iMOCO4.E

Intelligent Motion Control under Industry 4.E

Integral (system level) requirements for valuable twinning methods (first iteration)

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Abstract:

Common requirements on digital twins for the use in different parts of the IMOCO4.E project are investigated and specified within this deliverable. Requirements on condition monitoring, predictive maintenance, and self-commissioning were gathered from the building block providers, pilots, uses cases, and demonstrators. Requirements and specifications on interaction and deterministic communication with cloud layers is defined as well.

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4. Abbreviations

Abbreviation	Explanation
AI	Artificial Intelligence
BB	Building Block
COTS	Commercial Off-The-Shelf
FPGA	Field-Programmable Gate Array
DT	Digital Twin
HPC	High Performance Computing
FOC	Field-Oriented Control
ML	Machine Learning
P/D/UC	Pilot/Demonstrator/Use-Case
CNC	Computer Numeric Coding
CAM	Computer Aided Manufacturing
FEM	Finite Element Method

5. Executive Summary

The deliverable 5.1 addresses the requirement for the digital twin aspects to be used in all 4 layers of the IMOCO4.E project. It is the basis of WP5, which is dedicated to the development of digital twin concept for virtual commissioning, training, maintenance, and simulation within the industrial applications defined in various Pilots, Demonstrators and Use Cases of the project.

The requirements defined in this deliverable comprises how to secure and trust the data within digital twins as there will be continuous flow of data between the physical and virtual objects. Requirements for the development of AI methods to be connected to digital twin for the monitoring and predictive maintenance, specifically at instrumentation level (Layer 1). Requirements for using digital twin in virtual commissioning at control layer (Layer 2). Requirements for the development of augmented and virtual reality applications to be used as digital twin.

The image below depicts the difference between a digital model, digital generator, digital shadow, and digital twin. Various literature studies define what is digital twin, it is also worthwhile to indicate what a digital twin is not. The various views and misconceptions about the digital twin concept are shown in Figure 1. The relationship between the digital object and physical object may or may not be automatic. In the first view of Figure 1, digital model, digital object, and physical object are loosely connected and the synchronization or data flow between these occurs through manual intervention. There is no automated translation or interpretation between both objects. In the second view, the digital generator, a digital model is used to automatically generate or enhance a physical object. Thus, generation techniques as defined in the model-driven development could be used. In this alternative, the dataflow from physical object to digital object is missing or is based on manual intervention only. In the case of the digital shadow, mechanisms are provided (e.g., sensors) to provide an automatic data flow to the digital object. This could be needed for analysis or simulation purposes. In the last alternative, digital twin, the digital object, and physical object are causally connected and synchronized.

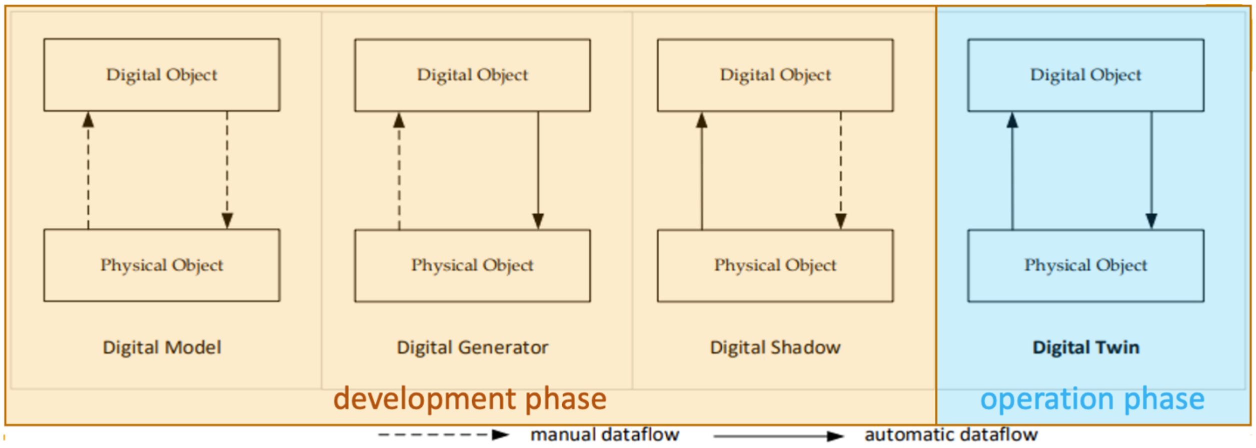

Figure 1: Identified relationships between digital object and physical object [16]

1. Introduction

Purpose of the Document

This deliverable is dedicated to the description of initial requirements for the 4 layers of IMOCO4.E project, which are partially based on inputs from WP2 (D2.1, D2.3), WP3 (D3.1) and WP4 (D4.1), while working in parallel. This report will summarize the all 4 layers requirements specific for the relevant BBs (1, 6 and 9), pilots, demonstrators, and use-cases.

Structure of the Document

This IMOCO4.E deliverable (D5.1) contains a first iteration of the requirements of the IMOCO4.E integral (system level) requirements for valuable twinning methods.

The deliverable provides a revision of different technologies and approaches for digital twin methods to be utilised in conditioning monitoring and predictive maintenance that will be addressed in the project, including state-of-the-art, and the IMOCO4.E complete framework architecture and connection to different BB's.

Tasks 3.1, 4.1 and 5.1 focus on requirements for specific architecture layers of the IMOCO4.E platform, implementation requirements and methodology. Deliverable 5.1 will present approaches for integration of digital twin methods for the condition monitoring and preventive maintenance, including brief revision of the shortcomings from the state-of-the-art, future requirements, and how this can be translated into the requirements that outline the work to be done in WP5.

Intended readership

This deliverable will be addressed to the partners involved in WP5, as well as any partner interested in the definition and development of system level digital twin methods for any industrial applications like conditioning monitoring & predictive maintenance, process optimization, hardware-in-loop optimization etc.

2. IMOCO4.E framework overview

In this chapter, IMOCO4.E's framework overview is provided in connection to WP5. The architecture is taken from the Deliverable D2.3 (Overall requirements on IMOCO4.E reference framework – 31-03-2022)

The IMOCO4.E reference architecture is configurable from the lowest layer (Layer 1 – sensors / actuators) to the human interfaces (Layer 4 – digital twin and AI analytics). D5.1 is focused on condition monitoring of actuators at Layer 1, module status at Layer 2, machine status at Layer 3 and factory status at Layer 4 in terms of granularity of condition monitoring and predictive maintenance using the digital twin concept. These topics covered in D5.1 corresponding to other layers of IMOCO4.E architecture shall not be seen as unnecessary overlap, but rather as glue components that allow to integrate technologies and developments being done at different levels across IMOCO4.E architecture.

As stated in D2.3, the first version of the IMOCO4.E reference architecture framework definition comprises the following viewpoints.

- → Architecture viewpoint
- → AI viewpoint
- → Digital twin viewpoint

Additionally, the BBs are abstracted as components.

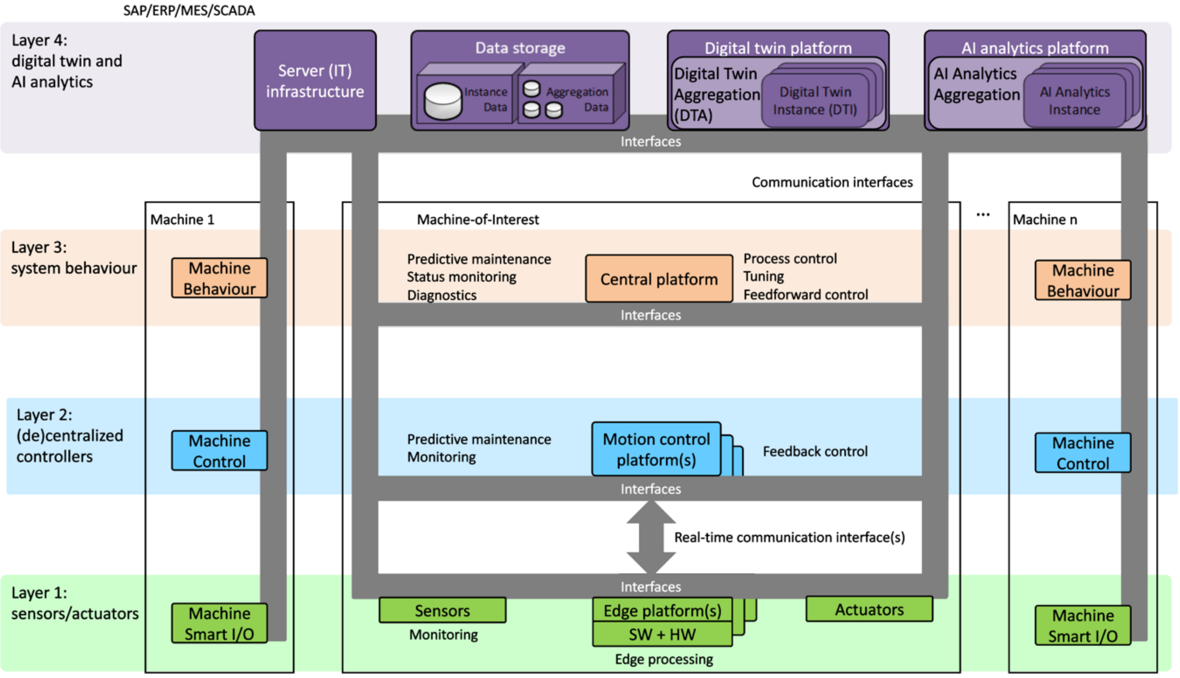

Figure 2: IMOCO4.E reference framework architecture viewpoint – initial version

The architecture viewpoint is illustrated in Figure 2 (version taken from D2.3)

The digital twin viewpoint with BB interactions is illustrated in Figure 3 (version taken from D2.3). The general principle here is that the physical entity comprises the machine (the sensors, platforms, actuators, and interfaces represented through the various BBs, and other components, e.g., COTS). The virtual entity is represented as digital twin platform. AI framework from BB8 shall perform the services and analysis. While BB9 handles the data collection, storage, and cyber-security. Digital twin consumes the data from the physical entity and sends the parameter changes for optimal machine performance to the relevant physical components or provides warnings or predictive maintenance schedules to the human users.

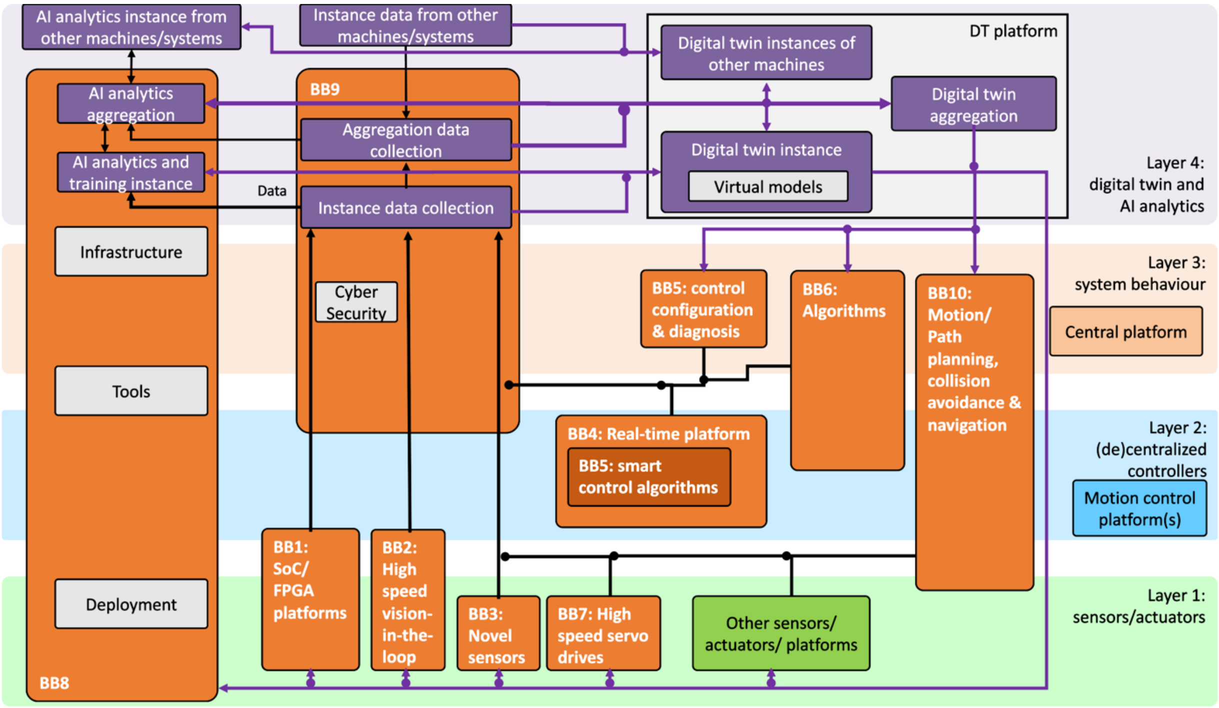

Figure 3: Digital twin viewpoint with BB interactions

<u>BB1 position in digital twins</u>: This building block will rely on heterogenous FPGA and ARM-based industrial AI-edge embedded computing platforms –as opposed to standard computer platforms –to incorporate high-performance computing close to the deep edge of the system. In line with the Industry4.0 vision, standard and open methodologies will be applied at different layers to orchestrate the different elements, while preserving the determinism and reliability of the control system. The direct interface with the physical signals will yield into latency and performance to power ratio improvements. Digital twins are virtual copies of entire systems (or even aggregation of systems). The granularity and level of detail of such a DT instance may or may not extend to the layer in which BB1 exists. In other words, a BB1 can be either "invisible", a black box or a white box in the DT. A potential progress in IMOCO4.E would be that a (full or partial) digital copy of BB1 exists in the DT.

<u>BB2 position in digital twins</u>: Building Block 2 will fuse requirements from High Performance Computing (HPC) and high-speed camera data acquisition on a Real Time deterministic

computing platform. Applications will include co-located closed loop feedback control and will implement algorithms from classic control as well as various machine learning algorithms. BB2 will generate input both data via imaging and High-Performance Computing for digital twin implementations in the IMOCO4.E project via novel architectures under the strictest time sensitive constraints.

<u>BB3 position in digital twins</u>: BB3 deals with the development of sensing ecosystems that are typically applied in motion control systems. Since this is very broad definition, scope of BB3 in the IMOCO4.E project is deliberately narrowed down to the following exemplary sensor types: radar, overmolded sensor, event camera, vibration sensor. Flexible wireless sensor node can provide useful initial information for digital twin model development and allows to utilize advanced high-level diagnosis based on availability of specific model parameters to estimate its change during the operation.

<u>BB4 position in digital twins</u>: The goal of BB4 is to enable multiple different workloads at the edge on a single board while ensuring safety and performance. The hypervisors will allow to partition the available computing resources to separate the AI models from the smart control algorithms or the vision-in-the-loop, and to enhance the performance guarantee required for the system. At the Digital Twin layer, BB4 will enhance quality checks, alarm detection and recovery to further increase automation and efficiency.

<u>BB5 position in digital twins</u>: BB5 constitutes a framework for smart control algorithms. The framework covers key solutions for mechatronic system, ranging from feedback algorithms including vibration damping, force control, predictive control, and robust control, towards data-driven learning algorithms, covering repetitive control, iterative learning control, and machine learning algorithms. As most of the proposed functionalities are model-based, linkage of BB5 with Digital Twins is strong. In this sense, white-type or physics-based Digital Twins will be a key component. Of course, the physics-based Digital Twins will be also used for direct application in control algorithms (e.g., robot kinematics Jacobian in impedance control). Grey-type digital twins will also be used, for example in the new learning control approaches proposed by partner TUE.

<u>BB6 position in digital twins</u>: Algorithms for condition monitoring, predictive maintenance, and self-commissioning of industrial motion control systems. Model based condition indicators suppose using models for deteriorating parameters estimation. These models implemented in condition indicators algorithms can be considered as digital twins of individual drive components. Condition monitoring algorithms can be developed/learned on digital twins in cases of nonexistence of data from real systems. Obtaining data for algorithms development is one of crucial problems in condition monitoring and predictive maintenance algorithms development.

<u>BB7 position in digital twins</u>: Miniature DC servo drive with advanced motion control features and EtherCAT communication, with possibility to add custom control algorithm into the drive firmware. The drive will allow fast access to its internal data to allow comparison between selected subsystem of the device and its digital counterpart. This feature can be used in testing

of drive internal subsystems like FOC motor control, tuning of speed and position control loops, etc. It would be useful if a digital twin of servo drive can be directly converted into servo drive code. In that way the digital twin is single point of truth for model-based systems engineering. This means it can also be used to predict behavior in conjunction with new motors and loads in a simulation stage. It is likely that the real system behavior will follow closely. It is also valuable in debugging (firmware) issues even after the product is released.

BB8 position in digital twins: AI, machine learning, deep learning algorithms in real-time. Sim2real [17] [18] transfer developments are closely related to digital twin ambitions of the project. Same motion planning algorithms will be used to control the real and the simulated robots. The planned physical setup for Sim2real digital twinning includes Universal Robot UR5, 2-finger gripper OnRobot RG2 or Robotiq 2F-140, laboratory table (later project stages replaced with manufacturing lines located in factory premises of company "Madara cosmetics"), camera setup (RGB-D camera), bottles for picking. The twin environment will include all listed physical components implemented in simulation environment Ignition Gazebo.

BB9 position in digital twins: BB9 aims to offer a thorough cybersecurity framework for Industrial IoT systems, focusing on secure communications and data exchange and especially feedback systems deployed in IMOCO4.E. An important aspect of the reference architecture is a common data streaming pipeline, which can be used for connecting both digital twins and analytical processing and aggregation.

BB10 position in digital twins: Motion / path planning, collision avoidance and navigation algorithms. There will be extensive consideration of simulation aspects in BB10. This is only possible with a powerful data description. Models regarding a real store floor are currently not completely available. Aspects concerning the presence of people are rarely addressed at present. Here, extended analyses are planned. All these data models pay into the digital twin aspect.

In D5.1 report there are various approaches towards the development of digital twin and further the usage of those digital twin in the industrial applications has been mentioned. The usage of digital twins shall be in all Layers of IMOCO4.E system.

In D2.3 it has been very clearly mentioned that the digital twin (DT) virtual models are part of the DT platform. The services and analytics are performed through the AI framework (BB8). The BB9 handles the data collection, storage and cyber-security. The DT platform uses the data from the physical twin, services, and models. Finally, the DT platform sends the parameter changes for optimal machine performance to the relevant physical components or provides warnings or predictive maintenance recommendations to human operators.

3. Focus of tasks

Trustworthy and secure dataset management, storage, and processing tools (Task 5.2)

This task comprises a definition of real-time, secure, and predictable interfaces with the cloud layer including time-sensitive networking to manage traffic with heterogeneous latency requirements, which will become part of BB9 'Cyber-security tools and trustworthy data management'. Through BB9, T5.2 will provide a solution for collecting, pre-processing, persistently storing and distributing data sets in industrial environments, ensuring trustful and secure data transmission, storage, and accessibility. BB9 will be specifically applied in Pilot 3, Use Case 1 and possibly in Pilot 5 and will serve the data exchange requirements of IMOCO4.E components belonging in other BBs. The internal design and features of BB9 render it highly suitable for supporting AI, ML, and data analytics operations.

BB9 will allow the real-time data exchange of text-based information between multiple endpoints in parallel through a robust and distributed pub/sub messaging system based on Kafka brokers. In addition, BB9 will offer a central aggregation and persistent storage of data based on ElasticSearch. Furthermore, BB9 will support data transformation and management operations as needed by the components with data exchange requirements to be implemented in the selected pilots, demos or use cases (P/D/UCs), where BB9 will be applied. BB9 will allow an efficient access of multiple endpoints to historical data aggregated in persistent storage. BB9 will be delivered as a fully scalable system with increased data reliability, safety and security features based on a microservice architecture with advanced replication, authorization, and authentication features. Moreover, BB9 can provide cyber-secure data transmissions by implementing threat detection and vulnerability assessment. BB9 will include a TSN solution for ensuring high bandwidth and latency quality standards. Finally, BB9 will incorporate a User-Interface for administration, monitoring and configuration purposes.

BB9 components will be provided in containerized fashion (i.e., Docker images), facilitating their deployment and configuration. BB9 can be tailored to the exact needs of each P/D/UC where it will be implemented and be adapted to the available infrastructure and data exchange requirements of IMOCO4.E components from other BBs that participate in each P/D/UC. BB9 is highly scalable and can be configured to meet specific performance demands by taking full advantage of the available computational resources that are present in the host infrastructure.

BB9 can serve the data exchange needs of any IMOCO4.E component, which can act as a client to the BB9 DMS, if it can transmit and receive data over the network. Kafka client implementations are available for most programming languages, including C/C++, Python, Go, Java, .NET, Clojure, Ruby, Node.js, Proxy (HTTP REST, etc) and Perl. Furthermore, IMOCO4.E components can access the BB9 persistent data storage repository for retrieving historical data by performing Elastic Search API queries. Elastic Search clients are available for most programming languages, including Java, JavaScript, Ruby, Go, .NET, PHP, Perl, and Python.

Based on the system-level overall IMOCO4.E requirements documented in D2.3, T5.2 has specified an indicative reference BB9 architecture for serving the potential project needs for data management. Figure 4 presents this architecture, where BB9 components are illustrated as white entities with black outlines. The diagram depicts potential characteristic interactions with other BBs, which are envisaged from the perspective of the BB9 internal operation.

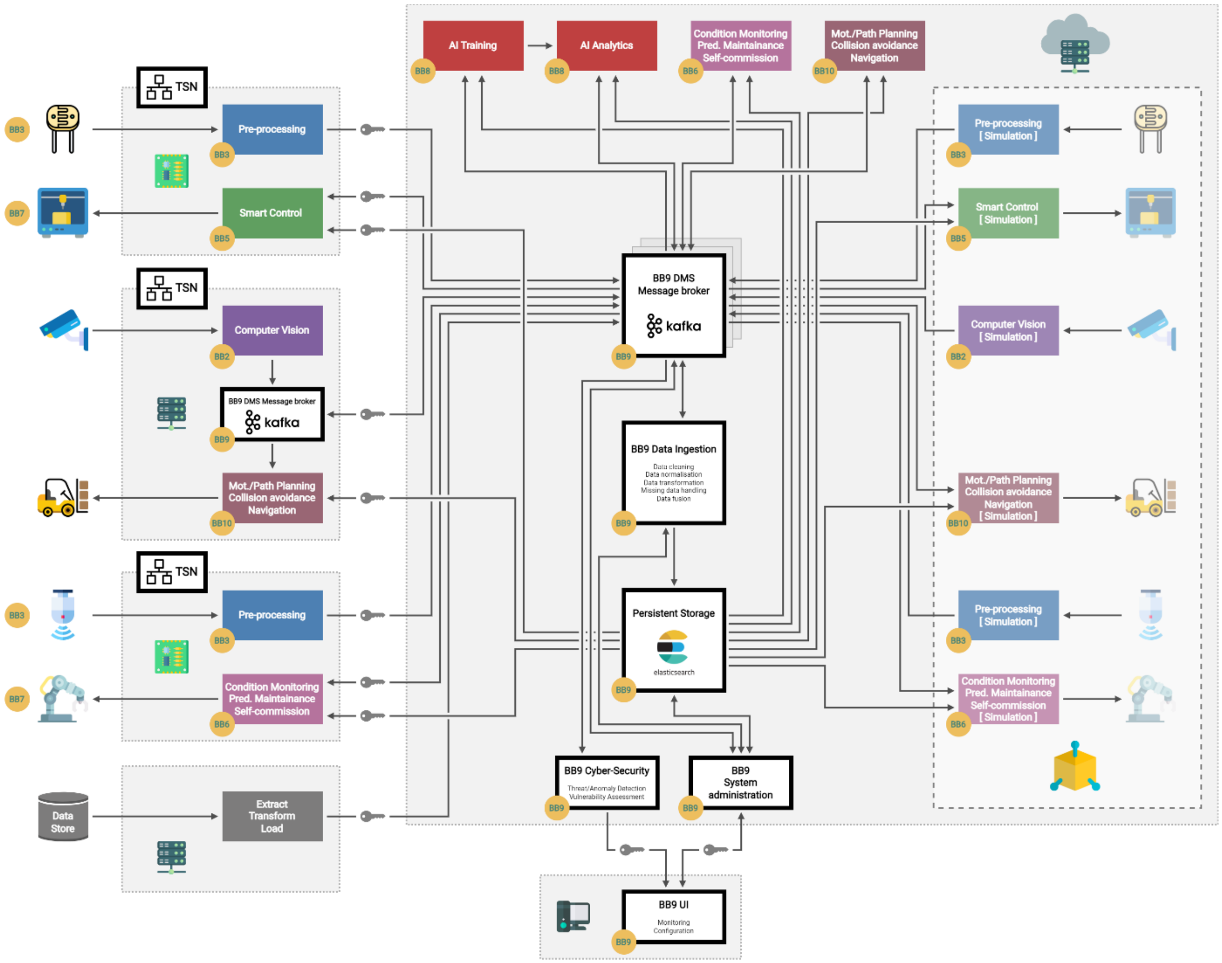

Figure 4: Indicative reference BB9 architecture presenting potential interactions with other IMOCO4.E BBs

AI methods for monitoring and predictive maintenance at instrumentation level (Layer 1) (Task 5.3)

Task 5.3 is focused on predictive maintenance in electric drives and mechanics utilizing AI methods. The task contains following activities:

AI methods for condition monitoring and predictive maintenance of mechatronic systems on higher IMOCO Layers are in scope of this activity. BB6 and BB8 are related to this activity, as well as Pilot 4. The system utilizes traditional sensors data and process variables available in electric drives to be gathered and processed in the storage of layers 3 or 4. The goal is to implement a capability to monitor state of the health of the drive mechanic system and predict its failures. Requirements for the method are for connectivity and data transfer throughput, data management and computing performance at Layer 3 and 4.

Methods for condition monitoring and predictive maintenance inside electric drive inverters for inverter predictive maintenance are among the goals of upcoming activities. Related project outputs are BB6, BB8 and UC1. Specific quantities must be measured to be able to compute condition indicators for specific faults of inverter power components. Requirements for additional measuring circuitry, resolution, sampling rate and synchronization are defined for that reason. Other requirements are defined for computing capacity in the inverter controller. A condition indicator is understood as a method for quantifying wear of the component or its individual failure mechanism progress. Condition indicator methods reduce high volume of data to single health status value of certain wear type of the component.

The last activity is a development and utilization of smart vibration sensors for condition monitoring of mechatronic systems. Edge computed signal processing is supposed in the smart vibration sensors. Ultra-low power electric consumption and wireless connectivity is planned for the sensors. Requirements for space integration, battery lifetime, computation performance for condition indicator calculation inside the sensor for data reduction and for minimizing data throughput via wireless interface.

Automatic Commissioning of motion control systems (Task 5.4)

This task involves designing and testing automatic commissioning techniques for motion control systems. The capabilities will be part of the BB6.

The automatic Commissioning will be based on hardware-in-the-loop (HIL), software-in-the-loop (SIL) and Digital twin (DT) paradigms, allowing rapid prototyping and continuous monitoring of the motion control systems. The results will be applied to Use Case 1, Use Case 2, Pilot 1, Pilot 2, and Pilot 3.

During IMOCO4.E, a digital twin will be designed to provide both a test-based for self-commissioning algorithm and synthetic data to test the control performance monitoring in failure scenarios. In this phase, it is crucial to provide the possibility to people with deep knowledge of the lift applications but without modelling/control skills to interact with the model to set up the possible failure in an easy way. This result can be achieved by designing appropriate user interfaces.

Conventionally commissioning is carried out during the last phase of the development process of complex mechatronic systems such as machine tools, telescopes, or robotic systems. This stage usually incurs cost and time deviations, especially for unique and complex projects, as problems from the previous stages (conceptual design, detailed design, assembly) are detected in the last stage and should be overcome. This increases time to market and hence costs associated with it.

Conventional Commissioning also presents risks of accidents, both for the system itself and, worse, for the involved human beings.

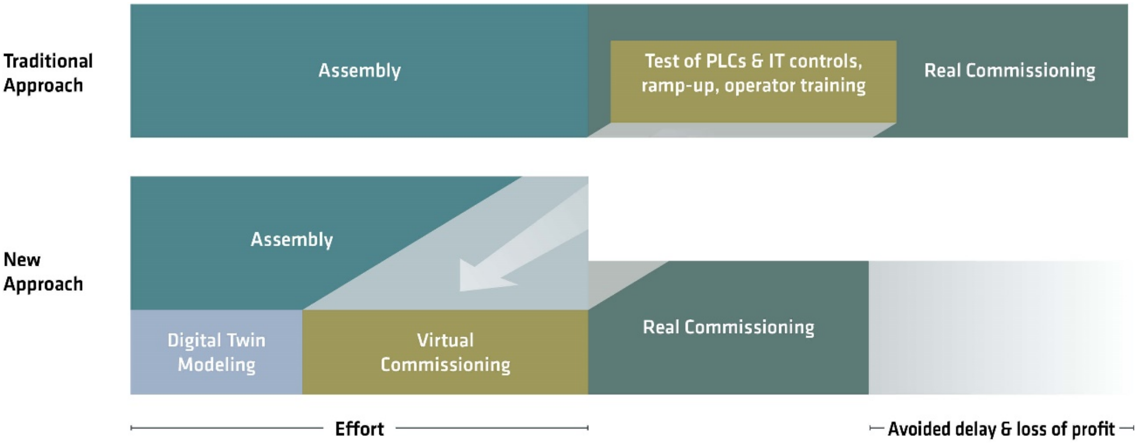

Figure 5:Benefits of Virtual Commissioning shortens project time and overall cost savings (G. Reinhart and G. Wünsch, "Economic application of virtual commissioning to mechatronic," Production Engineering, vol. 1, no. 4, pp. 371-379, 2007)

Virtual Commissioning has been a subject of study for the past two decades. XiL methodology, already studied in IMECH and with a key impact on other IMOCO tasks, presents different approaches to implementing Virtual Commissioning:

- Model in the Loop (MIL): models of both the control system and the plant to be controlled are developed and connected in the same simulation environment.
- Software in the Loop (SIL): in this case, the controller model is replaced by control code generated by the first but still running in a simulation environment.
- Processor in the Loop (PIL) or FPGA in the Loop (FIL): the code generated in the SiL approach is put on the real controller hardware (Processor or FPGA) to run the simulations and identify its limits.
- HiL: Apart from the real control processor, real communication hardware limitations are included, and deterministic real-time simulations can be run.

Even if MiL, SiL, and PiL approaches provide a useful environment for control strategy design and optimization, HiL approach is the one that perfectly suits the Virtual Commissioning concept as it is close to the real prototyping, and the control system development should be basically plug-and-play with the real plant.

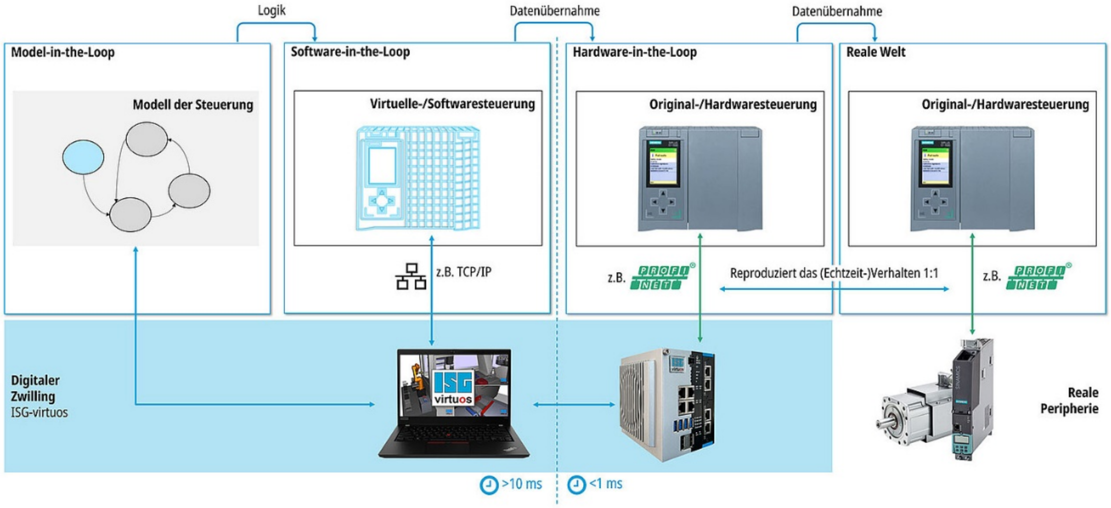

Figure 6: XiL approach for Virtual Commissioning as explained by ISG (https://www.isg-stuttgart.de/en/products/hardwareproducts)

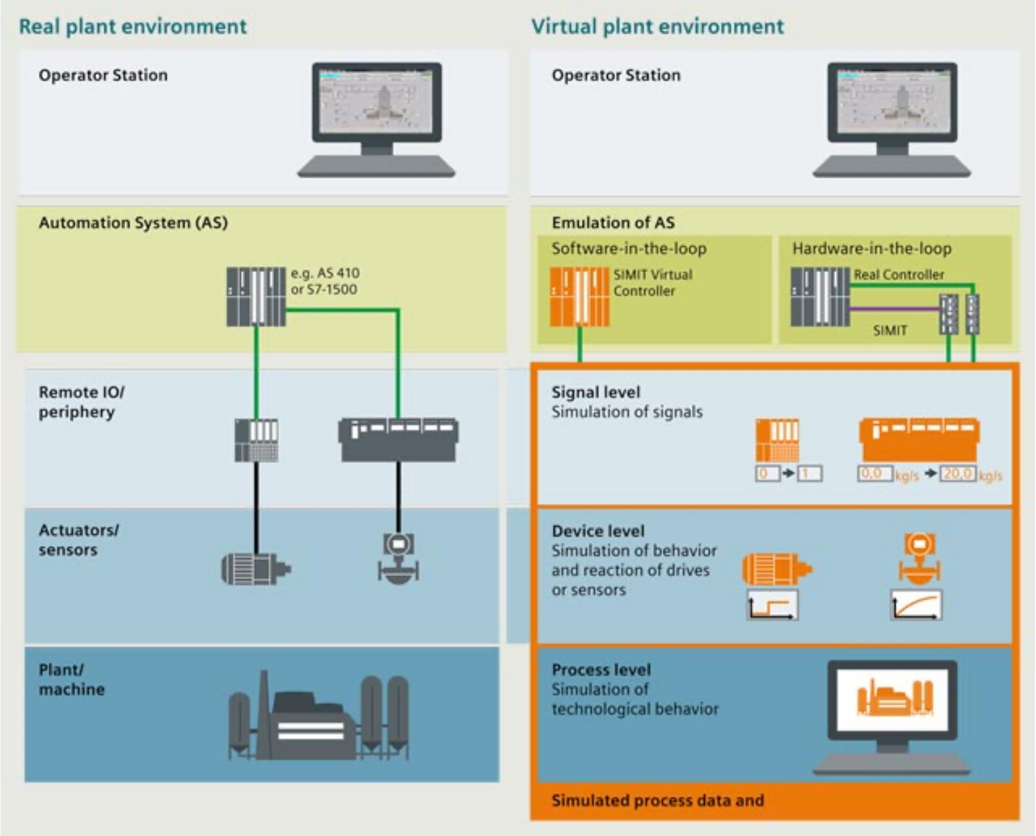

Figure 7: Virtual Commissioning using SIMIT Simulation Platform from SIEMENS

In IMOCO4.E, TEKNIKER will work in a Virtual Commissioning approach that will allow to quickly test automation/control applications against physical models. The approach will be multiplatform (at least, EtherCAT and PROFIDRIVE communications) and allow real-time simulations with limited hardware costs.

A plant modelling framework will be developed where models of the drives and mechanical systems will be integrated. Efforts will focus on drive modelling in order to provide the proper interfaces with the main control system that is being commissioned. A sequential action plan has been defined to provide a real-time simulation, including real fieldbus communications. The framework will allow flexible modelling of the mechanical system, from very simple rigid body models to complex multibody and flexible systems. The system will include a Test control module for automatic testing of both the controller and plant model side.

The general engineering lifecycle includes Deployment and Commissioning as one of the steps for production. It must be noted that this cycle can be viewed in the Use Case 2 (Machine Tool & Robot integration) from two very different perspectives.

The two actors that define the Use Case are the Machine Tool Builder and the Machine Tool User. When addressing the building of a machine tool, the deployment and Commissioning has a final phase where configuring, connecting, and tuning the different automation systems is usually done after building the machine.

The CNC itself must adapt to a very broad range of machines, drives, buses, sensors, and position encoders. Moreover, the kinematic chain of the machine must be defined in the CNC to produce accurate Cartesian movements following the programmed paths. Machine tools are expected to have high precision and high dynamics, demanding advanced control loops and very fine tuning. Robot configuration and interaction with the machine faces similar problems and careful path planning is needed to avoid collisions. This commissioning phase is done before machine starts series production.

After selling the machine, the lifecycle is defined to produce parts. The engineer decides the operations on the raw material and the tools to use. Programming a complex 5 axis machine can hardly ever be done without a CAM system and in this case means also planning the robot's trajectories. This is the second commissioning case, optimizing part production. As one can expect, simulation greatly reduces the machine tool commissioning and the ramp up time for parts production. In the scope of the project and use case, virtual Commissioning will be defined as the process of commissioning a Digital Twin of the machine (and the part) regarding all the relevant components, from mechanical parts to software objects.

The draft technical report of IEC/TC 65 ISO/TC 84 JWG 21 on Smart Manufacturing Reference Models has introduced the Digital Twin as: "a digital replica of physical assets (physical twin), processes and systems that can be used for various purposes." As stated in draft ISO/TC 184/SC 1 N514 [14], of AdHocGroup Digital Twin, in 2019, "This digital replica, existing entirely through the representation of the asset through models has to coexist with the physical asset it represents at any point in the asset's lifecycle".

The whitepaper published as part of Platform Industry 4.0: The Structure of the administration Shell [15], defines the AAS (Asset Administration Shell) as a series of sub models, representing different aspects of its asset. These are defined as a header and a body, where a definition of the models can be in the form of pdf, step files… Some of these can be considered digital twins, but AAS is centered on the structure of the information, and the models relate more with configuration phase. While in 2003 in a white paper from NASA (Grieves, M., 2014. Digital Twin: Manufacturing excellence through virtual factory replication) defined by first time a Digital Twin as "a virtual representation of a physical product containing information about the said product", many definitions have been published afterwards. The mentioned ISO/TC 184/SC 1 N514 provides two alternative definitions that are relevant:

2. A Digital Twin is a fit for purpose digital representation of something outside its own context with data connections that enable convergence between the physical and virtual states at an appropriate rate of synchronization.
3. A Digital Twin is a digital collection of information about an entity and has the following attributes:
   1. It serves a specific purpose.
   2. It provides the sufficient set of information about the entity required for that purpose.
   3. It represents the state of the physical entity at a known point in time and is kept synchronized with the entity with a frequency appropriate to the purpose.

Not only does the Digital Twin address different use cases. As seen in the figure of the Engineering Phases, it may persist across the entire lifecycle and can show or exhibit aspects of the virtual environment (data-driven, analytical, multi-physics, etc.), computational techniques, and aspects of the physical environment (process data, production data) to improve the life cycle phases (design, operation, maintenance…, etc.).

The same documents highlight that: "Key to understanding the information requirements that a Digital Twin needs to support is to consider the processes for the Physical Twin. These will include the lifecycle processes for the physical twin itself, and the processes that the physical twin is used to support, which may be the lifecycle processes of another physical twin, or a core process for an enterprise".

This is precisely what is shown in the Use Case 2 introduction. We have two lifecycles (or engineering toolchains) and the CNC-PLC-Robot Digital Twin must address their needs.

For virtual Commissioning, we can define Digital Twins as detailed models of the components that simulate their behavior with the required accuracy and related to: a) machine tool and robot commissioning and b) part programming in such machine tool and robot. This "variable geometry", as explained in the definitions, allows the inclusion of data-driven or analytic models, or a combination of them, and sharing data between the real parts and their simulations.

The Digital Twin for Use Case 2 must be developed in two scenarios:

For Machine Tool and Robot commissioning, the engineer usually faces very complex machines with linked axes, variable loads, simultaneous independent paths, mechanical restrictions and even machine configuration changes (working with different spindles, interchanging axes between channels or between a channel and the PLC…). This is a very complex and time-consuming task. Including a robot in the system, with its workspace and programming syntax, only makes it even worse.

What is needed is a digital twin where the engineer can model the relevant components, place them in a common workspace, configure the CNC parameters for the software modules and command the axes with PLC, Robot and CNC to complete the desired behavior. This model must consider all the kinematics and provide collision detection.

For the part programming, the engineer expects a simulation site where he/she can edit the CNC and Robot programs and share the machine tool workspace. The robot and machine must also share the coordinate system and axis definitions so that the first can access, for instance, the part to manipulate it (changing finished part for raw material) or changing tool in the spindle at different positions in space. The simulation must include the PLC and the relevant periphery (automatic tool changer, palletizer…) to represent the system behavior under different conditions accurately. The first objective is to reduce the programming errors that lead to defective parts, what is mandatory for big and complex pieces, and avoid collisions between the tool and the part or the robot and machine tool or part. A second objective relates to the production of medium-large series of the same part, where the accurate simulation of timings and CNC and Robot trajectories can substantially reduce lost times and increase quality through careful selection of CNC path generation parameters and simultaneous movements of the different components.

Finally, the Digital Twin must be present for collision avoidance even in manual mode, as controlling the robot or a 5-axis machine tool is error-prone, and the risk of damaging the part is very high.

A full Digital Twin will be developed for these cases. Specific developments are:

- Robot Kinematics and calibration (to share coordinate system).
- Combined graphical representation of machine and robot kinematics.
- Collision detection between robot and machine or piece.
- Dynamic models of both machine tool and robot for performance prediction. Main flexibilities will be included and tuned using experimental tests.
- Modelling relevant peripheral components if needed (tool changer?)
- CNC & robot simultaneous programming

Modern model-based controllers for mechatronic systems rely on accurate system models for their performance. These models concern all aspects of mechatronic systems, e.g., their mechanical, electrical, or thermal behaviour, and digital twins are valuable on each of these levels. For example, let's zoom in on the thermal aspects, for instance, in a 3D printing application. In such application, an accurate model of the system's thermal behaviour is required to compensate for thermal deformations. Often, it is attempted to optimize the mechatronic design or to regulate the environment such that the impact of the thermal behaviour becomes negligible or trivial to model. However, this is not possible for all applications. For instance, thermally optimizing low-cost mechatronic systems might not be economically feasible. It is also possible that substantial cooling/heat generation is intrinsic to the application, tying the thermal behaviour directly to the mechatronic performance. In such circumstances, accurate thermal models are required for optimal mechatronic performance.

A thermal model of a system comprises the thermal properties of its components, the heat transfer mechanisms between them (conduction, convection, and radiation), and the heat inputs. If all of these are known, it is straightforward in a mechatronics application to compute the system's thermal behaviour and compensate for the ensuing deformation through feedforward control.

Most of the mentioned elements of a thermal model can be entirely determined or identified through mature techniques. The thermal properties of the components and the conduction between them can be readily extracted from a FEM model. The radiation is often negligible and can be excluded. The heat inputs are often known as the process acts on them. However, the convection component is challenging to model as it is state-dependent (it depends on uncontrolled and unknown boundary conditions). Typically, simplifying assumptions are made for the convection, e.g., it is modelled as a constant term.

When the convection component of a thermal system has an important impact, the common simplified assumptions might be insufficient and advanced models are required, especially when transient behaviour is important. Effective approaches to model convection in the transient thermal behaviour are open research items. A digital twin for the transient thermal behaviour, incorporating data-driven online thermal system identification techniques, is envisioned to address the convection challenge.

Techniques that automate the identification of thermal systems and enable online updating of the achieved models are required to achieve virtual twins for the (transient) thermal behaviour. Given the nature of thermal systems, such techniques ideally show the following characteristics:

- Modular: thermal systems are composed of many modular building blocks, so modularity makes the technique scalable and reusable.
- Gray-box: physical-based models are likely to be insufficient for complex systems and can be augmented with data-driven models.
- Explicit uncertainty description: robustifies the feedforward compensation control policies when dealing with grey-box models that are hard to interpret. It also points out the uncertain parts of the model, which are best suited for further optimizations.
- Efficient: online system identification (updates) requires short computation times.

In this context, online variational Bayes system identification procedures will be investigated. The general concepts of such procedures will be studied to develop a generic and reusable tool for system identification, which is transferrable across domains due to the modularity and grey-box techniques. This will finally be operationalized for thermal applications.

Modelling and simulation of complex multi-axis systems, complex estimators (Task 5.5)

The focus of task 5.5 is on creating models that can be used within a digital twin. This means that they need to be flexible and fast enough to interact with real-time measured data and to be molded into a shape that closely mirrors to the real system.

Creating models of complex systems is not something new, there are many methods to create accurate models of complex systems. The power of these methods is that they are verry generic, they can be used for many different systems. This implies a high abstraction level of the building blocks e.g., an element in a finite element method. This high level of abstraction results in a high number of degrees of freedom and a long calculation time. This makes these models not suitable for usage in a digital twin, where in general many evaluations are needed in a relatively short time.

The goal of this task is to find appropriate methods to convert the full order models into reduced models that can be used in a digital twin. In this context, a reduced order model should be able to deal with parameter uncertainties, to be easily exchangeable and IP safe.

Augmented and virtual reality through digital twins (Task 5.6)

In task 5.6, the focus is on the overall development of digital twins. The activities consist of multi-domain modeling, selection of suitable computing real-time platform, implementation, and optimization about the near real-time operation and enhancing through virtual reality technology. Interfacing with design and simulation tools, digital twins and augmented reality will be realized since connectivity and integration of these tools is vital for wider exploitation. This task will also provide porting of deep neural networks to the platform accelerators, the configuration of OS, hypervisor, and networking.

Task 5.6 activities are divided into three subtasks: Digital twins tooling, Digital twins for testing, and Digital twins enhanced through virtual reality technology.

Digital twins tooling (Sub task 5.6.1)

Knowledge, Representation, and Reasoning (KRR) techniques for modeling and verification of digital twins will be investigated. Generation of Digital Twins from design data, design knowledge, and representation will be automated. Digital twin testing environments for the development and implementation of mobile machinery control systems will be developed as offline and virtual testing close to actual machinery and operational environment is in major role when enhancing the design and development processes. Especially the offline toolchain methods and tools, such as MATLAB, to simulate and test control system algorithms in early stages of development process are investigated. Also porting of algorithms and control software from initial development phases to actual online environment will be discussed. AI semantic feedback systems for environmental monitoring in remote teleoperated tactile robots will be provided.

Digital twins for testing (Sub task 5.6.2)

A digital test cell concept including a partly or fully simulated control system will be developed for end-to-end testing of mobile machinery. Digital twin toolchains will be prepared including tools for testing and implementation of mobile machinery control system algorithms as this type of real-alike virtualized control system components play a key role in testing the actual control algorithms for mobile machines. Further the digital twin replica of the mobile machine with VR-capabilities enhances the testing processes and is a requisite to exploit the development environment for comprehensive testing the machines control system functionalities.

Tooling life extension will be achieved with the help of digital twins to compensate for tool wear.

Digital twins enhanced through virtual reality technology (Sub task 5.6.3)

- **DT/VR activities in relation to:**
    - Research and development into CoBot models/representation in the DT/VR world.
    - Control and positioning of a virtual CoBot and gripper in the DT/VR world.
    - Testing and interaction with virtual objects in the DT/VR world.
    - Investigation and research into connecting various sensors to interface with the DT/VR world. **CoBot interaction with the DT/VR related activities:**
    - Research and development in relation to the interfacing of the HMI and ToF sensors to provide live data streams to the DT/VR world.
    - Research and investigation into sending actual movement coordinates of the CoBot from the remote edge device to be represented in the DT/VR world.
- **SoC – FPGA edge device related activities:**
    - Research and investigation into how the DT/VR world may be completely or partially implemented on the edge SoC – FPGA device.
    - Finalization of the most appropriate DT/VR compute infrastructure configuration.
- **DT/VR algorithm development related activities:**
    - Research and investigation into AI components and functionality that can enable and enhance the DT/VR world with predictive behavior capabilities in a use case context.
    - Generation of synthetic training data for creating and validating predictive models using DT/VR based digital twin systems and tools such as Microsoft AirSim and others as relevant.
    - Research, testing and evaluation of ToF AI semantic analytics/feedback for environmental monitoring of user arm/hand movements in the context of remote tele-operated robotics.

AI methods for monitoring and predictive maintenance at higher IMOCO4.E layers (Task 5.7)

This task is devoted to developing models and algorithms for monitoring and predictive maintenance using AI and ML approaches at higher IMOCO4.E layers and over these layers. Activities include the collection of data coming from Use Case 1 and Pilot 3 to start a subsequent experimental phase that will lead to the development of models and algorithms for asset monitoring and predictive maintenance. This activity will be carried out in parallel to the preparation of a survey about the main topics of T5.7. The main goal of the survey is to identify and present strengths and weaknesses of state-of-the-art approaches on the project use cases. The findings resulting from the survey will be considered as major inputs for the development of models and algorithms for predictive maintenance application and will be included in D5.7. Furthermore, the resulting survey is planned to be submitted for publication in a scientific venue or journal.

4. System-level requirements

Layer 1 – Sensors / Actuators

This section describes requirements on sensors and actuators which are not linked with building blocks, or they are rather linked with the Layer 1.

Table 1: Requirements on layer 1

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R001-D5.1-L1-hw	Sensors must have a reader / controller connected to upper layers (through BB1) by USB or Ethernet	S	I		Task5.4
R002-D5.1-L1-sw	FPGA platforms and high-speed cameras must have connectivity via APIs.	M	T		Task5.4, 5.5, 5.6

Layer 2 – (de)Centralized controllers – Motion control platform(s)

This section describes requirements on centralized controllers which are not linked with building blocks, or they are rather linked with the Layer 2.

Table 2: Requirements on layer 2

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R003-D5.1-L2-sw	A dockerized environment (e.g. Kubernetes cluster) needs to be configured at the host infrastructure to allow the deployment of BB9 components / services.	S	I		T5.2
R004-D5.1-L2-sw	Virtual Commissioning with, at least, PROFINET and EtherCAT communications should be supported	S	I		T5.4
R005-D5.1-L2-sw	An Apache Kafka client (Producer / Consumer API) needs to be implemented by any Layer 2 component that needs to exchange data with BB9.	S	I		T5.2
R006-D5.1-L2-sw	The Elastic Search API needs to be used by any Layer 2	S	I		T5.2

	component that needs to access the BB9 permanent storage.				
Performance					
R007-D5.1-L2-sw	Data-driven Robot Dynamics model for compliant control should be more accurate than an analytical model, especially in fast movements				T5.5
R008-D5.1-L2-sw	Virtual Commissioning solution should allow real time simulation of plants (sampling < 1 ms)	S	T		T5.5
Usability (operability)					
R009-D5.1-L2-sw	A HiL based Virtual Commissioning solution should be provided	M	I		T5.4/ T5.5
Reliability (fault tolerance, availability)					
R010-D5.1-L2-sw	The Virtual Commissioning system will allow automatic testing of controller and plant model code	S	I		T5.4
Tools/toolchains					
R011-D5.1-L2-sw	Matlab Simulink should be among available plant modelling environment	S	I		T5.5

Layer 3 – System behaviour – Central platform(s)

This section describes requirements on system behaviour which are not linked with building blocks, or they are rather connected with the Layer 3.

Table 3: Requirements on layer 3

ID	**Requirement**	**Priority**	**Verify**	**Comments**	**Tasks**
Interfaces and connectivity					
R012-D5.1-L3-sw	A dockerized environment (e.g. Kubernetes cluster) needs to be configured at the host infrastructure to allow the deployment of BB9 components / services.	S	I		T5.2
R013-D5.1-L3-sw	An Apache Kafka client (Producer / Consumer API) needs to be implemented by any Layer 3	S	I		T5.2

	component that needs to exchange data with BB9.				
R014-D5.1-L3-sw	The Elastic Search API needs to be used by any Layer 3 component that needs to access the BB9 permanent storage.	S	I		T5.2

Layer 4 – Digital twins and AI analytics

This section describes requirements on Layer 4 which are not covered by building blocks and requirements on digital twins.

Table 4: Requirements on layer 4

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R015-D5.1-L4-sw	A dockerized environment (e.g. Kubernetes cluster) needs to be configured at the host infrastructure to allow the deployment of BB9 components / services.	S	I		T5.2
R016-D5.1-L4-sw	An Apache Kafka client (Producer / Consumer API) needs to be implemented by any Layer 4 component that needs to exchange data with BB9.	S	I		T5.2
R017-D5.1-L4-sw	The Elastic Search API needs to be used by any Layer 4 component that needs to access the BB9 permanent storage.	S	I		T5.2

5. Building block requirements

BB1 - SoC/FPGA platforms for smart control and signal processing

Table 5: Requirements on BB1

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R018-D5.1-B1	The interfaces to BB1 shall be an industry standard	M	I		T5.1
R019-D5.1-BB	The BB1 should have interface with camera sensors	M	T		T5.6
R020-D5.1-B1	The BB1 should have enough memory to allow for buffering more than 6 image from the camera sensors	M	T		T5.6
Performance					
R021-D5.1-B1	The interface to/from BB1 shall support update rates of at least 20 kHz to Layer 2 and/or BBs	M	D		T5.3, 5.4, 5.5, 5.6
Usability (operability)					
R021-D5.1-B1	TSN Centralized Network Configuration to facilitate the network configuration and monitoring	S	T	OROLIA Network adaptation attending to application requirements and network telemetry (latency, congestion, failures). Control and telemetry features exposed through a standard API between TSN bridges and CNC Expected TRL: 4	T5.2
R022-D5.1-B1	BB1 shall have a configuration interface to modify all (pre-defined) configuration parameters without requiring firmware changes.	M	D		T5.1

Reliability (fault tolerance, availability)					
R023-D5.1-B1	Frame Replication and Elimination Reliability (IEEE 802.1CB) available for user designated data streams.	S	I	OROLIA Expected TRL: 6	T5.2
Scalability					
R024-D5.1-B1	BB1 shall offer a scalable amount of computational resources, e.g. by means of the firmware implementation or by offering a family of processing units with different capacities	M	D		T5.1
Tools/toolchains					
R025-D5.1-B1	BB1 shall use a toolchain that is open-source or industry-standard	S	I		T5.1
Safety					
R026-D5.1-B1	Exchanging data and / or controls between layers shall not affect human or machine safety of the total solution	M	T		T5.1

BB6 - Algorithms for condition monitoring, predictive maintenance, and self-commissioning of industrial motion control systems

Table 6: Requirements on BB6

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R027-D5.1-B6	Integration of additional sensor interfaces in power inverter controller may be required to be able to obtain data containing information of individual fault propagation observability	W	D	The goal is to use as much as possible existing sensors which are normally in the system. (BUT)	T5.3
R028-D5.1-B6	Predictive maintenance components should be integrated with relevant monitoring systems to create alerts and recommendations.	M	T	Utilization of existing communication channels and possibly new ones.	T5.7
Performance					
R029-D5.1-B6	Information availability in measured data – existing measurements should be	S	T	This part is research oriented; fast and precise	T5.3

	analyzed whether it contains information applicable for condition monitoring purposes of the inverter power components failures propagation or suitable sensing chains for defined quantities (with specified resolution, sampling rates, synchronization capability) have to be integrated into power inverter architecture.			measurement systems will be used and oversampling with number of bits reduction will be used during analysis to find required data rate and precision (BUT).	
R030-D5.1-B6	Computing performance in the power inverter controller is required to process high volume raw data and reduce them to simpler condition indicators.	C	D	BUT. Nowadays, computational power in the inverter controller should be sufficient. If not, functionality can be demonstrated online or on different computational hardware.	T5.3
R031-D5.1-B6	ML predictive maintenance components should be able to process incoming data and apply trained models in real time.	M			T5.7
Reliability (fault tolerance, availability)					
R032-D5.1-B6	Remaining useful life for individual components must be predicted with sufficient prediction horizon and sufficient confidence.	M	D	It would be good to predict the fault days or weeks before the fault will happen to give the space for maintenance planning. (BUT)	T5.3
Scalability					
R033-D5.1-B6	Condition indicator methods should be scalable for various inverter sizes and types. Model based methods are preferred to fulfil the requirement	C	T	If not possible, parametrization will be searched for. (BUT)	T5.3
Tools/toolchains					
R034-D5.1-B6	All condition indicator methods and RUL prediction methods	S	T	The development of algorithms will run in MATLAB Simulink,	T5.3

	should be compatible with MATLAB code generation			optimization on this level will be employed to generate usable code. (BUT)	

BB8 - AI-based components

Table 7: Requirements on BB8

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R035-D5.1-B8	To support integration across all layers, BB8 shall offer industry-standard interfaces to each of the IMOCO4.E layers to exchange data	M	I		T5.1
R036-D5.1-B8	Interfaces to deploy learned networks are present. Note: The main targets are BB1, BB2, BB5, and BB6	M	I		T5.1
R037-D5.1-B8	On-site update in-the-field	S	I		T5.1
R038-D5.1-B8	Sim2Real transfer provides synthetically trained object detection algorithms that detect objects of interest in 80% of images with said objects	S	D		T5.1
R039-D5.1-B8	BB8 shall support real-time inference (limited and deterministic)	S	D		T5.1
Maintainability (modularity, analysability, testability)					
R040-D5.1-B8	Support and be operational in multiple Pilots/Demos/Use-cases	S	D		T5.1
R041-D5.1-B8	Minimize downtime	S	D		T5.1
Performance					
R042-D5.1-B8	BB8 shall support a computing continuum in the sense that BB8 can operate in all layers, i.e. from	M	D		T5.1

	the instrumentation layer up to the cloud layer				
Compatibility (interoperability, co-existence)					
R043-D5.1-B8	BB8 shall offer customizability such that non-standard tasks (i.e., tasks which are typically performed in research) can be performed. Examples include flexibility in allowed controller structures and reference / feedforward signals.	S	T		T5.1
Usability (operability)					
R044-D5.1-B8	Any user could operate (without expert knowledge)	S	D		T5.1
R045-D5.1-B8	Only authorised users have access to systems and data	M	I		T5.1
Reliability (fault tolerance, availability)					
R046-D5.1-B8	BB8 shall offer AI components including one or more forms of verifiability, for example: - Providing a human-interpretable view of the algorithm. - Providing a framework to assess reliability in a simulation/digital twin environment	M	D		T5.1

BB9 - Cyber-security tools and trustworthy data management

Table 8: Requirements on BB9

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R047-D5.1-B9	Support real-time information exchange with a protocol based on message set abstraction (publish/subscribe model) that is able to handle parallel data streams between multiple endpoints	M	D		T5.2

R048-D5.1-B9	BB9 will be able to aggregate, transform and fuse incoming text-based data from multiple sources and of multiple data types (e.g., time-series and cross-sectional data, real and simulated data, raw sensor data, inference result data from AI components).	M	D		T5.2
R049-D5.1-B9	BB9 will provide persistent storage for the aggregated and fused data (see R199-D2.3-B9-com-DAT) in the cloud infrastructure (historical data).	M	D		T5.2
R050-D5.1-B9	BB9 will allow all authorised components to access incoming data streams collected from multiple sources (see R199-D2.3-B9-com-DAT) in real-time via a dedicated API.	M	D		T5.2
R051-D5.1-B9	BB9 will allow all authorised components to access historical data stored in the cloud infrastructure (see R200-D2.3-B9-com-DAT) via a dedicated API.	M	D		T5.2
R052-D5.1-B9-sw	BB9 architecture to be based on microservices to be delivered in containerised form and deployed on the edge/cloud (e.g., using Docker/Kubernetes cluster)	S	D		T5.2
R053-D5.1-B9	BB9 will be able to handle time-sensitive data streams between multiple endpoints in real-time while conforming to the bandwidth and latency requirements of connected IMOCO4.E components.	S	T		T5.2 T3.4
R054-D5.1-B9	Support real-time information exchange with a protocol based on message set abstraction (publish/subscribe model) that is able to handle parallel data streams between multiple endpoints	M	D		T5.2

Performance					
R055-D5.1	BB9 must be able to generate alerts in real-time (e.g., related to supported cyber-security threat detection, see R215-D2.3-B9-SEC).	M	D		T5.2
R056-D5.1-B9	All used libraries/frameworks/components must not have known security vulnerabilities nor infringement of (open source) license conditions.	S	D		T5.2
Usability (operability)					
R057-D5.1-B9	BB9 will be designed to support and be operational in multiple Pilots/Demonstrators/Use Cases	S	D		T5.2
Reliability (fault tolerance, availability)					
R058-D5.1-B9	BB9 will be able to continue operating despite receiving and processing invalid or wrong data.	S	D		T5.2
R059-D5.1-B9	Only authorised users will be allowed to access the system.	S	D		T5.2
R060-D5.1-B9	BB9 will provide high computing availability, having a continuous, uninterrupted, fault-tolerant operation.	S	D		T5.2
Security					
R061-D5.1-B9	Data security will be ensured at rest and in flight.	S	D		T5.2
R062-D5.1-B9	Access to the system's data and services will be granted only to authenticated users and components that have been granted the necessary privileges.	S	D		T5.2
R063-D5.1-B9	BB9 will support the automated detection of cyber-security threats and vulnerabilities that can be inferred from applying anomaly detection techniques to the BB9 data streams.	S	D		T5.2

R064-D5.1-B9	The system will alert the user if any supported cyber-security threat and vulnerability is detected and present an assessment (see R215-D2.3-B9-SEC).	S	D		T5.2
Safety					
R065-D5.1-B9	Data safety will be ensured through Data Replication support over secure channels between the infrastructure cluster nodes.	S	D		T5.2
Scalability					
R066-D5.1-B9	BB9 will be fully scalable so that it can easily be adapted to new integration needs or changes in performance, reliability, and data volume requirements.	S	D		T5.2
Tools/toolchains					
R067-D5.1-B9	A GUI will be provided for configuration purposes of BB9.	C	D		T5.2
R068-D5.1-B9	BB9 will provide an appropriate dashboard for visualising data and providing insight related to the operation of BB9 (e.g. system health status, data traffic, performance metrics, alerts)	C	D		T5.2

BB10 - Motion / path planning, collision avoidance and navigation algorithms

Table 9: Requirements on BB10

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R069-D5.1-B10	The short-term future path of the robot should be predictable for human traffic participants.	S	D		T5.1
R070-D5.1-B10	Path planning should take into account the presence and movement of human traffic participants and generate cooperative movement behaviour.	C	D		T5.1

6. Pilot requirements

Pilot 1 – Reusable Application Aspects

In D7.1, it is explained that Pilot 1 now consists of 7 themes, deployed, and demonstrated on a few selected applications. These 7 themes are intended to be highly reusable and hence have a rather generic signature, like BBs do. The requirements in the table below reflect this approach with a corresponding level of refinement and details.

Table 10: Requirements on Pilot-1

ID	Requirement/Specification	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R071-D5.1-P1-1	TCP/IP	M	I		T5.2
R072-D5.1-P1-2	TSN	W	I		T5.2
R073-D5.1-P1-3	Cloud and/or local servers	S	I		T5.2
Maintainability (modularity, analysability, testability)					
R074-D5.1-P1-4	Support for multiple systems with individual variants, configurations, and versions - at the same time	C/W	D		T5.2
R075-D5.1-P1-5	Support for simulated systems	S	D		T5.2 T5.5 T5.6
Performance					
R076-D5.1-P1-6	Data communication and processing in real-time, with restricted latency	S	T		T5.2 T5.6
R077-D5.1-P1-7	Real-time access to signals, parameters, and configurations	S	T		T5.4 T5.6
R078-D5.1-P1-8	Configurable tracing of signals (tracing on/off, sample rates, triggers, selected simultaneous signals)	C	T		T5.4
R079-D5.1-P1-9	Capable of downloading SW updates, motion control	C	T		T5.4 T5.5

	parameters and trained AI networks				
Compatibility (interoperability, co-existence)					
R080-D5.1-P1-10	Integrated in a network environment with other 'foreign' network devices	M	I		T5.2
Usability (operability)					
R081-D5.1-P1-11	Dashboard, to manage (on-boarding, off-boarding), configure, update and operate all available systems	S	D		T5.2
R082-D5.1-P1-12	Run algorithms (in the cloud) on system data, including AI network training	C	D		T5.2 T5.5
R083-D5.1-P1-13	Run simulations (in the cloud) of digital twins, including what-if scenarios	C	D		T5.2 T5.5
R084-D5.1-P1-14	Run AR/VR (Unity engine) sessions of real or simulated systems	S	D		T5.2 T5.6
Reliability (fault tolerance, availability)					
R085-D5.1-P1-15	Robust against connection loss, i.e. (automatic) reconnect and recover	C	T		T5.2
R086-D5.1-P1-16	Robust against (partial) data loss or data corruption	C	T		T5.4
Security (cyber-security, integrity, confidentiality, authenticity)					
R087-D5.1-P1-17	System client certification compliant to X.509 certificate and EST protocol	S	I		T5.2
R088-D5.1-P1-18	Support for authorization and roles: • No/read access on signals & data • No/read/modify access on parameters, configurations, and software updates	C	D		T5.2
Portability (adaptability, replaceability)					
R089-D5.1-P1-19	Cloud platform independence: Azure, ASW, Google Cloud, Arrowhead, Alibaba	W	I		T5.2
Scalability					

R090-D5.1-P1-20	Scalable w.r.t. the total number of connected systems	C	I		T5.2
R091-D5.1-P1-21	Scalable w.r.t. the rate of generated data	C	I		T5.2
R092-D5.1-P1-22	Scalable w.r.t. the storage size of data	C	I		T5.2
R093-D5.1-P1-23	Scalable w.r.t. the needed computing power of algorithms, simulations, optimizations, and AI training	C	I		T5.2
Safety					
R094-D5.1-P1-24	Any algorithms, AI-components and digital twin models shall not adversely affect the safety of the system.	M	D/T		T5.4 T5.5

Pilot 2 - Semiconductor Production

The requirements and specifications specific to the pilot 2 are mentioned below. Please, note that this is in addition to the overall requirements already detailed in the deliverable D2.3.

Table 11: Requirements on Pilot 2

ID	Requirement/Specification	Priority	Verify	Tasks
Interfaces and connectivity				
R095-D5.1-P2-1	Supported operating system for Pilot 2 - Windows	M	I	T5.2, T5.4, T5.7
R096-D5.1-P2-2	Supported digital twin interface with the production line a. TCP/IP b. SECS/GEM	M C	I	T5.2, T5.4, T5.7
R097-D5.1-P2-3	Type of data to be supported for the data management c. Equipment state monitoring (ESM) data (alphanumeric)	M	I	T5.2
R098-D5.1-P2-4	Real-time access to all parameters in control/instrumentation layer	M	D	T5.2, T5.4
Performance				
R099-D5.1-P2-5	Monitoring tooling should have functionality to monitor	M	D	T5.4, T5.7

	d. Settling time e. Overshoot f. Error tracking over time			
Usability (operability)				
R100-D5.1-P2-6	The self-commissioning function should be able to commission model-based feedforward controllers with: g. friction compensation h. mass compensation i. spring compensation j. gravity compensation	M	D	T5.4
R101-D5.1-P2-7	Live tracing of all control system signals (input, output) in time and frequency domains for commissioning and troubleshooting	M	D	T5.4
Reliability (fault tolerance, availability)				
R102-D5.1-P2-8	Monitoring tooling is able to detect trends that indicate upcoming issues or failures.	M	D	T5.4
Tools/toolchains				
R103-D5.1-P2-9	Tooling is suited for system identification and parameter estimation	M	D	T5.4

Pilot 3 - High Speed Packaging

The requirements and specifications related to WP5 for Pilot 3 are mentioned below. Please note that this list extends the one detailed for WP2, in the deliverable D2.3. The complete list of requirements and specifications for Pilot 3 collected and updated up to M11 can be found in D7.1.

Table 12: Requirements on Pilot 3

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R104-D5.1-P3-1	New approaches for multi-machine communications **GA type**: Functional **BBs**: BB9 **Layers**: L4, SYS (IF L3-L4) **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-DAT-14]	C	I	BB9 (to be developed mainly within T5.2) is responsible for the design and development of the network configuration to store, manage and transmit data among	T5.2, T5.6

				layers, machines, and application entities. Optionally, within WP5 (that is about "Digital Twin and their interaction with the cloud") it would be possible to define suitable virtual solutions (digital twin) of the envisioned BB architecture for Pilot 3 in the perspective of assessing the scalability of the overall solution deployed (T5.6)	
R105-D5.1-P3-2	TSN support **GA type**: Functional **BBs**: BB9 **Layers**: SYS (IF L3-L4) **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-DAT-14]	M	T	Network infrastructure and TSN implementation is due by BB9 (T5.2)	T5.2
Maintainability (modularity, analysability, testability)					
R106-D5.1-P3-3	New architecture reference for app development **GA type**: Technical (AI) **BBs**: BB6, BB8, BB9 **Layers**: L3, L4, SYS (IF L3-L4) **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-fw-17]	C	I	Requirement that refers to both the infrastructure (BB9 in T5.2) and the AI software tool (BB6/BB8 in T5.3)	T5.2, T5.3
Performance					
R107-D5.1-P3-4	Reduce human workload **GA type**: Technical	M	D	Requirement that refers to all the system with a focus	T5.2, T5.3,

	BBs: BB6, BB8 **Layers**: SYS **WP5 sub-type**: Goal **Parent REQ**: -			on BB6/BB8 algorithms and data pre-processing	T3.4, T5.7
R108-D5.1-P3-5	Reduce machine stops **GA type**: Technical **BBs**: BB6, BB8 **Layers**: SYS **WP5 sub-type**: Goal **Parent REQ**: -	M	D	Requirement that refers to all the system with a focus on BB6/BB8 algorithms and data pre-processing	T5.2, T5.3, T3.4, T5.7
R109-D5.1-P3-6	Trace products process **GA type**: Technical **BBs**: BB6, BB8 **Layers**: SYS **WP5 sub-type**: Goal **Parent REQ**: -	S	I	Requirement that refers to all the system with a focus on BB6/BB8 algorithms and data pre-processing	T5.2, T5.3, T3.4, T5.7
R110-D5.1-P3-7	Real-time decision-making functionalities (on-edge) **GA type**: Functional (AI) **BBs**: BB4, BB6, BB8 **Layers**: SYS **WP5 sub-type**: Capability **Parent REQ**: [Goal Req-D7.10-P3-2]	M	D	Ideally, this requirement is more related to on-edge applications of BB6/BB8 (i.e., T5.3, T3.4) instead of cloud ones (T5.7) and, of course, to the BB4 platform capabilities (T4.6). See also, Req-D7.10-P3-sw-5	T5.3, T3.4, T4.6
R111-D5.1-P3-8	Real-time decision-making functionalities (on-cloud) **GA type**: Functional (AI) **BBs**: BB4, BB6, BB8 **Layers**: SYS **WP5 sub-type**: Capability **Parent REQ**: [Goal Req-D7.10-P3-1]	M	D	This requirement extends Req-D7.10-P3-hw-3 for cloud solutions, which may be investigated as well. In this case also the network infrastructure and implementing TSN (BB9 – T5.2) are relevant	T5.3, T3.4, T4.6, T5.7, T5.2

R112-D5.1-P3-9	Continuous learning systems **GA type**: Functional (AI) **BBs**: BB6, BB8 **Layers**: L3, L4, SYS (IF L3-L4) **WP5 sub-type**: Capability **Parent REQ**: [Goals Req-D7.10-P3-1, Req-D7.10-P3-2, Req-D7.10-P3-3]	M	I	Cross-tasks topics for both BB6 and BB8 solutions and data pre-processing	T5.2, T5.3, T3.4, T5.7
Compatibility (interoperability, co-existence)					
R113-D5.1-P3-10	Enable sensor-controlled functions **GA type**: Technical **BBs**: BB6, BB8, BB2 **Layers**: L1, L3, L4 **WP5 sub-type**: Requirement **Parent REQ**: [Capabilities Req-D7.10-P3-hw-15, Req-D7.10-P3-hw-16]	S	T	This may concern both data pre-processing foreseen in T5.2 (BB6) and in T3.4 (BB8) as well as the camera vision solutions of BB2 (T3.2) and the possible additional sensor that may be considered for the Pilot 3 demonstration	T5.2, T3.4, T3.2
R114-D5.1-P3-11	Store data from various sources **GA type**: Functional **BBs**: BB4, BB9 **Layers**: SYS (IF L3-L4) **WP5 sub-type**: Requirement (Digital Twin) **Parent REQ**: [Capability Req-D7.10-P3-DAT-14]	S	T	Processed data in BB4 (via BB6 solutions) will allow BB9 (T5.2) to store data for efficient resource sharing, thus enabling multiple resources access to devices and application entities	T5.2
R115-D5.1-P3-12	Secure Quality Control via Machine Vision **GA type**: Technical **BBs**: BB2, BB6, BB8, BB9 **Layers**: SYS **WP5 sub-type**: Need **Parent REQ**: [Requirement Req-D7.10-P3-fw-117]	S	I	Requirement related mainly to the BB2 vision camera but also potentially to cross-tasks modelling issue (i.e., both data-driven modelling and therefore AI solutions of BB6/BB8	T3.2 (T5.2), (T5.3), (T3.4), (T5.6), (T5.7)

				or different modelling approaches that may be realized via virtualization, i.e., digital twin: T5.6)	
Usability (operability)					
R116-D5.1-P3-13	Automate complex tasks **GA type**: Technical **BBs**: BB6, BB8 **Layers**: L3, L4 **WP5 sub-type**: Capability **Parent REQ**: [Goal Req-D7.10-P3-1]	S	T	This requirement is related to both cloud (T5.7) and on-edge (T5.3, T3.4) applications of BB6/BB8	T5.3, T3.4, T5.7
R117-D5.1-P3-14	Automate equipment adjustment **GA type**: Technical **BBs**: BB6, BB8 **Layers**: L3, (L4) **WP5 sub-type**: Capability **Parent REQ**: [Goal Req-D7.10-P3-2]	C	D	Ideally, this requirement is more related to on-edge applications of BB6/BB8 (i.e., T5.3, T3.4) instead of cloud ones (T5.7)	T5.3, T3.4 (T5.7)
R118-D5.1-P3-15	Autonomous or semi-autonomous operations **GA type**: Functional (AI) **BBs**: BB6, BB8 **Layers**: L3, L4 **WP5 sub-type**: Capability **Parent REQ**: [Goals Req-D7.10-P3-1, Req-D7.10-P3-2, Req-D7.10-P3-3]	M	D	This requirement is related to both cloud (T5.7) and on-edge (T5.3, T3.4) applications of BB6/BB8	T5.3, T3.4, T5.7
R119-D5.1-P3-16	New approaches for automated quality checks **GA type**: Technical (AI) **BBs**: (BB6), BB8 **Layers**: (L3), L4 **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-fw-17]	M	I	Ideally, this requirement is more related to cloud applications of BB6/BB8 (i.e., T5.7) instead of on-edge ones (T5.3, T3.4)	(T5.3), (T3.4), T5.7

R120-D5.1-P3-17	Autonomous or semi-autonomous operations for alarm detection and classification (i.e., suggestion of recovery actions) **GA type**: Functional (AI) **BBs**: BB6, BB8 **Layers**: L3, (L4) **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-fw-19]	M	D	Ideally, this requirement is more related to on-edge applications of BB6/BB8 (i.e., T5.3, T3.4) instead of cloud ones (T5.7)	T5.3, T3.4, (T5.7)
R121-D5.1-P3-18	Autonomous or semi-autonomous operations for quality checks **GA type**: Functional (AI) **BBs**: BB6, BB8 **Layers**: (L3), L4 **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-fw-19]	M	D	Ideally, this requirement is more related to cloud applications of BB6/BB8 (i.e., T5.7) instead of on-edges ones (T5.3, T3.4)	T5.7, (T5.3), (T3.4)
R122-D5.1-P3-19	Train deep neural network with fused data sensors **GA type**: Functional (Digital Twin) **BBs**: BB6, BB8 **Layers**: L3, L4 **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-DAT-20]	M	T	Cross-tasks topics for data pre-processing (BB6 – T5.2) and BB6/BB8 solutions	T5.2, T5.3, T3.4, T5.7
Reliability (fault tolerance, availability)					
R123-D5.1-P3-20	New approaches for dynamic parameter changes **GA type**: Technical (AI) **BBs**: BB6, BB8 **Layers**: L3, (L4) **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-fw-18]	M	I	Ideally, this requirement is more related to on-edge applications of BB6/BB8 (i.e., T5.3, T3.4) instead of cloud ones (T5.7)	T5.3, T3.4 (T5.7)

R124-D5.1-P3-21	New approaches for data correlation extraction in presence of unbalanced data sets **GA type**: Technical (AI) **BBs**: BB6, BB8 **Layers**: L3 **WP5 sub-type**: Need **Parent REQ**: [Requirement Req-D7.10-P3-fw-117]	M	I	This may concern both data pre-processing foreseen in T5.2 (BB6) and in T3.4 (BB8)	T5.2, T3.4
R125-D5.1-P3-22	AI algo must work on synthetic data or those provided as machine log **GA type**: Functional **BBs**: BB6, BB8 **Layers**: SYS **WP5 sub-type**: Need **Parent REQ**: [Requirement Req-D7.10-P3-sw-110]	M	T	Cross-tasks topics for both BB6 and BB8 solutions and data pre-processing (that are required to define the kind of data they need to work with in the perspective of the envisioned applications)	T5.2, T5.3, T3.4, T5.7
R126-D5.1-P3-23	Cope with possibly missing info in available machine logs **GA type**: Functional **BBs**: BB6, BB8 **Layers**: SYS **WP5 sub-type**: Need description **Parent REQ**: [Need Req-D7.10-P3-sw-203]	M	T	Cross-tasks topics for both BB6 and BB8 solutions and data pre-processing It is necessary to define the kind of data the AI algorithms may need to work with them in the perspective of the envisioned applications	T5.2, T5.3, T3.4, T5.7
R127-D5.1-P3-24	No info on real sensor used (actual machine data may be not available) **GA type**: Functional **BBs**: BB6, BB8 **Layers**: SYS **WP5 sub-type**: Rule	M	T	Cross-tasks topics for both BB6 and BB8 solutions and data pre-processing	T5.2, T5.3, T3.4, T5.7

	Parent REQ: [Need description Req-D7.10-P3-sw-301]				
Security (cyber-security, integrity, confidentiality, authenticity)					
R128-D5.1-P3-25	Security by design **GA type**: Functional **BBs**: BB9, BB4, BB2 **Layers**: SYS **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-DAT-14]	C	I	Topic related to: network (BB9 - T5.2), BB4 platform specifications (T4.6) and vision cameras specifications (T3.2)	T5.2, T4.6, T3.2
R129-D5.1-P3-26	Security by default **GA type**: Functional **BBs**: BB9, BB4, BB2 **Layers**: SYS **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-DAT-14]	C	I	Topic related to: network (BB9 - T5.2), BB4 platform specifications (T4.6) and vision cameras specifications (T3.2)	T5.2, T4.6, T3.2
Portability (adaptability, replaceability)					
R130-D5.1-P3-27	Create suitable model to enable autonomous functionalities **GA type**: Functional (Digital Twin) **BBs**: BB6, BB8 **Layers**: L3, L4 **WP5 sub-type**: Capability **Parent REQ**: [Goals Req-D7.10-P3-1, Req-D7.10-P3-2, Req-D7.10-P3-3]	S	D	Cross-tasks issue (related to both data-driven modelling and therefore AI solution or different modelling approaches that may be realized via virtualization, i.e., digital twin)	T5.2, T5.3, T3.4, T5.6, T5.7
R131-D5.1-P3-28	New modelling approaches to highlight interdependences among independently designed machine parts **GA type**: Technical (Digital Twin) **BBs**: BB6, BB8 **Layers**: L3, L4 **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-fw-18]	S	I	Cross-tasks issue (related to both data-driven modelling and therefore AI solution or different modelling approaches that may be realized via virtualization, i.e., digital twin)	T5.2, T5.3, T3.4, T5.6, T5.7
Scalability					

R132-D5.1-P3-29	Data acquisition in distributed architectures **GA type**: Functional (AI) **BBs**: BB9 **Layers**: SYS (IF L3-L4) **WP5 sub-type**: Capability **Parent REQ**: [Goals Req-D7.10-P3-1, Req-D7.10-P3-2, Req-D7.10-P3-3]	S	T	BB9 (to be developed mainly within T5.2) is responsible for the design and development of the network configuration to store, manage and transmit data among layers, machines, and application entities.	T5.2
Tools/toolchains					
R133-D5.1-P3-30	Cloud infrastructure be able to retrieve data and run AI SW (algorithms for quality check automation and/or alarm detection & classification algorithms) **GA type**: Functional **BBs**: - **Layers**: L4 **WP5 sub-type**: Requirement **Parent REQ**: [Capability Req-D7.10-P3-sw-12]	M	D	This requirement is related to the cloud infrastructure capabilities (T5.7).	T5.7

Pilot 4 – Medical robotic Manipulator

The requirements and specifications related to WP5 for Pilot 4 are mentioned below. Please note that this list extends the general ones described in the deliverable D2.3. The complete list of requirements and specifications for Pilot 4 collected and updated up to M11 can be found in D7.1.

Table 13: Requirements on Pilot 4

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R134-D5.1-P4-1	Smart control algorithms, AI-components and digital twin models may use additional data	S	I		T5.3 T5.4 T5.5 T5.7

	or sensory input interfaces to train the model, however after completion it shall only make use of existing data and interfaces of the brown field system.				
Maintainability (modularity, analysability, testability)					
R135-D5.1-P4-2	All smart control algorithms, AI-components and digital twin models shall be testable in both simulation (e.g., by means of digital twins) and deployed on the physical target.	M	T		T5.3 T5.4 T5.5
R136-D5.1-P4-3	All collected data from different sources (e.g., factory, field) but the same system shall contain a common unique identifier to enable linking of the data sources.	M	I		T5.7
Performance					
R137-D5.1-P4-4	Real-time (digital twin) models or algorithms require at maximum a sample rates of 500Hz.	S	D		T5.3 T5.4 T5.5
Compatibility (interoperability, co-existence)					
R138-D5.1-P4-5	All smart control algorithms, AI-components and digital twin models shall be compatible and/or configurable/tunable for different variations of similar system / robot.	S			T5.3 T5.4 T5.5
Reliability (fault tolerance, availability)					
R139-D5.1-P4-6	Results from algorithms for condition monitoring and predictive maintenance shall have <5% false positive detections.	S			
Portability (adaptability, replaceability)					
R140-D5.1-P4-7	If a (digital twin) model or algorithm is applicable to multiple layers (e.g. for real-time deployment and for condition monitoring) it will allow for easy adaptability/re-use across by for instance selection of variants of	C	I		T5.3 T5.4 T5.5

	differing abstraction levels/complexity.				
Tools/toolchains					
R141-D5.1-P4-8	All smart control algorithms, AI-components and digital twin models that are intended for real-time deployment shall be compatible with code generation from MATLAB / Simulink.	M			T5.3 T5.4 T5.5
Safety					
R142-D5.1-P4-9	Any smart control algorithms, AI-components and digital twin models shall not adversely affect the safety of the system.	M			T5.3 T5.4 T5.5

Pilot 5, Mining/tunneling robotic boom manipulator

The requirements and specifications related to WP5 for Pilot 5 are mentioned below. Please note that this list extends the one detailed for WP2, in the deliverable D2.3. The complete list of requirements and specifications for Pilot 5 updated can be found in D7.1, thus this is in addition to the overall requirements already described in the mentioned deliverables.

Table 14: Requirements on Pilot 5

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R143-D5.1-P5-1	Interfacing the digital twin environment with control system is analogical with the actual physical interface.	M	D		T5.6
Maintainability (modularity, analysability, testability)					
R144-D5.1-P5-2	Configuration of the machine platform controllers' parameters can be done against the virtual environment.	M	D		T5.6
R145-D5.1-P5-3	Manipulator motion control algorithms (path planning and execution, collision avoidance, visual servoing) can be verified against the digital twin counterpart.	M	D		T5.6
Performance					

R146-D5.1-P5-4	Digital twin environment and xIL (hw&sw in the loop) environment runs in real time.	M	T		T5.6
R147-D5.1-P5-5	Robotic manipulator code can be run directly in the xIL/digital test cell control system.	M	T		T5.6
Compatibility (interoperability, co-existence)					
R148-D5.1-P5-6	Motion control algorithms should be configurable/adapted to different types of sensors and manipulators and testable against the digital twin	S	T		T5.6
Usability (operability)					
R149-D5.1-P5-7	Visualization of the control system I/O signals for analytics in the digital test cell environment	M	D		T5.6
R150-D5.1-P5-8	VR capability (Unity) of the digital twin	S	D		T5.6
Safety					
R151-D5.1-P5-9	Safety critical features of the mining machine can automatically be tested in the simulation environment	M	I		T5.6
Tools/toolchains					
R152-D5.1-P5-10	Motion control algorithms can be tested and verified in simulation (matlab/simulink) before commissioned to HIL environment	M	I		T5.6

7. Demonstrator requirements

Demonstrator 1 - High precision cold forming of complex 3D metal parts

Table 15: Requirements on Demonstrator 1

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R153-D5.1-D1-1	The system can function disconnected from the internet	M			
Maintainability (modularity, analysability, testability)					
R154-D5.1-D1-2	Test possibility after changes and maintenance	S			
R155-D5.1-D1-3	Maintenance possible during production (no stops needed)	S			
Performance					
R156-D5.1-D1-4	Reduce human workload	S			
R157-D5.1-D1-5	Reduce machine stops	M			
R158-D5.1-D1-6	Real-time decision-making functionalities	M			
R159-D5.1-D1-7	Continuous learning systems	S			
Compatibility (interoperability, co-existence)					
R160-D5.1-D1-8	Enable sensor-controlled functions	M	Req-D5.1-D1-8	Enable sensor-controlled functions	M
R161-D5.1-D1-9	Store data from various sources	S	Req-D5.1-D1-9	Store data from various sources	S
Usability (operability)					
R162-D5.1-D1-10	Autonomous or semi-autonomous operations for quality checks	M			
Reliability (fault tolerance, availability)					

R163-D5.1-D1-11	New approaches for data correlation extraction	S			
Cost					
R164-D5.1-D1-12	Minimize structural costs	S			
Scalability					
R165-D5.1-D1-13	Fit for different processes	M			
Safety					
R166-D5.1-D1-14	Must be safe for humans, products, machine/system and environment	M			

Demonstrator 3 - Autonomous intra-logistic transportation

Table 16: Requirements on Demonstrator 3

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R167-D5.1-D3	ROS-2 system on Mini-PC	S	T		

8. Use-case requirements

Use-case 1 - Industrial drive for smart mechatronics applications

Table 17: Requirements on Use-case 1

ID	Requirement	Priority	Verify	Comments	Tasks
Maintainability (modularity, analysability, testability)					
R168-D5.1-UC1-1	All the modules integrated in UC1 has to provide testing software in digital-twin or HIL testbed.	M			T5.3 T5.4 T5.7
Performance					
R169-D5.1-UC1-2	All the real-time modules integrated in UC1 has to run considering the task-sample time available on the drive (i.e. routine must work considering 1ms or 8ms cycle time)	M			T5.3 T5.4
Usability (operability)					
R170-D5.1-UC1-3	Digital twins integrated in UC1 needs user interface to be used with unskilled personnel.	M			T5.3 T5.4 T5.7
Tools/toolchains					
R171-D5.1-UC1-4	Modules integrated with UC1 has to communicated with MATLAB/Simulink. Real-time modules integrated with UC1 needs to be compatible with IEC611311-3 Structured Text standard. A MATLAB/Simulink copy should be provided.	M			T5.3 T5.4 T5.7

Use-case 2 - CNC for integrated machine tool and robot control

Table 18: Requirements on Use-case 2

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R172-D5.1-UC2-1	Data Gathering for Synchronization of Physical Object and Digital Object will use OPC-UA protocols	S	I	Eg. Calibration data for robot kinematics, IO data of PLC & CNC...	T5.5

R173-D5.1-UC2-3	For Synchronization of data oriented to virtual commissioning, high speed data gathering is needed	M	D	Data is gathered based on proprietary protocols. Translation to standard formats is mandatory.	T5.4
R174-D5.1-UC2-4	Geometric Data for 3D simulation of robot and machine must come in standard format (eg. .stp file)	M	D	Conversion to simulation formats will be done by specific tools.	T5.5
R175-D5.1-UC2-5	Dynamic models of axes (robot and machine tool) must come in Simulink or Simulink importable formats	M	I		T5.4/ T5.5
R176-D5.1-UC2-6	Robot Kinematics must me written at least in the CNC's format.	M	D	(a reader or format converter should be provided for other tools, eg. Simulink)	T5.4 / T5.4
Performance					
R177-D5.1-UC2-7	Simulations of the system must be significantly faster than real operation (>10x) for CNC and robot operation	S	T		T5.5
R178-D5.1-UC2-8	Reduced, dynamic only model is acceptable for virtual commissioning of MIMO loops	S	T		T5.4
R179-D5.1-UC2-9	Rapid prototyping of virtual commissioning results of CNC-Robot loops should be possible in the physical object.	M	T	Results are available in the CNC's data gathering tools to feed the Digital Twin.	T5.4
Compatibility (interoperability, co-existence)					
R180-D5.1-UC2-10	The DT (including the robot system) must be programmable in CNCs language. Machine Tool and robot share coordinate system.	M	T	To test real usability by the CNCs programmer.	T5.5
Usability (operability)					
R181-D5.1-UC2-11	The DTwin or Digital Template of the robot and Machine Tool must be controlled from the CNC as in	M	T	This includes some sort of periphery and PLC simulation.	T5.5

	the real prototype, including manual operation, etc.				
R182-D5.1-UC2-12	The DT must provide essential data for the CNC programmer, for instance collision detection, execution times.	M	D	To test real usability by the CNCs programmer	T5.5
Reliability (fault tolerance, availability)					
R183-D5.1-UC2-13	The Digital Twin, based on synchronization data, should emit a diagnostics status on loop or system health with the aid of baseline data.	S	I		T5.4
Tools/toolchains					
R184-D5.1-UC2-14	Matlab Simulink should be the environment for plant modelling	S	I		T5.5

Use Case 3 - Tactile Robot Teleoperation:

This section primarily lists requirements compiled under D2.3 with DT\VR related notes as applicable underneath. It also provides additional requirements specifically addressing the DT\VR research to be conducted as part of UC3.

Table 19: Requirements on Use-case 3

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
R185-D5.1-U3-1	Establishment of local (user-end) to remote (CoBot-end) communications between edge devices and the Universal Robot UR16e, CoBot. ***DT\VR:*** *Research required into DT\VR on the selected edge device(s) to be used as part of UC3.*	M	I-D	As the use case is developing the exact role and requirements for the DT\VR must be investigated fully.	T5.6
R186-D5.1-U3-2	The PROFINET-IRT Industrial Ethernet protocol is to be used as the initial communications infrastructure.	M	I-D	his is a function of the edge device capabilities. Also, the	T5.6

	DT\VR: *The communication requirements and exactly where the DT\VR will sit (local or remote end) must be defined as part of UC3.*			operator\user will need to see a representation of the remote end.	
R187-D5.1-U3-3	Future iterations of the use case may lead to investigations into appropriate design options to incorporate TSN advancements for Industry 4.X., if required and justified. ***DT\VR:*** *TSN as related to DT\VR requirements will be investigated if TSN forms part of the UC3 architecture in the future.*	W	I-D		T5.6
Performance					
R188-D5.1-U3-4	The local (user-end) edge device is to perform appropriate HMI processing and mapping to the remote (CoBot-end) edge device and the connected teleoperation CoBot. ***DT\VR:*** *This requirement is expected to drive part or all of the DT\VR platform towards the local end but this matter is still under investigation.*	M	I-D	Research is also required into a live video-feed to support the operator\user at the local end.	T5.6
R189-D5.1-U3-5	Improve overall system performance by identifying, investigating, reporting, and resolving (as is practically possible) end to end system latency points.	M	I	Latency aspects of edge-to-edge communication is core to UC3 and the latency role of the DT\VR\AR is a	T5.6

	DT\VR: *There is a requirement to understand how the DT\VR platform can be used to address latency in robot tele-operation. Naturally, there is also a requirement that the DT\VR does not impact overall UC3 latency aspects, and this also needs to be considered in terms of an overall solution.*			vital part of the research to be conducted.	
Compatibility (interoperability, co-existence)					
R190-D5.1-U3-6	Co-existence of Information Technology (IT) and Operation Technology (OT) on the same network infrastructure. ***DT\VR:*** *The DT\VR will have ever increasing requirements once the DT\VR has a clearly defined role to play in robot teleoperation. The DT\VR must also be engineered to co-exist with IT and OT on the same industrial network infrastructure.*	M	I		T5.5, 5.6
Usability (operability)					
R191-D5.1-U3-7	***DT\VR:*** *The DT\VR must be extremely easy to set-up and use to assist the user in the tele-operation process. The DT\VR must also deliver value add in terms of insights and services to assist the user in conducting and managing the tele-operation task at hand.*	M	I-D	Usability and value add for the operator\user are vital requirements for the DT\VR services.	T5.6
Reliability (fault tolerance, availability)					

R192-D5.1-U3-8	***DT\VR:*** *In terms of reliability, the requirement is that the DT\VR must provide a near-real-time model of exactly what has taken place at the remote CoBot end. The absolute is that the DT\VR is achieving near video imagery in terms of its internal representation of the CoBot remote end of the tele-operation process.* *Such a reliable near real-time representation is mandatory for the local user to have the required trust level in what the DT\VR is formally processing as its internal representation of the remote tele-operation environment.*	M	I-D	As discussed above, a live video feed may also be required as an operator\user working with or without a VR headset must be considered in the loop.	T5.6
Security (cyber-security, integrity, confidentiality, authenticity)					
R193-D5.1-U3-9	***DT\VR:*** *For real-world implementation of a DT\VR for robot tele-operation, there is a requirement to investigate the services of BB9 interfaces in relation to cyber threat detection components that can be interfaced with the DT\VR and other UC3 sensors, edge, CoBot and communications functionalities.*	W	I	Security is a core concern for tele-operation. While it may not be possible to embed such components in the short-term, cyber-security must be an integral overall requirement for robotic tele-operation.	T5.6
Scalability					

R194-D5.1-U3-10	***DT\VR:*** *The requirements to have a scalable and flexible DT\VR infrastructure is important in the longer term and should be a key component of any DT\VR architecture.* *The DT\VR must be engineered with scalability and adaptability in mind to address varying industrial tele-operation scenarios.*	S	I	This requirement is seen as the most challenging in terms of scalability and flexibility for an industrial setting.	T5.6
Tools / Tool chains					
R195-D5.1-U3-11	Edge focused research and development will be conducted using the SoC-FPGA devices. This work will investigate both local (user-end) and remote (CoBot-end) edge-based teleoperation and AI processing in the context of the use case. ***DT\VR:*** *Once the role of the DT\VR is clearly defined then there is a requirement that it is seamlessly integrated into related UC3 toolchains etc.*	M	I-D	Req-D2.3-U3-1-hw-sw-com As discussed above this is very much an evolving requirement for the DT\VR	T5.6
R196-D5.1-U3-12	The UR16e API and related SDKs are to be utilised throughout the use case in the development of all required functionality. ***DT\VR:*** *There is a requirement to research and engineer how the CoBot UR16e will be represented in the DT\VR and how the CoBot coordinate*	M	I-D	Req-D2.3-U3-2-sw-com	T5.6

	data will be consumed and utilised in the DT\VR.				
R197-D5.1-U3-13	Produce several use case related data sets incorporating HMI (tactile glove) and ToF (depth camera) sensor data streams to be used for AI/ML/RL tools and algorithm research and development work. ***DT\VR:*** *There is a specific requirement to define how the DT\VR can be used to assist in the generation of sensor input datasets. Also, specific requirements are required in relation to the processing or post-processing of sensor data streams by the DT\VR.*	M	I-D	Req-D2.3-U3-3-sw This requirement directly relates to the role of the DT\VR in the generation of datasets for AI research and developments for tele-operations.	T5.6
R198-D5.1-U3-14	Investigative research into DT/VR/AR features which will be incorporated into the end-to-end tactile CoBot teleoperations system.	C/W	I	Req-D2.3-U3-4-sw-com	T5.6
R199-D5.1-U3-14	Several use-case related data sets from latest generation ultra-low power accelerometers, to assess suitability for gesture recognition. ***DT\VR:*** *This requirement has evolved from gesture recognition to incorporate full arm, wrist and hand movements. In a DT\VR context there is a requirement to investigate the human in the loop here and to identify how*	C	I-D	Req- D2.3-U3-5-hw This requirement mainly relates to how the real-world in an industry 4.X setting is formally represented in the DT\VR world.	T5.6

	the human tele-operation task is formally represented in the DT\VR world and to identify if it is at the local, remote, or indeed both ends of the tele-operation process.				

9. Conclusion

D5.1 provides a revision of the shortcomings, state-of-the-art and contributions of IMOCO4.E related to digital twin methods at system level. The focus of D5.1 is on Layer 1, 2, 3 & 4 – Pilot 1, 2, 3, 4 & 5 – Use Case 1, 2 & 3 and Demonstrator 1 & 3. There are different technologies and approaches that are introduced that will be the core of WP5. It is also illustrated how these different components are connected to different BBs (mainly BB1, BB6, BB8, BB9 and BB10).

D5.1 also integrates the generic requirements related to each BB (mainly BB1, BB6, BB8, BB9 and BB10, in this order) gathered from D2.3 and D7.1. Then more specific requirements are introduced related to identified shortcomings of current approach and state-of-the-art. D5.1 also outlines how IMOCO4.E will address these identified shortcomings and necessities for the future with specific contributions beyond the state of the art.

During the preparation of this deliverable one important thing attracted our attention. We have realized that the understanding of the definition of digital twin is different among partners. During the plenary meeting and also during our regular teleconferences of the project, we came across this issue, and we somehow put the understanding on the same ground and did define digital twin as per the Figure 1.

In this first iteration we did capture all possible requirements from the partners that will be used in the development of digital twins and serve the purpose of Pilots, Use Cases, Demonstrations. Still, there are few possible requirements left and that is what we are going to focus on our next iteration of this deliverable which is D5.2. Other than these requirements, we will focus on collecting those requirements that partners has realized during the development (as development of digital twins did get started in few of the cases) and not been mentioned in this report.

In this deliverable along with D5.2, our motive is to provide a very specific document to the industry that defines requirements and specifications on digital twin and their components and how to develop those to serve their purpose.

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