

DIGITAL TWIN TECHNOLOGIES FOR SMART MANUFACTURING

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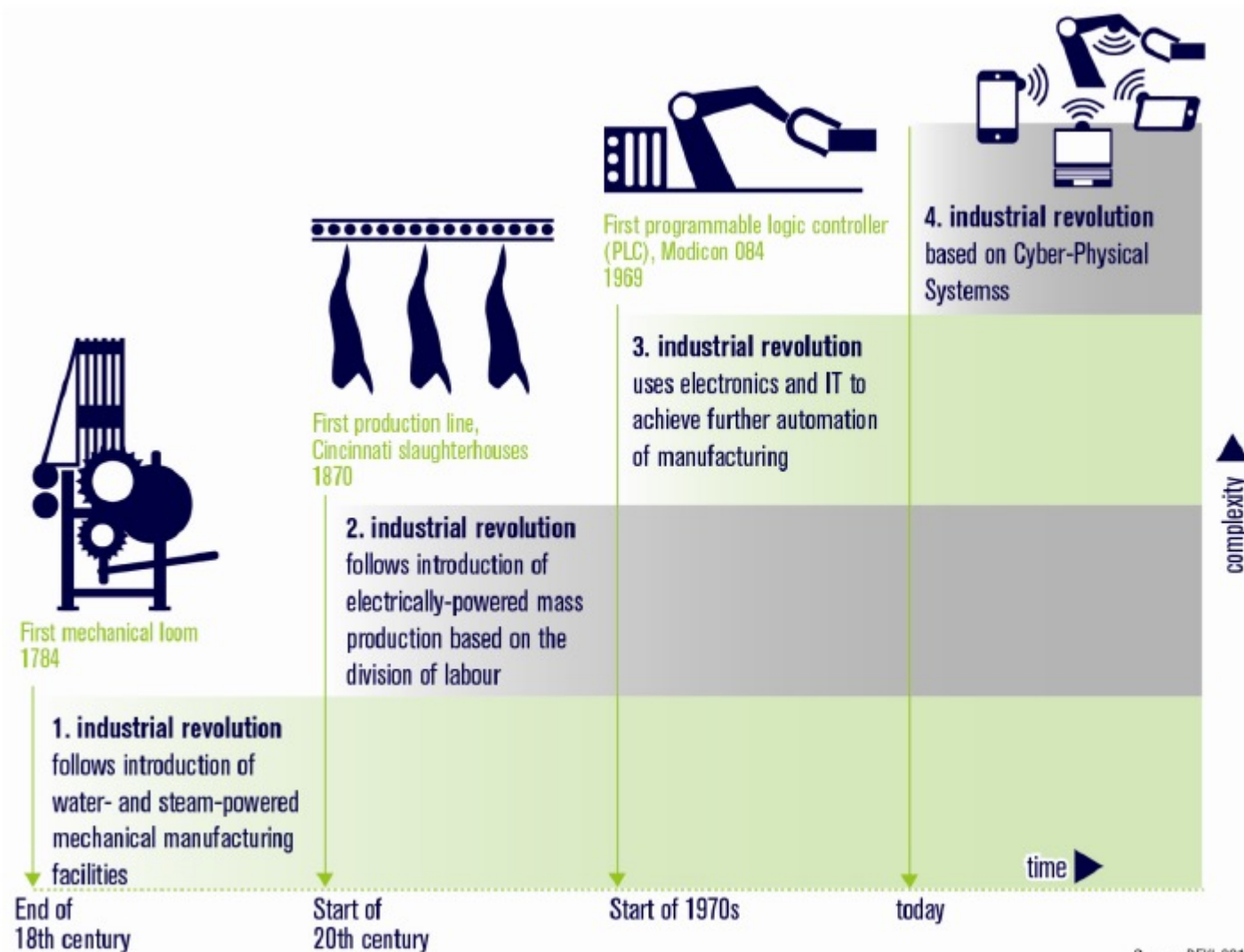
The University of Auckland

March 2022

Agenda

- Industrie 4.0 and smart manufacturing (CPPS)
- Digital Twin defined
 - Definitions/Applications/Models/Twinning methods
- International standard for DT framework
- Demonstrative cases

From Industrie 1.0 to Industrie 4.0 - the German vision



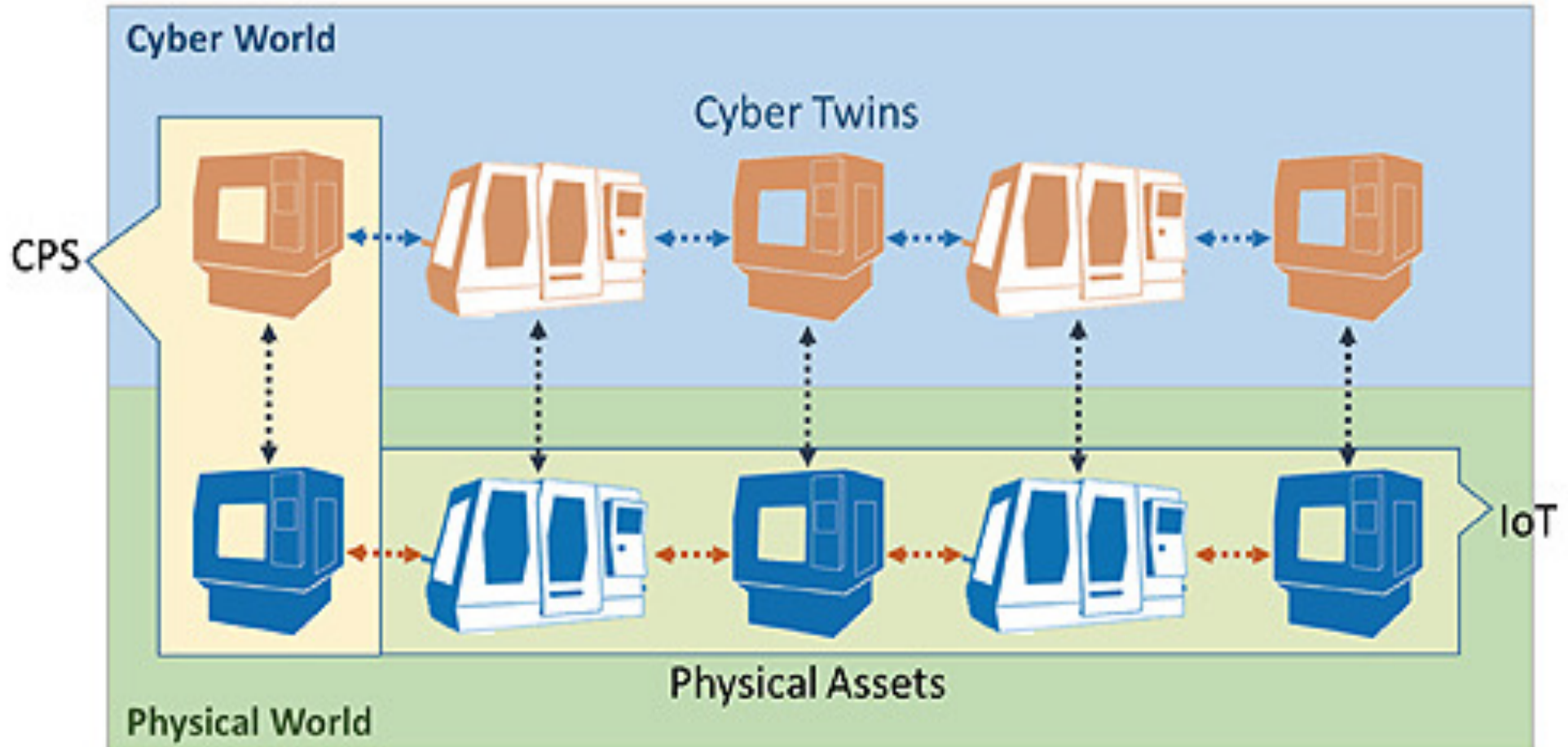
Source: DFKI 2011

cf. achatech

Cyber Physical System (CPS) in support of smart manufacturing

- Marry the *virtual digital (cyber-twin/digital twin)* world with the *real physical* world
- Total connectedness with intelligence
- Semantic machine-to-machine (M2M) communication
 - closed embedded systems
 - self-monitoring, self-healing, proactive communications with other machines and/or operators
- Cyber-physical production systems (CPPS)

Cyber Physical System vs. Internet of Things (IoT)



September 23, 2015, Design World

Digitalization levels and Integration intensity

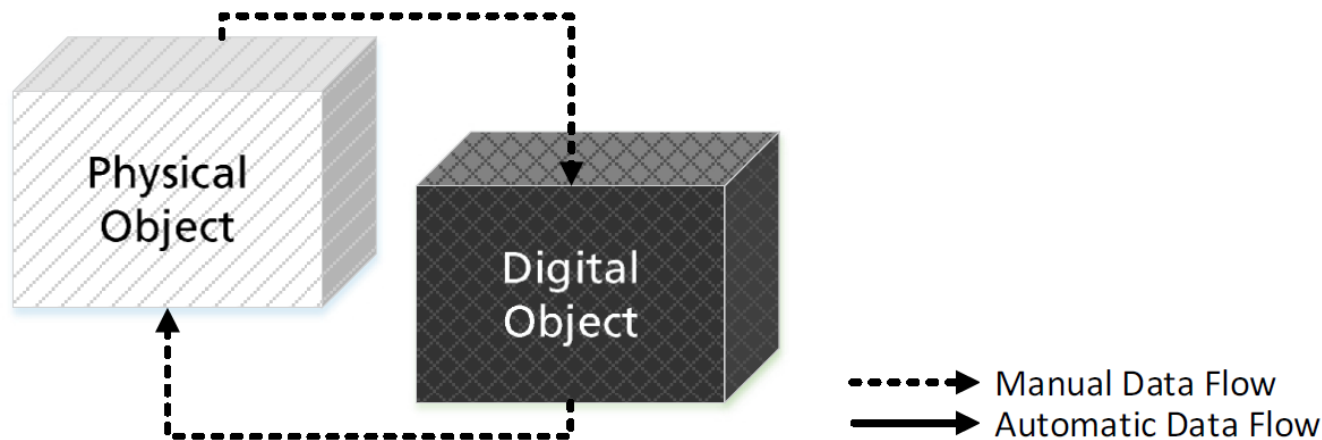
Depending on the level of data integration between the physical and digital counterpart, we can have

- Digital Model
- Digital Shadow
- Digital Twin

They exist for different reasons and applications

Digital Model of a physical object

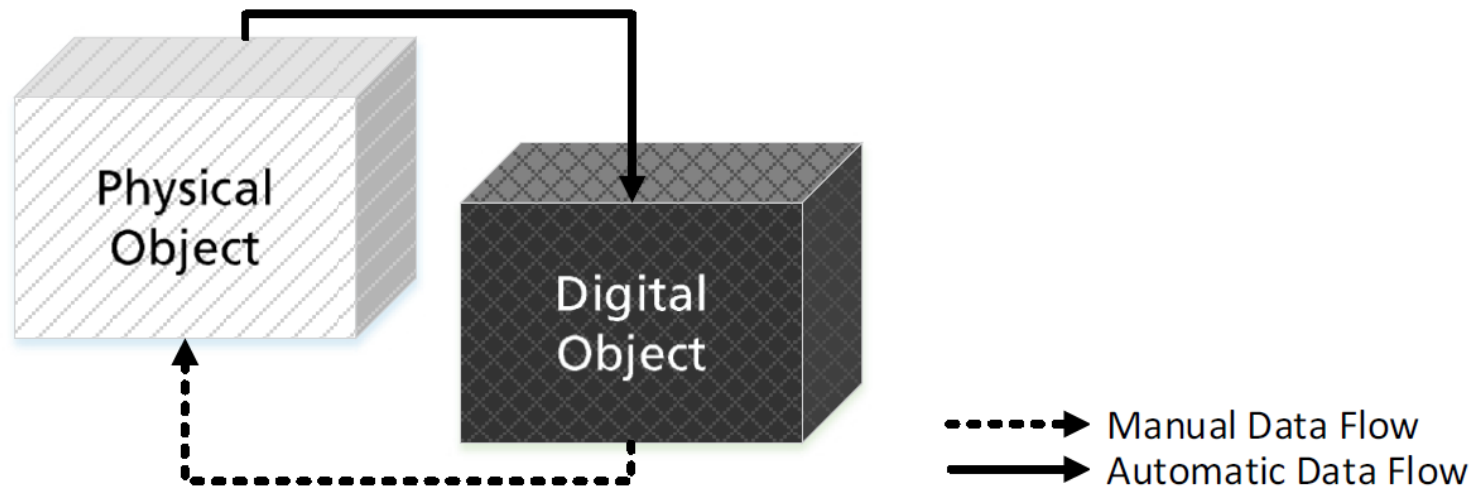
Digital Model is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and its digital counterpart.



Kritzinger, W, et al. "Digital Twin in manufacturing: A categorical literature review and classification", IFAC Papers On Line 51-11 (2018) 1016–1022

Digital Shadow of a physical object

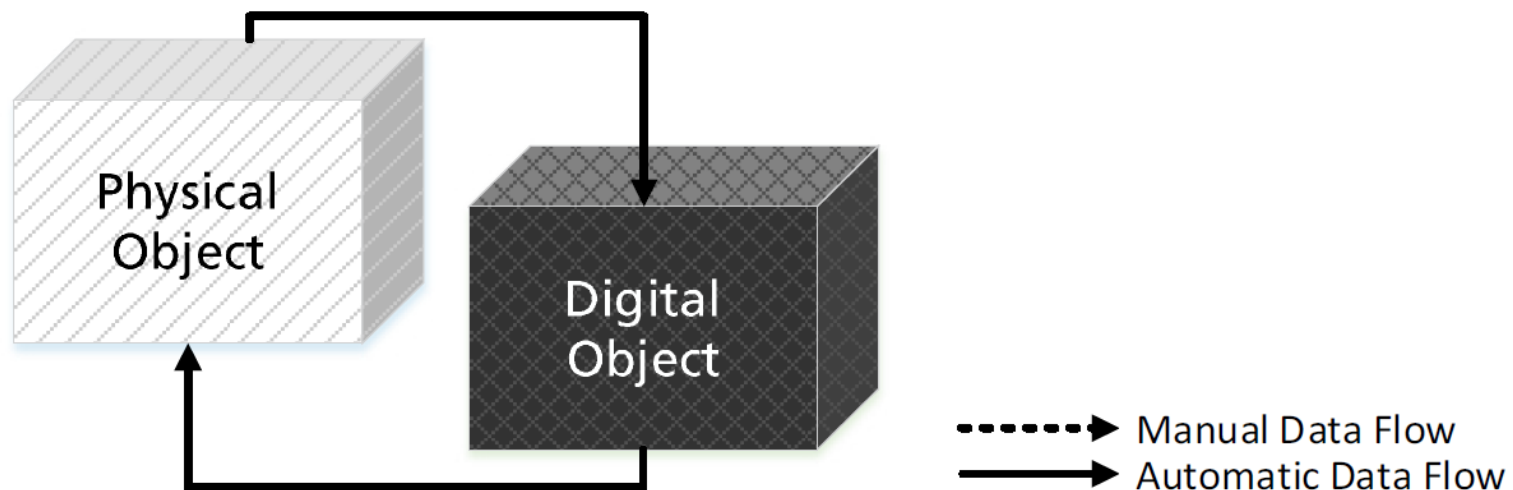
There is an automated one-way data flow between the state of an existing physical object and its digital counterpart.



Kritzinger, W, et al. "Digital Twin in manufacturing: A categorical literature review and classification", IFAC Papers On Line 51-11 (2018) 1016–1022

Digital Twin of a physical object

- The data flows between an existing physical object and its digital counterpart are fully integrated in both directions.
- A change in the state of the physical object directly leads to a change in the state of its digital counterpart and vice versa.



Kritzinger, W, et al. "Digital Twin in manufacturing: A categorical literature review and classification", IFAC Papers On Line 51-11 (2018) 1016–1022

Define Digital Twins:-

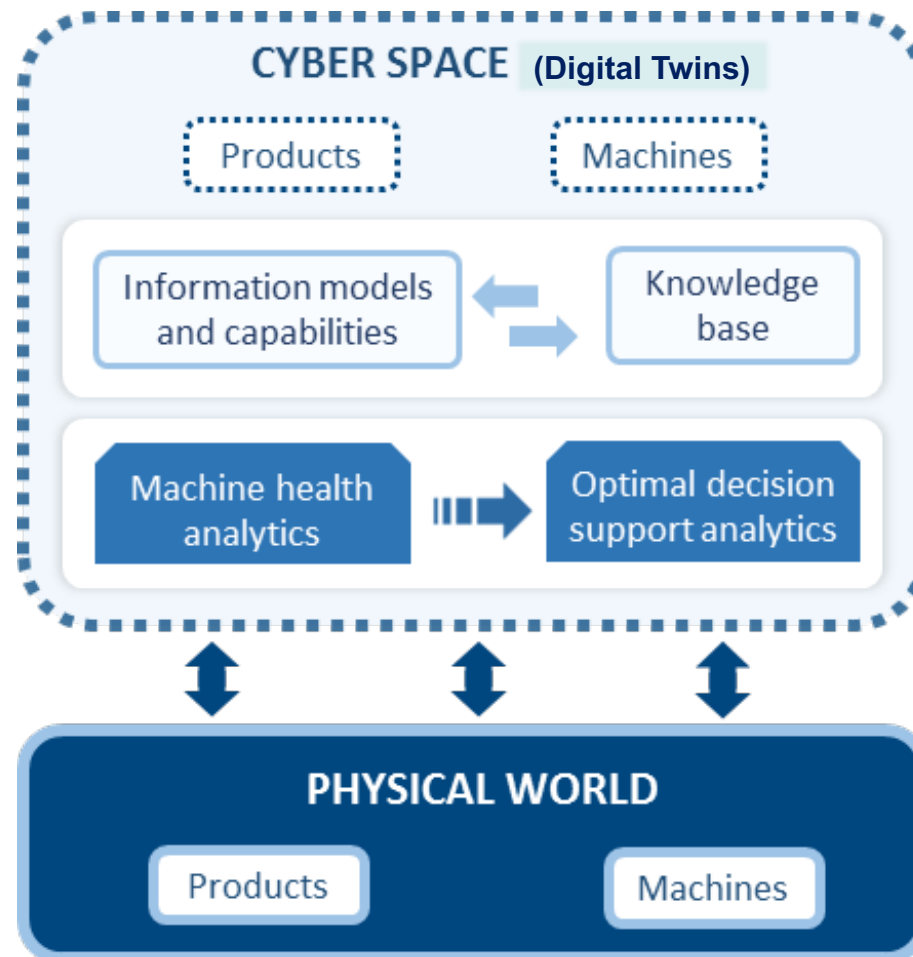
“An integrated multi-physics, multi-scale, probabilistic *simulation* of an as-built system, enabled by *Digital Thread*, that uses the best available models, sensor information, and input data to *mirror* and *predict* activities/performance over the life of its corresponding physical twin.”

E.M. Kraft, The US Air Force Digital Thread / Digital Twin – Life Cycle Integration and Use of Computational and Experimental Knowledge II . The Evolution of Integrated Computational / Experimental Fluid Dynamics, in: 54th AIAA Aerosp. Sci. Meet., 2016: pp. 1–22

Examples of Digital Twin

- Digital Twin for Smart Manufacturing
- Digital Twin of Products
- Digital Twin of Manufacturing Assets
- Digital Twin of People
- Digital Twin of Networks

The Role of Digital Twins in a Cyber-physical System

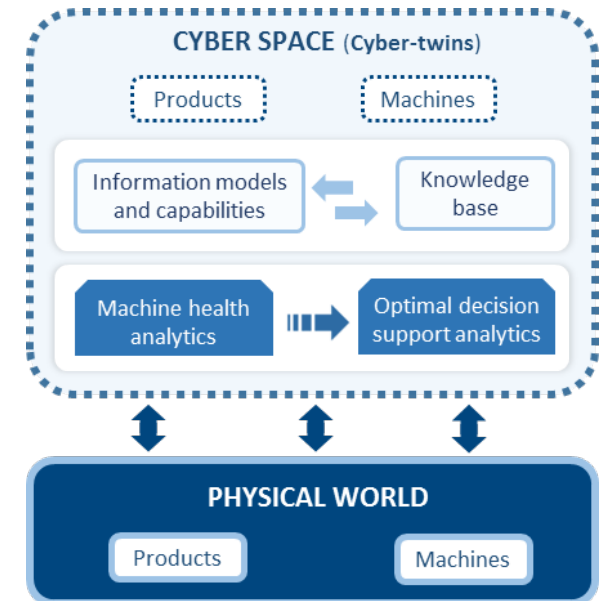


Development of a Digital Twin

- Building a high-fidelity digital mirror to describe the equipment
- Establishing the interaction between the equipment and its digital mirror
- Consolidating/converging the data from the physical space and virtual space to generate information in support of various applications

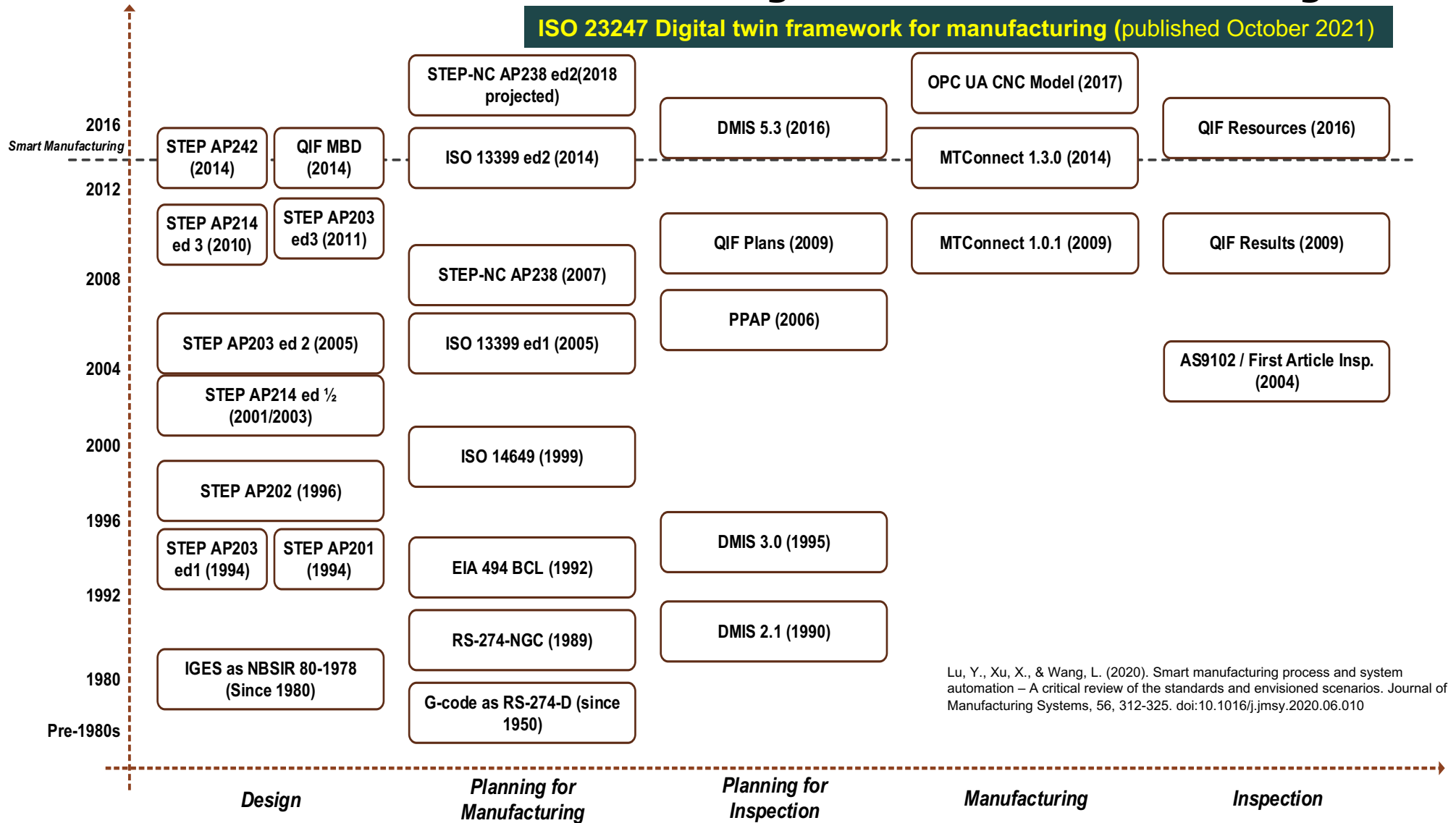
Digital Twinning Mechanisms

- Fieldbus networks
 - ControlNet
 - DeviceNet
 - Modbus-RTU or ASCII
 - Profibus / Foundation Field Bus
 - PROFINET
 - Modbus-TCP/IP
- Ethernet-based industrial networks
 - EtherNet/IP
 - EtherCAT
 - Time Sensitive Networks (TSN) (Ethernet IEEE 802.1)
 - Highway Addressable Remote Transducer (HART)
- Industrial wireless networks
 - Wireless Sensor Networks (WSN)
 - WiFi-based (IEEE 802.11)
 - Bluetooth-based (IEEE802.15.1)
 - Zigbee-based (IEEE 802.15.4)
- Other technologies
 - MQTT, OPC UA, MTConnect



International Standards for Digital Twins in Manufacturing

ISO 23247 Digital twin framework for manufacturing (published October 2021)



Lu, Y., Xu, X., & Wang, L. (2020). Smart manufacturing process and system automation – A critical review of the standards and envisioned scenarios. *Journal of Manufacturing Systems*, 56, 312-325. doi:10.1016/j.jmsy.2020.06.010

Digital Twin for Manufacturing

Applications of Digital Twin for manufacturing

Real time control

Off-line analytics

Health Check



Predictive maintenance

Digital Twin



Personnel



Equipment



Material



Process



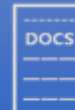
Facility



Environment



Product



Supporting Document

Data Collection & Device Control



Personnel



Equipment



Material



Process



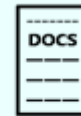
Facility



Environment



Product



Supporting Document

Observable Manufacturing Elements

Benefits

In-loop planning & validation



Production scheduling assurance



Enhance understanding of manufacturing elements



Dynamic risk management



Cost reduction



ISO 23247

Demonstrative Cases of Digital Twins at Laboratory for Industry 4.0 Smart Manufacturing Systems (LISMS)

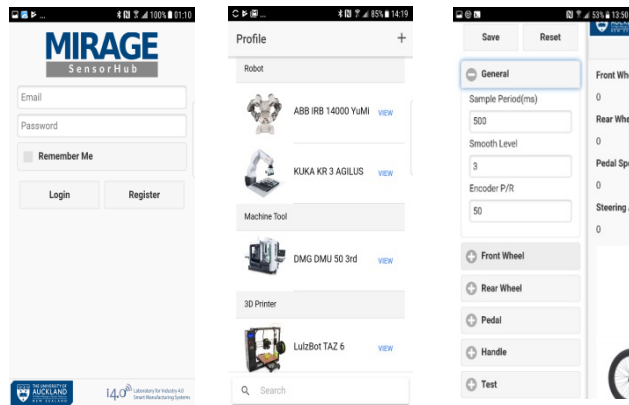
- Digital twin of a custom product (bicycle)
- Digital twin of machine tool - Cyber Physical Machine Tool
- Retrofitting a legacy Kuka robot for its digital twin

MIRAGE Modular Industrial Realtime Augmented Graphic Engine

MIRAGE Sync



A cross-platform mobile APP that is capable of managing multiple products.



User Management

Product Profiles

Sensor Configuration

MIRAGE Hub



A configurable sensing module that gathers all the sensor data from product.



MIRAGE helps users monitor the running status of each equipment. Digital twins are managed locally by the manufacturer using MIRAGE Station, and the configurations of particular facilities are kept by user with MIRAGE Sync. Representing each node in the Internet of Things (IoT), the sensing module MIRAGE Hub can be easily adapted for specific instruments.

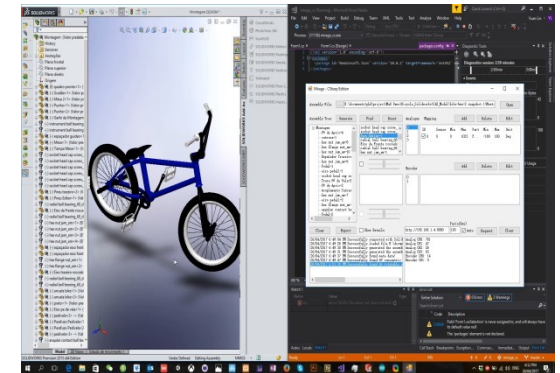
MIRAGE Cloud

MIRAGE Cloud is the centre of the system, which keeps all the profiles of a product. It facilitates the synchronization between the physical product and its corresponding digital-twin.

MIRAGE Station



MIRAGE Station is connected to the digital-twin of a product. Once synchronized with physical product, the digital-twin reflects the running status of the product.

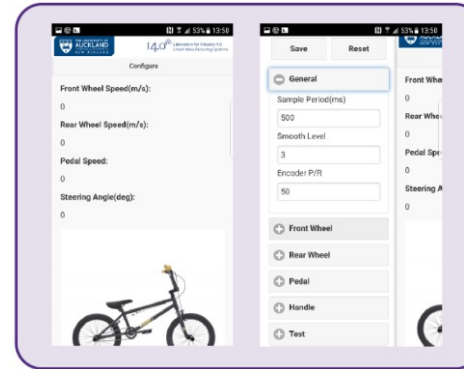
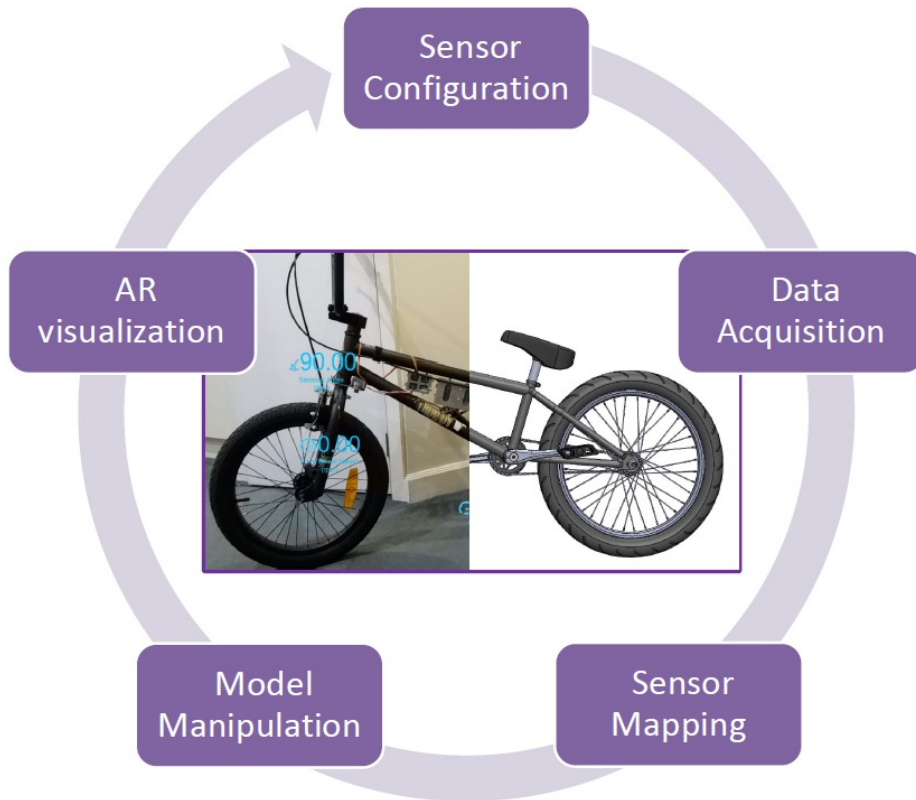


Model Analysis and Synchronization

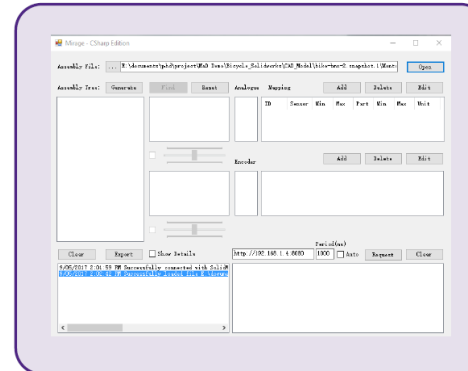


AR Visualization

Digital Twinning of a Bicycle



HMI



Physical and virtual components coupling



AR applications

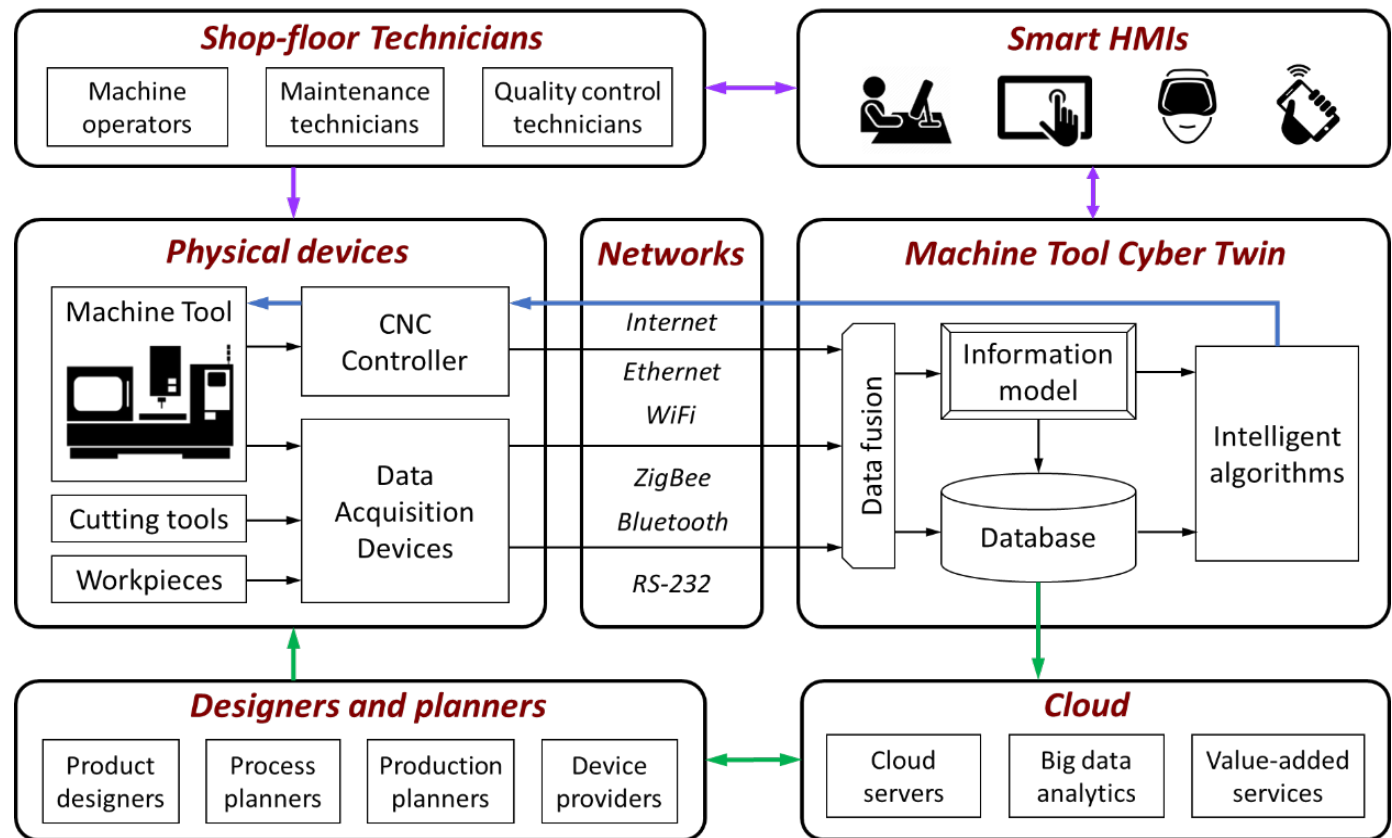
Cyber-Physical Machine Tools for Smart Manufacturing

Cyber-Physical Machine Tool (CPMT)

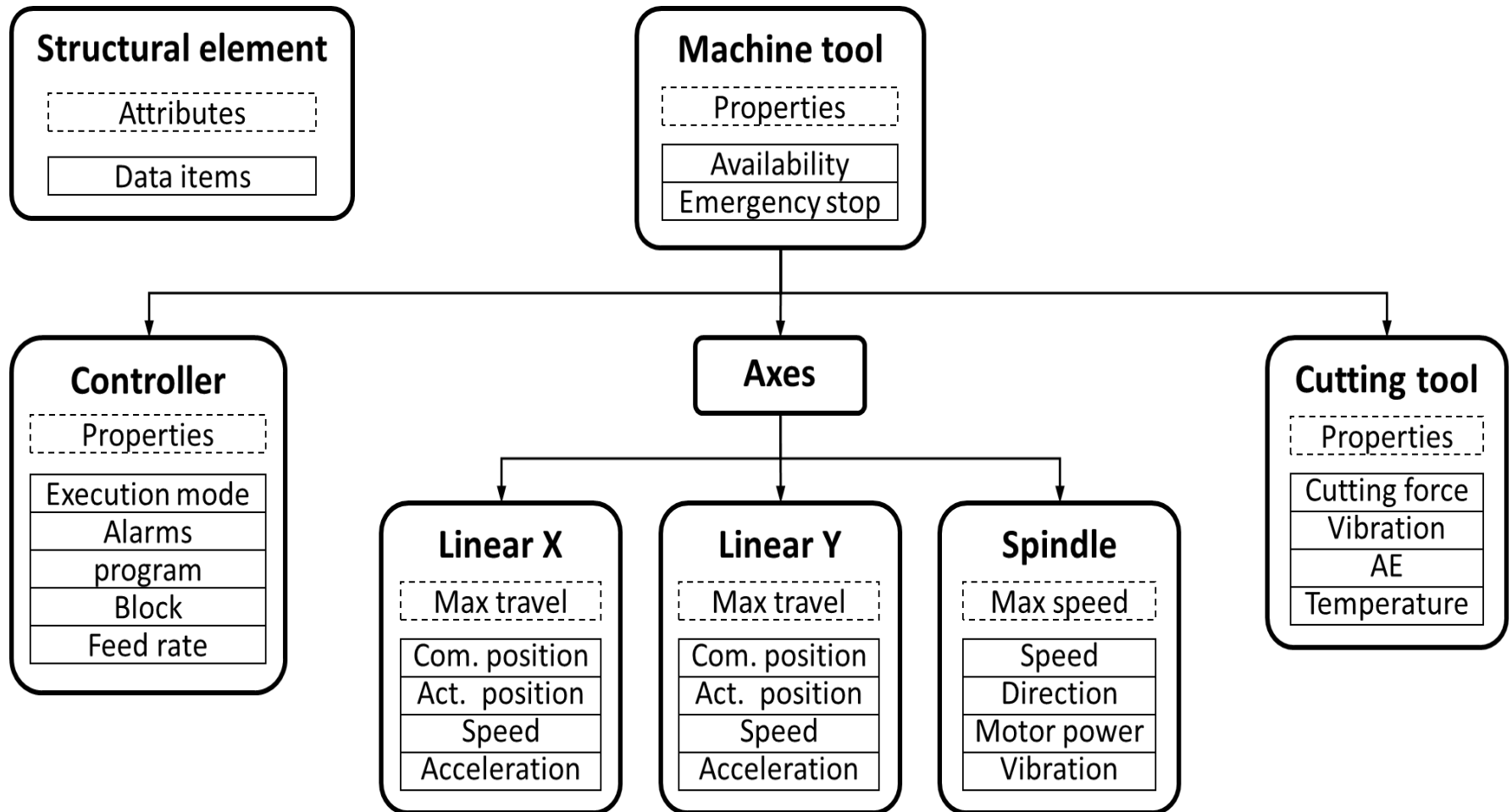
- Deep integration of machine tool, machining processes, computation and networking
- Monitoring, embedded computations and control of the machining processes, with feedback loops in which machining processes can affect computations and vice versa

Features

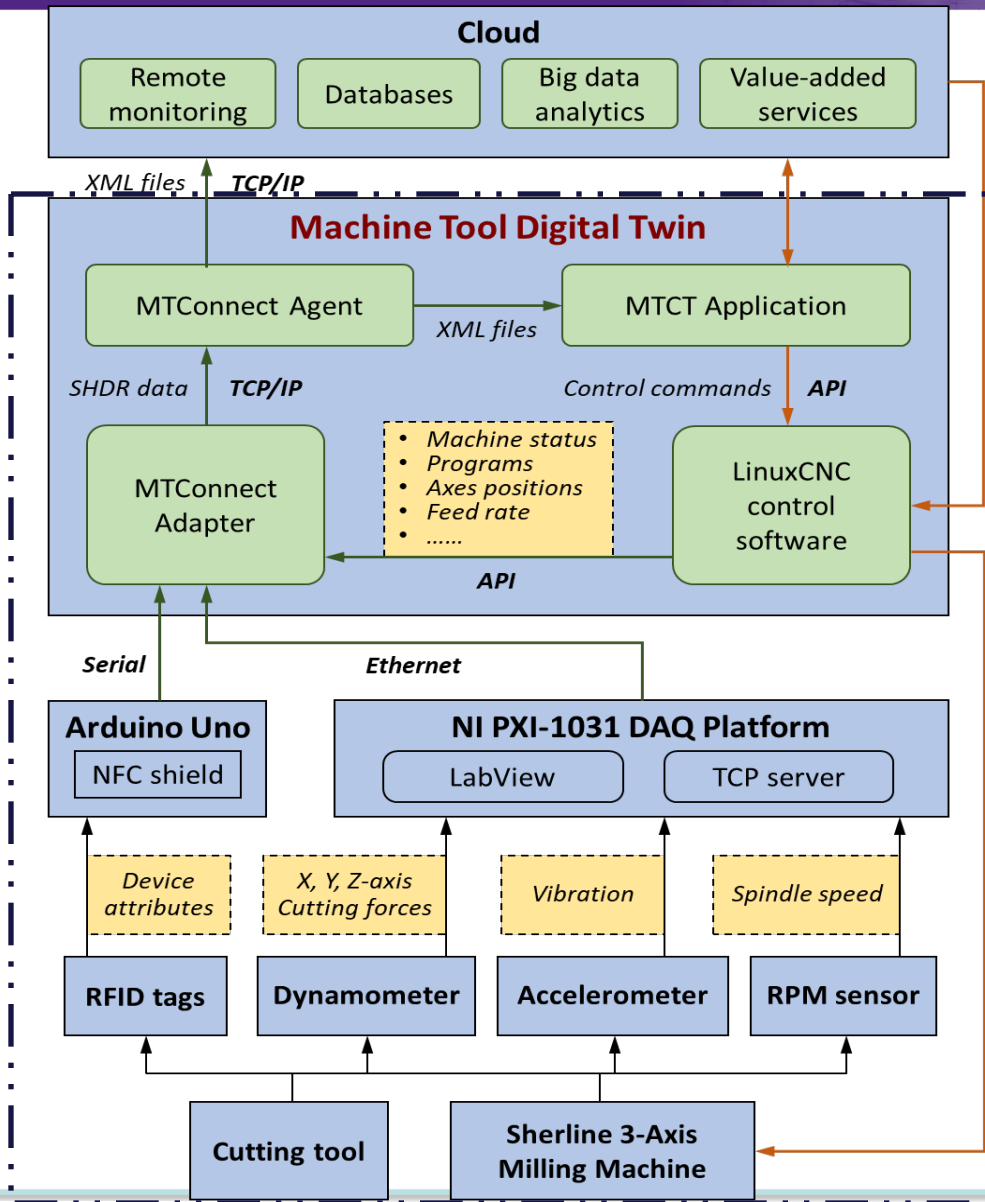
- CPS-based machining system
- Digital Twin technology
- IoT-enabled real-time data acquisition
- Advanced human-machine interactions
- Cloud-based solutions



MTConnect-based Information Model of a Lathe

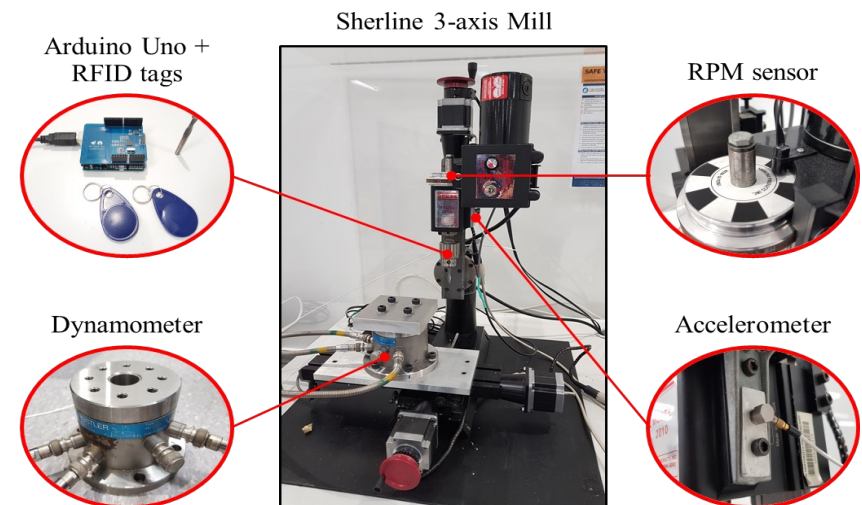


MTConnect-based CPMT Prototype



CPMT Digital Twin:

- Represents the capability, structure and real-time status of the machine tool
- Provide field-level data to HMIs and cloud-based services
- Monitors and controls the machine tool with built-in data analytics



Real-time Process Monitoring via CPMT DT

CPMT-Cyber Twin

File Settings About

Machine Tool Structure 1

- http://192.168.1.121:5000/probe
 - Header Version : 1.3.0.17 Creation Time : 2017-11-26 6:18:44 PM Buffer Siz
 - Device : Sherline-3Axis
 - Manufacturer : SerialNumber :
 - Component : Axes Type : Axes
 - Component : C Type : Rotary
 - Name : Speed Data : SAMPLE Type : SPINDLE_SPEED
 - Name : vibMaxMag Data : SAMPLE Type : VIBRATION
 - Name : vibMaxMagFreq Data : SAMPLE Type : VIBRATION
 - Component : X Type : Linear
 - Name : Xact Data : SAMPLE Type : POSITION
 - Name : Xcom Data : SAMPLE Type : POSITION
 - Component : Y Type : Linear
 - Name : Yact Data : SAMPLE Type : POSITION
 - Name : Ycom Data : SAMPLE Type : POSITION
 - Component : Z Type : Linear
 - Name : Zact Data : SAMPLE Type : POSITION
 - Name : Zcom Data : SAMPLE Type : POSITION
 - Component : controller Type : Controller
 - Component : path Type : Path
 - Name : program Data : EVENT Type : PROGRAM
 - Name : CurrentLine Data : SAMPLE Type : LINE
 - Name : feedrate Data : SAMPLE Type : PATH_FEEDRATE
 - Name : feed_ovr Data : SAMPLE Type : FEEDRATE_OVR
 - Name : maxVelocity Data : SAMPLE Type : SPEED
 - Name : power Data : EVENT Type : POWER_STATE
 - Name : alarm Data : EVENT Type : EMERGENCY_STOP
 - Name : mode Data : EVENT Type : CONTROLLER_MODE
 - Name : execution Data : EVENT Type : EXECUTION
 - Component : CUTTING FORCES Type : Sensor
 - Name : ForceX Data : SAMPLE Type : LINEAR_FORCE
 - Name : ForceY Data : SAMPLE Type : LINEAR_FORCE
 - Name : ForceZ Data : SAMPLE Type : LINEAR_FORCE
 - Component : CUTTING TOOL Type : Sensor
 - Name : tool_id Data : EVENT Type : TOOL_ID
 - Name : tool_type Data : EVENT Type : TOOL_TYPE
 - Name : tool_geometry Data : EVENT Type : TOOL_GEOMETRY
 - Name : Data : EVENT Type : AVAILABILITY
 - Name : Data : EVENT Type : ASSET_CHANGED
 - Name : Data : EVENT Type : ASSET_REMOVED

Address

Machine Tool 2

Name Manufacturer Time Stamp

Controller

Power Execution Controller Mode

Program Current Line

Feed rate Feed rate override

Axes

X Pos Actual Y Pos Actual Z Pos Actual

X Pos Comm Y Pos Comm Z Pos Comm

Spindle Speed Vibration

Cutting Forces

Force X Force Y Force Z

Cutting Tool

ID Type Diameter

Data visualization and analytics 3

Data Visualization Multi-Data Visualization Machine Status Cutting Forces Vibration

Y - Axis : Status

Active

Interrupted

Ready

X - Axis : Time

Machine Status

- Active (59%)
- Ready (26%)
- Interrupted (15%)

Data Log 4

Timestamp	Value	Sequence
11-26-2017 05:26:14.355509 AM	1.12696...	29834
11-26-2017 05:26:14.455730 AM	1.45142...	29841
11-26-2017 05:26:14.555909 AM	0.96472...	29849
11-26-2017 05:26:14.656108 AM	0.75382...	29857
11-26-2017 05:26:14.756279 AM	0.49425...	29863
11-26-2017 05:26:14.856471 AM	-0.02488...	29871
11-26-2017 05:26:14.956691 AM	0.00756...	29879
11-26-2017 05:26:15.056914 AM	1.25674...	29886
11-26-2017 05:26:15.157085 AM	0.75382...	29894
11-26-2017 05:26:15.257221 AM	1.06206...	29902
11-26-2017 05:26:15.357393 AM	1.46764...	29910
11-26-2017 05:26:15.457603 AM	1.11073...	29918
11-26-2017 05:26:15.557787 AM	0.07245...	29926
11-26-2017 05:26:15.657904 AM	1.01339...	29934
11-26-2017 05:26:15.758090 AM	-0.49535...	29941
11-26-2017 05:26:15.858277 AM	-0.18711...	29948
11-26-2017 05:26:15.958444 AM	0.68893...	29956
11-26-2017 05:26:16.058618 AM	0.34824...	29964
11-26-2017 05:26:16.158802 AM	0.33202...	29971
11-26-2017 05:26:16.258967 AM	0.54292...	29978
11-26-2017 05:26:16.359162 AM	1.07829...	29986
11-26-2017 05:26:16.459361 AM	0.36447...	29994
11-26-2017 05:26:16.559569 AM	-0.67381...	30012
11-26-2017 05:26:16.660121 AM	0.00756...	30020
11-26-2017 05:26:16.760321 AM	-0.15466...	30028
11-26-2017 05:26:16.860492 AM	0.54292...	30035
11-26-2017 05:26:16.960662 AM	-0.57647...	30042
11-26-2017 05:26:17.060819 AM	0.16979...	30049
11-26-2017 05:26:17.161016 AM	0.36447...	30057
11-26-2017 05:26:17.261215 AM	1.46764...	30064
11-26-2017 05:26:17.361359 AM	-0.34934...	30072

Augmented Reality of the Cyber-Physical Machine Tool

User Interface

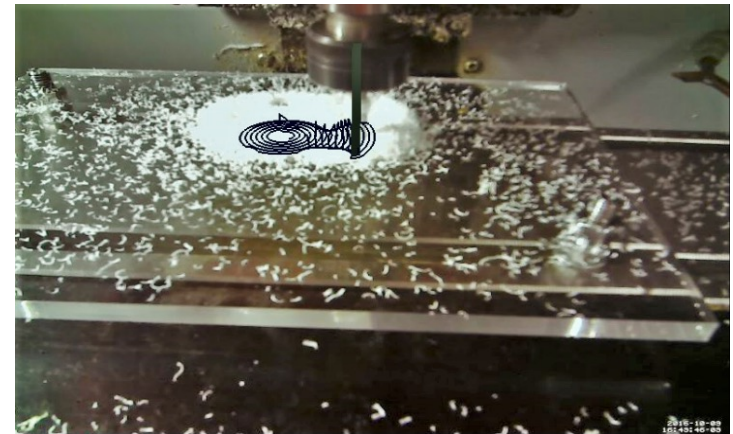
The screenshot shows a software interface for a machine tool. It features a central video feed of the machine tool with a red box around it. To the right of the video feed is a data panel with the following parameters:

Machine X	179.9996
Machine Y	50.0002
Machine Z	140.0004
Offset X	179.9996
Offset Y	50.0002
Offset Z	140.0004
Spindle Speed	0.0000
Feed Rate	0.0000
X Velocity	0.0000
Y Velocity	0.0000
Z Velocity	0.0000
X Acceleration	0.0000
Y Acceleration	0.0000
Z Acceleration	0.0000

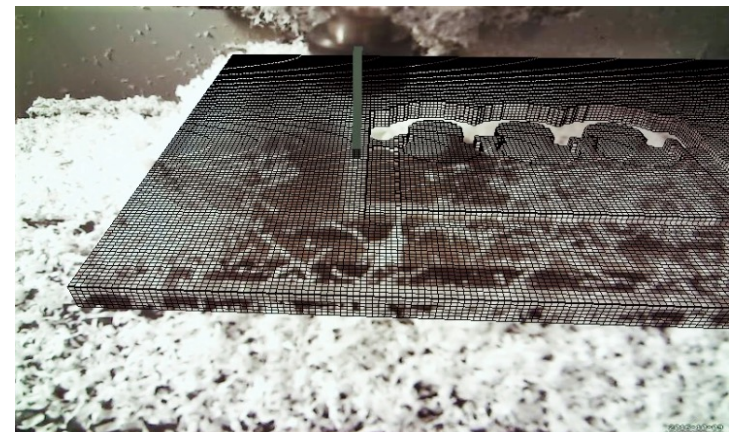
Below the data panel is a control panel with buttons for: Calibrate, Load Calibration, Toggle Physical Toolpath Display, Toggle Unsafe Milling Volume, Toggle CAD Model, Toggle Material Removal, Clear Tool Path History, Toggle Axis Display, and Toggle Drill Tip Display. At the bottom right, there is a status bar showing "Feed Rate - 100%" and "Feed Rate +" buttons, and a red alarm indicator that says "Outside safe milling volume".

1. AR-assisted process monitoring & machining simulation
2. Real-time machining data visualization
3. Real-time CNC control
4. In-process feed rate control
5. Alarms and warnings

AR-assisted process monitoring



AR-assisted machining simulation



Retrofitting a Legacy System for its Digital Twin

Equipment

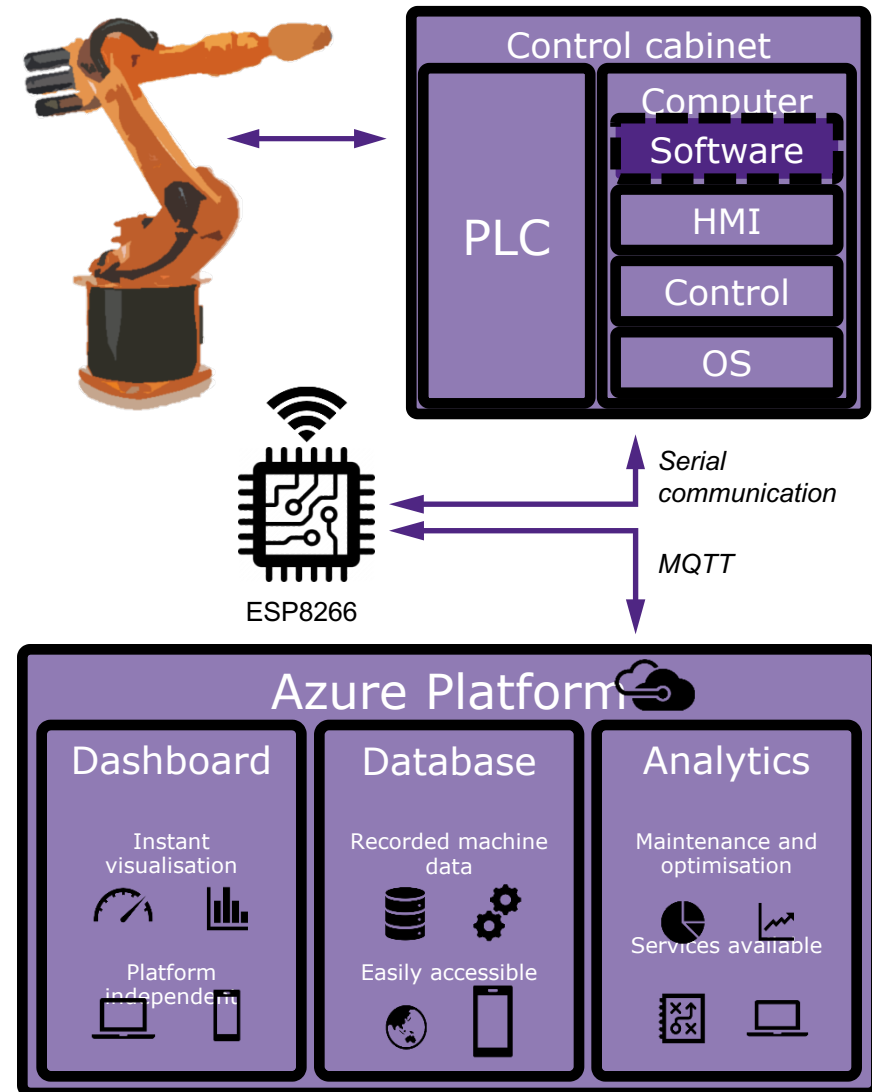
- KUKA KR16 industrial robot and its KR C2 control system
- WiFi-enabled chip (ESP8266)
- Microsoft's Azure Platform
- Know-how

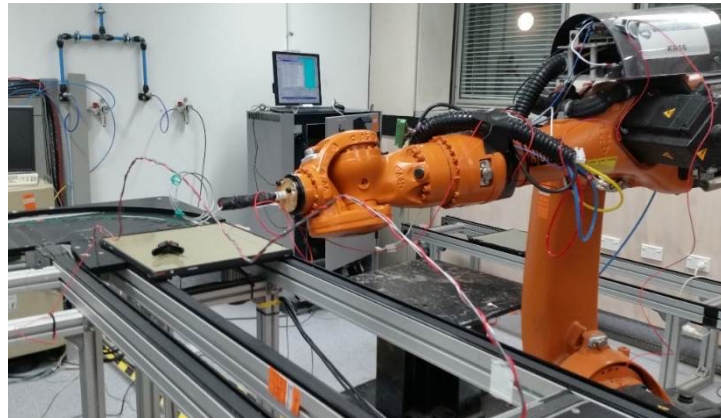
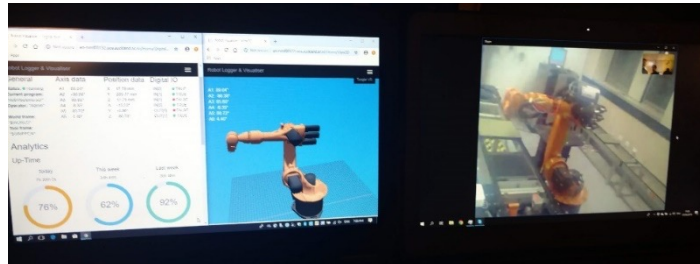
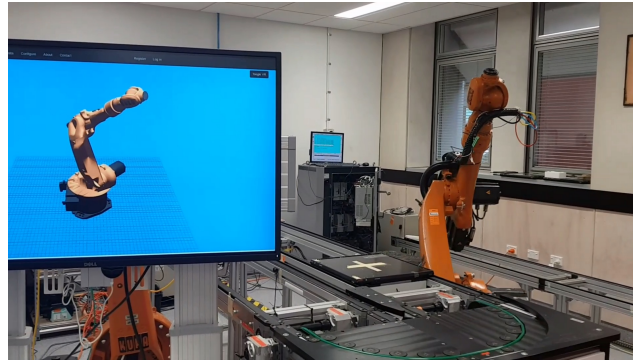
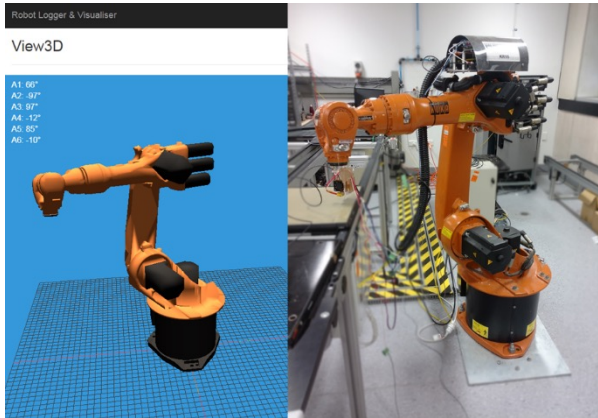
Functions:

- **Background monitoring:** Custom software on the control computer runs in the background and sends machine data via serial port to the connected chip. The chip connects to the wireless network and forwards the data via internet using an IoT messaging protocol (MQTT). This method deals with hardware and software limitations and does not interfere with existing setup or usage.
- **Mobile visualisation:** The data can be accessed and visualised with near real-time capability through a custom website. It is not limited to a local machine, application or specific platform.
- **Storage and analytics.** A database stores the received data. Historical data can be used to analyse the uptime or reconstruct the robots movements if necessary (e.g. QA). Custom tools can be developed or available services used to connect to the database and perform further sophisticated analyses.

Prospective industrial applications

- DT development for a legacy device
- Extension of asset's lifetime
- Mobile and worldwide asset monitoring
- Optimisation of machine uptime
- Assessment of historical data for reconstruction and QA

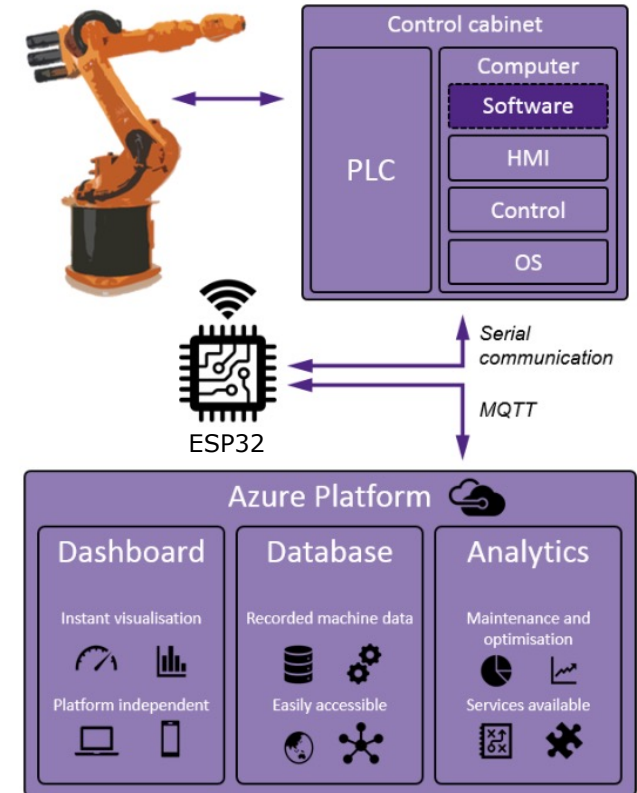




Robot Logger & Visualiser

Retro-fitting for data acquisition and analytics

(To see the demo click the image)



Final Words

- The crux of Industry 4.0 is cyber-physical systems (CPS)
- The key component of CPS is digital twin– digitisation of physical systems
- Digital twin is still a “hot” topic, but most of all an enabling tool for smart manufacturing
- ISO standards on digital twin framework for manufacturing (2021)
- Digital twin examples

THANK YOU FOR YOUR ATTENTION!

Acknowledgement

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Martin Zhu, Sarah Huang, Tang Ji



Scan to take a virtual tour of our lab

<http://www.dibadata.com/lab.html>

Laboratory for Industry 4.0 Smart Manufacturing Systems

(<http://www.mech.auckland.ac.nz/en/about/ourresearch/research-facilities/LISMS.html>)

(<https://lisms.auckland.ac.nz/>)