Zephyr® Project
Developer Summit

Prague, June 26-30, 2023

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Developer Summit

Build a Pump Monitor for Railway Applications with Zephyr OS

Oliver Völckers, BeST Berliner Sensortechnik GmbH
ov@bestsensor.de

Jonas Remmert, Phytec Messtechnik GmbH
j.remmert@phytec.de

Zephyr Project Page:
https://www.zephyrproject.org/portfolio/best-sensor-pump-monitor-jrov2201/

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Oliver

- Introduction to Pump Monitor Project (6 slides)
- Can AI recognize Wastewater Flow? (6 slides)

Jonas

- Overview Firmware (4 slides)
- Power Management (4 slides)
- Lessons Learned (3 slides)

Questions

Improve Deutsche Bahn ICE Train Toilets

Toilets in ICE high-speed trains out-of-order. Why?

- wastewater tank full, because not properly emptied
- pump failures go unnoticed, too late to fix toilet

Task: develop a system that monitors wastewater pump quality automatically and reliably

Mobile Monitoring System

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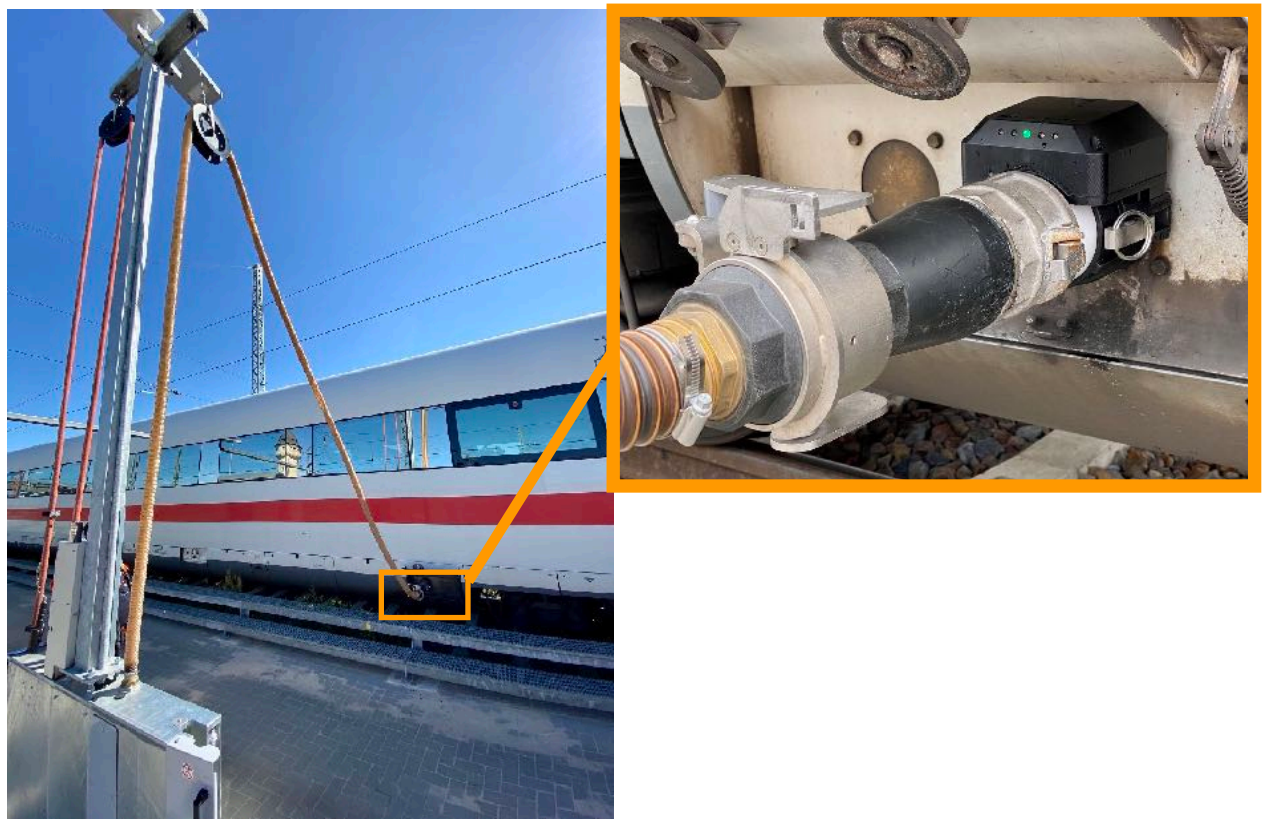
Pumps equipped with adapter including sensor system

No energy supply, no wired connection, no gateway

Connection via mobile radio

Battery-operated system



Application-Specific Sensor

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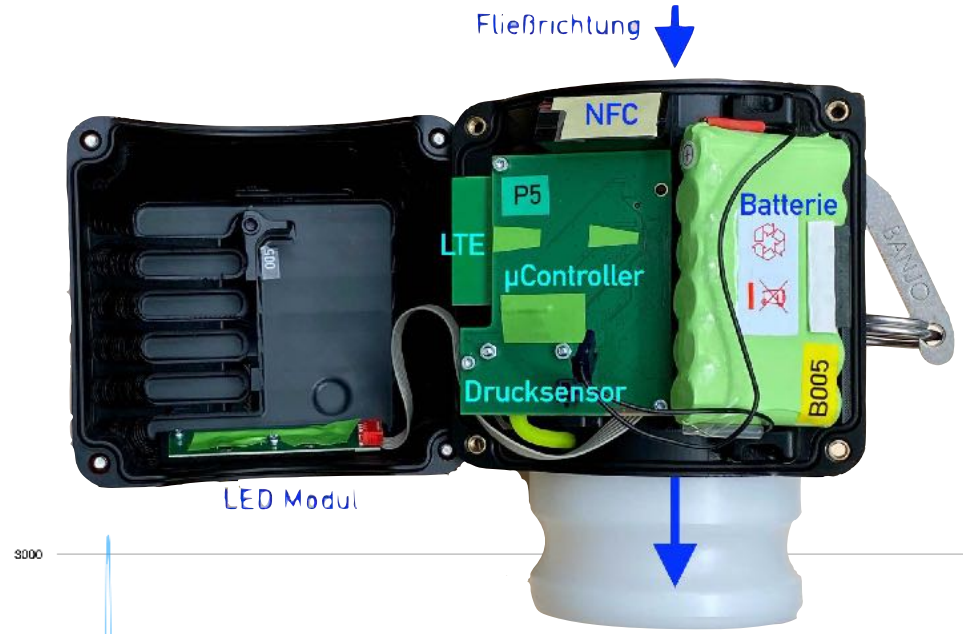
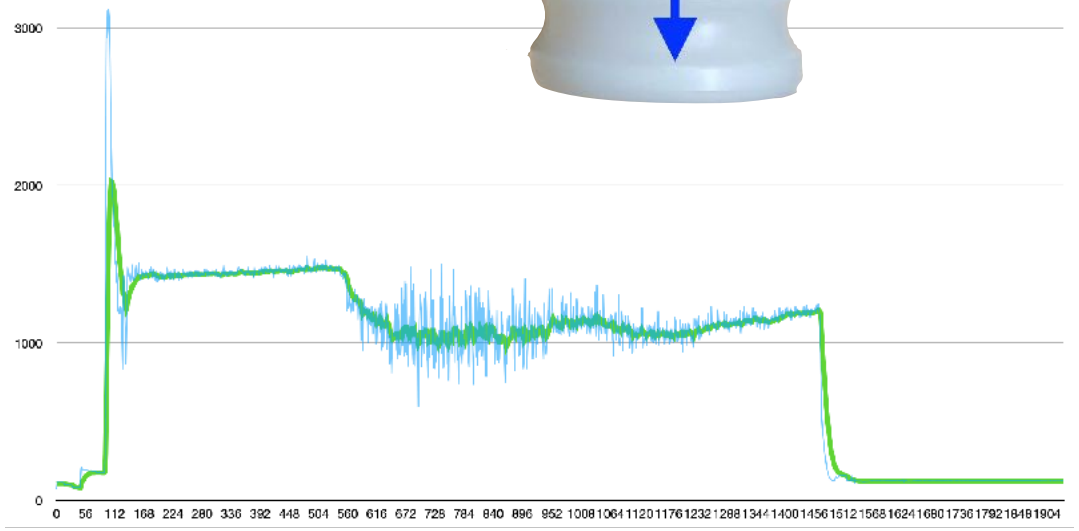
Conventional flow meters cannot differentiate between empty pipe and blockage

Waste water is variable: solid, liquid, gas, mixtures such as foam

Hybrid sensor: pressure, vibration, temperature, humidity sensors





Why we use Zephyr RTOS

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Bare-metal programming -> too small
Full PC OS like Linux -> too big
Zephyr RTOS -> right size

Multitasking of peripherals
real-time operation
energy saving

Nordic Semiconductor nRF9160 SDK
based on Zephyr

Open Source

https://www.zephyrproject.org/products-running-zephyr/

Results

We developed a monitoring system that detects and reports failures automatically

Result now (June 2023): series of 36 modules in 24/7 operation for over one year

More than 50,000 deposits analysed, unambiguous detection, immediate reporting of failures

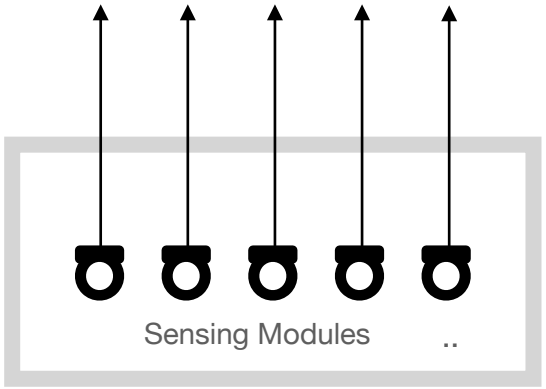
Embedded Signal Processing: Cloud vs. Edge

Cloud Computing

- requires only simple nodes
- all data collected into the cloud
- powerful central processing, but must be online

Edge computing

- processing performed locally
- keeps traffic low
- can handle interrupted connections
- cloud functions optional



Detect Wastewater Flow with Machine Learning?

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Input

- training data
- with annotations

Output

- model that associates patterns

Decisive factors:

- training data must be extensive
- distribution must be homogenous

ML example: iPhone iOS 16.5.1 search for "Hund" (dog)

Homogenous Distribution?

For ML to work, training data must reflect the universe

- if yes, fine (A)
- if not, failure (B)
- if sometimes, results are mixed (C)
- often, we do not know – example: pump monitor

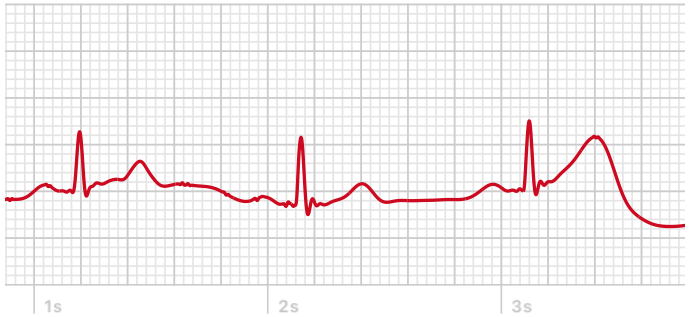
Image Source: Thomas R. Schwarz / Wikipedia

A B C

Domain-Specific Knowledge Helps

Example: ECG

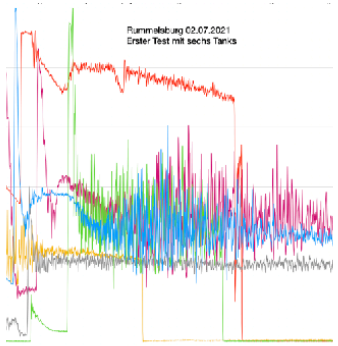
- reflects activity of heart
- experience of medical experts



ECG example (OV, Apple Watch)

Example: Pump monitoring

- knowledge about wastewater
- reflects water flow
- changes with temperature etc.



Real-world experience counts

- AI does not replace human knowledge

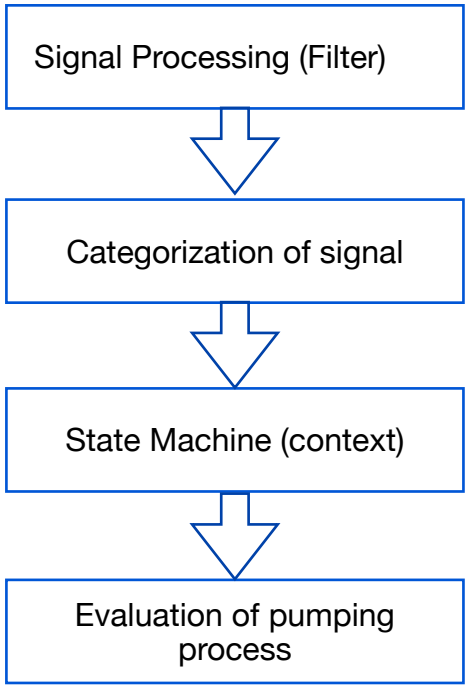
Real-time Signal Processing

Pattern recognition

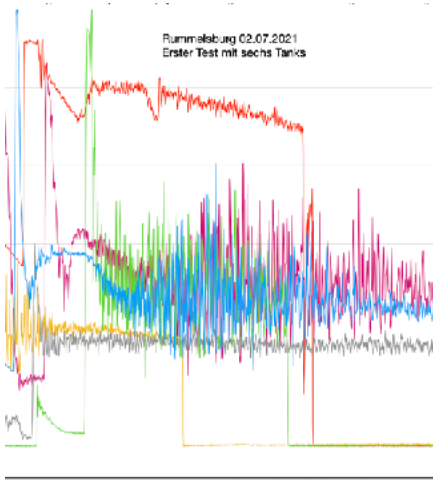
- do it as early as possible
- use all available processing power
- must be fast enough to always catch up with sensor data stream

Use adequate resolution

- more is not always better
- reduce frequency if possible



Pump monitor example



Continuous signal

Explanation Component

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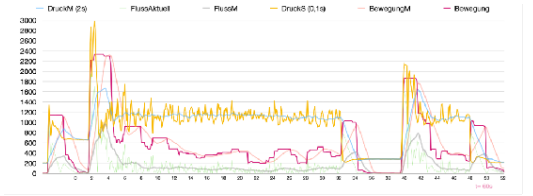
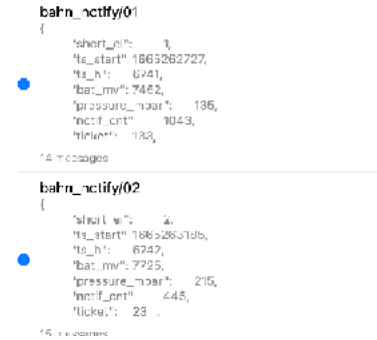
Traditional AI is black box

- training cannot be traced
- why does horse appear as dog?!
- errors unacceptable for medical & security



Pump monitor example



WHY?

Explanations can be provided

- rules for filtering can be documented
- logic of conclusions can be traced
- rationale can be generated automatically!

Because

- pumping duration >10s
- no longer breaks
- always minimum pressure of xyz mBar

Summary: Embedded Signal Processing

Signal processing is hard

- there are no shortcuts
- good algorithms require years of experience
- excellent algorithms are precise and fast

Domain knowledge

- is required for an excellent system
- without domain knowledge, system has prejudice
- AI helps to build knowledge base, but not sufficient

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Pump Monitor: Zephyr Firmware Application

- Overview Firmware
- Power Management
- Lessons Learned

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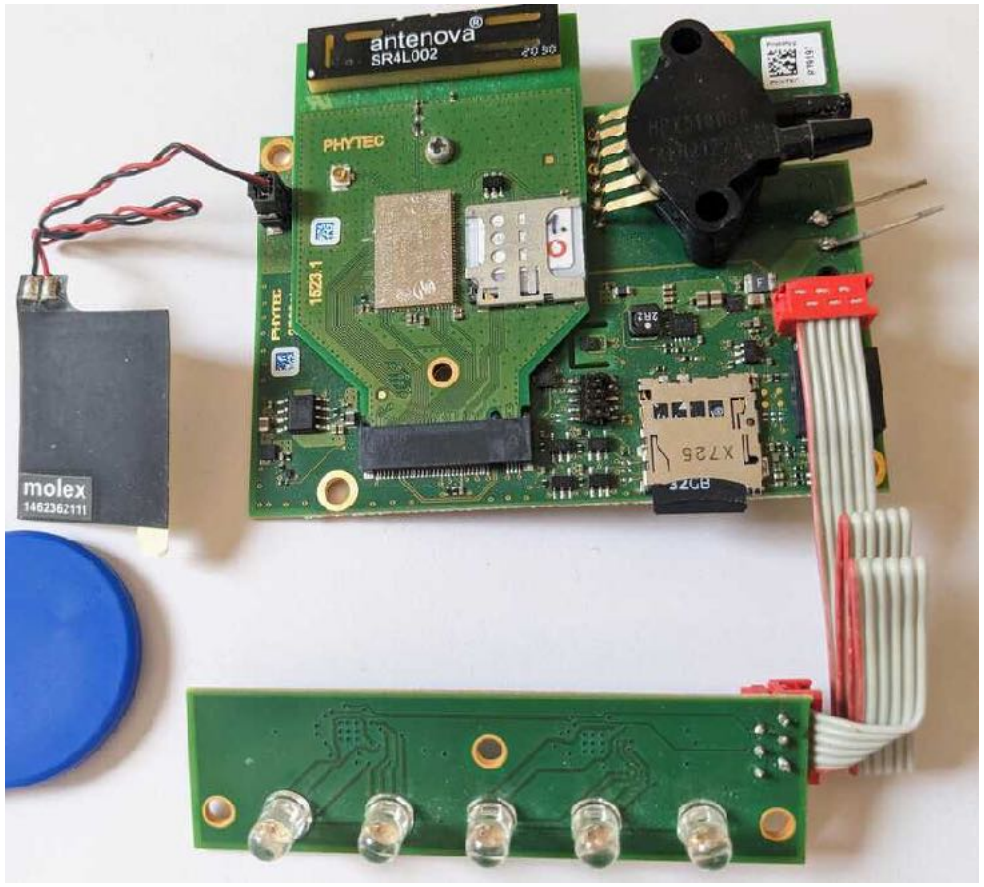
Scope of the Application

1. Read NFC tags
2. Monitor pressure samples
3. Provide direct user feedback
   - LED bar responds to pressure
4. Evaluate pressure gradient, report
5. Send to MQTT broker via LTE-M



Pump Monitor PCB, LED Board and NFC Antenna

Hardware Components

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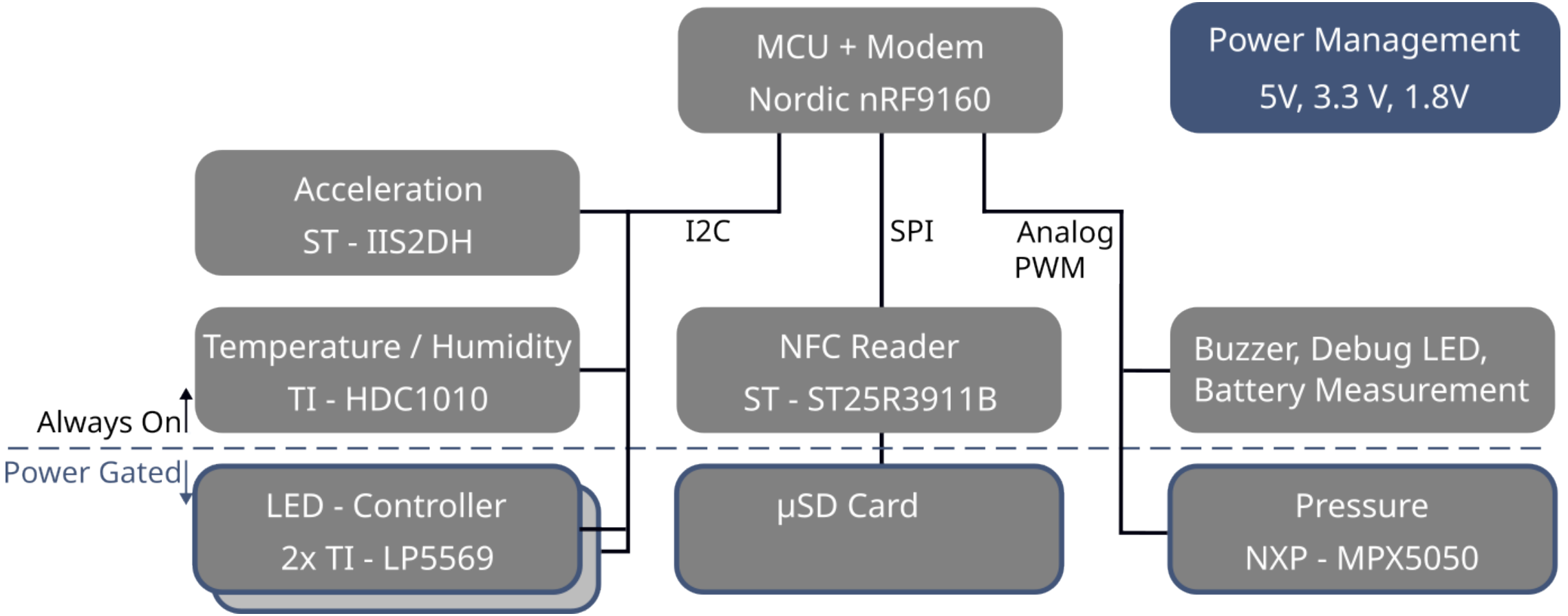
Device power usage more important than interface



Hardware Block Diagram of the Pump Monitor

Choice of Modules important to meet the Brief

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Threads, workqueues, timer API

Sensor-, LED- and storage APIs (on-device, SD card)

Nordic nRF-Connect SDK

- Modem support for nRF9160
- Driver for NFC reader (ST25R3911B)

MQTT, JSON

Power management subsystem

System States

Accelerometer wakes up system

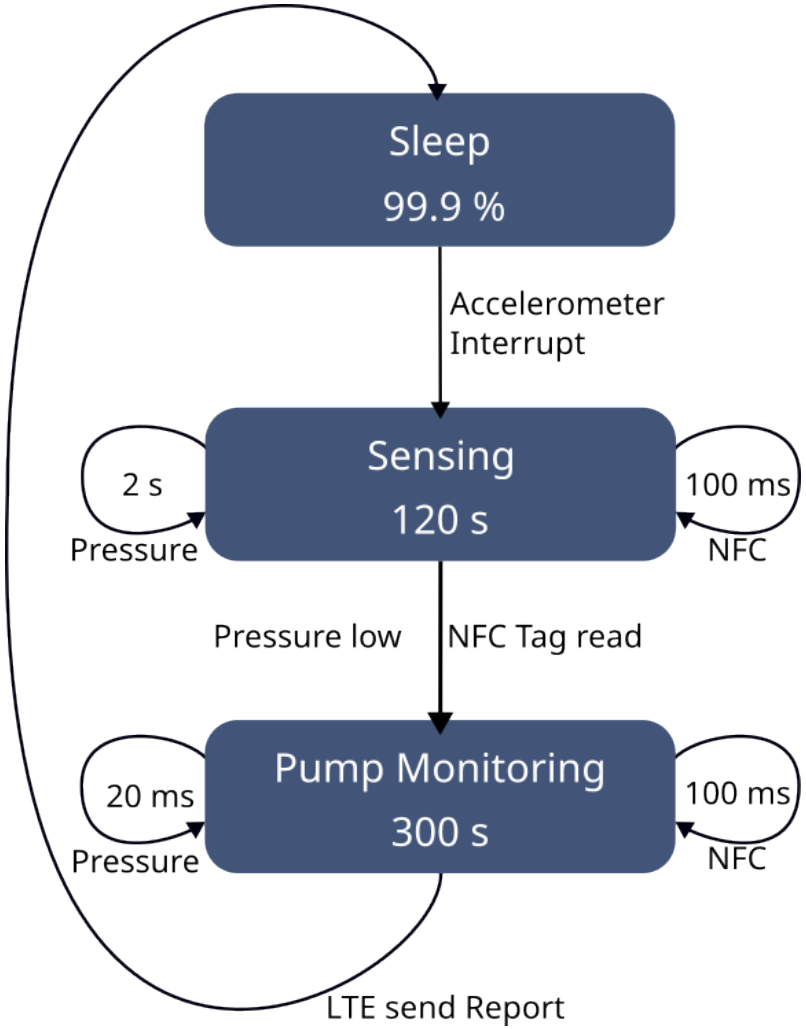
Start pump monitoring if:

A. NFC tag read

B. Pressure below threshold detected

50 Hz pressure sampling frequency

Most of the energy consumed in pump monitoring



Main States of the Application

Minimized Pressure Sensor Current in "Sensing"

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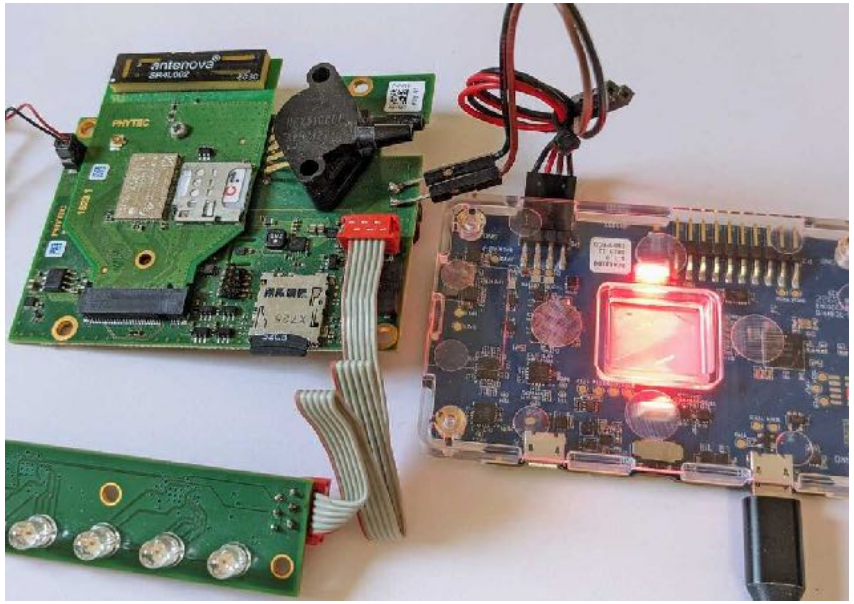
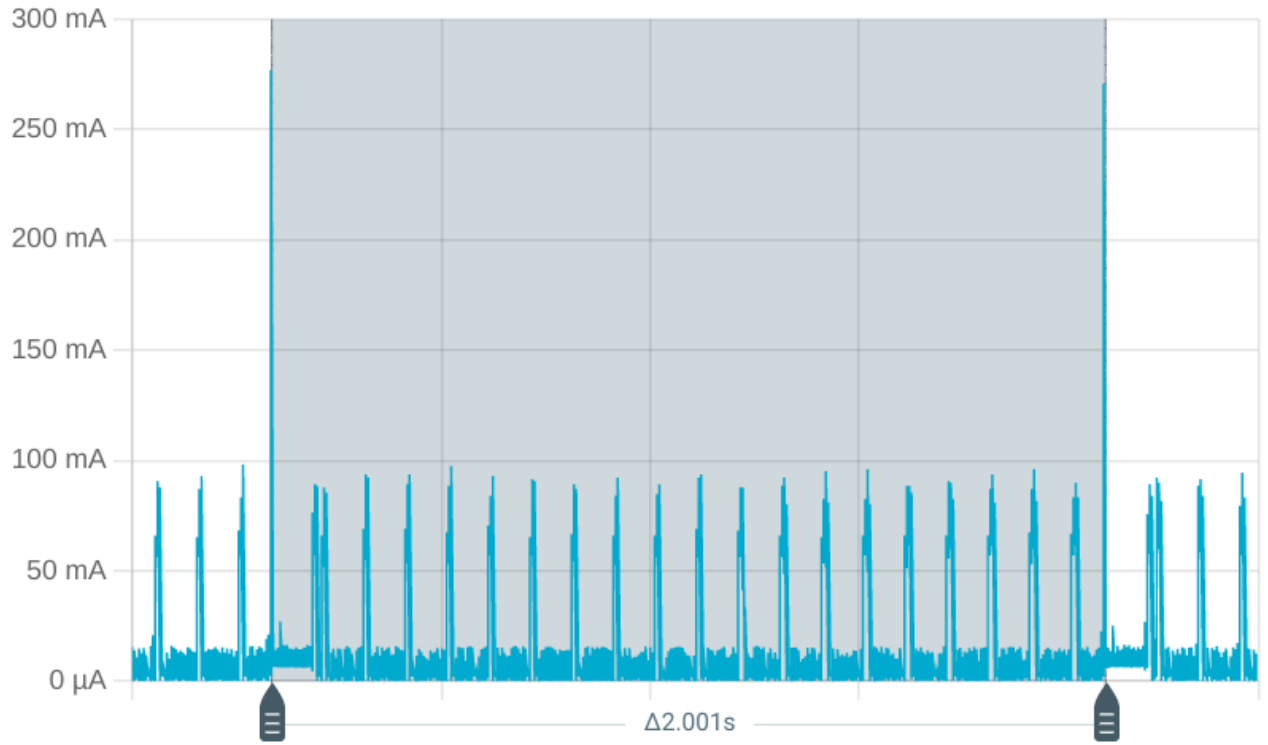
Pressure sensor mostly off



Power Profiler powering the Pump Monitor PCB



Current Diagram - 2 s Pressure Sensor sampling during "Sensing"

Frequent NFC Polling: Optimal Readability

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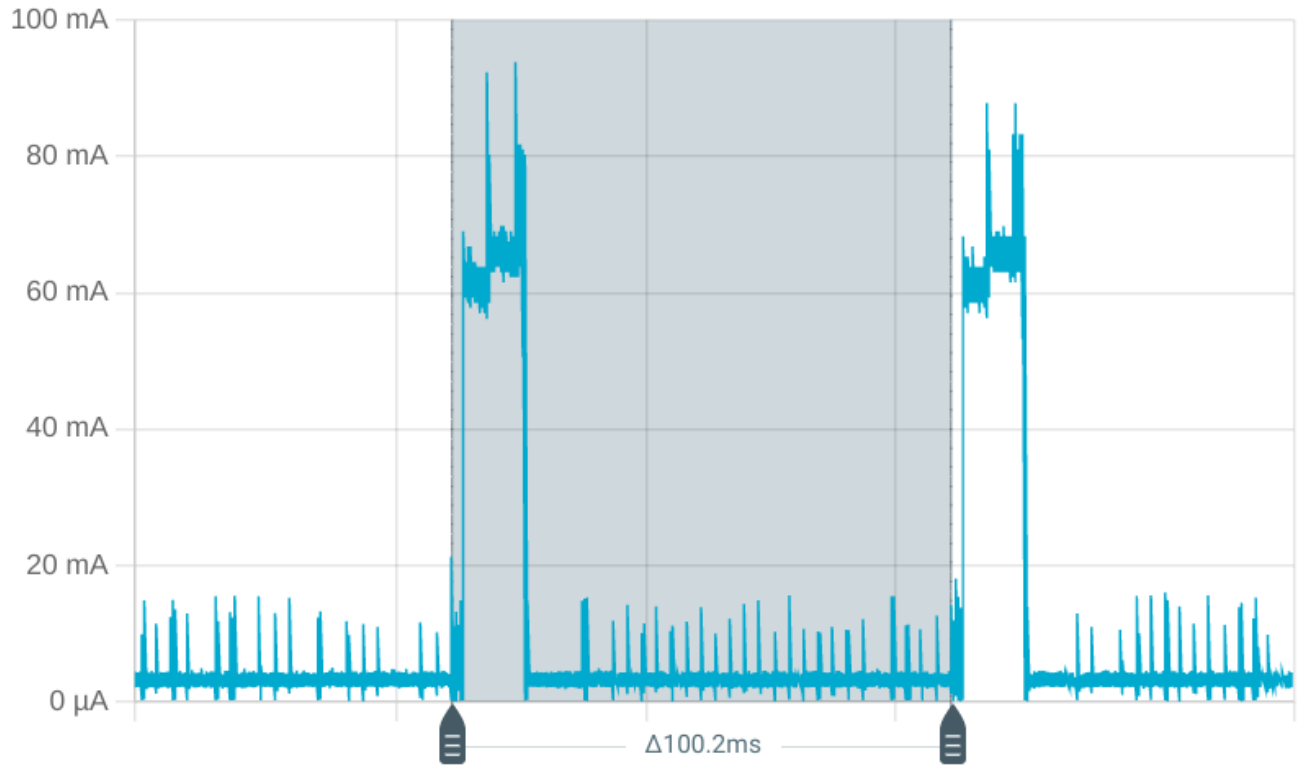
10 Hz polling frequency for good responsiveness

- No user input
- System "just works"



Current Diagram - 100 ms NFC polling Interval

Typical Energy Impact of CPU and Devices

50 Hz pressure sensor sampling rate

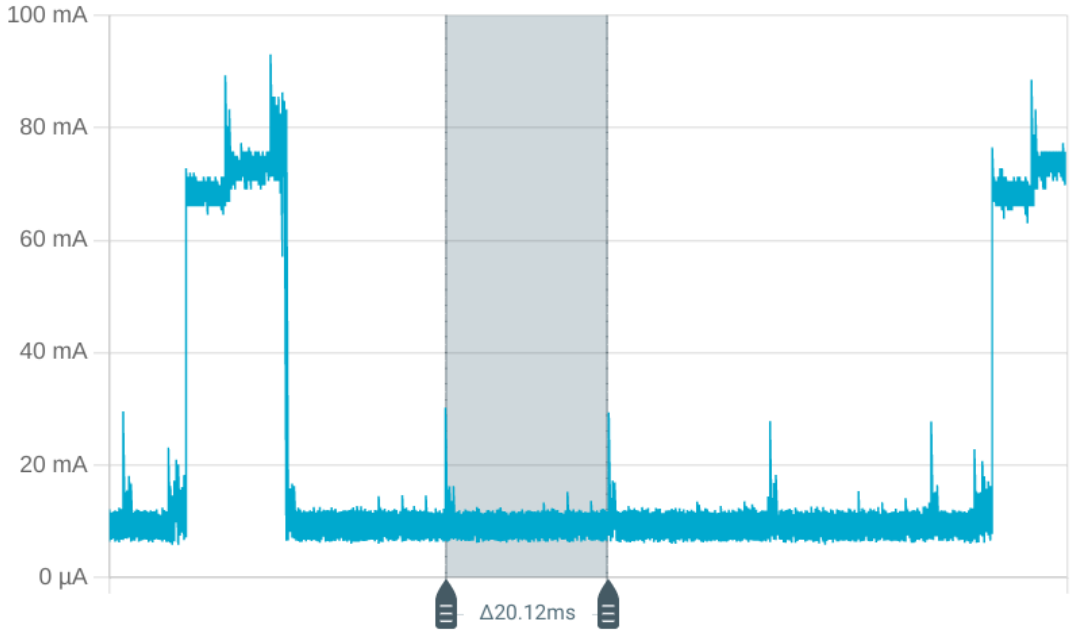
Cheap (energy)

- CPU time
- Temp-/ Humidity sensor
- Accelerometer

Expensive (energy)

- Radio
- Pressure sensor
- NFC reader
- LEDs

-> Cheap CPU time enables Edge computing



Current Diagram - 20 ms Pressure Sensor Sampling during "Monitoring"

Issues to solve when Switching off Devices

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Analog pressure sensor

- 20 ms warmup time
- no re-initialization

TI LP5569 LED controller

- set *chip_en* Register after power on

Device power management

- Application or driver triggers device power management
- *pm_action* function called on PM events
- device voltage controlled by regulator

```
/* drivers/led/lp5569.c */
static int lp5569_pm_action(const struct device *dev,
                            enum pm_device_action action)
{
        const struct lp5569_config *config = dev->config;
        int ret;

        switch (action) {
        case PM_DEVICE_ACTION_TURN_ON:
        case PM_DEVICE_ACTION_RESUME:
                ret = lp5569_enable(dev);
                if (ret < 0) {
                        LOG_ERR("Enable LP5569 failed");
                        return ret;
                }
                break;
        [..]
        }

        return 0;
}
```

PM Implementation in the LP5569 Device Driver

Design Decisions

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Power gating vs. always on

- Disabling power for the LP5569 LED driver
- Re-initialize LP5569 allows hot-plugging

5 V requirement pressure sensor

- Robust sensor more important

MQTT / TLS / TCP vs. Lw2M2 / CoAP / DTLS / UDP

SD card for logging pressure samples

- State of the LTE-M / NB-IoT Network was unknown

Lessons Learned

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Develop features in application modules

Specification (HW) vs. Rapid prototyping (SW)

- Some requirements had not been defined at project start
  - NFC Tag Format
  - Start of pumping process if no NFC Tag available

Field test with limited number of devices

- Opportunity to learn

LTE-M network reliable

Operations

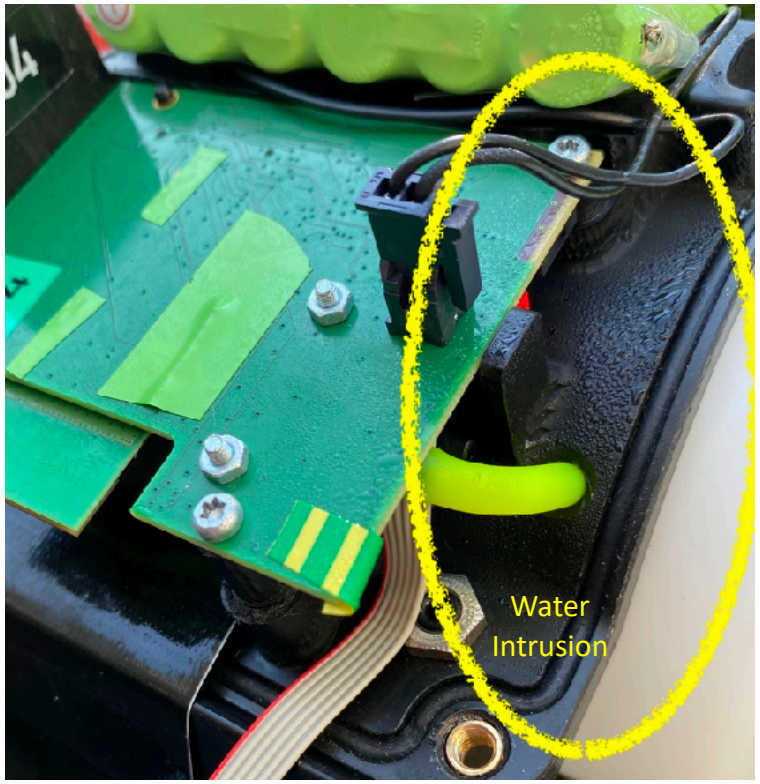
MQTT to SQL database for monitoring

Daily telemetry statistics

- Humidity, temperature
- Wake-up cycles
- Active time (*Sensing*, *Monitoring*)

Water intrusion alarm

What's next?



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Questions?

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