# VIRTUAL PROTOTYPING IN SYSTEMC AMS FOR VALIDATION OF TIGHT SENSOR/FIRMWARE INTERACTION IN SMART SENSORS

Alexandra Küster[1], Rainer Dorsch[1], Christian Haubelt[2], Karsten Einwich[3]

[1]Bosch Sensortec GmbH, [2]University of Rostock, [3]COSEDA Technologies GmbH

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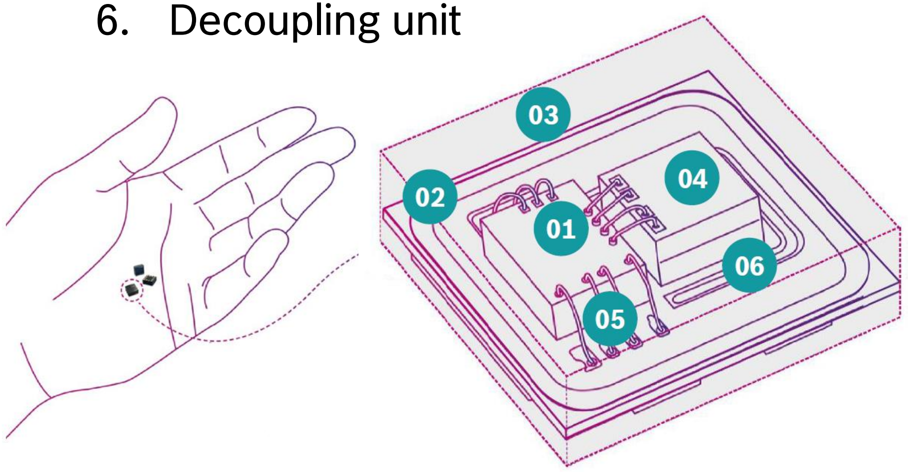
# Introduction
## Smart Sensors

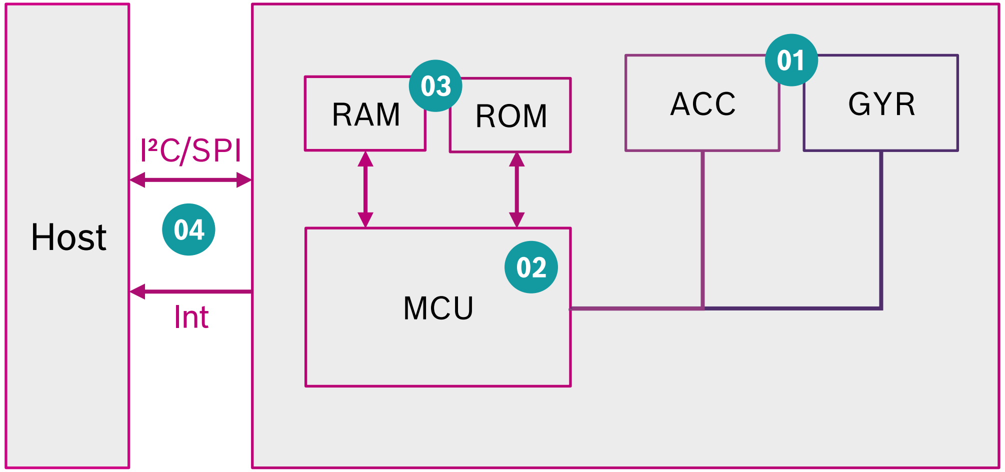
### Physical setup

1. Application Specific Integrated Circuit (ASIC)
2. Printed Circuit Board (PCB)
3. Housing
4. Micro-Electro-Mechanical System (MEMS)
5. Bonding wires
6. Decoupling unit




### Functional setup

1. Sensing unit — *MEMS*
   Read-out circuitry — *mech. → analog → digital*
2. Microcontroller unit — *smart component*
3. Memory — *calibration data, algorithms*
4. Host interface — *sensor setup; data read-out*

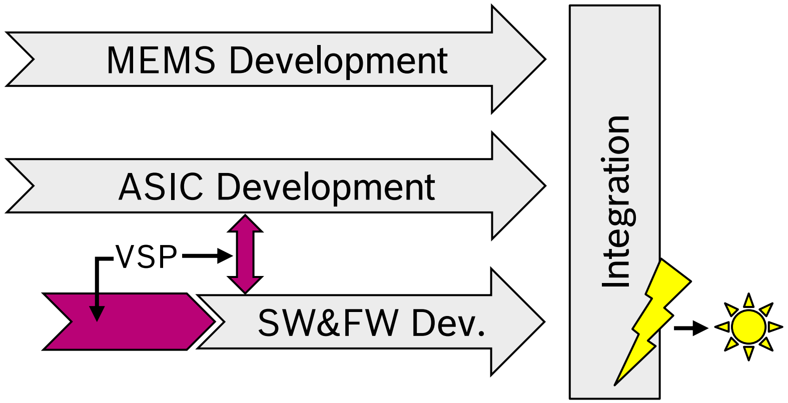


# Introduction

## Virtual System Prototypes (VSPs)

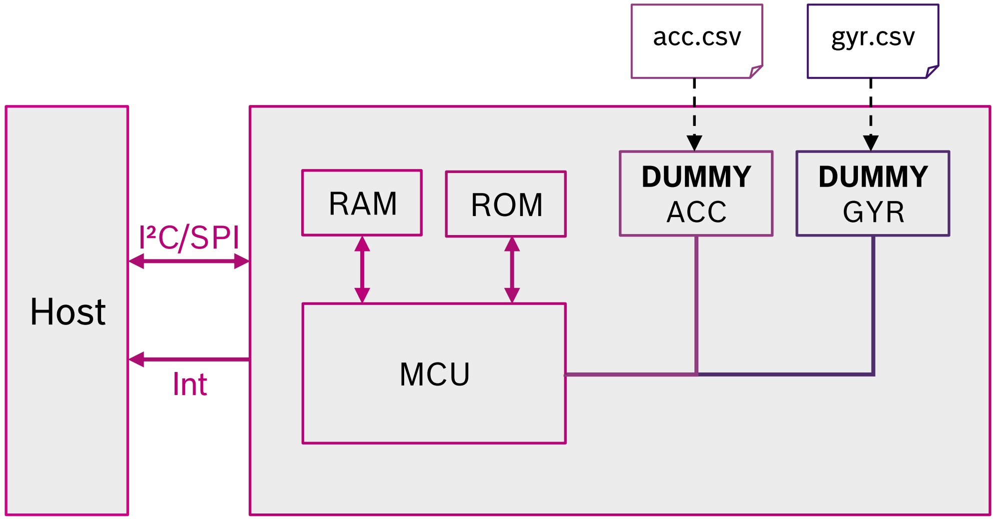
### Motivation

- better hardware/software integration
- integration tests on simulation level
- frontloading of software development
- support firmware developers
  - better traceability and system insights




### Characteristics

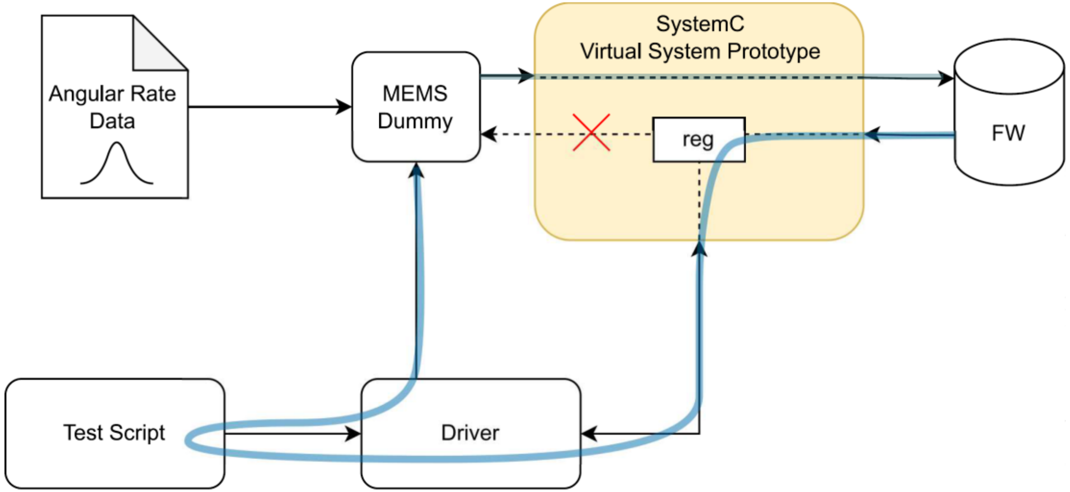
- fast system-level model
- SystemC + instruction set simulator
- transaction-level modeling, event-driven
- software + digital hardware



# Introduction
## Problem Statement

The interaction between MEMS and firmware inside the **VSP** is **unidirectional**.

The interaction between MEMS and firmware inside the **sensor** is **bidirectional**.




➡ Test cases must compensate the **missing impact path**. Thus, they get **complex** and **error-prone**.

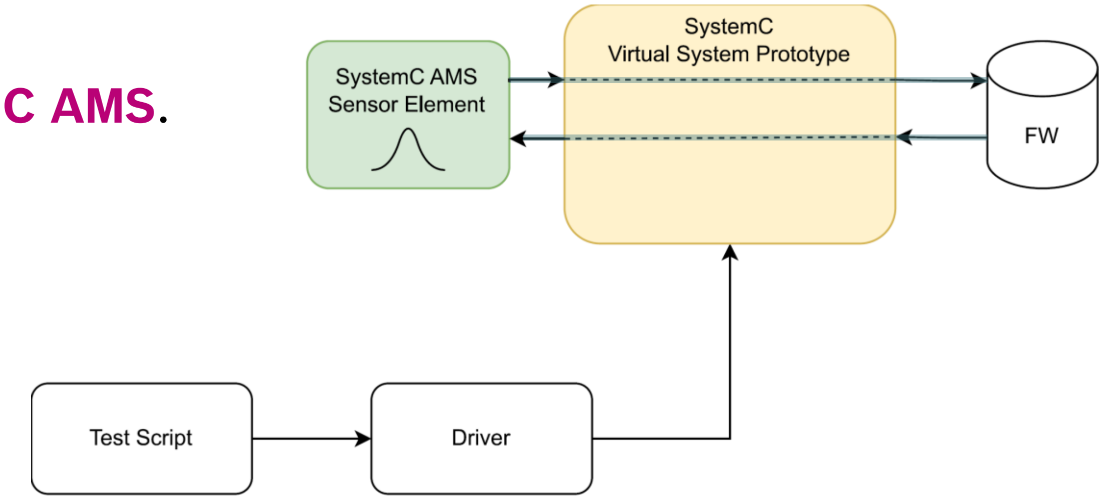
# Introduction
## Proposed Approach

A sensor element (MEMS + frontend) is added to the VSP. It is written in **SystemC AMS**.

The interaction between MEMS and firmware inside the **VSP** is **bidirectional**.

➡ Test cases become

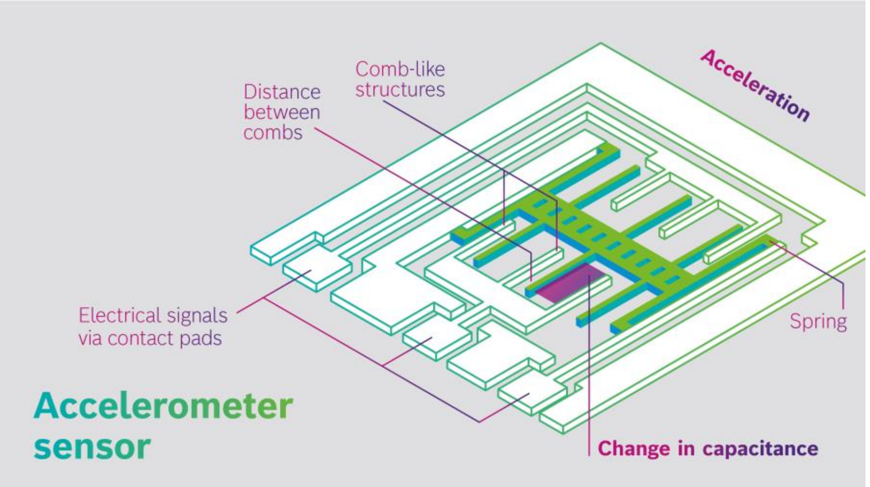
- less complex
- independent of input files
- reusable for hardware tests
- more expressive (transient behavior visible)

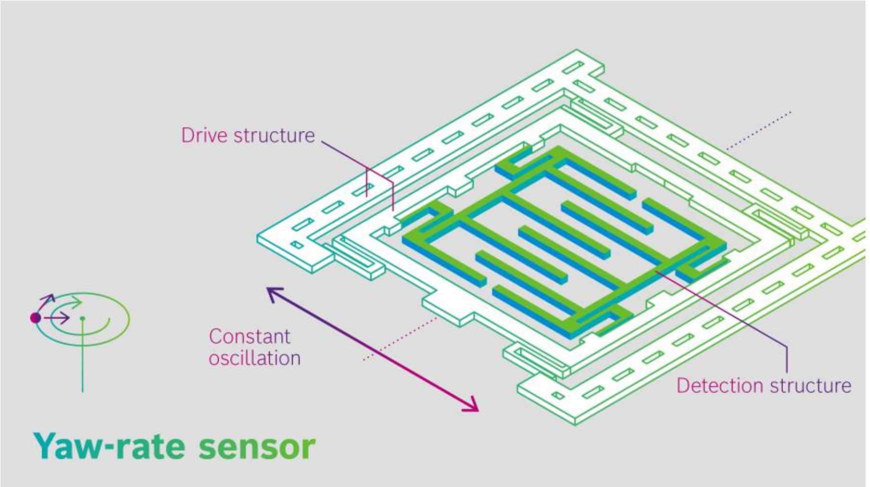


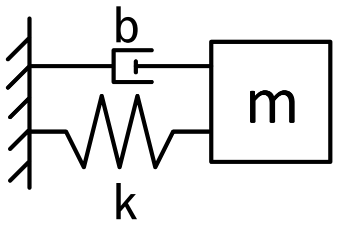
# Agenda

1. Introduction & Problem Statement
2. MEMS Basics
3. Virtual System Prototype
4. Case Study
5. Results & Discussion
6. Conclusion

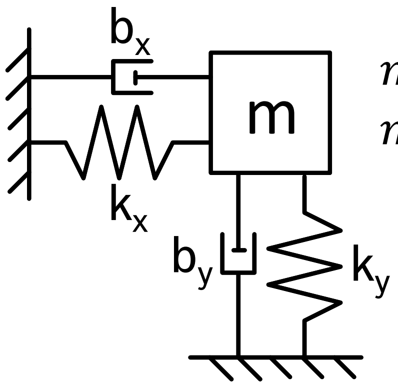
# Fundamentals
## Micro-Electro-Mechanical Systems (MEMS)




$$m\ddot{x} + b\dot{x} + kx = F$$




$$m\ddot{x} + b_x\dot{x} + k_x x = F_x$$
$$m\ddot{x} + b_y\dot{x} + k_y x = F_y$$

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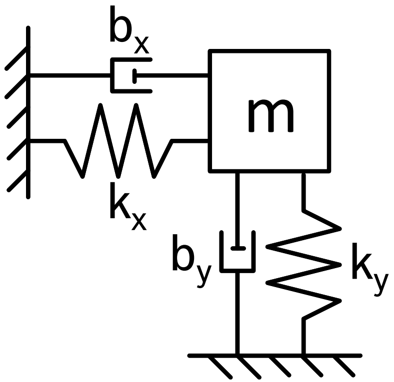
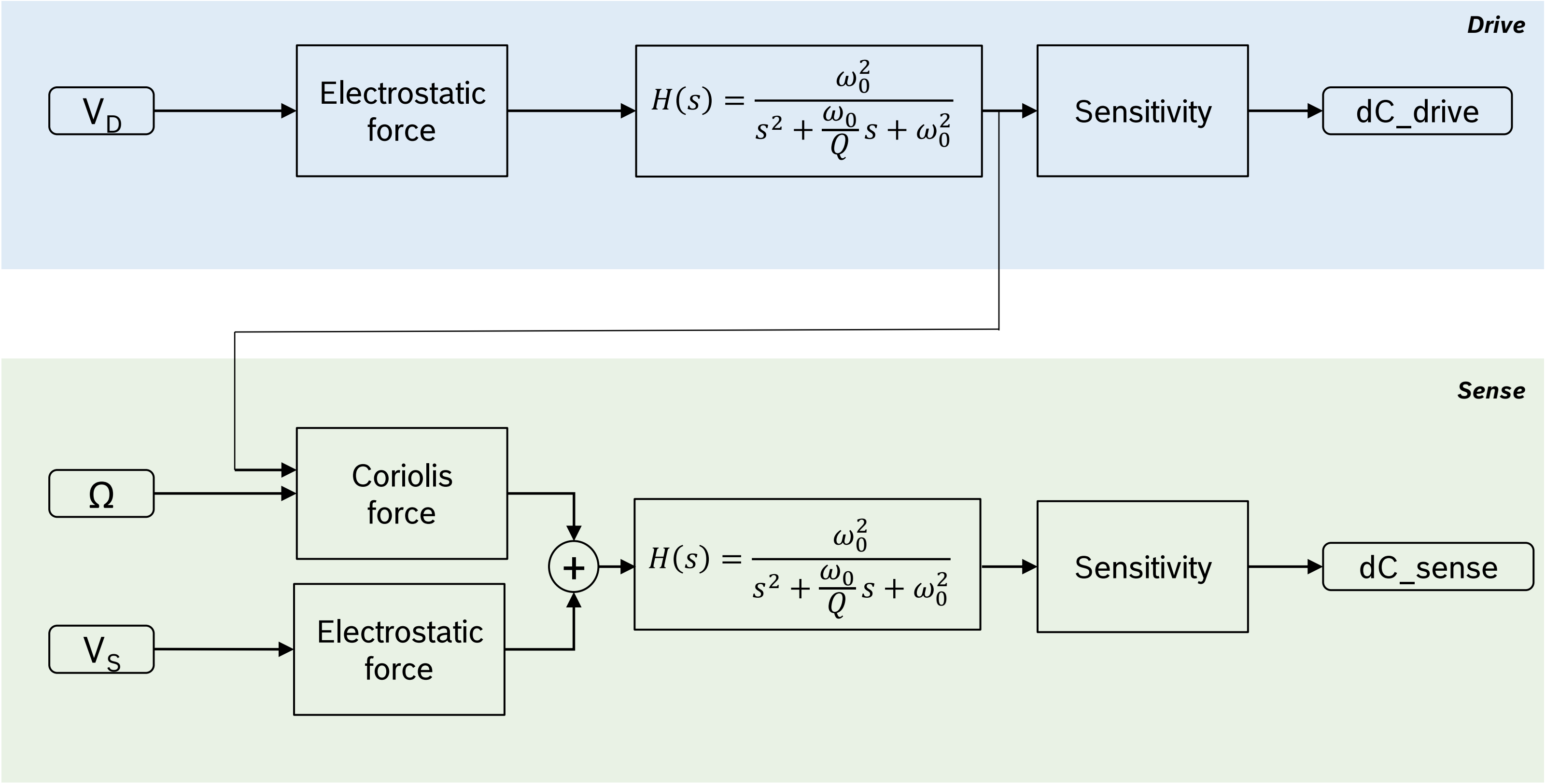
# Virtual System Prototype
## MEMS Implementation





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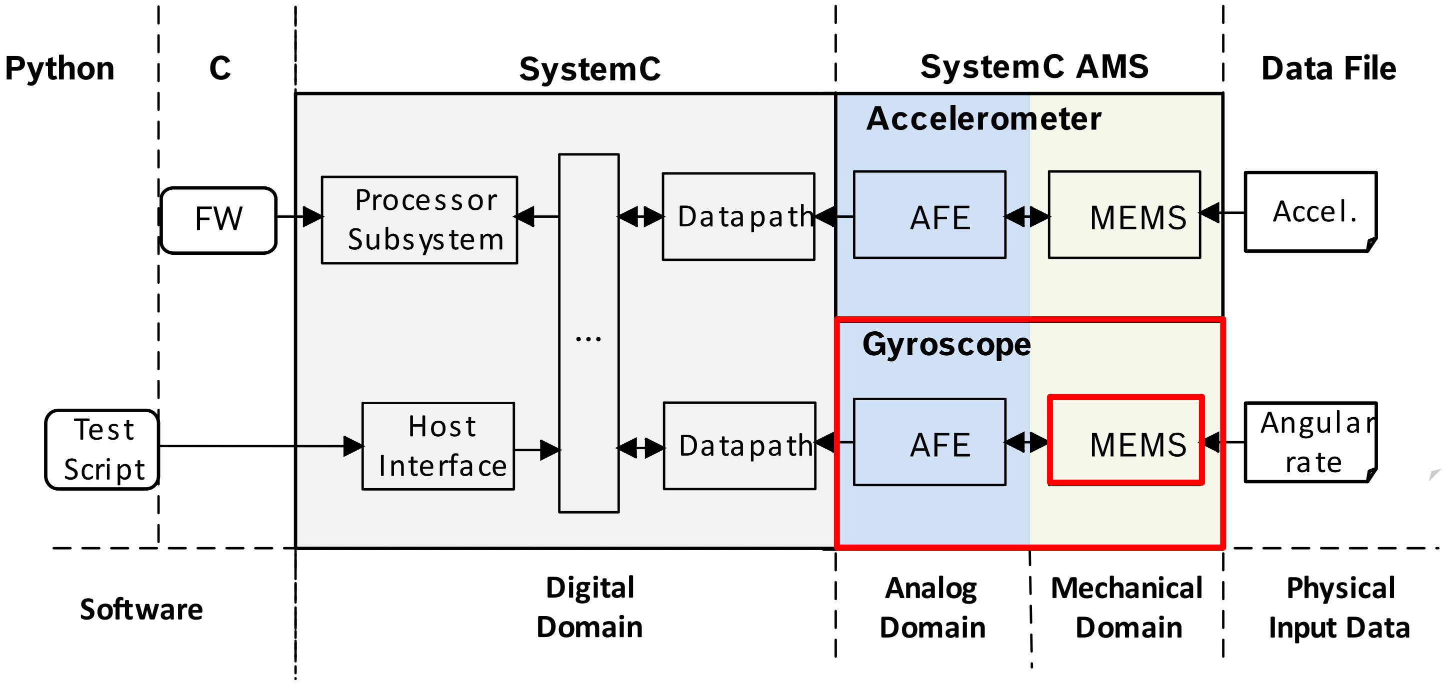
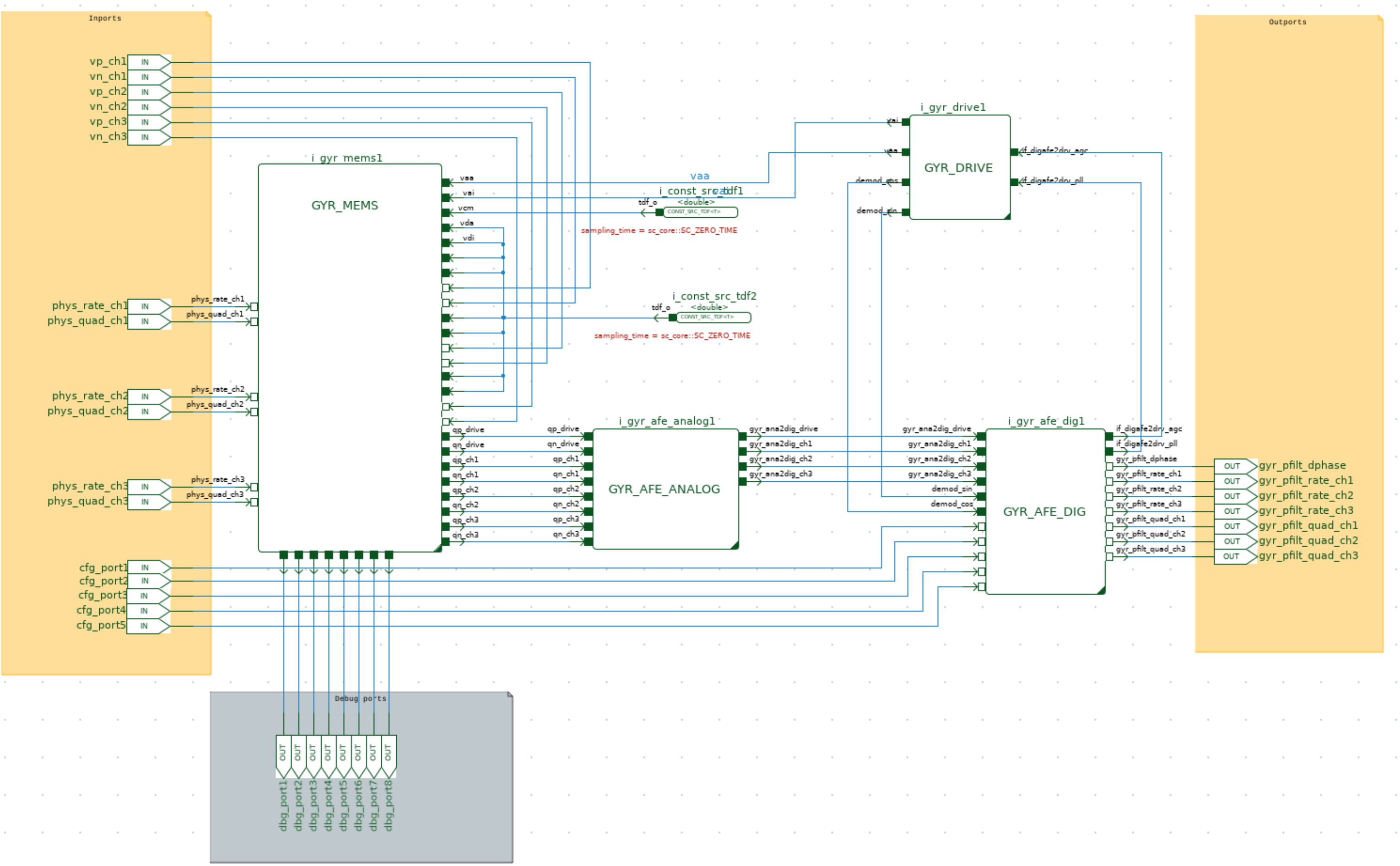
# Virtual System Prototype
## System Overview





Bosch Sensortec | Alexandra Küster | 15.09.2022, FDL 2022

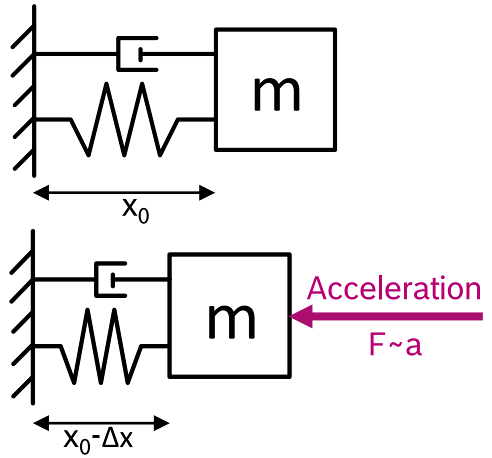
# Virtual System Prototype
## Implementation

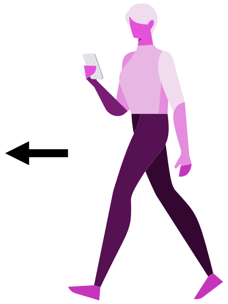


# Agenda

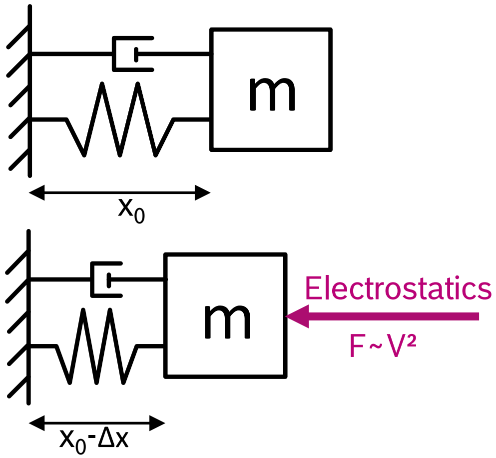
# Case Study
## Built-in Self Test for Accelerometer

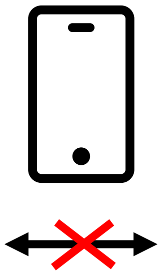
Normal sensing mode



Self test mode



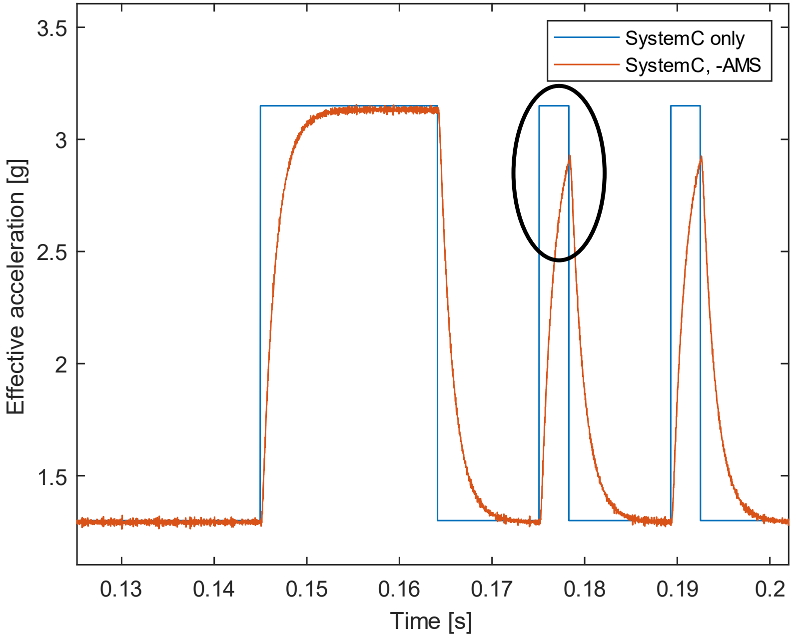
The built-in self test excites the MEMS electrostatically to check the correct mechanical functionality.

# Case Study
## Built-in Self Test for Accelerometer

Activate built-in self test → Wait for feature execution → Evaluate test results

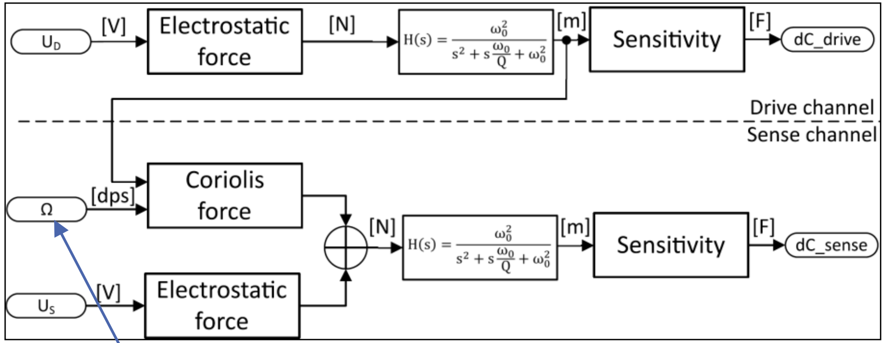
Activate built-in self test mode → Enable electrostatic force → Disable electrostatic force → Check pass/fail

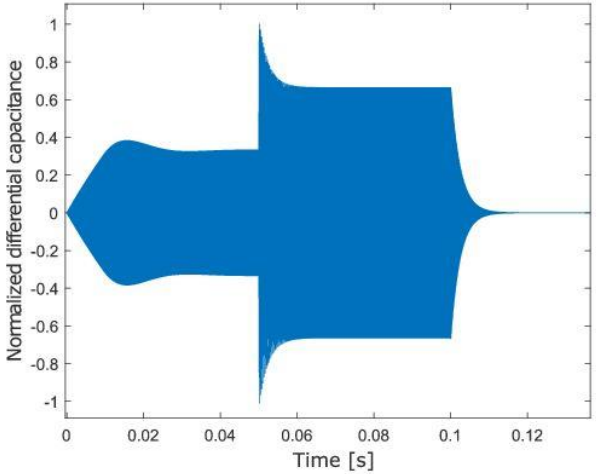
2x

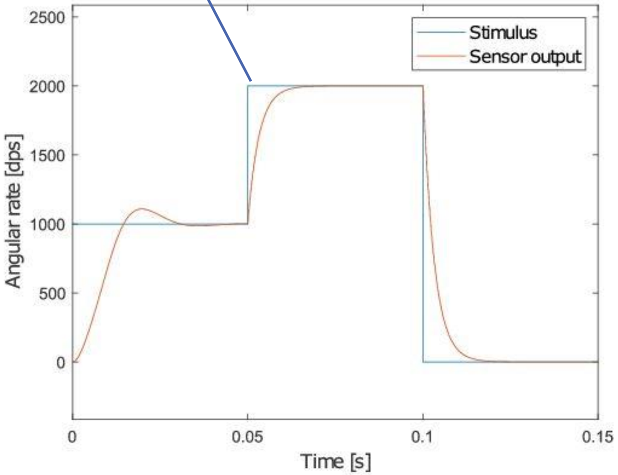



➡ Transient sensor behavior becomes visible

# Case Study
## Gyroscope Model Validation

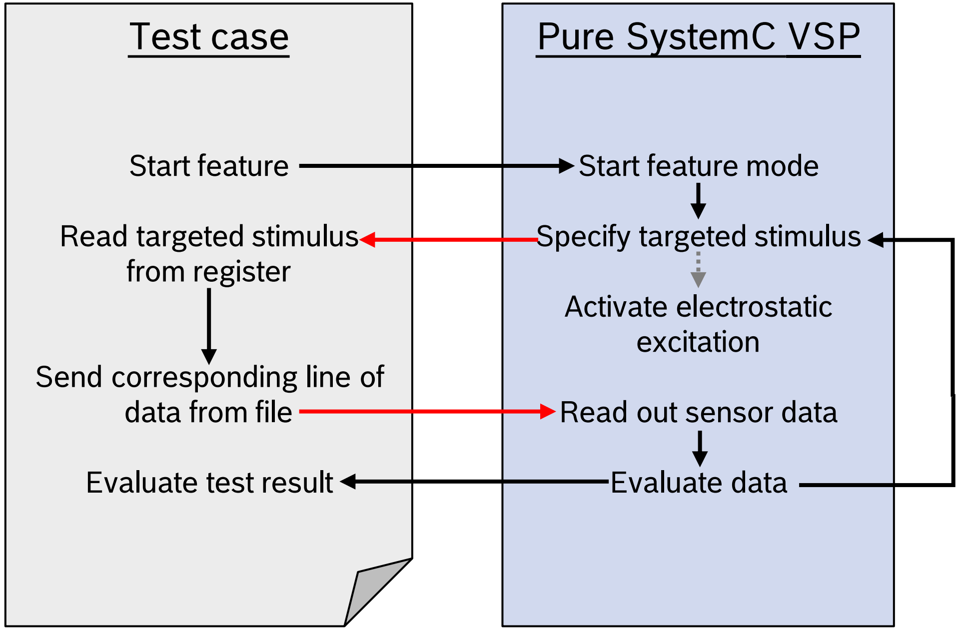


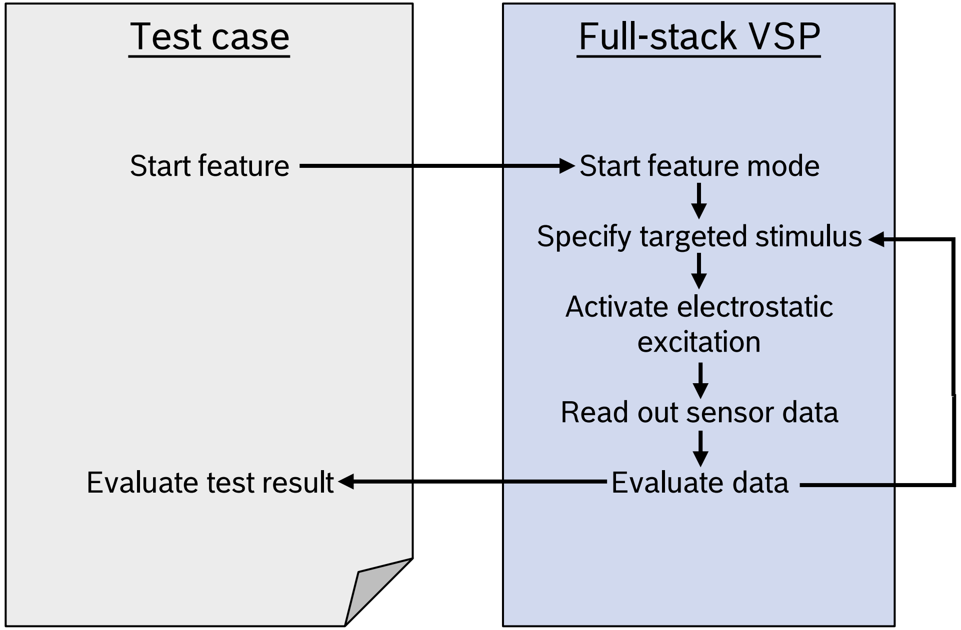




- sensor is stimulated with piecewise constant angular rate
- sensor output follows input
- differential cap ringing at drive frequency
- startup of drive oscillation influences sense output

# Case Study
## Sensor/Firmware Interaction in Gyroscopes




needs proper synchronization



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# Results and Discussion
## Benefits

Comparison of firmware test procedures

| | Virtual Prototype Version | |
|---|---|---|
| | **Pure SystemC** | **Full-stack** |
| **File input** | Measurements | None |
| **Complexity of test case** | High | Low |
| **Error sources** | Test case, VSP | VSP |
| **Insights into system behavior** | Limited to algorithmic, no physical insights | Algorithmic and physical insights |
| **Timing errors covered** | No | Yes |
| **Reusability for hardware** | Low | High |

- The overall confidence in the test result increases significantly
- Firmware developers gain better insights into the sensor's behavior
- Simulation and hardware tests can be matched by reuse

# Results and Discussion
## Performance Analysis

| Acc | Pure SystemC | Full-stack | Ratio |
|---|---|---|---|
| **Initialization Procedure** | 0.173s*<br>*0.160s*** | 1.655s<br>*0.160s* | 9.59 |
| **Firmware Procedure** | 0.303s<br>*0.045s* | 0.742s<br>*0.045s* | **2.45** |
| **Test Execution** | 0.476s<br>*0.205s* | 2.397s<br>*0.205s* | 5.04 |

| Gyr | Pure SystemC | Full-stack | Ratio (norm. to simulated time) |
|---|---|---|---|
| **Initialization Procedure** | 1.3s<br>*0.136s* | 20.6s<br>*0.136s* | 15.85 |
| **Firmware Procedure** | 113.0s<br>*1.923s* | 487.1s<br>*1.739s* | **4.77** |
| **Test Execution** | 114.3s<br>*2.0592* | 507.7s<br>*4.88s* | 4.88 |

*wall-clock time ** simulated time

- The increase of simulation time stays reasonable
- Transient behavior is reflected in the VSP
- Large idle times during initialization increase the ratio




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Heterogeneous virtual system prototypes are well-suited for the validation of tight sensor/firmware interaction.

They can be developed in SystemC/-AMS.

Simulation performance is degraded <5x compared to a SystemC-only approach.

# THANK YOU FOR YOUR ATTENTION.

# ANY QUESTIONS?


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