# ANALYTICAL SCHEME FOR THE CALIBRATION OF MAGNETIC POSITION SYSTEMS

Stefano LUMETTI[1], Perla MALAGÒ[1], Dietmar SPITZER[2], Sigmund ZARUBA[2], Michael ORTNER[1]

[1] Silicon Austria Labs GmbH

[2] Infineon Technologies AG

November 20th, 2020

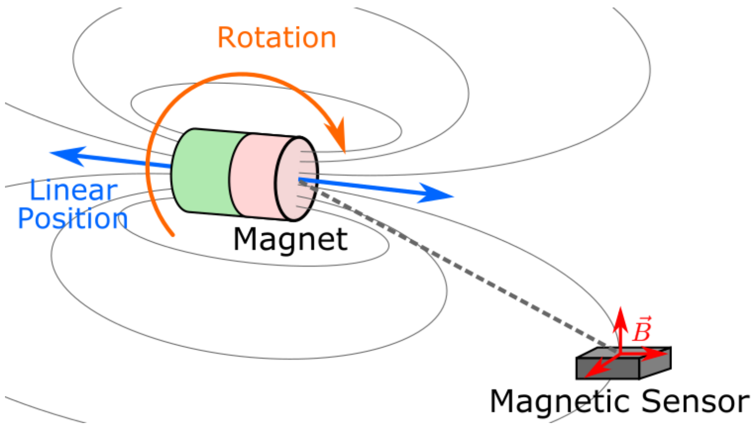
SAL
SILICON AUSTRIA LABS

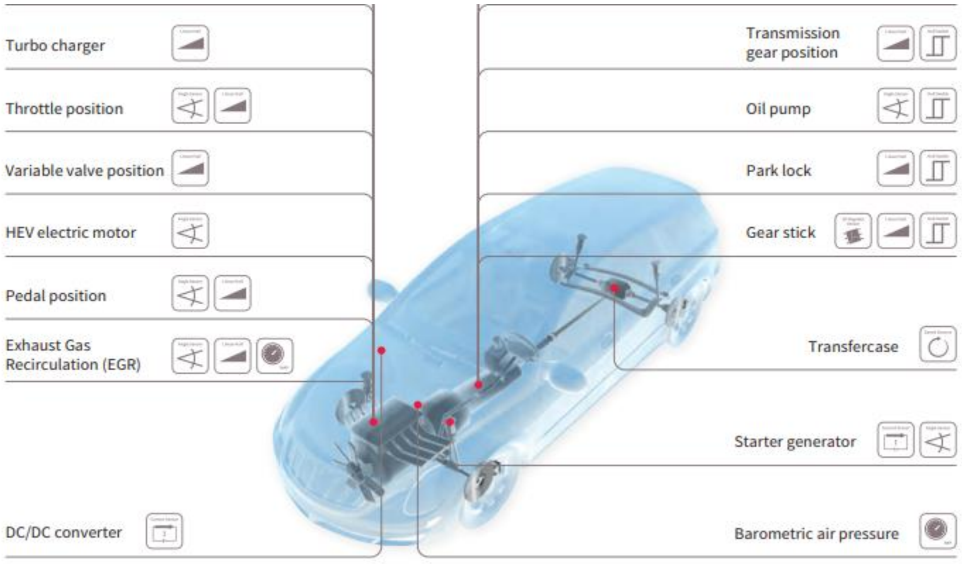
# OUTLOOK

# MAGNETIC POSITION AND ORIENTATION SYSTEMS

- **Magnetic position and orientation sensing** refers to the detection of a relative mechanical motion between a magnet and a magnetic sensor through a magnetic field measurement
- Several different implementations are possible, including **linear position**, **rotation** but also more **complex motion patterns**
- The **advantages** of magnetic position sensing include wear-free operation, long lifetimes, robustness in dirty environments, high resolution, cost-efficiency
- Nowadays, more than 100 magnetic position and orientation system applications can be found in the automotive sector alone, including gear shift detection, rotating shafts in the gear box, wheel speed sensing, ABS, indication levers, steering wheels, side mirrors, gas and brake pedals

Magnetic position and orientation detection

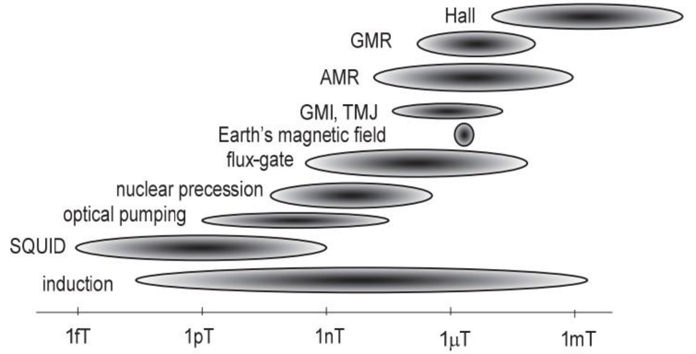



Automotive applications (source: Infineon.com)

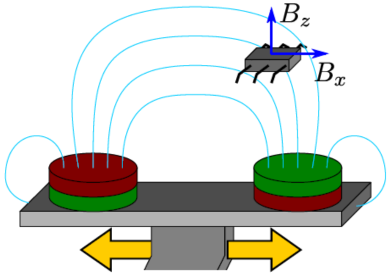
# MAGNETIC POSITION AND ORIENTATION SYSTEMS

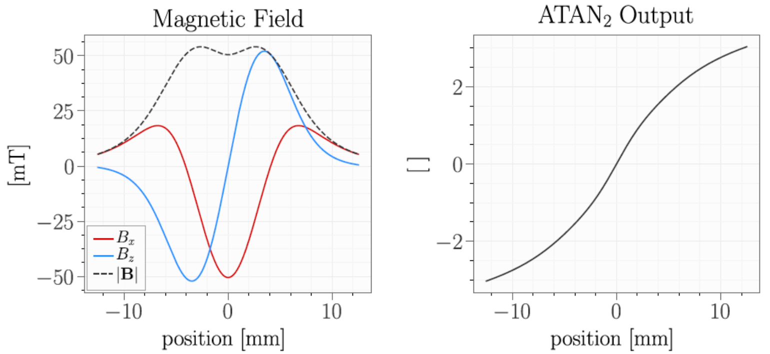
- Multiple established **magnetic field sensing** technologies exist, each with its advantages and disadvantages
- Sensors integrated in industrial applications are typically based on **Hall**, XMR or fluxgate technology
- Magnetic field **sensors** for **1D**, **2D** and **3D** measurements are available



**Magnetic sensor technologies (Janosek, 2017)**

- 2D example: linear position detection in automotive shift forks
  - The linear motion generates an odd ($B_{odd}$) and an even ($B_{even}$) field component
  - A linear output is given by $\arctan_2(B_{even}, B_{odd})$, which generates a one-to-one correspondence with the position



**Magnetic linear position detection in a shift work set-up**

**3D magnetic field sensor for automotive applications**

# MAGNETIC POSITION AND ORIENTATION SYSTEMS

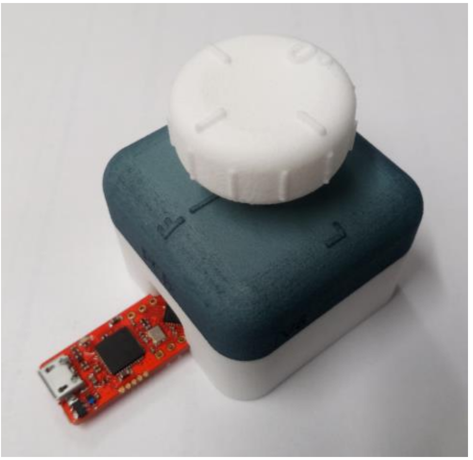
## How to design a magnetic position and orientation system?

- **Constraints**
  - Requirements: motion range, desired resolution
  - Geometry: where the sensor and the magnet can be placed
  - Magnetic sensor: detection limit, resolution, noise
  - Fabrication tolerances: initial construction tolerances, dynamic tolerances during operation
  - External stray fields
  - Linearity of the output: which computation is possible (e.g. is a micro-controller available?)
  - Cost optimization: reduce magnetic material, use cheap sensors
- **System parameters**
  - Magnet layout (all possible shapes, forms, orientations and positions)
  - Sensor choice and position

## Motivation of our work

**BMW iDrive controller**

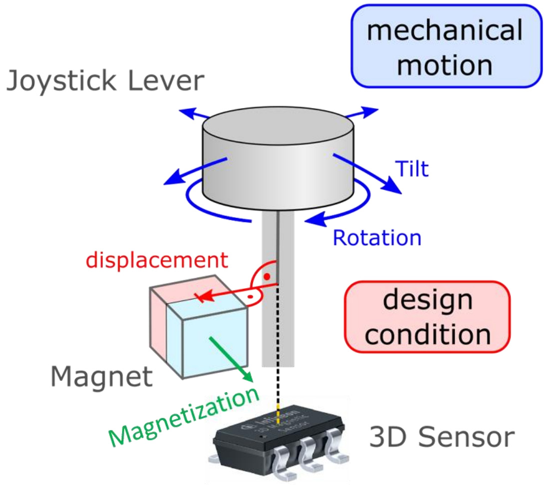

**Mini-Drive**

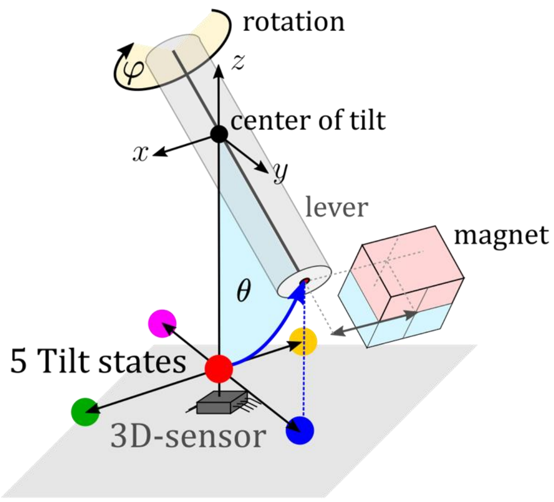


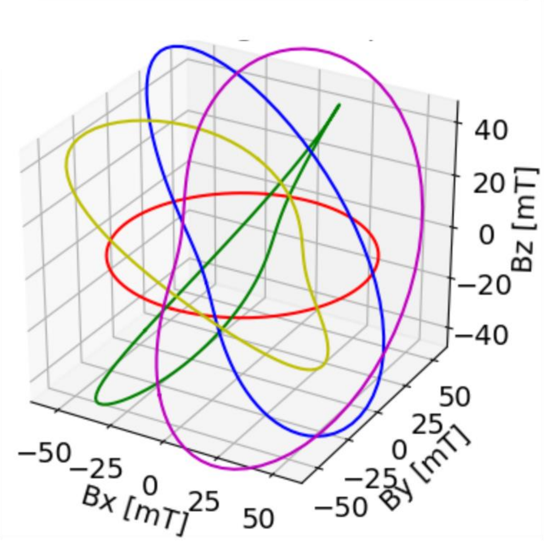
- *Mini-Drive system*: detection of the motion of a **3-axis joystick** by means of a **single magnet** and a **single sensor**
- *Aim*: Cost-efficiency
  - **Cheap** fabrication and sensor technology
  - User-friendly, **fast** and computationally efficient calibration

# MINI-DRIVE CONCEPT

- Detection of the motion of a **3-axis joystick** by using only **one sensor** and **one magnet**
  - **full rotation** of the joystick lever about its axis
  - **2D tilt** motion → only 5 discrete states are detected (i.e. central position and full tilt in four directions)
- **One-to-one correspondence** between mechanical states and sensor output
  - A magnet is fixed at the end of the lever with a **lateral displacement** with respect to the rotation axis
  - The **magnetization** of the magnet is perpendicular both to the lever axis and to the magnet's lateral displacement
  - A **3D Hall** magnetic field sensor is placed centrally below
- For each tilt state a **full rotation** of the lever corresponds to a **closed loop** in the magnetic state space



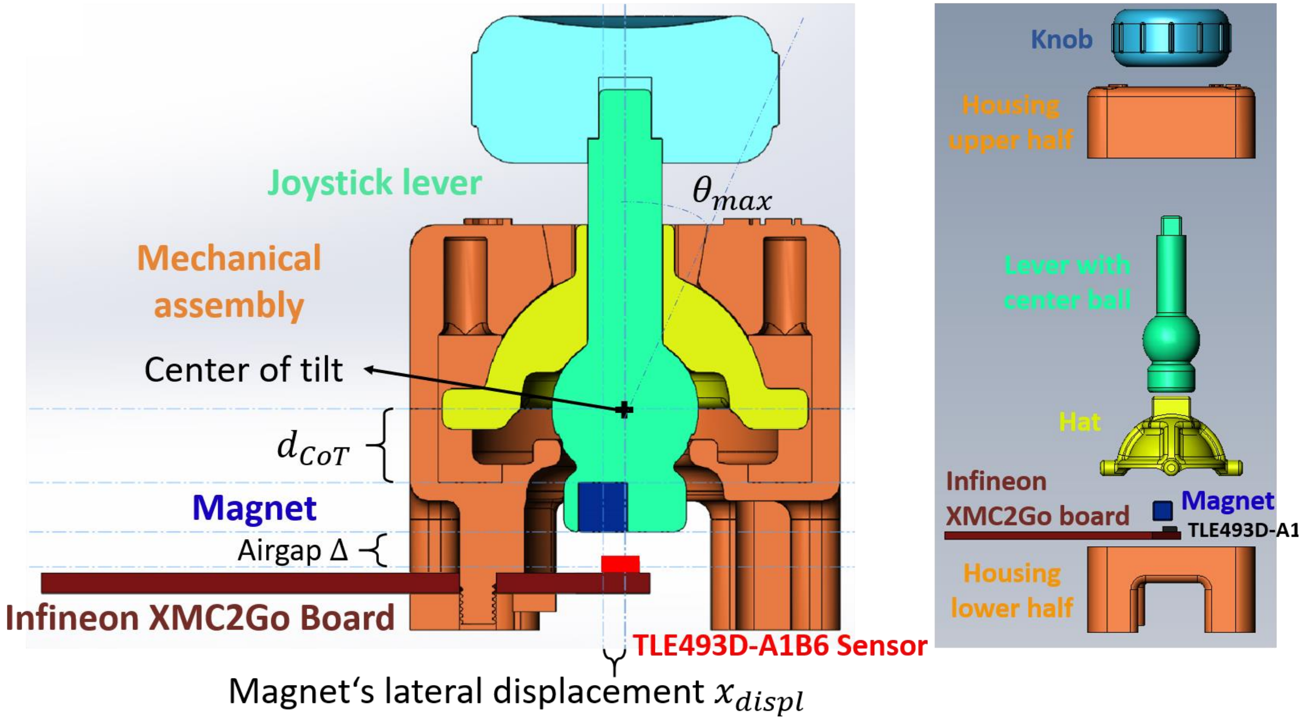




*The magnetic loops are **maximally separated** from each other thanks to the specific system layout*

# MINI-DRIVE FABRICATION

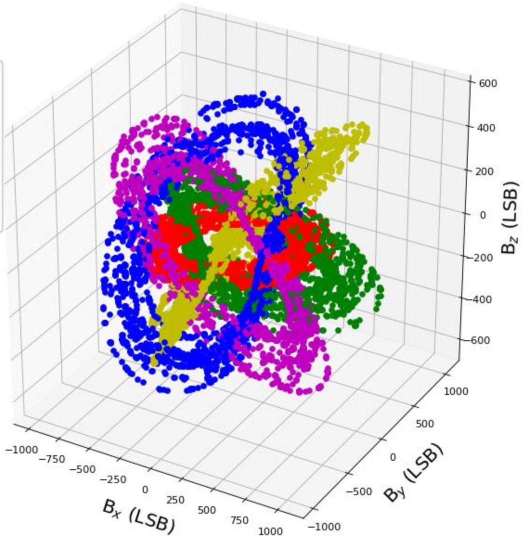
- The **center-ball** defines the center of tilt and allows for full rotation about the lever axis
- A cross-shaped cavity in the upper half of the housing limits the possible tilts to **four discrete directions** only
- **Center-lock mechanism** allowing the lever to recover its zero-tilt position after release
  - A “hat” presses the center-ball in a circular cavity
  - Printed springs apply a force on the lateral appendices of the “hat”
- A **cubical NdFeB magnet** is embedded at the bottom of the lever
- An **Infineon XMC2Go** board with a **3D Hall magnetic field sensor** is integrated in the system
  - Sensor features: low power consumption, 12-bit data resolution, range of $\pm$130 mT




- Main geometrical parameters:
  - Distance from the center of tilt $d_{CoT}$
  - Airgap Δ
  - Magnet lateral displacement $x_{displ}$
  - Maximum tilt angle $\theta_{max}$

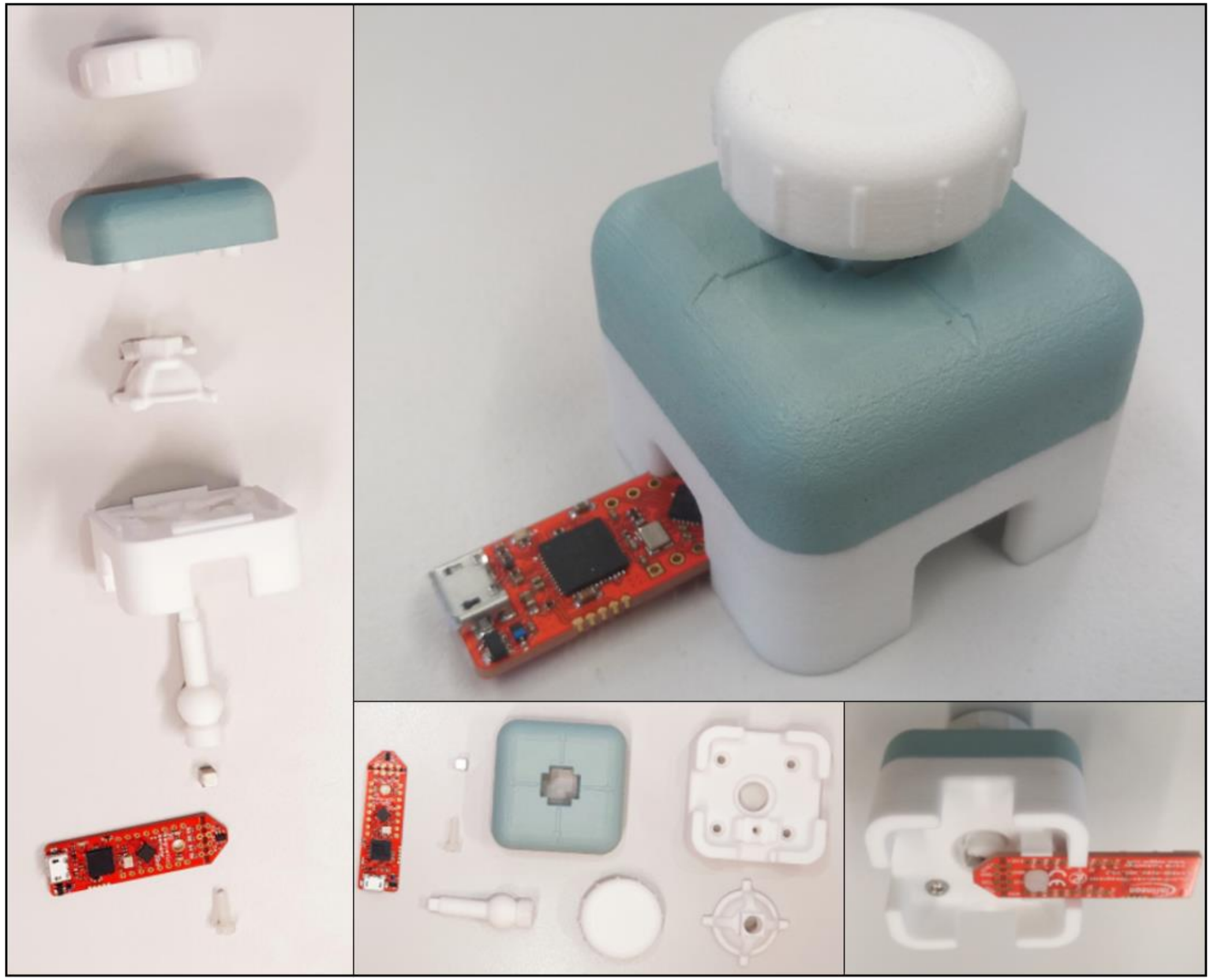
# MINI-DRIVE FABRICATION

- The Mini-Drive components are fabricated using a high-resolution industrial **3D printer**
- Nominal **construction parameters**:
  - $d_{CoT} = 6.3$ mm
  - $x_{displ} = 3$ mm
  - $\Delta = 3$ mm
  - $\theta_{max} = 10°$
- **Tolerances**:
  - $\delta_{d_{CoT}} = 0.3$ mm
  - $\delta_{x_{displ}} = 0.1$ mm
  - $\delta_{\Delta} = 0.3$ mm
  - $\delta_{\theta_{max}} = 0.2°$




*Fabrication tolerances result in large variations among different devices in the magnetic field space*

***A calibration of the devices is needed***

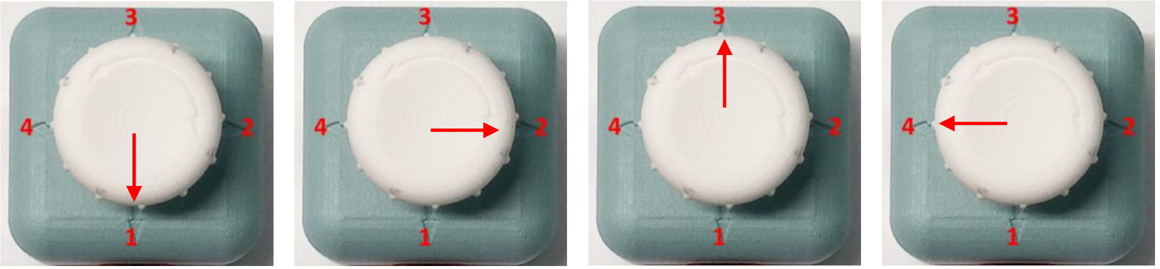


# READ-OUT & FIELD COMPUTATION

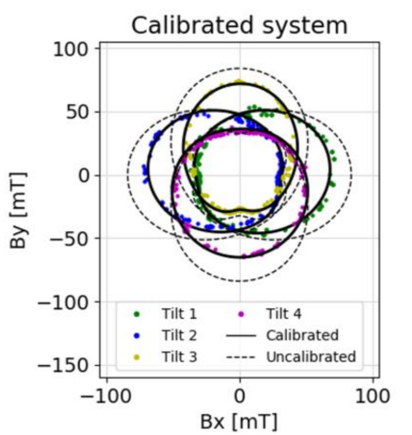
- Information about the system state is obtained by solving the so-called **inverse problem**, i.e. by determining the position of the magnet starting from a magnetic field measurement
- Challenges:
  - Solving the inverse problem **within milliseconds** to enable real-time measurement
  - **Limited computational resources** are typically available (sensor ICs or microcontrollers)
- Mini-Drive approach:
  - Construction of a **look-up table** (very efficient due to the small state space, i.e. five loops with 36 to 180 rotation states each)
  - Computation of the inversion by **direct comparison** between the magnetic field measurement and the look-up table (which takes only few milliseconds on the microcontroller of the Infineon XMC2Go board)
- The look-up table is created from **3D analytical solutions** for the magnetic field:
  - The fields are computed using the open-source **Magpylib** toolbox, based on a Python interface
  - The analytical solution for cuboid magnets is a closed-form expression and its vectorized implementation can be computed **within few milliseconds** on standard x86 CPUs
  - Comparison to FEM computations shows that the error of the Magpylib analytical solution is **less than 1%**

# CALIBRATION SCHEME

- A **calibration** of the Mini-Drives is necessary to eliminate the influence of the **fabrication tolerances**
- We propose a simple procedure in which the user is asked to provide **four well-separated measurement points**
  - For each magnetic loop:
    - **Four consecutive 90° rotations**
    - Each rotation followed by **one tilt in all directions**



- The calibration task consists in **fitting the magnetic loops onto the calibration data** by **variation of the system tolerances**
  - A **differential evolution optimizer** is combined with an analytical computation of the field of cuboid magnets
  - A **cost function** is minimized, defined as the ratio of the distance from the correct loop to the distance from the nearest incorrect loop
- The calibration procedure generates a set of tolerances
  - The tolerances are employed to compute the 5 magnetic loops
  - A **look-up table** of arbitrary rotational discretization is created from the calculated loops

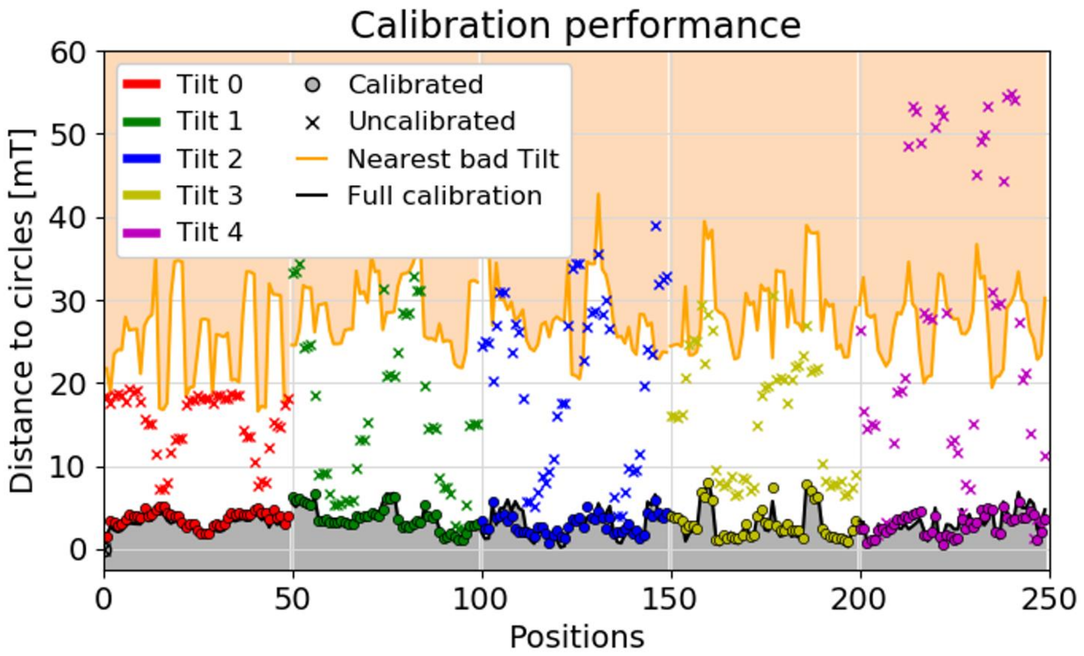


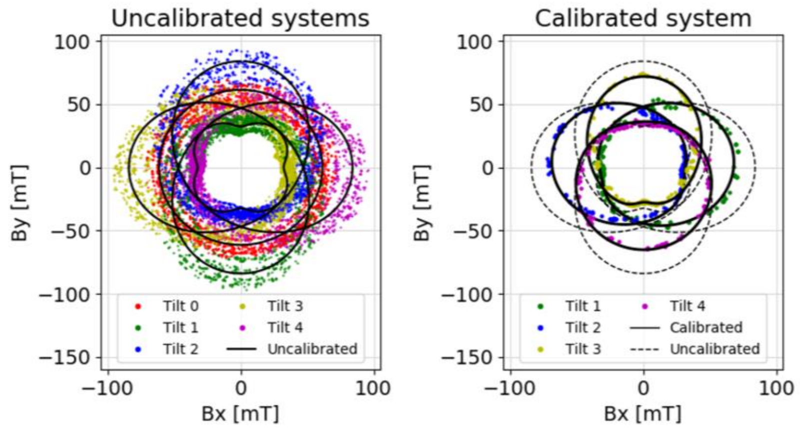
# CALIBRATION RESULTS

- Calibration including:
  - Magnet position (3 DoF)
  - Magnet magnetization (3 DoF)
  - Tilt angles (4 DoF)
  - Sensor position (3 DoF)
- Many **uncalibrated states** lie above the nearest-bad tilt threshold

  → The uncalibrated Mini-Drive would yield incorrect system state output
- The **calibrated states** lie much closer to the correct loops (< 8 mT) than to the wrong ones (> 17 mT)

  → Easy identification of the correct states in the calibrated Mini-Drives
- **4-point calibration** is surprisingly **efficient**
  - The best possible result is achieved in most cases
  - The use of more points for the calibration does not bring any significant improvement



# CONCLUSIONS

- **Mini-Drive** devices
  - Simple **3-axis joysticks** with only **one sensor** and **one magnet**
  - Manufactured via cheap **3D printing**
- Novel scheme based on **analytical methods** for the calibration of the Mini-Drives
  - Calibration based on the **analytical solution for the magnetic field**
    - **Fast** analytical field computation (Magpylib toolbox)
  - A **differential evolution algorithm** is applied to solve a multivariate optimization problem that includes multiple relevant fabrication tolerances
- **User-friendly calibration scheme** requiring the measurement of only four points for each tilt
- This novel scheme enables to calibrate **more than 10 degrees of freedom within few seconds** on conventional PCs
- Potential for the **extension of this method** for the design and calibration of other novel and cost-efficient magnetic position systems

# THANK YOU
# FOR YOUR ATTENTION