# MONITORING AND FORECAST OF RESIN INFUSION PROCESSES WITHOUT CONTACT TO PART

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DLR

# Motivation for Resin Flow Monitoring and Forecast

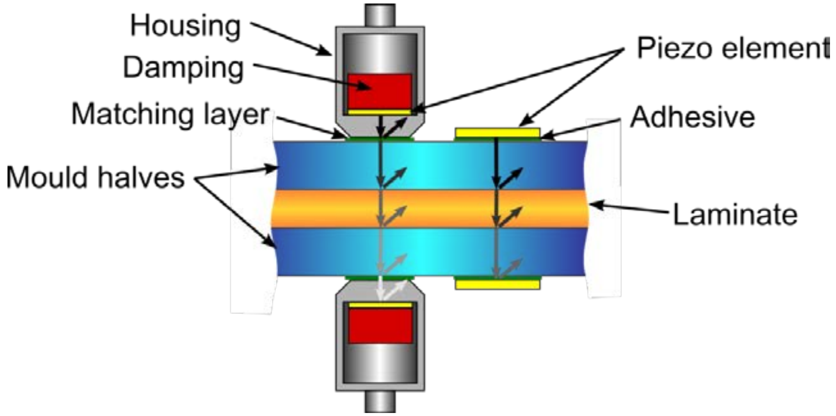
- Deviations in material and temperature etc. lead to different flow patterns
- Race tracking can lead to insufficient impregnation and gas entrapments
- Only experts with deep understanding can rate a running process and might induce the right measures to ensure successful fill

# Ultrasonic Process Monitoring: In-house Developed Sensors

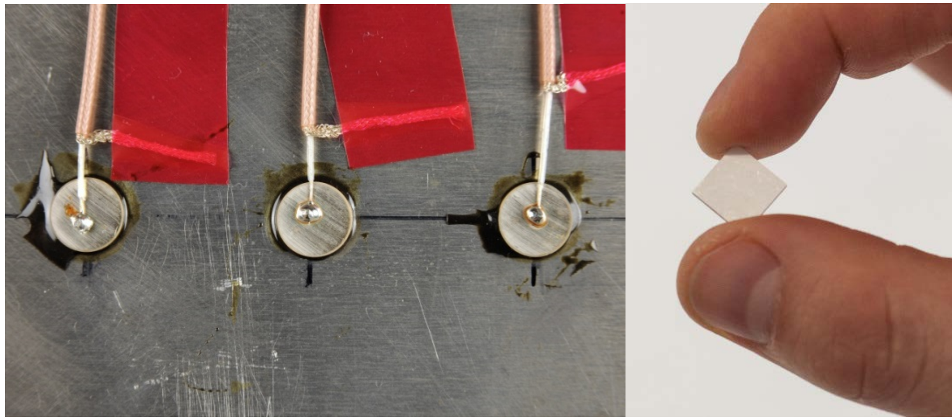
- Sound impulses are sent through mould and laminate
  - No direct contact to part, vacuum integrity and part surface not affected
- Allows monitoring of resin arrival, cure, gelation, vitrification and thickness

- Conventional transducers
  - Difficult to integrate, limited temperature range
  - Unreliable due to critical couple interface

- Resolved by direct application of piezo element on mould
- High reliability and measurement performance, low cost, easy integration




**Conventional sensors versus tool mounted piezo elements**

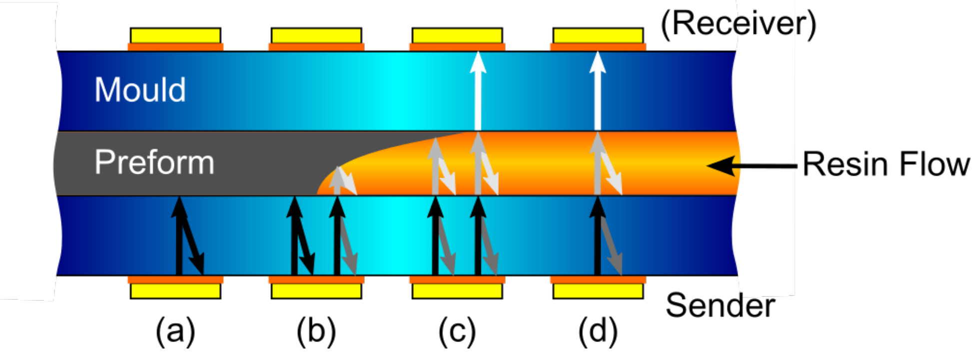


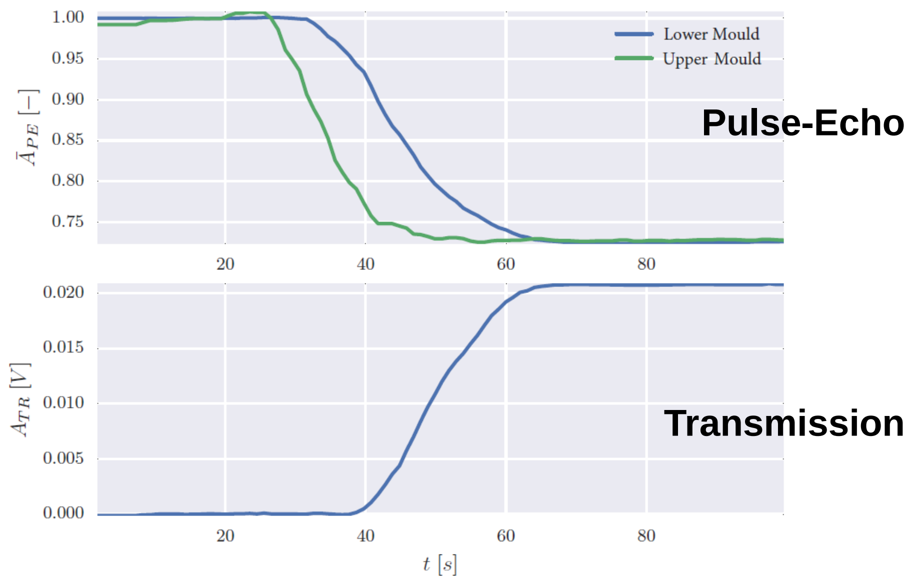
**Low cost ultrasonic process monitoring sensors**

# Flow Front Monitoring

- *Pulse-Echo:*
  - Before resin arrival →Total reflection at mould-cavity-interface
  - On resin arrival → Reflection amplitude drops until sensor cross section is completely wetted, then constant

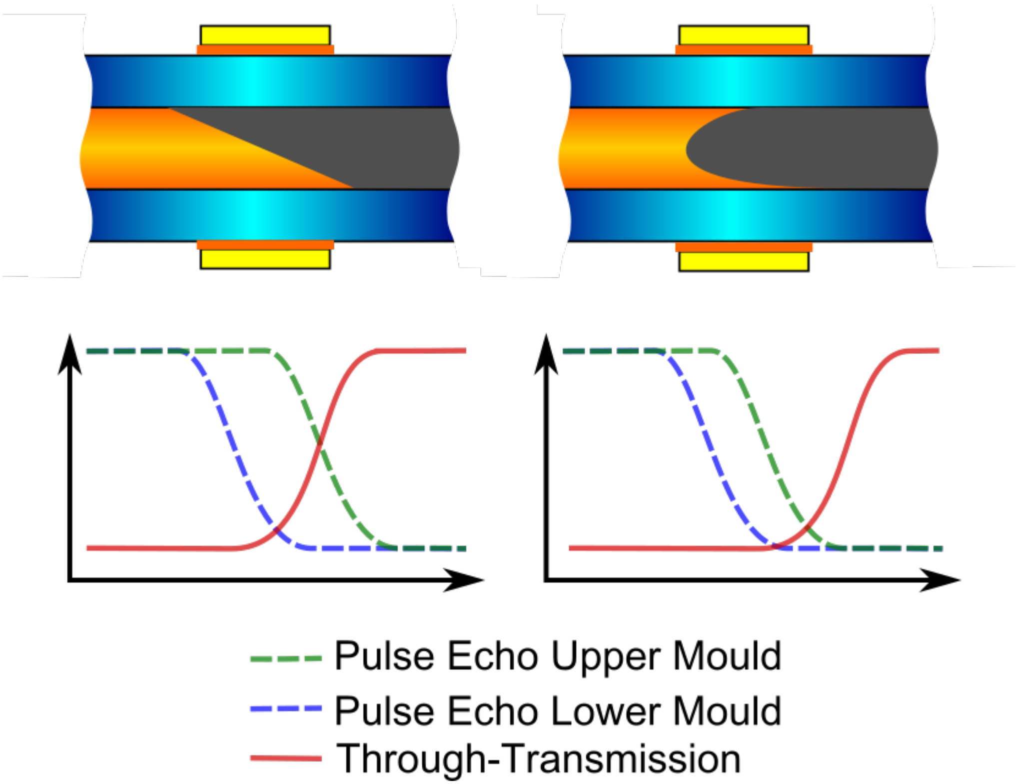
- *Transmission:*
  - Sound can only be propagated through wetted preform
  - Amplitude increases upon resin arrival until subsection completely filled over thickness
  - But gas bubbles etc. also attenuate amplitude → amplitude increase after the bubbles have passed



# Flow Front Monitoring

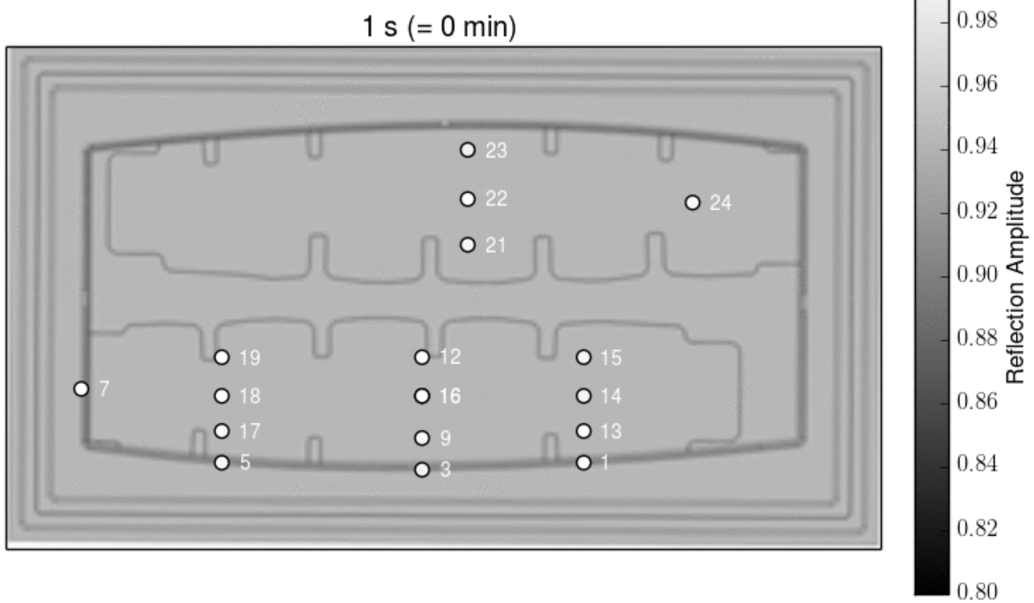
- Combination of the two pulse echo and the transmission signal can be used for flow front shape reconstruction
- Distinction between wedge and U shape
- Delay shows wedge angle

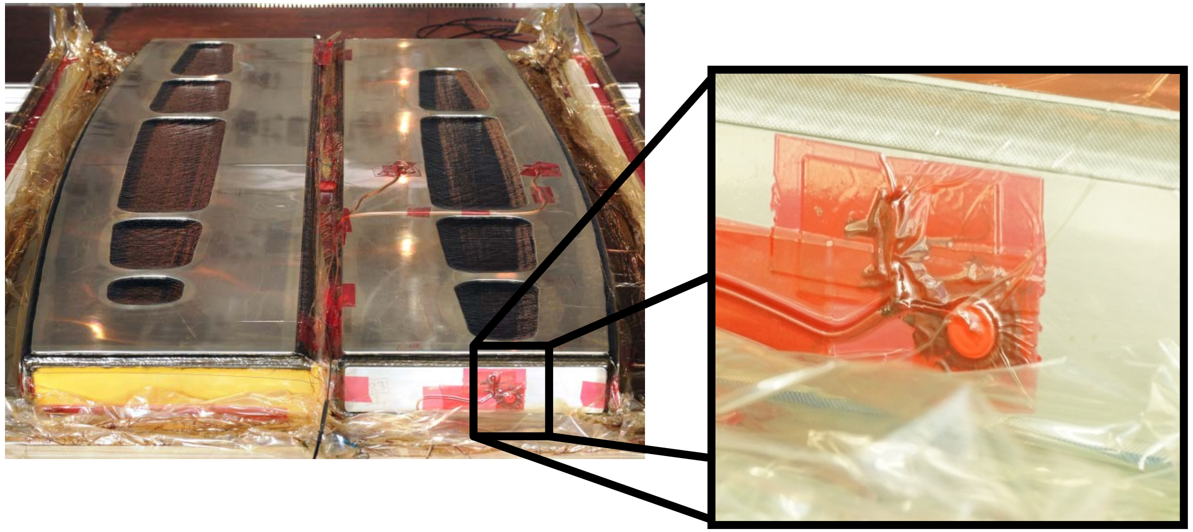


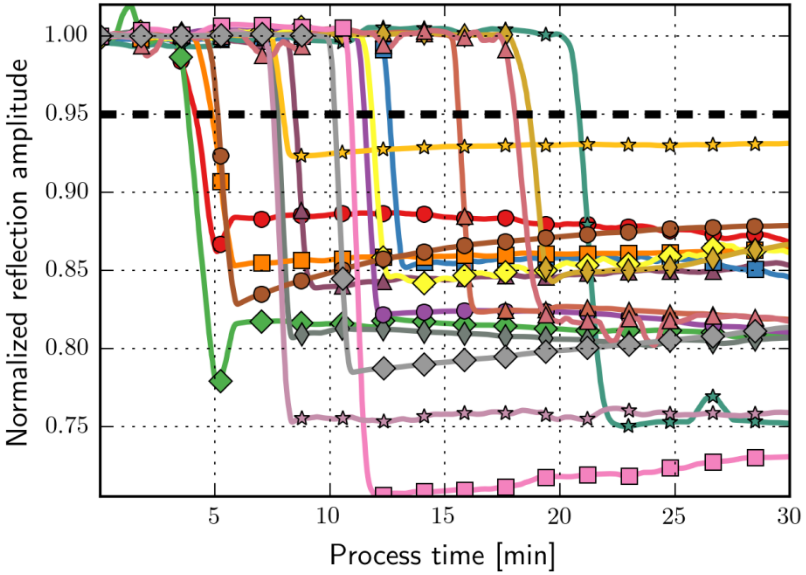

**Principle of reconstructing the flow front shape over thickness from sensor results**

# Flow Front Monitoring
## Application example

- Autoclave based infusion of two ribs of a wing box demonstrator
- EU project LOCOMACHS
- 24 ultrasound sensors
- Process close to industrial aeronautical manufacturing





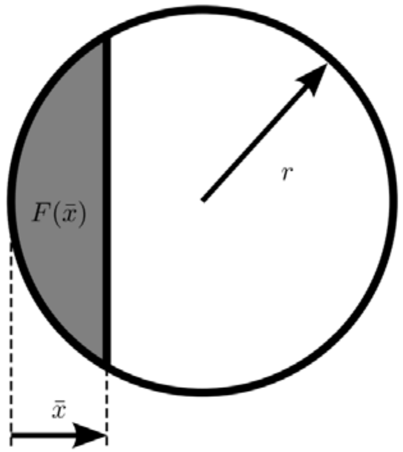
# Flow front velocity monitoring

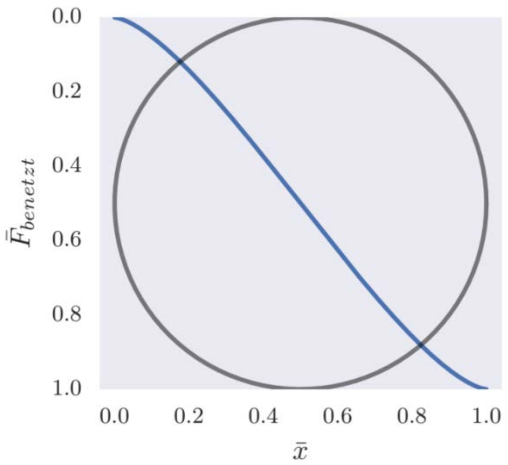
- Reflection amplitude depends on ratio of wetted sensor cross section

$$\bar{A}_{PE} = 1 - \frac{S_{wetted}}{S_{Sensor}} \cdot \left(1 - \frac{R_1}{R_0}\right)$$

- Amplitude drop speed depends on flow front speed

→ Flow velocity = Sensor Dimension / Time span of amplitude drop

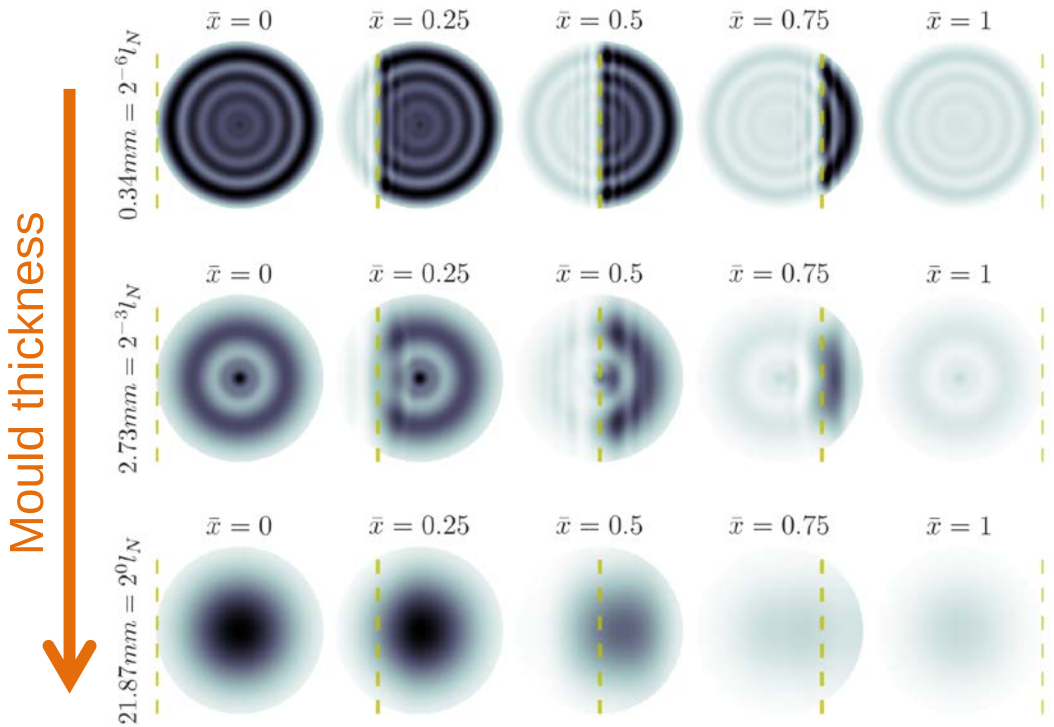


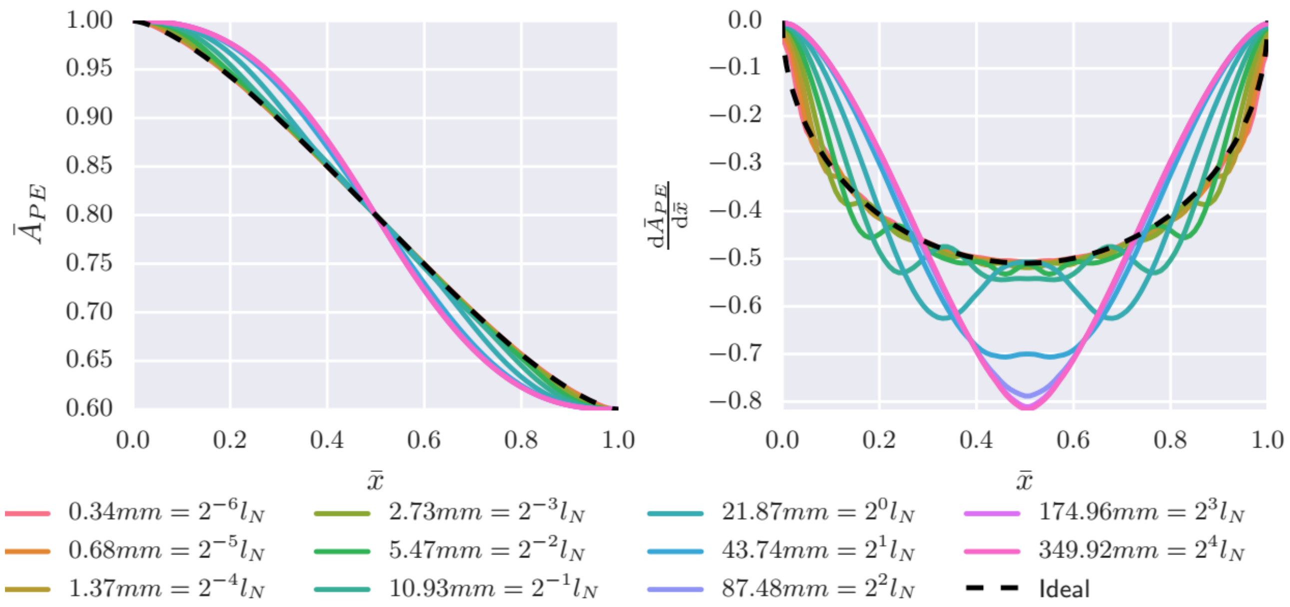



# Flow front velocity monitoring

## Simulation of pressure distribution and amplitude drop over flow front position

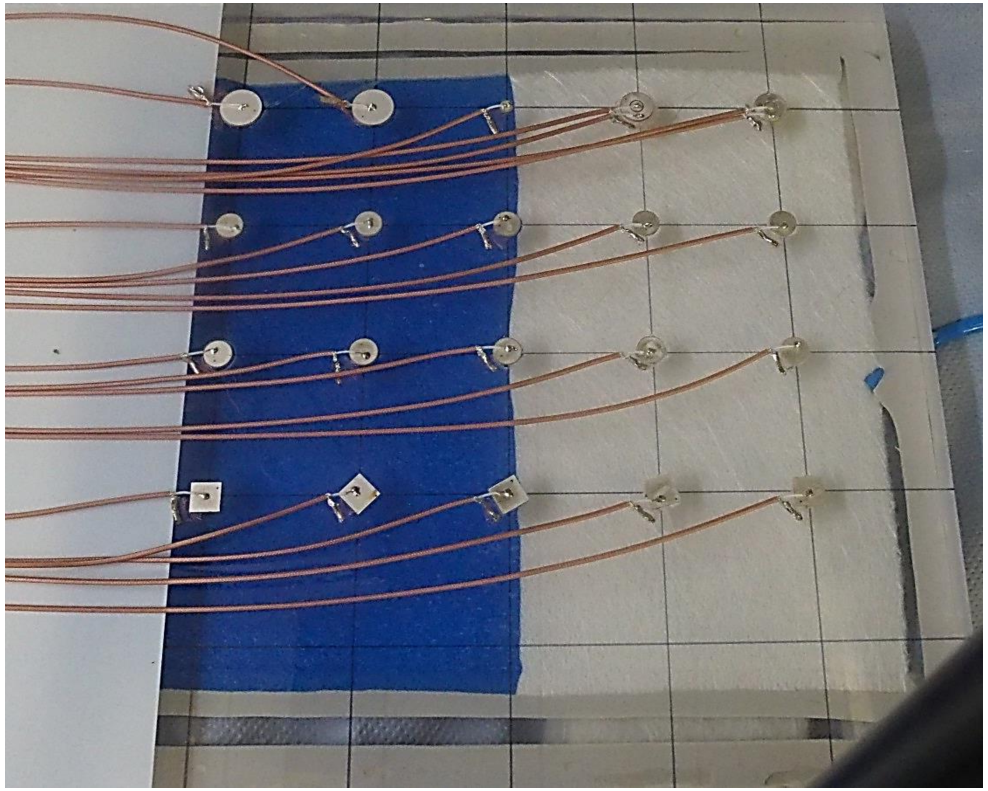
- In reality pressure field not homogenous and depending on mould material and thickness
- With increasing mould thickness pressure focused on center, effective sensor diameter reduced
- For precise velocity measurement correction (simulation) or calibration (measurement) needed

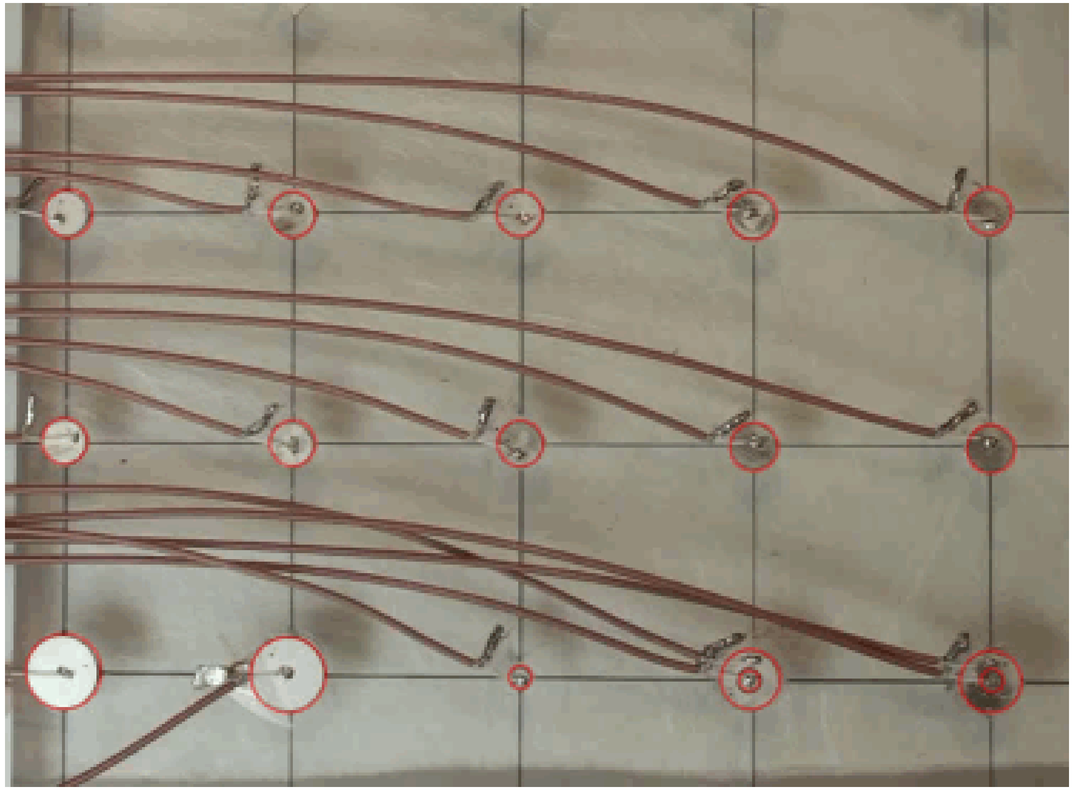


# Flow front velocity monitoring

- Validation with transparent mould (PMMA) and image processing for flow front position and velocity and sensor contour

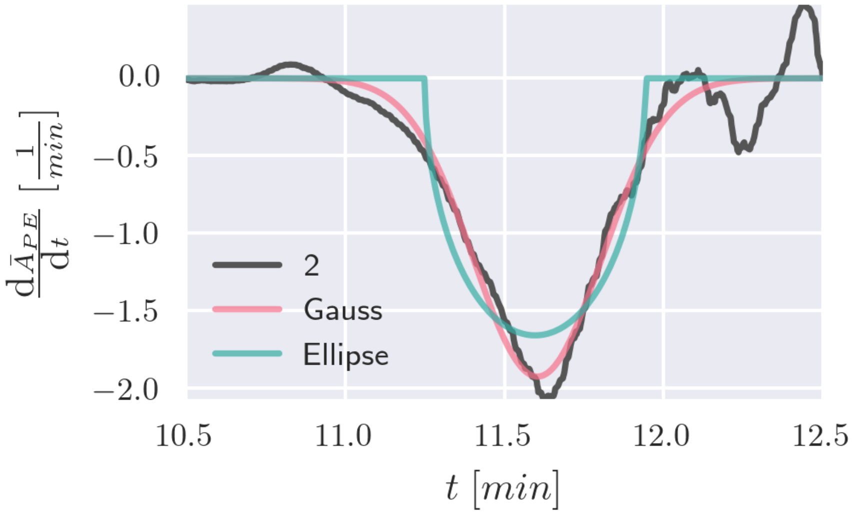


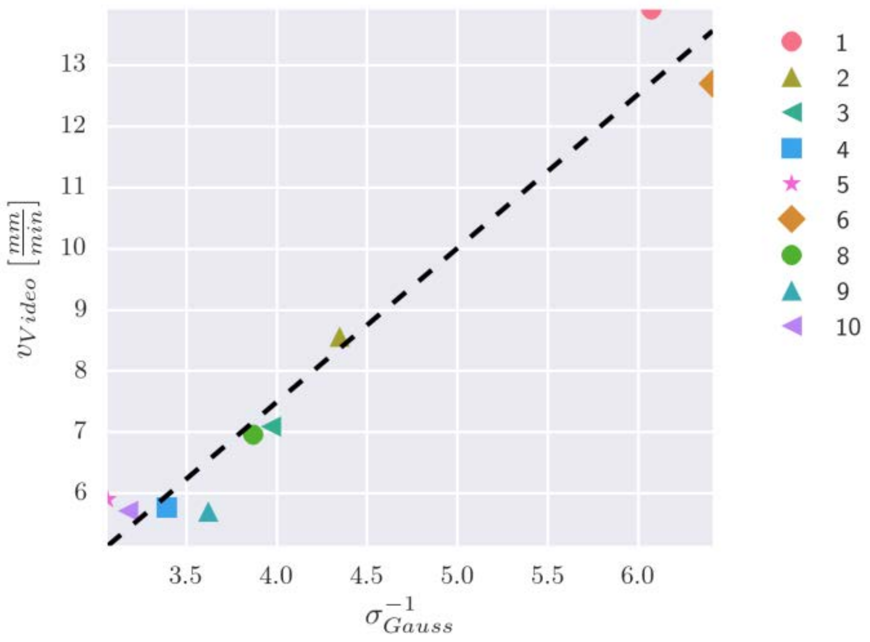


OpenCV

# Flow front velocity monitoring

- Flow velocity obtained by curve fit into measured curve
- Nomalized error ~3.5%
- Correction factor required, can be obtained from pressure field simulation or through calibration
- Works for thin and thick mould walls

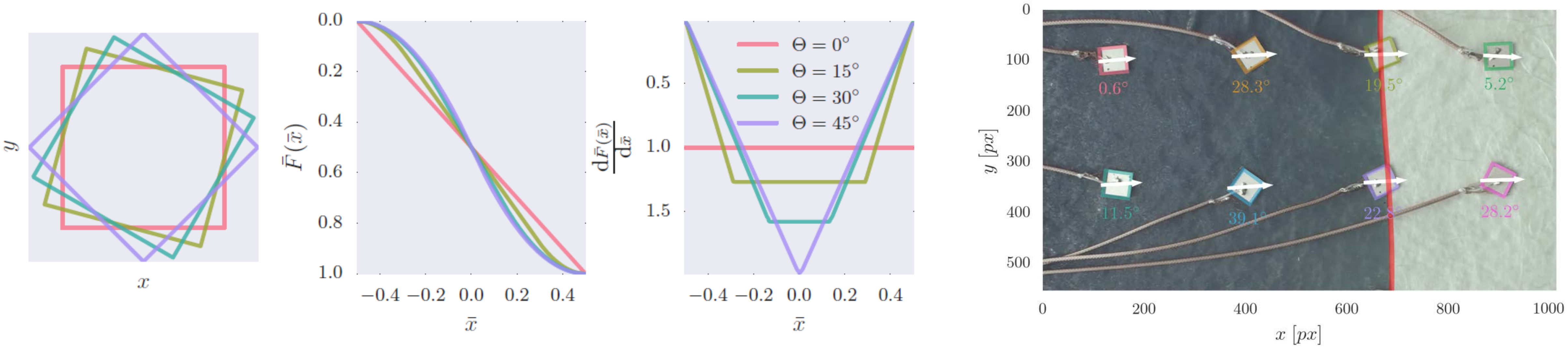


# Flow front direction monitoring

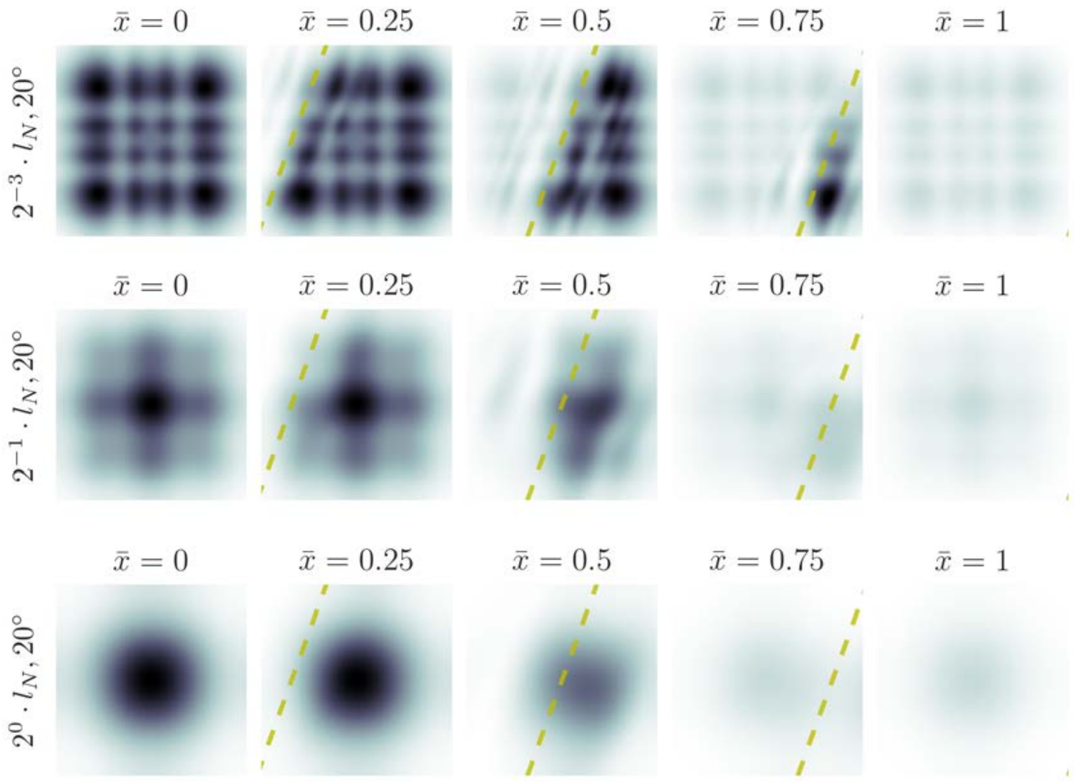
- Amplitude drop curve depends on flow direction for sensors that are not rotationally symmetric
- → Using to estimate angle between flow direction and sensor

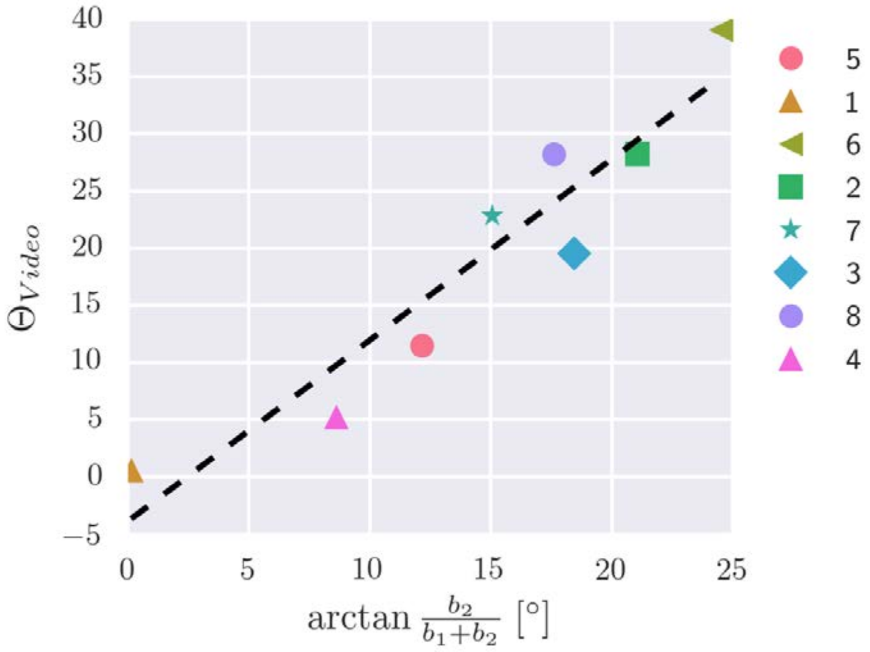
- Example of quadratic sensor:



# Flow front direction monitoring

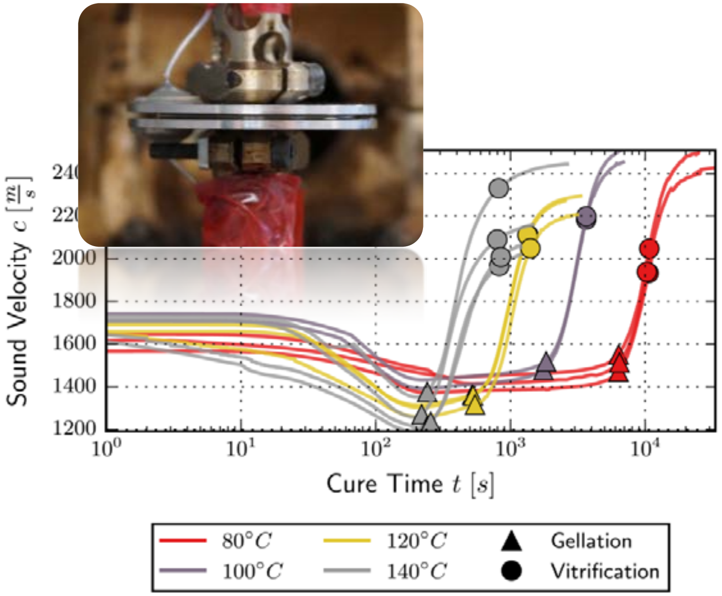
- Quadratic character only at low mould thicknesses
- Only for small mould thicknesses a precise angle measurement is possible



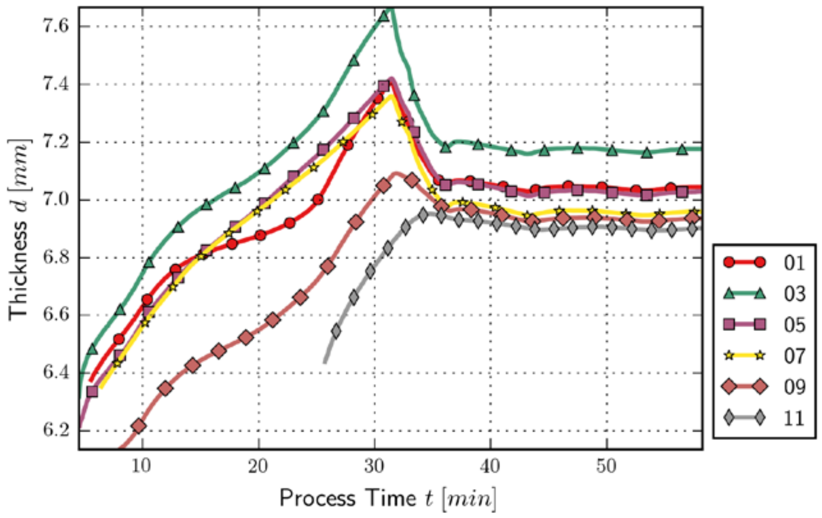



# Laminate thickness monitoring

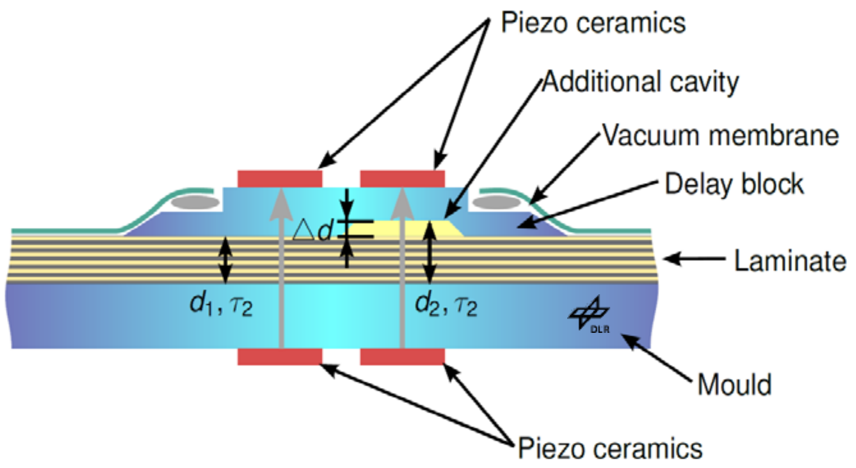
- Time of flight of transmission signal = Laminate thickness / Sound velocity
- In general low increase of sound velocity before gelation
- In this case very slow reacting resin at infusion temperature → Sound velocity increase negligible
- Compensation through calibration measurement or special sensor setting




Gellation and vitrification points

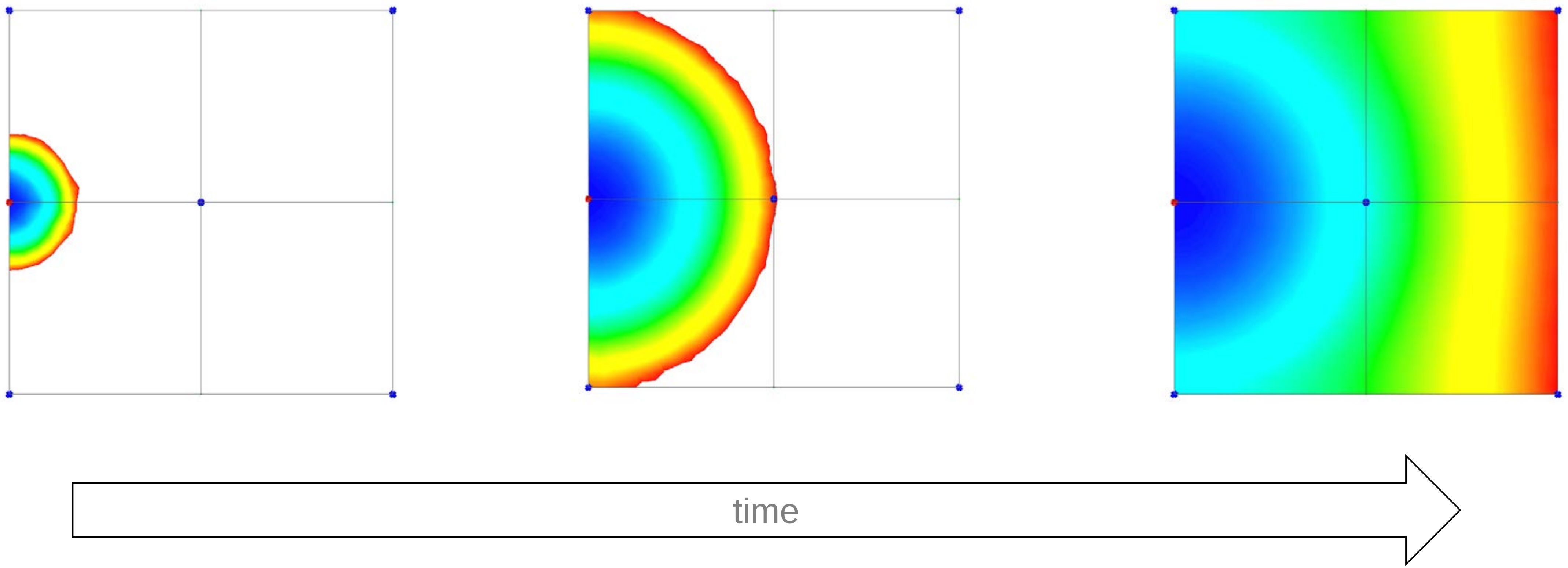



Laminate thickness monitoring by ultrasound

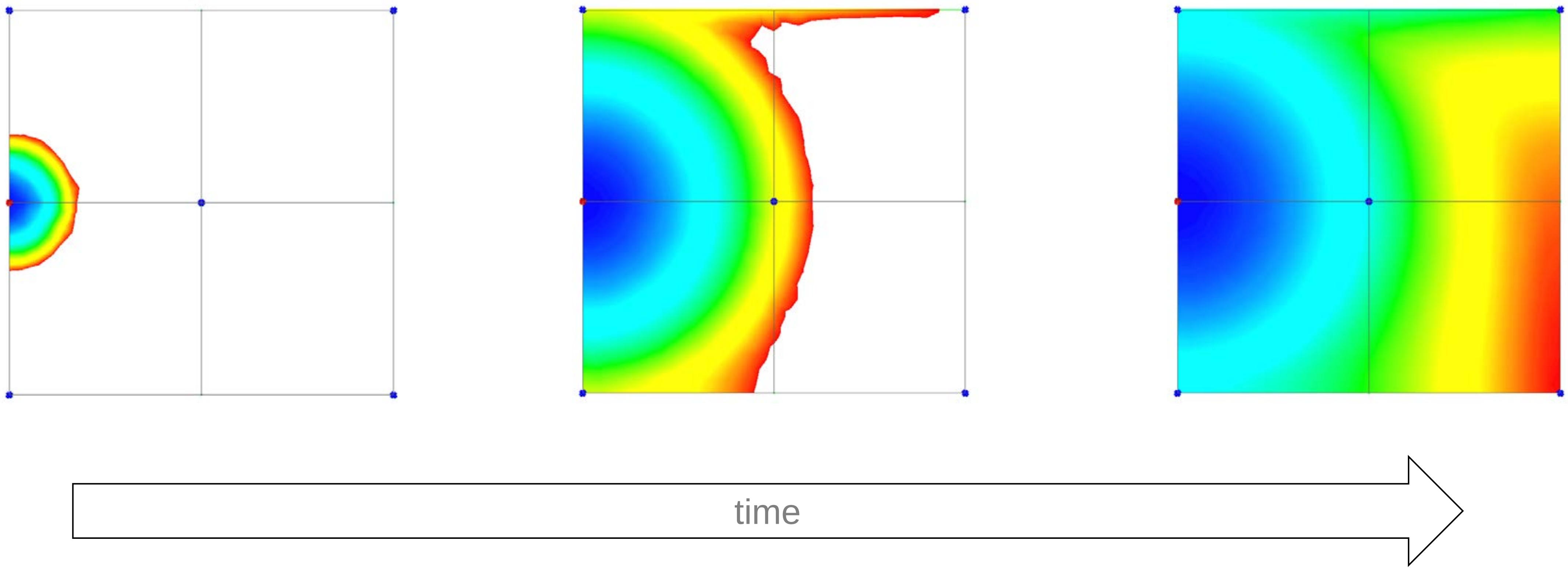



Sensor setting for separate sound velocity and thickness measurement

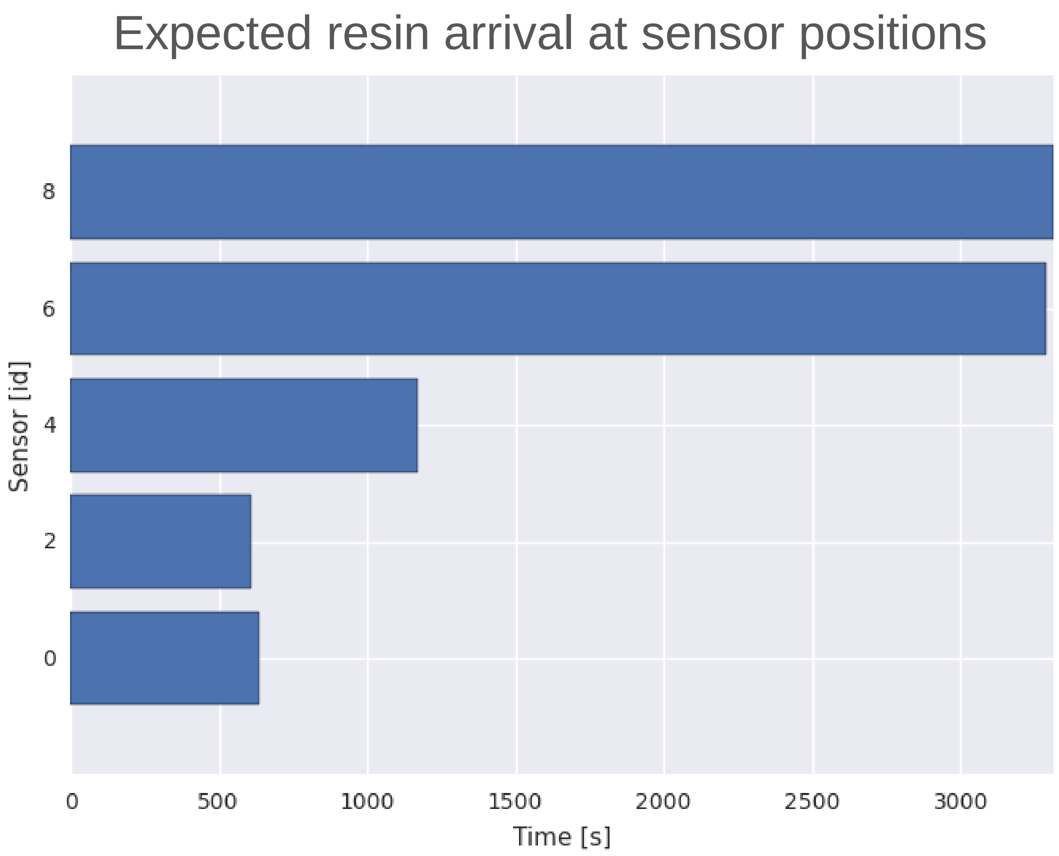
# Monitoring and forecast system
## Expected flow front propagation

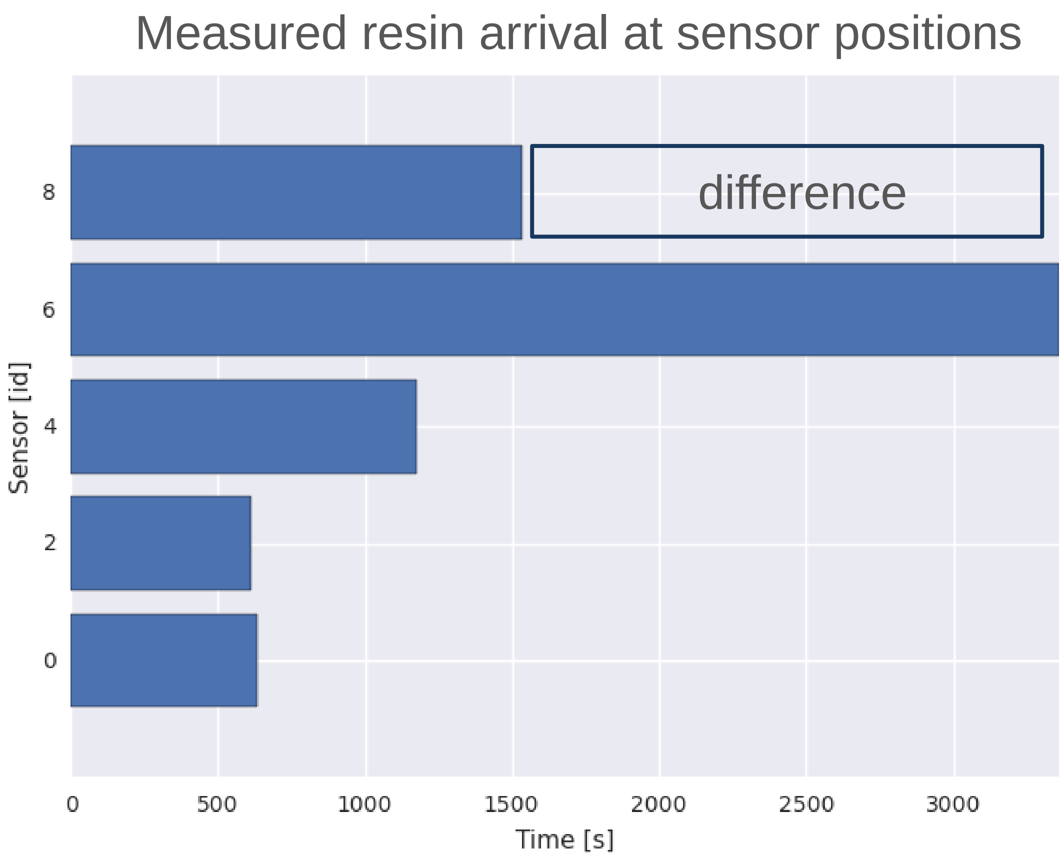


# Monitoring and forecast system
## What we might get

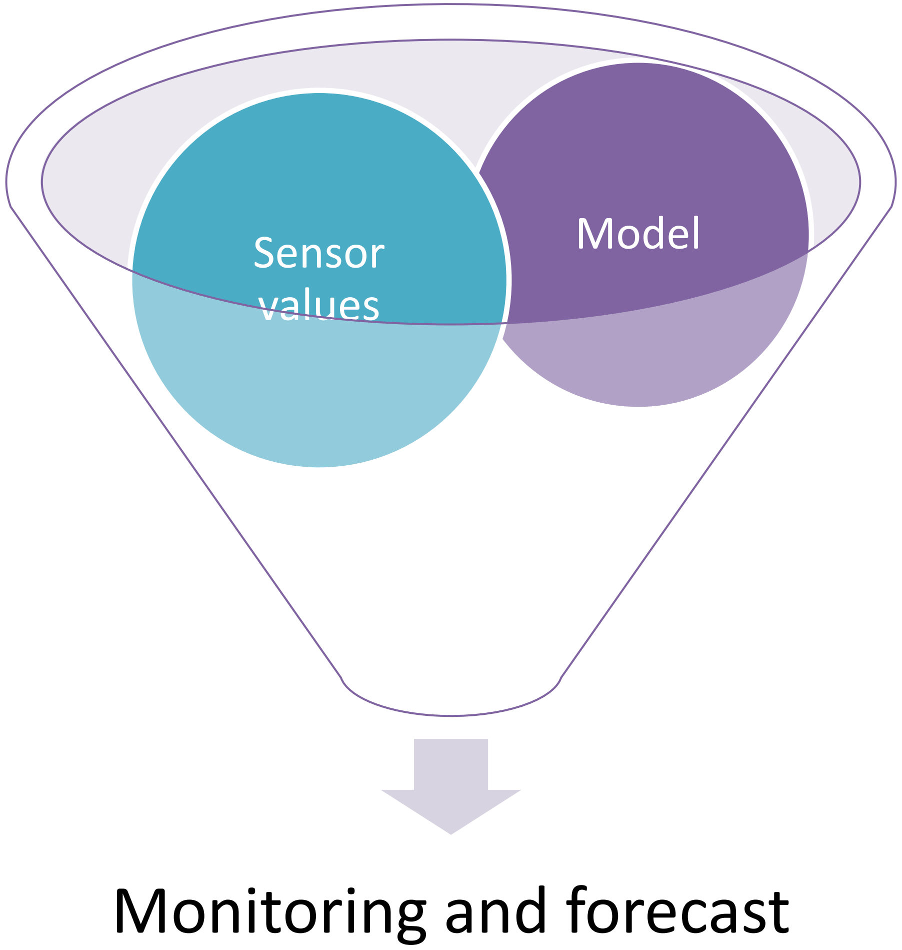


# Monitoring and forecast system
## Sensor values

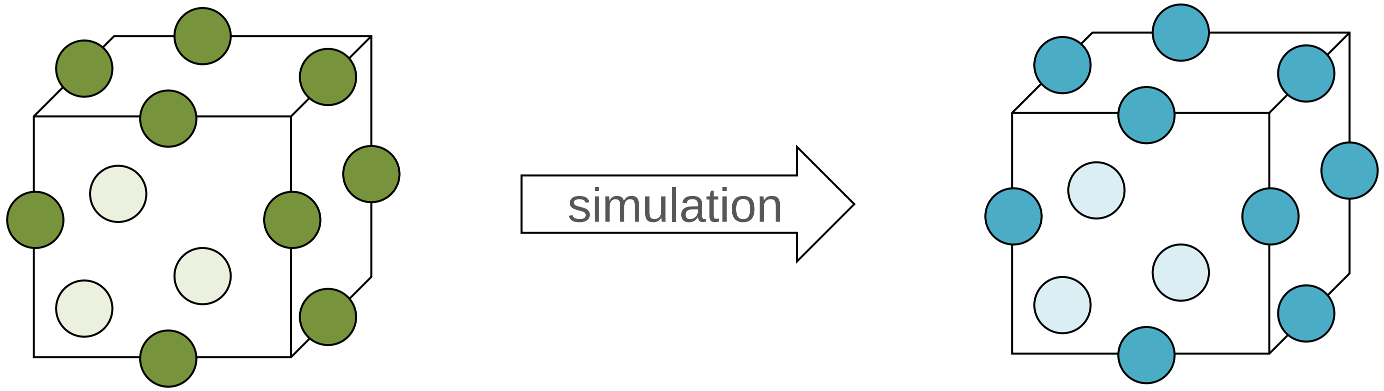


# Monitoring and forecast system
# The way it should work



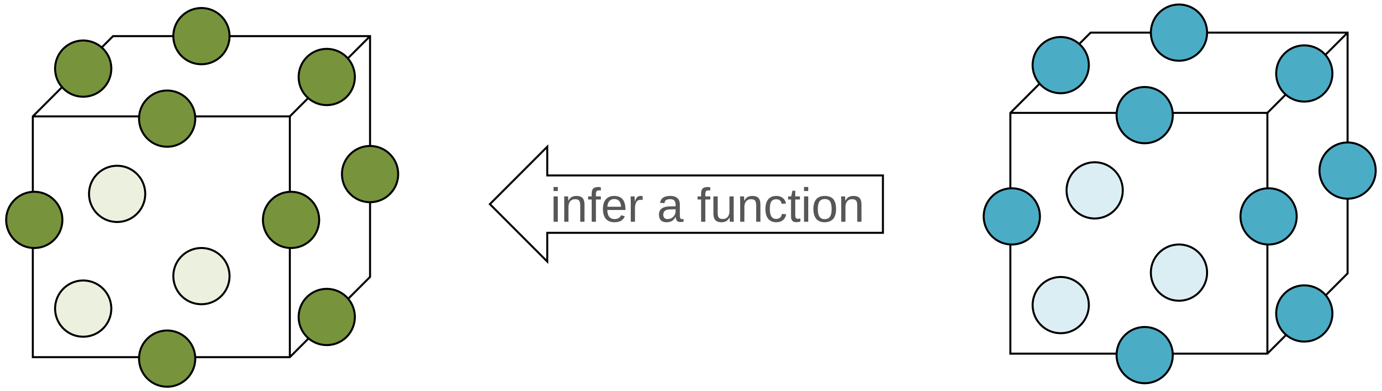
# Monitoring and forecast system
## Design of experiments and generation of training data




Variation of simulation parameter

Training data (sensor values)

# Monitoring and forecast system
# Supervised machine learning



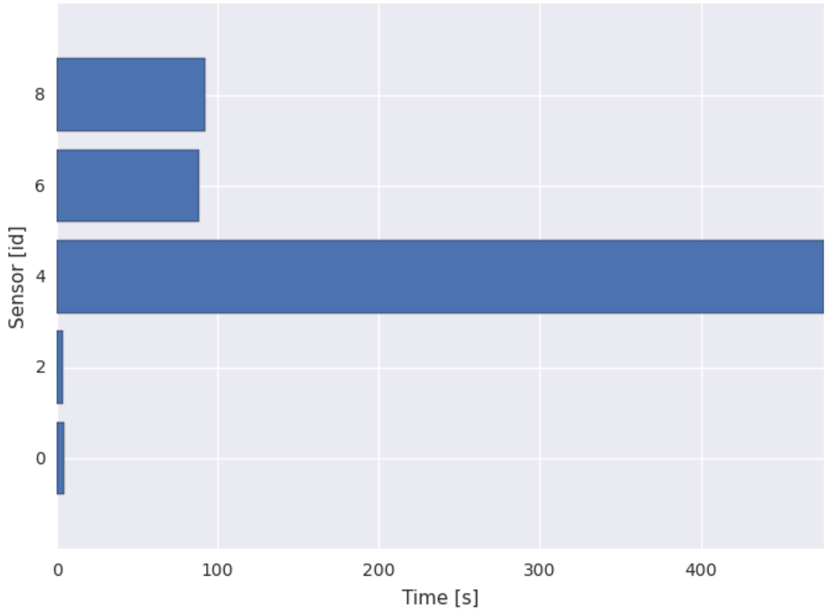

Variation of simulation parameter

Training data (sensor values)

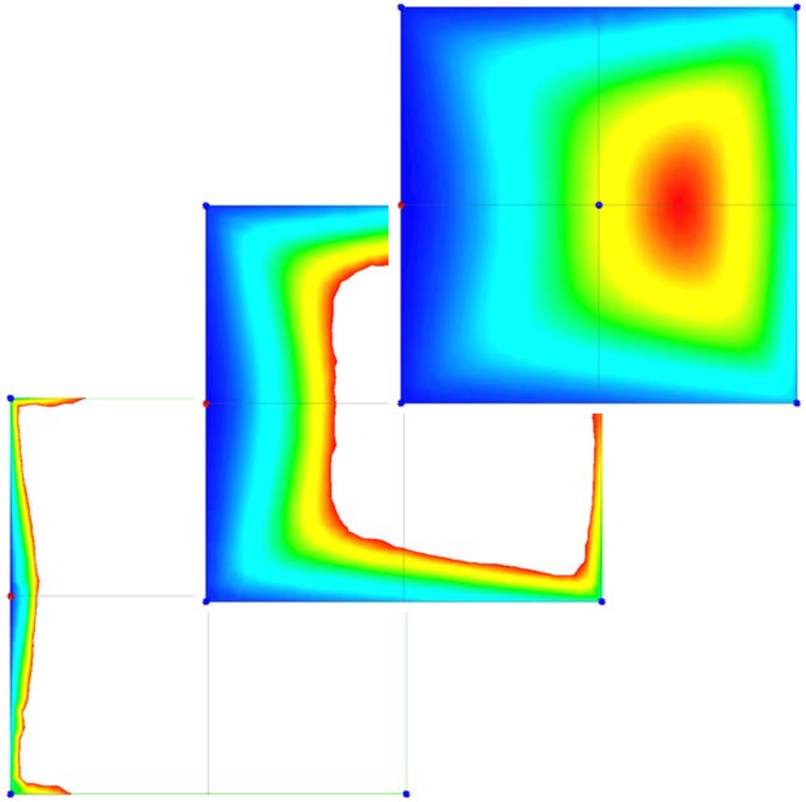
# Monitoring and forecast system

## Predict parameter, visualize current degree of filling and forecast further process evolution

Resin arrival at sensor positions




Predict best fitting simulation parameter



# Conclusions

- Low cost ultrasound sensors
- No contact to part required
- Allow high number of sensors
- Monitoring of the most crucial parameters:
    - Flow front arrival, shape, velocity (and direction)
    - Laminate thickness
    - Cure, gellation, vitrification

- Only experts can forecast risk of incomplete fill from sensor data
- Solution:
    - Using a machine learning algorithm to find simulation parameters that match sensor data
    - Run simulation to forecast infusion
    - Rate infusion forecast and decide if measures have to be undertaken
    - Algorithm trained through simulation results with varied process parameters

# Thank you for your attention!