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Machine Learning Supported Self-Sensing Micropump to Detect Air Bubbles to Improve Dosing Accuracy



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Self-Sensing of Piezoelectric Actuators

Introduction to piezoelectric micropumps

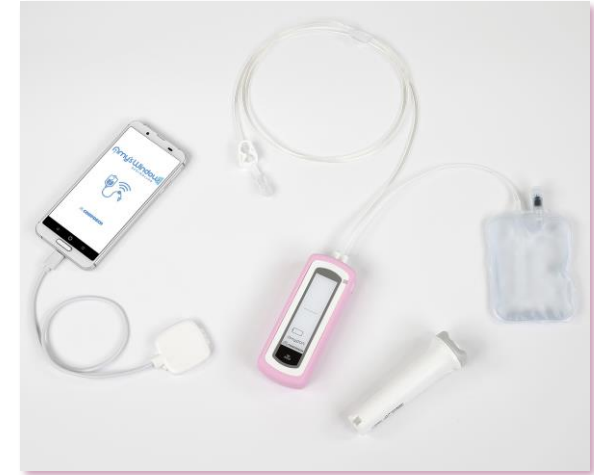
- **Base plate** of 2 mm with a diameter of 20 mm
- **Two passive check valves** of 25 µm thickness
- **Piezoelectric diaphragm** with a diameter of 18 mm
 - **Steel foil** of 100 µm thickness
 - **Piezoelectric ceramic** of 200 µm
- **Etching** is used to **structure** the foils
- **Laser welding** to **bond** stack of foils
- **Diaphragm** compound is glued
- Through the **volumetric displacement** of the piezoelectric diaphragm in combination with the two passive check valves a **constant flow** of around 16 ml/min is realized



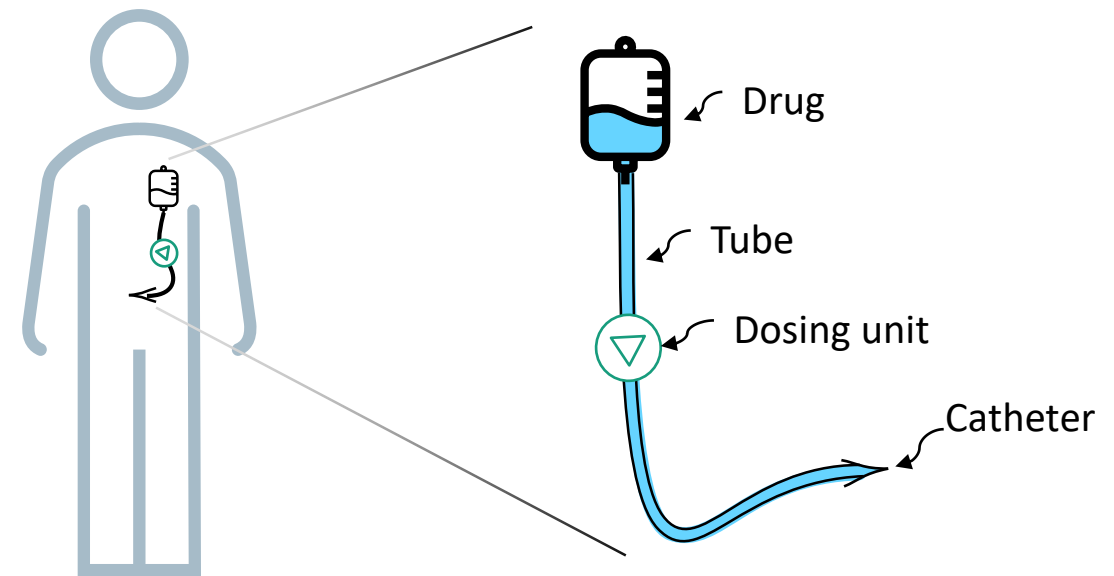
Self-Sensing of Piezoelectric Actuators

Problems with micropump driven drug delivery

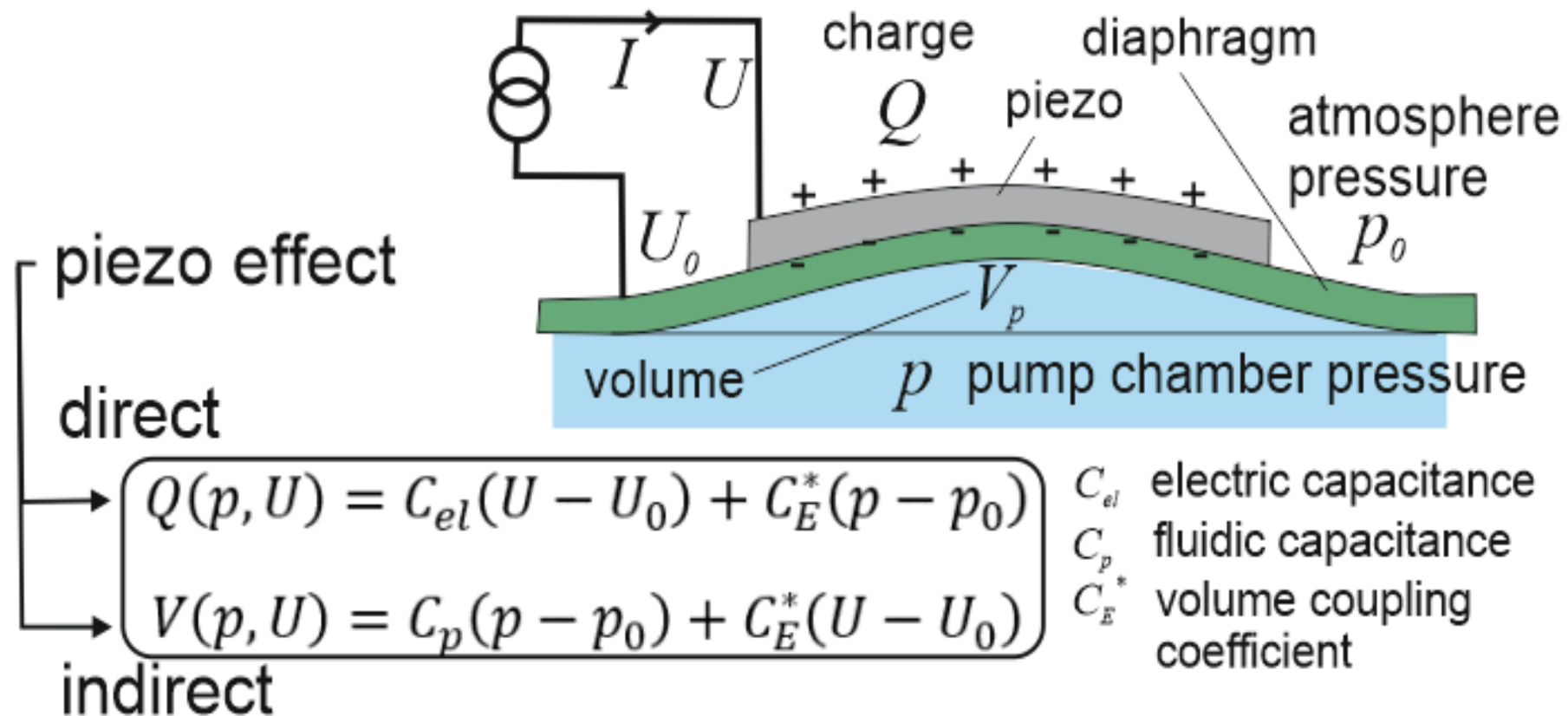
- When **administering drugs** with piezoelectric micropumps, small **bubbles** or **blockages** can lead to large **dosing errors**
- **Additional sensors** are used to **ensure safety and dosing accuracy**:
 - Medium Sensors to detect gasbubble
 - Pressure sensors to detect occlusion
- Due to regulations in medical technology, sensors that come into contact with patients or medications cannot be reused
- This results in **higher costs** and increased **system complexity**



Daiken Medical: COOPDECH AMY PCA



Self-Sensing: principle of piezo diaphragm actuator



Self-Sensing of Piezoelectric Actuators

Theory of a Self-Sensing micropump for drug dosing

- A radically **new approach** is taken to **detect bubbles and** changes in **backpressure** during operation of the piezoelectrically driven micropump
- Instead of only using the **indirect piezoelectric effect** for **actuation**, also the **direct piezoelectric effect** is used as a **sensor**
- Changes of medium and changes in backpressure are modulating the **Self-Sensing signal**
- **Self-Sensing signal** is basically the **loading current** of the piezoelectric diaphragm
- **Detection of bubbles and occlusions** can be realized:
 - Without additional sensors
 - Without modifying the micropump
 - **Only by analyzing the Self-Sensing signal**

$$V(p, U) = C_p \Delta p + C_E^* \Delta U$$

$$Q(p, U) = C_{el} \Delta U + C_E^* \Delta p$$

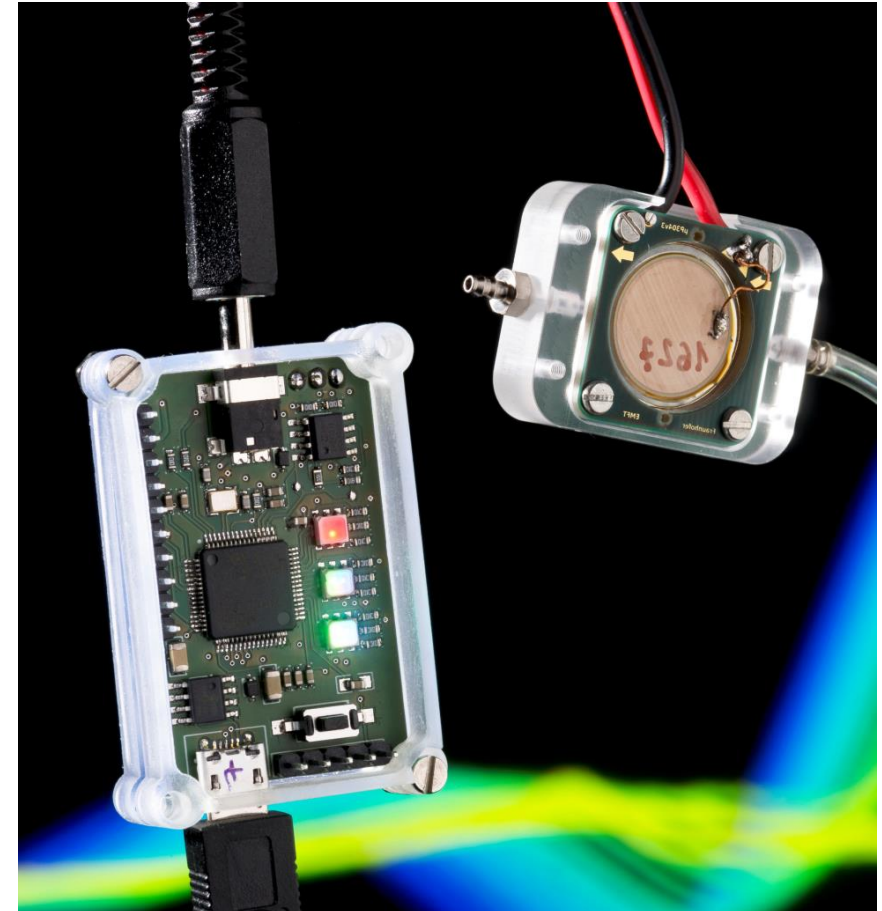
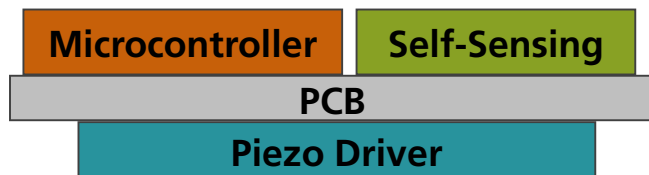
$$I = \frac{dQ}{dt}$$

$$I = C_{el} \frac{dU}{dt} + \Delta U \frac{dC_{el}}{dt} + \Delta p \frac{dC_E^*}{dt} + C_E^* \frac{dp}{dt}$$

Self-Sensing of Piezoelectric Actuators

Idea of a Self-Sensing micropump for drug dosing

- Classical approaches are not suitable due to the complex types of modulation
- Therefore Artificial Intelligence methods (AI-methods) are used
- They have to run directly on the microcontroller of the driving unit
- **Features of the intelligent micro pump electronics (edge device):**
 - Controlling of the Piezo-Driver
 - Sampling of Self-Sensing signal (loading current)
 - Live stream of sampled data via USB
 - Realtime execution of AI-methods on the edge device
- **All those features are realized on a STM32F4 microcontroller**



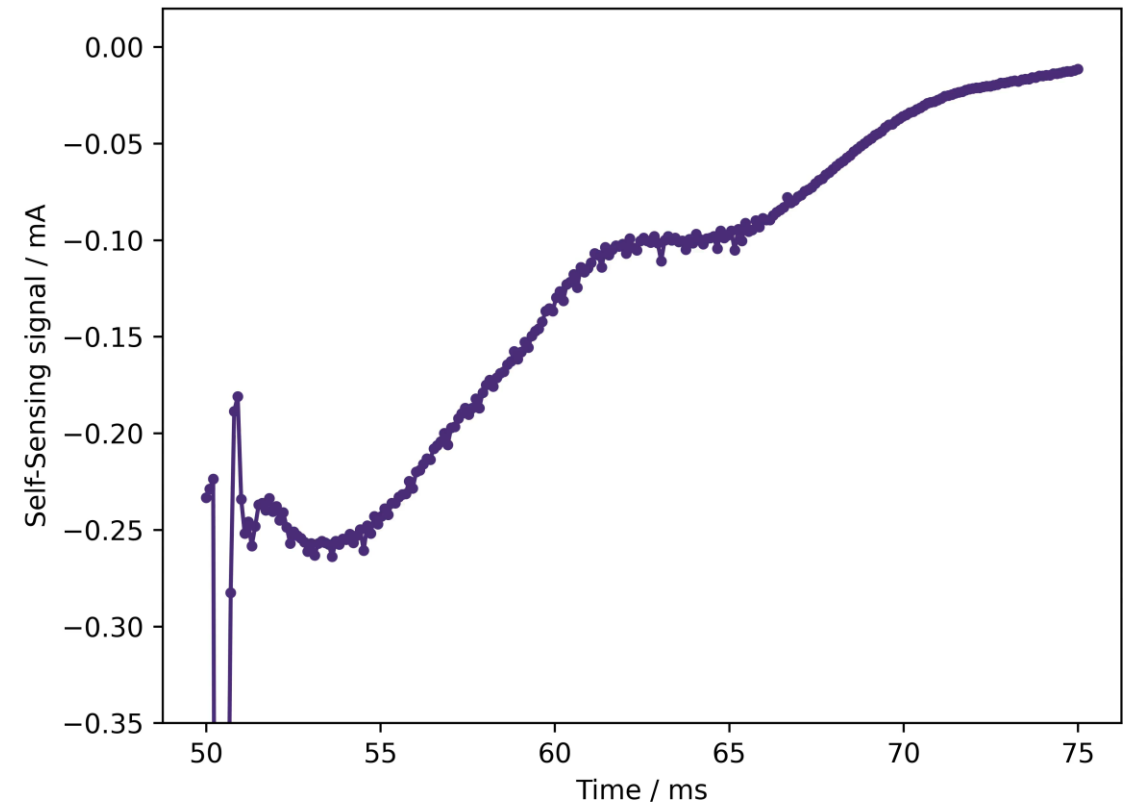
Self-Sensing of Piezoelectric Actuators

Idea of an intelligent micropump

- **Self-Sensing signal in real time:**

- The pump frequency is 10 *Hz*
- 50 *ms* for the supply mode ("inhale") and 50 *ms* for the pump mode ("exhale")
- First **25 *ms* of pump mode** is shown, which is represented by the time span between 50 *ms* to 75 *ms*
- Data is measured by an ADC of a STM32F4 microcontroller at a **sample rate of 10 *kHz***

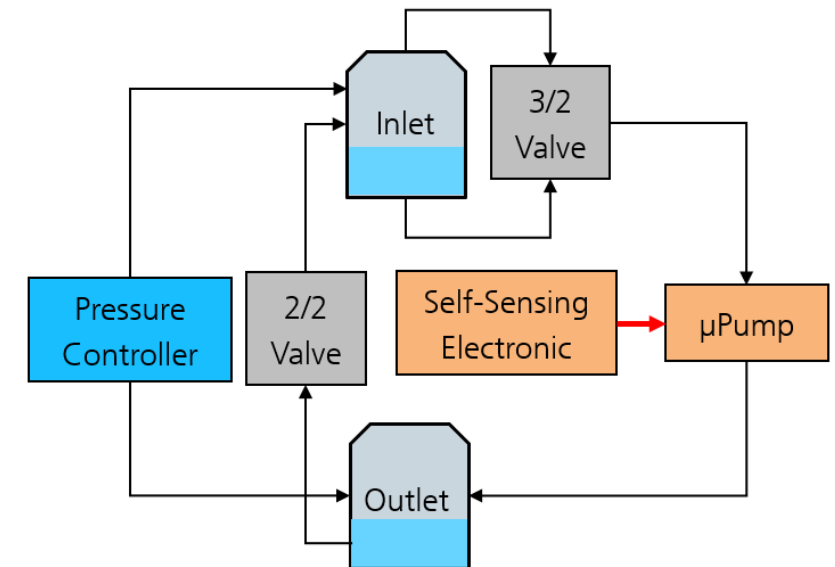
➤ **For the usage of Artificial Intelligence
Labelled training data is needed**



Self-Sensing of Piezoelectric Actuators

Testbench: Actuators

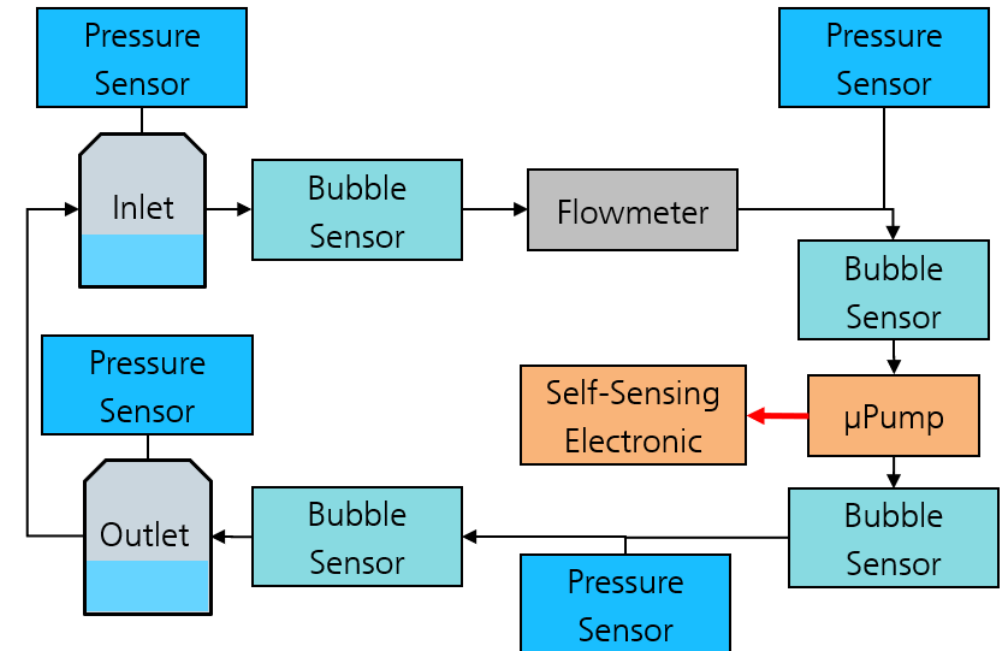
- The testbench **controllers sets** the required **scenarios**:
 - Changing of the medium
 - Inserting gas bubbles
 - Applying changes in backpressure
- The **Self-Sensing electronic applies** the **high voltage** signal to the micropump
- To **change medium** a 2/3 valve is used on the inlet
- To **insert bubbles** the valve is switched at high frequencies depending on the flow rate and the desired bubble size
- To set different **pressure scenarios** a pressure controller is used
- The 2/2 valve between inlet and outlet enables to let the water flow back to the inlet without disconnecting the tubes



Self-Sensing of Piezoelectric Actuators

Testbench: Sensors

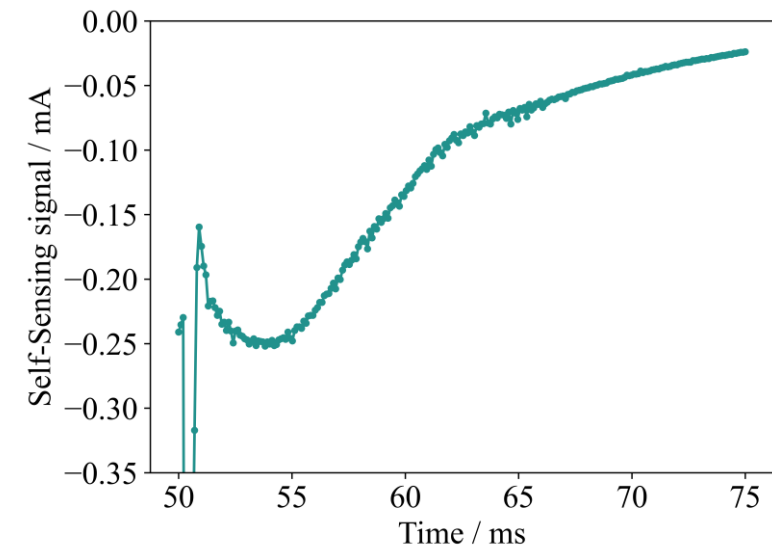
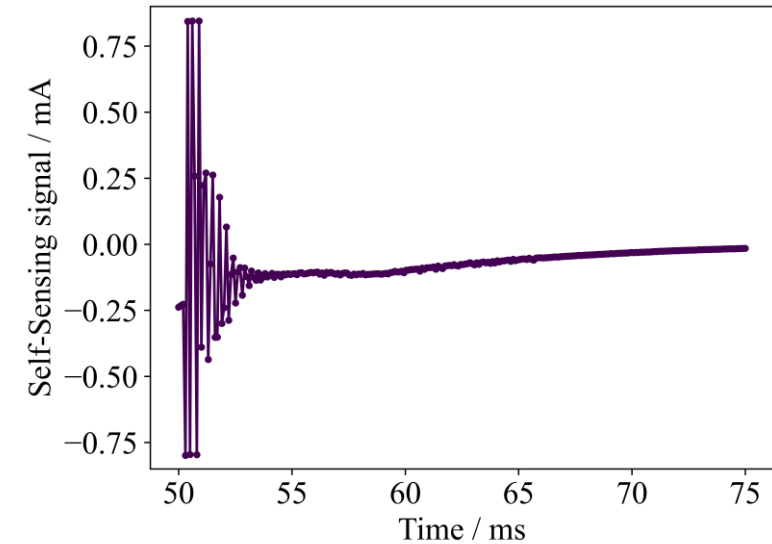
- Testbench **sensors** to **detect** the applied **environmental conditions**
- **Self-Sensing electronic** provides **trigger** signal for the external sensors and **samples** the self-sensing signal corresponding to the sensor data
- **Pressure sensors** are located on the inlet and outlet reservoir and on the pump inlet and outlet
- **Bubble Sensors** are located on the system inlet and outlet and on the pump inlet and outlet
- A **flowmeter** is installed to measure the flowrate generated by the pump



Self-Sensing of Piezoelectric Actuators

Measurements: normal operation under water and air

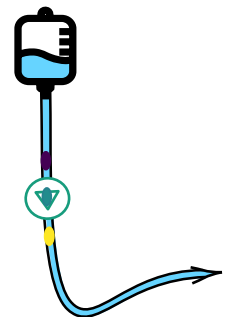
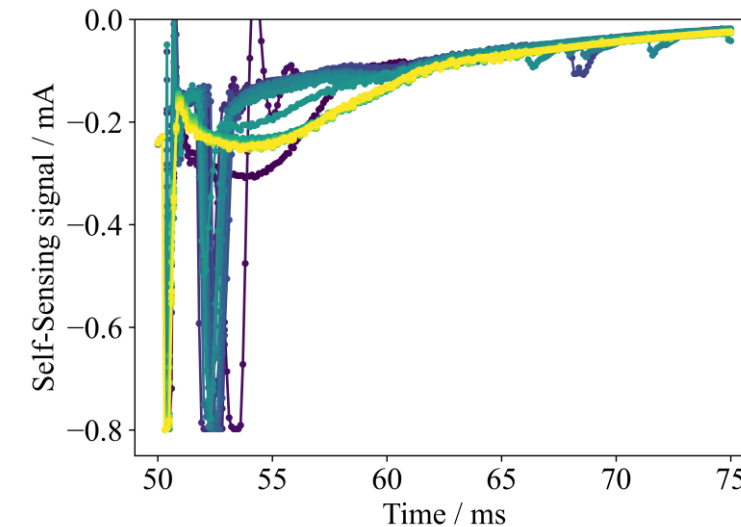
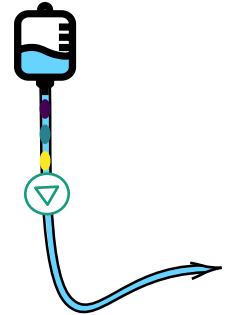
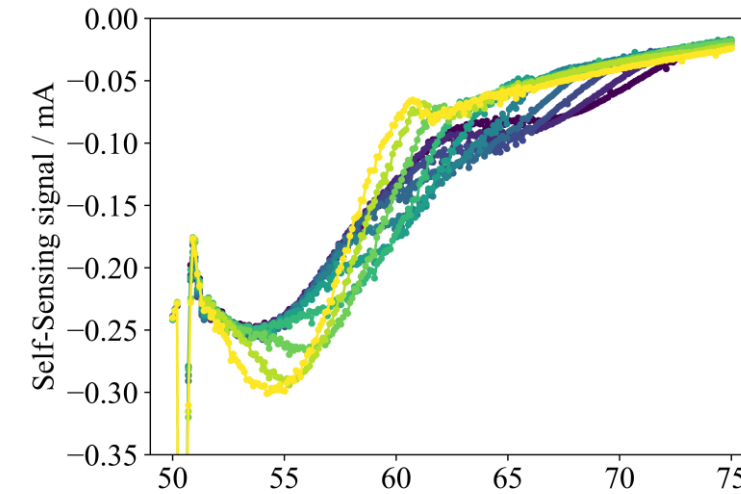
- Characteristic system response of a piezoelectric driven micropump while **pumping air**
- Damped oscillations with a frequency of about 4.5 *kHz* are clearly visible in the first 2.5 *ms*
- Characteristic system response for a piezoelectric micropump while **pumping water**
- A resonance of 10 *ms* is characteristic for water as transported medium



Self-Sensing of Piezoelectric Actuators

Measurements: bubble arrival and transition

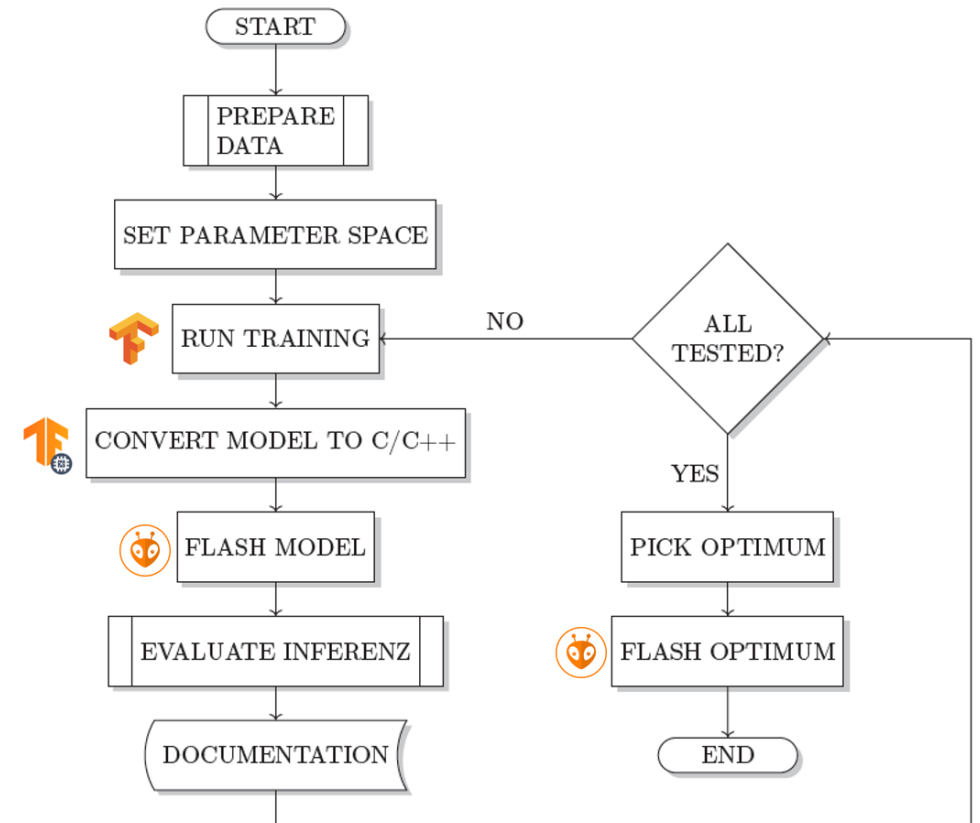
- Visualization of the **arrival of a bubble** over a distance of 30 *cm*
 - While the bubble comes closer (blue to yellow) the frequency of the resonance increases
 - **Bubble transition** from the inlet (blue), through the pump chamber (greenish blue) to the outlet (yellow)
 - While the pump chamber is occupied by the gasbubble chaotic changes in the Self-Sensing signal are prominent
- **Now we have suitable labelled Self-Sensing data to train our Artificial Intelligence models**



Self-Sensing of Piezoelectric Actuators

The intelligent micropump: AI methods on the edge

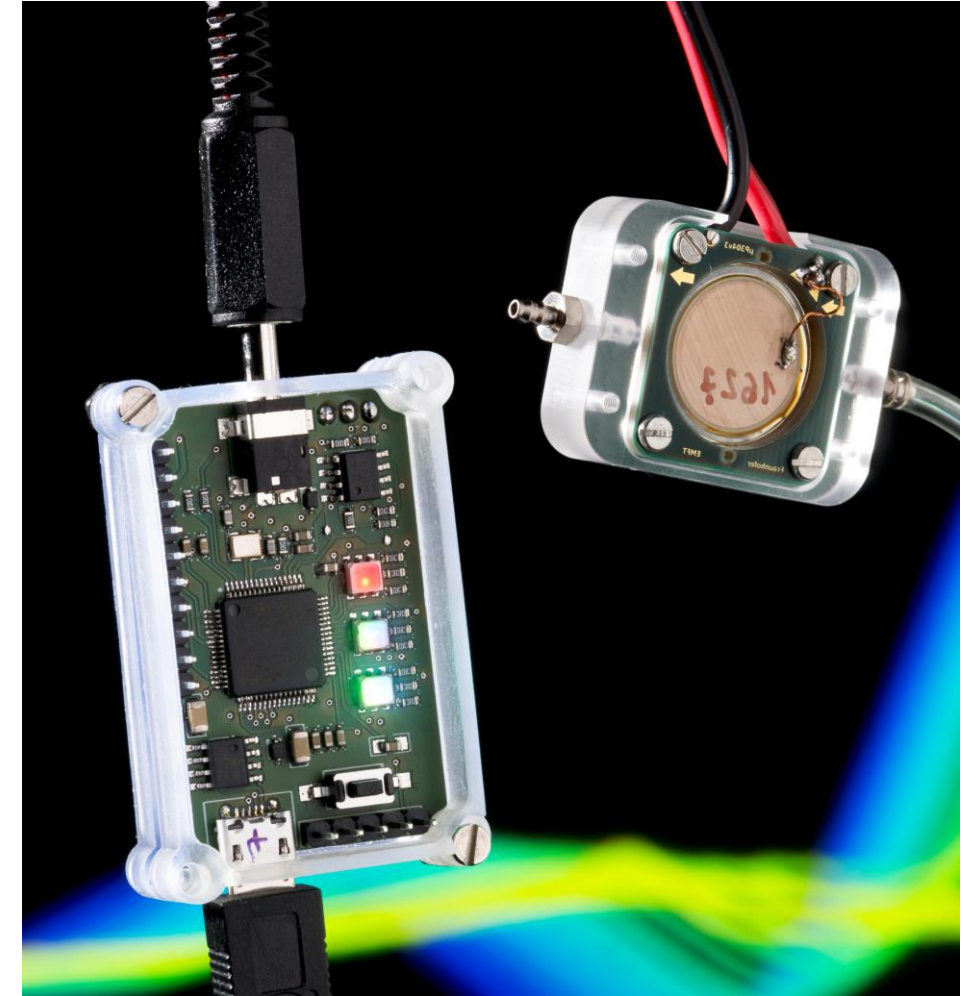
- **Optimization algorithm** find appropriate model from a grid of hyperparameters:
 - **Highest accuracy**
 - **Lowest memory usage**
 - **Fastest runtime**
- The algorithm implements all configurations and evaluates the **best implementation on the edge device**
- The final model has around:
 - **8300 parameters**
 - **Run time** of less than **15 ms**
 - **Memory footprint** of nearly **80 kBytes** of flash



Self-Sensing of Piezoelectric Actuators

The intelligent micropump: Edge-Device

- By using AI methods implemented on the edge device, we can **detect bubbles** with an accuracy of **up to 99.97 %**
- With the knowledge of the stroke volume of the actuator, we can **estimate** the amount of the **undosed drug**
- Necessary electronic updates:
 - **Small increase in the footprint** of the electronics
 - **Software update** onto the standard microcontroller
- This disruptive new technology **extends the functionality** of the micropump at **almost the same cost and size** as previous versions



Thank you for your attention!

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