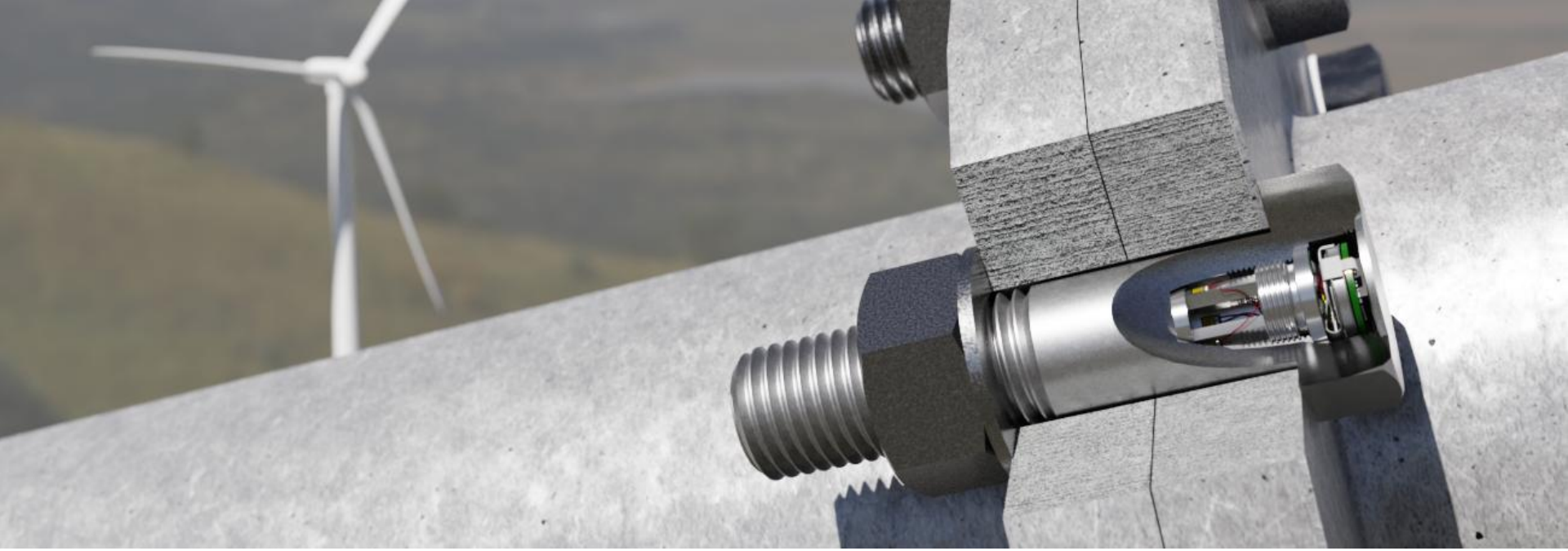




# Sensor-integrating screws for multi-axial force measurement

Funded by Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) - 551302077



Funded by



Deutsche  
Forschungsgemeinschaft  
German Research Foundation

Felix Herbst  
*TU Darmstadt*



Fabian Deeg  
*KIT*



# Project Partner Overview



Prof. Kupnik

*Felix Herbst*



Prof. Matthiesen

*Julian Peters  
Fabian Deeg*

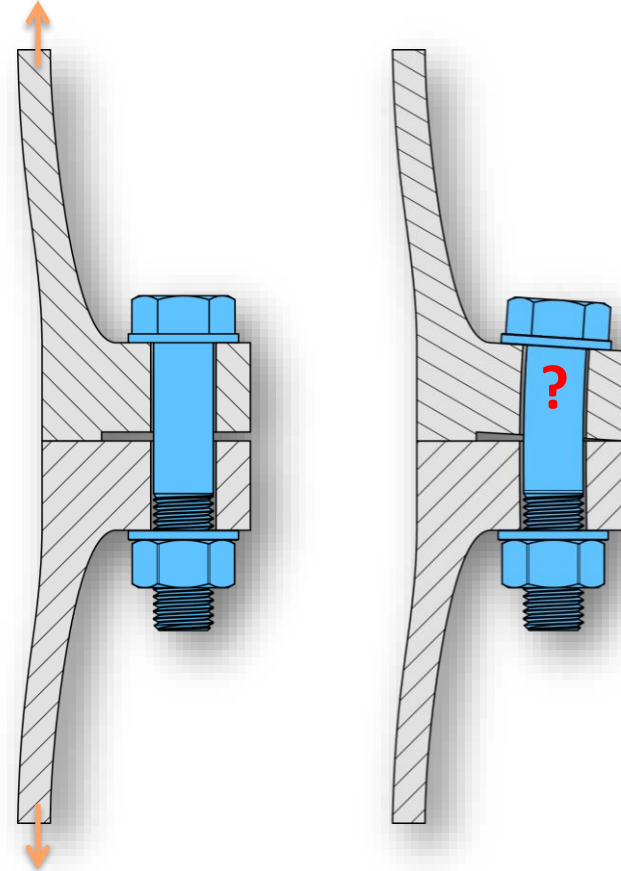
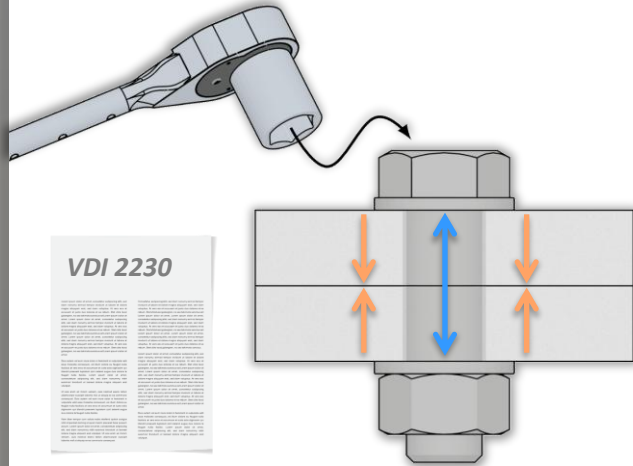


Prof. Hofmann

*David Riehl  
Dirk Leickner*



# Motivation

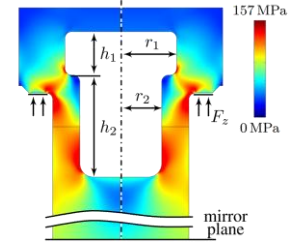


# 1<sup>st</sup> Project Phase

Design Methodology

Sensor Design

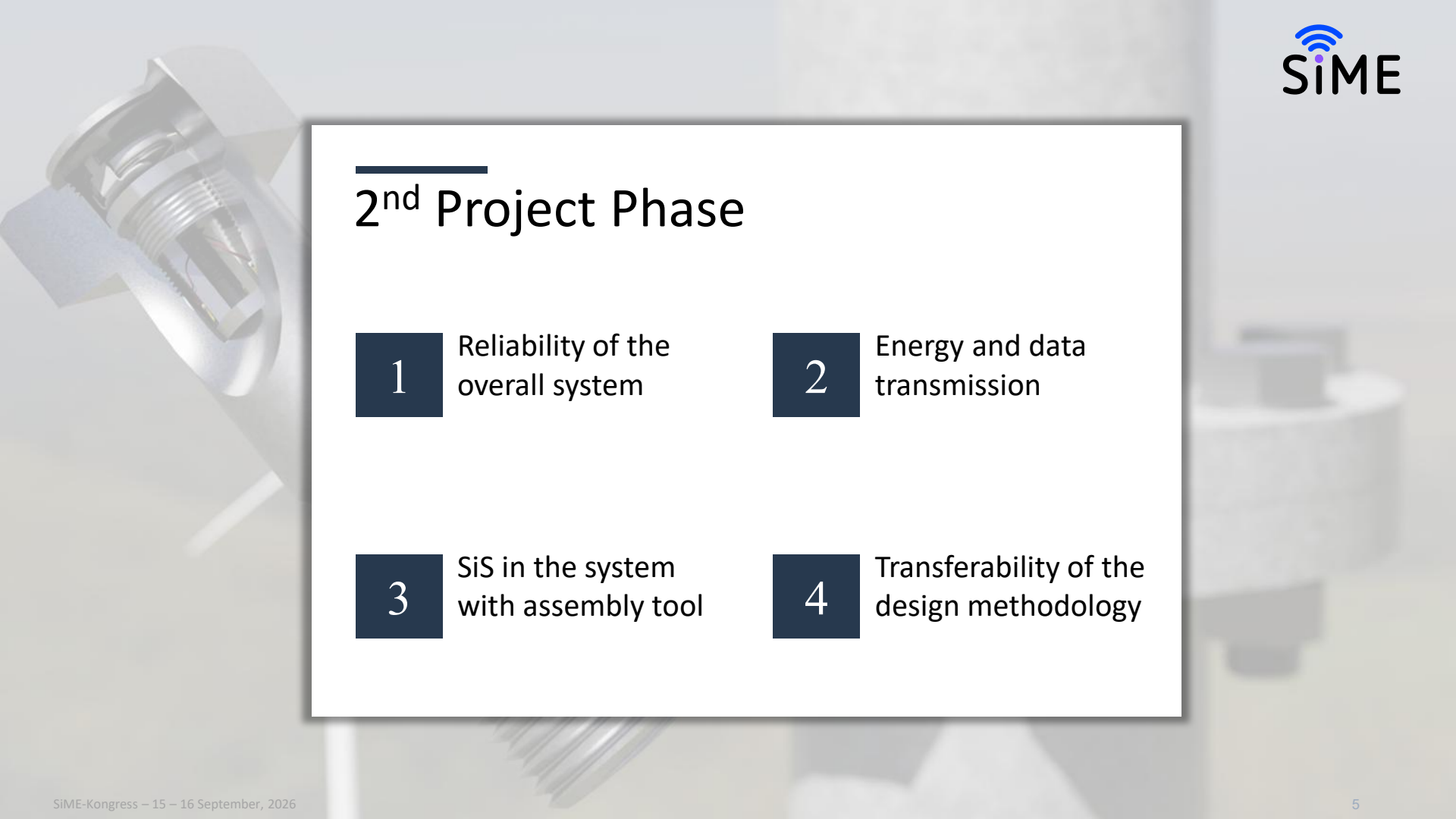
Electronics



Pictures taken from own publications:

F. Herbst et al., "Sensor-Integrating Bolt for Multiaxial Force Measurement," in IEEE Sensors Journal, vol. 24., 2024, doi: 10.1109/JSEN.2024.3427833

D. Riehl et al. "Design of a sensor integrating bolt for multiaxial force measurement and development of a design methodology." Forsch Ingenieurwes 89, 2025 doi: 10.1007/s10010-025-00924-w

The background of the slide is a grayscale image of a mechanical assembly, possibly a valve or a connector, with various components and threads visible.

## 2<sup>nd</sup> Project Phase

1

Reliability of the  
overall system

2

Energy and data  
transmission

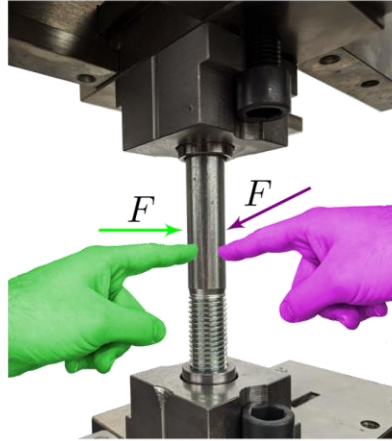
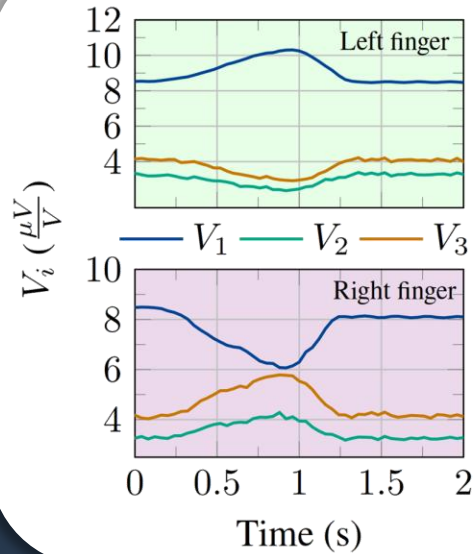
3

SiS in the system  
with assembly tool

4

Transferability of the  
design methodology

# Multiaxial force sensor

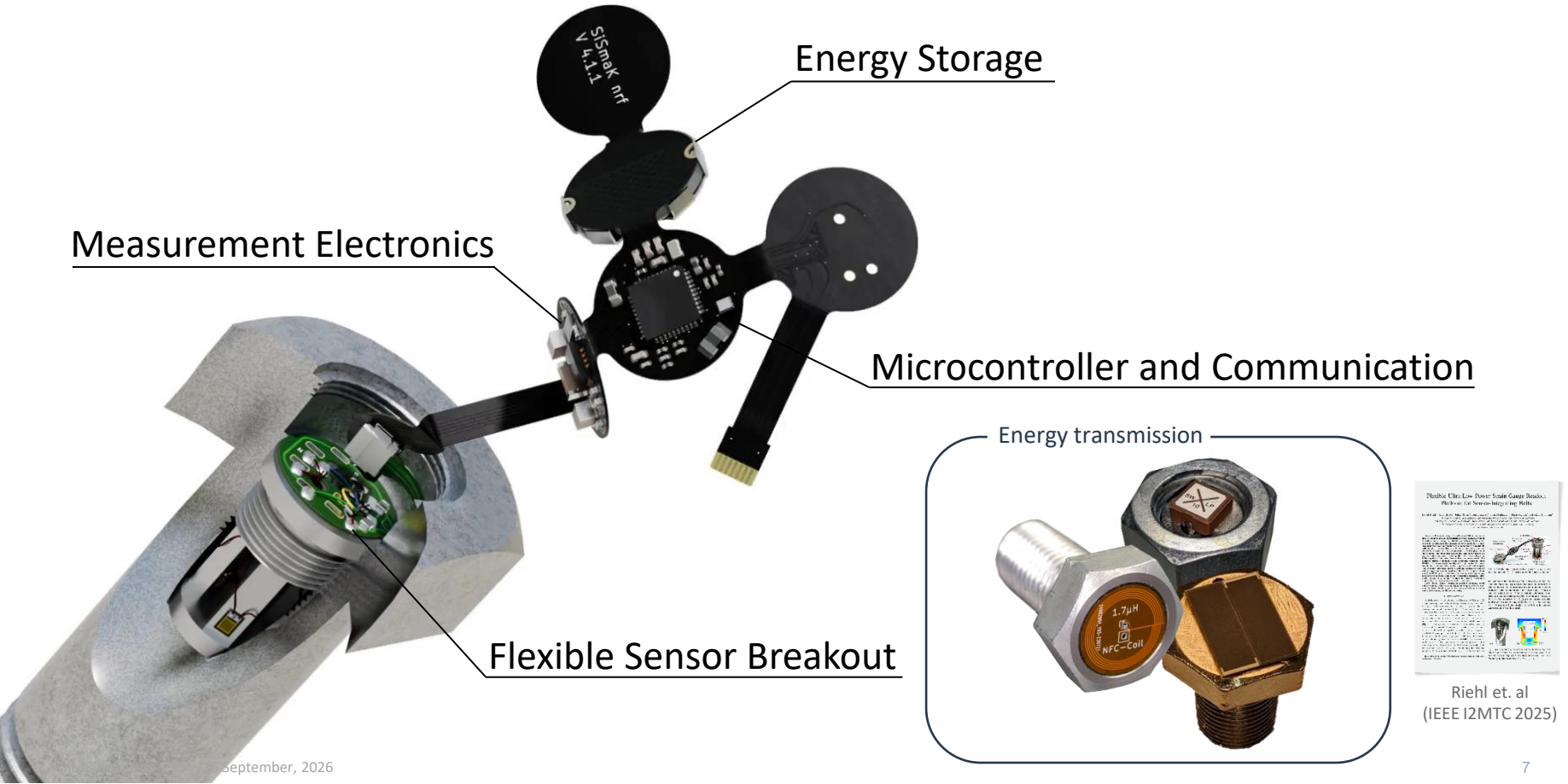


Herbst et. al  
(IEEE Sensors 2024)

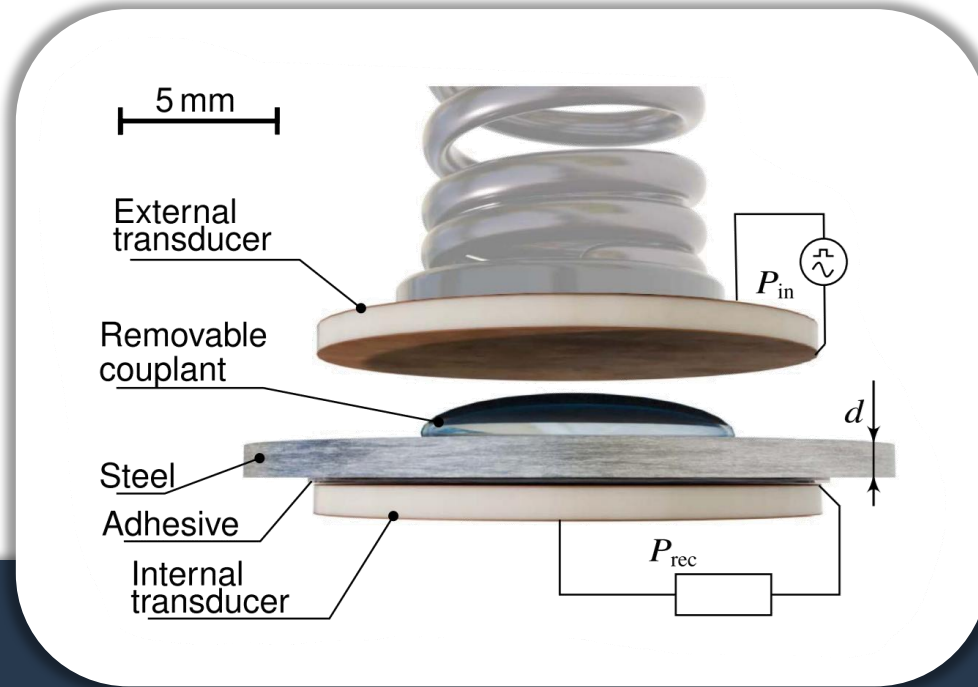
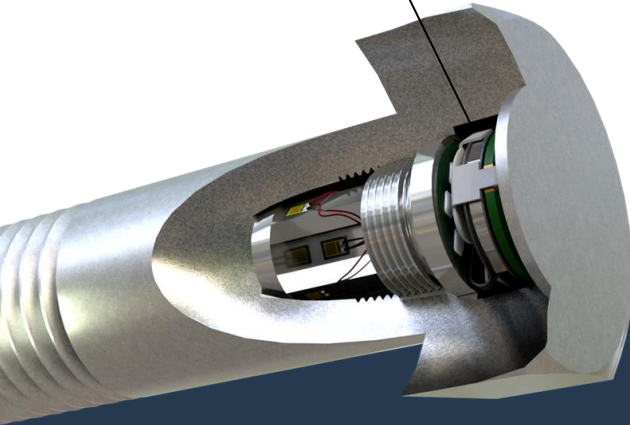
## Sensor characterization

|                |                              |
|----------------|------------------------------|
| Lin. error     | $\pm 0.11\%$<br>$\pm 0.82\%$ |
| Hys. error     | $\pm 0.52\%$<br>$\pm 1.53\%$ |
| Overall error: | <b>2.5%</b>                  |





Fully Encapsulated

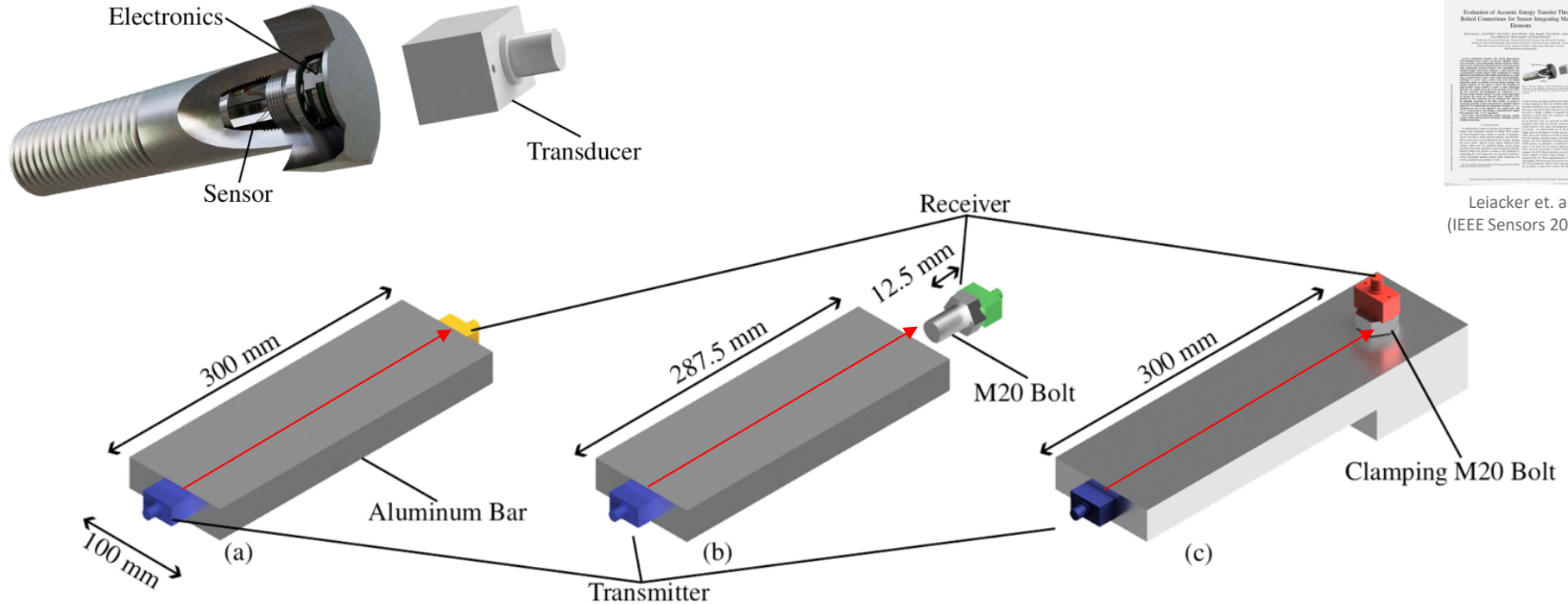


Suppelt, Herbst et. al  
(IEEE Sensors Letters, 2025)

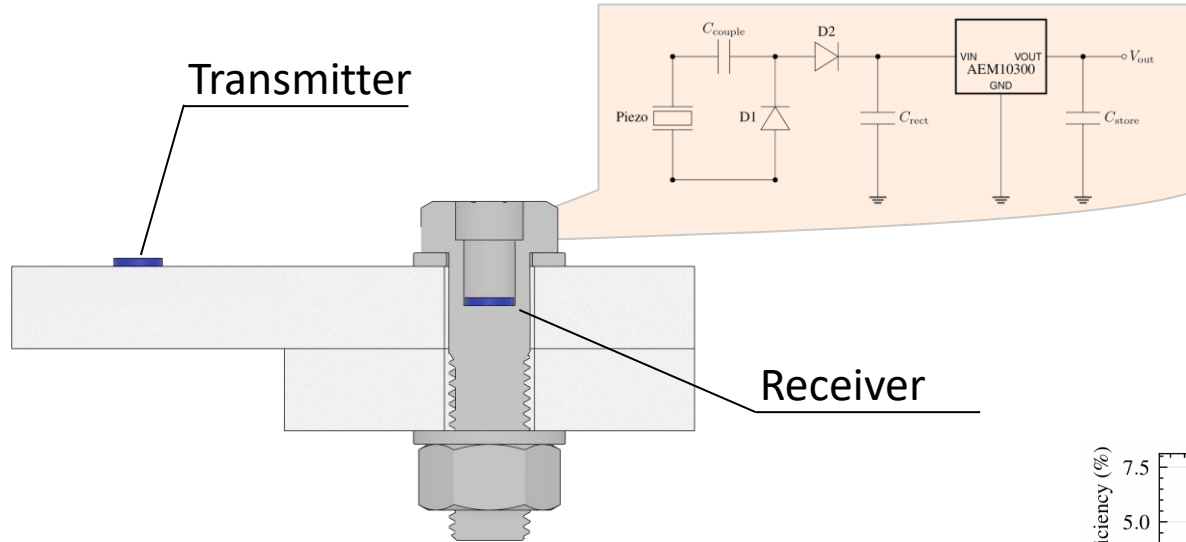
# Communication and Energy Transmission



Leiaccker et. al  
(IEEE Sensors 2025)



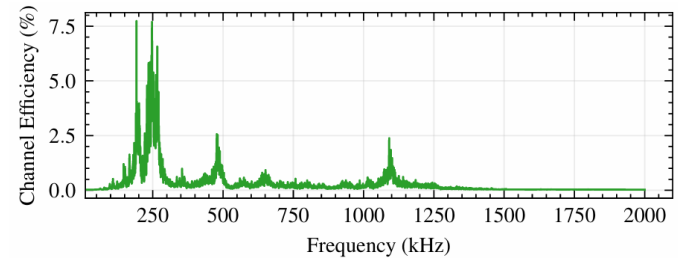
# Transmission Channel Analysis



Leiacker et. al  
(IEEE Sensors 2026)



**Radial vs axial mode**





## On demand

*Measure only when triggered  
e.g. Readout at maintance, after incidents*

## Continuous

*Measure in regular intervals  
e.g. every minute  
Application: Optimal maintance intervals*

## Assembly

*Directly control and document  
axial (and bending) forces*



## Bolt tightening

- Preload is the force generated by tightening the bolt
- Bolted joints need a preload force to clamp parts together
- Common tools control torque or angle (auxiliary variables), not preload
- Friction, joint stiffness, and environmental conditions make preload only estimable from torque or angle
- Same tool setting can lead to substantially different preload

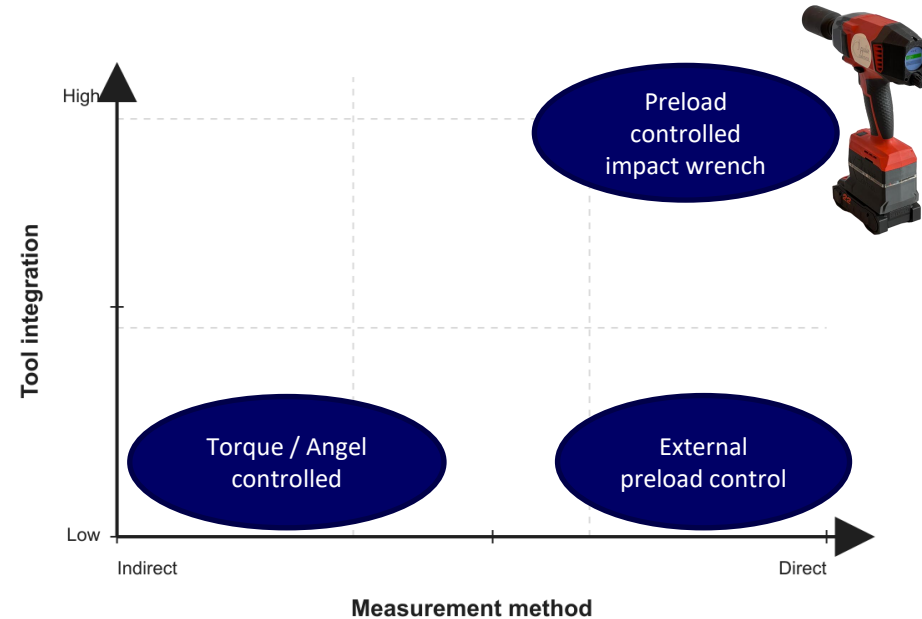
## Vision: Direct preload feedback

- Preload measured in a sensor-integrating bolt (M20)
- Feedback to e.g., impact wrench
- Automatic shut off at preload setpoint
- Lower assembly uncertainty compared to common standards
  - VDI 2230 indicates preload distribution of up to approx.  $\pm 60\%$  for conventional impact tightening

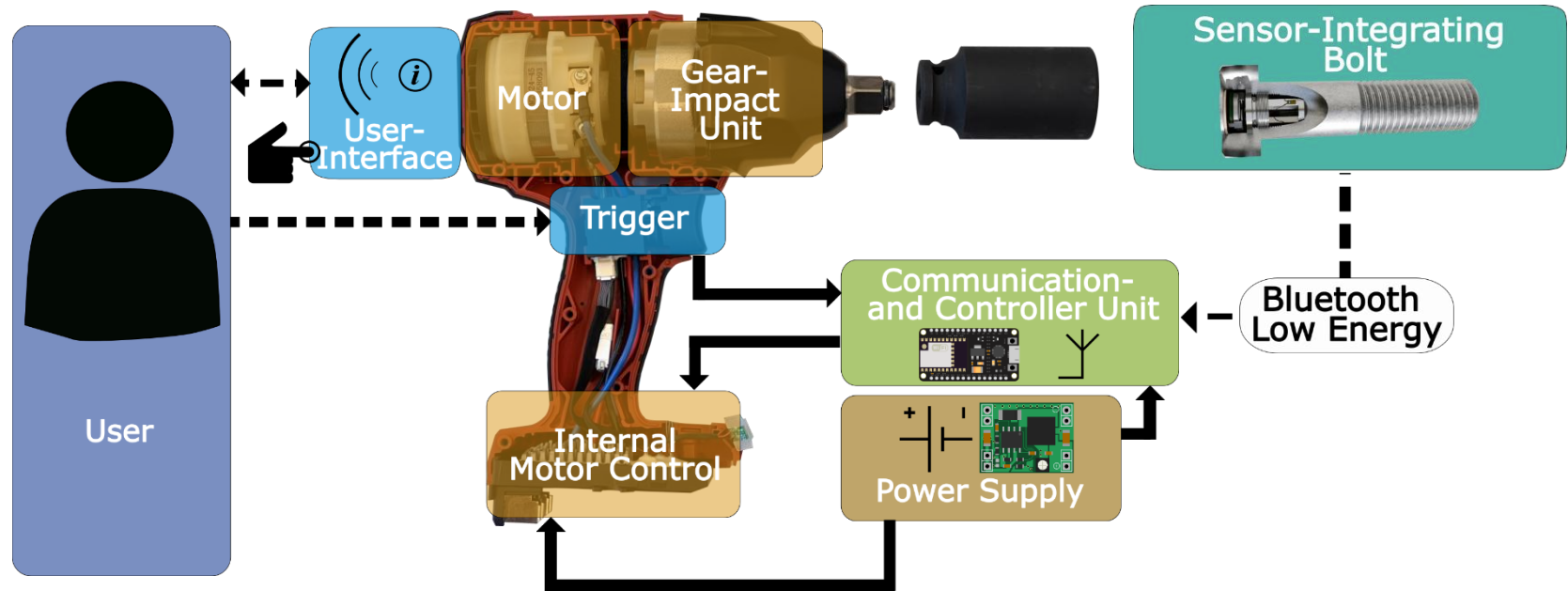


# Direct preload tightening is not measurable with a power tool

- Controlled by auxiliary variables: tool integrated, but no preload measurement
- Direct preload sensing: accurate, but external or separate
- Impact wrench tightening: practical, but high preload uncertainty

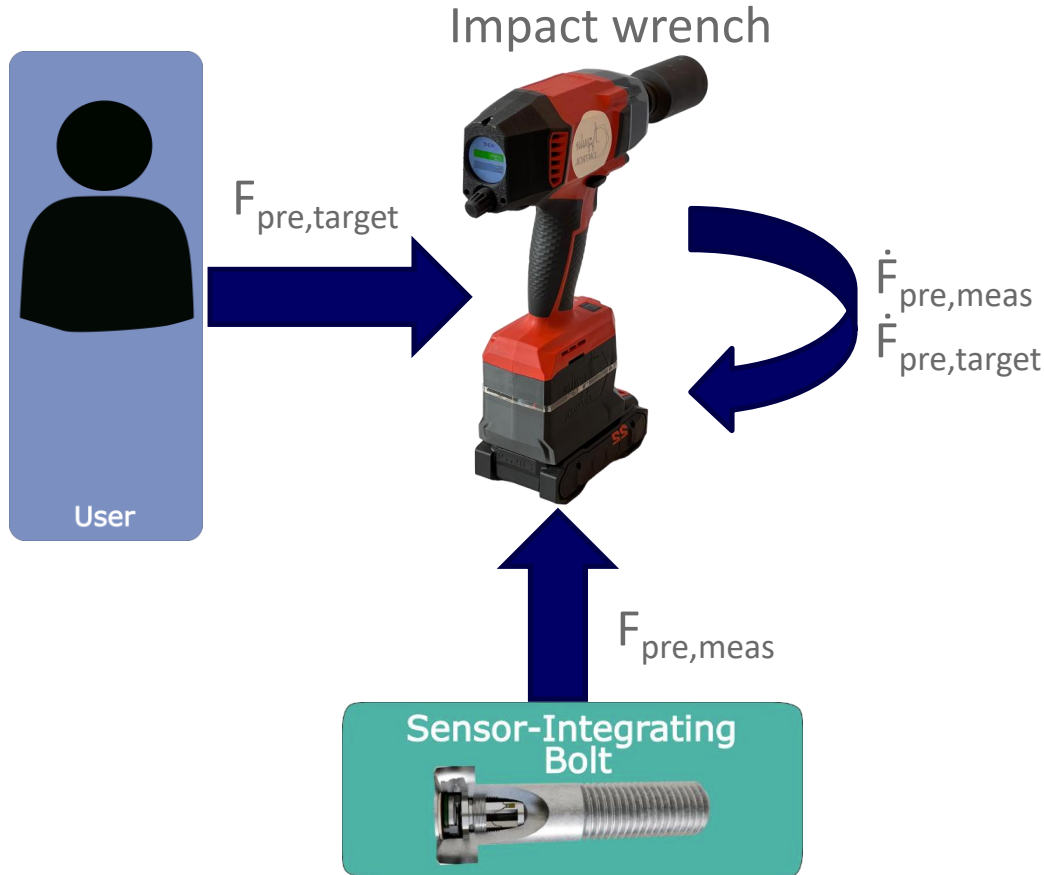


# Method: System architecture



- Measurement and BLE transmission < 4 ms
- Controller update every 10 ms
- Impact interval approximately 17 ms

# Hardware prototype for closed loop impact tightening



## Current prototype

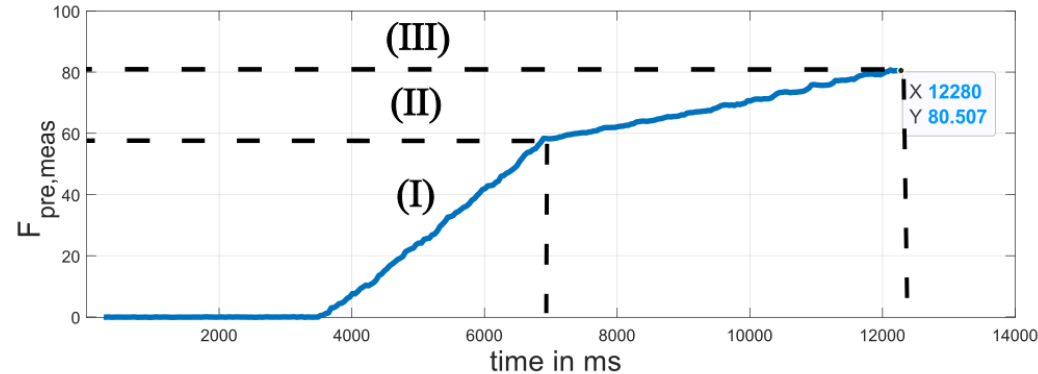
- M20 sensor-integrating bolt
- Preload feedback via Bluetooth Low Energy
- Tool-specific inline controller
- Manual operation remains available

## Legend:

|                           |                        |
|---------------------------|------------------------|
| Measured preload:         | $F_{pre,meas}$         |
| Rate of Measured Preload: | $\dot{F}_{pre,meas}$   |
| Preload setpoint:         | $F_{pre,target}$       |
| Rate of preload setpoint: | $\dot{F}_{pre,target}$ |

# Control strategy: Three-stage preload control

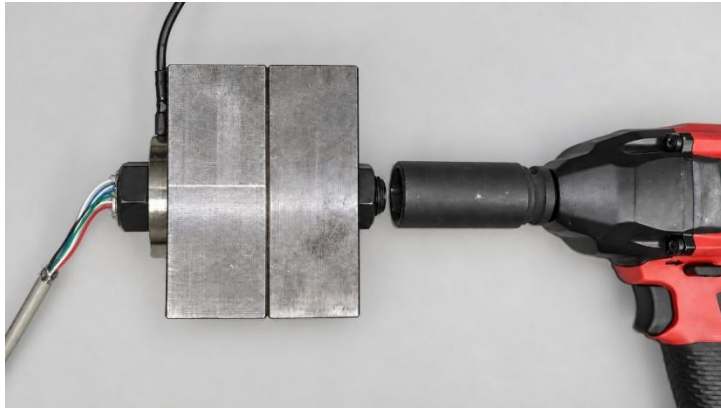
- The controller modulates the trigger signal to regulate the preload rate
- **Mode I: Fast tightening**  
Below 70% of the target preload  
Target preload rate: 20 kN/s
- **Mode II: Slow tightening**  
Above 70% of the target preload  
Target preload rate: 4 kN/s
- **Mode III: Automatic shut-off**  
At the target preload



Measured example tightening run at 80kN setpoint

## Validation Setup:

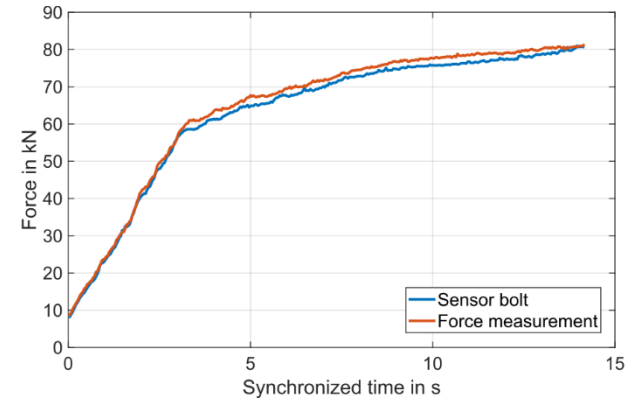
- SiS signal used for feedback control
- Force measurement ring recorded the preload independently



Test configuration with an independent force measurement ring. SiS power supply and signal processing remain external.

## Results:

- SiS and reference signal show comparable force progression
- SiS remained operational throughout all 47 tightening cycles



Representative tightening cycle at 80 kN setpoint

# Proof of Concept: Repeatable setpoint attainment using SiS feedback

## Test conditions:

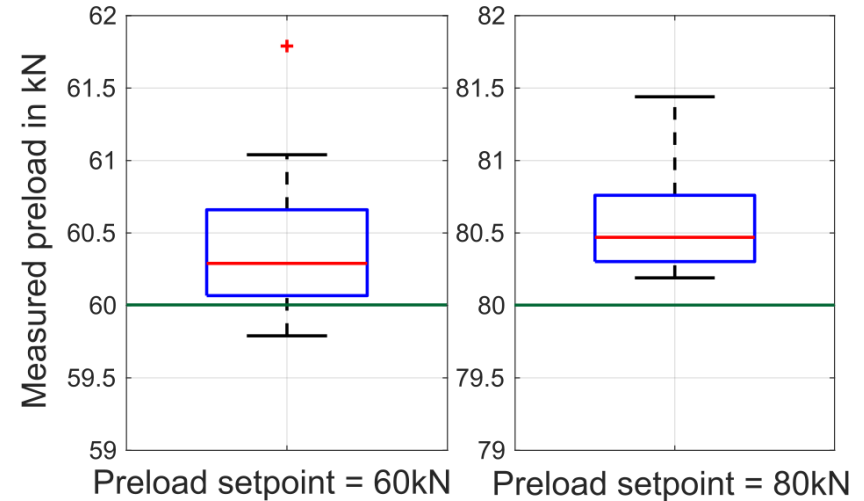
- 13 tightening cycles per setpoint
- Target preload: 60 kN and 80 kN
- Closed-loop control based on the SiS signal

## Control results:

- 60 kN: distribution < 3%
- 80 kN: distribution < 2%
- Automatic shut-off at target preload

## Context:

- VDI 2230: Impact tightening can show up to approx.  $\pm 60\%$  preload distribution



# Direct preload feedback enables controlled impact tightening

- Direct preload control: The measured preload serves as the shut-off criterion, reducing reliance on the friction-dependent torque–preload relationship.
- Repeatable setpoint attainment: Target preloads of 60 and 80 kN were reached consistently under laboratory conditions.
- Independent comparison: The SiS and force measurement ring showed comparable preload progression and final values during nut-side impact tightening.



Direct preload feedback reduces  
reliance on the friction-dependent  
torque–preload relationship.

Project Website



**Fabian Deeg, M.Sc.**  
KIT – Karlsruhe Institute  
of Technology



**Felix Herbst, M.Sc.**  
TUDa – Technical  
University of Darmstadt



**Dirk Leiacker, M.Sc.**  
TUDa – Technical  
University of Darmstadt



**Dr.-Ing. David Riehl**  
TUDa – Technical  
University of Darmstadt