4th 3D Metrology Conference 2019
Automation – Digitization – Data Intelligence

SMART AND DIGITALLY-ENABLED MULTI-WAVE LIGHT SENSOR TECHNOLOGY

ALL-IN-ONE TOOL FOR CLOSED-LOOP FABRICATION, INSPECTION AND QUALITY CONTROL

Presented by: Pasquale Franciosa

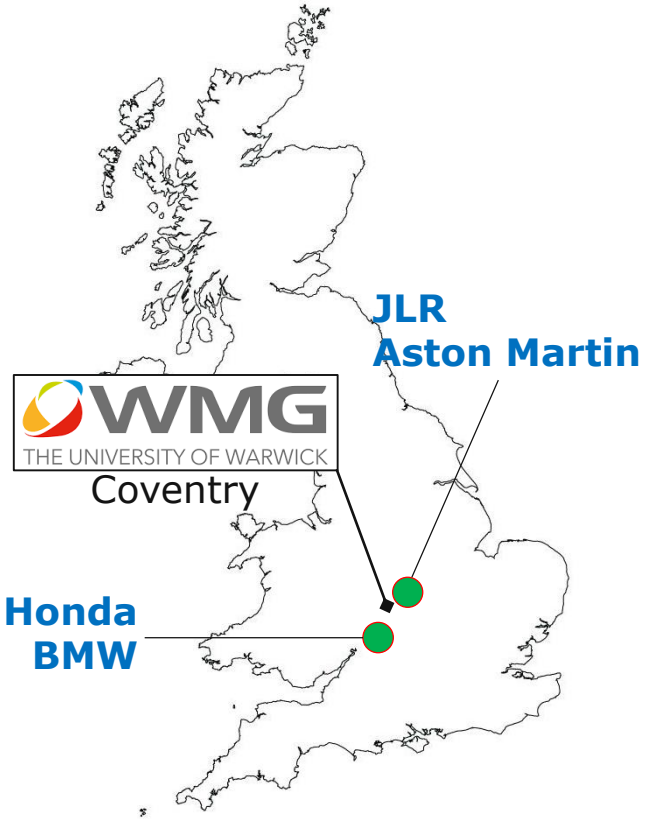
Pasquale Franciosa, Darek Ceglarek
Warwick Manufacturing Group (WMG), University of Warwick, Coventry, United Kingdom

Here East, London 5th – 7th November 2019

WMG @ WARWICK UNIVERSITY

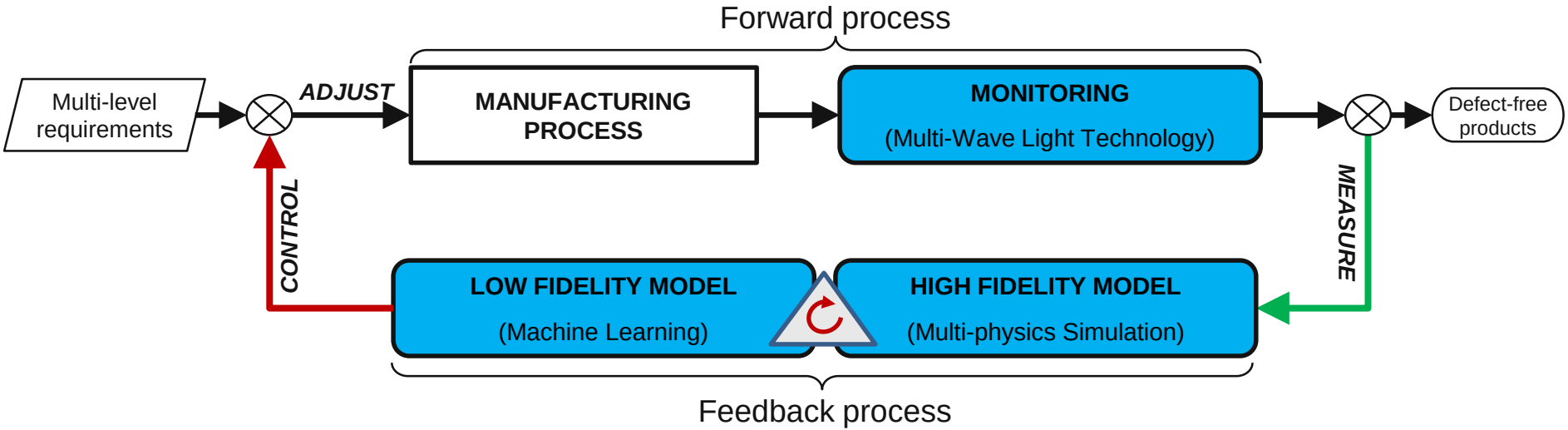
- An academic department at the **Uni. of Warwick, UK**
- Employing over 700+ staff
- Working across seven research and education centres on the Warwick campus
- An annual programme of £200m (industrial and in-kind support)
- Strong relationships with over 1,000 global companies, and supporting 1,800 SMEs
- Strategically located in the heart of the **Automotive Hub**
- Part of the **HVM Catapult network**

Supporting product & process maturation from concept (TRL 3-4) to pre-production (TRL 6-7)



OUR MOTIVATION/VISION

CLOSED-LOOP IN-PROCESS (CLIP) QUALITY CONTROL

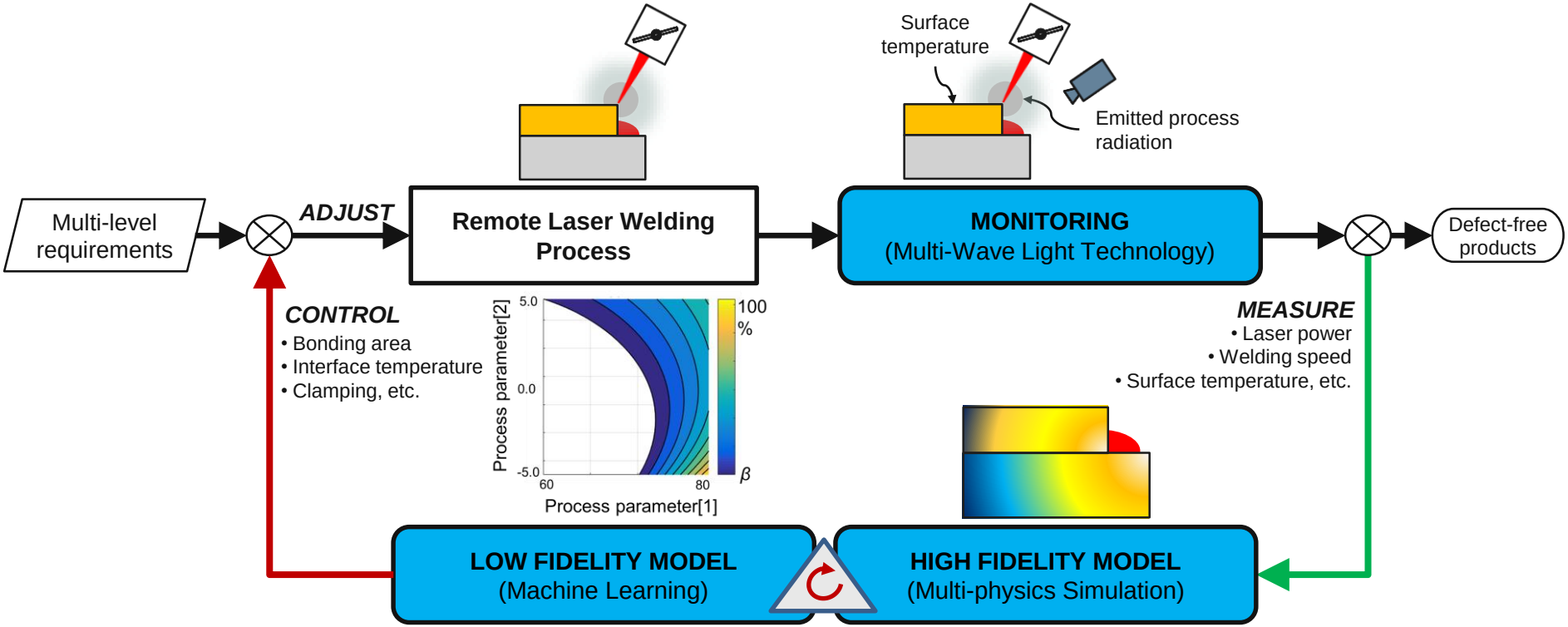


THE KEY CHALLENGES (the 4 «V»)

(1) Velocity - speed at which new data is generated in-process
(2) Volume - amount of data generated in-process
(3) Variety - types of data generated in-process
(4) Veracity - trustworthiness of the data

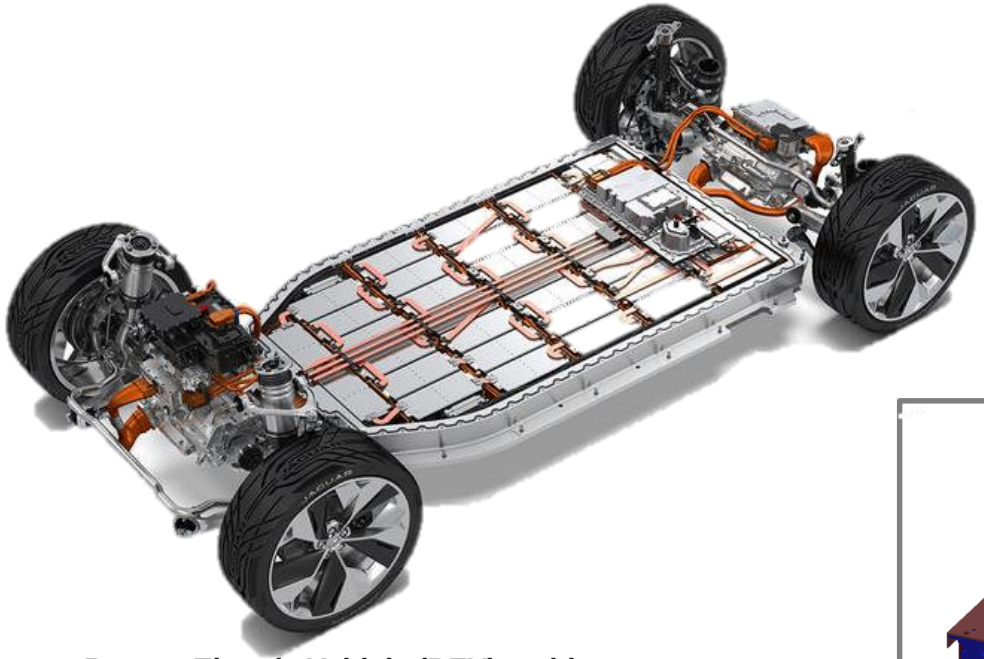
… LET'S PUT INTO CONTEXT

AUTOMOTIVE BATTERY ASSEMBLY WITH REMOTE LASER WELDING



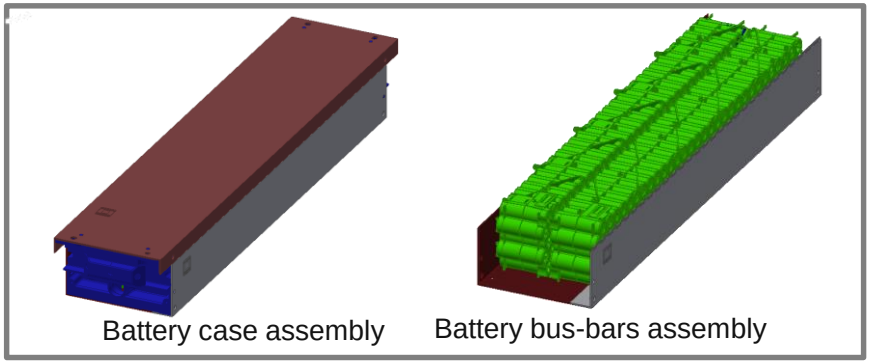
… LET'S PUT INTO CONTEXT

AUTOMOTIVE BATTERY ASSEMBLY WITH REMOTE LASER WELDING



Battery Electric Vehicle (BEV) architecture

BEV battery pack

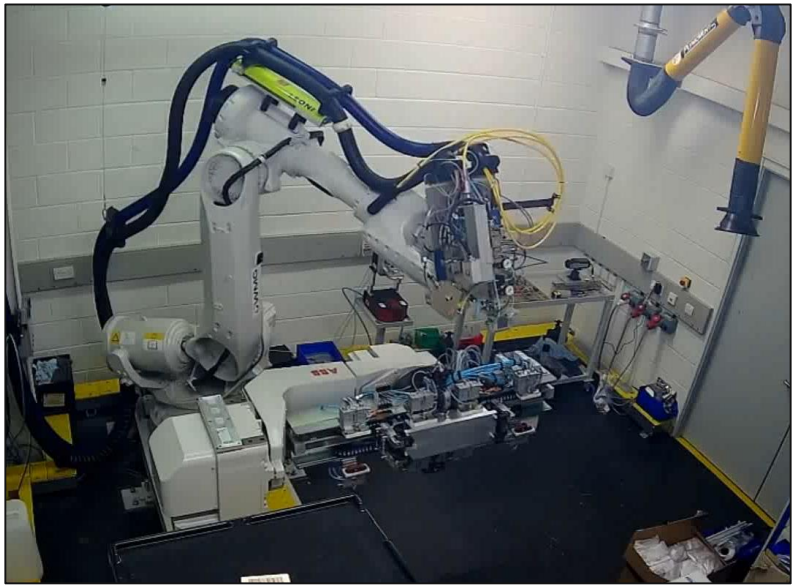


BEV battery module

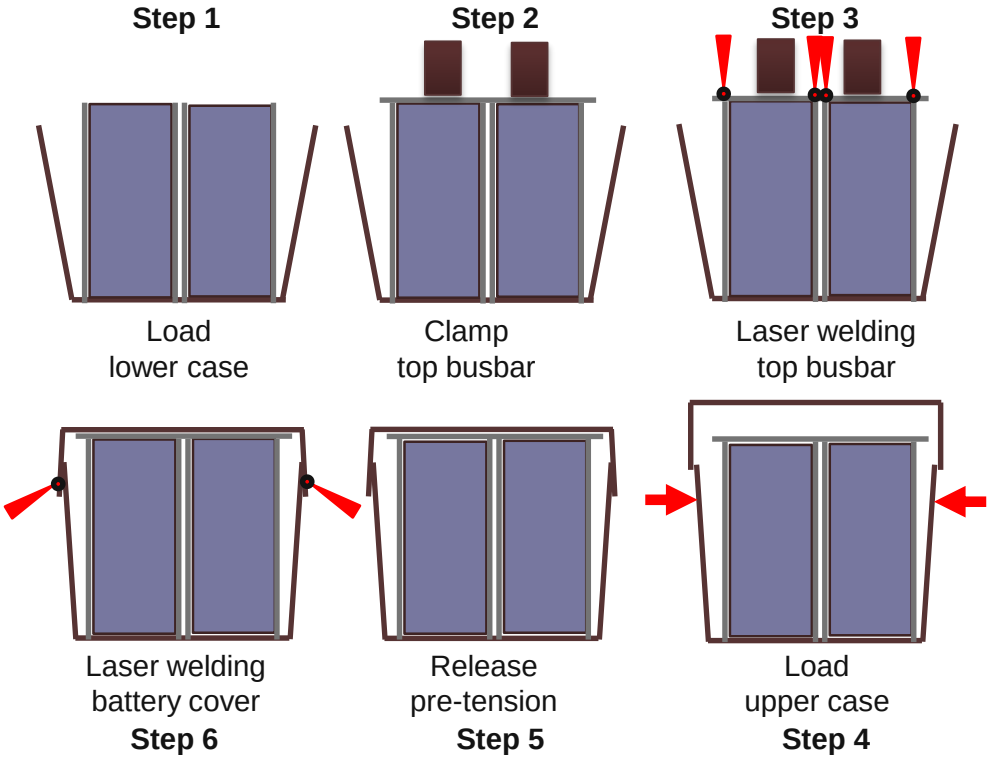
https://jalopnik.com/the-fascinating-engineering-behind-vws-electric-car-pla-1829257860

… LET'S PUT INTO CONTEXT

AUTOMOTIVE BATTERY ASSEMBLY WITH REMOTE LASER WELDING

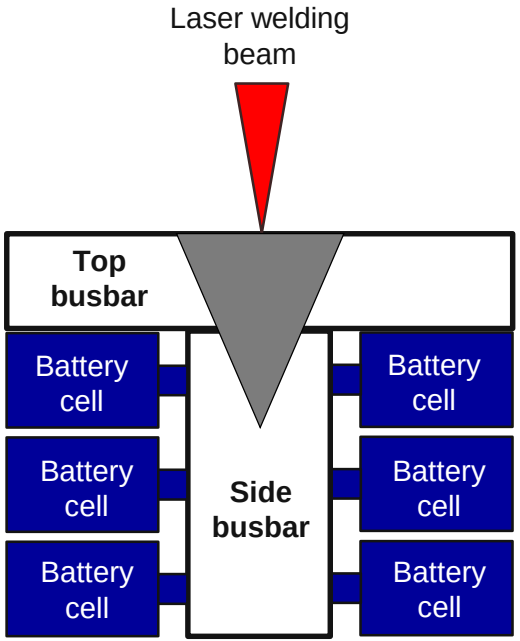


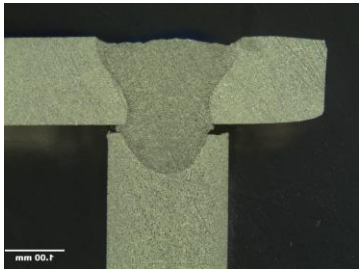
Demonstration of Step 6



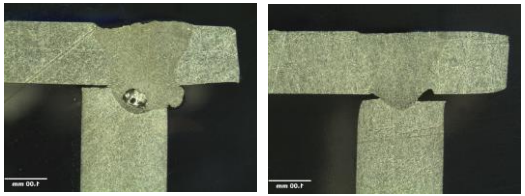
… LET'S PUT INTO CONTEXT

AUTOMOTIVE BATTERY ASSEMBLY WITH REMOTE LASER WELDING





Example of sound weld



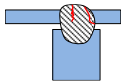
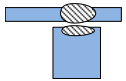
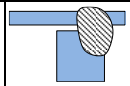
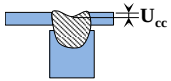
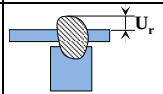
Example of defective weld

Failure of battery cell subject to temperature raise (abuse testing)

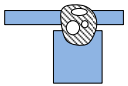
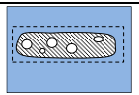
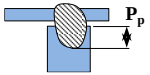
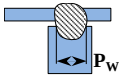
… LET'S PUT INTO CONTEXT

AUTOMOTIVE BATTERY ASSEMBLY WITH REMOTE LASER WELDING

Seam surface-related defects

ID	KEY QUALITY INDICATOR	PICTORIAL IMAGE	ALLOWABLE VALUE (Quality level "C")
1	Cracks, Crater cracks, Shrinkage cavity		Not permitted
2	Seam discontinuity		Not permitted
3	Side weld		Not permitted neither LH nor RH
4	Seam concavity, Ucc		Ucc ≤ 0.2· upper thickness
5	Seam roll-up, Ur		Ur ≤ 0.5mm

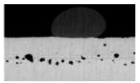
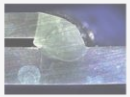
Inner defects

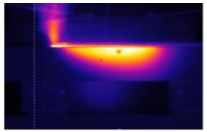
ID	KEY QUALITY INDICATOR	PICTORIAL IMAGE	ALLOWABLE VALUE (Quality level "C")
6	Pores (cross section)		(1) Max pore diameter ≤ 0.1 · upper thickness (2) Sum of pore diameter ≤ 0.05 · total cross section area
7	Pores (longitudinal section)		(1) Max pore diameter ≤ 0.1 · upper thickness (2) Sum of pore diameter ≤ 0.05 · total cross section area
8	Depth of fusion, Pp		Pp ≥ 0.25·bottom thickness
9	Leg length, Pw		Pw ≥ 1.4mm (assuming effective welding length 24mm)

OPPORTUNITY

MULTI-WAVE LIGHT TECHNOLOGY – "ALL-in-ONE: fabrication-monitoring-inspection-control"

"Micro-scale" — **Multi-scale Data** — "Macro-scale"



Multi-level Requirements

Key Performance Indicators (KPIs)	• Grain structure • Phase distribution	• Chemical composition • Weld porosity	• Joint structure • Dimensional integrity	• Joint structure	• Thermal profile (high temperature) • Joint structure	• Thermal profile (low temperature)
Multi-dimensional & Multi-type Data	• 2D pixel	• 2D pixel • 3D voxel	• 1D signal • 2D pixel • 3D cloud of points	• 1D signal • 2D pixel	• 1D signal • 2D pixel	• 1D signal • 2D pixel
Key Measurement Characteristics (KMCs)	• SEM	• CT • EDX	• Optical measure • Laser radiation	• Plasma radiation • Laser radiation	• Thermal radiation • Laser radiation	• Thermal radiation • Laser radiation
Multi-Wave Light Technology						
(wavelength, λ)	Secondary electron **< 2 nm**	X-ray **< 10 nm**	Visible Light **[0.4 to 0.7] μm**	Near Infrared **[0.7 to 1] μm**	Short Infrared **[1 to 4] μm**	Long Infrared **[8 to 20] μm**

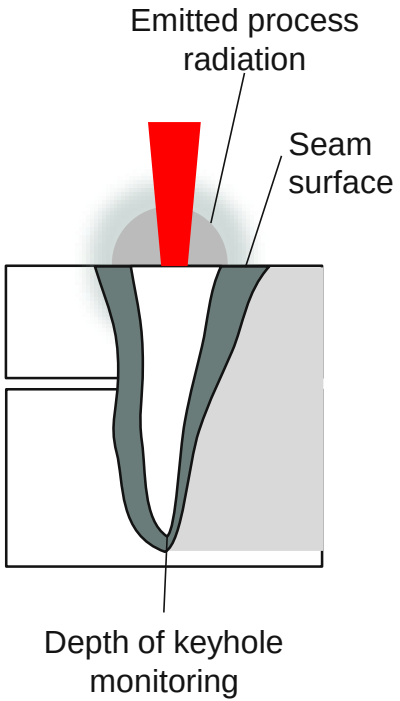
Off-process data streams

In-process data streams

OPPORTUNITY

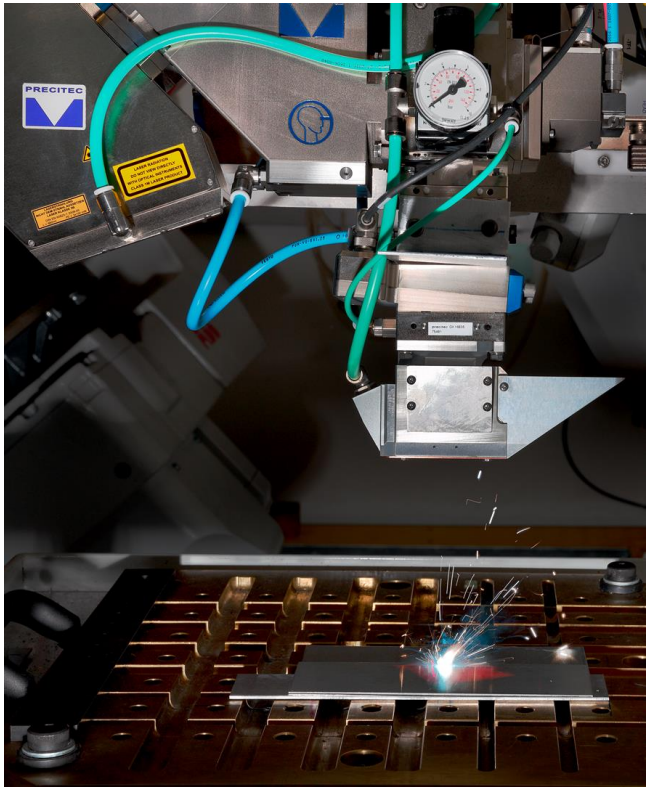
MULTI-WAVE LIGHT TECHNOLOGY

Mode of monitoring	Sensor	Measured seam quality indicator	Light Spectrum
Seam surface	Co-axial Camera	**Direct** measurement 1. Seam convexity 2. Seam discontinuity 3. Seam pores …	**Visible**
Depth of keyhole monitoring	Interferometer/ OCT	**Direct** measurement: 1. Seam penetration	**Infrared**

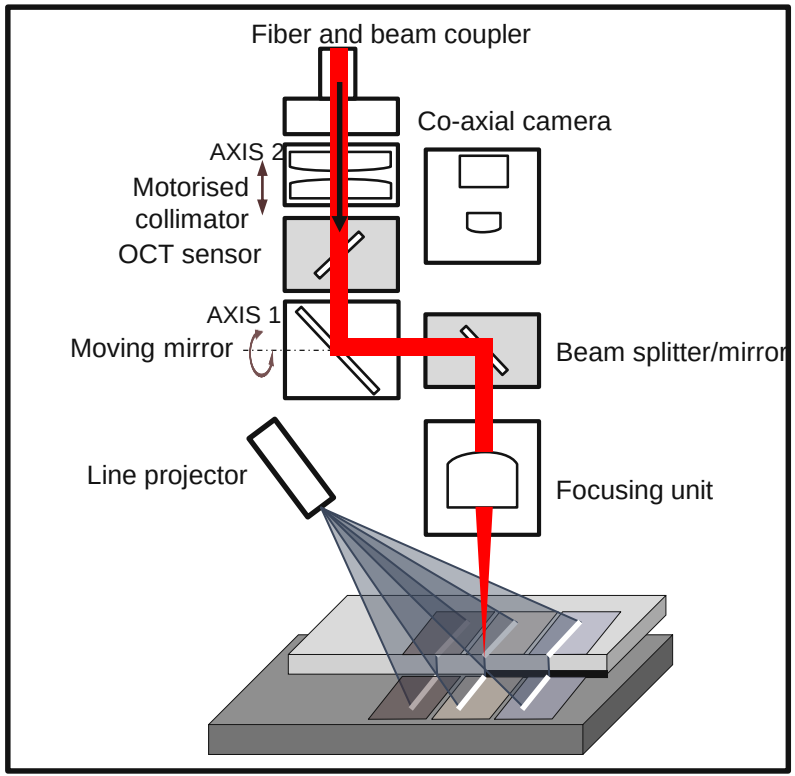


EXPERIMENTAL SETUP

- **Laser**: 6 kW diode laser (LaserLine GmbH, Germany), with a beam parameter product of 6 mm·mrad
- **Optical delivery**
  - Core fiber of 150 μm diameter
  - WeldMaster (near)remote welding head (Precitec GmbH, Germany), with 150 mm collimating length, and 300 mm focal length
  - Rayleigh length ~3.0 mm
- **Process**:
  - No shielding gas nor filler wire
  - Samples wiped with acetone before welding to remove surface contaminations



EXPERIMENTAL SETUP



Optical paths

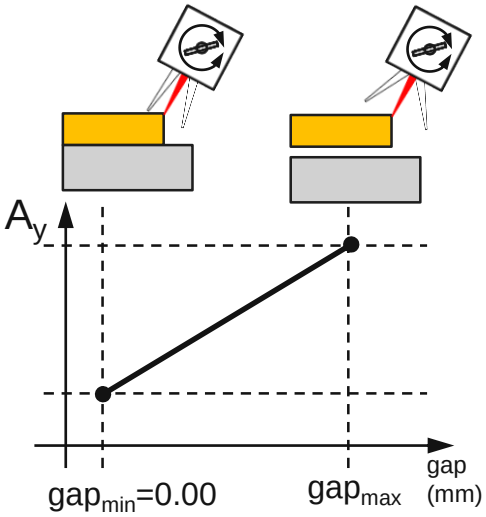
- Main beam delivery
- Co-axial camera
- OCT sensor

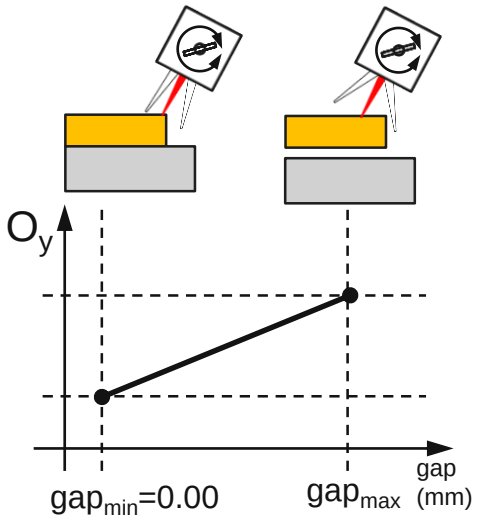
Wavelength spectrum: ~1080nm
(process laser radiation)

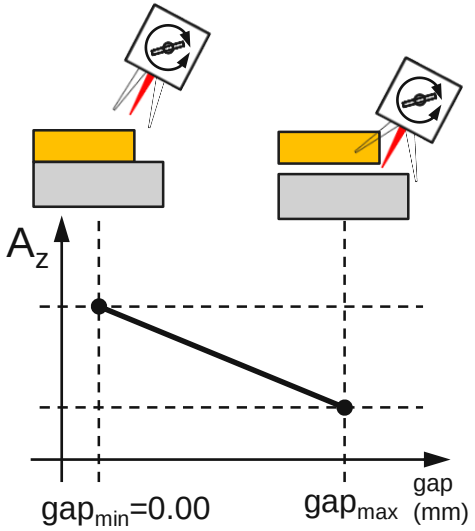
EXPERIMENTAL SETUP

Main beam delivery - CLOSED-LOOP GAP BRIDGING MODULE

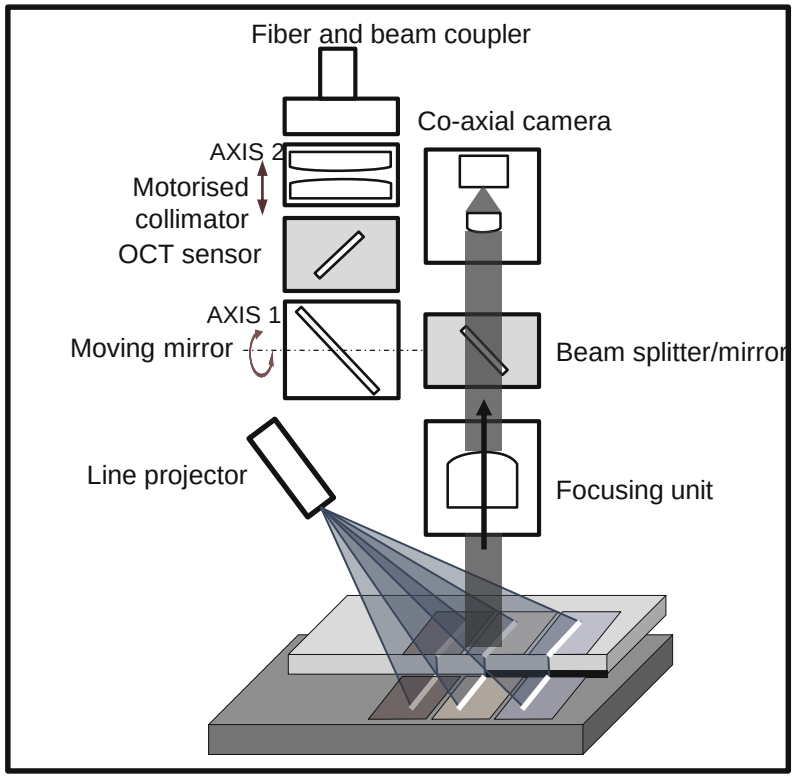
Adaptive modulation of welding process parameters to bridge part-to-part gaps







EXPERIMENTAL SETUP



Optical paths

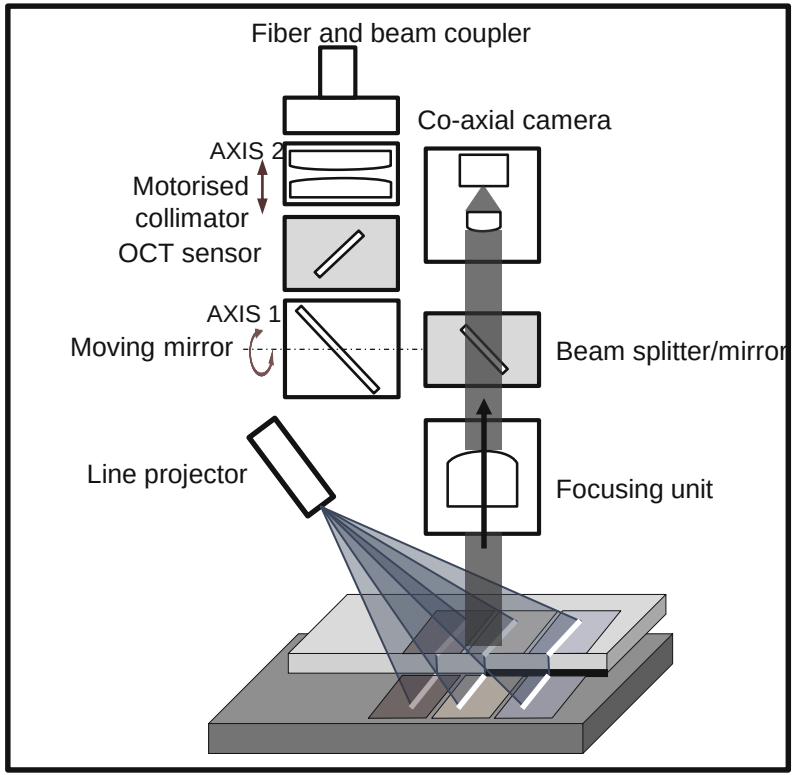
- Main beam delivery
- **Co-axial camera**
- OCT sensor

Wavelength spectrum: [400, 600]nm

Pixel size: 0.03 mm/pixel
Field of view: 30x30 mm
fps: up to 2400
Exposure: 1 ms
Image size: 468x650 pixel

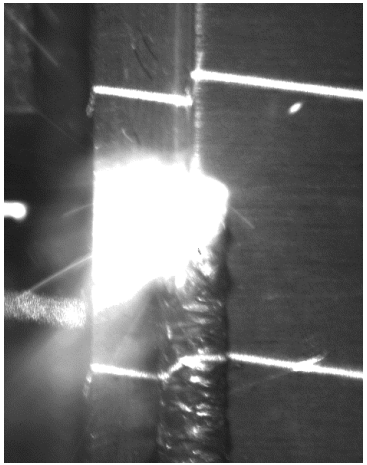
IN-PROCESS MONITORING

Co-axial Camera



- Seam INSPECT can detect only surface-related defects
- It is based on a “image processing kernel”
- Based on image threshold principle (grayscale / BW)

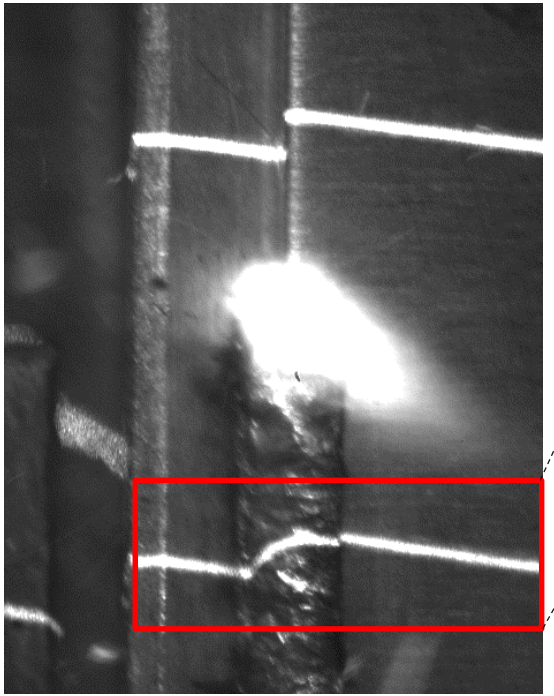
Typical image with “no-defect found”

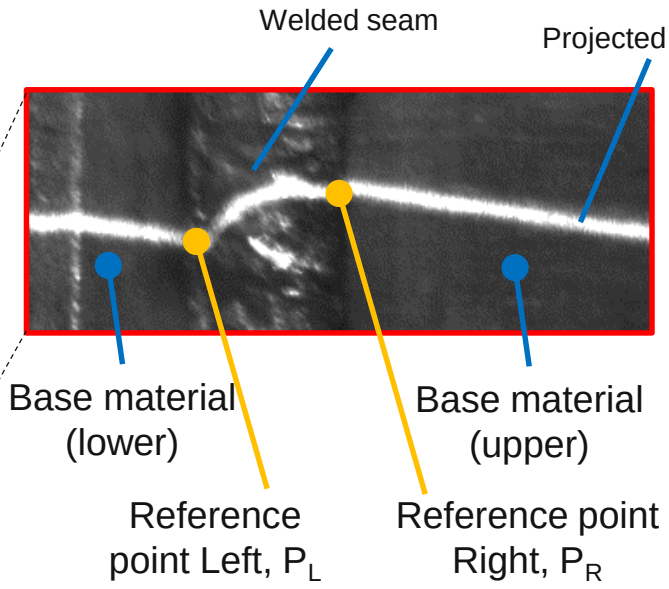


Typical image with “defect found”

IN-PROCESS MONITORING

Co-axial Camera





Key principles/steps

- Detection of projected laser line
- **Automatic detection of P_L and P_R**
- Calculation of measurement line through P_L and P_R
- Calculation of weld indicators (concavity, convexity, etc.)

IN-PROCESS MONITORING

Co-axial Camera

Automatic detection of P_L and P_R

Option[1]: image contrast between base material and welded seam
- Contrast could be improved by spectral filtering

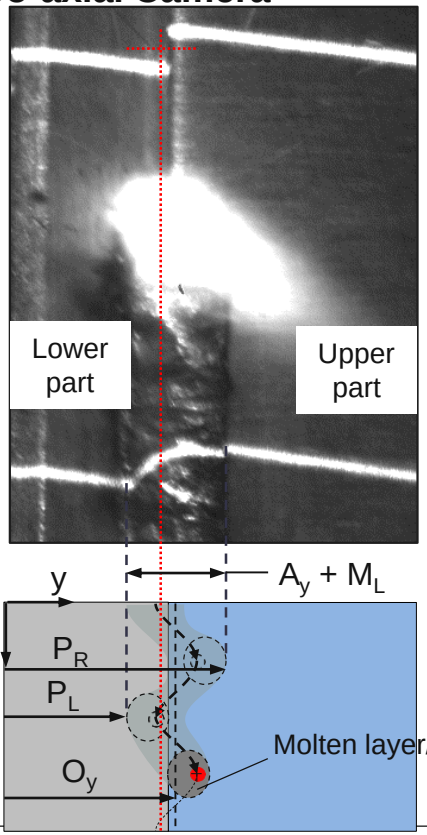
Option[2]: identify sharp variation (gradient) in the laser line
- To use gradient (first derivative of the laser line signal)
- Derivative affected by local noise (spatters, etc.). Calculation could be improved by spectral filtering

Option[3]: identify breaking points in the laser line
- To use laser line only => no gradient
- To implement a “Piecewise Linear Time Series Segmentation”

Option[4]: option[3] enhanced/augmented with multi-physics CAE simulation
- To use laser line only => no gradient
- To solve heat conduction mode (with keyhole) with moving laser beam source

IN-PROCESS MONITORING

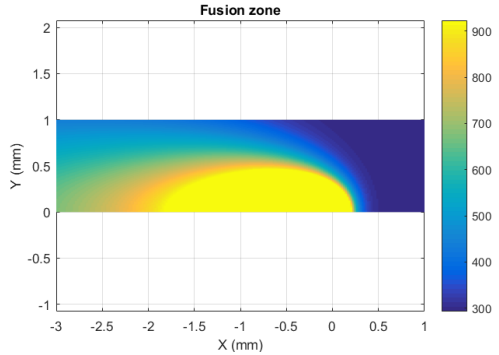
Co-axial Camera

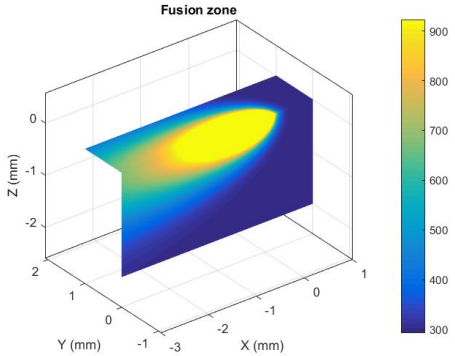


Key steps

- Calculate O_y from "**CLOSED-LOOP GAP BRIDGING MODULE**"
- Calculate A_y from "**CLOSED-LOOP GAP BRIDGING MODULE**"
- Define molten layer, M_L, (it depends on thermal properties of material)
- **Calculation of P_L and P_R** (in the image reference frame – "pixel")
  - $P_R = O_y + 0.5(A_y + M_{L,left})$
  - $P_L = O_y - 0.5(A_y + M_{L,right})$

Notice: M_L is pre-computed from multi-physics CAE simulation

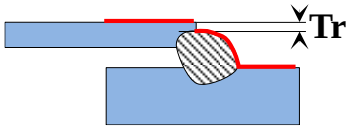
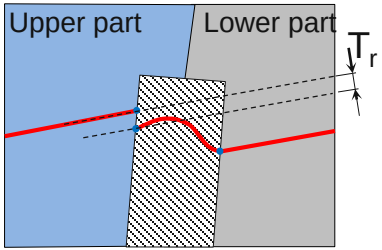


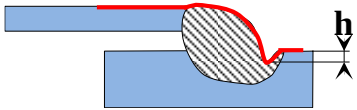
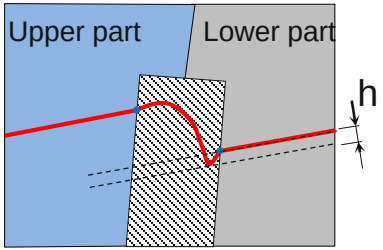


IN-PROCESS MONITORING

Co-axial Camera

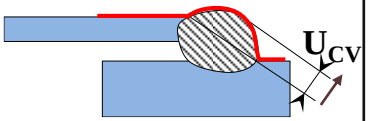
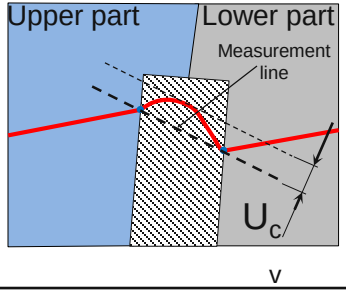
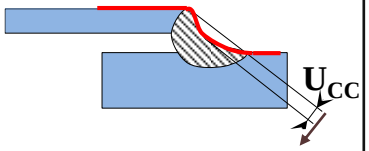
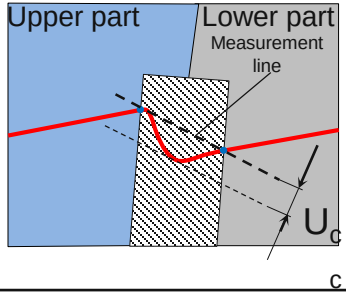
Weld defect	Cross section	Camera view	(Machine) Learning principle

Reduced leg length			• These defects are identified by comparing the projected line against a pre-defined “pattern defect”
			• A similarity index is used for this purpose
			• Qualitative output is provided:
			  • 0 = no pattern identified
			  • 1 = pattern identified

Undercut			• Defects are identified by measuring the max normal distance between the line parallel to the “measurement line” and passing by P_R (RH) or P_L (LH), and the projected laser line • Quantitative output is provided

IN-PROCESS MONITORING

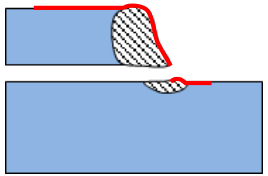
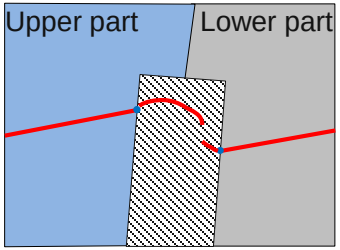
Co-axial Camera

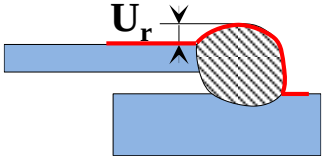
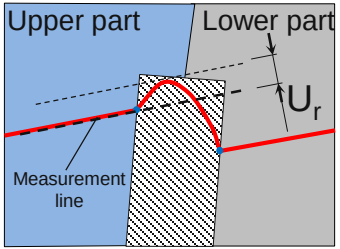
Weld defect	Cross section	Camera view	Notes
Seam convexity			• These defects are identified by measuring the max normal distance (“seam height”) between the line passing by P_R and P_L (measurement line) and the projected laser line • Quantitative output is provided ▪ Seam height is positive for seam convexity ▪ Seam is negative for seam concavity
Seam concavity			

IN-PROCESS MONITORING

Co-axial Camera

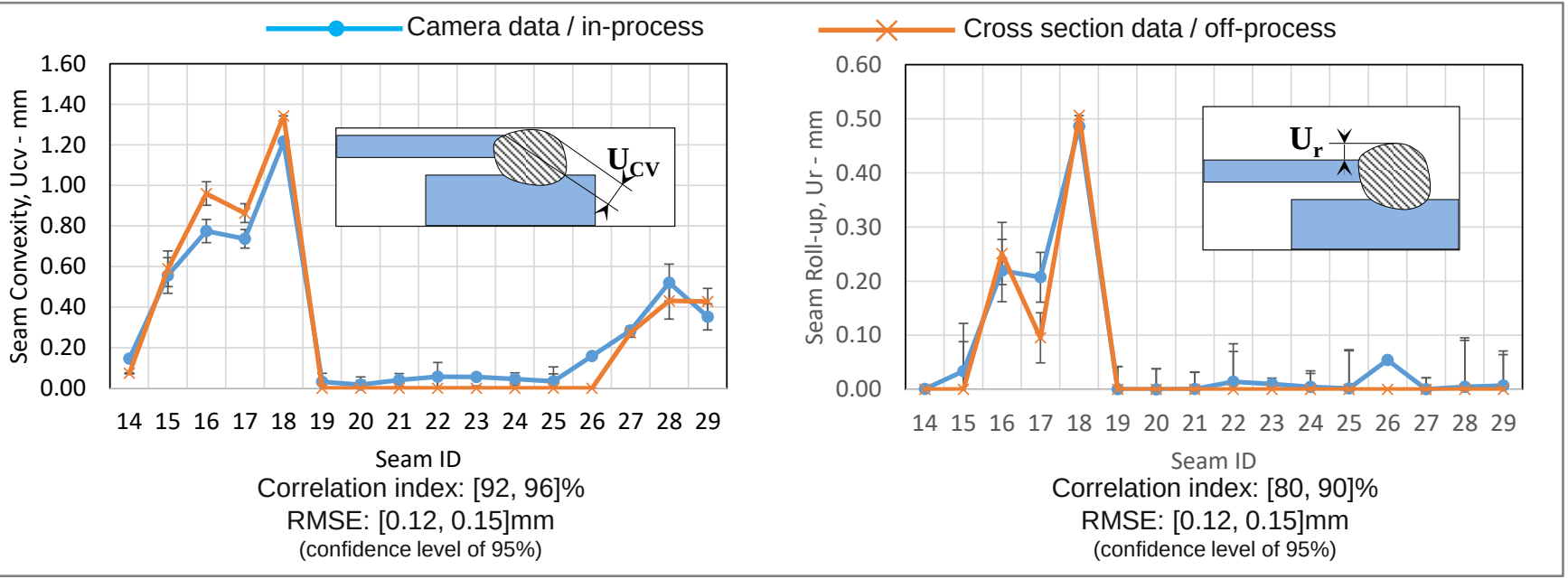
Weld defect	Cross section	Camera view	Notes

Seam discontinuity*			• Defects are identified by checking/finding discontinuity in the projected laser line
			• "Max jump" method is used
			• Quantitative output is provided:
			  • 0 = no gap identified
			  • 1 = gap identified

Seam roll-up			• Defects are identified by measuring the max normal distance between the line parallel to the "measurement line" and passing by P_L (RH) or P_L (LH), and the projected laser line • Quantitative output is provided

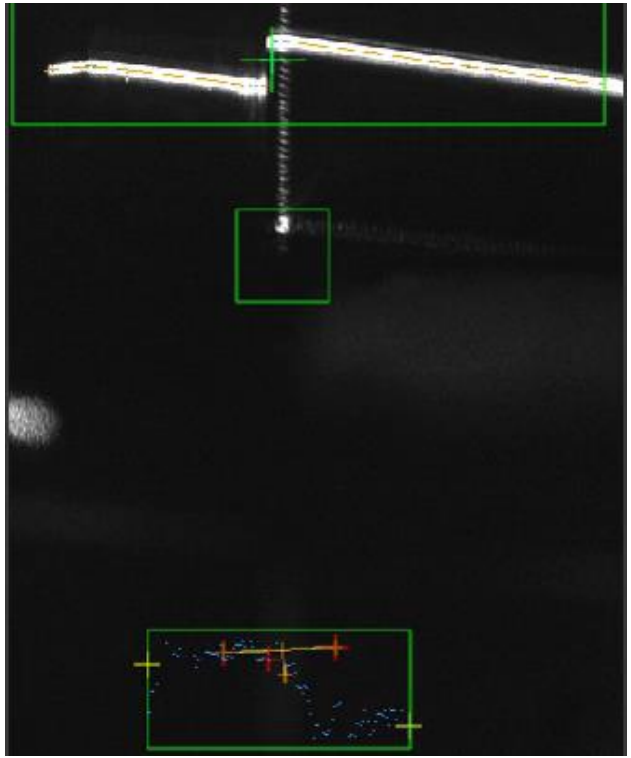
IN-PROCESS MONITORING

Co-axial Camera



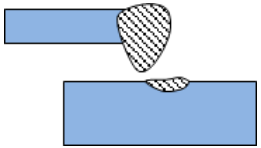
IN-PROCESS MONITORING

Co-axial Camera

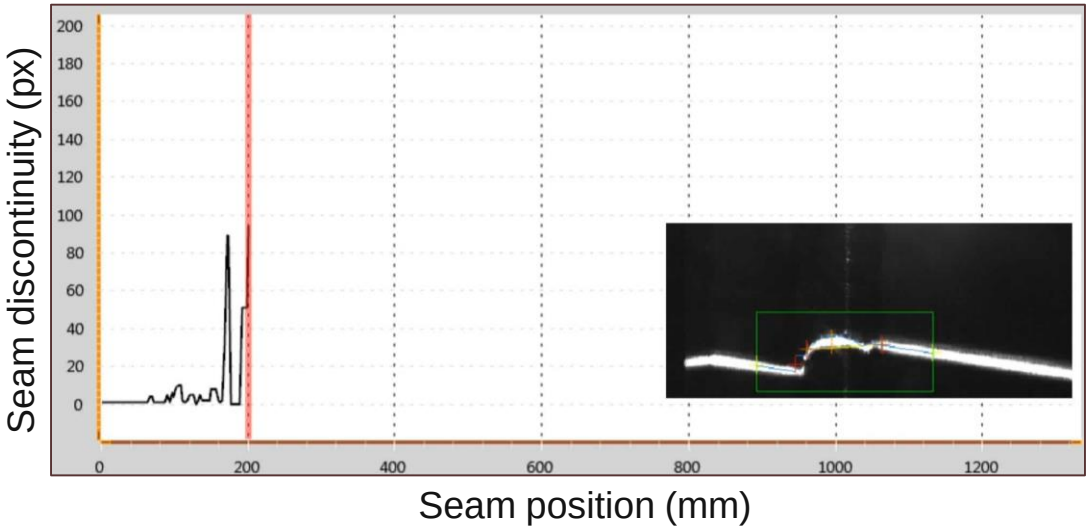


DEMONSTRATION

The filter computes both “line jump” and variation in line gradient.
1 pixel~=0.03mm

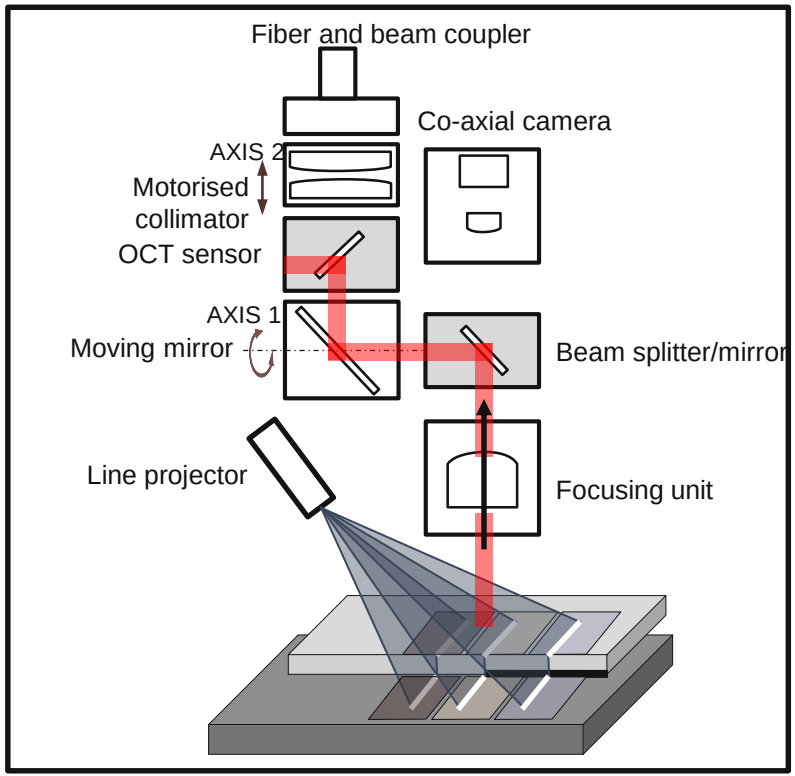


Seam discontinuity



IN-PROCESS MONITORING

Optical Coherent Tomography (OCT)



Optical paths

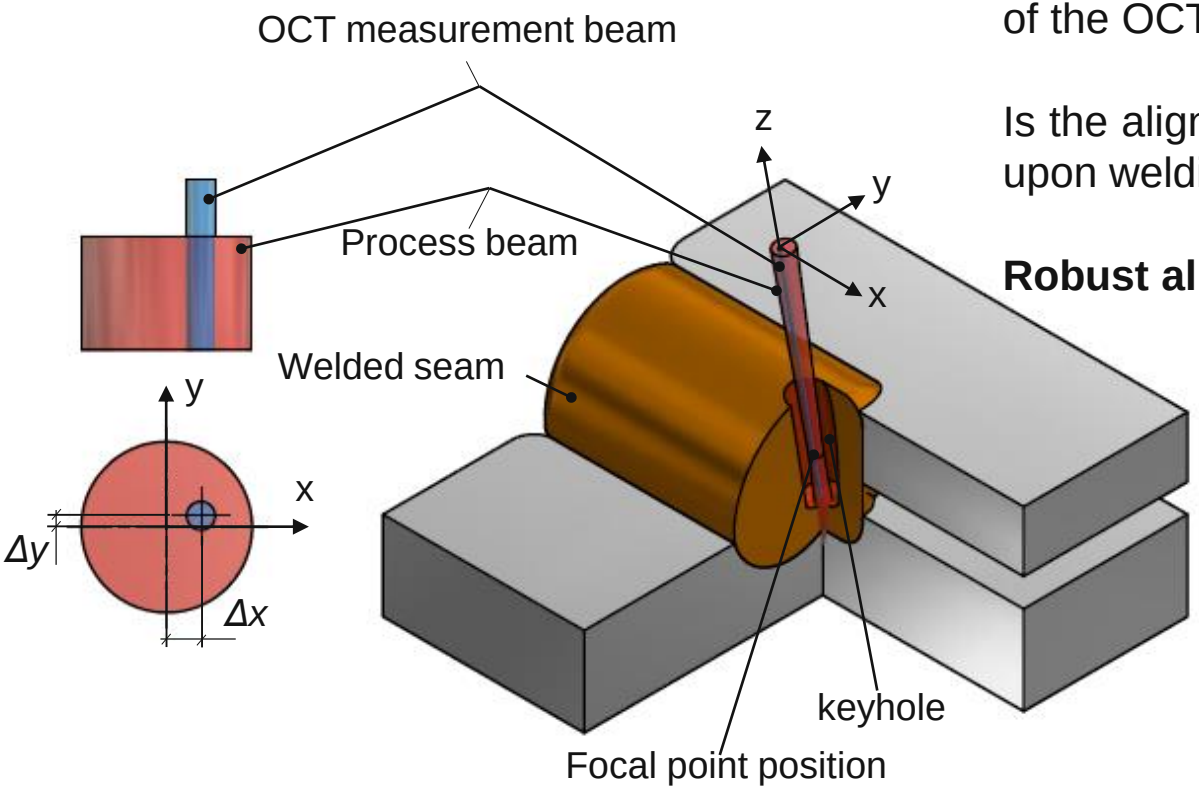
- Main beam delivery
- Co-axial camera
- **OCT sensor**

Wavelength spectrum: ~1550nm

Sampling rate: 70 kHz
Laser power: 10 mW (super luminescence diode)
Spot diameter: 0.05 mm
Max. measurement range: 10 mm

IN-PROCESS MONITORING

Optical Coherent Tomography (OCT)



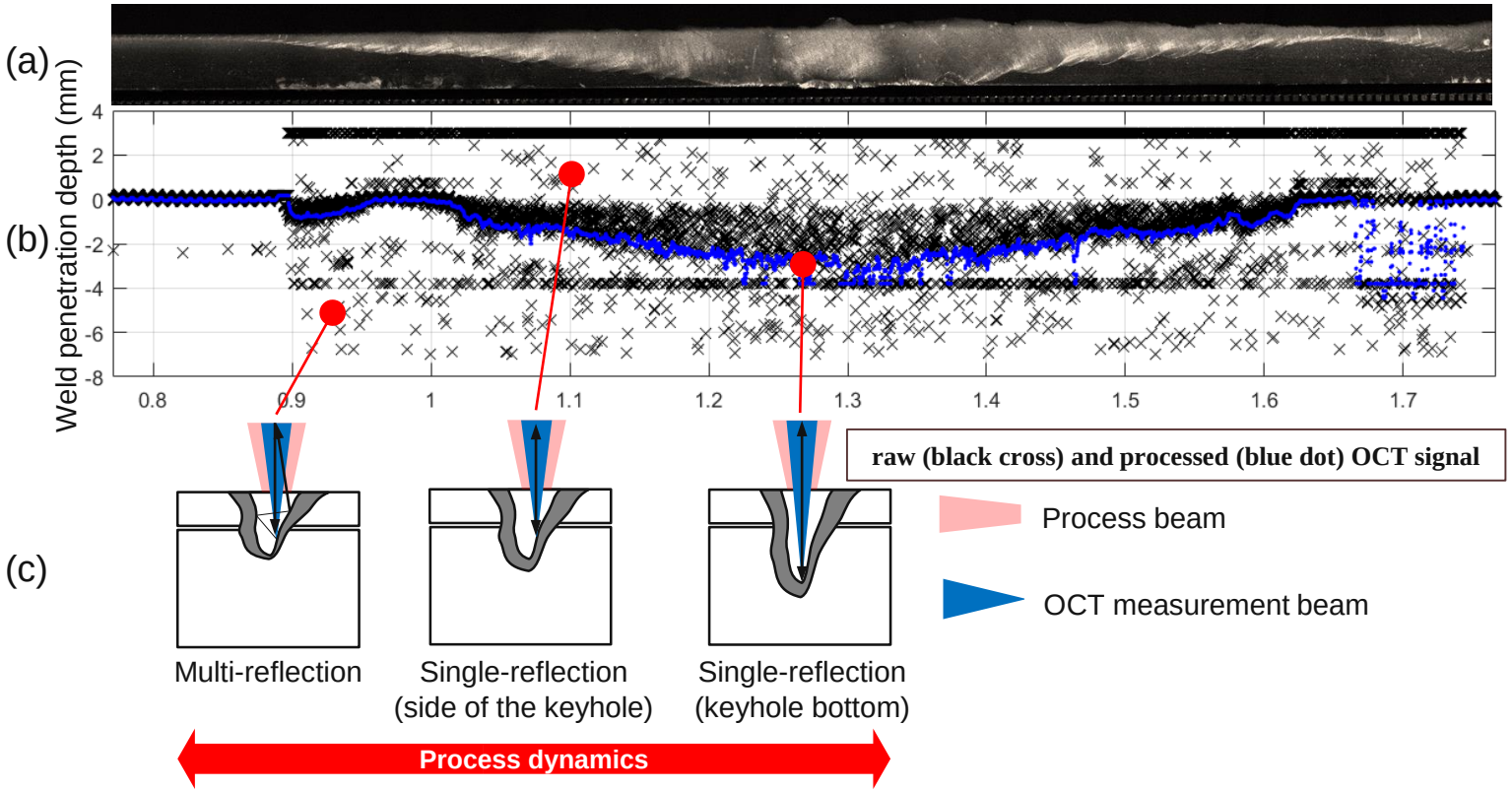
We aim to find the optimal alignment (Δx, Δy) of the OCT beam wrt the process beam?

Is the alignment of the OCT beam dependent upon welding process parameters?

Robust alignment vs. adaptive alignment?

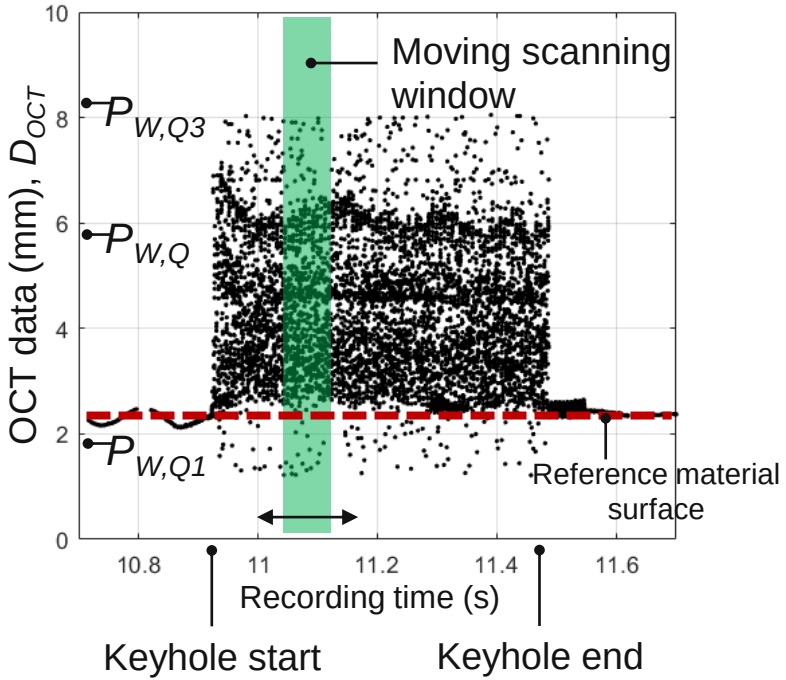
IN-PROCESS MONITORING

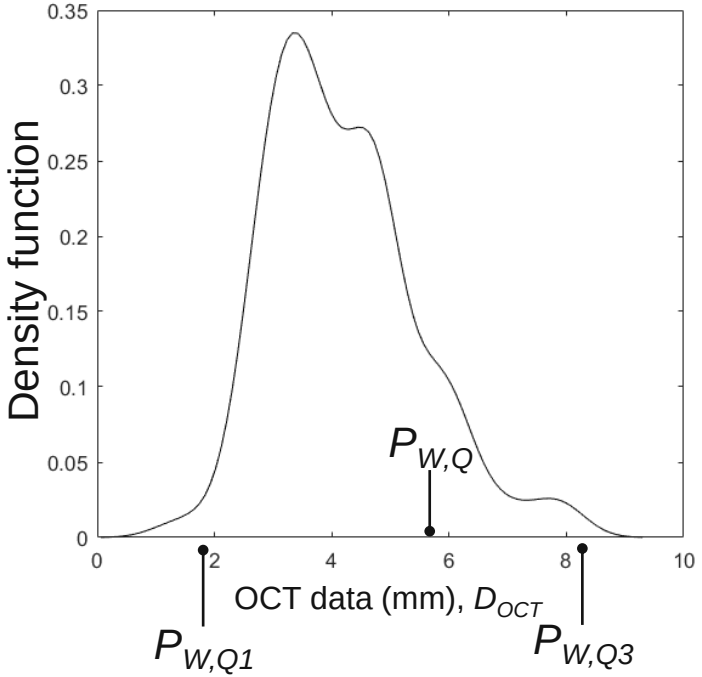
Optical Coherent Tomography (OCT)



IN-PROCESS MONITORING

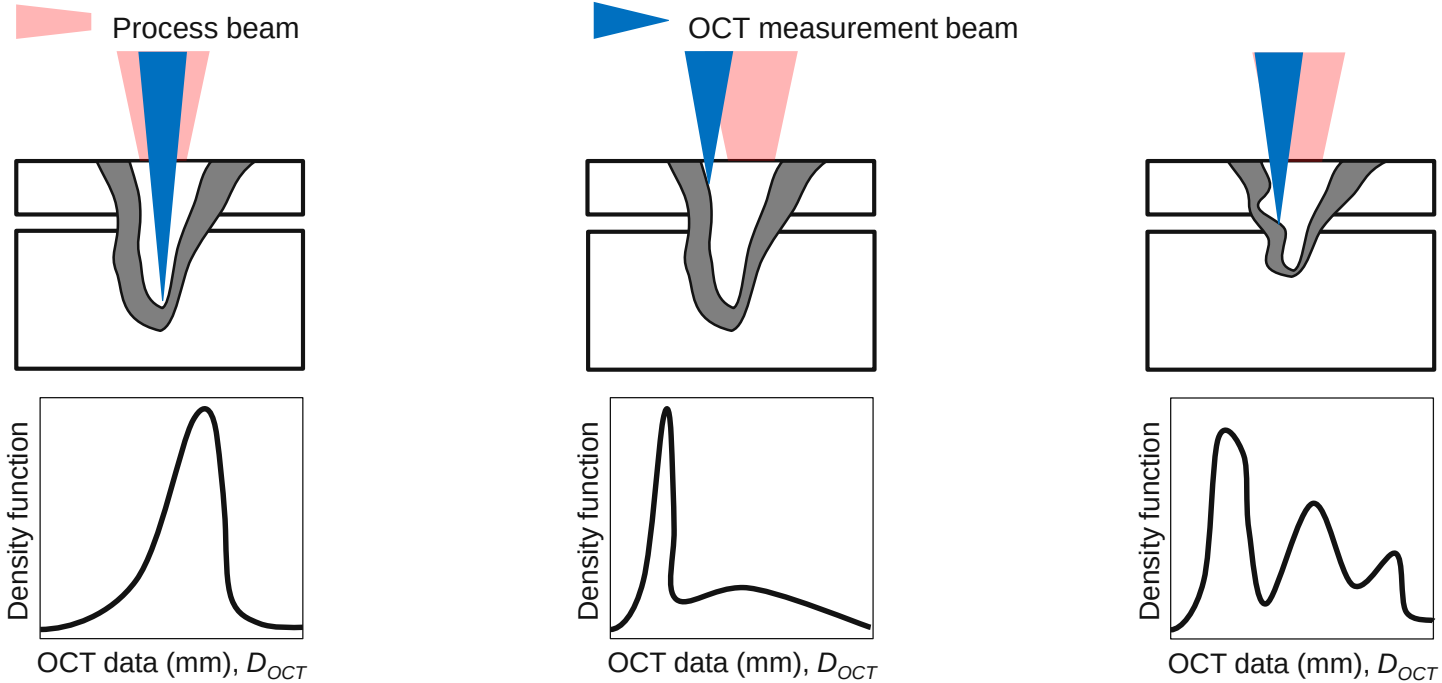
Optical Coherent Tomography (OCT)





IN-PROCESS MONITORING

Optical Coherent Tomography (OCT)



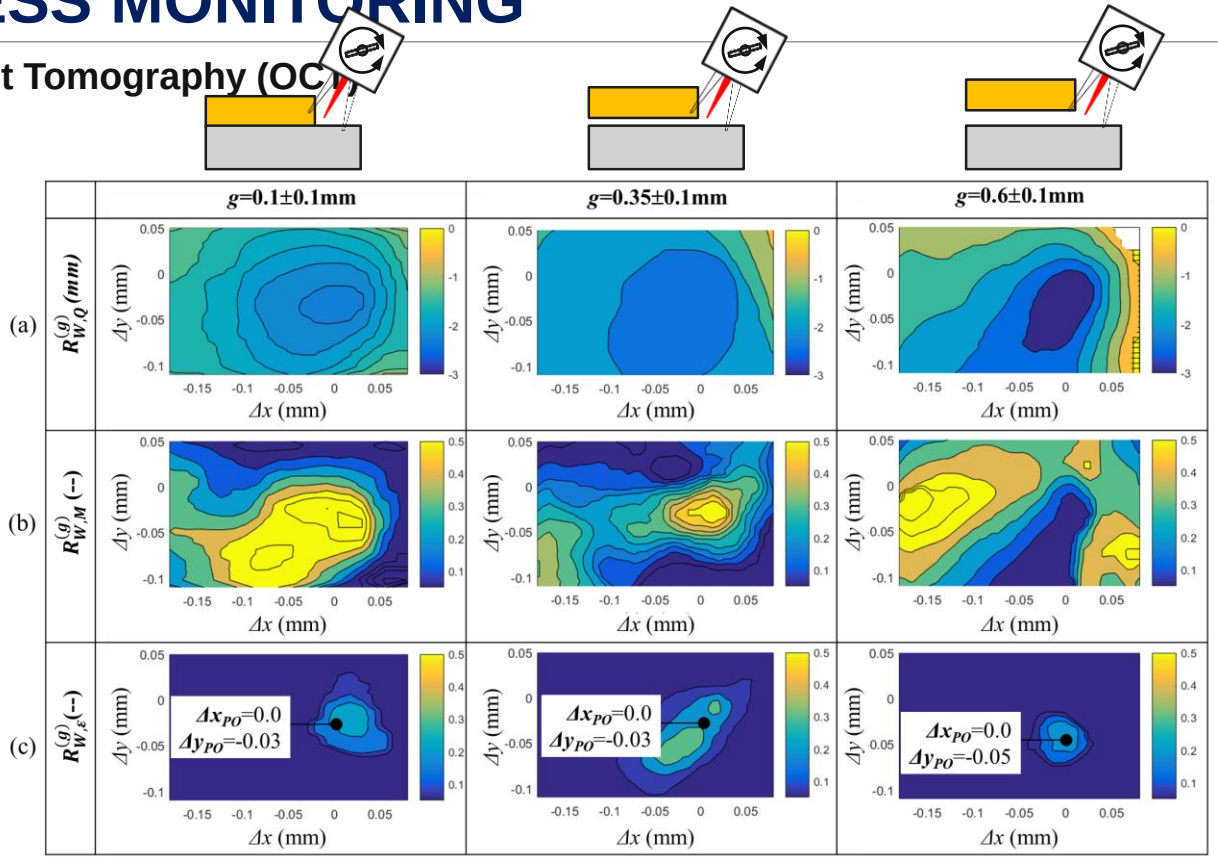
(a) - single-modal

(b) – bi-modal

(c) – multi-modal

IN-PROCESS MONITORING

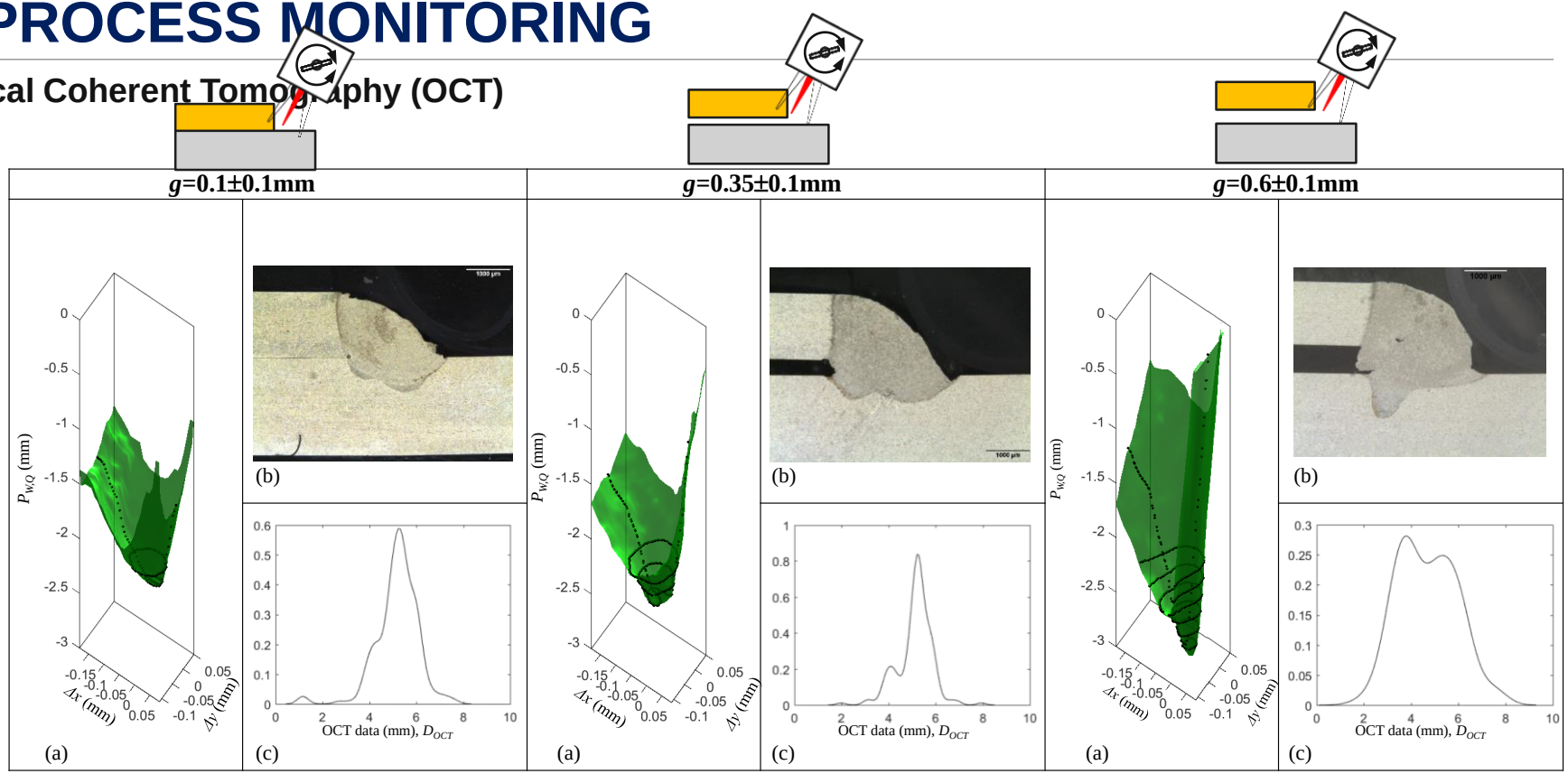
Optical Coherent Tomography (OC



(a) weld penetration depth; (b) normalised modality index; (c) normalised weld penetration depth accuracy

IN-PROCESS MONITORING

Optical Coherent Tomography (OCT)



(a) 3D view of the keyhole shape; (b) Representative cross-section; (c) density function of OCT data

MULTI-WAVE LIGHT SENSOR TECHNOLOGY

Take home messages:

All-in-one tool to enable closed-loop in process quality control, moving towards zero-defect manufacturing

Challenges:
(1) **Data** => Multi-scale, multi-dimension, multi-type data stream
(2) **Models** => Multi-fidelity models
(3) **Requirements** => Multi-level requirements

Opportunity:
(1) Flexibility
(2) Scalability
(3) In-process adaptive control
(4) Connectivity

Thanks for your attention!

Any questions and/or comments?

Dr. Pasquale Franciosa

WMG, University of Warwick, UK

E-mail: **p.franciosa@warwick.ac.uk**

M: +44(0) 7440022523
T: +44(0) 24765 73422

Acknowledgements

ADVANCED PROPULSION CENTRE UK

CATAPULT High Value Manufacturing

EPSRC Engineering and Physical Sciences Research Council