CISTER - Research Center in
Real-Time & Embedded Computing Systems

Framework for Proactive Maintenance in the Real World

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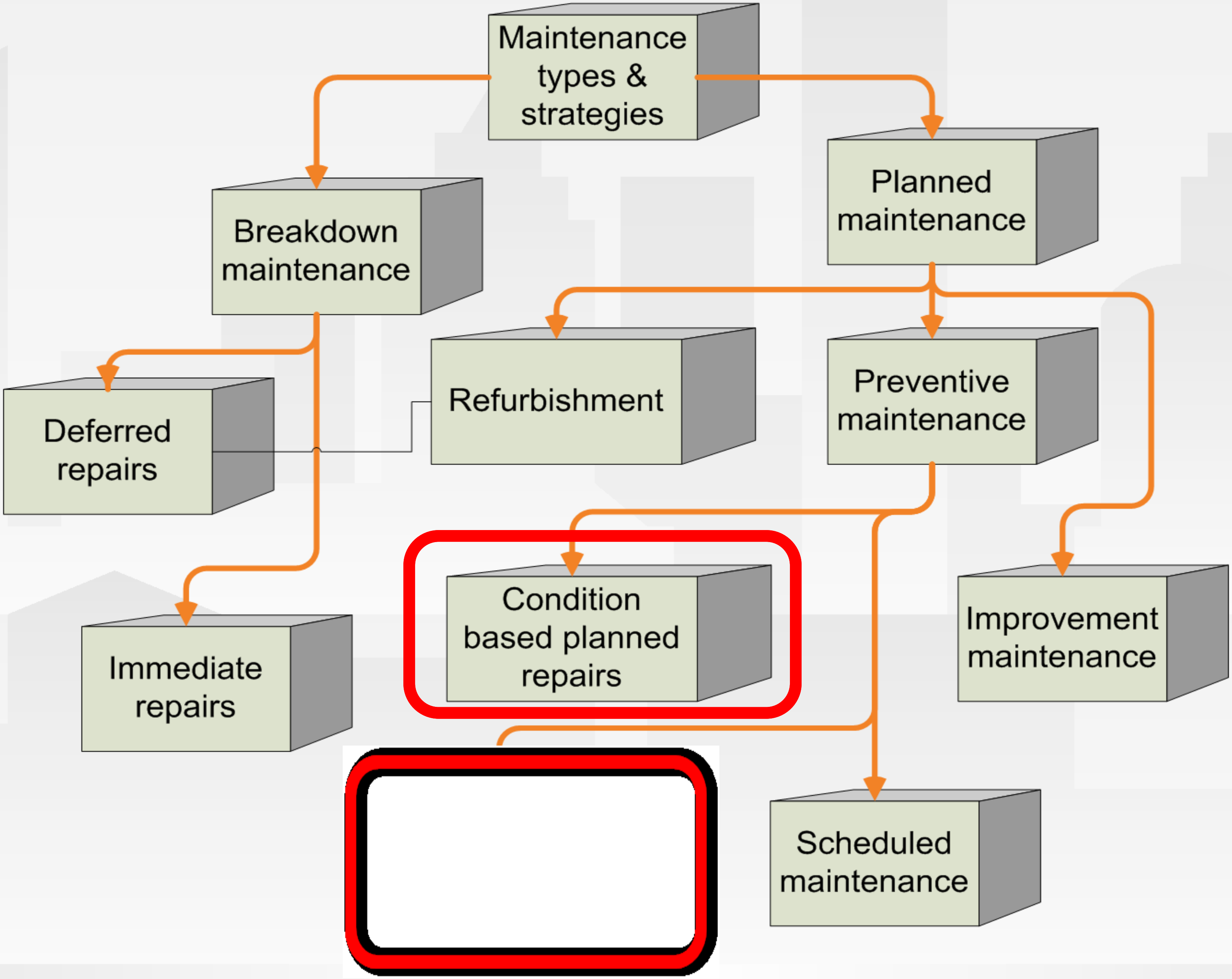
Outline

- Modern maintenance
  - Goals
  - Supporting technologies: IoT, CPS, cloud computing
- A platform for maintenance
- Applications in the real world
- Future of maintenance

Different Kinds of Maintenance

- Corrective Maintenance (CM)
  - also called Run-to-failure reactive maintenance, and fire-fight approach
  - Advantage: minimizing manpower to keep things running
  - Disadvantage: unpredictable production capacity, high overall maintenance costs
- Preventive Maintenance (PrM)
  - periodic maintenance execution that can range from equipment lubrication to replacement
  - based on specific periods of time, amount of machine usage (number of working hours) and/or mean time to failure (MTTF) statistics.
  - Advantage: it improves equipment lifetime, it reduces malfunction probability
  - Disadvantage: may occur prematurely, or too late (failures can occur)
- Predictive Maintenance (PdM), or Condition-Based Maintenance
  - relies on physical measurements of the equipment condition (e.g.: temperature, vibration, noise, lubrication, corrosion)
  - maintenance happens in a need-based when a certain threshold is overcome.
  - It is a tool to improve corrective and predictive maintenance
- Proactive Maintenance (PM)
  - builds on PdM, focuses on the root causes of the problems, by modeling the machines and their environments, and comparing with data from the machines
  - depends on the availability of an efficient and effective monitoring infrastructure


Maintenance types & strategies
Breakdown maintenance
Planned maintenance
Deferred repairs
Refurbishment
Preventive maintenance
Immediate repairs
Condition based planned repairs
Improvement maintenance
Scheduled maintenance

Examples

In CBM the maintenance engineer needs answers to questions like:

- Which machines need maintenance?
  - Where is it located?
  - How can I identify it?
  - When should I do this action?
- What are the necessary actions?
  - What spare parts do I need?
  - How do I carry out the work?
  - How should I report the work?

It's all about information

Technologies to the rescue

- Development of processing power & cheap sensors
- High interest to IoT, Cyber-Physical Systems
  - Manufacturing companies want to widen their business to maintenance i.e. provide services for their products
  - Companies want to improve their productivity with higher Overall Equipment Effectiveness (OEE)
- Big data, 3 V's (Volume, Velocity, Variety)
  - Need for automatic diagnosis, AI
  - Knowledge Discovery in Databases (KDD)

Internet of Things (IoT)

- Part of the “Embedded” family (CPS, Wireless Sensor Networks, Machine to Machine communication, Body Area Networks, etc.)

- IoT considers all embedded systems as connected to the Internet
  - Allows for ubiquitous access to the embedded systems
  - Makes use of mature protocols and well accepted software libraries, thus:
    - IoT applications are faster to implement and easier to maintain
    - lower time to market and cheaper maintenance

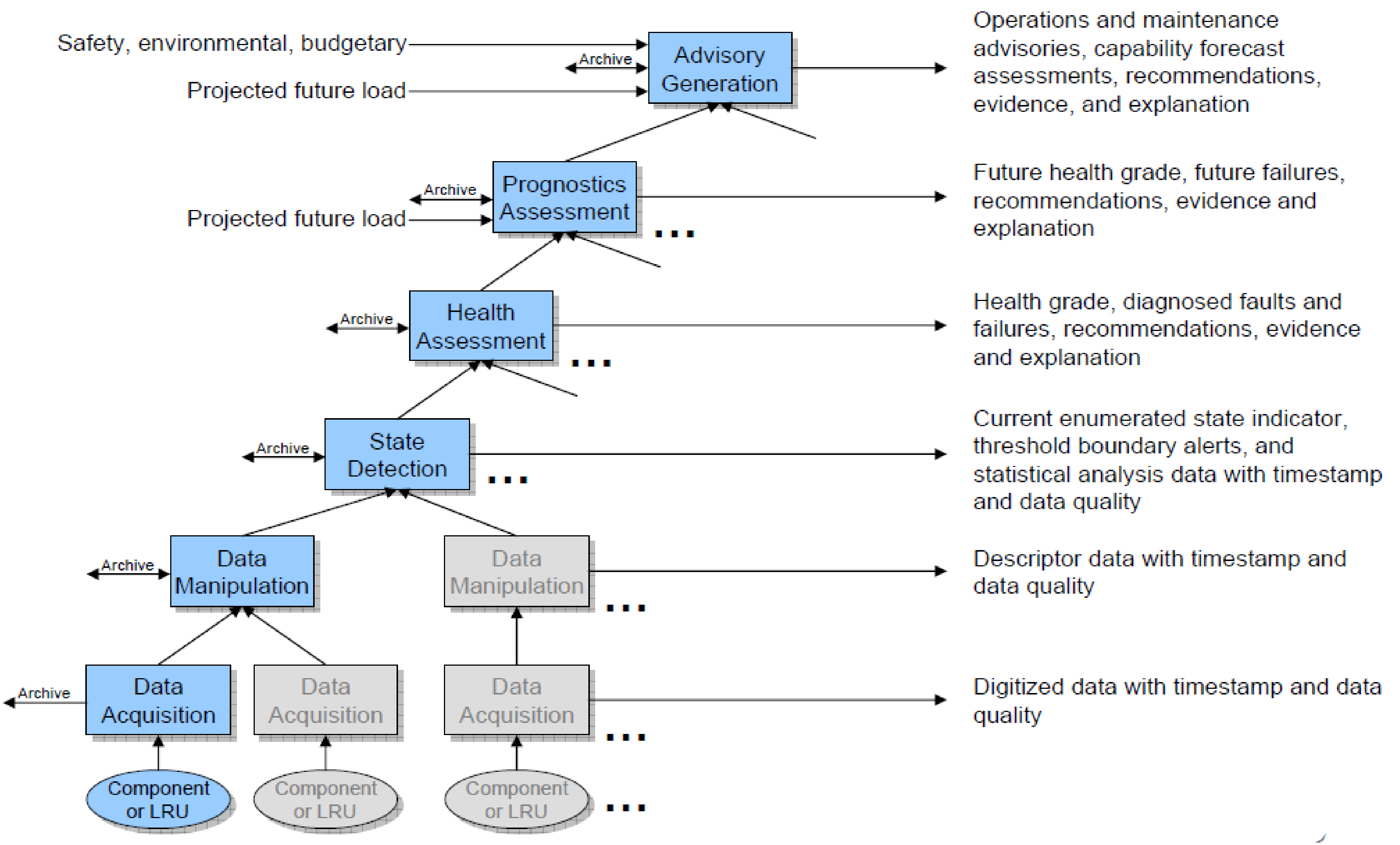
Cyber-Physical System (CPS)

- Term introduced in 2006
  - Has currently many definitions, such as:
    - Technologies that allow to manage interconnected systems between physical assets and computational capabilities
    - Systems of collaborating computational entities that are connected to the surrounding physical assets providing and using services to/from the internet
    - A system consisting of computational, communication and control components combined with physical processes
    - A bridge between the physical and cyber worlds

The Cloud

- High-performance computing
- Well-structured architecture
  - Allows for
    - easy deployment of new applications,
    - elasticity,
    - maintanability / general management
- **Well-accepted technology**
- **Well documented development platforms**

ISO 13374: Condition Monitoring and Diagnostics of Machines

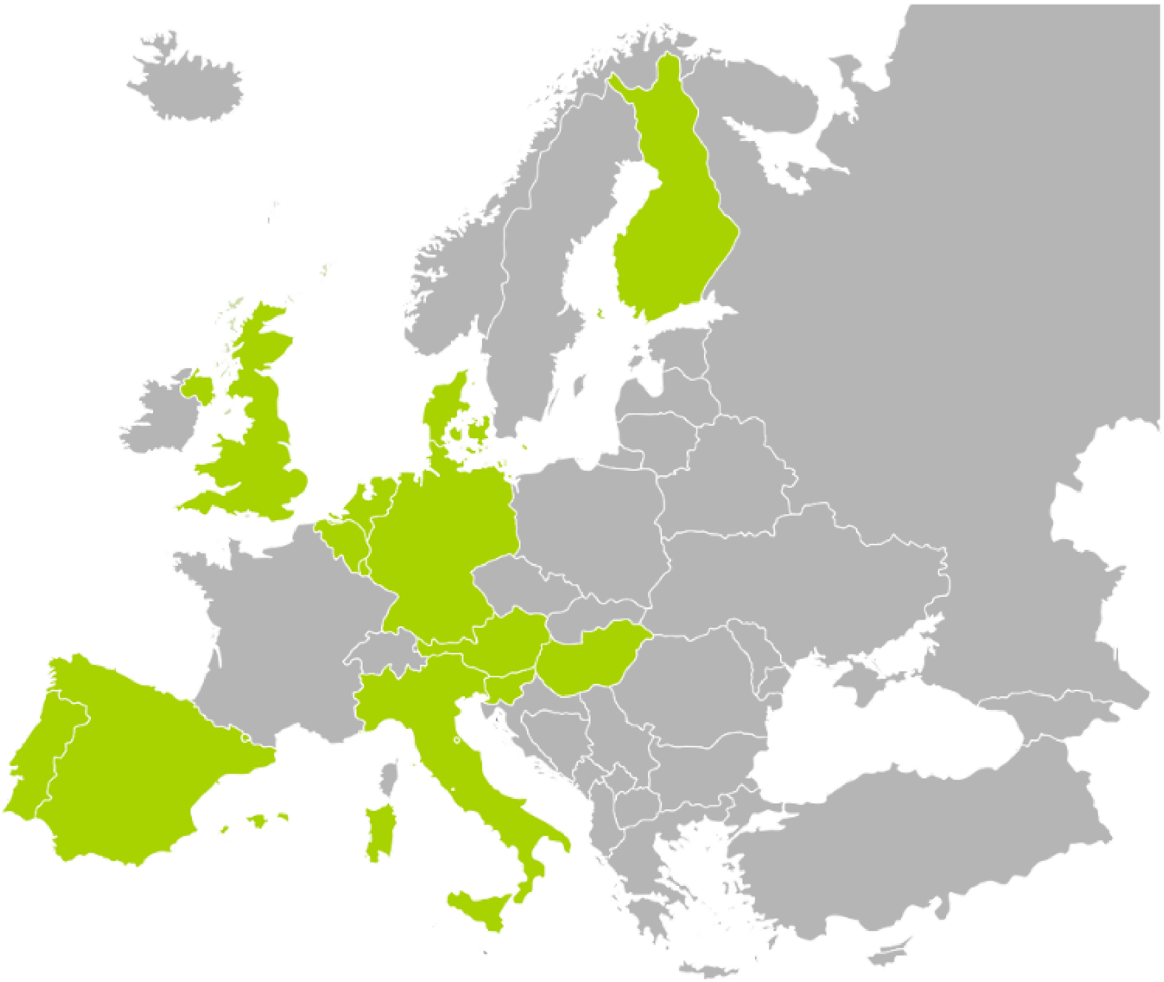


The MANTIS project

EU Joint Undertaking

Funded by ECSEL program and national agencies

47 partners from 12 countries

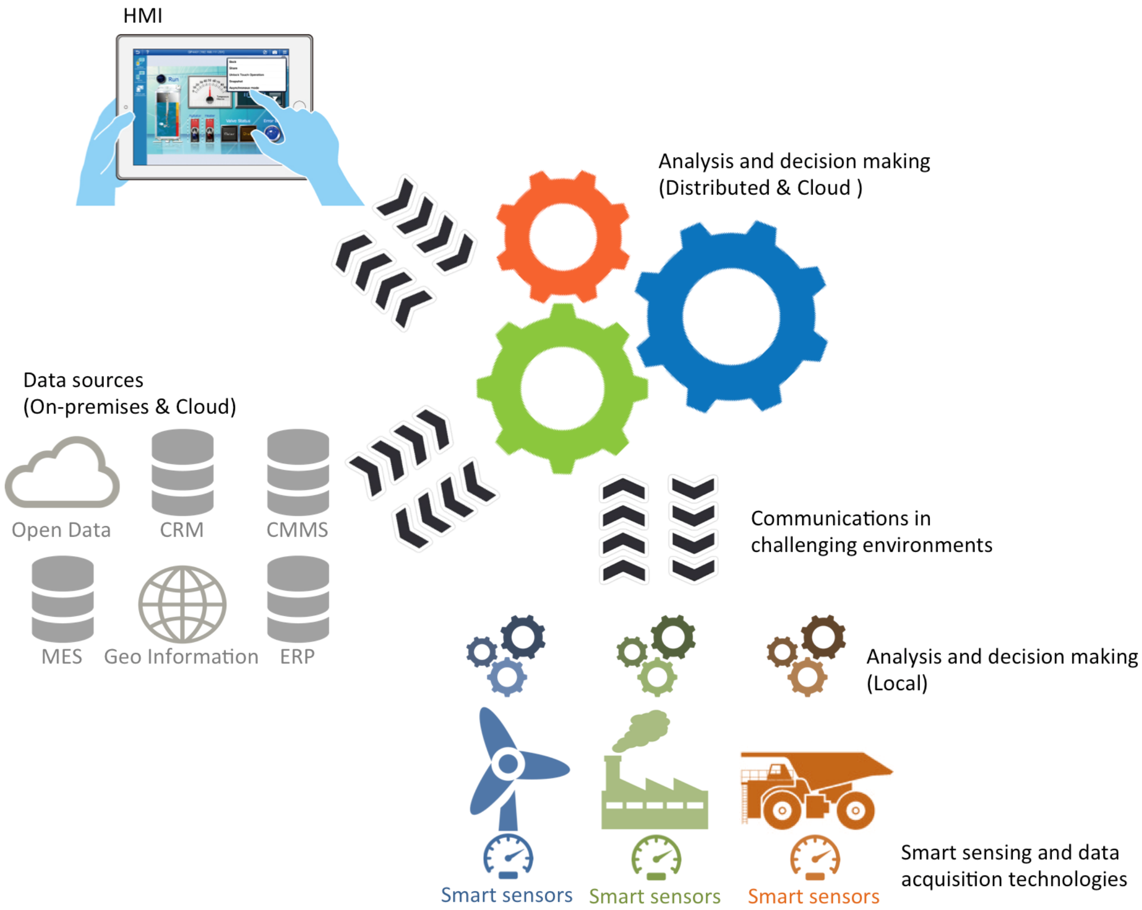


Objectives of the MANTIS

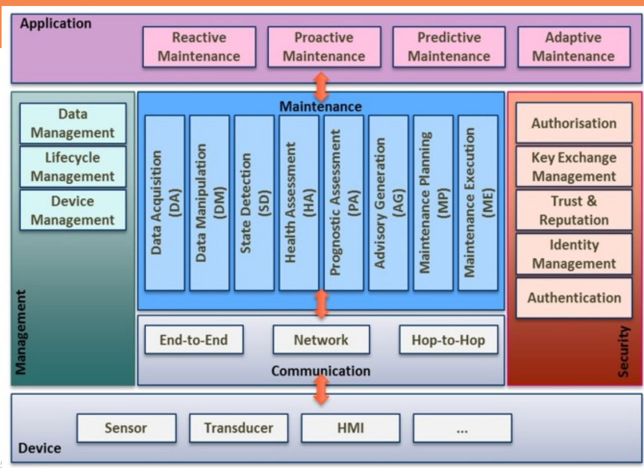
- The use of data structures that enable the collection of maintenance information (events, root cause analysis, fault prediction and remaining useful life results …)
- The use of data structures that enable large volume of data to be processed in real time or in batch processes.
- Integration of complex and heterogeneous large-scale distributed systems from different application domain.
- The design of CPS-populated systems to enable collaborative proactive maintenance strategies.

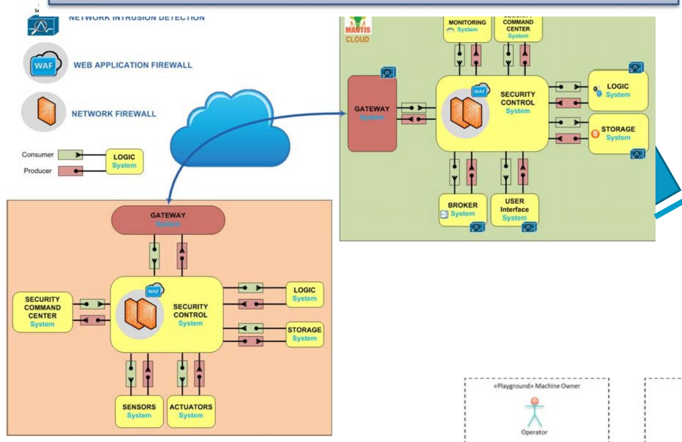
The MANTIS platform

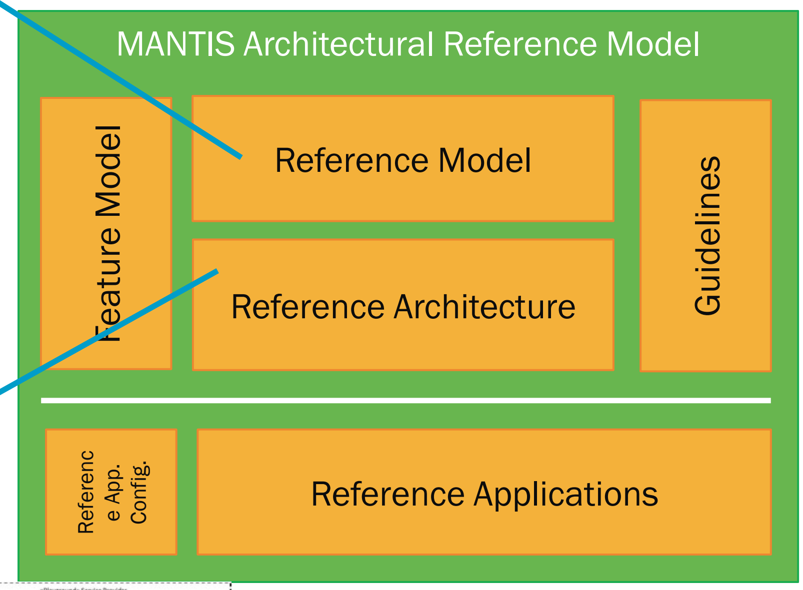
- Developed a framework for proactive maintenance, based on:
  - real-time sensor data acquisition
  - high-performance communication middleware, connecting local networks in the factories and the cloud through challenging environments
  - data analysis and decision making, both local (in the factory) and on the cloud
  - advanced HMI

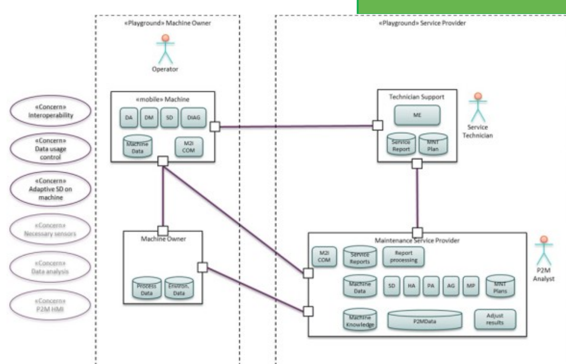


Reference Model of the MANTIS

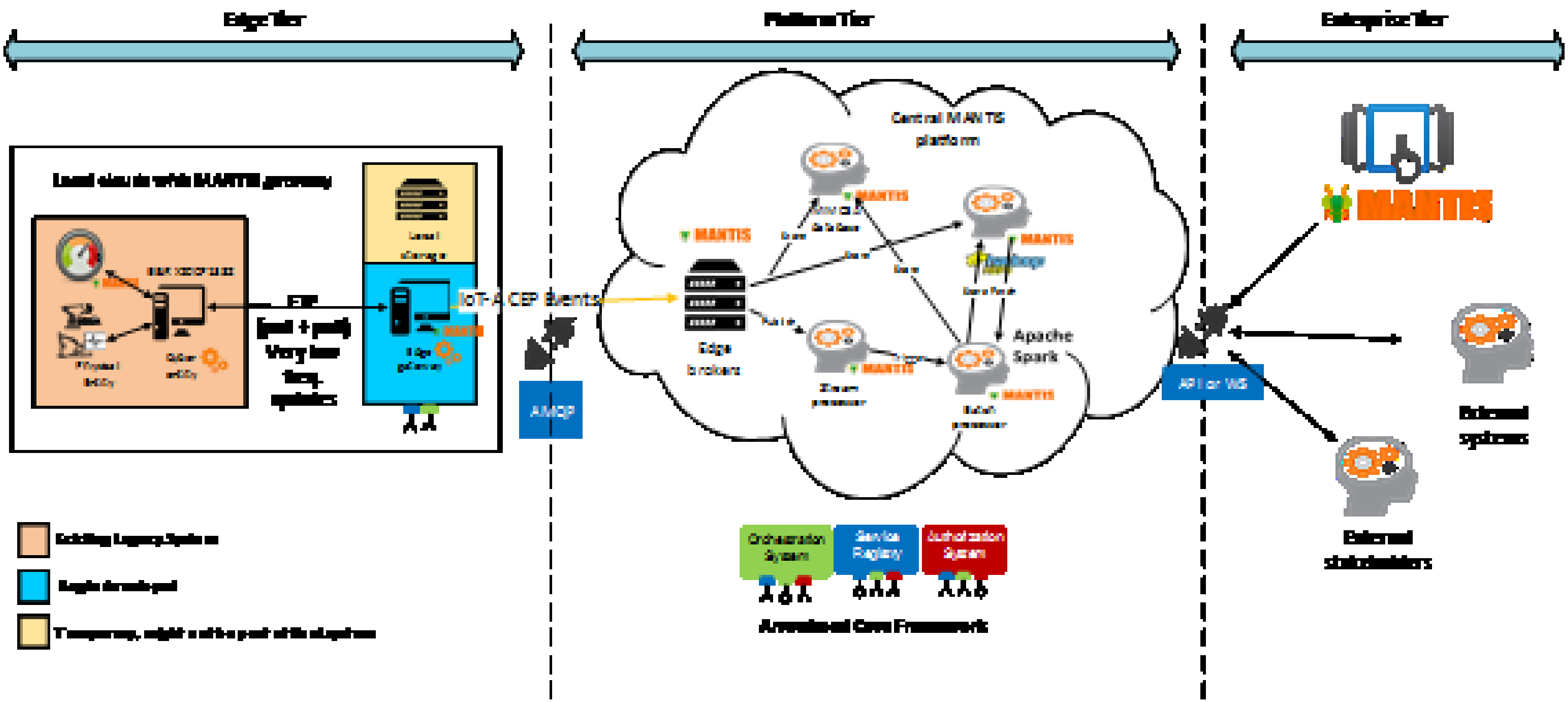








Reference Architecture of the MANTIS



Edge Tier elements

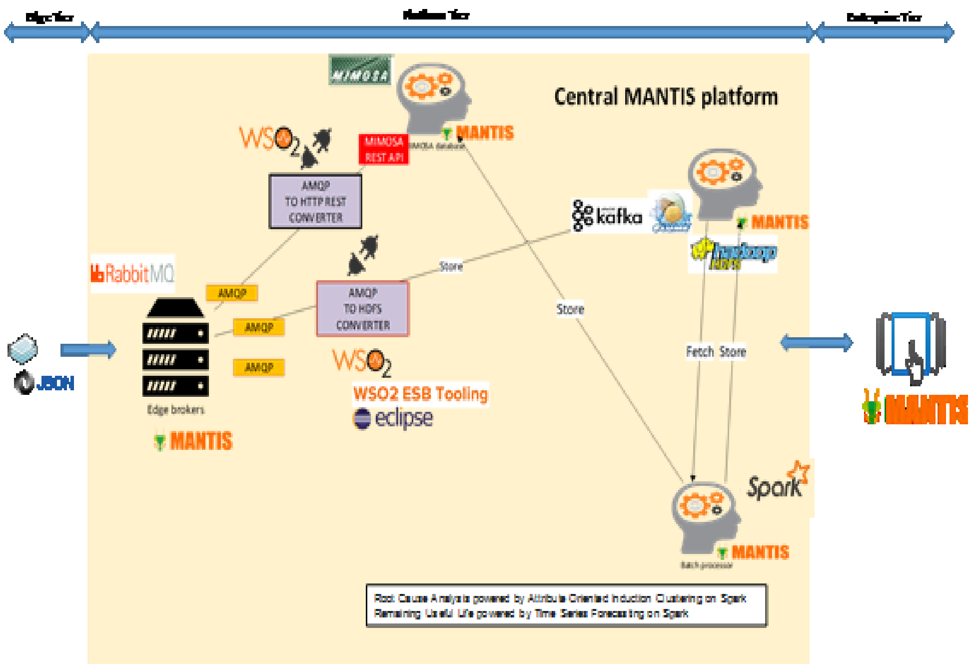
- Edge computing:
  - optimizing cloud computing systems by performing data processing at the edge of the network, near the source of the data
- It can be used to
  - reduce the data sent to the platform
  - secures the machines inside the factory from the outside
  - Supports additional protocols to connect to other devices
  - Converts between different data formats
  - enable on-site maintenance operations with low latency,
  - allow for maintenance operations when connection to the cloud is absent / challenged.

CBM at Low level (Edge)

- The edge tier provides for
  - Local data storage
  - Limited analytics
  - Local HMI
  - Lifecycle management support.
- CPS are involved and are executing their general production operations.

Platform Tier elements

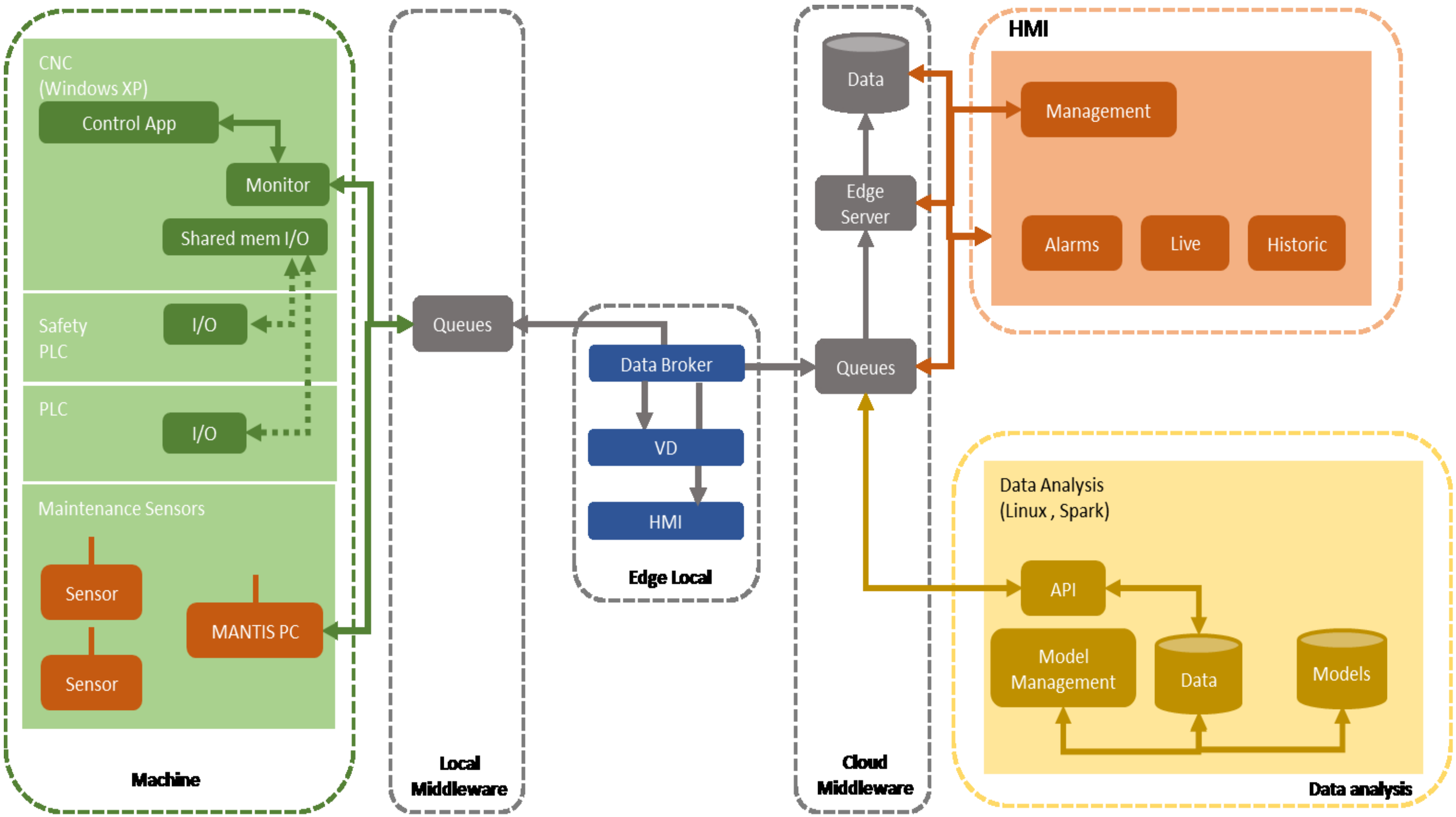
- Data Access and Ingestion through the Edge Broker
  - Publish/subscribe servers
  - Translator/Converters
- Data Storage systems
  - Mimosa
  - Distributed File Systems
- Batch Processor
- Stream Processor



CBM at High level (Platform)

- Remaining Useful Life (RUL) of components: continuous tracking of telemetry (usage) data and estimating how much time the given device or component has left before needs to be replaced
- Fault Prediction (FP): the system shall predict based on diagnostic data an inbound failure mode (different to wear-out to be detected by RUL),
- Root Cause Analysis (RCA): when an unpredicted, complex failure occurs, the system shall deduct the actual module (cause) that caused the break.

Concrete Architecture of the MANTIS



Components: Machine

- Machine
  - PLC: that controls the machine – no direct access
  - CNC controller: HMI to configure and operate the machine
    - Already capable of producing basic diagnostic functions
  - Sensors, both already on the machine, or added

Components: local middleware

- Local middleware
  - Connects all factory machines with the Edge Local
  - Can be implemented in different ways. Examples:
    - REST and AMQP
    - OPC-UA over AMQP
  - Trendy tech: OPC-UA enables the connection of the machine with other IT systems: MES, SCADA, ERP, etc.

Components: Edge Local

- Edge Local
  - Secures the machines inside the factory from the outside
  - Supports additional protocols to connect to other devices
  - Connects to the cloud
  - Converts between different data formats
  - Focus on Data: data storage, visualization with local HMI, data filtering and aggregation

Components: Cloud Middleware

- Current trend: storing all data using a MIMOSA-like design
  - High potential for interoperability
- Intermediates with the Data Analysis and HMI modules
- Makes available a set of services which are used by the HMI to configure the system, used to support system start-up and resume system operation in case of a crash
- Communication should be based on high-performance messaging bus
  - Example: AMQP / RabbitMQ

Components: Data Analysis

- Data Analysis
  - Prediction Models:
    - used for the detection, prognosis or diagnosis of machine failures. The models can be built for one machine family, or can be generic and adapted to different machine families.
  - Data and Prediction Interface
    - outputs predictions (to th HMI) from the models, and provides data to feed and train the models.
  - Intelligent Maintenance Decision Support System (IMDSS)
    - used to manage the models (model generation, selection, training and testing), IMDSS is composed of:
      - Knowledge Base of diagnosis and prediction models
      - Rule based Reasoning Engine which includes all the rules that are necessary to deduce new knowledge - helps the maintenance to diagnose failures

Issues with Data Analysis development

- Errors are extremely rare, 1 error every 150 days
  - impacts the performance of the models, both in terms of learning and prediction accuracy
- Some machine show a failure rate of once every 500 days, therefore we opted on short term predictions via real-time stream analysis
- Communications infra-structure takes care of fusing data from various sources (controller signals, controller sensors, external wireless sensors, etc.), insuring synchronization and time stamps data.
  - These timestamps are used by the failure detection algorithm to label the signal indicating were the failure occurred and allow visualisation by the HMI,

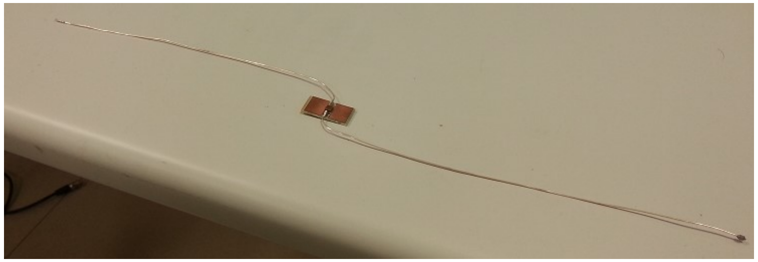
Components: HMI

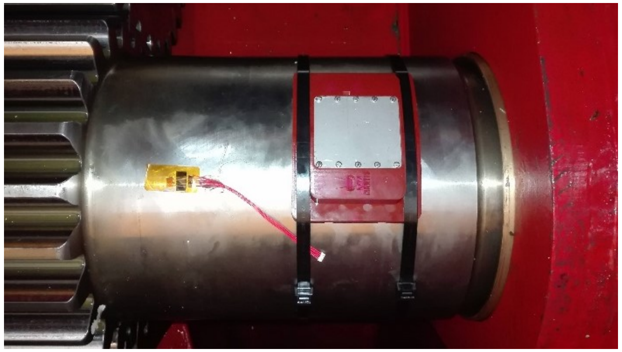
- Human Machine Interface
  - Controls system start-up
  - Visualization of data
  - Shows analysis results

- Main issue of data vs information

Focus on Sensors and CPS

- CBM uses intelligent techniques, such as machine learning
- Every technique depends on data on the working condition of the machine, and on the environment
- Data is
  - Collected by means of sensors
  - Preprocessed by means of sensors
  - Used for early decisions in the factory by the sensors
  - Communicated through challenging environment to gateways by the sensors



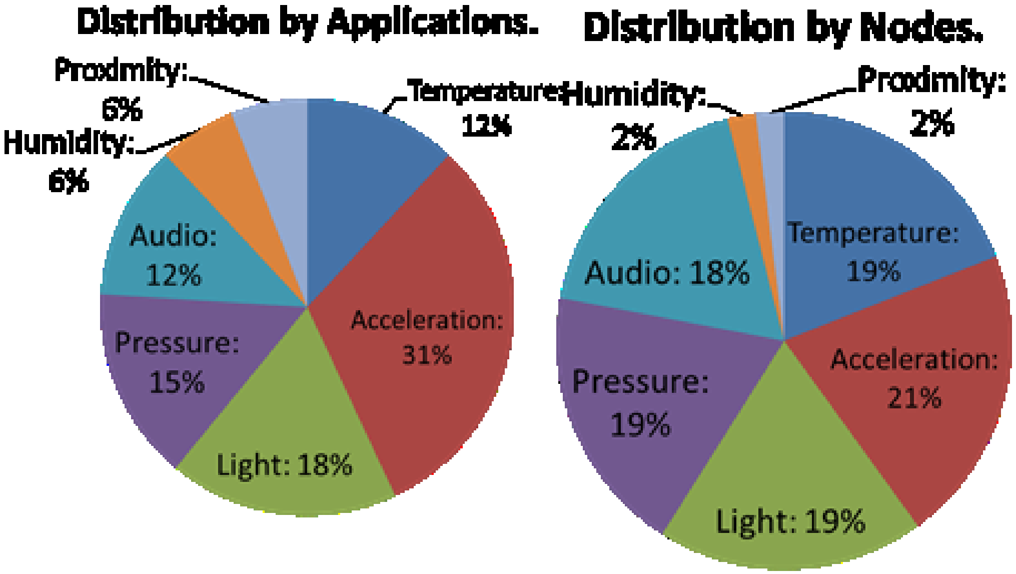


Categories of Sensors

- Sensors can be categorized using different approaches
- A pragmatic approach (in relation to real life use cases) considers the sensors as physical elements, or virtual ones
- With the same pragmatism, physical sensors are either
  - Off-the-shelf (bought)
  - Custom (built)
- Virtual sensors are always built (programmed)

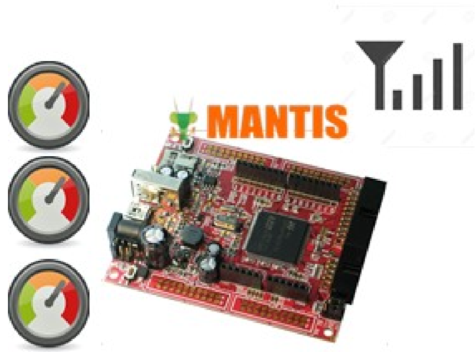
Off-the-shelf Sensors

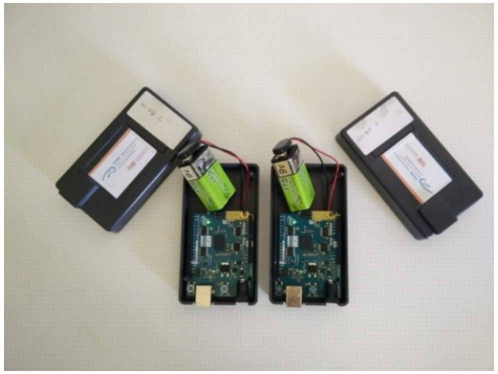
- Measure very common parameters
- Previous works already analysed types of sensors by frequency of usage
- Seven sensor types were identified
- All these sensors are better bought
  - Connected with CPS platforms (Arduino, Raspberry pi, etc), e.g. by I2C



Custom Sensors

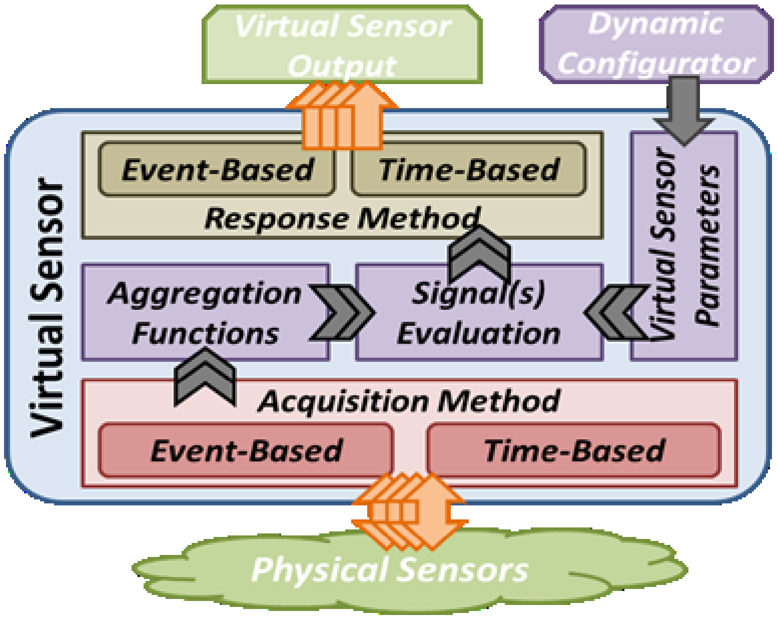
- They are special-purpose
  - E.g.: crack detection, torque easurement, analyse wear of material and retrieve oil status
- Not mass produced
- “Buy” would thus be very expensive
- Better to “build”





Virtual Sensors

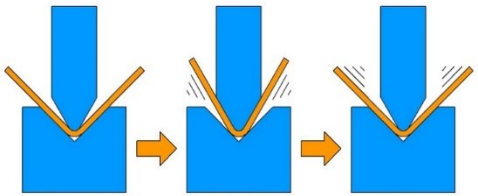
- They work on data collected by other sensor(s). Usually
  - They are software
  - They “run” in the factory
- *Aggregation Functions* compute new data
  - By combining data from multiple sources
  - By applying process models
  - By considering time series
- *Signal(s) Evaluation* takes decision / evaluates results



Sheet Metal Bender pilot

Mantis in Portugal: Sheet Metal Bender

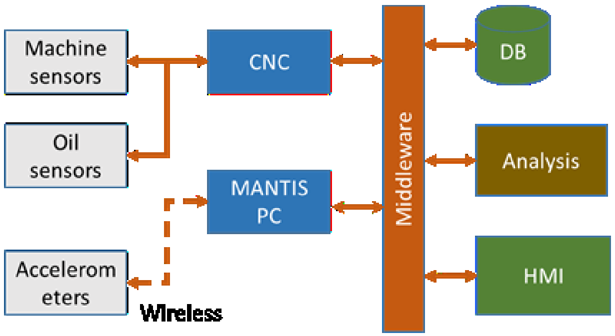
- Press Braking: deforming a metal sheet (workpiece) along a given axis by pressing it between clamps (tools).
  - Workpiece from 0.6 to 50 mm thick and lengths from 150 mm to 8 m long
  - In order to have a finished part, a metal sheet will be consecutively bent at several places – e.g. to make a computer box.
- The machine is able to exert a force up to 2200 kN using 2 electric motors of 7.5 kW each, and it is able to bend metal with high precision.
- Compensates for the bending of the ram and structure deformation in order to achieve very high precision.

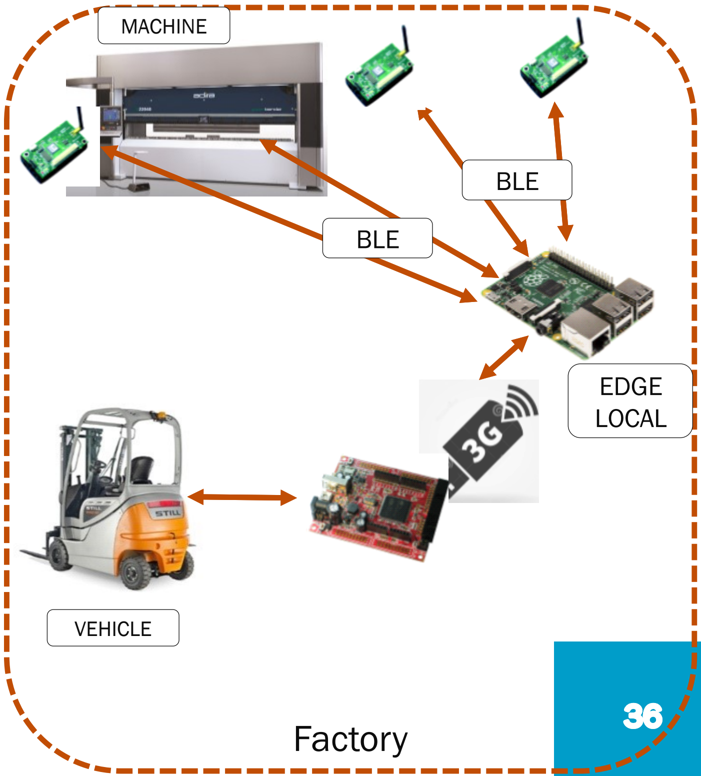


Implementation

Edge Tier:

- Acquire internal machine sensor and actuator data
  - 30 ms period, 50 variables, for every machine cycle: ≈ 300 MB/day
  - Data are on an Access DB file on the CNC
- Add maintenance specific sensors to the machine:
  - Accelerometers on the blades
  - Oil sensors
- Join all data from a factory on a Edge computer,
  - Preprocessing
  - Local HMI



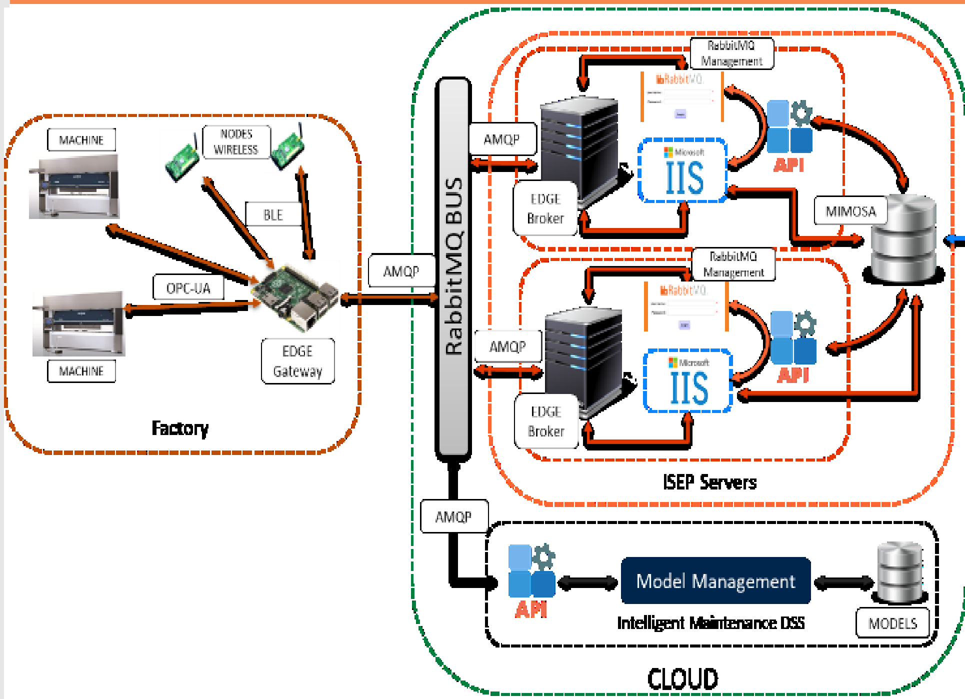


Platform Tier:

- Transfer all information for analysis to the cloud
  - Communication Middleware based on RabbitMQ
- Analyse data using Machine Learning

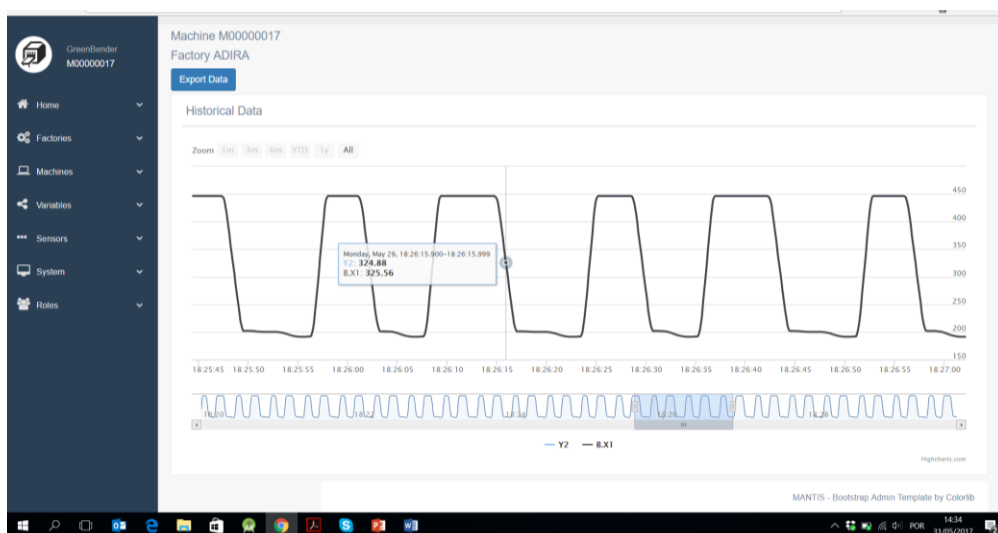
Enterprise Tier:

- HMI to visualise data from the machines
  - Sensor data
  - Maintenance-related data



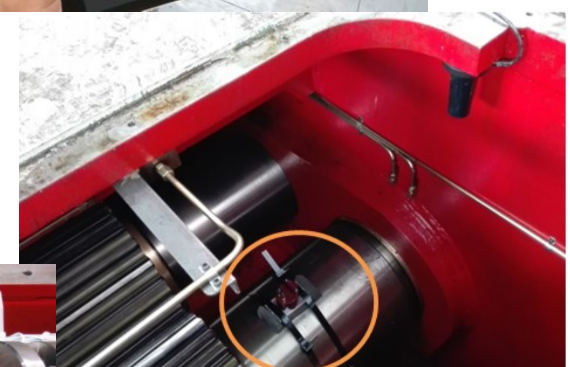
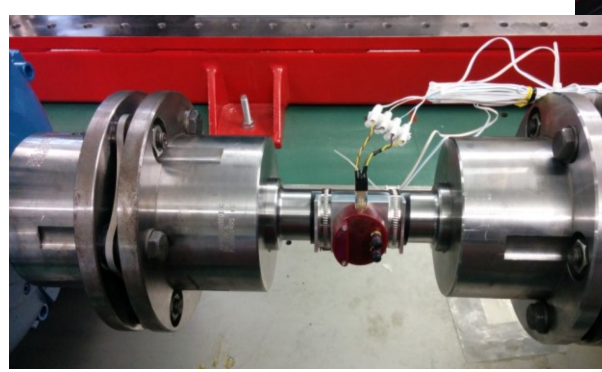
Full Deployment View

Human Machine Interface



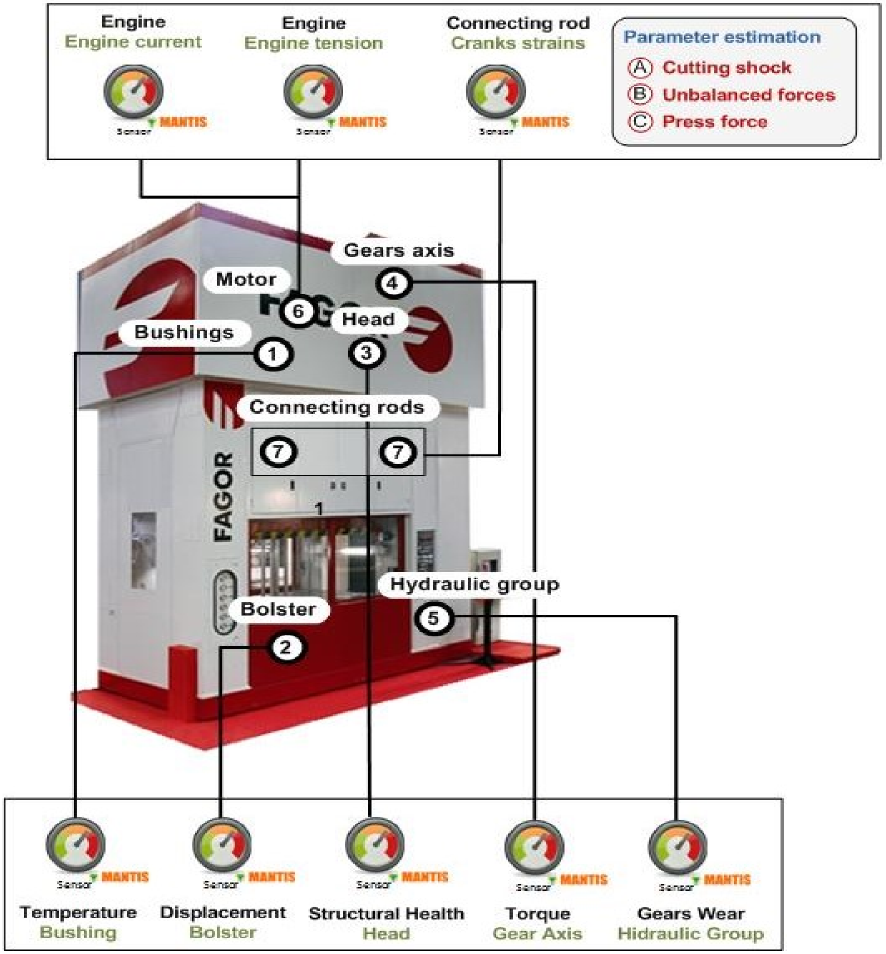
Mantis in Spain 1: Press Machine

- Cut/shape metal with a die
- Target:
  - 40 million strokes, each one with a force of 2000TN
  - High precision
  - High availability
- Incorporated CPS into most critical components

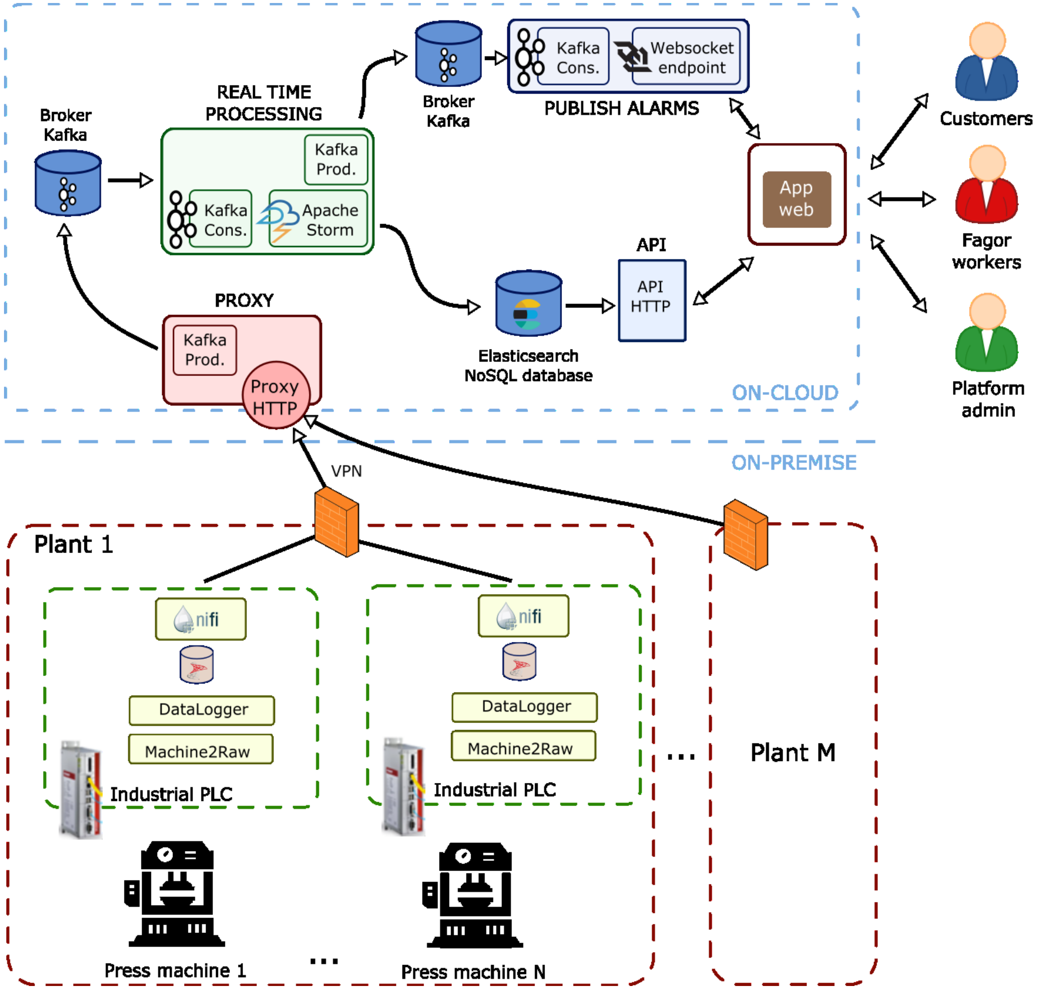
Components requiring CPSs

- Bushings (Temperature and oil condition status)
- Bolster (Relative displacements)
- Head (Structural health)
- Gear axis (Torque)
- Engine (Tension and current)
- Connecting rod (Displacement, forces)



Implementation

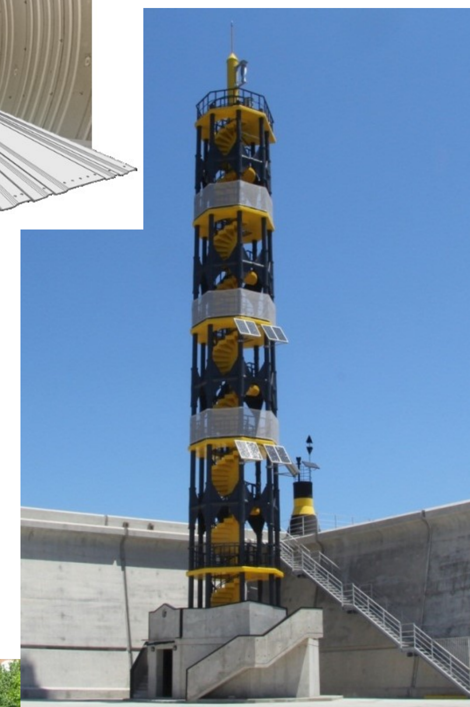
- Edge Tier (On-premise):
  - Machine2Raw: extracts the data from the different PLCs
  - Datalogger: stores data in a local database (SQL server)
  - Apache NIFI: processes the raw data stored in the local database. After processing the data, Apache NiFi transfers the data to the cloud through the Proxy
- Platform Tier (On-cloud):
  - Elastic Search: (NoSQL database)
  - Apache Kafka: distributed queue message system to decouple the different applications
  - Proxy: published data to different Kafka topics
  - Real Time Processing: three objectives: Extracting raw data categorised using Kafka topics, persisting data in elastic search, executing data analytics to detect possible alarms
  - API: REST API that connects to a web front end
- Enterprise Tier:
  - Visualizes data using web applications



MANTIS in Spain 2: Pultrusion

- Composite glass fibers, basalt, carbon, natural fibers are impregnated with resin and passed through a heating line.

- Result: highly strengthene composite structures with low weight, elevated mechanical and chemical resistance, and electrical and thermal insulation.
- Material used for example for waterproofing Pajares tunnes (Asturias, Spain), for Valencia Lighthouse (Spain), for the pedestrian bridge in Madrid (Spain)

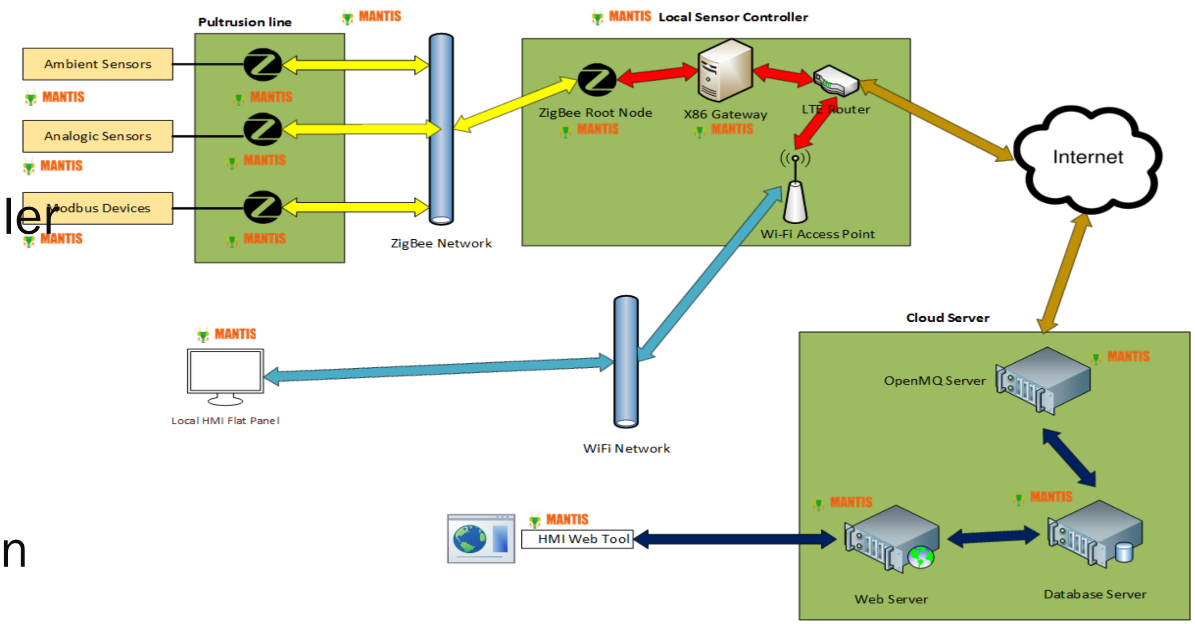


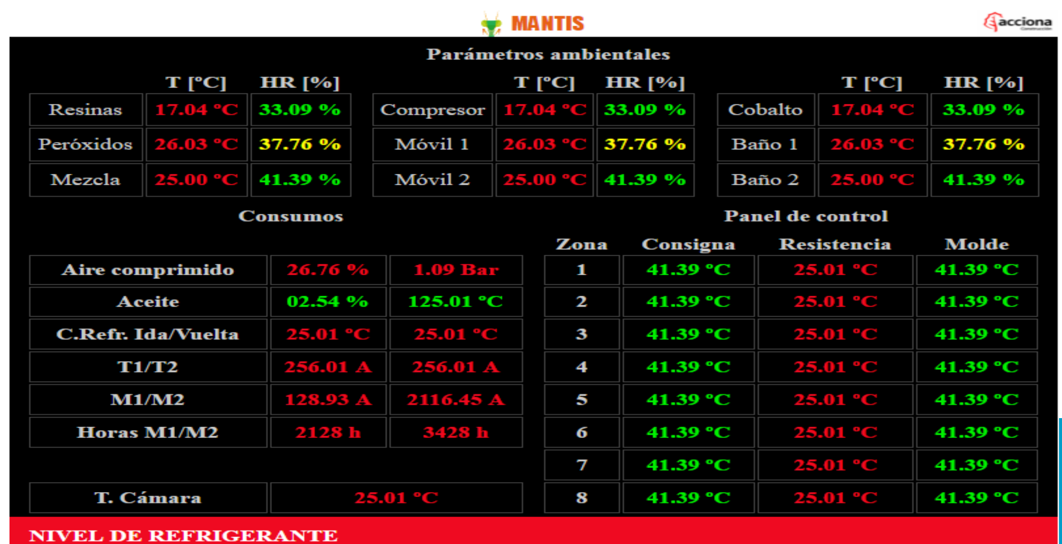
The Pultrusion Machine

- Pultrusion is a continuous process for manufacture of composite materials with constant cross-section.
- Mantis collects data using different sensors in the workshop:
  - Temperature, humidity, air extraction capacity, etc
- and installed in the machine itself:
  - Injection System Temperature, Oil tank presses system, etc

Mantis implementation

- Different parts / subsystems:
  - Sensors (edge tier)
  - Local Sensors Controller (edge tier)
    - Zigbee[4] Root Node
    - X86 Gateway
    - LTE Router
    - Wi-Fi Access Point
  - Local HMI (edge tier, in the bottom figure)
  - Cloud Servers (platform and enterprise tiers)
    - OpenMQ Server (message-oriented middleware platform, reference implementation for the JMS)
    - Database Server
    - Web Server





Parámetros ambientales

	T [°C]	HR [%]		T [°C]	HR [%]		T [°C]	HR [%]
Resinas	17.04 °C	33.09 %	Compresor	17.04 °C	33.09 %	Cobalto	17.04 °C	33.09 %
Peróxidos	26.03 °C	37.76 %	Móvil 1	26.03 °C	37.76 %	Baño 1	26.03 °C	37.76 %
Mezcla	25.00 °C	41.39 %	Móvil 2	25.00 °C	41.39 %	Baño 2	25.00 °C	41.39 %

Consumos

Aire comprimido	26.76 %	1.09 Bar
Aceite	02.54 %	125.01 °C
C.Refr. Ida/Vuelta	25.01 °C	25.01 °C
T1/T2	256.01 A	256.01 A
M1/M2	128.93 A	2116.45 A
Horas M1/M2	2128 h	3428 h
T. Cámara	25.01 °C	

Panel de control

Zona	Consigna	Resistencia	Molde
1	41.39 °C	25.01 °C	41.39 °C
2	41.39 °C	25.01 °C	41.39 °C
3	41.39 °C	25.01 °C	41.39 °C
4	41.39 °C	25.01 °C	41.39 °C
5	41.39 °C	25.01 °C	41.39 °C
6	41.39 °C	25.01 °C	41.39 °C
7	41.39 °C	25.01 °C	41.39 °C
8	41.39 °C	25.01 °C	41.39 °C

NIVEL DE REFRIGERANTE

MANTIS in the Nederlands: Medical Devices Maintenance

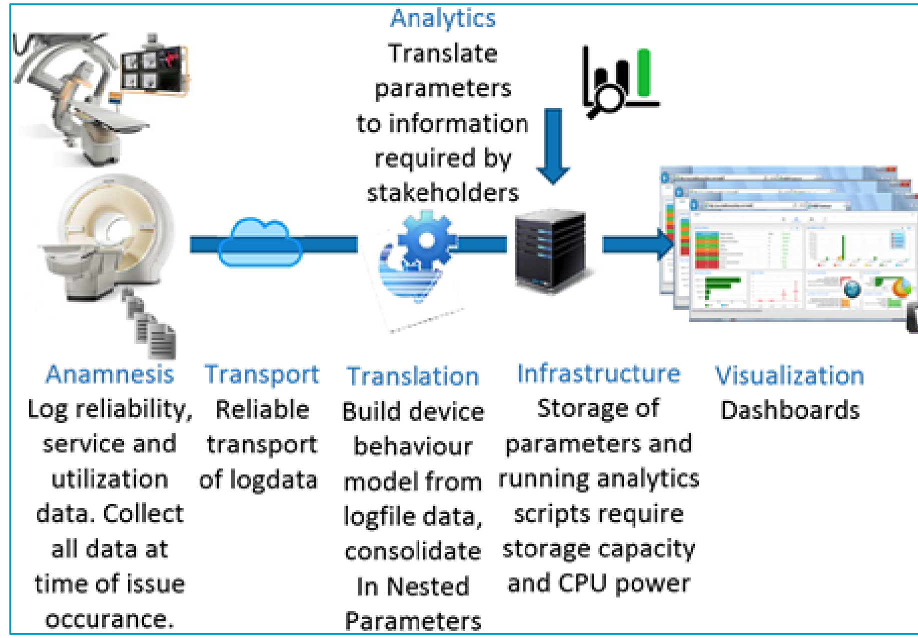
- Medical devices performing non-invasive patient diagnosis
- Medical device must be kept in optimal operational conditions
- Device is life-critical
- Device cannot fail when in use, since
  - not financially possible to have redundancy
  - moving of patients to another hospital might not be possible

- Strategy:
  - complete range of off-the-shelf sensor type
  - data are distilled into more advanced information by means of virtual sensors

How it is done

Every systems contains many sensors and generates large log files daily

- Anamnesis: optimize (filter) logging
- Transport: make all data available worldwide in the cloud
- Translation: different machines' data to be translated to behavioral models and consolidated in a limited set of relevant parameters
- Infrastructure: the translation requires significant computing power and storage space
- Analytics: the obtained parameters have to be analyzed with respect to the maintenance challenges
- Visualization: the results have to be visualized for end-users



Solution: The e-Alert controller

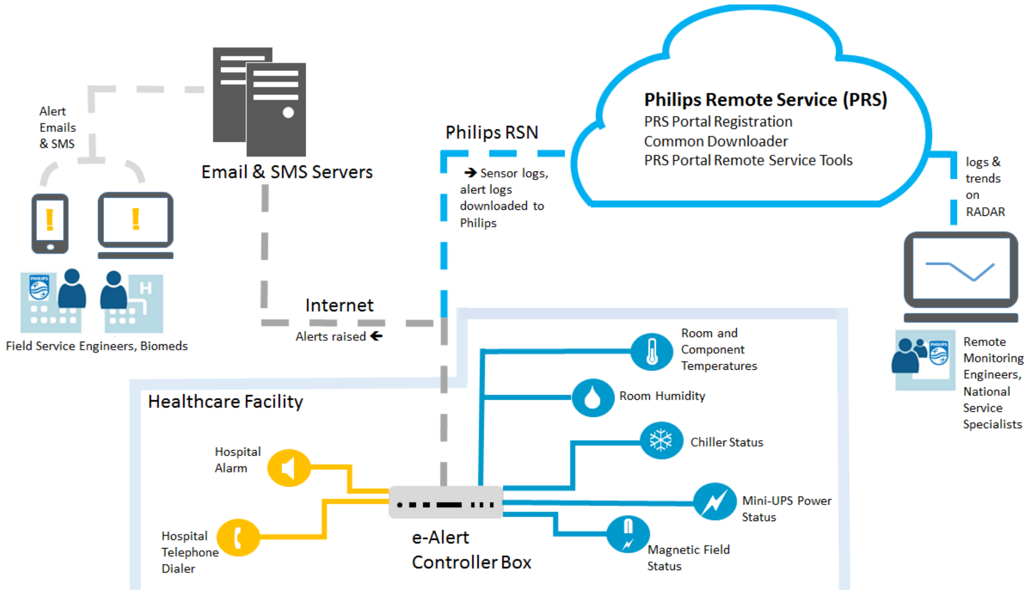
- Can sample connected sensors (max 8 sensors per interface box)
- Can be connected (daisy-chained) for scalability

e-Alert controller software

The e-Alert controller provides:

- A web-based user interface
  - to configure sensors (e.g.: thresholds)
  - to see sensor data (online and history)
- Email/SMS send server and Email/SMS receivers
  - to connect to the Philips Remote Service (PRS)

- PRS can:
  - Aggregate and statistically analyze sensor values
  - determine an operational profile, specific to that medical device, to finetune the configured alert thresholds for that specific device



Comparison of the use cases

- Different use cases had different requirements, and satisfied by different kinds of techniques
- All use cases feature real world factories and installation
- Sheet Metal Bender
  - Protects a traditional machine as a whole
  - Machine already having many sensors, but easy to add new sensors
  - Exploited composition of data from off-the-shelf sensors
- Press Machine
  - Protects a machine with close to no sensors
  - Targeted each critical part of the machine
  - Better to “build” custom sensors integrated with the critical parts
- Pultrusion Machine:
  - Huge machine
  - All the shop floor was sensorized
- Medical Device
  - Life-critical machines
  - Deployed in existing networks (hospitals)
  - Important to
    - Filter data, scale the data collection, adapt to different machines
    - Real processing of the data in the cloud

Future of maintenance strategy

Provocative questions:

- Is it cybernetic or is it human?
- Is real-time feasible?
- How to determine granularity in space and time?
- Open (customer-in-the-loop) or closed maintainability?
- How to employ advanced communication paradigms (e.g.: blockchains)?
- Insourcing or outsourcing?
- Explicit modeling or data-driven pragmatics?
- Service robotics for maintenance?

Thank you!!!

Much more on the upcoming book:

M. Albano, E. Jantunen, G. Papa, U. Zurutuza, “The MANTIS book: Cyber Physical System Based Proactive Maintenance”, River Publishers ed., July 2018

... and it will probably be open access!!!