Inductive Communication and Localization Method for Wireless Sensors in Photobioreactors

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David Demetz was born in South-Tirol, Italy, in 1994. He received the Dipl.-Ing. degree in Mechatronics from the Umit Tirol, Hall in Tirol, Austria and the University of Innsbruck, Austria (Joint Degree Programme), in 2019.
In 2019 he joined the Institute of Measurement and Sensor Technology, at the Umit Tirol, Austria. His research interests include wireless sensors, inductive coupling systems and signal processing.

Content

- Photoreactors in general and the internal illumination of them
- Inductive communication method for wireless sensors
- Inductive sensor localization: theory and results
- Simulation: localization accuracy improvement by using multiple receivers

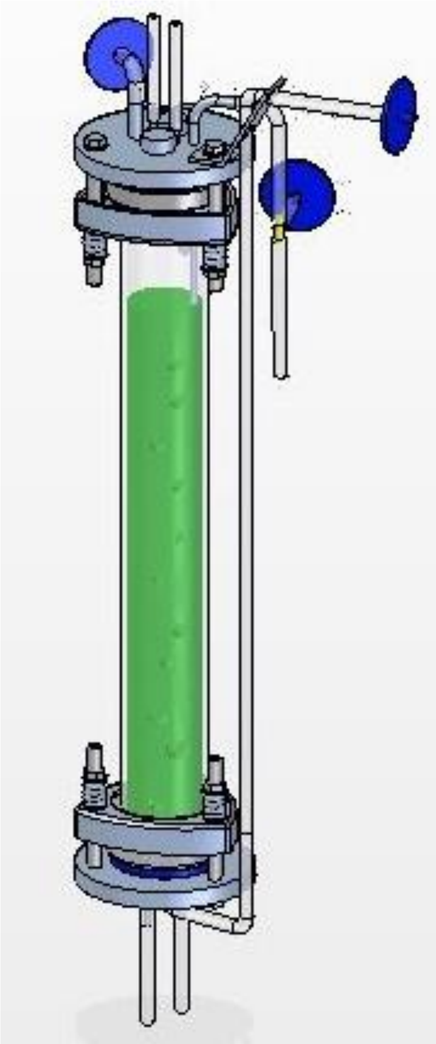
Photoreactors in general

Are used to

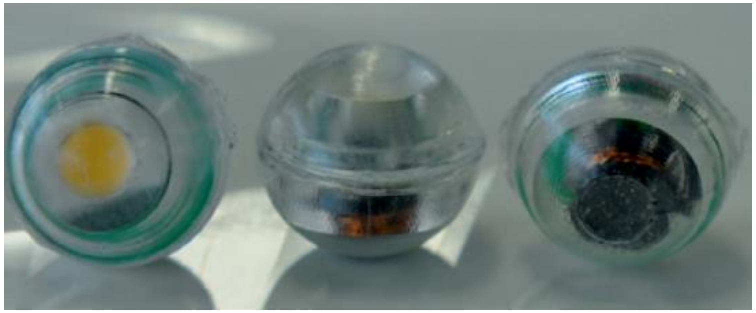
- cultivate photosynthetic active microorganisms and cells
- to perform photocatalytic reactions

General problem:

- limited penetration depth of light



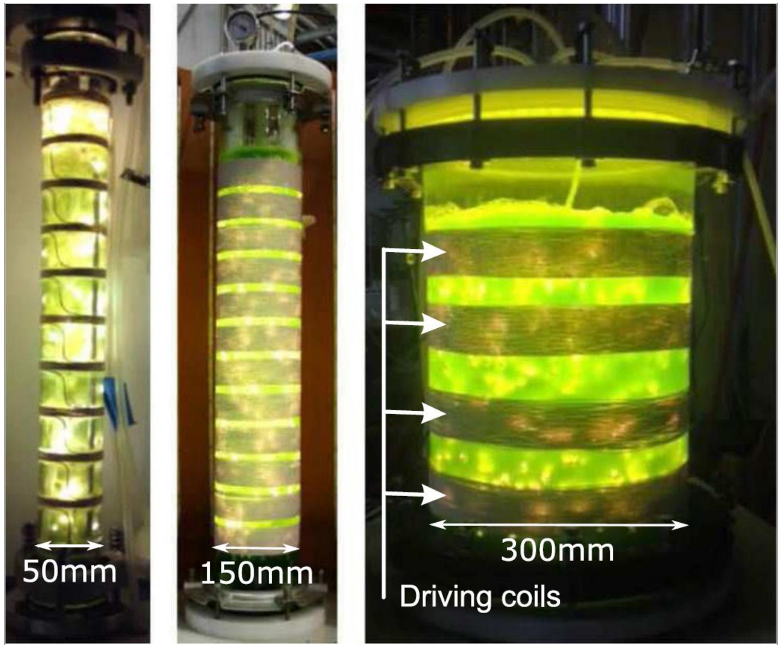
Internally illuminated photoreactors



Wireless light emitters (WLE)

- Inductively supplied spherical light emitters (WLEs) which are floating in the reactor media

- The driving Coils at the outer circumference of the reactor are driven by a class-e power amplifier



Internally illuminated photoreactors

Internally illuminated photoreactors

The next step:

- inclusion of sensors for measuring crucial parameters
- e.g. temperature, pH-value, oxygen and carbon dioxide concentrations, …
- wireless sensors to counteract the drawback of measuring the respective parameter only at one point in the reactor
- determining the position of the sensor leads to a spatial resolution of the measured parameter

Communication

- **Methods for underwater communication:**
  - **Our choice:**

Electromagnetic (EM) data transmission

~~Acoustic data transmission~~

~~Optical data transmission~~

- **Problem:** sensors are inside a with (salt-) water filled Photoreactor (electrically conducting media) -> lossy media -> attenuation of electromagnetic waves

- Attenuation:
  - increases with higher frequency
  - increases with higher conductivity σ of the propagation media

The acoustic and the optical methods are not well suited for our aim:

- The optical method would not be feasible due to the many obstacles in the reactor; for example the WLEs.

- The acoustic method is unsuitable due to the physical separation between transmitter and receiver by the reactor wall.

Communication

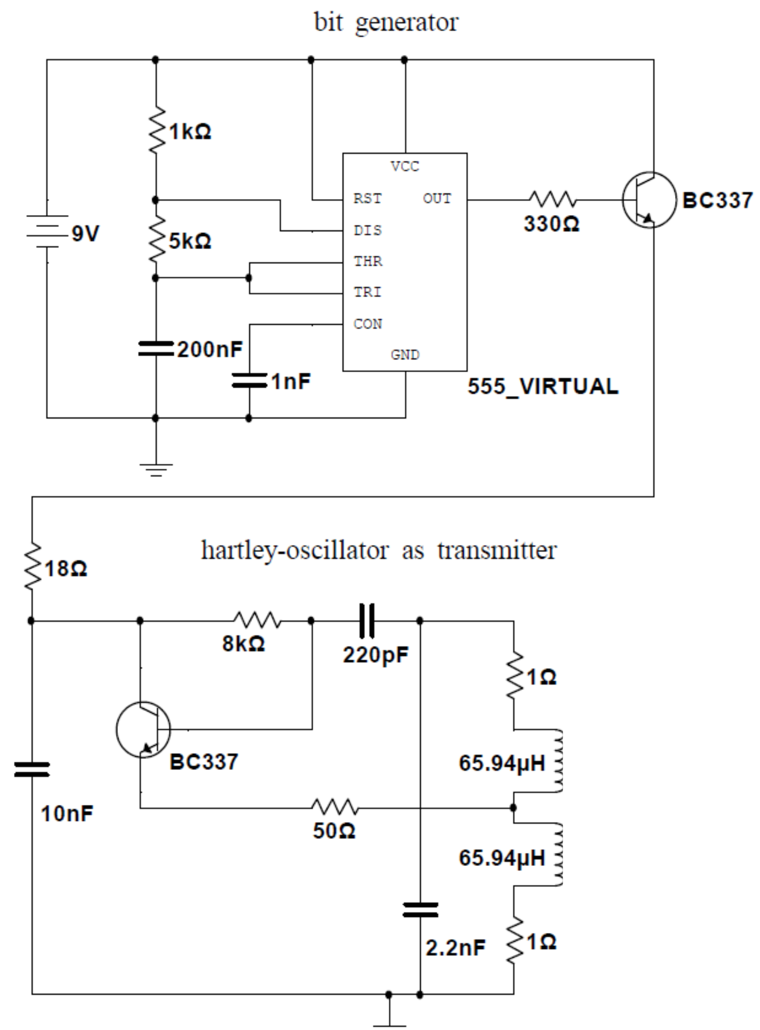
- **Physical requirements for the communication layer:**
  - low frequencies
  - based on the inductive principle since the relative magnetic permeability of water (and saltwater) is ≈ 1 (like air).
- **Our choice: inductive communication link with a carrier frequency of 298kHz -> <u>only the quasi-static field component results relevant</u>**
  - On-off keying is used as a modulation technique.

Transmitter circuit

- Bit generator to simulate the digital sensor data stream. This circuit generates a square signal where the high level represents the ‘1’ bit and the low lever the ‘0’ bit.

- On-off-keying: the square wave of the bit generator is used to switch the oscillator on and off.

- Transmitter: Hartley oscillator



Transmitter circuit

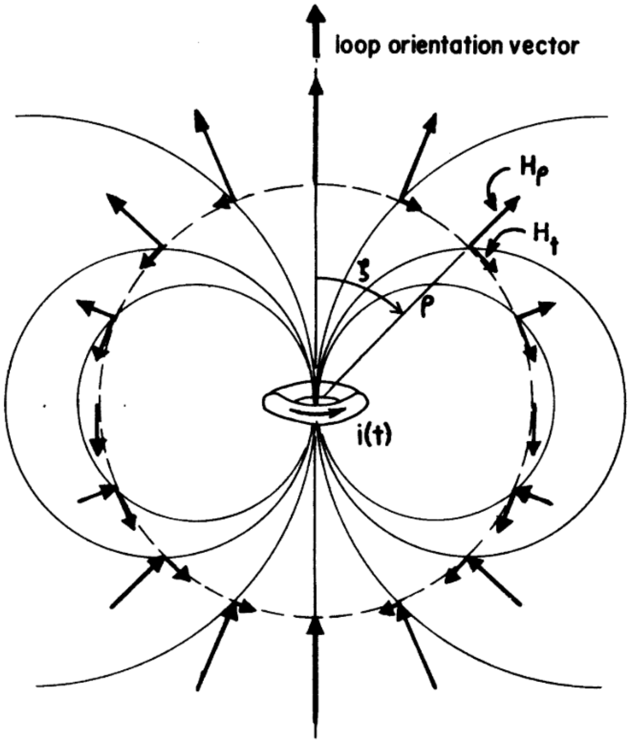
Localization Theory

- **For the localization task we use the magnetic dipole field equation to model the magnetic field of the transmitter coil**

  - Magnetic field strength in radial H_ρ and tangential H_t component

$$H_\rho = \frac{NIA}{2\pi\rho^3}\cos\varsigma$$

$$H_t = \frac{NIA}{4\pi\rho^3}\sin\varsigma$$



Magnetic dipole field

- Measuring the magnetic field at well defined positions outside the reactor makes the calculation of the transmitter position possible.

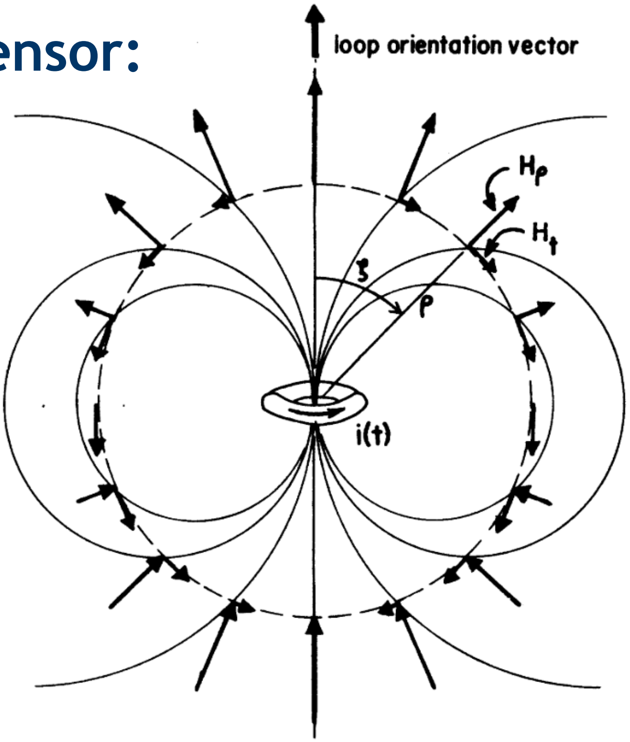
Localization Theory

Coupling between aligned source and sensor:

- Coupling equation for the simplified aligned (see next slide) case:

$$\vec{f}_{rx} = \left(\frac{C}{\rho^3}\right) \boldsymbol{S} \vec{f}_{tx}$$

- $\boldsymbol{S} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -0.5 & 0 \\ 0 & 0 & -0.5 \end{bmatrix}$
- transmitter signal vector $\vec{f}_{tx}$
- receiver signal vector $\vec{f}_{rx}$
- C … constant value depending on the coil properties and the sensor gain
- ρ… distance between transmitter and receiver



Magnetic dipole field

Localization Theory

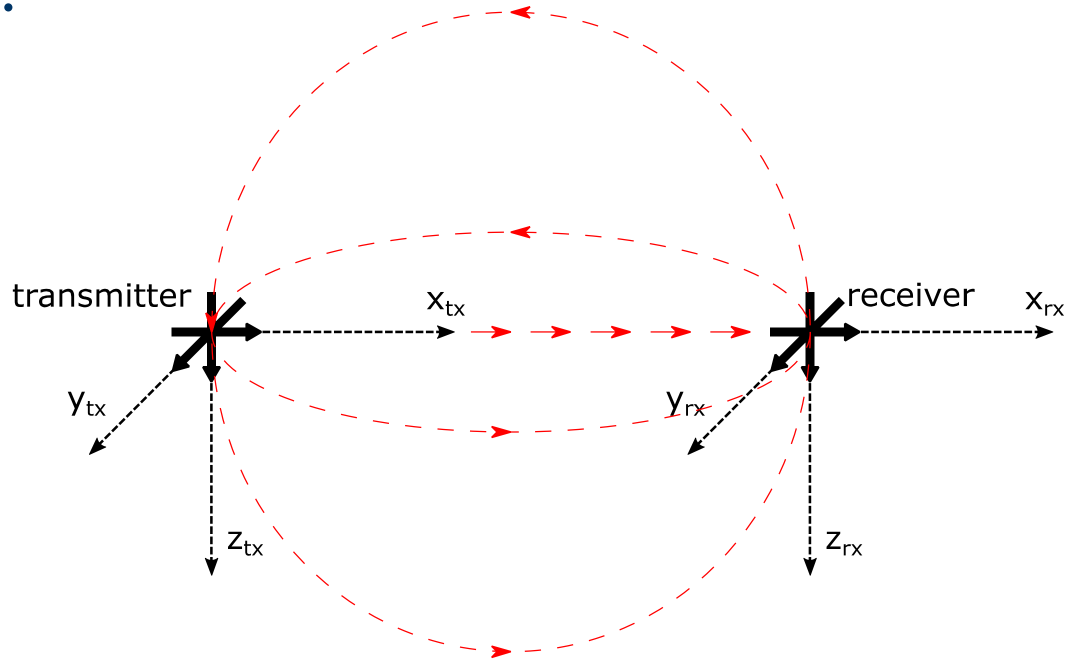
Coupling between aligned source and sensor:

- Alignment conditions:

$$\vec{e}_{x-rx} = \vec{e}_{x-tx}$$

$$\vec{e}_{y-rx} \mid\mid \vec{e}_{y-tx}$$

$$\vec{e}_{z-rx} \mid\mid \vec{e}_{z-tx}$$



Alignement conditions

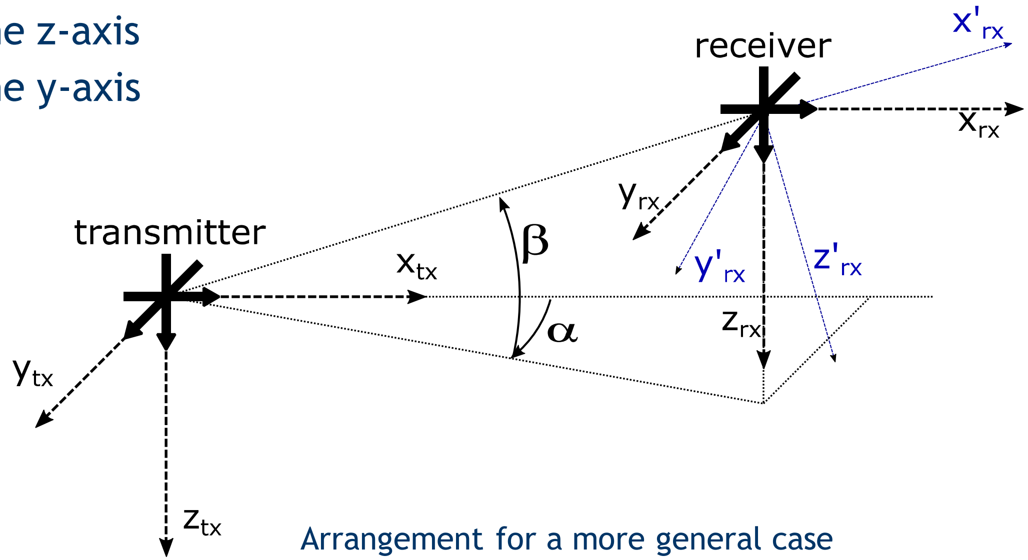
Localization Theory

Coupling between source and sensor:

- Coupling between transmitter and receiver (not aligned)

$$\vec{f}_{rx} = \left(\frac{C}{\rho^3}\right) \boldsymbol{T_\alpha}^{-1}\, \boldsymbol{T_\beta}^{-1}\, \boldsymbol{S}\, \boldsymbol{T_\alpha} \boldsymbol{T_\beta}\, \vec{f}_{tx}$$

  - $\boldsymbol{T_\alpha}$ … rotation matrix around the z-axis
  - $\boldsymbol{T_\beta}$ … rotation matrix around the y-axis



Arrangement for a more general case

Localization Theory

Our method

- Two receivers for measuring the magnetic field at a defined positions.

- Solving the equation

$$\boldsymbol{T_\alpha}^{-1}\,\boldsymbol{T_\beta}^{-1}\,\boldsymbol{S}\,\boldsymbol{T_\alpha}\boldsymbol{T_\beta}\,\vec{f}_{tx} - \vec{f}_{rx} = \mathbf{0}$$

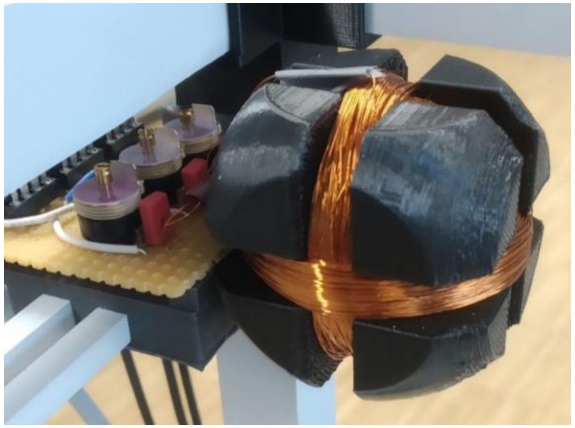
  with $\vec{f}_{tx} = (\mathbf{0}\ \mathbf{0}\ \boldsymbol{a})^{\boldsymbol{T}}$ for the angles α and β (and for a) enables the calculation of a directional vector $\vec{r}$ which points from the measurement point to the transmitter position.

- The position is calculated by determining the point where the two directional vectors come closest (ideally the intersection).

Localization Hardware

Receiver design

- The magnetic field at a known position is measured with a „3d-Coil“.
- Three coils are positioned orthogonally to each other for measuring the x- y- and z-component of the magnetic field of the transmitter.

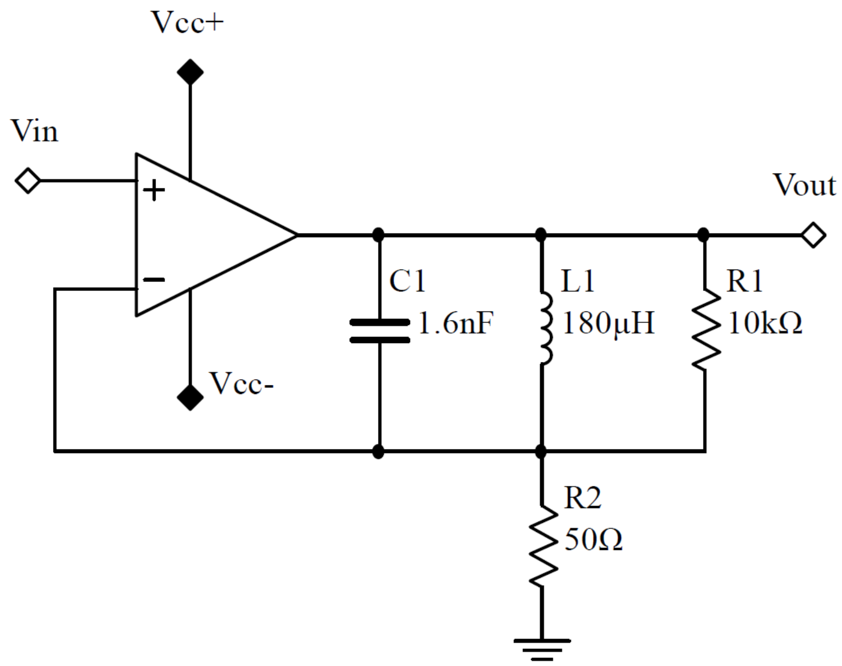


3d-coil-receiver

Localization Hardware

Receiver design

- Coil as main receiver component.
- The coil signal is amplified with a resonant filter in order to amplify the receiver signal only at the transmitting frequency.

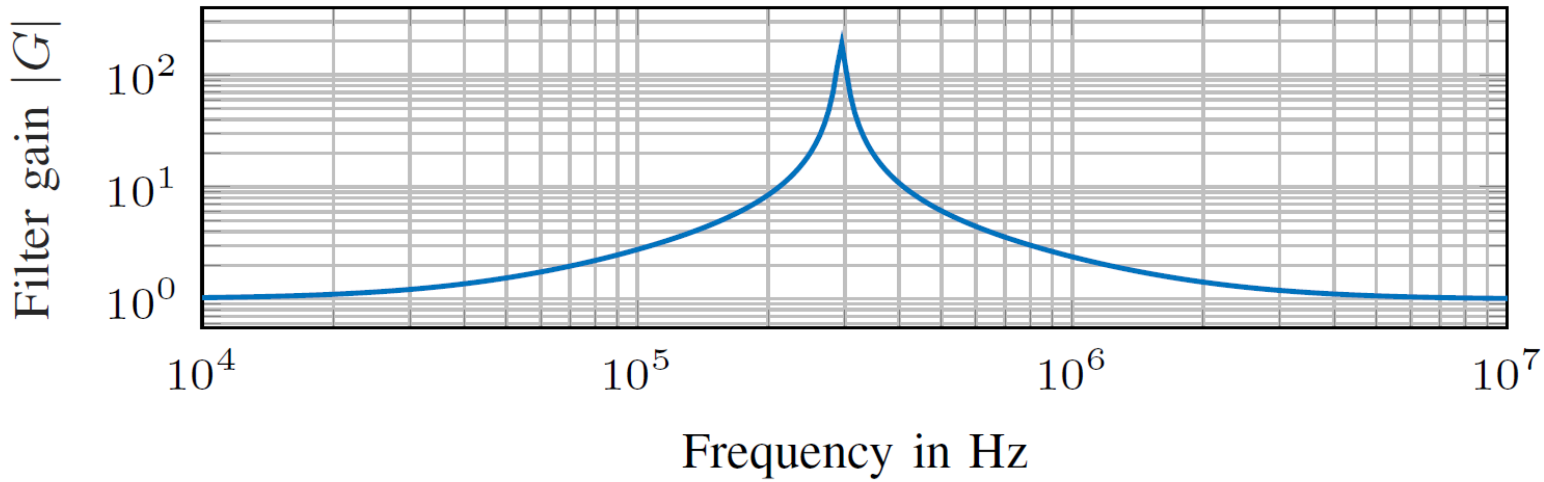


Resonant filter

Localization Hardware

Receiver design

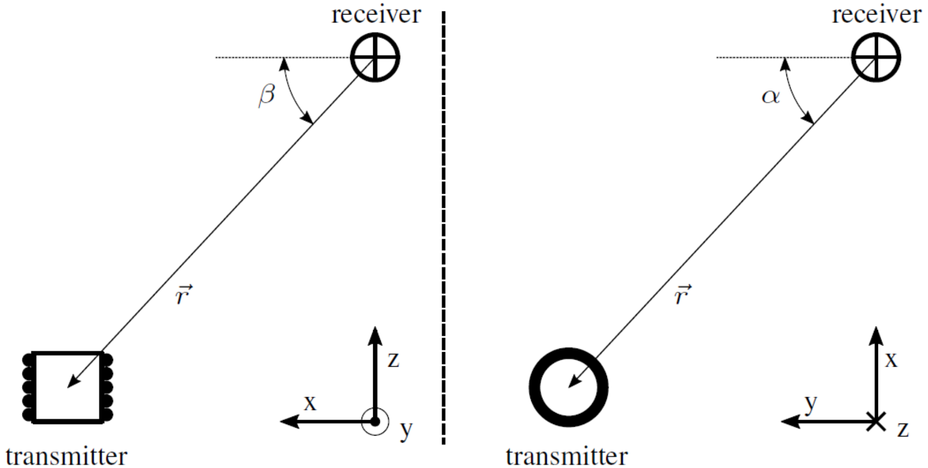
- Bode magnitude plot of the resonant filter:



Localization Setup

Our system

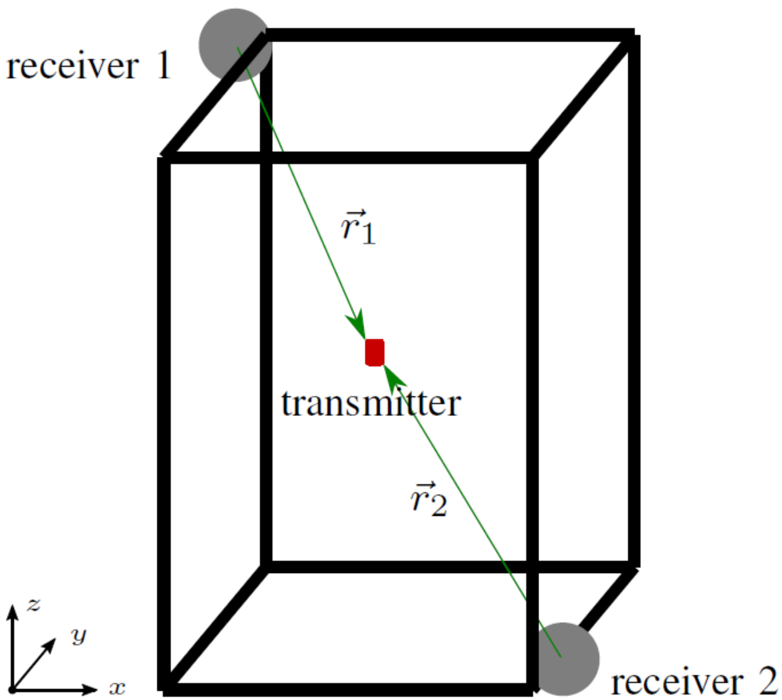
- With the measured magnetic field and based on the magnetic dipole equation a directional vector $\vec{r}$ is calculated for each receiver. This vector points from the receiver to the transmitter.
- The directional vector $\vec{r}$ is defined by the two angles α and β.
- By using two or more receivers the transmitter position is calculated by finding the point were the direction vectors comes closest, ideally the intersection.



Definition of the directional vector $\vec{r}$

Localization Setup

Receiver positions:



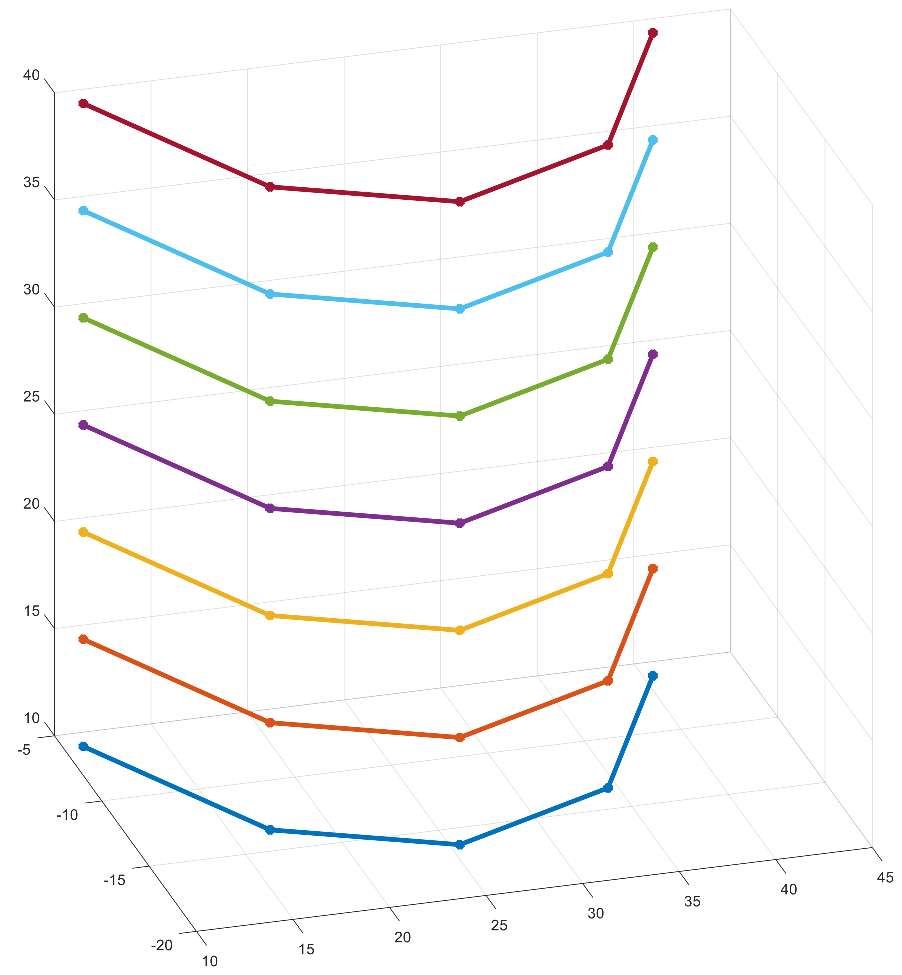
Receiver arrangement

- The setup used for the first localization measurements is entirely made out of plastic materials in order to not influence the magnetic field.

Localization Measurements

Measurement points:

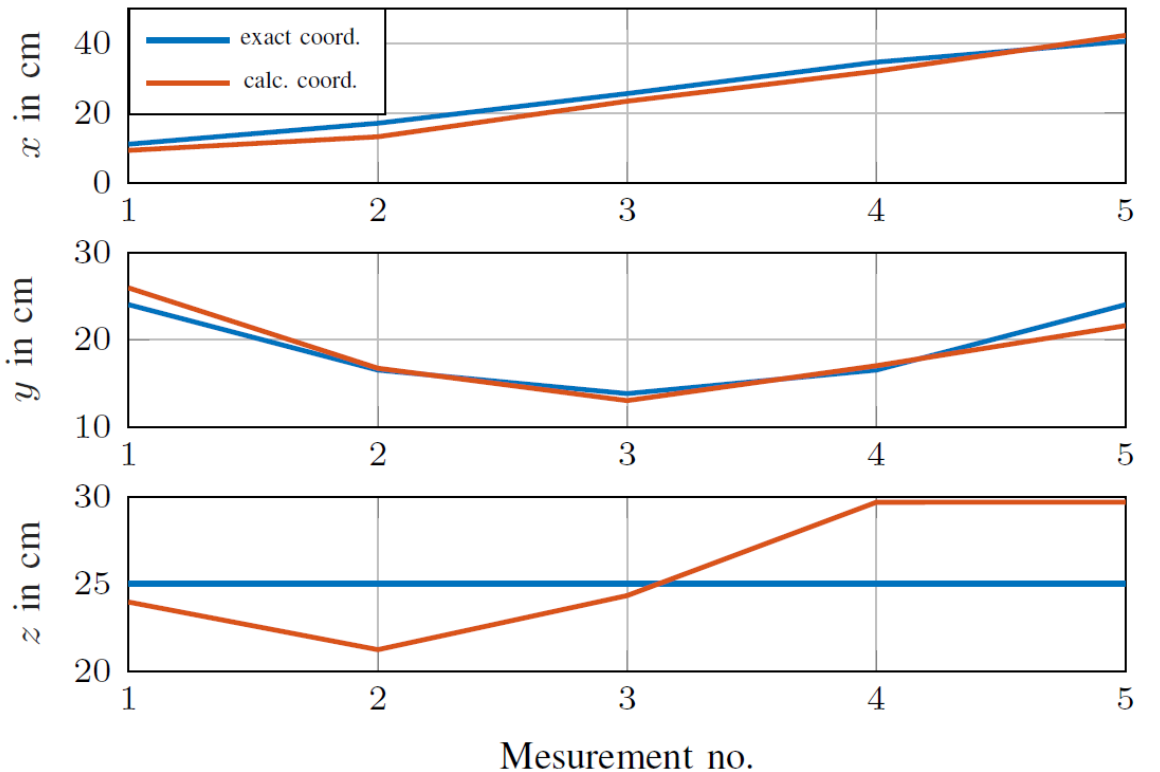
- Five measuring points at seven different heights in our region of interest.
- The x and y coordinates of the individual points are the same at all heights.



Measurement pattern (unit: cm)

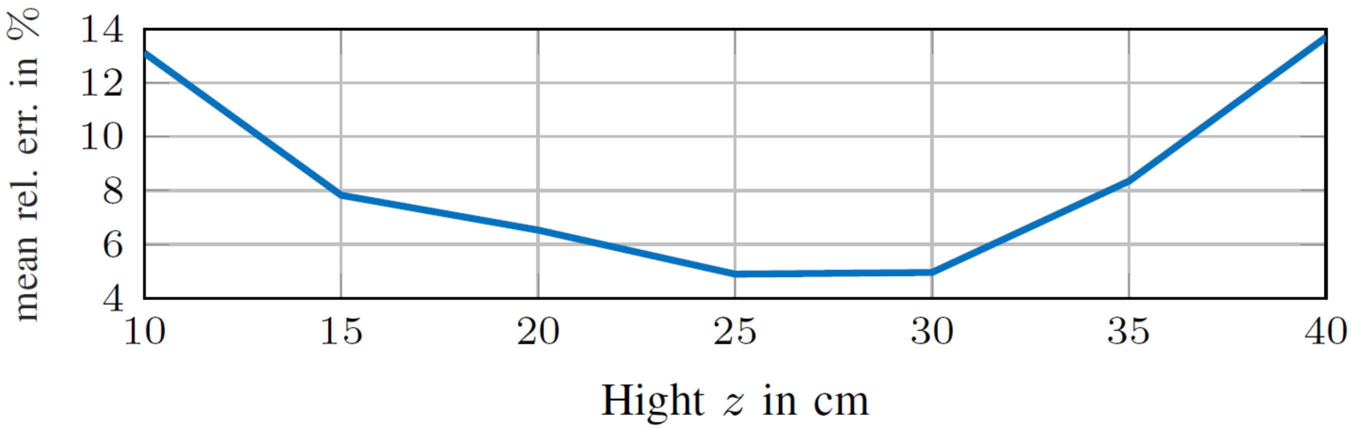
Results

- Real position vs. measured position (25cm height)



Results

- Mean values of the relative errors of all three coordinates at different heights



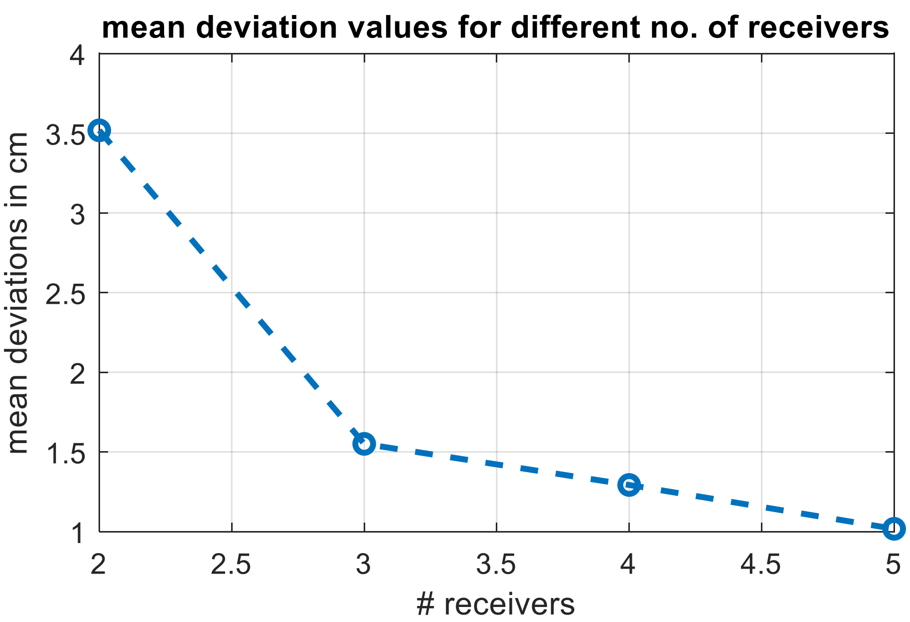
For low as well as for high z-coordinates, the distance to one receiver increases and, therefore, the accuracy decreases.

Simulation results

- Accuracy improvement by using more than two receivers

  - Mean value of the magnitude of the deviation vectors between the exact positions and calculated positions with added noise.

- signal amplitude variation:
  - random values in the range between 0 and 5% of the calculated exact amplitude
- overlap of white noise
  - random values in the range between 0 and 50% of the signal amplitude
- power supply magnetic field overlap
  - random values in the range between 0 and 50% of the signal amplitude



Thank you for your attention!

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