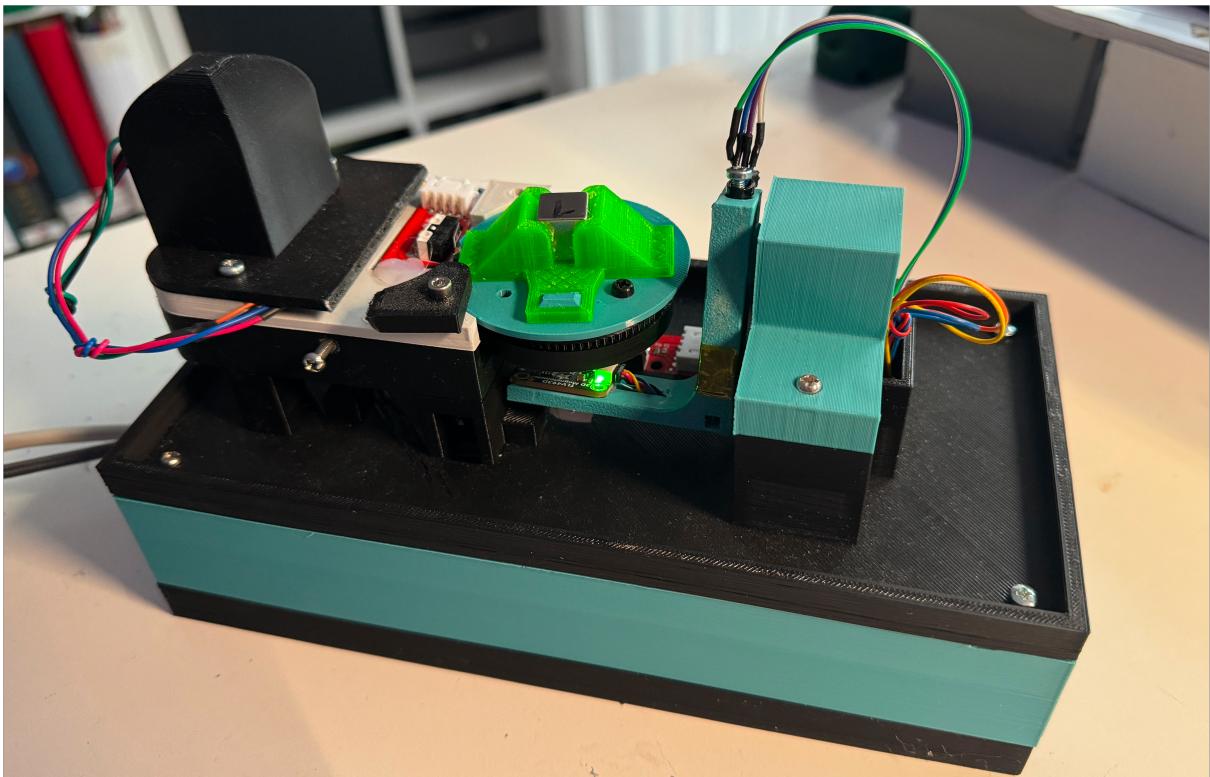
- einfacherster aufbau rp pico + sensor

### 4.6.2 1D: Dual Sensor

- gleicher abstand zwei gleicher sensoren
- schnelle erkennung der plarisationsebene ggf offset vom mittelpunkt dieser

### 4.6.3 Full-Sphere

- komplexester aufbau sensor + mechanik
- polar mechanisches system
- full sphere sensor



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

#### **4.6.4 Integration of an Professional Teslameter**

- einfach anbindung professioneller teslameter
- Voltkraft

# 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

- grafik zeigen
- einzelne module erläutern

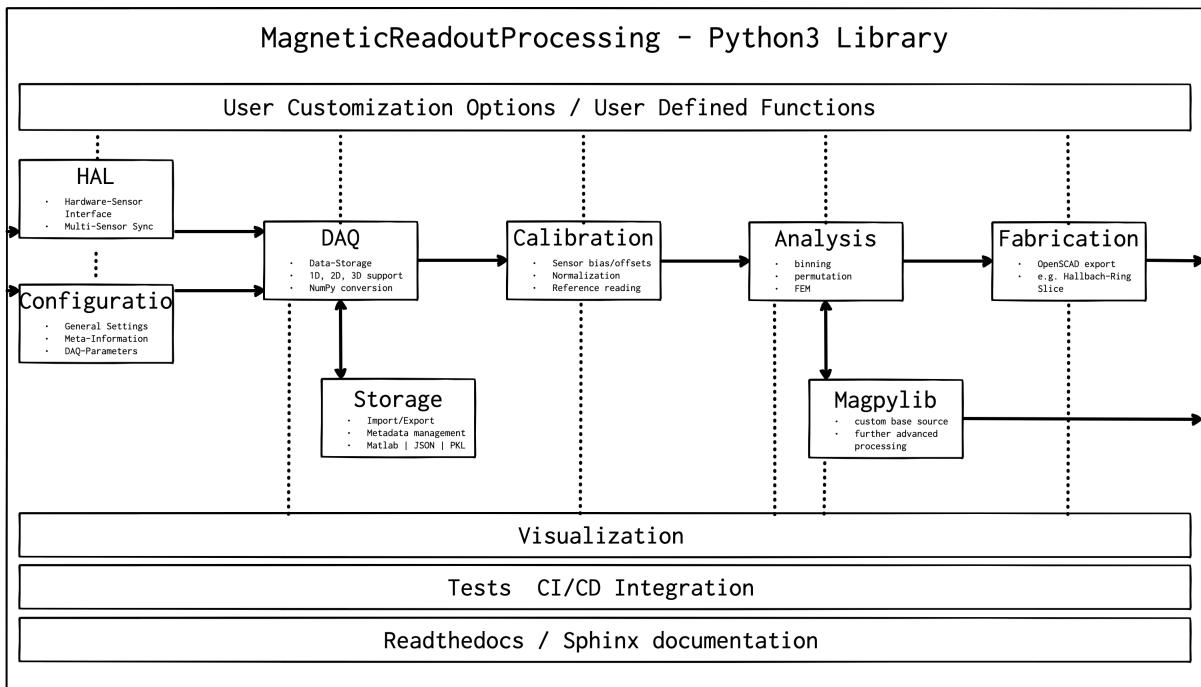
### HAL

- 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”

### Visualisation

### 5.1.3 Export

- format import export



**Figure 5-1: MRPlib COMPLETE FLOW**

- matlab

### Meta-Data

#### 5.1.4 Multi-Sensor setup

At the current state of implementation, it is only possible to detect and use sensors that are directly connected to the Personal Computer (PC) with the library. This has the disadvantage that there must always be a physical connection. This can make it difficult to install 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](#)5-2 module has been developed. This can be a single board computer (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

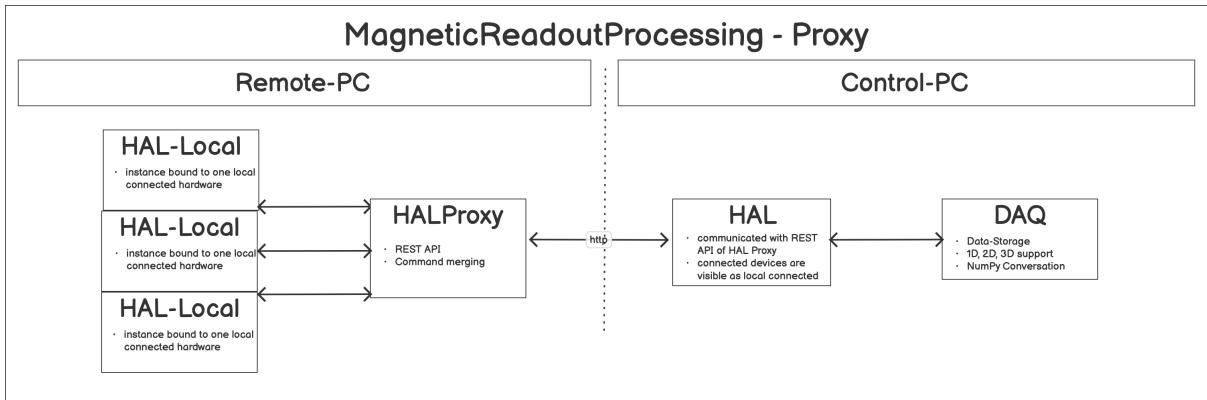


Figure 5-2: MRPlib Proxy Module

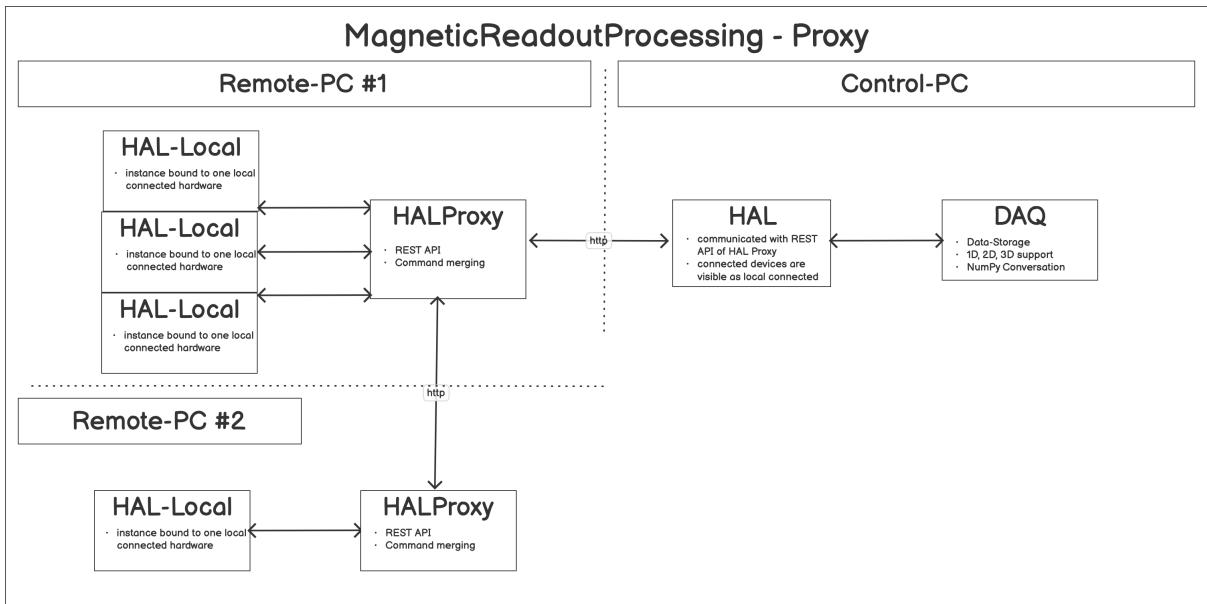


Figure 5-3: mrp proxy multi

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 `remote (+pc)#2` is connected to `remote (+pc)#1`. This is then visible as a sensor opposite the Control PC, even if there are several proxy instances behind it.

### 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`

## 5 Software readout framework

---

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 on the `remote` PC side.

```
1      # START PROXY INSTNACE WITH TWO LOCALLY CONNECTED SENSORS
2      $ python3 mrppproxy.py proxy launch /dev/ttySENSOR_A /dev/
3          ttySENSOR_B # add another proxy instance http://
4          proxyinstance_2.local for multi-sensor, multi-proxy
5          chain
6      Proxy started. http://0.0.0.0:5556/
7      PRECHECK: SENSOR_HAL: 1337 # SENSOR A FOUND
8      PRECHECK: SENSOR_HAL: 4242 # SENSOR B FOUND
9      Terminate Proxy instance [y/N] [n]:
```

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

```
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
23     # RUN A SENSOR COMMAND AND GET THE TOTAL SENSOR COUNT
24     $ wget http://proxyinstance.local:5556/proxy/command?cmd=
25         combinedsensorcnt
26     {
27         "output": [
28             "2"
29     ]
30 }
```

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 $ python3 mrpproxy.py proxy launch /dev/ttySENSOR_A /dev/
    ttySENSOR_B
```

### Sensor Syncronisation

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 Universal Serial Bus (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 (see chapter 4.5). This no longer works for long distances and the syncronisation must be made via the network connection.

If time-critical synchronisation is required, Precision Time Protocol (PTP) and Puls Per Second (PPS) output functionality can be used on many single-board computers, such as the RaspberryPi Compute Module.

- was ptpt, bild pps output
- alle clients über ptpt verbunden
- dso bild von jeff gerling über rpi4 ptpt

### Command-Router

- nummerierung zuerst lokale sensoren dann weitere proxy sensoren
- commando templating

#### 5.1.5 Examples

# 6 Usability improvements

## 6.1 Commandline interface

- automatische sensor dedektion
- planung verschiedener messungen mit untersch. hardware
- zentrale abarbeitung

## 6.2 Programmable data processing pipeline

6-1

- datenanalyse für nicht programmierer
- automatisierter aufbau der call-tree
- mit typcheck
- alle funktionen mit bestimmter signatur werden automatisch aus globals geladen und stehen nutzer zur verfügung

```
1 # pipeline_example_measurement_processing.yaml
2 settings:
3   enabled: true
4   export_intermediate_results: false
```

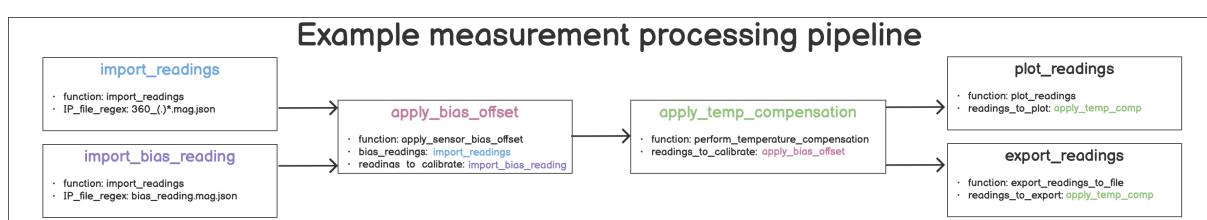


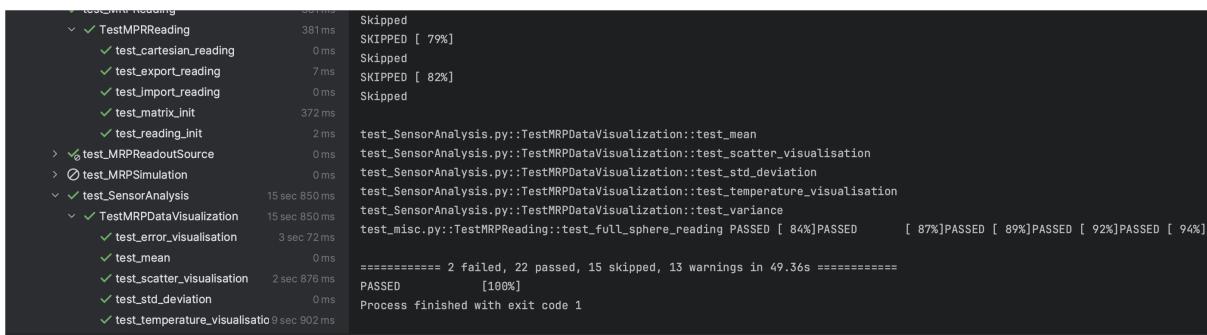
Figure 6-1: example measurement analysis pipeline

```
5  name: pipeline_example_measurement_processing
6
7  stage import_readings:
8    function: import_readings
9    parameters:
10      IP_input_folder: ./readings/fullsphere/
11      IP_file_regex: 360_(.)*.mag.json
12
13 stage import_bias_reading:
14   function: import_readings
15   parameters:
16     IP_input_folder: ./readings/fullsphere/
17     IP_file_regex: bias_reading.mag.json
18
19 stage apply_bias_offset:
20   function: apply_sensor_bias_offset
21   parameters:
22     bias_readings: stage import_bias_reading
23     readings_to_calibrate: stage import_readings
24
25 stage apply_temp_compensation:
26   function: apply_temperature_compensation
27   parameters:
28     readings_to_calibrate: stage import_readings
29
30 stage plot_normal_bias_offset:
31   function: plot_readings
32   parameters:
33     readings_to_plot: stage apply_temp_compensation
34     IP_export_folder: ./readings/fullsphere/plots/
35     IP_plot_headline_prefix: Sample N45 12x12x12 magnets
36           calibrated
37
38 stage export_readings:
39   function: export_readings
40   parameters:
41     readings_to_plot: stage apply_temp_compensation
42     IP_export_folder: ./readings/fullsphere/plots/
```

### 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 library applications. Tests also ensure consistent and reliable performance, which is particularly important when libraries are used by different users and for different usecases.

## 6 Usability improvements



```
test_MPRReading:
  ✓ TestMPRReading
    ✓ test_cartesian_reading      381ms Skipped
    ✓ test_export_reading        0 ms SKIPPED [ 7%]
    ✓ test_import_reading       0 ms Skipped
    ✓ test_matrix_init          372 ms SKIPPED [ 82%]
    ✓ test_reading_init         2 ms Skipped

  > ✘ test_MPRReadoutSource   0 ms
  > Ø test_MRPSimulation     0 ms
  ✓ test_SensorAnalysis
    ✓ 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
      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_minc.py::TestMRPReading::test_full_sphere_reading PASSED [ 84%]PASSED [ 87%]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 6-2: MRP library test results for different submodules executed in PyCharm IDE

During the development of the library, test cases were also created for all important functionalities and use cases. The test framework [PyTest](#)[8] was used for this purpose, as it offers direct integration in most IDEs (see 6-2) and also because it provides detailed and easy-to-understand test reports as output in order to quickly identify and correct errors. 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.

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

```
        None)
25      # LOAD READING FROM FILE
26      reading_imported.load_from_file(self.
27          import_export_test_filepath)
28      # CHECK IF ENTRIES ARE POPULATED
29      self.assertIsNotNone(reading_imported.additional_data)
30      self.assertIsNotNone(reading_imported.data)
31  if __name__ == '__main__':
32      unittest.main()
```

One problem, however, is the parts of the 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](#)[7]. 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 software and executed via virtualisation on the systems provided by [Github Actions](#)[7].

## 6.4 Package distribution

One important point that improves usability for users is the simple installation of the library. As it was created in the Python programming language, there are several public package directories where users can provide their software modules. Here, [PyPi](#)[5]6-3[4] is the most commonly used package directory and offers direct support for the package installation programm Python Package Installer (PIP).

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
```

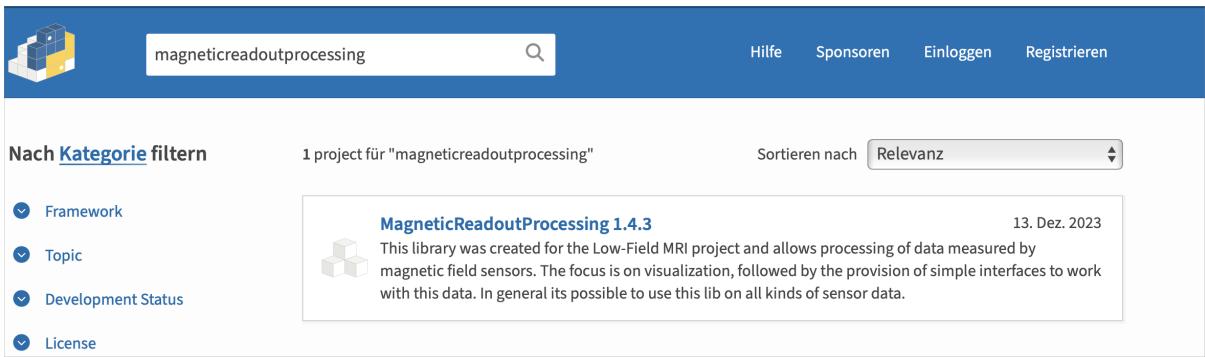


Figure 6-3: MagneticReadoutProcessing library hosted on PyPi

```
4 # install the specific version 1.4.0
5 $ pip3 install MagneticReadoutProcessing==1.4.0
```

To make the library compatible with the package directory, 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 directory.

Since the 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 library installation configuration [setup.py](#) for this purpose.

```
1 # $ cat ./setup.py
2
3 # dynamic requirement loading using 'requirements.txt'
4 req_path = 'requirements.txt'
5 with pathlib.Path(req_path).open() as requirements_txt:
6     install_requires = [str(requirement) for requirement in
7                         pkg_resources.parse_requirements(requirements_txt)]
8
9     setup(name='MagneticReadoutProcessing',
10           version='1.4.3',
11           url='https://github.com/LFB-MRI/MagnetCharacterization',
12           '/',
13           packages=['MRP', 'MRPcli', 'MRPUDpp', 'MRPproxy'],
14           install_requires=install_requires,
15           include_package_data=True,
16           package_data={": ["**/*.mag.json", "**/*.yaml", "
17                           **/*.html", "**/*.js", "**/*.css", "**/*.md",
18                           "**/*.json", "**/*.ts", "**/*.xml"]},
19           entry_points={
20               'console_scripts': [
21                   'MRPCli = MRPcli.cli:run',
22                   'MRPUDpp = MRPUDpp.uddp:run',
23                   'MRPproxy = MRPproxy.mrpproxy:run']})
```

```
20         ]
21     }
22 )
```

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 library folder.

### 6.4.1 Documentation

In order to provide comprehensive documentation for the enduser, the source code was documented using Python-`docstrings`[6] and the Python3.5 type annotations:

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

```
1      # MRPDataVisualisation.py - example docstring
2      def plot_temperature(_readings: [MRPReading.MRPReading],
3                            _title: str = '', _filename: str = None, _unit: str = "degree C") -> str:
4          """
5              Plots a temperature plot of the reading data as bar-
6              graph figure
7
8              :param _readings: readings to plot
9              :type _readings: list(MRPReading.MRPReading)
10
11              :param _title: Title text of the figure, embedded into
12                          the head
13              :type _title: str
14
15              :param _filename: export graphic to an given absolute
16                              filepath with .png
17              :type _filename: str
```

## 6 Usability improvements

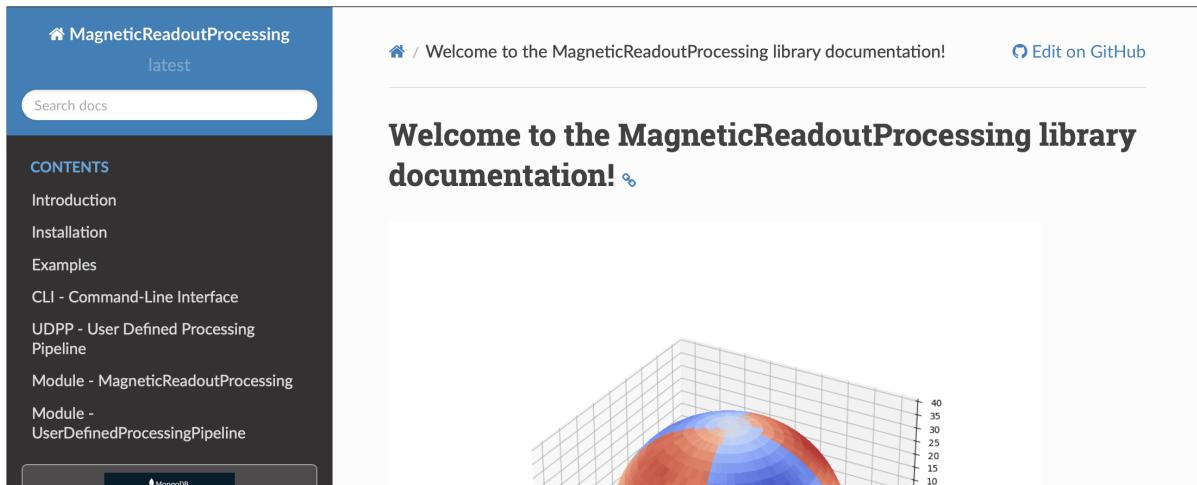


Figure 6-4: MagneticReadoutProcessing documentation hosted on ReadTheDocs

```
14
15      :returns: returns the abs filepath of the generated .
16          png image file
17      :rtype: str
18      """
19
20      if _readings is None or len(_readings) <= 0:
21          raise MRPDataVisualizationException("no readings
22              in _reading given")
23      num_readings = len(_readings)
24      # ...
```

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

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](#) services, which provide Python 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<sup>6-4</sup> on [PyPi](#).

The process of creating and publishing the documentation has been automated using [GitHub Actions](#)[7], so that it is always automatically kept up to date with new features.

# 7 Evaluation

## 7.1 Prequesites for evaluation

## 7.2 Evaluation configuation

### 7.2.1 Sensor readout

### 7.2.2 Processing pipeline

## 7.3 Test scenarios

## 7.4 Results

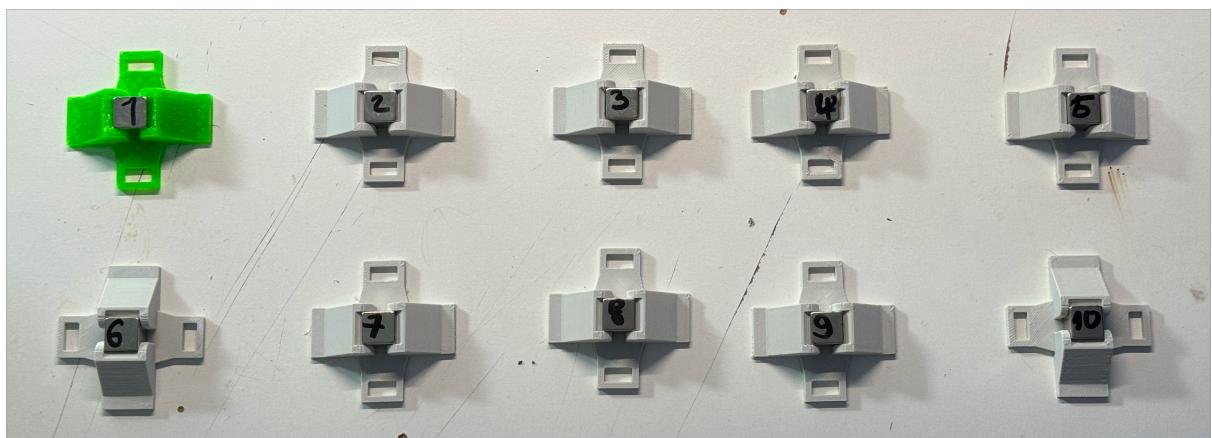


Figure 7-1: testmagnets in holder

# **8 Conclusion and dicussion**

## **8.1 Conclusion**

## **8.2 Problems**

## **8.3 Outlook**

- magfield camera

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# Akronyme

**CLI** Command Line Interface. 6, 19

**HAL** Hardware Abstraction Layer. 11

**HTML** Hypertext Markup Language. 20

**I2C** Inter-Integrated Circuit. 4

**IDE** Integrated development environment. 16, 20

**IP** Internet Protocol. 13

**PC** Personal Computer. 10–13, 17

**PDF** Portable Document Format. 20

**PIP** Python Package Installer. 17

**PPS** Puls Per Second. 13

**PTP** Precision Time Protocol. 13

**REST** Representational State Transfer. 10, 12

**USB** Universal Serial Bus. 13

# Abbildungsverzeichnis

<b>4-1</b>	Sensors CL-Interface . . . . .	6
<b>4-2</b>	Query sensors b value using CLI . . . . .	6
<b>4-3</b>	1D sensor contrsuction with universal magnet mount . . . . .	7
<b>4-4</b>	Full-Sphere sensor implementation using two Nema17 stepper motors in a polar coordinate system . . . . .	8
<b>5-1</b>	MRPlib COMPLETE FLOW . . . . .	10
<b>5-2</b>	MRPlib Proxy Module . . . . .	11
<b>5-3</b>	mrp proxy multi . . . . .	11
<b>6-1</b>	example measurement analysis pipeline . . . . .	14
<b>6-2</b>	MRP library test results for different submodules executed in PyCharm IDE . . . . .	16
<b>6-3</b>	MagneticReadoutProcessing library hosted on PyPi . . . . .	18
<b>6-4</b>	MagneticReadoutProcessing documentation hosted on ReadTheDocs . . . . .	20
<b>7-1</b>	testmagnets in holder . . . . .	22

# **Tabellenverzeichnis**

4.1 Implemented digital halleffect sensors . . . . .	4
------------------------------------------------------	---