Laser Welding at CRF:
from research to manufacturing plant

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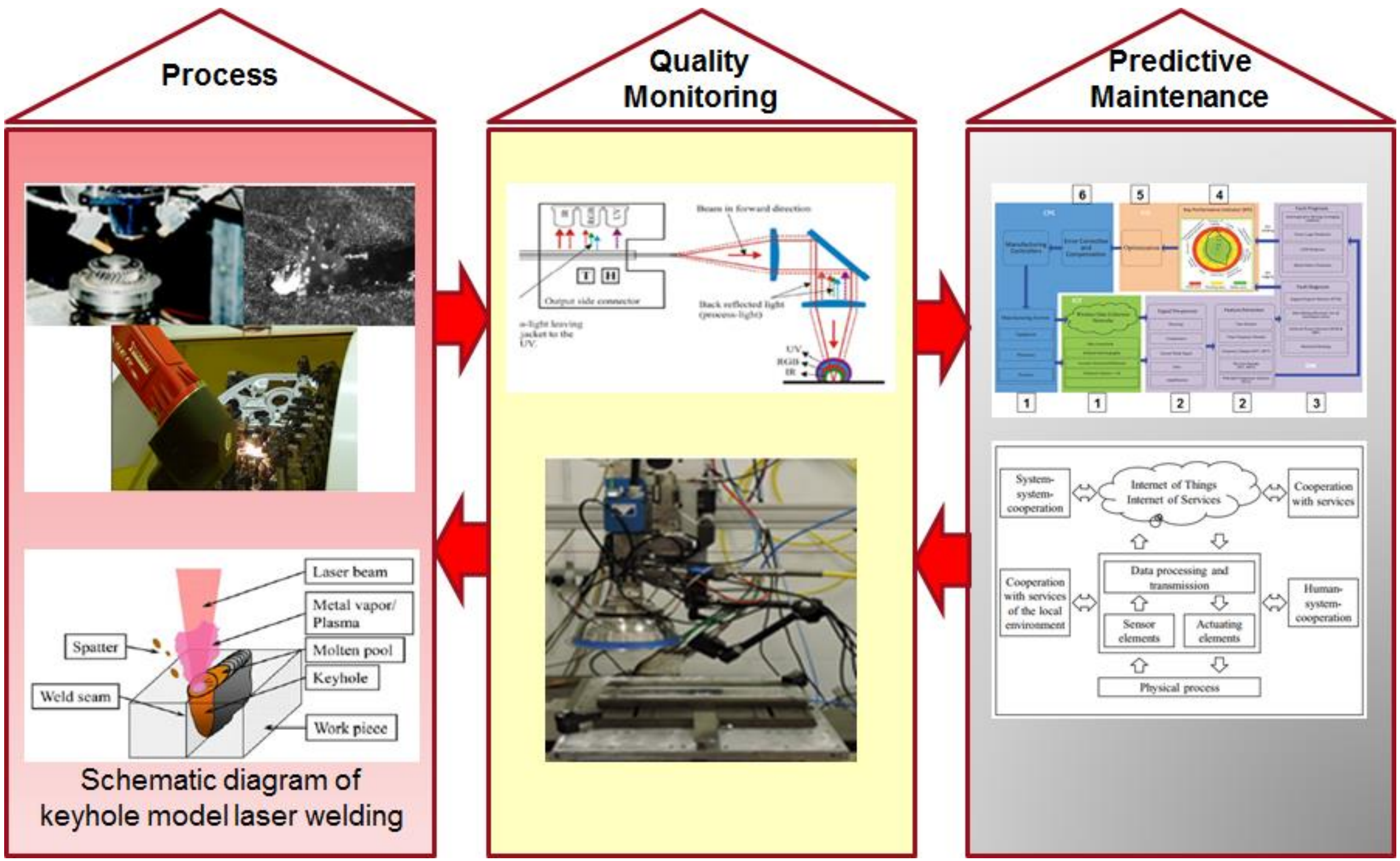
Laser welding is one of the technologies used in the manufacturing of automotive

Automotive manufacturers are replacing spot welding methods with laser welding **due to its high speed, non-contact and precision with low heat effects**

Laser Welding @ CRF is based on three pillars



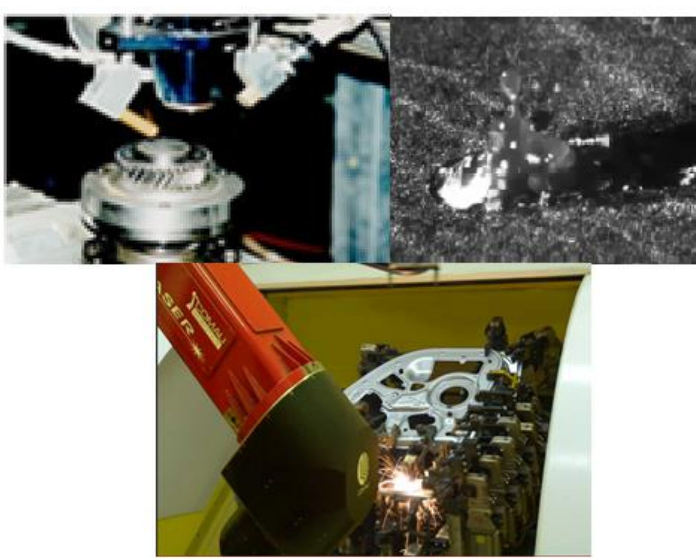
Schematic diagram of keyhole model laser welding

Process

The development of new laser welding processes is still essential

Laser welding recurring challenges:

1. exactly defined welding seams in width and depth
2. unusual material combinations or novel alloys
3. components having difficult geometries up to finest joints with lowest thermal load



history of the laser welding process @ CRF

79 – began to weld gear wheels by CO_2 laser

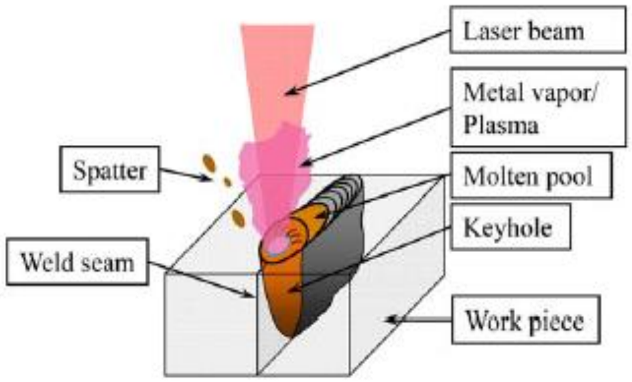
- ❑ welding of rear door for Lancia with CO_2 laser
- ❑ TWB for the centre pillar, by a 5 kW CO_2 laser
- ❑ non-linear TWB with Nd:YAG lasers
- ❑ Nd:YAG laser welding of roof to side panel
- ❑ Diode laser for polymers
- ❑ Activities with Disc Laser and Fiber Laser
- ❑ Remote Laser Welding
- ❑ Welding of dissimilar materials and composite materials
- ❑ …….

Quality monitoring

primary concern for companies:
weld defects detection

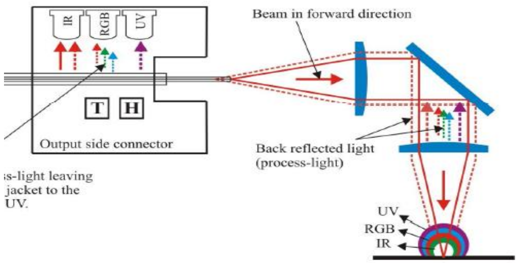
Motivation

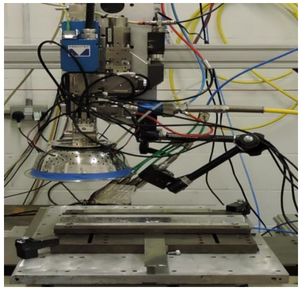
- ❑ Safe detection of critical errors
- ❑ Avoidance of production losses
- ❑ Automated inspection of all parts
- ❑ Provide feedback for process control
- ❑ Minimization of the cycle time



Schematic diagram of keyhole model laser welding

The laser-material interaction, that occur during laser welding, **emits energy in a variety of forms**



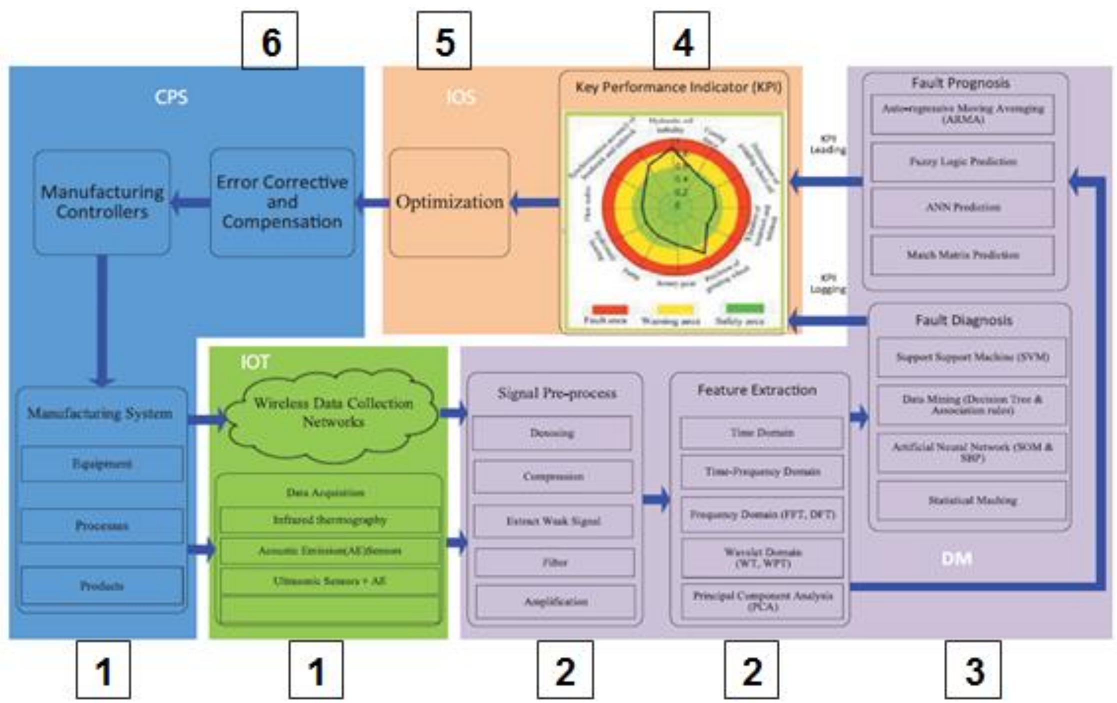


different on-line inspection systems have being developed

Predictive Maintenance (IPdM)

- **Predictive Maintenance (PdM) uses data analysis to predict the failure of machines and their components.**
- **PdM utilizes** predominantly non-destructive testing technologies (camera, infrared, acoustic, vibration, etc.) via **sensors, recently in combination with the measurement of different process parameters**.

intelligent predictive maintenance solution



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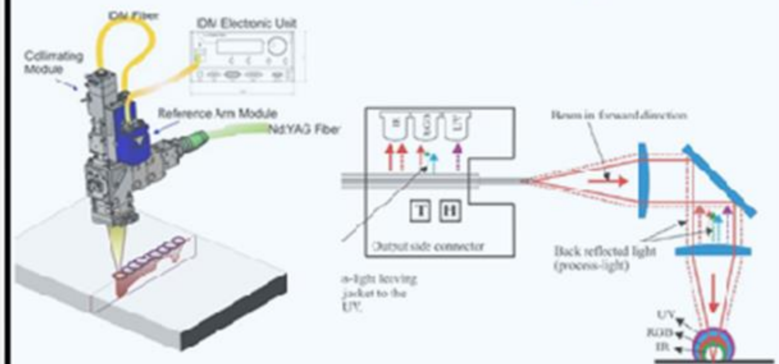
Laser Welding
@
CRF

Process

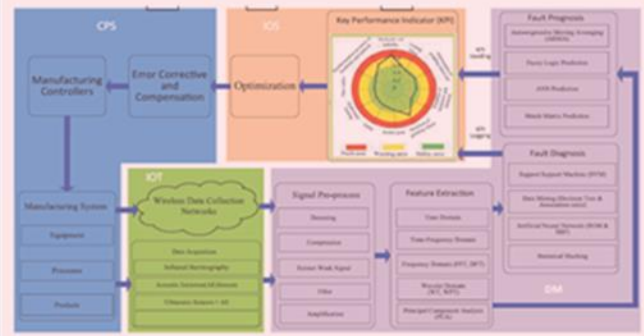
- ✓ materials
- ✓ optics
- ✓ parameters
- ✓ robots
- ✓ laser

Monitoring



- ✓ Sensors
- ✓ HW for Data acq.
- ✓ SW for analysis
- ✓ melt pool dynamics
- ✓ model of keyhole

Maintenance



- ✓ CPS
- ✓ IoT
- ✓ Signal pre-process
- ✓ Features extraction
- ✓ Fault prognosis
- ✓ Key performance indicator
- ✓ Optimization
- ✓ Error corrective & compensation

Production
@
Fiat Plants

Maserati Levante   Alfa Giulia   Jeep Renegade

Production
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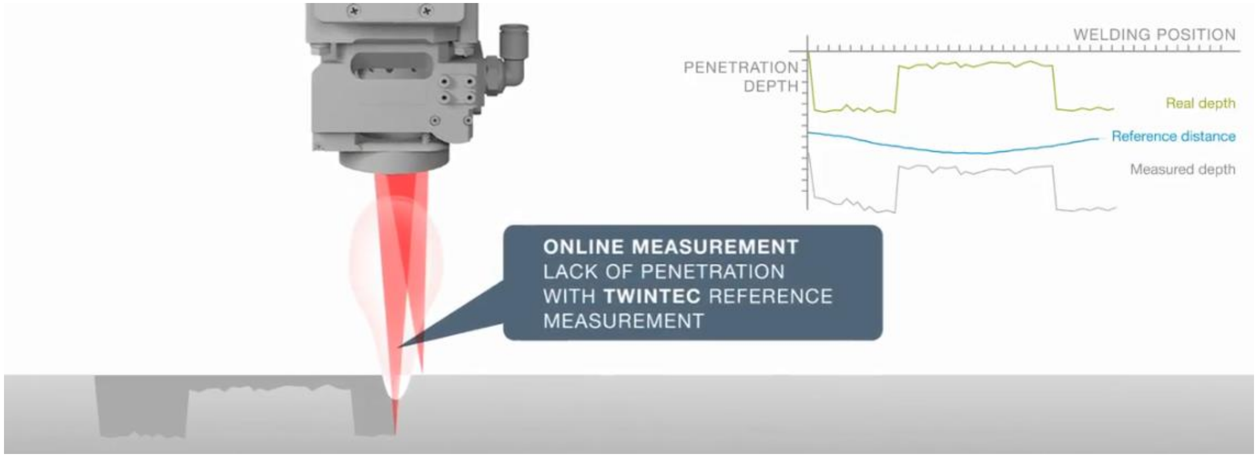
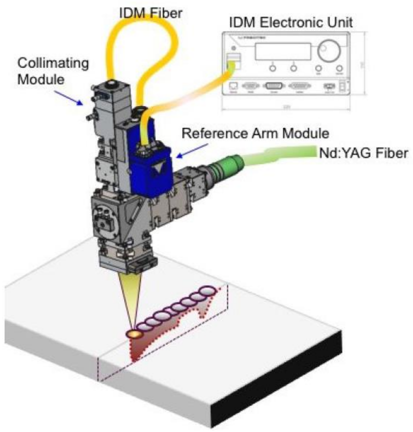
October 2018

Monitoring equipment - 1st approach

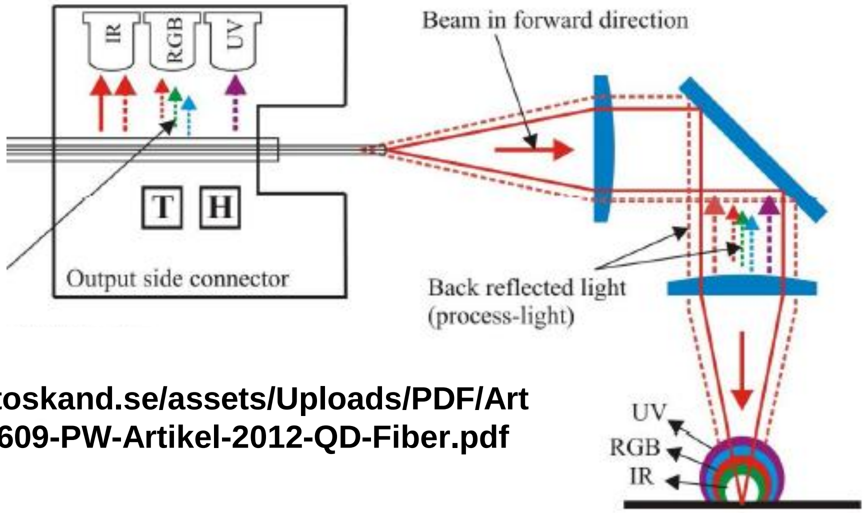
IDM TwinTec - Determination of the penetration depth during laser welding





- **The seam depth is a significant and critical seam property value in laser beam welding.**
- The <u>Precitec IDM system determines the penetration depth</u> in the deep welding processes at all metal-to-metal joints.
- **<u>Smallest deviations inside the vapor capillary can now be used for component evaluation</u>**. Due to the simultaneous distance measuring to the workpiece surface **TwinTec** distance changes during processing do not distort the measurement result.
- Only its absolute depth is used for the quality assessment of a workpiece.

Monitoring equipment – 2nd approach



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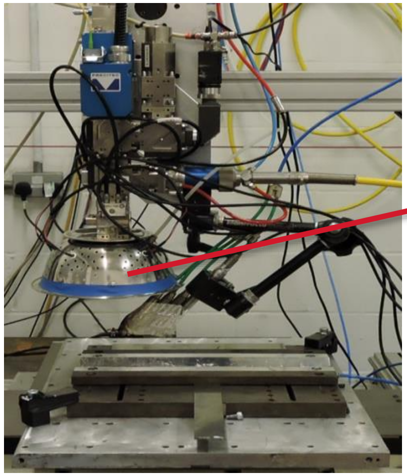
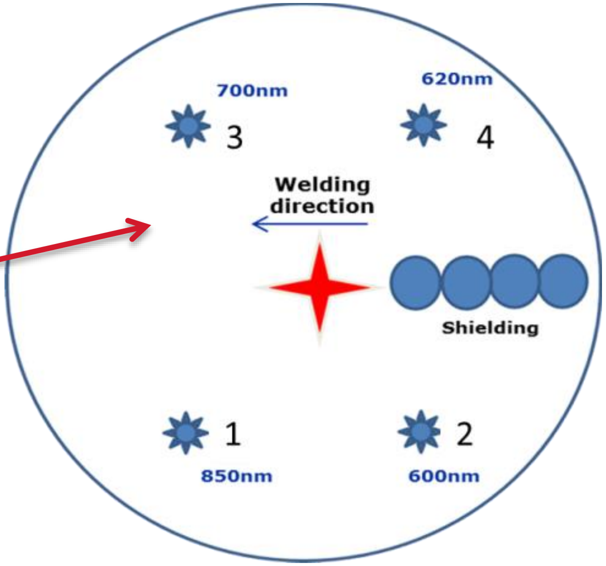
free standing





- Welding trials were carried out to generate process emissions
- Analysis of signals generated by two optical-based sensors:
  - Photodiodes responsive to either visible or near-infrared (NIR) emissions
  - In-process Depth Meter (IDM) sensor from Precitec
- Correlation with different types of weld features, imperfections and/or process anomalies

- Welds with known defects were produced by making the following changes:
  - Laser beam power
  - Cleanliness along the joint interface
  - Changes in joint gap
  - Changes in the laser beam alignment position with respect to the joint line

- ✓ **IDM: correlation between signal data and keyhole depth variations**
- ✓ **Photodiodes: signals correlated with different types of weld discontinuities, such as incomplete penetration, lost of power, internal porosity and beam to joint alignment**

Laser Process Monitoring

Investigation of an established optical monitoring method, using **photodiodes in the visible and infrared (IR) ranges**, to correlate the produced monitoring signals with different types of weld features, imperfections and/or process anomalies.

occurrences of internal porosities

changes in penetration depth & beam to joint alignment

changes in laser power & poor joint preparation

cleanliness or fit-up

Advanced signal analysis methodology

→ ***Singular Spectral Analysis (SSA)***

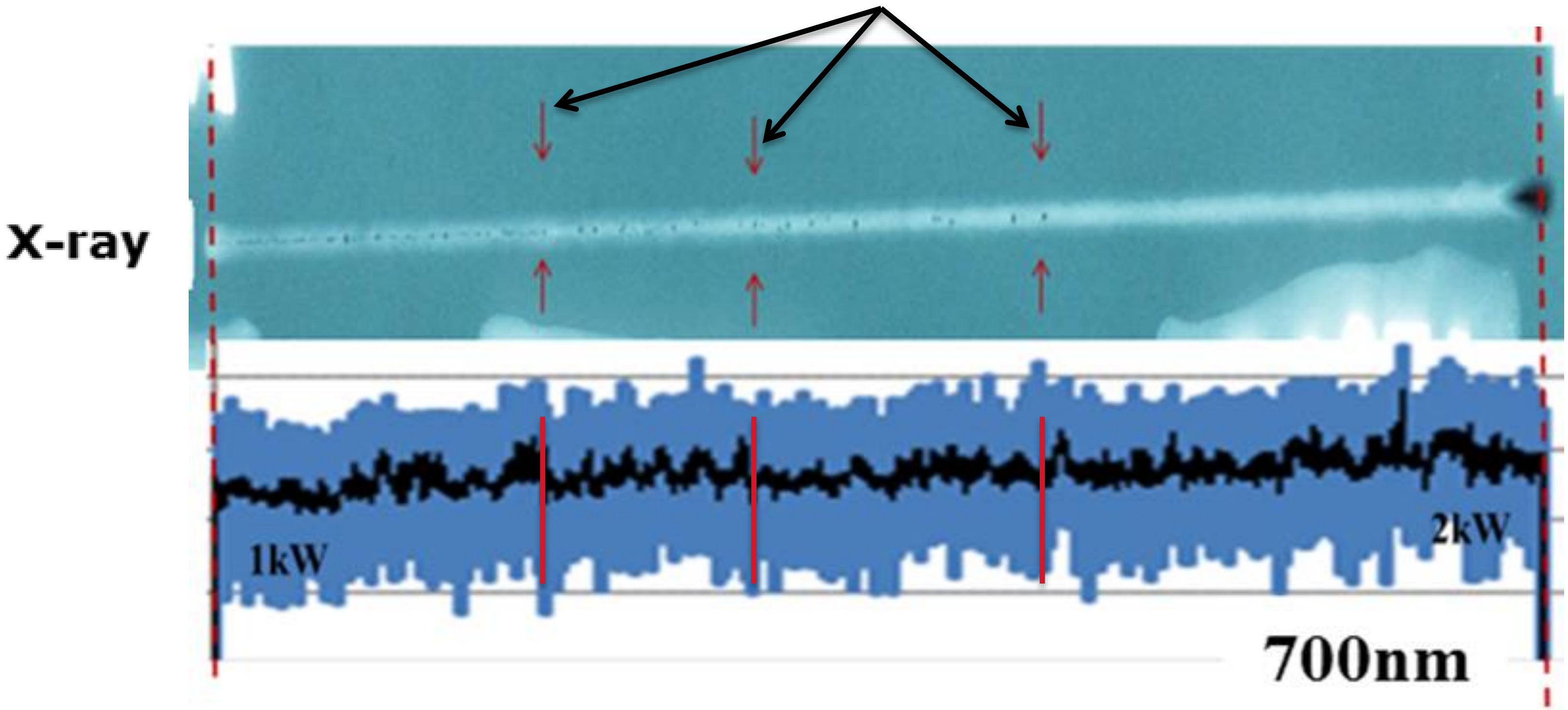
→ ***Orthogonal Empirical Mode Decomposition (OEMD)***

Fast | **Accurate** | **No reference**

→ ***Variational Mode Decomposition (VMD)***

Ni 718 – BoP; Internal porosity

the arrows indicate **some locations where peaks in the signal data appeared to be in the proximity of the pores**



laser power ramped up from 1 to 2kW as welding proceeded, **to increase the level of penetration and correspondingly decrease the internal porosity content**

Comparing the photodiode raw signal data and the X-ray radiograph

↓

it did not appear possible to establish any strong correlation between these signal peaks and individual pores detected within the radiograph

↓

1. the optical signals detected during the laser welding are typically **contaminated by different kind of noises that affect the photodetector**.
2. it is necessary to smooth and de-noise the signal for getting a “clean” signal.
3. the traditional method to de-noise process signals is to use digital **Butterworth filters**. Nonetheless, more advanced filtering techniques such as **discrete wavelet transforms, Wiener filtering** have also been used to that end. Although these methods have proven useful, their **main drawback is the complexity of devising an automatic and systematic procedure**

Advanced signal analysis methodology

- ***Modified Singular Spectral Analysis (MSSA)***
- ***Orthogonal Empirical Mode Decomposition (OEMD)***
- ***Variational Mode Decomposition (VMD)***

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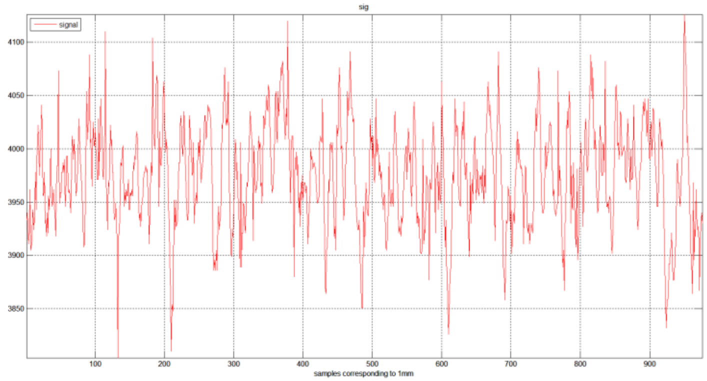
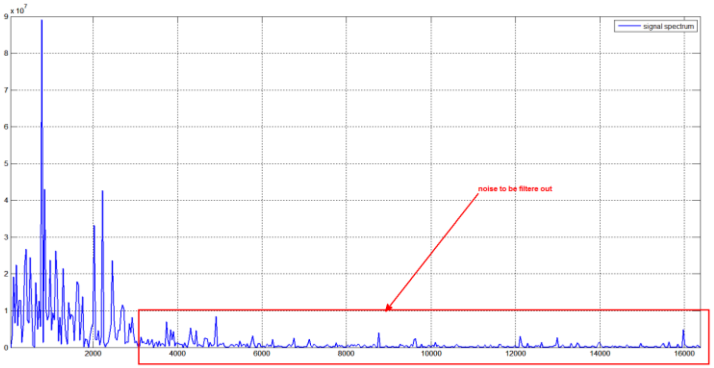
Modified Singular Spectral Analysis (MSSA)

(MSSA) as an alternative to traditional digital filtering methods.

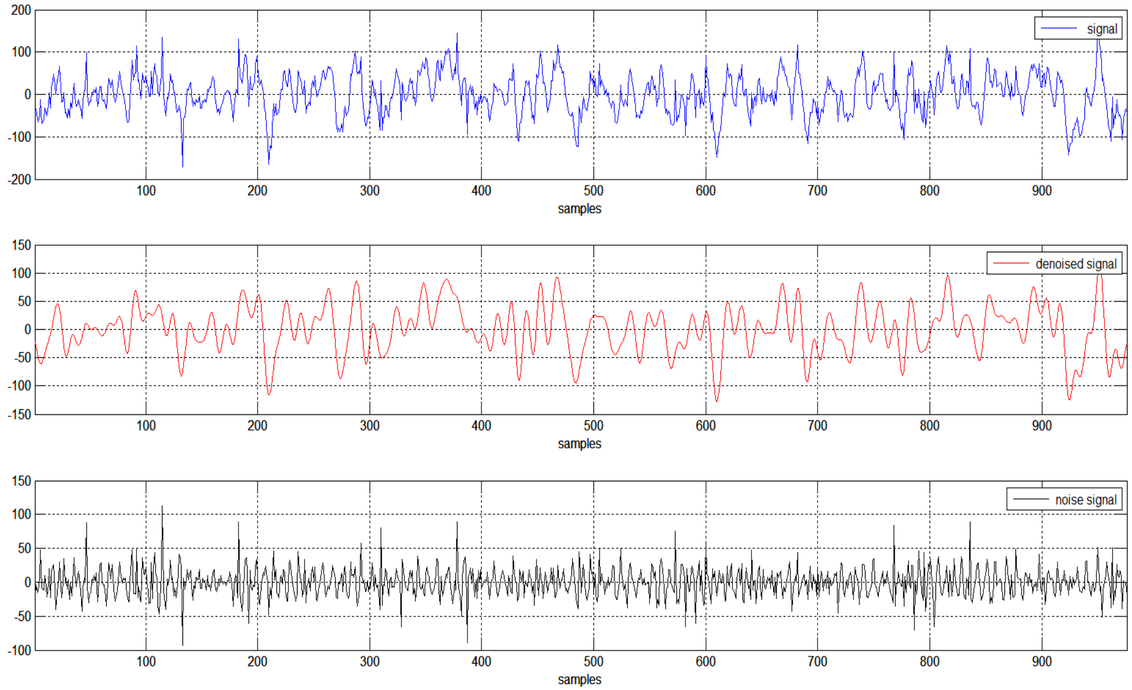
Example



signal to be smoothed



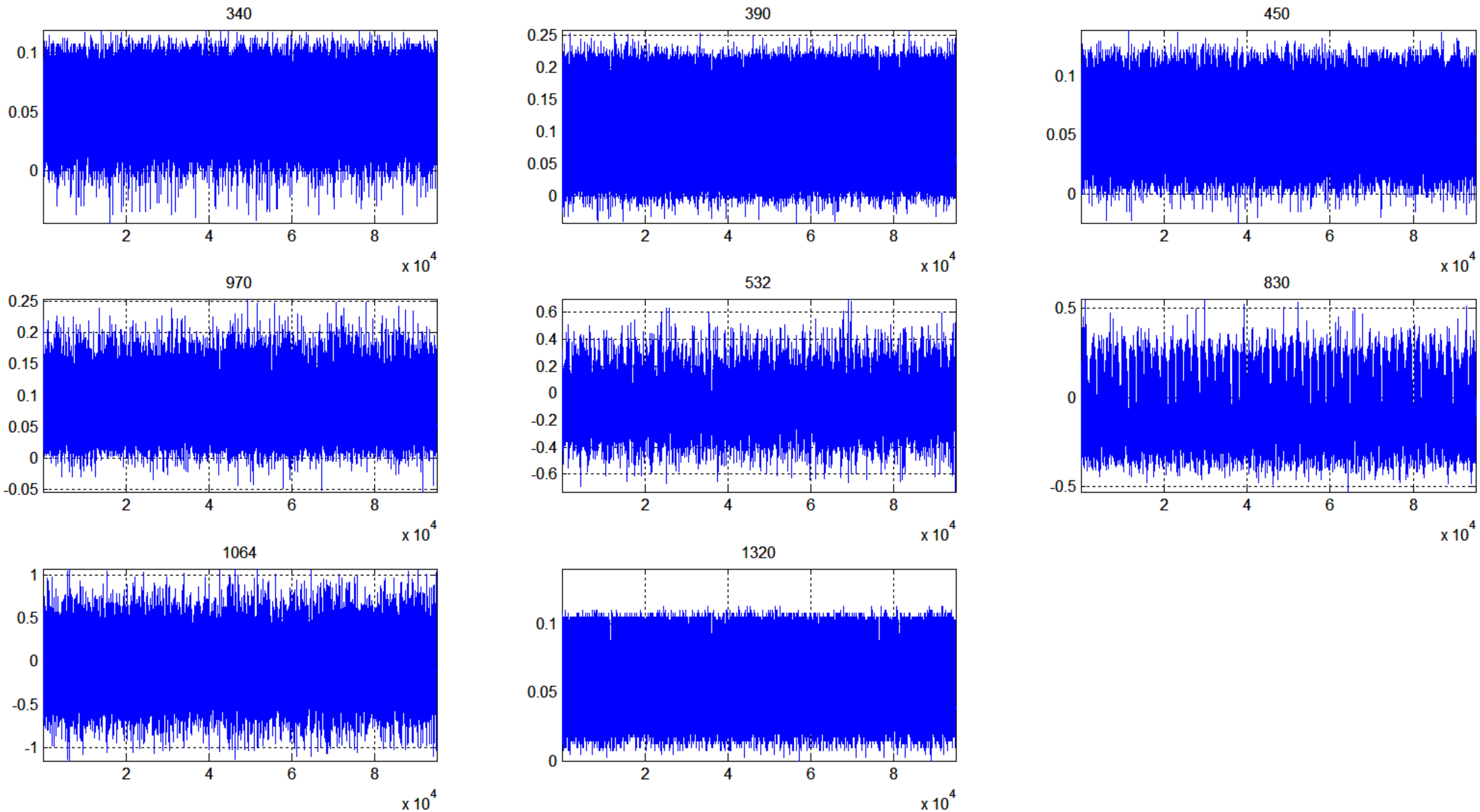
signal spectrum



- signal
- de-noised signal
- noise

Modified Singular Spectral Analysis (MSSA)

Inco\P0118_const_power



Modified Singular Spectral Analysis (MSSA)

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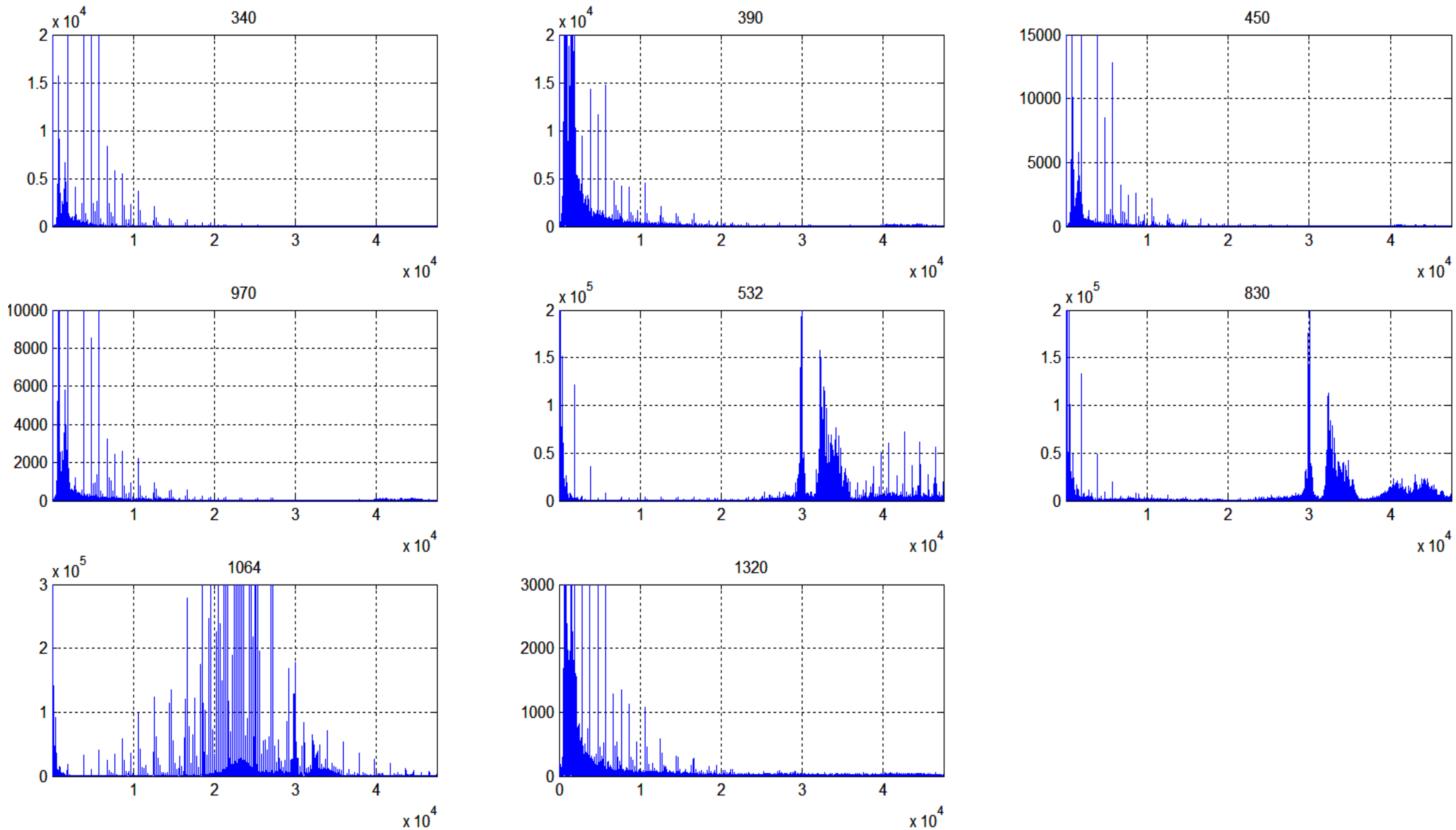

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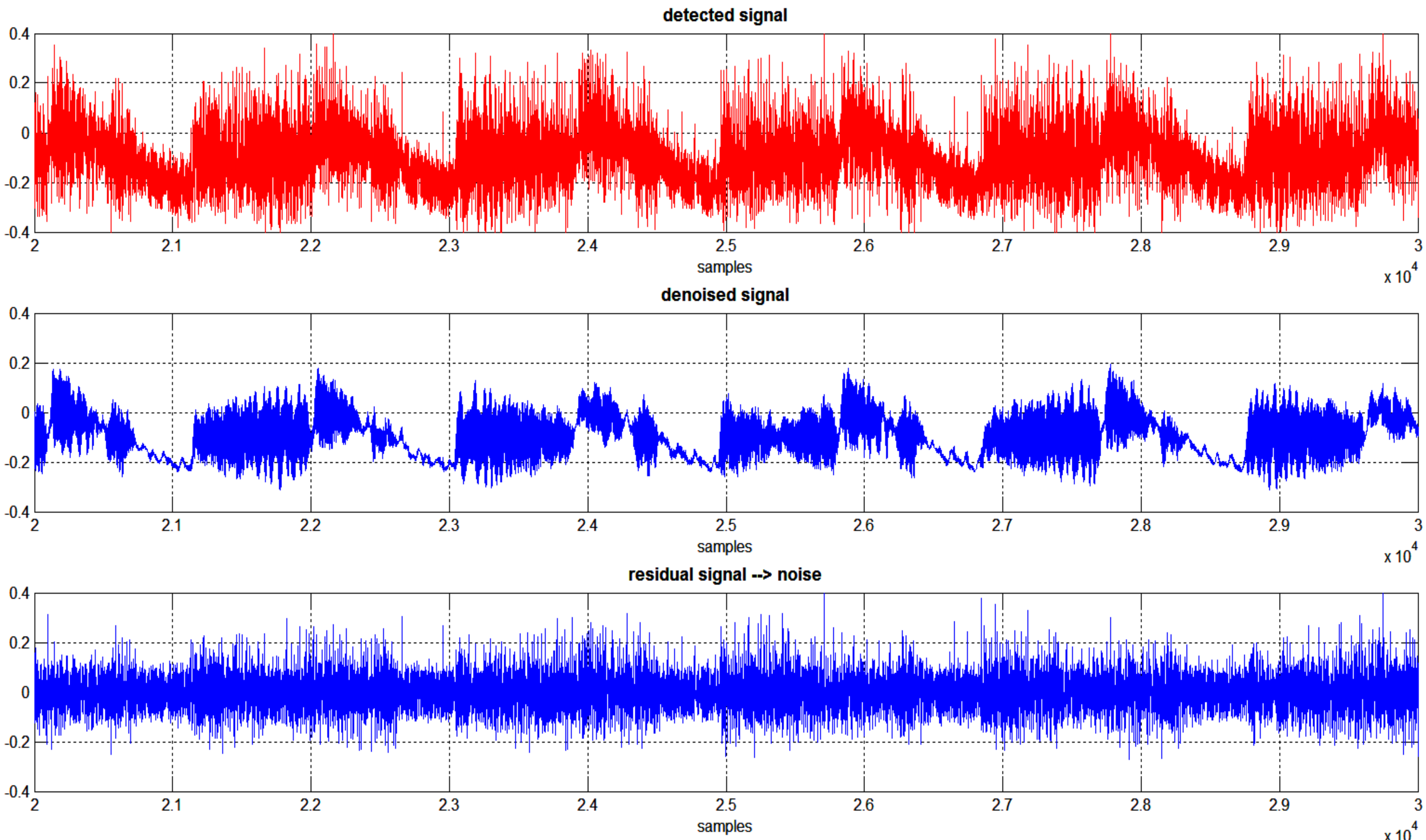
Modified Singular Spectral Analysis (MSSA)



zoom – 10000 samples

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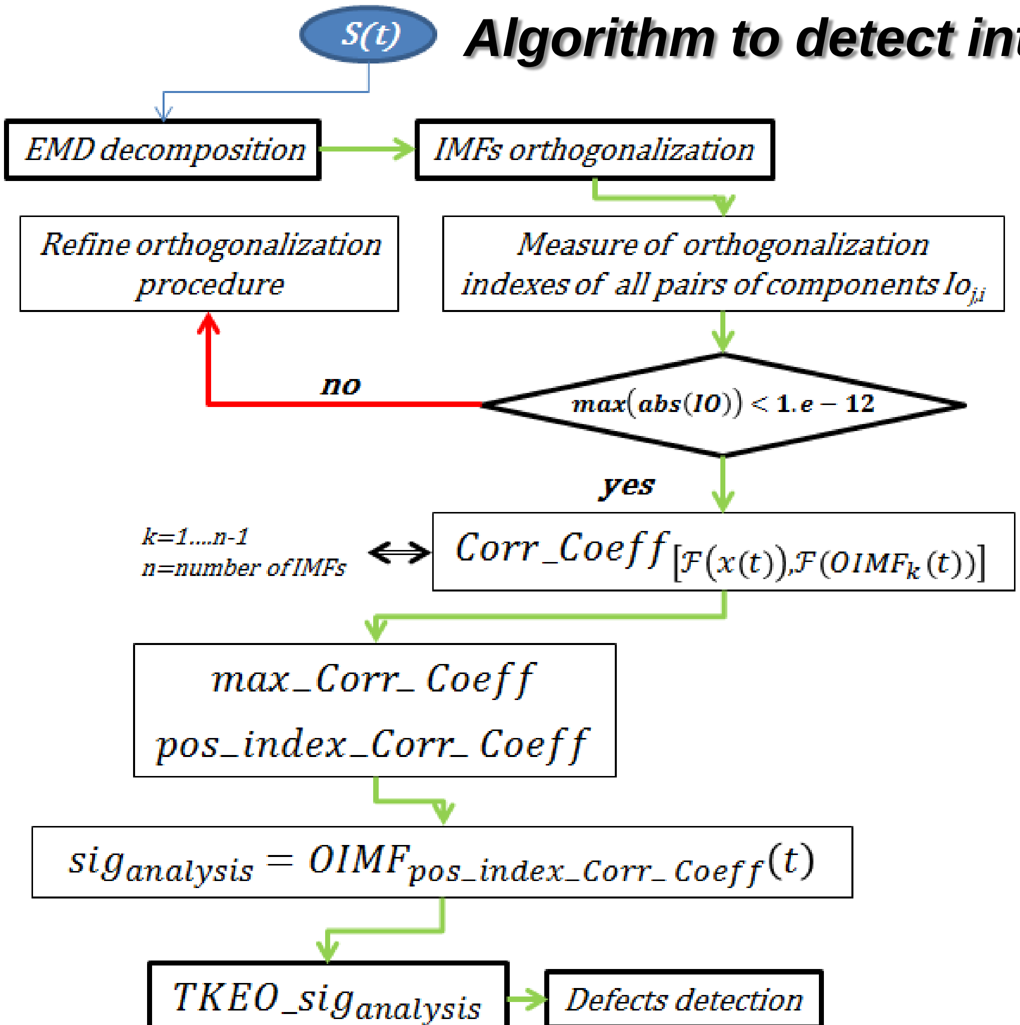
Orthogonal Empirical Mode Decomposition (OEMD) theory coupled to the Teager Kaiser Energy Operator (TKEO)

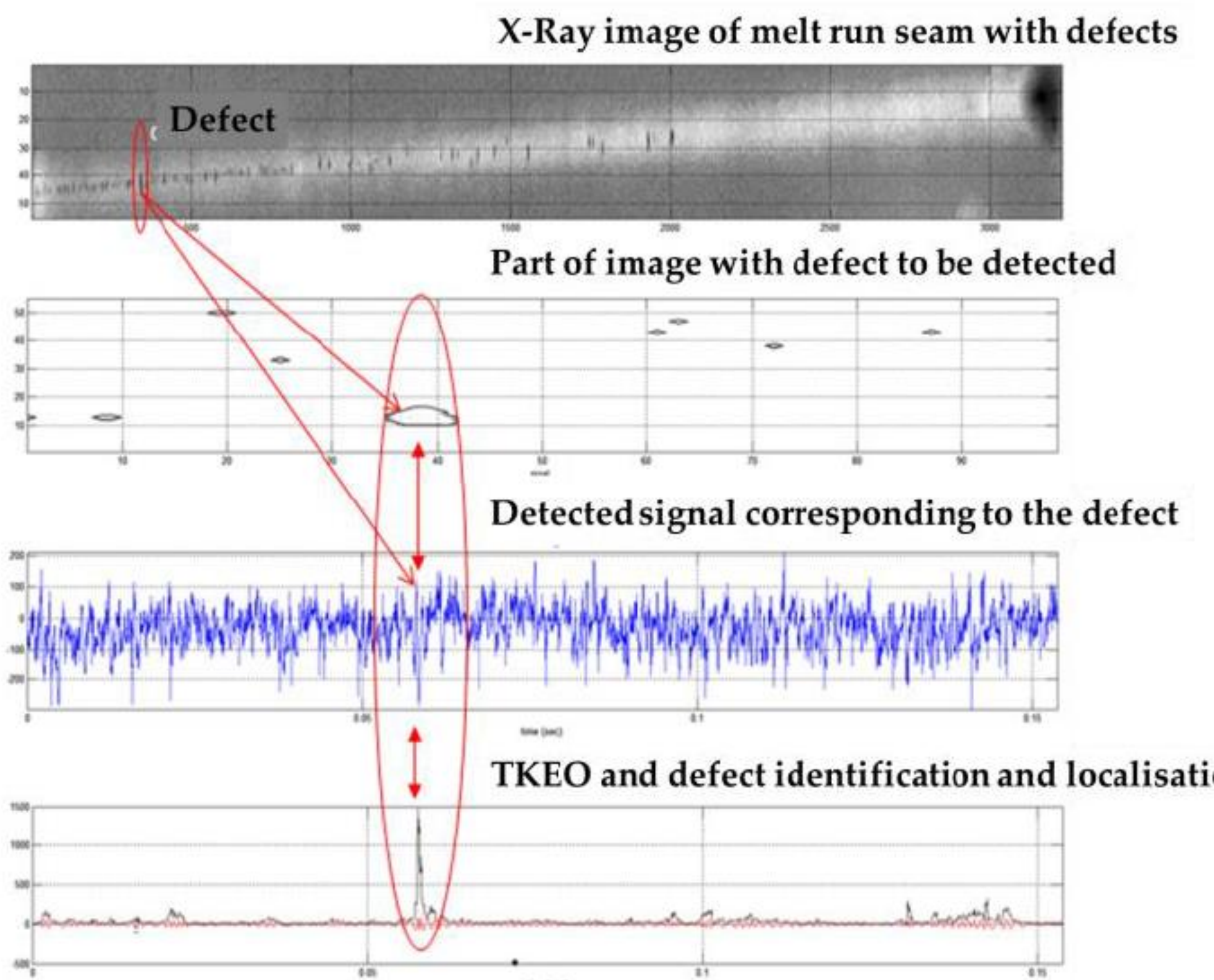
Algorithm to detect internal pore formation



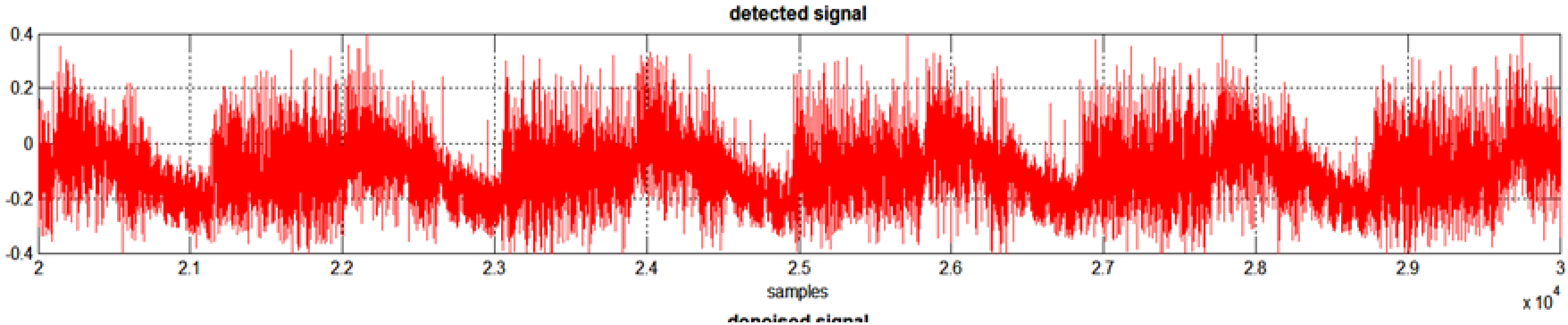
- **Ni 718 – BoP**
- **1msec to acquire 1024 data**
- **For example, for a 5sec signal ~0.5sec are required to receive feedback on any porosity within the weld**
- **Almost real time**

Orthogonal Empirical Mode Decomposition (OEMD) theory coupled to the Teager Kaiser Energy Operator (TKEO)

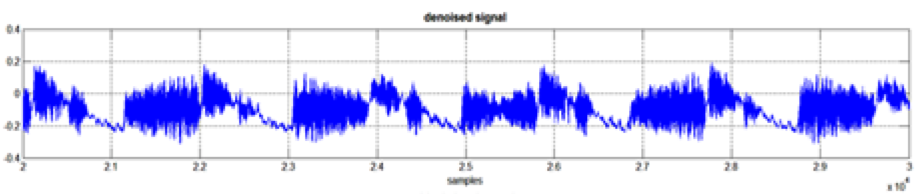
OIMF to correlate photodiode signal data to pores occurring within a melt run in nickel 718 alloy



Signal + Denoising & separation in different frequency bands + Energy evaluation + Choosing appropriate bands



Variational Mode Decomposition (VMD)



Band 1
f1…..f2
E1(f)

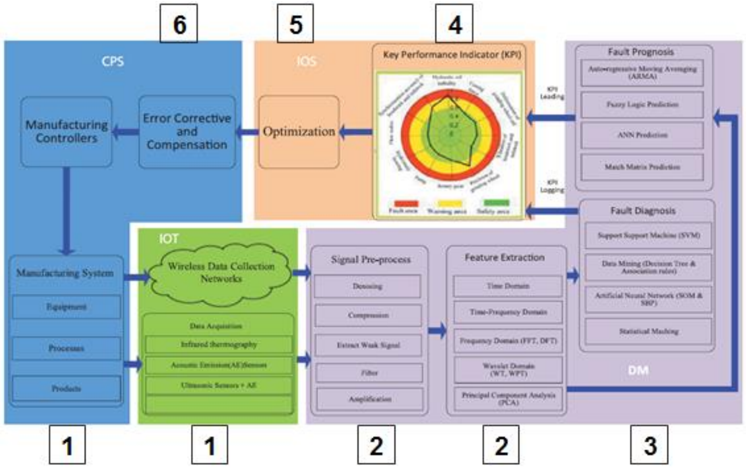
Band n
F n-1…..fn
En(f)

More significant bands (Energy) + model

Industry 4.0 & Intelligent Predictive Maintenance (IPdM)

intelligent predictive maintenance solution

- process + sesnsor = **data generation**
- transmitted by **IoT**
- **Data Mining** for analysis of machine/process condition
- **IoS** to
  1. individuate a stoppage to be recognized early
  2. generate corrective measures to be planned and introduced in the most effective way.



The Internet of Service (IoS) allows the early detection of an interruption and to plan the corrective measures to be used.

intelligent predictive maintenance solution

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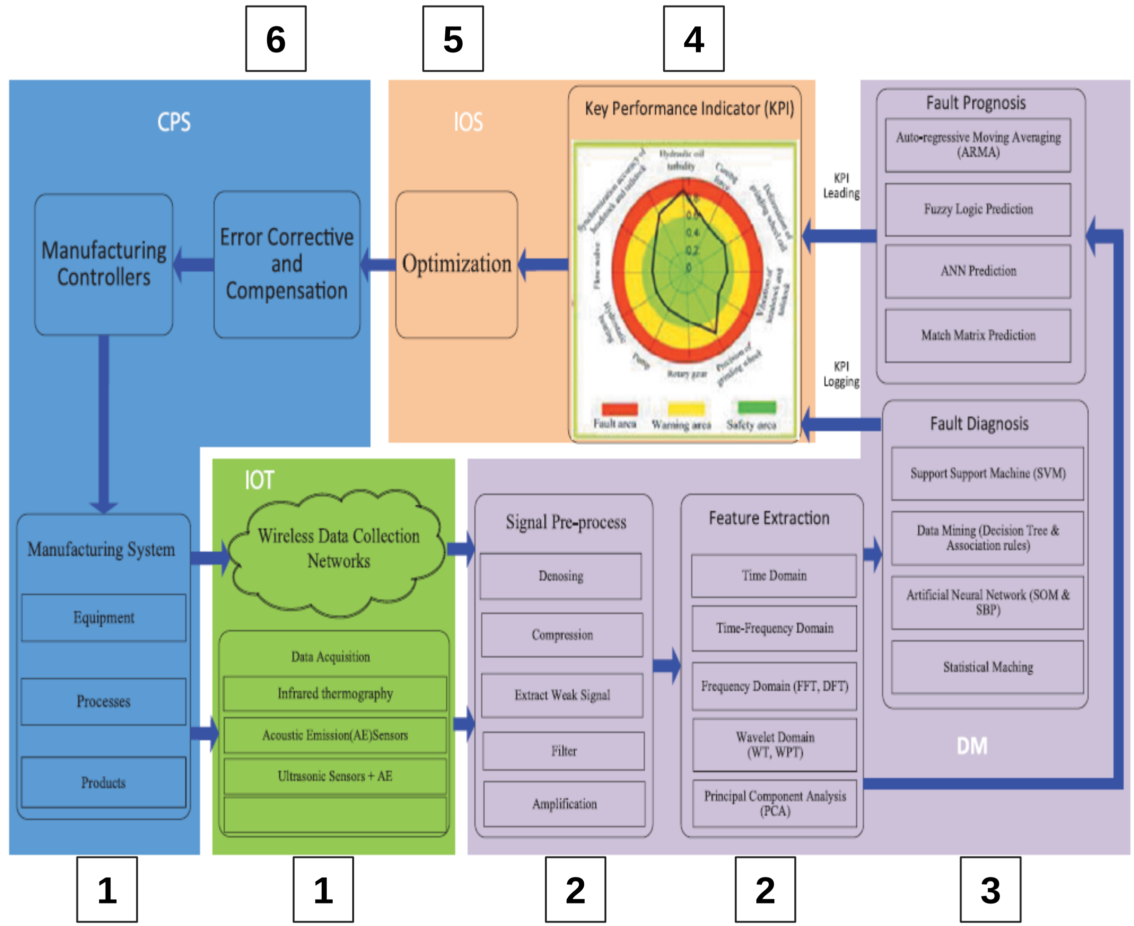
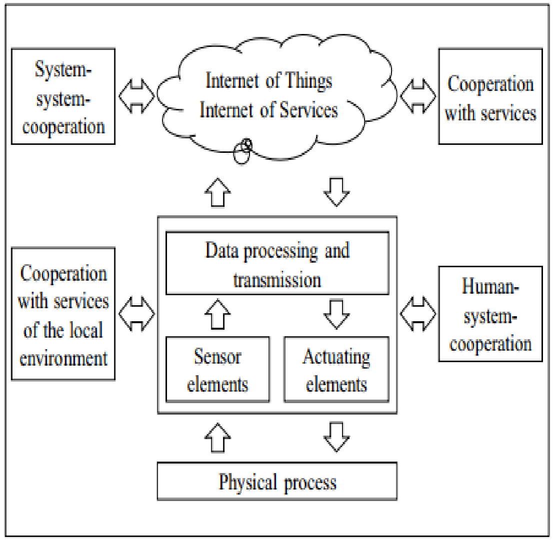


six main modules in *IPdM*

(1) sensor and data acquisition, **(2)** signal pre-processing and feature extraction, **(3)** maintenance decision-making, **(4)** key performance indicators, **(5)** maintenance scheduling optimization,**(6)** feedback control and compensation.

The development of intelligent monitoring and autonomous decision-making processes is important in order to control and optimize both industrial companies and entire value-adding networks efficiently.

- **Cyber-Physical System consists of a 'physical entity' and its 'cyber-twin' connected together**.
- **This 'cyber-twin' can virtually replicate the behavior of the physical machine, and give an insight on how will the machine react when prompted with various actions**.
- The connection can be done using sensors and actuators.
- Connected CPSs are called as Internet of Things (IoT).
- Functions of centralized industrial systems are shifted to decentralized CPSs linked in an IoT

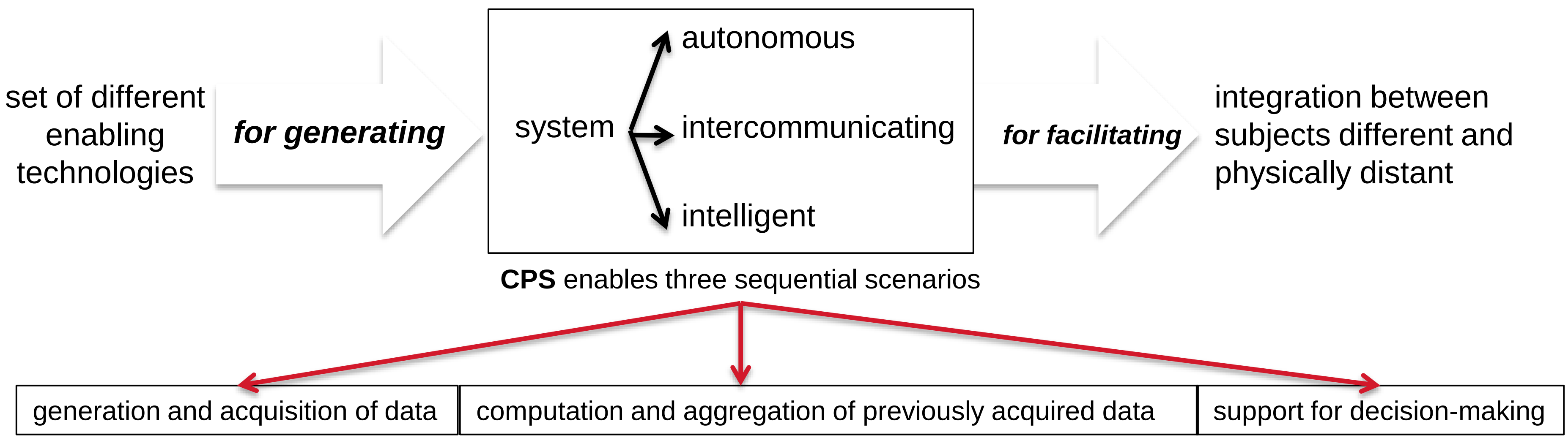


structure of a CPS

The ongoing industrial revolution, **Industry 4.0, is transforming traditional manufacturing industries**.

- **CPS provide a connection between the virtual and the physical world** combined with various capabilities.
- These allow the **realization of a smart factory, characterized by high mutability and ergonomic working conditions**

Cyber-Physical Systems (CPS)



Connected CPSs are called as Internet of Things (IoT).

CPS, IoT, IoS, Computational Intelligence (CI), Data Mining (knowledge discovery), Swarm Intelligence (SI)

There are six main modules in *IPdM*

Sensor and data acquisition module

- **selecting a suitable sensor and an optimal sensor strategy**.
- The data acquisition process transforms the senor signals into domains that contain the most information of the condition of the equipment.
- Various sensors, can be used to collect different data.

Signal pre-processing and feature extraction module

- **signal processing, which enhances the signal characteristics and quality**. The techniques in signal processing include filtering, amplification, data compression, data validation, and de-noising that will improve the signal-to-noise ratio
- **feature extraction, which extracts features from processed signals that are characteristic of an incipient failure or fault**. Generally, the features can be extracted from three domains: time domain, frequency domain, and time–frequency domain.

Maintenance decision-making module

Maintenance decision-making module offers sufficient and efficient information to maintenance personnel’s decision on taking maintenance actions.

The models for decision-support could be divided into four categories: (1) physical model, (2) statistic model, (3) data-driven model, and (4) hybrid model.

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Key performance indicators (KPI) module

A diagram of KPI, also called spider chart or health radar chart, is used for indicating the degradation of components.
Each radio line shows the component condition from zero (perfect) to one (damage).
The colors show the levels of the components, such as safe, warning, alarm, fault, and defect.
The diagram will help operators or mangers to evaluate the performance of the equipment visually.

Maintenance schedule optimization module

IPdM applies Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Bee Colony Algorithm (BCA) and tries to find the optimal dynamic predictive maintenance scheduling.
All these methods are selectable in *IPdM* to solve maintenance scheduling optimization problems.

Error correction, compensation, and feedback control module

This module will make error correction, compensation, and feedback control based on the results from the maintenance decision-support module.