

Evolution of Sensor-Integrating Gears: Advances to Achieve Autonomous Condition Monitoring Towards the Whole Service-Life

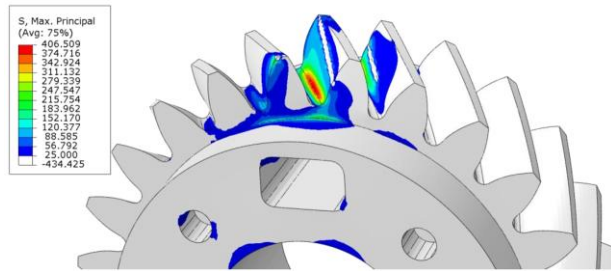
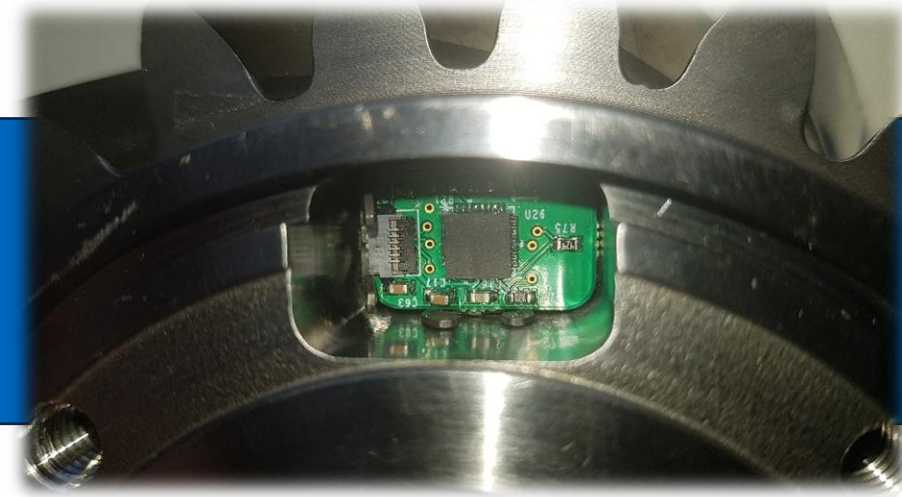
Sensor-Integrating Machine Elements Congress
Darmstadt, 15.09.2026

Project Leads: Prof. K. Stahl, Prof. B. Vogel-Heuser, Prof. F. Derbel – TUM/HTWK
Associates: Dr.-Ing. M. Otto, E. Knoll, D. Hujo-Lauer, C. Wagner, R. Fromm, R. Thiel

Motivation on Sensor-integrating Gears

In-situ measurement in the gear:

- Improved detection of physical processes!
- Detect damage where it occurs!
- No detour via bearing or housing!



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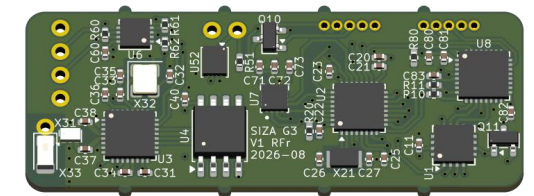
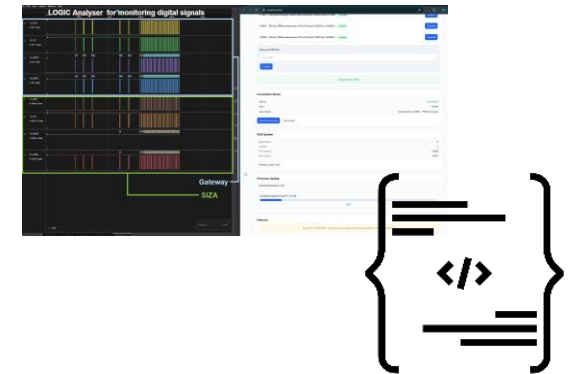


E. Knoll, M. Otto, C. Wagner, R. Fromm, B. Vogel-Heuser, F. Derbel, and K. Stahl, "Effect of sensor position and grade on gear damage classification," *Forschung im Ingenieurwesen*, 2026.

- **Integration & load-bearing capacity** — General function must be preserved
- **Autonomous power supply** — No external energy supply provided
- **Wireless data transmission** — Communication from within the metallic housing
- **Environment & robustness** — Oil, temperature, centrifugal acceleration, vibration
- **Adaptive operating strategy** — Strategy adapts with the gear's service life
- **Networking & IT integration** — Multi-SiME Integration and connectivity

Outline

- **1. Mechanics** — *Prof. K. Stahl / Dr.-Ing. M. Otto / E. Knoll, FZG TUM*
 - Cavity design in the gear structure
 - Testing under realistic conditions on the test rig
- **2. Software** — *Prof. B. Vogel-Heuser / D. Hujo-Lauer / C. Wagner, AIS TUM*
 - Adaptive operating strategy over gear lifetime
 - Update-over-lifetime & networking
- **3. Electronics** — *Prof. F. Derbel / R. Fromm / R. Thiel, HTWK Leipzig*
 - SiME gateway
 - Electronics & sensor integration in the gear
- **4. Data Analysis** (*interdisciplinary*)
- **5. Networking**
- **6. Outlook**



Adaptive SiZA-Framework for Load-carrying Capacity

SiZa - Gen1



SiZa - Gen2

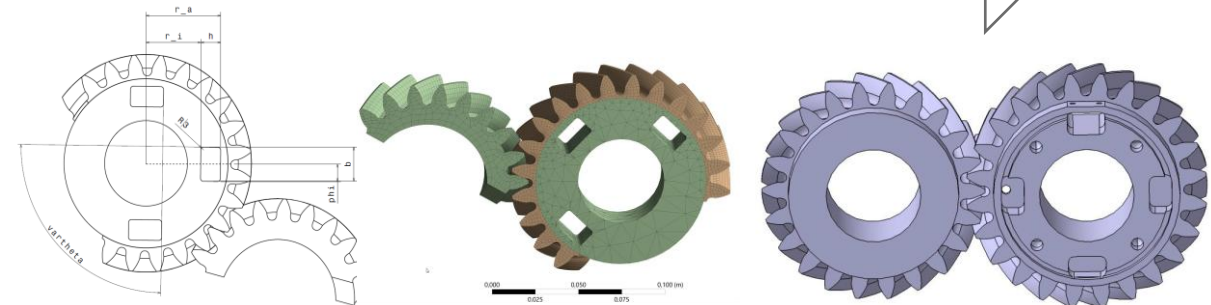


SiZa – Gen3



Parametrized CAD/FEA model of the SiZA gear (Catia V5 + ANSYS Workbench) for the structured analysis and design of sensor-cavity influence on tooth-root load-carrying capacity

At higher amount of cavities: Spoke between cavities is more critical than tooth root which is not considered within ISO 6336-3



S. Miliczek, "MA: Untersuchung des Einflusses der Sensorintegration auf die Tragfähigkeit und Ableitung einer analytischen Vergleichsauslegung," Master Thesis, Technical University of Munich, 2025.

Overview of SIZA Software

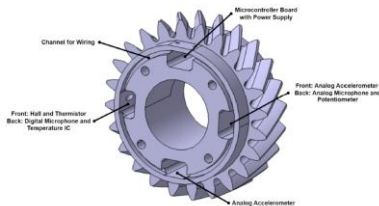
Web Application



SIME-Gateway

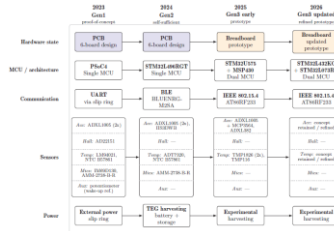


SIME

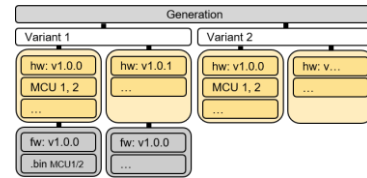


Versioning

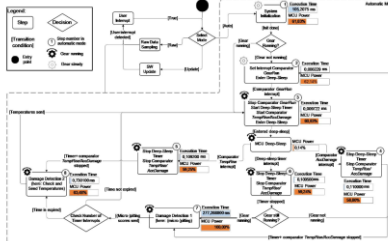
Versioning – HW/FW versions IDs



Versioning – Tracks HW/FW Variants

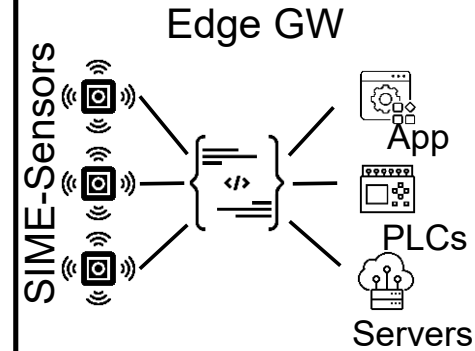
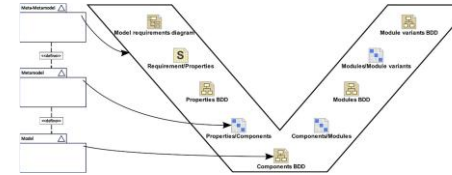


Operating Strategy

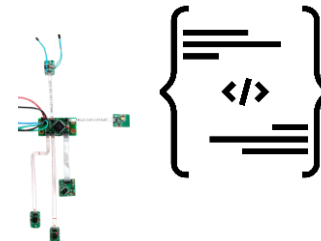


Functionality

SIME Integration – Model-based Dashboard

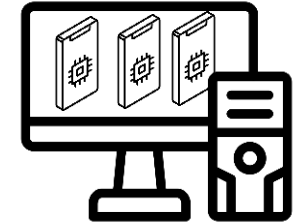


Embedded Sensors

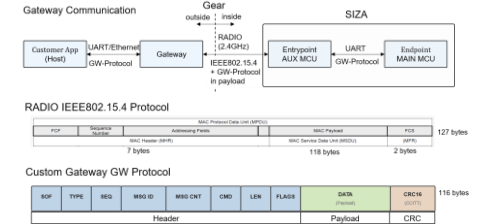


Updates

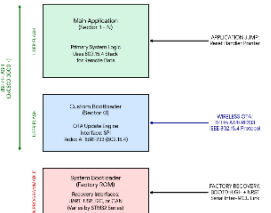
OTA Updates – Firmware Delivery



OTA Updates – Relays Updates to Sime

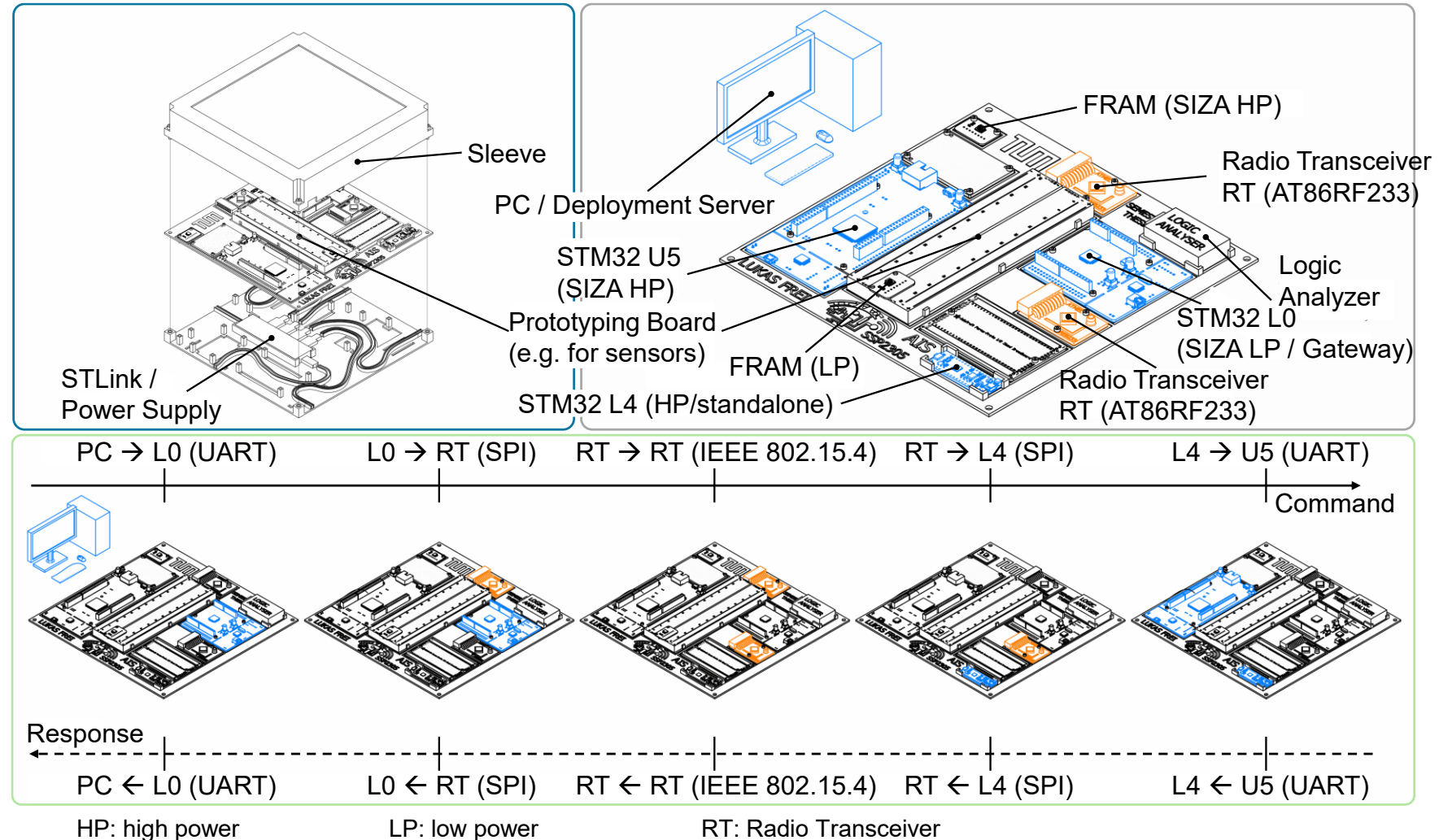


OTA Updates – Receives OTA wirelessly



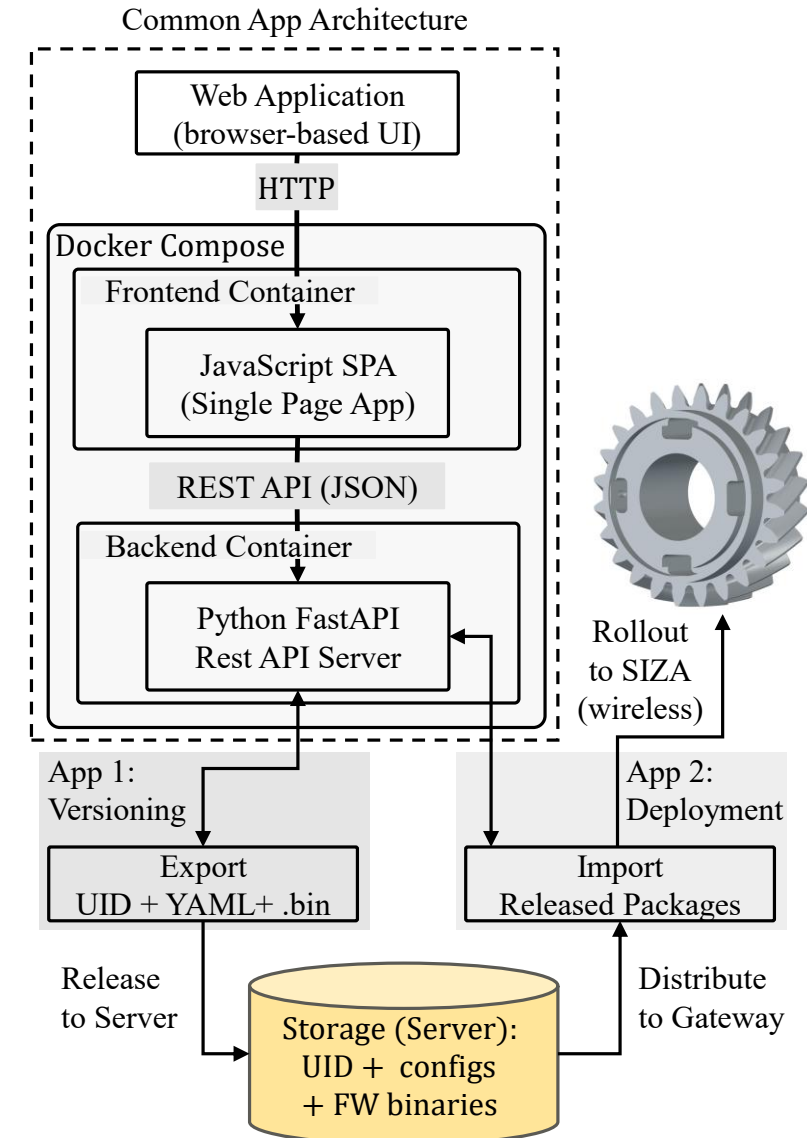
Test Setup for SiME Integration

- Demonstrator developed to verify the **complete pipeline**
- Covers **microcontrollers** used, as well as the **intended communication protocols**
- **Flexibly adaptable** and testable, so **other SiME** can be integrated
- **Goal:** establish suitable test method for OTA and versioning concept for **verification before actual deployment** on the test setup



Versioning and Over the Air Updates

- **Challenge:** Updatability requires consistent versioning of hardware and software changes as well as their mutual dependencies
- **Versioning scheme:** Four-level hierarchy, *Generation*, *Variant*, *Hardware Version*, *Firmware Version*, each following semantic versioning
- **Architecture:** Central server distributes releases; gateway verifies compatibility and controls the wireless update rollout to the gear
- **Context enrichment:** Unique version & device IDs enable retrospective enrichment of measurement data with context information
- **Benefit:** Seamless traceability across multiple SIZA generations with minimal energy and data overhead



C. Wagner, L. Frei, D. Hujo-Lauer, R. Fromm, E. Knoll, M. Otto, K. Stahl, F. Derbel, and B. Vogel-Heuser, "Versioning Concept for Wireless Sensor-integrating Gears as Evolving Updateable Embedded Systems," IEEE IECON, 2026.

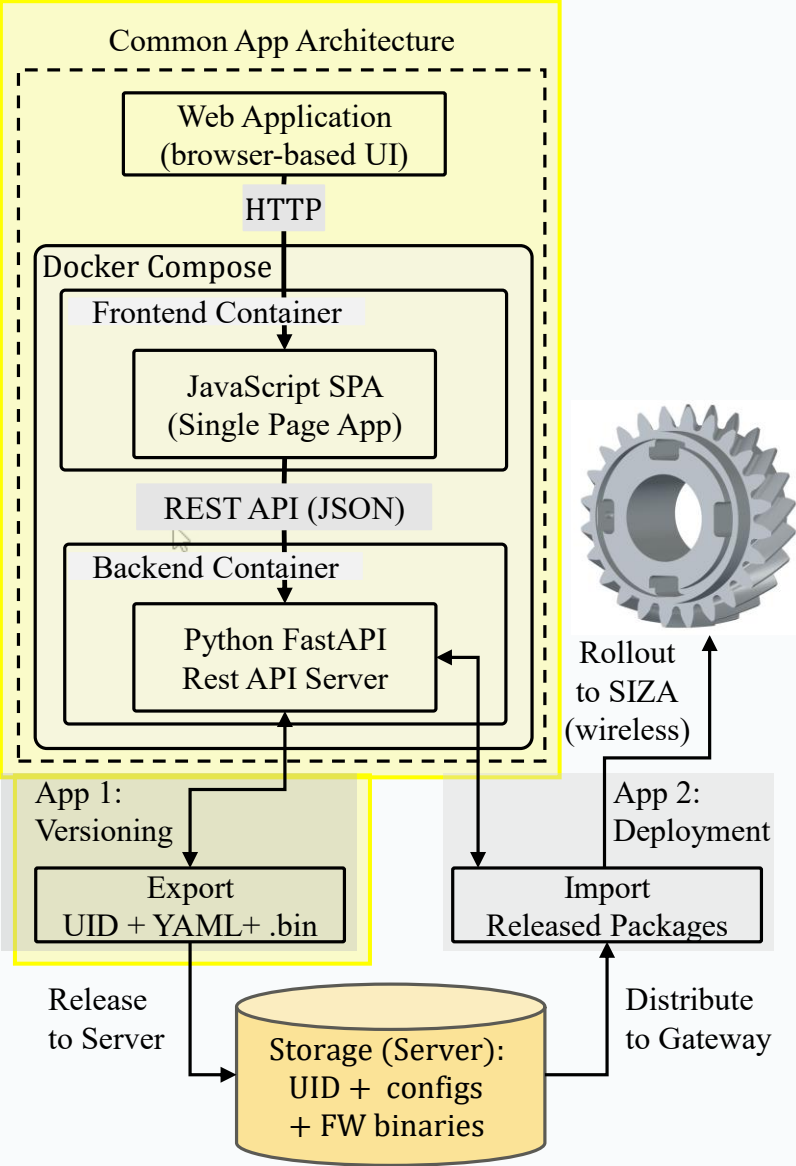
Help & Documentation

Welcome to the IoT Device Configuration Manager. This documentation explains the concepts, workflow, and architecture of the system.

Expand All Collapse All

- 1. What is SIZA?
- 2. What is a Generation?
- 3. What is a Variant?
- 4. What is a Hardware Version?
- 5. What is a Firmware Version?
- 6. Why This Classification?
- 7. What is a Component Type?
- 8. What is a Component (Module)?
- 9. Configuration Workflow Overview
- 10. How to Export Configuration
- 11. Program Architecture - Directory Structure
- 12. App Structure - Windows and Subwindows
- 13. How a Window/Subwindow is Implemented
- 14. How to Add a New Window (Step-by-Step Guide)

Title



FileEditViewCaptureMeasureHelp

LOGIC Analyzer for monitoring digital signals

D4L0_SCK
SPI - Clock

D5L0_CS
SPI - Enable

D7L0_MOSI
SPI - MOSI

D6L0_MISO
SPI - MISO

D1L4_SCK
SPI [1] - Clock

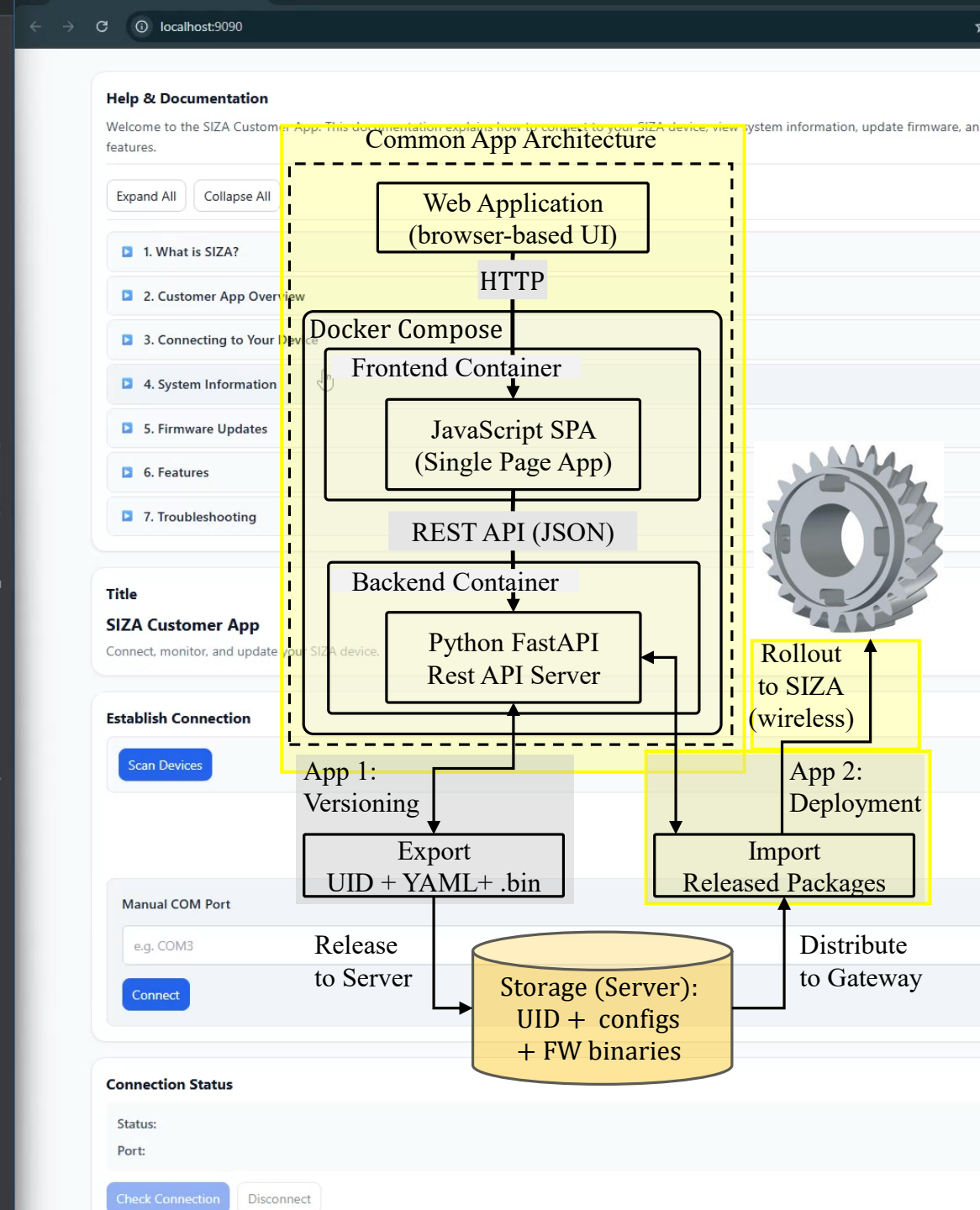
D3L4_CS
SPI [1] - Enable

D0L4_MOSI
SPI [1] - MOSI

D2L4_MISO
SPI [1] - MISO

Live

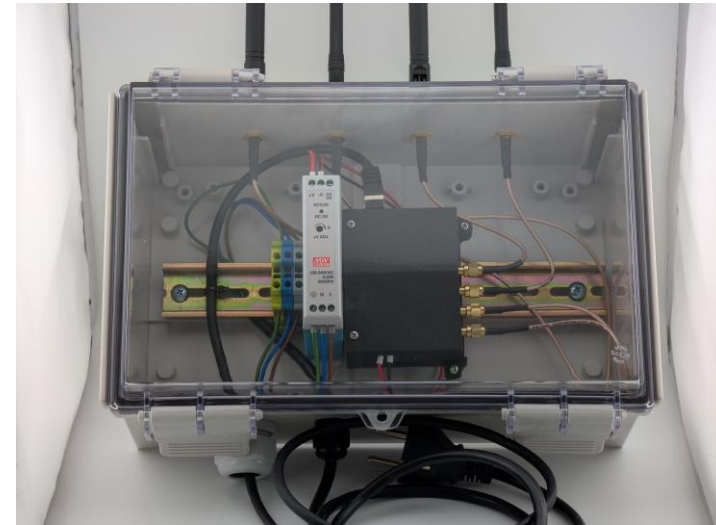
Memory0 MB



Multi-SiME Gateway

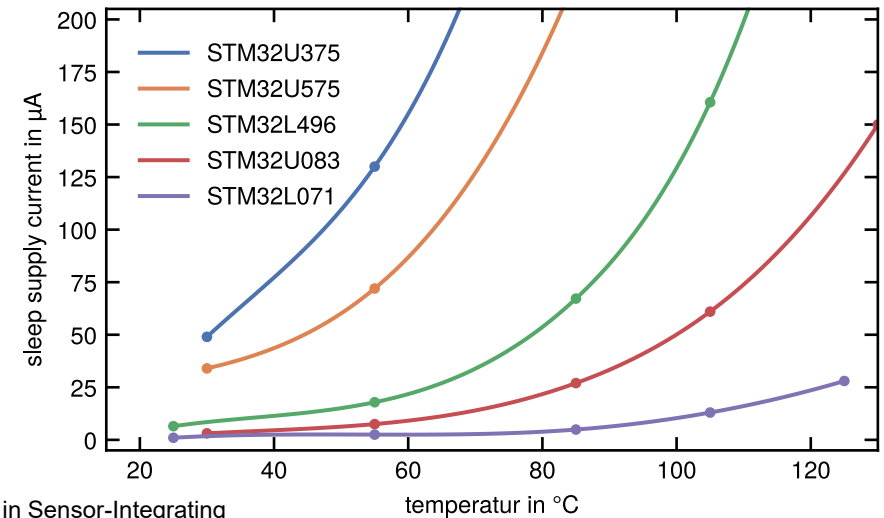
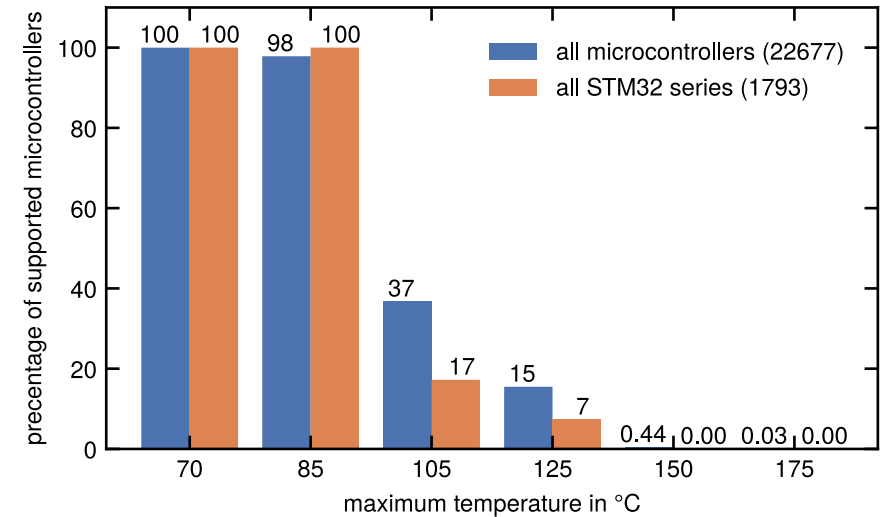
A foundation for scalable, open interaction among a wide variety of SiME in an industrial setting

- Shared gateway: coordination of data and data streams
- Flexibility thanks to a multi-protocol architecture:
 - Use of 2.4 GHz systems with high data rates and
 - 868 MHz systems, which are integrated deeper into the machine structure or transmit over longer distances
- Modular Design: Standardized modules ensure minimal costs, adaptability, and scalability



SiME Design for High Temperatures

- **SIZA Gen 3 electronics support 125°C**
- Implications for Component Selection:
 - Significantly fewer components available (e.g., microcontrollers)
 - Higher leakage currents at high temperatures (exponential increase)
 - Dedicated RF transceivers instead of SoC (system on a chip)
- High temperatures and long battery lifetime
 - Consistently turning off components that are not needed
 - Small microcontroller for scheduling
 - High-power microcontroller for calculations
 - Proprietary communication protocol with sensor-initiated communication and long sleep periods (IEEE 802.15.4 PHY)

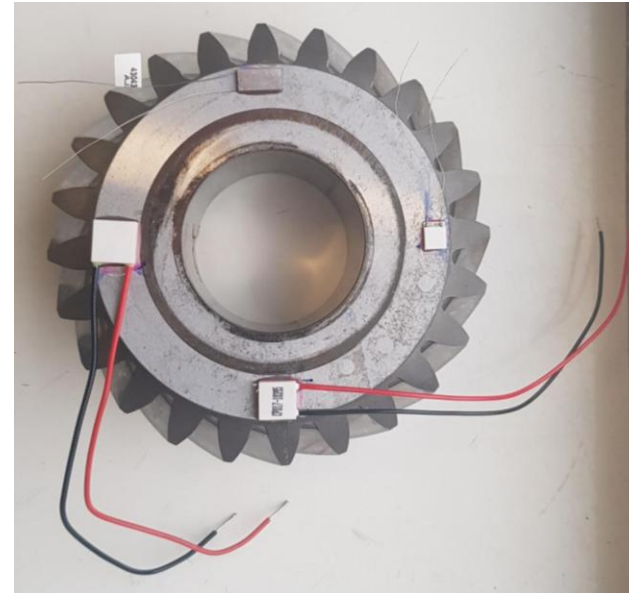


R. Fromm, E. Knoll, C. Wagner, K. Stahl, B. Vogel-Heuser, and F. Derbel, "The Hidden Cost of Performance: How Microcontrollers Drain Batteries in Sensor-Integrating Machine Elements," in Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 2026.

Thermal Energy Harvesting

Practical tests on the FZG test rig

- Temporary installation on the front face of the gear, based on simulations designed to achieve a maximum temperature difference at the harvester
- Four selected harvesters:
 - Adaptive MGM250-17-10-16
 - Tark Thermal Solutions 430437-508
 - Same Sky CP14-M
 - Same Sky CP017-10395
- Reliability problems with Same-Sky harvesters
- Harvester output dependent on torque, rotation speed, and positioning of oil injection
- Up to 3.5 mW of DC harvester output achievable
- **Enough energy to measure every 3.5 minutes**

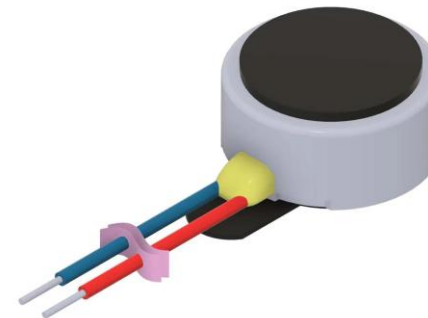


T. Kreutle, "Praktische Untersuchung des Einsatzes thermischer Harvester für die dezentrale Energieversorgung an Zahnrädern," Bachelor Thesis, Technical University of Munich, 2026.

Vibration Energy Harvesting

Practical tests on the FZG test rig

- Installation in axial cavities → Placement in the radial and circumferential directions
- Idea: Circumferential harvesting using a gravitational field reduces dependence on resonance frequencies caused by forced oscillations
- Two investigated harvesters:
 - Linear Pulse Touch Flat Vibration Motor (Aliexpress)
 - PUIaudio HD-LA0503-LW28 Vibration Motor



<https://www.mouser.de/de/ProductDetail/PUI-Audio/HD-LA0503-LW28?qs=%252BHhoWzUJg4JRddGDY3P1CA%3D%3D>



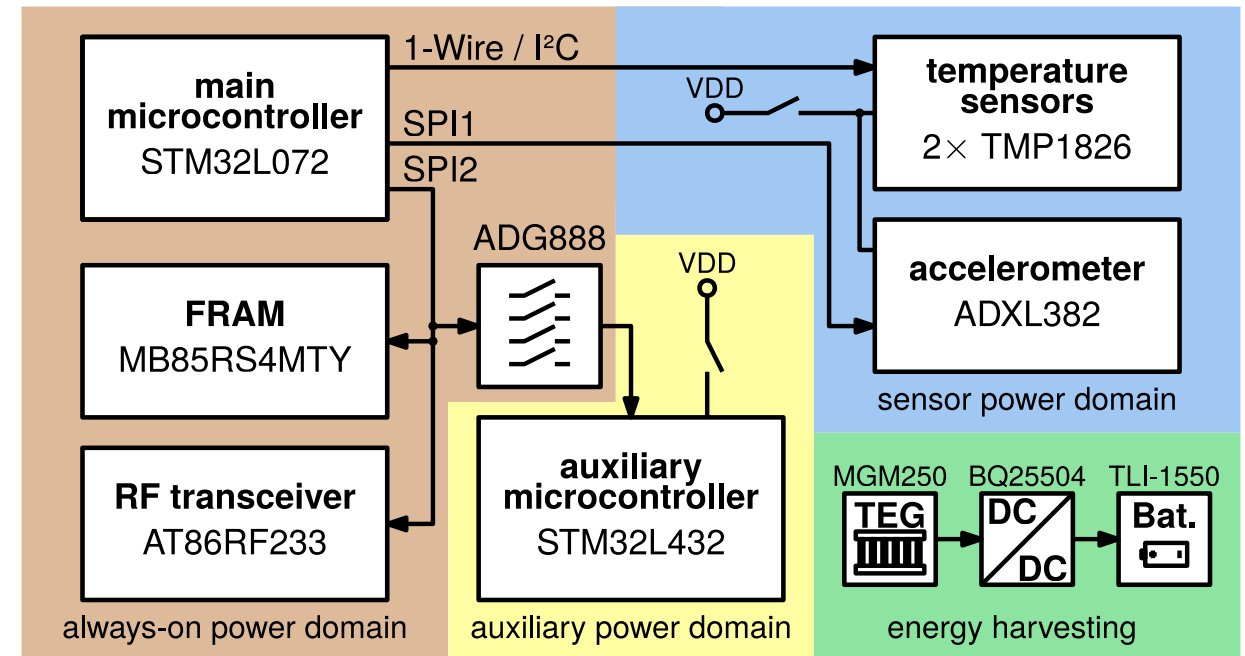
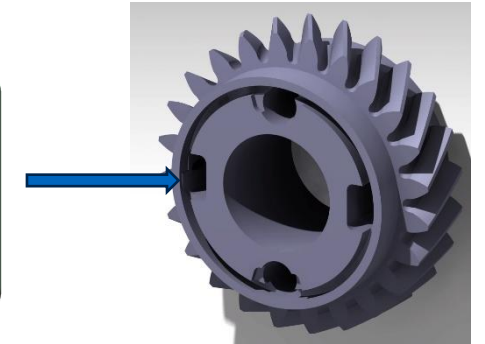
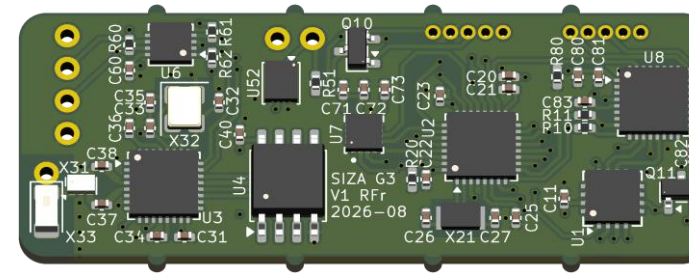
<https://de.aliexpress.com/item/1005006421331249.html>

➔ **Harvesters do not produce a meaningful amount of energy, nor do they produce more energy when in resonance**

SIZA Gen3 – More Efficient, More Powerful, and More Durable

Highlights of Gen3

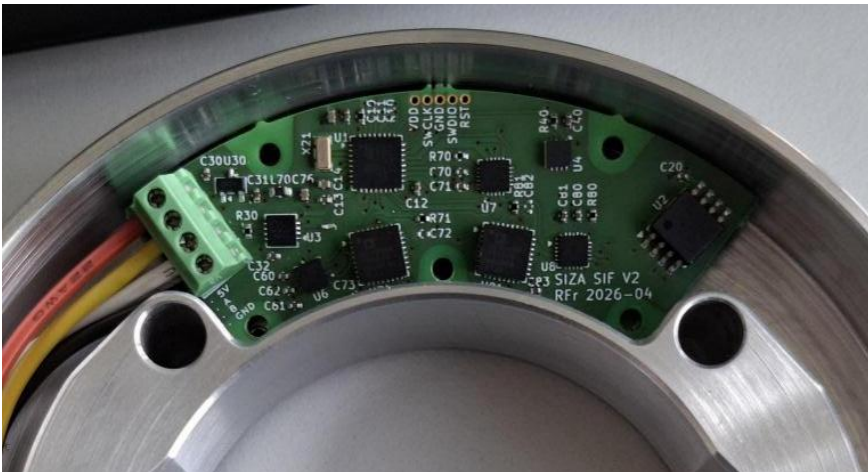
- Fully-specified for 125°C
- Package reduction: one cavity for measurement technology and evaluation
- Multi-processor architecture (switchable STM32L4)
- Optimized sensor technology:
 - Acceleration sensing
 - Digital temperature sensing
 - Shutdown logic for energy saving
- Increased robustness in power supply:
 - Energy harvesting
 - Batteries



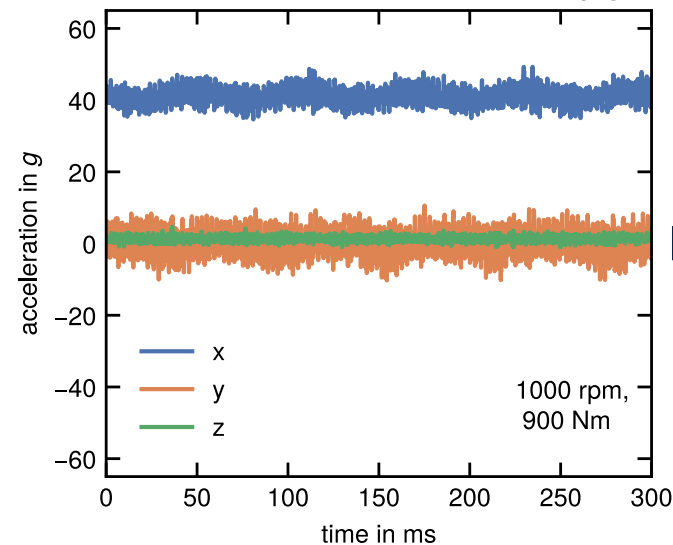
Experimental Validation

SIZA Sensor Interface – Testing advanced acceleration sensors

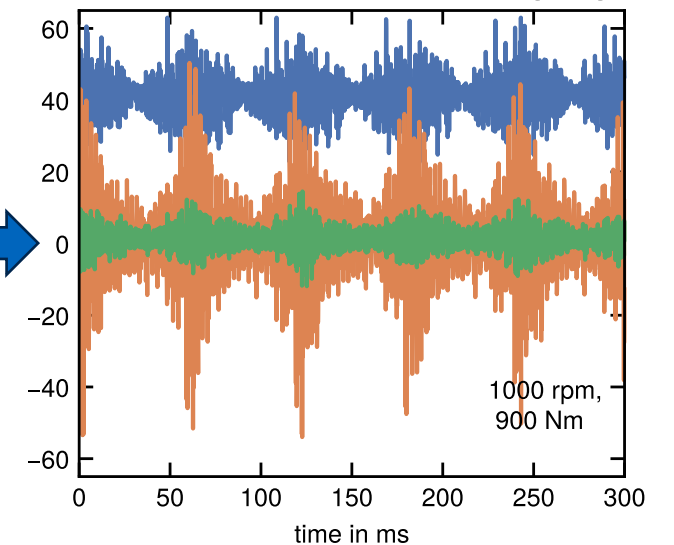
- Previous SIZA Gen 1+2 measurements using analog ADXL1003/5 sensors
- Tests with SIZA sensor interface PCB: ADXL382 digital three-axis sensor
- Goal: significant power consumption reduction and improved interference rejection at the cost of measurement range



ADXL382 time series with a healthy gear



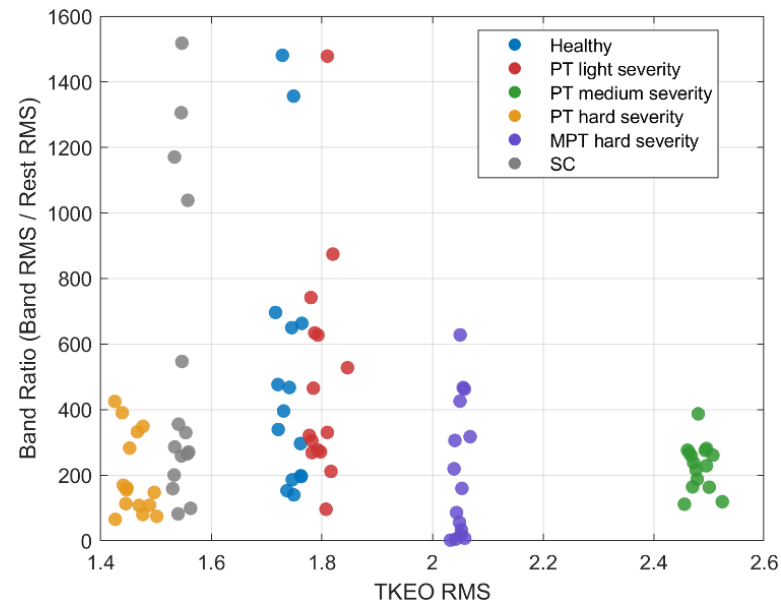
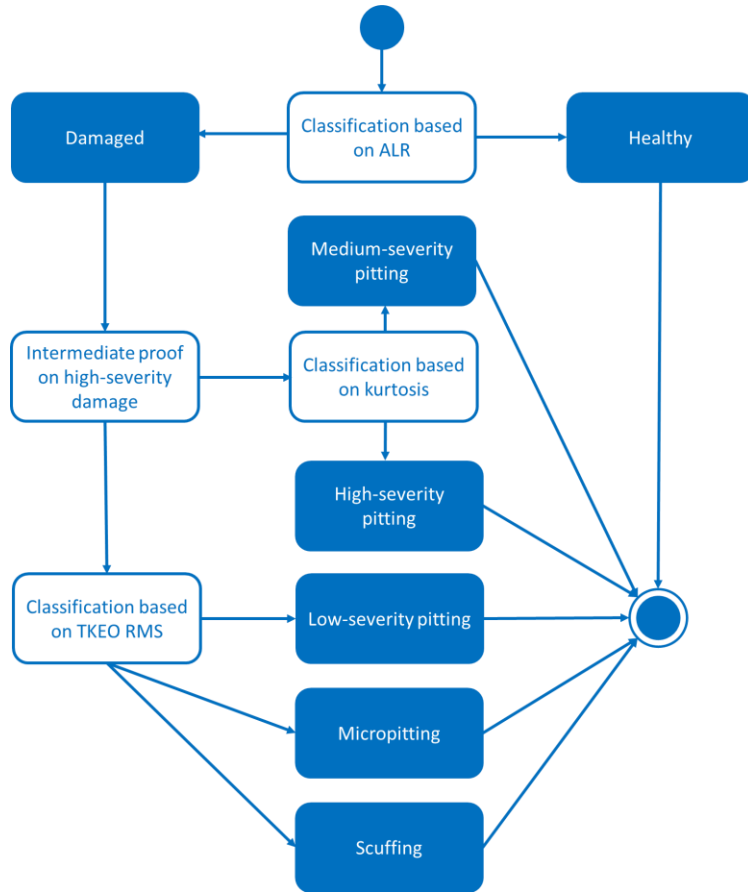
ADXL382 time series with a damaged gear



C. Wagner, R. Fromm, E. Knoll, M. Otto, K. Stahl, F. Derbel, and B. Vogel-Heuser, "Evolution of Sensor-Integrating Gears: Advances to Achieve Autonomous Condition Monitoring Towards the Whole Service-Life," *Forschung im Ingenieurwesen*, 2027.

Experimental Validation

SIZA Gen 1 – Damage classification based on decision tree

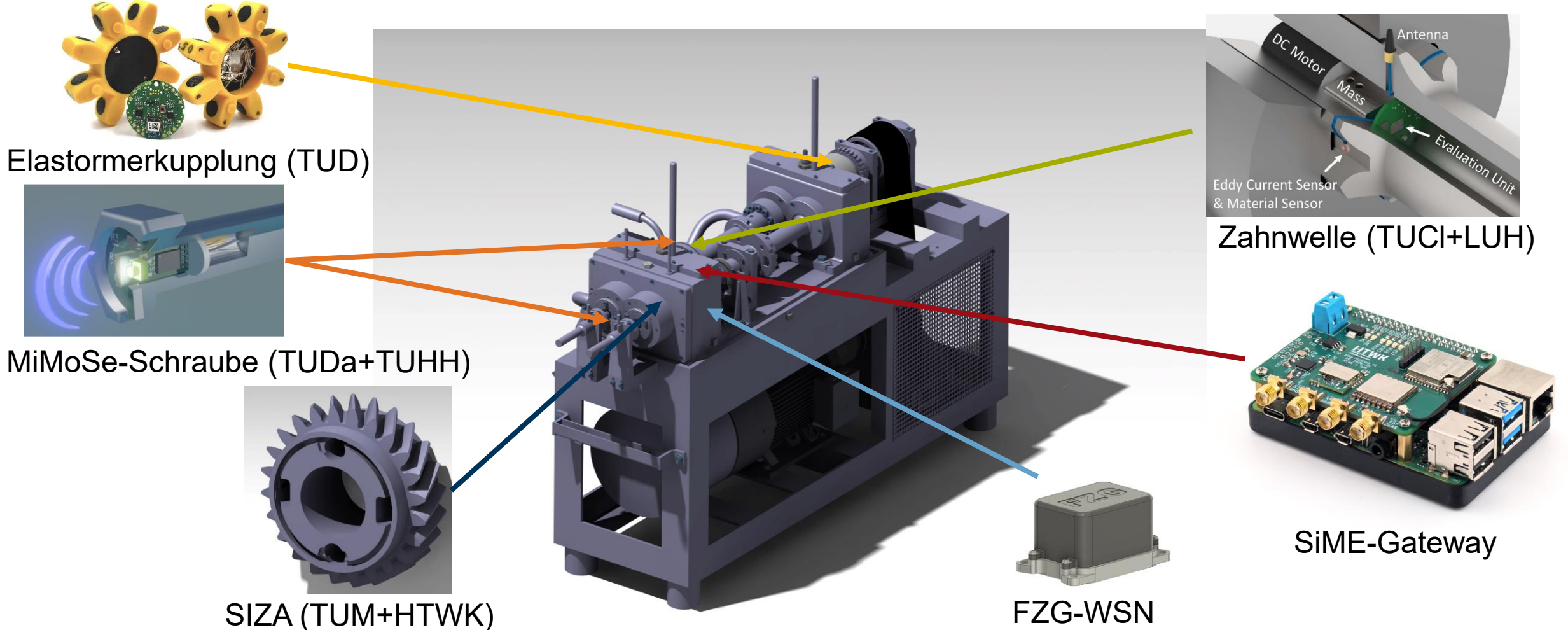


E. Knoll, S. Brunner, M. Otto, R. Fromm, C. Wagner, F. Derbel, B. Vogel-Heuser, and K. Stahl, "Low-Requirement Damage Classification Through Sensor-Integration in Gears," Mechanical Systems and Signal Processing (submitted – preprint published), 2026.

Preprint: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=6901100

SiME Networking at the FZG Gear Test Rig

Joint testing of the function and networking of various SiME under real-world conditions



Outlook

Let's Connect!

Interested in industry collaboration or academic exchange?
Reach out! We'd love to hear from you.

Next Steps:

- **Finalize SiZA Gen2 testing** — complete the remaining test campaign
- **SiZA Gen3 endurance testing** — validate temperature-based wear estimation
- **SiME networking on the gear test rig** — integrate and test
- **AI-based damage classification** — classification quality, and robustness
- **SiME modeling & modular firmware** — MBSE approach for SiME Software

