Intelligent Motion Control under Industry 4.E

D3.2 Perception and instrumentation:
Layer 1: requirements and specifications
(Final Version, V1.0)

Due Date: M18 – 2023-02-28

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Abstract:

From the IMOCO4.E Use-cases, Pilots and Demos obtained, global requirements need to be derived which will serve as constraints for the development of new AI and near-to-the-edge hardware and instrumentation at Layer 1: sensor and actuator development and their design needs to be aimed on the interaction with the higher layer levels: 2, 3 to 4. It poses requirements in the embedded software stack to enable compatibility and hardware-software co-development.

From the IMOCO4.E Use-cases, Pilots and Demos information observed, it can be noted that the divergence in requirements is large, in particular when centralized controlled motion is compared to smart distributed sensing, smart distributed control and smart distributed actuation. Also, the level of interfacing is (still) broad, varying from analogue (0-10 volts, 4-20 mA), to SPI, USB and all kinds of other digital interfaces. The main backbone communication is via EtherCAT or CAN-Open (or similar real-time bus up to DMA).

The variety in the required control loop speed is large too: ITEC doing 100 kU/hour down to vibration and swing control of a few Hz. The requirement for consumed power is limited by the battery-operated sensors systems versus the wired or contactless powered sensor applications.

What is an open issue is the amount of 'new' data that is required from the sensors and actuators beyond the functional set-point data exchange. This kind of data will be required for BB-5 to BB-9 and needs to be developed i.e., integrated into new hardware layer designs. Furthermore, representative sensors and actuators behavior models are needed to enable realistic Digital Twin models.

How smart does a sensor, encoder, controller, drive and actuator need to (or can) be to create motion systems more effectively and suited for AI and Digital Twining? The design platform and architecture need to be changed accordingly and many of the BB defined need to be re-defined (and re-developed or adjusted) with the second revision.

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BUT	Requirements definition on Layer 1 concerning low power wireless vibration sensors development for UC1 together with Gefran
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IML	Submitted content for Layer 1/3 and Demonstrator 3.
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INL/ECS	Submitted content for BB1 and Demonstrator 2
ITEC	Requirements gathering, classification and coordination. Provided Pilot 2 content.
OROLIA	Submitted content for BB1 the 23rd of December 2022.
EVI	Extended requirements concerning Pilot 3
Tyndall (TNI\UCC) ADI, EMD	Submitted content for Use Case 3 (UC3) on Tuesday 20th December 2022.

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Abbreviations

Abbreviation	**Explanation**
3D	3 Dimension
ADAT	Automatic Die Attach
AGV	Autonomous Ground Vehicle
AMC2	Access Modular Controller
AI	Artificial Intelligence
API	Application Programming Interface
BBx (e.g., BB1)	Building Block x (e.g., Building Block 1)
CAD	Computer-Aided Design
CAN-OPEN	Controller Area Network – the Open Communication Solution Dissemination Project
CD	Continuous Development
CI	Continuous Integration
CNC	Computer Numerical Control
COTS	Commercial Off-The-Shelf
DC	Direct Current
DevOps	Development Operations
DoF	Degree-of-Freedom
DMS	Distributed Message Service
DT	Digital Twin
DTA	Digital Twin Aggregation
DTI	Digital Twin Instance
DVC	Data Version Control
Dx.x (e.g., D2.4)	Deliverable x.x (e.g., Deliverable 2.3)
EtherCAT	Ethernet for Control Automation Technology
ERP	Enterprise Resource Planning
FB	Feedback
FPGA	Field Programmable Gate Array
GAN	Generative Adversarial Network
GUI	Graphical User Interface
HMI	Human-Machine Interface
HTTP	HyperText Transfer Protocol
HW	Hardware
I/O	Input/Output
IMOCO4.E	Intelligent Motion Control under Industry 4.E
IPC	Industrial Personal Computer
IRT	Isochronous Real Time
IT	Information Technology
LIDAR	LIght Detection And Ranging

LIMS	Laboratory Information Management Systems
MBSE	Model-Based Systems Engineering
MCP	Motion Control Platform
MES	Manufacturing Execution System
MIMO	Multi-Input Multi-Output
ML	Machine Learning
MLOps	Machine Learning Operations
MQTT	Message Queuing Telemetry Transport
M&E	Motor and Encoder
NFC	Near Field Communication
OPC-UA	Open Platform Communications – Unified Architecture
PC	Personal Computer
PHP	Hypertext Preprocessor
PIL	Processor-in-the-Loop
PL	Performance Level
PLC	Programmable Logic Controller
QA	Quality Assurance
REST	REpresentational State Transfer
RFID	Radio-Frequency Identification
RGB-D	Red, Green Blue – Depth
RL	Reinforcement Learning
ROS	Robot Operating System
RTOS	Real-Time Operating System
R&D	Research & Development
SaaS	Software-as-a-Service
SAP	Systems, Applications and Products in data processing
SCADA	Supervisory Control and Data Acquisition
SE	System Exploitation
SI	System Integration
SILx (e.g., SIL3)	Safety Integrity Level x
SLAM	Simultaneous Localization And Mapping
SO	System Operational
SoC	System-on-Chip
SPI	Serial Peripheral Interface
ST	Scientific and Technological
SW	Software
TCP/IP	Transmission Control Protocol/ Internet Protocol
TOF	Time-of-Flight
TSN	Time-Sensitive Networking
UCx (e.g., UC3)	Use Case x (e.g., Use Case 3)
UI	User Interface

UPS	Uninterrupted Power Supply
USB	Universal Serial Bus
VR	Virtual Reality
WAN	Wide Area Network
WLAN	Wireless Local Area Network
WPx (e.g., WP2)	Work Package x (e.g., Work Package 2)
XIL	X-in-the-Loop
.NET	Network Enabled Technologies

Executive Summary

Task 3.1 Instrumentation Layer requirements and specifications

(Leader: **EMC**; involved: SCC, UWB, EDI, ROV, TUE, ING, TNL, GMV, ITML, INL, NXP, TECO, CNET, OE, TNO, ECS, UMO, EVI, IKE, COR, TNI, VIS)

The Aim of Work package 3 "Instrumentation Layer design and development" is dedicated to the development of smart sensing, actuating components, drive and control ECUs as new AI and near-to-the-edge hardware and instrumentation for the I-MOCO4.E platform (the 'Layer 1' elements) and their proper interconnection with the higher levels of the motion control system. It deals with novel communication interfaces for fast and reliable data acquisition by means of various wired and wireless sensors providing high fidelity information about the actual state of the controlled plant. Power electronics and low-level control of various actuator types will be developed as well. The Instrumentation Layer building blocks lay foundations for the employment of advanced software algorithms of the higher Motion Control Layer which are pursued in WP4.

Task 3.1 will precise and update the instrumentation layer requirements briefly sketched in Task 2.3 and 2.4. The task outputs will also be influenced by communication with both consortium and external industrial partners (through WP2). The collected requirements will grow into detailed specifications on Instrumentation layer (**D3.1**, D3.2 - iterative process described in Task 2.3). The final requirements: D3.2, are tightly related to the pilot, demo and use-case application needs (outputs of Task 7.1) and to the initial testing results of BB sub-systems (partly adopted from liked projects) as outputs from Tasks 6.2 and 6.3. The work of WP3 will be broken into the following subtasks:

1. Analysis of interaction/ interferences with other mature facilities and equipment (i.e., re-used existing modules i.e., OEM and COTS modules and components)
2. Requirements and specifications for signal and image processing algorithms based on relevant pilots, further linked to Task 3.3 (UWB, EDI, TUE, TNL, ITML, CNET, GEF, IKE, TNI)
3. Requirements and specifications for sensors (e.g., velocity, acceleration, acoustic, cameras, etc.) and actuators (e.g., piezo movers, reluctance actuators, etc.), further linked to Task 3.2 (INL, EMC, ECS, SIE, TNO, OE)
4. Wireless requirements analysis and technology evaluation, specification for robust and reliable WSN, further linked to Task 3.4 (UWB, EDI, TNL, INL, OE, ECS, UMO, IKE, COR, TNI, VIS)
5. Requirements and specifications for high-speed vision sub-components, further linked to Task 3.5 (TNO, SCC, UWB, INL, NXP, UMO)
6. Requirements and specification for smart servo drive ECUs, further linked to Task 3.6 (SCC, ING, TNL, EMC)
7. Requirements and specification for multi-many-core embedded control HW, further linked to Task 3.7 (SCC, TUE, ING, TNL, FAG, NXP, SIE, IMA, UMO, EVI)

1. Introduction

1.1 Purpose of the Document

The purpose of the document is to collect the foreseen needs in specifications and requirements for Layer 1: "Instrumentation Layer design and development". Task 3.1 is dedicated to the development of smart sensing and actuating components and drive ECUs of the IMOCO4.E platform (the 'Layer 1' elements) and their proper interconnection with the higher levels of the motion control system, including the behavior modeling (if necessary) to be used with the Digital Twin simulation environment.

1.2 Structure of the Document

The initial structure of the document is straight forward means to collect the requirements and specifications of the partners involved. In this second part of task 3.1, the requirements and specifications will be grouped for the partners dealing with the developments in WP3.

1.3 Requirements gathering process

The partners of all IMOCO4.E Pilots, Demos and Use-cases, who have dedicated needs w.r.t. the Layer 1 developed components, to be incorporated in their Pilots, Demos and Use-Cases applications, either OEM, COTS or dedicated developed, have contributed to this task.

Based on the least common nominator of these collected requirements, a selection shall be made w.r.t. the requirements which can be implemented by the partners involved in the development of Layer 1 contributions.

1.4 Intended readership

During the process of gathering the specifications and requirements all partners of IMOCO4.E are requested to read and give their input and comments on this document. Thereafter, the resulting and condensed specifications and requirements will be leading for the partners involved in WP-3. Furthermore, all partners of IMOCO4.E will be informed about which specifications and requirements will most likely be met and which specifications and requirements need to be resolved in another manner.

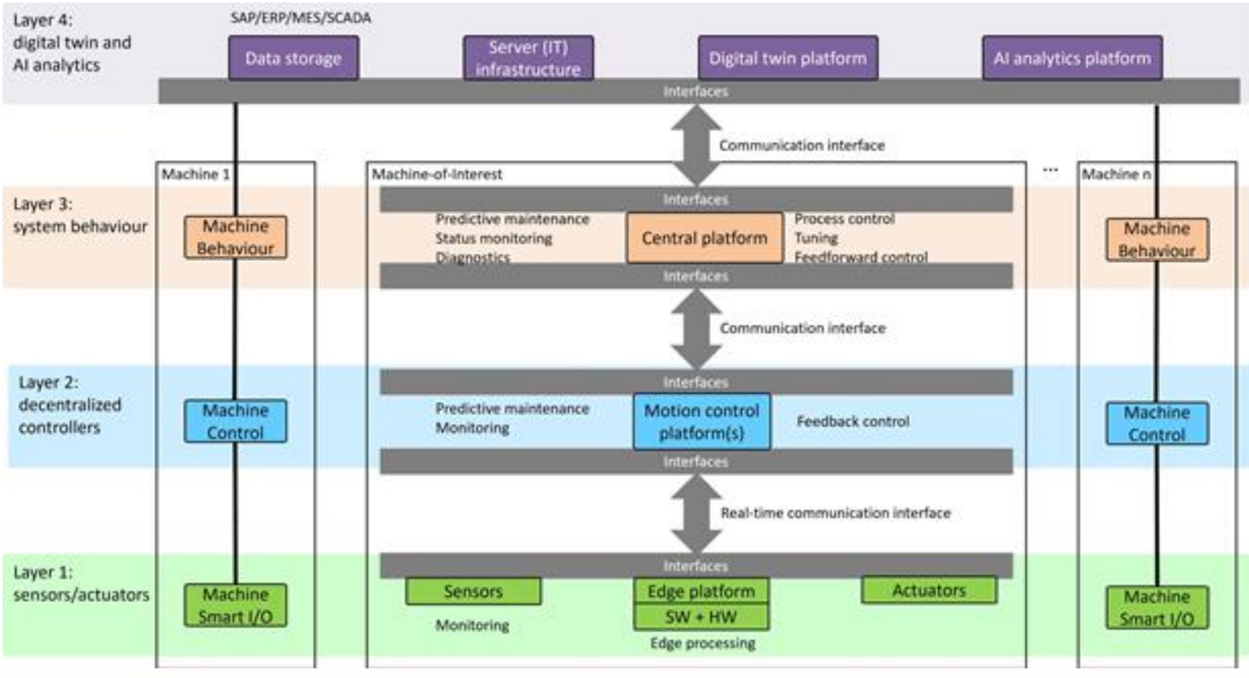

Figure 1.1 – IMOCO4.E framework

2. Requirements specification for IMOCO4.E

2.1 Requirements gathering process

During the first few months of the project, the specifications and requirements were vague, leading to the initial deliverable D3.1. Now, halfway through the project, these specification and requirements have become clearer, such that the developments can follow these tighter specification and requirements of smart sensing and actuating components and drive ECUs of the IMOCO4.E platform, leading to this deliverable D3.2. It is intended to have an updated version when entering the final stage of the project to reflect the progress and implementation of these hardware related specifications and requirements.

N.B. This 3rd deliverable (D3.3) is not foreseen in the master project plan for IMOCO4.E.

2.2 Instrument layer requirements classification

The requirements are classified using the following characteristics (partially derived from the ISO 25010 standard on software and data quality):

1. Interfaces and connectivity
2. Maintainability - represents the degree of effectiveness and efficiency with which a product or system can be modified to improve it, correct it or adapt it to changes in environment, and in requirements. This characteristic is composed of the following sub-characteristics:
    a. Modularity - A system is modular when it can be decomposed into several components that may be mixed and matched in a variety of configurations. The components can connect, interact, or exchange resources, by adhering to a standardized interface.
    b. Analysability -
    c. Testability -

3. Performance
4. Compatibility - Degree to which a product, system or component can exchange information with other products, systems or components, and/or perform its required functions while sharing the same hardware or software environment.
    a. Interoperability - Degree to which two or more systems, products or components can exchange information and use the information that has been exchanged.
    b. Co-existence
5. Usability - Degree to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.
    a. Operability - Degree to which a product or system has attributes that make it easy to operate and control.
6. Reliability - Degree to which a system, product or component performs specified functions under specified conditions for a specified period of time.
7. Security - Degree to which a product or system protects information and data so that persons or other products or systems have the degree of data access appropriate to their types and levels of authorization.
8. Portability - IMOCO4.E methodology will enable each machine to maintain excellent performance under slight variations in machine conditions, with the use of ML and advanced learning control. This enables the portability of production processes across multiple machines, since processes will run almost identically on these machines.
    a. Adaptability - Degree to which a product or system can effectively and efficiently be adapted for different or evolving hardware, software or other operational or usage environments.
9. Cost
10. Scalability
11. Tools/toolchains
12. Safety

Note: For future projects it may be better to have the task ID instead of the deliverable ID, since the deliverables get different updated indexes and keep previous requirements, this will mix-up different indexes.

2.3 Requirement coding scheme

Each requirement ID is prefixed with Req-, the deliverable ID (D3.1/ D3.2 for this deliverable), the applicable IMOCO4.E relation(s),

- Lx: layer x
- Bx: BB x
- Px: pilot x
- Dx: demonstrator x
- Ux: use-case x

the optional reference framework-specific relation,

- hw: hardware
- sw: software
- fw: firmware

- com: communication

and the optional requirement classifier.

- SAF: safety
- SEC: security
- DAT: data protection

E.g., Req-D3.1-L1-1, Req-D3.1-P2-hw-SAF-2, Req-D3.1-P2-3. In case of multiple identical codes from the various tasks, a common nominator shall be defined which covers all 'interrelated' requirements.

We make sure that the requirement IDs are unique so that the other deliverables can reference the defined requirement IDs within the IMOCO4.E project.

The requirements are prioritised through the 'MoSCoW' method.

- M: must have (necessary requirements for the IMOCO4.E project)
- S: should have (additional desired requirements with high priority)
- C: could have (additional requirements with low priority)
- W: would have (future requirements, ideally after the completion of the IMOCO4.E project)

We consider the following requirement verification methods:

- I: inspection (observation using basic senses)
- D: demonstration (use the system as it is intended)
- T: test (more precise and controlled demonstration using scientific principles and procedures)
- A: analysis (validation of the system by scientific methods)

The expected technical maturity will be quantified using the technology readiness level (TRL) criteria.

	TRL	Description
Research	1	Basic principles observed
	2	Technology concept formulated
	3	Experimental proof of concept
Development	4	Technology validated in lab
	5	Technology validated in (industrially) relevant environment
	6	Technology demonstrated in (industrially) relevant environment
Deployment	7	System prototype demonstration in operational environment
	8	System complete and qualified
	9	Actual system proven in operational environment

3. System-level requirements

Should we have IMOCO4.E specific requirements or are these to be copied from COTS devices? The main differences are the smartness of the devices, the need for recognition, latency, cyber-security and their parallelism to enable DT, near-to-the-edge modelling, machine learning and AI.

3.1 Architectural requirements on Layer 1

3.1.1 Requirements on layer 1: Sensors, Actuators and Network

Table 3.1- Requirements on layer 1 – sensors, actuators and networks

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D3.1-L1-hw	Used vision sensors are easy to connect to a PC-based processing unit (USB2, USB3)	S	I	EDI	
Req-D3.1-L1-D2-hw	Sensors must have a reader/ controller connected to upper layers (through BB1 or BB4) by USB or Ethernet	S	I	INL/ECS, UWB, EVI	T3.3, T3.2
Req-D3.2-L1-hw-01	Devices for vibration sensing should have wireless interface, e.g., BLE.	S	D	BUT, UWB	T3.2
Req-D3.2-L1-hw-02	Radar sensor has a data interface via Ethernet or USB. Ethernet is preferred.	M	T	IMST	T3.2

Maintainability (modularity, analyzability, testability)					
Req-D3.2-L1-fw-03	Firmware of sensor can be updated via Ethernet or USB interface.	S	T	IMST	T4.5
Performance					
Req-D3.2-D3-hw	Antenna parameters for the new front end: elevation angle, MIMO configuration. 10 dB angle limit for the field of view.	M	T	IMST	T3.2
Req-D3.1-L1-hw	Robotic gripper and motors able to hold weight at least 0,2 kg	M	D	EDI	
Req-D3.1-D2	Sensors must be able to read temperature within the range -40 to 85 ºC with at least ±0.5 ºC accuracy and in the range 0 ºC to 45 ºC with at least 0.3 ºC accuracy.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Sensors must be able to read variations of pressure and temperature, at least 10 Hz.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Pressure and temperature measurement data must be communicated, at least 1 Hz.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Sensors must stand the injection molding pressure and temperature.	M	T	INL/ECS	T3.2, T7.2.2
Req-D3.2-L1-hw	Used camera needs to provide RGB images.	M	I	IML	T3.4
Req-D3.2-L1-hw-04	The vibration sensing device should have measurement resolution of at least 0.01 m/s^2, at least measurement range +/-4 g and maximal supported acceleration above 20 g.	S	D	BUT, UWB	T3.2
Req-D3.2-L1-hw-05	Device for vibration sensing should be capable of achieving minimum sampling period 1 ms.	S	D	BUT, UWB	T3.2
Req-D3.2-L1-hw-06	Device for vibration sensing should be able to activate measurement by motion and/or vibrations.	S	D	BUT	T3.2
Req-D3.2-L1-hw-07	Device for vibration sensing could have simple controls (buttons) on the device for	C	D	BUT	T3.2

	basic settings (e.g., on/off, reset).				
Req-D3.2-L1-hw-08	Device for motion sensing must provide data with lowest possible latency (below 500us) to allow feedback control.	S	D	UWB	T3.2
Req-D3.2-D3-hw	Sensors can detect static and moving targets at a maximum distance of at least 8 meters in an indoor environment.	S	T	IMST	T3.2
Req-D3.2-D3-hw	A fitting Radome covers the upper PCB without causing an average loss of >3dB.	S	T	IMST	T3.2
Compatibility (interoperability, co-existence)					
Req-D3.2-L1-hw-09	Transmitting hardware in device for vibration sensing should be compatible with receiver based on ESP32 system.	S	I	BUT	T3.2
Req-D3.2-L1-hw-10	Transmitting hardware in device for vibration sensing should be compatible BLE version 5.0 or newer.	S	I	BUT	T3.2
Req-D7.10-P3-fw-117	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
Req-D7.10-P3-fw-201	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 or different modelling approaches	T3.2 (T5.2) (T3.4) (T5.7) (T6.7)
Usability (operability)					
Req-D3.1-D2	Sensors must be fitted on the tool molding area.	M	I	INL/ECS	T3.2, T7.2.2

Req-D3.2-L1-hw-xx	Device for vibration sensing should be able to record at least 1M of time data points for further data processing.	S	I	BUT	T3.2
Req-D3.2-L1-hw-xx	Device for vibration sensing could be operatable in industrial environment conditions, according to EN 50178.	C	I	BUT/GEFRAN, UWB	T3.2
Req-D3.2-L1-hw-xx	Device for vibration sensing would have ingress protection of level IP 54.	W	I	BUT/GEFRAN	T3.2
Req-D3.2-L1-hw-xx	Device for motion sensing should have ingression protection of level IP 68.	S	I	UWB	T3.2
Req-D7.10-P3-hw-15	Perception functionalities to enable automatic adjustment of machine behaviour (BB2) **GA type**: Functional (AI) **BBs**: BB2 **Layers**: L1 **WP5 sub-type**: Capability **Parent REQ**: [Goal Req-D7.10-P3-3]	M	D	Related to vision camera of BB2	T3.2
Req-D7.10-P3-hw-16	Perception functionalities to enable automatic adjustment of machine behaviour (BB3) **GA type**: Functional (AI) **BBs**: BB3 **Layers**: L1 **WP5 sub-type**: Capability **Parent REQ**: [Goal Req-D7.10-P3-3]	S	D	To be investigated (there is some interesting sensor that may be used to generate/collect data to implement the alarm detection & classification scenarios?) Currently not considered	
Reliability (fault tolerance, availability)					
Req-D3.2-L1-hw-17	Device for vibration sensing would be able to operate for at least 10 years.	W	I	BUT/GEFRAN	T3.2
Req-D3.2-L1-hw-18	Device for vibration sensing could perform internal self-calibration and self-diagnostics to be able to detect internal fault of the device and report it to the upper layer device.	C	I	BUT/GEFRAN	T3.2

Security (cyber-security, integrity, confidentiality, authenticity)					
Req-D7.10-P3-SEC-112	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
Req-D7.10-P3-SEC-113	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)					
Req-D3.2-L1-hw-19	Device for vibration sensing should be portable to be able to mount it freely on the lift cabin or use it during routine-based inspection, e.g., with weight of 100 grams or lower.	S	D	BUT	T3.2
Req-D3.2-L1-hw-20	Device for vibration sensing would be able to perform firmware updates through wireless connection or galvanic interface (e.g., USB).	W	I	BUT/GEFRAN, UWB	T3.2
Req-D3.2-L1-hw-21	Device for motion sensing must support wireless charging (to allow molding with IP68)	M	I	UWB	T3.2
Cost					
Scalability					
Tools/toolchains					
Safety					

3.1.1 Requirements on layer 2

Non-specific.

3.1.2 Requirements on layer 3

Table 3.2 - Requirements on layer 3 – system behavior layer

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Maintainability (modularity, analyzability, testability)					
Req-D2.3/D3.1-L3-D4	Systems perception models should be retrainable by a non-Machine Learning expert.	S	D	EDI	
Performance					
Compatibility (interoperability, co-existence)					
Usability (operability)					
Req-D3.1-L3-sw	The perception model should handle as less different data as possible (input: img-data + optional depth data; output: pose)	S	T	IML	T3.4
Reliability (fault tolerance, availability)					
Security (cyber-security, integrity, confidentiality, authenticity)					
Portability (adaptability, replaceability)					
Cost					
Scalability					
Tools/toolchains					
Safety					

3.2 Connectivity requirements

System-to-system connectivity between layers and systems shall be optimized to limit the bandwidth needed and to obtain safe i.e., tolerable latency. Some latency may be a time lost in the smart device itself, due to the processing of the information at that level. With time-critical processes, the use of time stamping is inevitable.

Connectivity to machines may be wired or wireless again determined by the latency and/or the loss of the wireless link, due to interference or jamming. With friction and mass critical designs, the cable stiffness, device volume or weight of the communication interface is the crucial and dominant.

Wireless data transfer will be slightly faster than wired; 3 versus (typical) 7 ns/m of propagation delay, but the transfer from the electrical to the optical or RF domain and vice-versa will be more time consuming than using straight electrical interfaces. However, while going to the Gb/s data transfer over a single wire-pair, the signal losses will be high too, with the necessity for cable loss correction and/or data reconstruction.

4. Building block requirements

4.1. BB1

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D2.3	The interfaces to BB1 shall be an industry standard (such as USB, Ethernet, expansion port or optical fiber connectors).	M	I		T3.1
Req-D2.3	BB1 shall support standard and vendor-neutral Wired 1G Ethernet.	M	I		T3.3, T3.4
Req-D2.3	BB1 should have an interface with camera sensors.	M	T		T3.4
Req-D2.3	BB1 should have enough memory to allow for buffering more than 6 images from the camera sensors.	M	T		T3.4
Req-D3.2-B1	Sensors could be connected to other devices using wireless interfaces.	C	D	To be considered or discarded by stakeholders. NEW	T3.1, T3.2
Maintainability (modularity, analyzability, testability)					
Req-D3.2-B1	The device's firmware should be able to be updated using the defined interfaces.	S	D	To be considered or discarded by stakeholders. NEW	T3.1, T3.2
Req-D3.2-B1	Continuous monitoring of the hardware to find faulty behaviours.	C	T	To be considered or discarded by stakeholders. NEW	T3.1, T3.2
Performance					
Req-D2.3	End to End deterministic latency for time constrained TSN data streams.	M	T		T3.1
Req-D2.3	Delivery guarantee for rate constrained TSN data streams.	M	T		T3.1
Req-D2.3 or D3.1	The interface to/from BB1 shall support update rates of at least 20 kHz to layer 2 and/or BBs.	M	D		T3.1
Req-D3.2-B1	Deterministic communication should be maintained to transmit the signals from the sensors and actuators (implemented with sampling frequency sensors or regular actuator commands).	S	D	To be considered or discarded by stakeholders. NEW	T3.1, T3.5
Compatibility (interoperability, co-existence)					

Req-D3.2-B1	Sensors and actuators used together must have low interference with each other. Wireless sensors require dedicated frequency bands or interoperable protocols.	M	D	To be considered or discarded by stakeholders. NEW	T3.2, T3.5
Req-D3.2-B1	Devices must have a compatible range of working signals, such as similar voltage levels.	S	D	To be considered or discarded by stakeholders. NEW	T3.1
Usability (operability)					
Req-D2.3	BB1 shall have a configuration interface to modify all (pre-defined) configuration parameters without requiring firmware changes.	M	D		T3.1
Reliability (fault tolerance, availability)					
Req-D3.2-B1	Sensors and actuators should be self-calibrated, or factory calibrated.	S	T	To be considered or discarded by stakeholders. NEW	T3.2, T3.5
Req-D3.2-B1	Include redundant sensors to ensure fault tolerance.	C	D	To be considered or discarded by stakeholders. NEW	T3.1
Security (cyber-security, integrity, confidentiality, authenticity)					
Req-D3.2-B1	Wireless broadcast signals should be encrypted to ensure the security of signals.	S	D	To be considered or discarded by stakeholders. NEW	T3.1, T3.2
Portability (adaptability, replaceability)					
Cost					
Scalability					
Req-D2.3	BB1 shall offer a scalable number of computational resources, e.g., by means of the firmware implementation or by offering a family of processing units with different capacities.	M	D		T3.1
Tools/toolchains					
Safety					

4.2. BB3

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					

Req-D3.1-D2	Controller must provide communication and power supply, both wireless.	M	D	INL/ECS	T3.3
Maintainability (modularity, analyzability, testability)					
Performance					
Req-D3.1 - D3-hw	Antenna parameters for the new front end: elevation angle, MIMO configuration. 10 dB angle limit for the field of view.	M	T	IMST	T3.2
Req-D3.1-D2	Sensors must be able to read temperature within the range -40 to 85 ºC with at least ±0.5 ºC accuracy and in the range 0 ºC to 45 ºC with at least 0.3 ºC accuracy.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Sensors must be able to read variations of pressure and temperature, at least 10 Hz.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Pressure and temperature measurement data must be communicated at least 1 Hz.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Sensors must stand the injection molding pressure and temperature.	M	T	INL/ECS	T3.2, T7.2.2
Compatibility (interoperability, co-existence)					
Usability (operability)					
Req-D3.1-D2	Sensors must be fitted on the tool molding area.	M	I	INL/ECS	T3.2, T7.2.2
Reliability (fault tolerance, availability)					
Security (cyber-security, integrity, confidentiality, authenticity)					
Portability (adaptability, replaceability)					
Cost					
Scalability					
Tools/toolchains					

Safety					

4.3. BB8

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Maintainability (modularity, analyzability, testability)					
Performance					
Req-D2.3/D3.1-B8-D4	Sim2Real transfer provides synthetically trained object detection algorithms that detect objects of interest in 80% of images with said objects	S	D	EDI	
Compatibility (interoperability, co-existence)					
Usability (operability)					
Reliability (fault tolerance, availability)					
Security (cyber-security, integrity, confidentiality, authenticity)					
Portability (adaptability, replaceability)					
Cost					
Scalability					
Tools/toolchains					
Safety					

4.4. BB9

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D5.1-B9	Support real-time information exchange with a protocol based on message set abstraction (publish/subscribe model) that can handle parallel data streams between multiple endpoints	M	D		T5.2
Req-D5.1-B9	BB9 will be able to aggregate, transform and fuse incoming text-based data from multiple	M	D		T5.2

	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).				
Req-D5.1-B9	BB9 will provide persistent storage for the aggregated and fused data (see R048-D5.1-B9) in the cloud infrastructure (historical data).	M	D		T5.2
Req-D5.1-B9	BB9 will allow all authorized components to access incoming data streams collected from multiple sources (see R048-D5.1-B9) in real-time via a dedicated API.	M	D		T5.2
Req-D5.1-B9	BB9 will allow all authorized components to access historical data stored in the cloud infrastructure (see R049-D5.1-B9) via a dedicated API.	M	D		T5.2
Req-D5.1-B9-sw	BB9 architecture to be based on microservices to be delivered in containerized form and deployed on the edge/cloud (e.g., using Docker/Kubernetes cluster)	S	D		T5.2
Req-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
Req-D5.1-B9	Support real-time information exchange with a protocol based on message set abstraction (publish/subscribe model) that can handle parallel data streams between multiple endpoints	M	D		T5.2
Performance					
Req-D5.1	BB9 must be able to generate alerts in real-time (e.g., related to supported cyber-security threat detection, see R063-D5.1-B9).	M	D		T5.2
Req-D5.1-B9	All used libraries/frameworks/components must not have known security vulnerabilities nor infringement	S	D		T5.2

	of (open source) license conditions.				
Usability (operability)					
Req-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)					
Req-D5.1-B9	BB9 will be able to continue operating despite receiving and processing invalid or wrong data.	S	D		T5.2
Req-D5.1-B9	Only authorized users will be allowed to access the system.	S	D		T5.2
Req-D5.1-B9	BB9 will provide high computing availability, having a continuous, uninterrupted, fault-tolerant operation.	S	D		T5.2
Security					
Req-D5.1-B9	Data security will be ensured at rest and in flight.	S	D		T5.2
Req-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
Req-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
Req-D5.1-B9	The system will alert the user if any supported cyber-security threat and vulnerability is detected and present an assessment (see R063-D5.1-B9).	S	D		T5.2
Safety					
Req-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					
Req-D5.1-B9	BB9 will be fully scalable so that it can easily be adapted to new integration needs or changes in performance,	S	D		T5.2

	reliability, and data volume requirements.				
Tools/toolchains					
Req-D5.1-B9	A GUI will be provided for configuration purposes of BB9.	C	D		T5.2
Req-D5.1-B9	BB9 will provide an appropriate dashboard for visualizing data and providing insight related to the operation of BB9 (e.g., system health status, data traffic, performance metrics, alerts)	C	D		T5.2

4.5. BB10

For the topic "Intelligent motion control", the requirements for Demo 3 and BB10 correspond. The descriptions can therefore be found under Demo 3

5. Pilot requirements

5.1 Pilot 1

No input received.

5.2 Pilot 2

Table 2. Pilot 2 requirements

ID	Requirement	Priority	Verify	Comments
Req-D3.1-P2-01	Operating temperature (in Celsius): +20 - +24	M	D	Typical working temperature for semiconductor equipment
Req-D3.1-P2-02	**Control sample rate** Min – 8 kHz Max – 20 kHz	M	T	
Req-D3.1-P2-03	**Machine throughput** Min – 60 kUPH Max – 100 kUPH (36 ms per unit)	M C	T	
Req-D3.1-P2-04	Machine assembly precision <6 um 1 sigma <3 um 1 sigma	M C	T	

5.3 Pilot 3

No input received.

5.4 Pilot 4

In Pilot 4 the main hardware and instrumentation at Layer 1 was already realized during the predecessor project of IMOCO4.E (I-Mech). During this project an EtherCAT motion drive was developed, which allows for extensive monitoring and collection of high frequency motion data. In IMOCO4.E this motion data will be a main source of data.

With the layer 1 developments from I-Mech available, there were no activities on layer 1 planned for Pilot 4 within IMOCO4.E. However, as part of BB10, we want to explore possibilities of path planning on Pilot 4 and potentially extend it with sensor information to enable collision avoidance. For this sensor the requirements are described in the table below.

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D3.2-P4-com	Sensors shall provide industry standard wired interface for data exchange (e.g., EtherCAT, Ethernet or USB).	M	I		T3.2

Req-D3.2-P4-hw	The sensor shall not require a power supply voltage greater than 24Vdc.	M	I		T3.2
Maintainability (modularity, analyzability, testability)					
Req-D3.2-P4-sw	if the sensor has some form of onboard "AI" processing that determines its output, the "raw" data of the sensor shall be traceable for analysis.	C	I/D		T3.2
Performance					
Req-D3.2-P4-hw	The sensor shall update obstacle data with at least 5Hz.	S	I/D		T3.2
Req-D3.2-P4-hw	Within 1.5m distance the sensor will detect obstacles of at least 10cm in size with an accuracy of at least 5cm.	S	T		T3.2
Compatibility (interoperability, co-existence)					
Usability (operability)					
Reliability (fault tolerance, availability)					
Security (cyber-security, integrity, confidentiality, authenticity)					
Portability (adaptability, replaceability)					
Cost					
Scalability					
Tools/toolchains					
Req-D3.2-P4-sw	The sensor shall have a model implementation in a virtual environment to enable offline testing.	S/C	D		T3.2
Safety					
Req-D3.2-P4-hw/sw	The sensor shall fault safe. This means that by output of the sensor the receiver of the data can determine that the sensor is in a fault state (e.g., a watchdog signal or checksum mismatch)	S/C	I		T3.2

5.5 Pilot 5

No input received.

6. Demonstrator requirements

6.1. Demonstrator 1

No input received.

6.2. Demonstrator 2

Demonstrator 2 relies mainly on BB3 (novel sensors). The main hardware and instrumentation at Layer 1 for this demonstrator are novel wireless self-powered sensors with pressure and temperature sensing functionality. The requirements for the sensors are described in the table below.

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D3.1-D2	Controller must provide communication and power supply, both wireless.	M	D	INL/ECS	T3.3
Maintainability (modularity, analyzability, testability)					
Performance					
Req-D3.1-D2	Sensors must be able to read temperature within the range -40 to 85 ºC with at least ± 0.5 ºC accuracy and in the range 0 ºC to 45 ºC with at least 0.3 ºC accuracy.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Sensors must be able to read variations of pressure and temperature, by at least 10 Hz.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Pressure and temperature measurement data must be communicated by at least 1 Hz.	M	T	INL/ECS	T3.2
Req-D3.1-D2	Sensors must stand the injection molding pressure and temperature.	M	T	INL/ECS	T3.2, T7.2.2
Compatibility (interoperability, co-existence)					
Usability (operability)					
Req-D3.1-D2	Sensors must be fitted on the tool molding area.	M	I	INL/ECS	T3.2, T7.2.2
Reliability (fault tolerance, availability)					
Security (cyber-security, integrity, confidentiality, authenticity)					

Portability (adaptability, replaceability)					
Cost					
Scalability					
Tools/toolchains					
Safety					

6.3. Demonstrator 3

The sensors and actors used in demonstrator 3 are separated into two groups:

1. Vehicle internal sensors and actors, which are part of a series vehicle. These sensors are based on the current state-of-the-art in vehicle control and not considered in IMOCO
2. Vehicle attached environment-sensing components (sensors). These are either part of the robotic extension kit of the series vehicle or introduced via IMOCO. These sensors are considered in the following.

The vehicle attached components (mainly sensors) stems from the component groups:

3. Radar-based sensors (as described in 6.3.1)
4. Camera-based sensors (see 6.3.2)
5. Lidar-based systems (see 6.3.3)

The demonstrator 3 operation environment – the warehouse – represents a highly distributed control problem in which many logistic operations are performed in parallel and by several mobile entities (workers, trucks of different types and manufactures). Consequently, the overall process control is distributed over different levels from the single entity up to the high-level warehouse control. This requires sensors with a high degree of interoperability as they have e.g., to provide data to the single truck (e. g. by wired connection) as well to an edge-cloud using robust, reliable as well as security or partly safe communication.

As all sensors groups represent different technology streams, they and their use in demonstrator 3 are roughly described separately in the following.

6.3.1. Radar based sensors

The following requirements for the radar system have been chosen by IMST in the first measurements. They are based on the discussion results with project partners. Further specifications can be done as soon as specific measurement scenarios are clear.

The ones to be clarified are:

- MIMO configuration for angular resolution in azimuth
- Opening angle in azimuth (10 dB)
- Height detection in elevation (for passage under a subway)
- Opening angle in elevation (10 dB)
- Radiated power (EIRP)

The radar should be able to face following scenarios at maximum given distance of 10 meters:

- Travel path limited by fixed/static equipment such as shelves, high storage, columns, etc.
- Obstacles in the travel path: people (moving, standing), people crossing the travel path, goods from the storage area, size and min./max. distance.
- Lateral paths and obstacles: Detection to be determined experimentally

6.3.2. Camera-based sensors

The main innovation in IMOCO referring to demonstrator 3 is made within this sensor group. Following the main research aspiration in AI, application of AI-methods (like DNNs) in done on visual image data mainly. Therefore, most of the requirements named below are focussing this sensor group.

6.3.3. Lidar-based sensors

This sensor group can be seen as the current industrial state-of-the-art for robotic environment sensors. Within IMOCO demonstrator 3 will partly make use of lidar based sensors, whereas they are not in the innovation focus of the demonstrator. Nevertheless, the main requirements relevant to this sensor group are given in the requirement table below.

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D3.2-D3-sw	A plugin must exist to use the cameras within the GStreamer framework.	M	I	IML	T3.4
Req-D3.1-D3-hw-x	2D lidar sensers shall provide an ethernet interface for configuration and data transfer	M	A	STILL	
Req-D3.1-D3-hw-x	2D lidar sensors shall provide industrial grade connection technology like M12 connectors.	M	I	STILL	
Req-D3.1-D3-sw-x	2D lidar sensors shall provide UDP communication for measurement data	M	I	STILL	
Req-D3.1-D3-hw-x	2D lidar sensors should be configurable completely by ethernet.	S		STILL	
Req-D3.1-D3-hw-x	The Edge Device shall be equipped with a high-speed Ethernet interface	M	A	STILL	
Maintainability (modularity, analyzability, testability)					

Req-D3.1-D3-hw-x	The system shall be easily accessible via over the air access	M	I	STILL	
Performance					
Req-D3.1 -D3-sw	Use of the 77-81 GHz band: 2 GHz in the first measurements.	S	D	IMST	T3.2
Req-D3.1-D3-sw	The perception model should work independent of different environments. In the best case without re-training.	S	T	IML	T3.4
Req-D3.1-D3-hw	The sensors shall capture Information in RGB format. Optionally, depth information shall be acquired. The acquisition rate shall be at least 10 frames per second.	M	D	STILL	
Req-D3.1-D3-hw	The camera resolution shall be at least 640x480	M	I	STILL	
Req-D3.1-D3-hw	The camera field of view shall be in a reasonable range to capture all surrounding objects in both driving directions (e.g., more than 60 degrees)	M	I	STILL	
Req-D3.1-D3-hw	The edge processing unit shall be able to infer state of the art deep neural network architecture with at least 5 frames per second.	M	D	STILL	
Req-D3.1-D3-hw	The environmental requirements for the camera and edge device shall fulfil current standards and guidelines for intralogistics usage.	M	I	STILL	
Compatibility (interoperability, co-existence)					
Req-D3.1-D3-hw	The vision-based solutions shouldn't require different cameras if possible.	S	I	IML	T3.4
Usability (operability)					
Req-D3.1 -D3	Definition of Measurement scenarios.	M	I	IMST	T3.2
Reliability (fault tolerance, availability)					

Req-D3.1-D3-sw	The perception model should work even with some dirt on the camera lens.	C	T	IML	T3.4
Security (cyber-security, integrity, confidentiality, authenticity)					
New	The edge device shall be protected against access from unauthorized users.	M	I	STILL	
Portability (adaptability, replaceability)					
Cost					
Scalability					
Tools/toolchains					
Req-D3.1-D3-sw	A programming interface and/or an interface to state-of-the-art robotic systems shall exist.	M	I	STILL	
Safety					

6.4. Demonstrator 4 - Vision-based (AI) pick & place robotics for randomly arranged and differently shaped bottles

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D2.3-D4	Screen and input HW for inspection and correction of perception and control modules	M	I		
Req-D2.3-D4	Internet connection for possibility to remotely inspect behaviour of perception and control modules	S	I		
Maintainability (modularity, analyzability, testability)					
Req-D2.3-D4	Demonstrator should be easily maintained by basic operators				
Performance					
Req-D2.3/D3.1-D4	Number of successful picks from a random pile in a minute up to 70	M	D		
Req-D2.3/D3.1-D4	95% successful placement of the bottle into a socket on first try	M	D		
Compatibility (interoperability, co-existence)					

Req-D2.3-D4	Demonstrator should be compatible with an existing production line	M	D		
Req-D2.3-D4	Demonstrator should be compact size	M	D		
Usability (operability)					
Reliability (fault tolerance, availability)					
Security (cyber-security, integrity, confidentiality, authenticity)					
Portability (adaptability, replaceability)					
Cost					
Req-D2.3-D4	Overall cost of deploying the demonstrator (without R&D) < 200,000 EUR	S	I		
Scalability					
	Demonstrator can be adjusted to several conveyors/ production lines	S	I		
Tools/toolchains					
Safety					

7. Use-case requirements

7.1. Use-case 1

No input received.

7.2. Use-case 2

No input received.

7.3. Use-case 3 – Tactile Robot Teleoperation

The Tactile Robot constitutes the next generation of collaborative robots, equipped with sensing capabilities to process humanlike tactile sensation. Human safety and labor/skill shortages in industry will be improved dramatically, as potentially dangerous, or complex operations involving inspection, repair, or even decommissioning, will be performed by a remotely controlled Tactile Robot.

The use case will implement safe remote teleoperation via a tactile robot. Humans in the loop will be considered through complex HMI coupled with a digital twin representation of the process implemented in virtual reality. The application will be enabled with high performance AI embedded close to the edge, mitigating motion control errors introduced because of sensor and user input limitations.

ID	Requirement	Priority	Verify	Comments	Tasks
Interfaces and connectivity					
Req-D3.2-U3-1-com	Connectivity of the communications interface for the PolarFire SoC-FPGA (MPFS250T-FCVG484EES) placed at the local user-end with the PolarFire SoC-FPGA (MPFS250T-FCVG484EES) placed at the remote CoBot-end.	M	I-D	This connects the local user end to the remote tele-operated robot using two PolarFire SoC-FPGA edge devices.	3.3
Req-D3.2-U3-2-com	Driver engineering for the RapID-NI-V2007 to interface the PolarFire SoC-FPGA (MPFS250T-FCVG484EES) with the PROFINET-IRT.	M	I-D	This driver for the RapID connects the edge devices to the PROFINET-IRT.	3.3
Req-D3.2-U3-3-com	SIEMENS S7-1550 for the integration of new devices, time synchronization between devices and reading the messages (data packets) from devices at pre-defined cycle times.	M	I-D	The Programmable Logic Controller (PLC) in Profinet industrial network is the network manager.	3.3
Req-D3.2-U3-4-com					

	Optimization of the Frames Per Second (FPS) connectivity between 3D ToF camera and PolarFire edge components	~~W~~ S	I D	May need an intermediate device such as a PC\Server	3.3 3.2
Maintainability (modularity, analyzability, testability)					
Req-D3.2-U3-1-com	The UC3 platform should be able to produce test and analysis data such that on-going improvements and maintenance can be carried out to advance the state of the art in latency reduction for local to remote HRI, HMI, tele-operations processes.	W	I	A critical requirement is component analytics such that latency improvement research can be carried out as part of on-going research and development.	3.3\3.2
Performance					
Req-D3.2-U3-1-hw-sw	**Frame rate:** 5 frames per second at 640 x 480 sized frames.	S	I-D	This research involves continual improvements work in edge-based AI processing and use case related processing services.	3.3/3.2
Req-D3.2-U3-2-hw-sw	**Object detection:** 90% object detection per frame.	S	I-D		
Req-D3.2-U3-3-hw-sw	**Latency:** Using AI prediction techniques and algorithms, testing is required to identify novelty of such methods for latency minimization in robotic tele-operations.	S	I-D		
Req-D3.2-U3-4-hw-sw	Application and bespoke development of position tracking algorithms using 3D ToF data, capable of detecting wrist movement of a standing human at a fixed distance from the camera to an accuracy of 98%, at the local end, in	S	I-D		

Req-D3.2-U3-5-hw-sw	normal lighting conditions with a latency of < 200 ms. Application and bespoke development of object tracking algorithms using 3D ToF data, capable of detecting objects in the remote scene (at the robot/gripper end) in 3D space; objects to be sized at 5 cm or larger.	S	I-D	Applied research into real-world capabilities of ToF camera technologies deployed in an industrial setting. Investigations into object tracking using ToF for typical pick and place tasks at the remote robot end.	3.2 3.2
Compatibility (interoperability, co-existence)					
Req-D3.2-U3-1-hw-sw	Co-existence of Information Technology (IT) and Operation Technology (OT) on the same network infrastructure.	W	I	This technology will significantly decrease the network wiring that results in lower cost of implementing industrial networks.	2.1/3.3
Usability (operability)					
Req-D3.2-U3-1-hw-sw	Development of an intuitive user interface (UI) with options to fully control the robot with functionality for set-up\restart, safety controls, recovery, speed controls, emergency stop, etc. Also, the UI will be required to evolve when new capabilities and functionalities are integrated into the UC3.	W	I	This UI will provide value added services at the user end and will evolve with varying use cases.	3.2/3.3

Reliability (fault tolerance, availability)					
Req-D3.2-U3-1-hw-sw-com	The platform should have in-built fault tolerant capabilities, be able to recover from user or robot	S	I	This is a critical requirement for HRI and HMI interactions.	3.3

	errors and fail gracefully as relevant.				
Security (cyber-security, integrity, confidentiality, authenticity)					
Req-D3.2-U3-1-hw-sw-com	There is a requirement to investigate BB9 for cyber security services that can be integrated within the use case platform. This will certainly be a more formal requirement that will be extremely relevant as the use case moves up the TRL scale.	W	I	Cyber security is a critical component of future tele-operation platforms and must form an integral service layer at both local and remote ends.	
Portability (adaptability, replaceability)					
Req-D3.2-U3-1-hw-sw-com	General requirement(s) that the use case is engineered with the potential for portability and adaptability to varying form of industrial tele-operation tasks for the enablement of remote factory/ production working in the future.	S	I	Robotic tele-operation platforms must have in-built flexibility in their architecture for applications to varying use cases in the future.	3.2\3.3
Cost					
Req-D3.2-U3-1-hw-sw-com	The complexity of engineering robotic tele-operations solutions for manufacturing and other scenarios for the foreseeable future will vary pending the specific use case(s). Variable costs will be a factor until flexible and reusable components are developed and engineered. With this in mind, the requirement in relation to costs for use case three relates to the mandatory conducting of a cost-benefit analysis for any real -world deployment of the tele-operations platform. Such a requirement is required to ensure the project is realistic in terms of typical industrial robotics projects	W	I	Cost-benefit analysis is a mandatory requirement for robotic tele-operations projects.	

	that may scale from tens of thousands up to tens of millions in terms of specific industrial deployments.				
Scalability					
Req-D3.2-U3-1-hw-sw-com	The use case three engineered solution could be able to scale to different users being able to use the platform and also to enable the users to work across different robots.	C	I	Multi-user, multi-sensory and multi-robotic platforms	3.2\3.3\3.4
Tools/toolchains					
Req-D3.2-U3-1-hw-sw-com	Software development using the VectorBlox SDK which will involve research and deployment of CNNs at the local end for the mapping of HMI-IMU and ToF sensor data streams to robot activations at the remote end and as required for applied task specific object detections at the remote end.	M	I-D	This is ML related research and engineering into the use and deployment of CNNs on the PolarFire edge devices.	3.2\3.3
Req-D3.2-U3-2-hw-sw-com	Algorithm research and development to detect objects in a frame with dimensions of approximately 5cm in size on the remote robot end.	S	I	Remote end object detection research requirements.	3.4
Req-D3.2-U3-3-hw-sw-com	Develop methods and techniques to transfer object detection inferences and robot movement predictions in a standard format (JSON) to the local user end with a maximum latency of one second or under.	S	I-D	Transfer of AI inferences between remote and local ends.	3.4
Req-D3.2-U3-4-hw-sw-com	Research, engineering and development of an applied sensory fusion algorithm that has functionality to fuse 3D ToF depth imagery (ADI ToF camera), motion tracking sensors (Vive motion trackers) and IMU data (from the	S	I-D	Research into AI\ML prediction techniques at the remote end and also as required at the local end of the tele-operations platform.	3.4\3.2

	Tyndall glove) in order to estimate/ predict human arm, wrist and finger movement estimates for translation to robot arm and gripper movements at the remote end.				
Req-D3.2-U3-5-hw-sw-com	Research and investigation into how low-level robot coordinate geometry data can be translated into a sub-set of higher-level gestures and such that AI\ML techniques may be applied at the user local end. As a result, opportunities may exist, such that auto-prediction may be investigated in the context of latency reduction between local user and remote robot ends.	S	I-D	Research into auto-prediction for latency reduction between the local and remote edge components.	3.4
Req-D3.2-U3-6-hw-sw-com	The development of a secure method of communications between the local and remote ends for the quality assured transmission of robot activation data (gesture detection and\or gesture predictions).	S	I-D	End to end security services as part of the platform toolchain.	
Req-D3.2-U3-7-hw-sw-com	For high-level gestures generated\predicted at the local or remote end, then there is a requirement for the conversion of communicated gestures into a series of robot commands at the remote end for arm movements and precision gripper movements based on the pre-defined industrial task activation steps.	M	I-D	Conversion of user generated movements into formal robot activations at the remote end.	3.2\3.4
Req-D3.2-U3-8-sw-com	Generally available APIs and related SDKs (C/C++, Python) to interface the	M	I-D	Platform development SW and HW tools.	3.2\3.3

	remote PolarFire SoC-FPGA (MPFS250T-FCVG484EES) edge device with the UR16e CoBot and the UR16e finger gripper device.	M	I-D	AI\ML dataset generation for model testing and evaluation.	3.4
Req-D3.2-U3-9-sw	Produce a number of use case related data sets, incorporating HMI-IMU (tactile glove), motion trackers and ToF (depth camera) sensor data streams to be used in both cloud and PolarFire embedded AI\ML related research.	S	I-D	AI\ML algorithms research, evaluation and re-engineering.	3.4
Req-D3.2-U3-10-hw	Research and development using generally available open-source APIs and SDKs to develop, test and re-engineer (as applicable) detection algorithms for the various 3D ToF camera data used in the use case sensor architecture.	S	I-D	AI\ML algorithms research, evaluation and re-engineering.	3.4
Req-D3.2-U3-11-hw	Evaluate and utilize publicly available pre-trained real time object detection models with a significant level of accuracy such as R-CNN, R-FCN, or YOLO for the processing, object detection and inference over RGB image frames.	S	I-D	AI\ML algorithms research, evaluation and re-engineering.	3.4
Req-D3.2-U3-12-hw	Evaluate and utilize publicly available 3D depth data sets such as Matterport3D, NYU-Depth V2, or ARKitScenes that have facilitated significant level of depth prediction accuracy for ML training in relation to ToF depth data.				
Safety					
Req-D3.2-U3-1-hw-sw	Continually addressing the health and safety aspects of the functionality to be	S	I-D	User safety as a critical, mandatory and core aspect of	

	implemented at both the user local end and the remote robot end of the tele-operation platform.			the use case research into tele-operated robotics.	
General					
Req-D3.2-U3-1-hw-sw	Develop a small set of initial test-cases to focus the use case three. For example, tele-operation without digital twin. • **Scenario 1:** Robot is driven to pick and drop two small objects (e.g. stress balls) into two bins. Remote user\operator also has two balls and two bins. User\operator picks and drops balls in bins; robot mimics operator actions. • **Scenario 2:** Robot is driven to pick and drop two small objects (e.g. stress balls) into two bins. Remote user\operator, operating in VR environment, has digital twin representation of the two balls and two bins. User\operator picks and drops balls in bins; robot mimics operator actions.	S	I-D	On-going experiment activities for use case three.	3.2\3.3\3.4

7.4. Use-case 4

No input received.

7.5. Summary of the specifications and requirements

The specifications and requirements as collected from the above inventory are sub-divided is a few groups as mentioned in section 3.3:

- Operation: supply, power, wireless charging and/or contactless power, remote adjustments of settings and configuration, temperature range of application
- Performance: speed, latency, refresh rate, measurement distances, resolution
- Serviceability: remote firmware update, self-calibration, identification to upper system
- Interfacing: wireless, wired, bandwidth, QoS
- Security: cyber-security, robust data formats and package received acknowledgement
- Manufacturability: moulding, IP-rating
- Useability: beyond IMOCO4.E scope

What is less or not highlighted as outcome of this 2nd survey for D3.2:

- Loss of wireless link due to jamming and the necessary time to recover.
- In case of smart sensors, how to forward errors or out of range sensor results.
- W.r.t. supply/power, none of the partners have referred to PoE, though Ethernet and EtherCAT is often mentioned aside USB-2/3 and ProfiBus.
- The DT, AI descriptive models for the to-be-used HW device: sensor, actuator, controller, including its limitations.
- The explicit requirements necessary for IMOCO4.E hardware beyond the COTS available parts and systems

It is expected that the above issues will be resolved, implemented, circumvented by the partners involved while implementing the various tasks.

8. Operability requirements

The systems must be able to operate in various environments e.g., semiconductor, physical and chemical (cleanroom) laboratory environments as well as automotive production areas with welding equipment. As such, there will not be a one size fits all boundary constraint.

The main differences will be in:

- Measurement ranges of the physical quantities and their tolerances w.r.t. to their electrical representation
- Temperature, pressure, humidity range
- Pollution degree
- Power quality
- EM environment, including EM-fields from nearby wireless connectivity, motion control and wireless power transfer (WPT)

8.1 Safety and safe operation

The term safety applies in the IMOCO4.E methodology to the human environment w.r.t. generated noise, pollution, radiation as well as dangerous motion from autonomous robots and production machinery.

8.1.1 Motion safety

As torque and force are the paramount parameters with the autonomous robots and production machinery, they need to be well guarded to ensure human safety of the operators as well as a limitation on foreseeable machine damage.

Though the focus in IMOCO4.E will be on electrical autonomous robots and production machinery, also hydraulic and pneumatic sources for motions must be taken into account (when used).

The two "sister standards" IEC/EN 60204 series (Machine Directive: 2006/42/EC) and ISO 12100 (Risk Assessment and Risk Reduction) are closely related to regulatory aspects. Both standards are transposed as national / regional standards across the world, including in Europe, US, China, Japan, and many other countries and their closely related regulatory activities.

Further examples of horizontal safety standards include:

IEC 61140 (Protection against electric shock)

IEC 60529 (Protection by enclosures)

IEC 60664 (Insulation coordination for equipment within low-voltage systems)

In the area of group safety and product standards, the following could be regarded as highly "regulatory relevant":

IEC 60335 series (Household appliances)

IEC 61010 series (Industrial equipment)

IEC 62368-1 series (Safety of multi-media equipment)

IEC 60598 Luminaries

IEC 60601-1 (series) Medical electrical equipment

The EN versions of these standards, for example, are listed in the Official Journal of the European Commission to support the respective European Directives. The application of these standards also leads to acceptance of products by the authorities in countries such as the United States and China.

8.1.2 Electrical safety

All electric and electronic autonomous robots and production machinery needs to be electrical safe according to the international requirements (and their national deviations). Typically, these requirements are part of the Machine Directive as well as the Low Voltage Directive.

8.1.3 Electromagnetic compatibility: emission and immunity requirements

All electric and electronic equipment must satisfy the European EMC directives, as applicable to the products considered.

8.1.4 Radio equipment

All products which incorporate wireless and/or radio related functions must satisfy the Radio Equipment Directive (RED), for which the EMC requirements are superseded i.e., extended by the ETS 301-489-1. Additionally, the wireless and/or radio related functions must satisfy the ETS related requirements for the products used. Pre-qualified modules may be used to circumvent testing against the specific ETS. The use of short-range-devices (SRD) are recommended to avoid formal type testing.

9. Conclusion

After collecting all the feedback from the IMOCO4.E partners, involved with the Layer 1 developments, from either WP3 and/or the Pilots, Use-Cases and/or Demo's, it shows that the most stringent specifications and requirements apply functionality.

To serve functionality, measurement speed, refresh rate, latency, bandwidth, data reliability: data acknowledge-after-reception, timestamping, a wide range of operational temperatures, are of utmost importance.
Aside these requirements, it is still assumed that multiple video frames shall be captured fully with high frame rates and high resolution and processed at a processing host rather than within a smart(er) camera which can be remotely configured to obtain the relevant data only, keeping processing latency and interface restrictions in mind.

Most foreseen Layer 1 applications rely on existing interface protocols, either wired: Ethernet or EtherCad, or wireless: BLE, as where power needs for the application needs to be supplied from rechargeable batteries, an interface cable: USB-2/3 and or ProfiBus, wired (24 volts DC) or contactless for charging or power transfer.

With the development of new sensors and actuators, it is assumed that these devices can be remotely updated for firmware, configuration and settings, to make them re-usable.

With today's designs, the need for (cyber)security is also on the list as due to the open-network chosen: Ethernet, the likelihood for data corruption or data tapping will be possible.

The need to develop industrial reproduceable concepts focused on manufacturability is emphasized too.

Aside cyber-security, little emphasis is given to terroristic actions like jamming: in particular wireless interfaces, which can act on these new systems too. The main criticality is the time necessary to recover i.e., re-establish a link without the loss of critical functionality of the running process.

10. References

[1] T.b.d.