Intelligent Motion Control under Industry 4.E

D4.2 Requirements for advanced motion control (final iteration)

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Abstract:

The deliverable is dedicated to the description of the final requirements for the control layer (Layer 2). This document expands on the requirements defined in D4.1 as well as D7.1 and D7.2. This report will summarize the control layer requirements specific for the relevant BBs (BB4, BB5 and BB10), pilots, demonstrators and use cases.

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TUE / TEK / UGR / UWB	BB5 Requirements
VTT / IML / STILL / IMST	BB10 Requirements
PHILIPS	Pilot 4 requirements

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Abbreviations

Abbreviation	Explanation
AI	Artificial Intelligence
ANN	Artificial Neural Network
BB	Building Block
COTS	Customizable off the Shelf
DT	Digital Twin
FRF	Frequency Response Function
LPV	Linear Parameter-Varying
MAE	Mean Average Error
MIMO	Multiple Inputs Multiple Outputs
NFC	Near-Field Communication
SISO	Single Input Single Output
SMART	Specific, Measurable, Attainable, Relevant and Time-bound
TCP	Tool Center Point
TPU	Tensor Processing Unit
TSN	Time Sensitive Network
WP	Work Package
XiL	X-in-the-Loop (X=Model, Software, Processor or Hardware)

Table 1: Abbreviations Table

Executive Summary

Deliverable 4.2 describes the final requirements for the control layer (layer 2) on the IMOCO4.E project. It follows Deliverable 4.1 (Requirements for advanced motion control (first iteration)) [1] which focused on the new challenges and current state-of-the-art of advanced motion control in the cyber-physical industry and pointed towards the objectives of WP4 of the IMOCO4.E project.

This document is an expansion of D4.1 and adds a more detailed and specific list of requirements needed for the work to be done in WP4.

Keywords: Intelligent Motion Control, Advanced Motion Control, Requirements, Control Platform, Algorithms Library, Path Planning, Collision Avoidance, Navigation Algorithms.

1. Introduction

1.1 Purpose of the Document

The deliverable is focused on the description of the final requirements to be fulfilled by the technologies to be developed within the IMOCO 4E control layer (mainly Layer 2). This document is a synthetization of Deliverable 4.1 and aims at quantifying and better detailing all the requirements to be met in WP4.

1.2 Structure of the Document

After this introduction, Section 2 presents an updated overview of the connections between WP4 Building Blocks and IMOCO4.E Pilots/Use Cases/Demonstrators. These connections have been key contributors to the requirements defined in this deliverable.

Sections 3 to 5 present the requirements for the three Building Blocks involved in WP4: BB4, BB5 and BB10. Given that D4.1 [1] already provided an elaborate review of the state of the art and the progress scoped for this project, this document will focus on specifying the final requirements of the motion control layer. These requirements will be presented into a set of tables arranged by Building Blocks (BB). The main BBs related to WP4 are BB4 (Real-Time Smart-Control Platform), BB5 (Smart control algorithms library) and BB10 (Motion/path planning, collision avoidance and navigation algorithms).

Each requirement will have an ID composed by the requirement number (Rxx), the deliverable ID (D4.2 for this deliverable), the applicable IMOCO4.E relation or relations,

- 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

To guarantee traceability of the requirement definition process, the requirement IDs defined in previous deliverables (D2.3, D4.1) are maintained.

The priority of the requirements will be detailed through the MoSCoW method. MoSCoW stands for:

- M (must have): requirement necessary for the IMOCO4.E project.
- S (should have): additional requirements with high priority.
- C (could have): additional requirements with low priority.
- W (would have): requirements that could be implemented after the completion of the IMOCO4.E project but don't have to be met during this project.

For verification, the following methods will be considered:

- 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 document is closed with some conclusion and presenting how the requirements presented will be used to design and validate the required technologies.

1.3 Intended readership

This deliverable will be addressed to the partners involved in WP4, as well as any partner interested in the definition and development of Layer 2 technologies.

2. WP4 Building Block Connections

		BB4	BB5	BB10
Use Cases	**UC1**. Industrial drive for smart mechatronics applications		UNIBS & UWB	
	UC2. CNC for integrated machine tool and robot control		FAG & TEK	
	UC3. Tactile robot teleoperation			
	UC4. Advanced and intuitive robot control and programming		UWB	
Pilots	**P1**. 3D printing	SIOUX	SIOUX	
	P2. Semiconductor manufacturing	TUEm & ITEC	TUEm & ITEC	
	P3. High speed packaging	CRIT & UNIMORE		
	P4. Healthcare robotics		PMS & TUE	PMS
	P5. Mining/tunneling robotic boom manipulator			NORMET
Demonstrators	**D1**. High precision cold forming of complex 3D metal parts			
	D2. Smart sensoring on injected plastic parts	UNIMORE		
	D3. Autonomous intra-logistic transportation			STILL
	D4. Vision-based AI pick & place robotics for randomly arranged and differently shaped bottles			

Table 2: WP4 Building Block connections

3. BB4 Real-time smart-control platform requirements

ID	Requirement	Priority	Verify	Technical details (SMART)	Tasks
Interfaces and connectivity					
R114-D2.3	BB4 shall offer industry standard interfaces to: 1. Encoders (e.g. Biss-C, EnDAT) 2. Drives (e.g. EtherCAT) 3. Layers 1 and 2 (e.g. EtherCAT)	M	I	COTS components are needed to interoperate with TSN	T3.1 T4.1 T5.1
R115-D2.3	BB4 must be able to run on an ARM based platform.	M	I	Considered platforms are Xilinx UltraSCale+ ZCU102, Nvidia Jetson Xavier	T4.6
R116-D2.3	BB4 must be able to execute Matlab components	M	T	AI-algorithms are provided by BB6/BB8 as Matlab components	T4.6
R1-D4.2-P3	BB4 should provide TSN support	S	T	Network infrastructure and TSN implementation is due by BB9/BB4	T4.6
R2-D4.2-P3	BB4 must have USB and/or ETH interface	M	I		T4.6
R3-D4.2-P3	Virtual/real camera should be interfaced with the predictable multi-core platform	M	T	Physics simulation environment can be interfaced	T4.6
R4-D4.2-D2	BB4 must provide communication with NFC reader through USB port.	M	I	Hardware platforms must have USB ports to connect NFC readers.	T4.6
Maintainability (modularity, analyzability, testability)					
R117-D2.3	BB4 shall be ready for the vertical distribution of smart control algorithms	M	D	Interfacing with BB9	T4.6
R5-D4.2-P3	XIL testing and debugging setup for functional verification of the vision-in-the-loop system	M	T		T4.6
R6-D4.2-P3	A predictable and composable real-time operating system will be used in P3	M	T	Worst-case-response-time needs to be calculated	
R7-D4.2-P3	Control functionality will be tested in vision-in-the-loop implementation	M	T	Control performance must be validated	T4.6

Performance					
R118-D2.3	BB4 shall support control loop update rates of at least 10 Hz	S	D		T4.6
R8-D4.2-P3	Multi-rate sensor data processing should be supported	S	T		T4.6
R9-D4.2-D2	BB4 must be able to acquire data from tags read by the NFC reader	M	D	e.g., (temperature sensor + pressure sensor + ID tag)	T4.6
R10-D4.2-D2	BB4 must be able to record data into a database	M	D		T4.6
R11-D4.2-D2	BB4 must allow the inspection of the acquired data	M	D		T4.1
Compatibility (interoperability, co-existence)					
R119-D2.3	BB4 should be compatible with codegenerated from Simulink	M	D	Interfacing with BB5	T4.1
R120-D2.3	BB4 shall be compatible and portable withx86-based platforms	S	D		T4.1
Portability (adaptability, replaceability)					
R121-D2.3	BB4 shall offer customizability to run any combination of custom control loops in parallel, including MIMO control loops	M	D		T4.1
R122-D2.3	BB4 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		T4.1
Usability (operability)					
R12-D4.2-P3	Pilot 3 must have real-time control capability	M	D	This might be achieved by running a real-time OS (e.g., FreeRTOS)	T4.6
R13-D4.2-P3	Pilot 3 must be able to run generic neural networks	M	D	Neural networks could be used to run: 1. An outer control loop with relaxed timing constraints (e.g., in the order of milliseconds, or even seconds) to adjust the parameters of the hard real-time loops	T4.6

				2. Algorithms for anomaly detection or predictive maintenance	
Cost					
R123-D2.3	BB4 shall have a target cost of goods of 10k€ for a basic version	M	I		T4.6

Table 3: BB4 Real-time smart-control platform requirements

4. BB5 Smart control algorithms library requirements

ID	Requirement	Priority	Verify	Technical details (SMART)	Tasks
Interfaces and connectivity					
R124-D2.3	AI-based algorithms should be compatible with commercially available TPU's	C	I	Allows for application in embedded solutions	T4.1
R125-D2.3-L2	BB5 can be connected to Matlab/Simulink (Layer 2 to Layer 3) for configuration, etc.	C	A		T4.1 T4.3 T4.4
R1-D4.1	Gain or phase stabilization of dominant resonance modes must overlap with target closed-loop bandwidth	M	A	Perform stability analysis (Nyquist...) and robustness analysis (gain, phase and modulus margins)	T4.3
R15-D4.1	Control algorithms for switched reluctance motors should consider that reversing the direction of current does not reverse the direction of torque	M	I	This is essential for bi-directional control	
R27-D4.1	Model Predictive Controller should be executed in COTS controllers	M	A	Partner-specific requirement related to implementability	
R15-D4.2	Digital-twin cobot-entity shall be connected to torque cobot control algorithms with ROS/GAZEBO compatibility or other similar communication middleware and robotic simulators	M	D	ROS (Robot Operating System) is an open-source software development kit for robotics applications. ROS offers a standard software platform to developers across industries that will carry them from research and prototyping all the way through to deployment and production	T4.2 T4.3 T4.4
R16-D4.2	Real-Time (RT) torque cobot control algorithms shall be compatible with ROS/ROS2 for cobot interconnectivity.	M	I	ROS 2 improves communication stack with the real-time data distribution service (DDS) protocol. DDS acts as middleware for internode	T4.3 T4.4

				communication and uses the quality-of-service (QoS) profile to provide real-time communication, scalability, performance enhancement, and security benefits.	
R17-D4.2-P2	BB5 will have support for tracing all signals, including current-loop, in real-time and for on-line changing of parameters	S	D	Software scope to aid diagnosis and commissioning in conjunction with the ability to change parameters manually online.	T4.3
R18-D4.2-P4-BB5, BB6, BB8-L2, L3, L4	Smart control algorithms' AI-components and Digital Twins (DT) shall only use existing data and interfaces of the brown field system after training and calibration	S	I/D	AI-components and DT models may use additional data or sensory input interfaces to for training or calibration. Aditionally, path planning/obstacle avoidance may use sensors for the future green field systems.	T4.1 T4.3 T4.4 T5.1
R19-D4.2-P4 -BB5, BB6, BB8, BB10-L2,L3, L4	Smart control algorithms shall have an input, output and configuration (parameter) interface in SI-units	S	I/D	Additionally, if not covered by the output interface a diagnostic and test interface shall be present for algorithms at Layer 1,2,3.	T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
R20-D4.2-UC1	BB5 will be validated using xiL methodology	C	D		T4.2
R21-D4.2-UC2	The position setpoint must be used as a control variable when using position control in the Stäubli UnivalDrive robot	M	I	Stäubli UnivalDrive communication interface only allows position interaction between external controllers and robot drives.	T4.3

R22-D4.2-UC2	The control loop sampling rate should take less than 4 ms	S	I	To match Stäubli UnivalDrive EtherCAT interface limitations	T4.3
R23-D4.2-UC2	The robot and CNC should use the same protocols and data formats	M	D	The CNC exports robot data (positions, etc) by the same standard protocols and formats that is used for Machine Tool Data(OPC-UA)	
R24-D4.2-UC4	Use case 4 shall allow hand-guidance of the robotic arm with the use of a haptic device allowing intuitive programming of desired motion trajectories without the necessity of hand coding and/or teach-pendant jogging	M	D	The goal is to provide intuitive interfaces to program collaborative robots via a simple 6DoF controller device attached to the robot end effector. This motion-task definition should be accessible even to low-skilled operators without a deep background in robotics.	T4.3
Maintainability (modularity, analysability, testability)					
R126-D2.3-L2	All smart control algorithms shall have a clear documentation that explains input, outputs, description, and parameter settings	M	I		T4.1 T4.3 T4.4
R127-D2.3-L2	Smart control algorithms and models shall be tested in simulation	M	T	Validated in WP6. Testing includes stability and performance analysis	T4.1 T4.2 T4.3 T4.4
R128-D2.3-L2	Control functionalities should be able to be tested by automatic means and accordingly documented (requirement traceability)	C	T		T4.1 T4.3 T4.4
R11-D4.1	Systematic design procedures allow automatic or semi-automatic synthesis and parameterization of the control structures without requiring a highly skilled operator	C	I	Learning algorithms in T4.4 should operate automatically	T4.4

R25-D4.2-P2	Model-based methods for design, diagnosis and system identification must support rapid mechanical design iterations.	M	D	These are easy means of studying the effects of non-rigid bodies and imperfect actuators.	T4.2 T4.3
R26-D4.2-P2	Prototyping should be based on Rapid (MiL) strategies.	S	D	e.g. using Sfunctions or FMI interfaces to Amesim physical models	
R27-D4.2-P2	In pilot 2, system identification will use user-friendly FRF models, both SISO and MIMO	S	D	Frequency range: selectable, usually 1-500 Hz Quantification of confidence bounds on FRF models (i.e. to design robust controllers)	T4.2 T4.6
R28-D4.2-P2	Vision-in-the-loop control will include sensor fusion of camera and encoder signals	M	D	Demonstrate at TRL3 and integrate at TRL4/5.	T4.3 T4.6
R29-D4.2-P4-BB5, BB6, BB8, BB10-L2,L3, L4	All BB components (e.g. smart control algorithms, AI-components and digital twin models) shall be documented	S	I	Documentation should include input/output/parameter interfaces and user guidance	T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
R30-D4.2-P4-BB5, BB6, BB8, BB10-L2,L3, L4	Smart control algorithms shall be testable in simulation	S	T	e.g. by means of digital twins	T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
R31-D4.2-P4-BB5, BB6, BB8, BB10-L2,L3, L4	Internal signals of the smart control algorithm which are relevant for testing or analysis shall be made available on the interface	S	I		T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
Performance					

R6-D4.1	Sufficient performance improvement on vibration control systems must be compared to conventional control schemes	S	T		T4.3
R9-D4.1	Computation burdens should be compatible with available computation power on the drives	M	D	Real-time application necessitates computability	T4.3 T4.4
R12-D4.1	Sufficient performance improvement on repetitive control systems must be compared to conventional control schemes	S	T		T4.3
R20-D4.1	Iterative and learning techniques must be able to achieve good performance even in the presence of (trial-variant) disturbances	S	T	Validation by multiple test sets in simulation and experimentation	T4.3 T4.4
R24-D4.1	Friction compensation must be executed at a high sampling frequency	M	D	Minimum sampling of 1 kHz	T4.3 T4.4
R28-D4.1	Model Predictive Controller should be executed at a high sampling rate	S	I	Minimum sampling of 1 kHz	T4.3 T4.4
R32-D4.2	Torque cobot control shall perform with the same level of accuracy (if not better) than position cobot control	S	T	The cobot control error will be measured using the mean average Euclidean distance of the end effector to the objective point (MAE) along a given trajectory. *Use case example: Baxter cobot over a circular trajectory. Position control achieves a MAE of 0.0796 (in meters). Torque control via an ANN controller can reach a MAE of 0.00718*	T4.3 T4.4

R33-D4.2	Torque cobot control shall use lower overall torques than position cobot control	M	T	The control torque will be measured using the mean torque of each cobot joint along a given trajectory. *Use case example: Baxter cobot over a circular trajectory. Position control achieves a mean torque of 3.426 Nm. Torque control via an ANN controller can reach an average torque of 3.323 Nm*	T4.3 T4.4
R34-D4.2-P4-BB5, BB6, BB8, BB10-L2, L3, L4	Real-time smart control algorithms, AI-components and digital twin models shall be able to execute in real-time on provided execution platform	M	D/T		T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
R35-D4.2-P4-BB5,BB6, BB8,BB10 - L2, L3, L4	Smart Control algorithms shall be robust against (incidental) disturbances	S	T		T4.3 T4.4
R36-D4.2-UC1	Use case 1 should improve the lift virtual functionality	S	D		T4.2 T5.5
R37-D4.2-UC2	Use case 2 should show an improvement of the absolute dynamic robot accuracy	S	D		
R38-D4.2-UC2	Use case 2 should have adaptive impedance control integration using a force sensor located at the TCP with the	S	D	The robot must be able to smoothly contact	

	contact force within ±2% of the desired force magnitude			surfaces and adapt to this contact.	
R39-D4.2-UC2	The robot should be calibrated in order to improve its precision	S	D	The CNC includes a calibration system and software to enhance robot's precision	
Power efficiency					
R14-D4.1	Solutions to the over-parametrized commutation problem should penalize power consumption	S	I		T4.3 T4.4
Compatibility (interoperability, co-existence)					
R129-D2.3-L2-L3	The algorithm library in BB5 shall be compatible with BB4	M	D		T4.1 T4.3 T4.4 T4.6
R130-D2.3-L2-L3	All models should be compatible with Matlab/Simulink	S	D		T4.2 T4.3 T4.4
R131-D2.3-L2-L4	Modelling should be compatible with code generation tools	M	D		T4.1 T4.2 T4.3 T4.4
R132-D2.3	BB5 shall be compatible with smart control blocks developed in I-MECH	S	D		T4.2 T4.3 T4.4
R24-D4.1	Friction compensation must be added to the control action of the applied controller (current control loop input)	M	I		T4.3 T4.4
R40-D4.2	Modelling should be compatible with code generation tools	S	T		
R41-D4.2-	Smart control algorithms, AI-components and digital twin models shall be	M	I/D		T4.1 T4.3 T4.4

P4-BB5, BB6, BB8, BB10-L2,L3, L4	compatible with or can be integrated into Matlab / Simulink environment				T4.5 T5.1 T5.3 T5.4
R42-D4.2-UC1	Co-simulation between two different simulation platforms	C	D	In order to study the MIL and SIL capabilities, the Simcenter Amesim electromechanical elevator model is divided into two parts: the plant and the control, where the Lift virtual model is developed in Simcenter Amesim and the control in Matlab Simulink.	T4.2
R43-D4.2-UC2	Developed functionalities in use case 2 should be applicable to different platforms	S	I	FAGOR CNC is the main target, but functionalities should be easily deployed to other platforms (e.g. TwinCAT)	T4.3
R44-D4.2-UC2	Different kinematics should be integrated seamlessly in the CNC	M	I	To adapt to different configurations and sizes, the CNC must read or interact with Robot specific data (Kinematics…) that is installed, not included in CNC’s version	
R45-D4.2-UC4	Hand-guidance system must be compatible with existing real-time control systems	M	D	The hand-guidance system should work with the existing real-time control software employed in the current generation of collaborative robotic platforms	T4.3

Usability (operability)					
R133-D2.3	BB5 shall be able to be executed in real-time on provided execution platforms (e.g. via BB1, BB4)	M	T		T4.1 T4.2 T4.3
R5-D4.1	Systematic design procedures of vibration control systems must allow automatic or semi-automatic synthesis and parameterization of the control structures without requiring a highly skilled operator	M	I		T4.3
R13-D4.1	The strategy used for repetitive control should allow for flexibility towards different tasks	S	T		T4.3
R22-D4.1	Techniques in machine learning, applied to control, must have interpretable hyper-parameters such that the user knows what to expect when changing the values	W	I	The optimization method for the hyperparameters should at least be interpretable.	T4.3 T4.4
R31-D4.1	Given an LPV system, the structure of the LPV controller must be able to be specified by the user	S	I	Structure of controllers provide interpretability	T4.4
R46-D4.2-P4-BB5, BB6, BB8, BB10-L2,L3, L4	Smart control algorithms, AI-components and DT models that are intended for real-time deployment shall not adversely affect the responsiveness of the system to user requests	M	I/D	User shall not experience noticeable unintended lag in responsiveness	T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
R47-D4.2-P4-BB5, BB6, BB8, BB10-L2,L3, L4	Any smart control algorithms, AI-components and DT models that exhibit human interaction shall be safe and simple	M	I/D/T		T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4

R48-D4.2-UC2	CNC controller functionalities must be included in use case 2	M	I	e.g., CNC code interpreter, trajectory generator/interpolator, etc.	
R49-D4.2-UC2	Part production shall be programmed by Virtual Commisioning	S	D	Virtual Commissioning will be provided for programming the machine and robot via 3D joint simulation of them with collision detection	
R50-D4.2-UC4	A body shaping feature of the hand-guidance system could be implemented for robot redundancy resolution.	C	D	The control system should allow exploiting additional degrees of freedom in the robot kinematics with respect to the desired motion task. The body shaping feature can change the configuration of one or more robot joints while maintaining desired end-effector position and/or attitude. This can help the operator to steer the robot, e.g., in confined spaces.	T4.3
Reliability (fault tolerance, availability)					
R134-D2.3-L2-L4	Control algorithms should have self-diagnosis functions	S	I		T4.1
R51-D4.2-P2	FRF models shall provide quantified confidence bounds	S	T		T4.2
Portability (adaptability, replaceability)					
R135-D2.3	BB5 shall offer customizability such that non-standard tasks (i.e., tasks which are typically performed in research) can be	S	T		T4.1 T4.3 T4.4

	performed. Examples include flexibility in allowed controller structures and reference/feedforward signals				
R23-D4.1	Real-time algorithms must be sufficiently resource-efficient to be applicable to hardware that is standard in industry	M	D		T4.3 T4.4
R52-D4.2-P4-BB5, BB6, BB8, BB10	If a model or algorithm is applicable to multiple layers (e.g. for real-time deployment on L3 and for condition monitoring on L4) it shall allow for easy adaptability/re-use	C	I/D	For instance selection of variants of differing abstraction levels	T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
Scalability					
R53-D4.2-P4-BB5, BB6, BB8, BB10-L2,L3, L4	Smart control algorithms, AI-components and digital twin models shall be compatible and/or configurable/tunable for different variations of similar system / robot	S	I/D		T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
Tools/toolchains					
R54-D4.2-P4-BB5, BB6, BB8, BB10-L2,L3, L4	Smart control algorithms, AI-components and digital twin models that are intended for real-time applications shall be compatible with code generation from Matlab / Simulink	M	I/D		T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4
R55-D4.2-BB5, BB6, BB8, BB10-	Smart control algorithms, AI-components and digital twin models shall be testable in a simulation / virtual environment (against a DT)	S	I/D		T4.1 T4.3 T4.4 T4.5 T5.1 T5.3 T5.4

L2,L3, L4					
R56-D4.2-UC1	Simcenter Amesim & Matlab Simulink could be used for XiL methodology	C	D	Amesim is a powerful software used for system-level simulation that accurately models mechatronic systems. On the other hand, Simulink is known for its efficacy in the control field. By coupling an Amesim model of a mechanical elevator and its Simulink control unit in order to give the optimum command so that the elevator reaches the desired floor at a specified speed	T4.2
Safety					
R136-D2.3-L2-L4	Smart control algorithms of collaborative robots (Cobots) need to be compliant with safety standards	M	A		T4.1 T4.2 T4.3 T4.4
R16-D4.1	Compliant applications must use torque-based control schemes	M	A		T4.3 T4.4
R18-D4.1	Stability of the system in both training and tests must be demonstrable, i.e, it must be safe	M	D	Test using Nyquist, convergence, singular values, etc.	T4.3 T4.4
R57-D4.2	Control functionalities will not make the robot move dangerously (for itself and for operators)	M	I		
R58-D4.2-P4-BB5, BB6, BB8, BB10	No BB shall adversely affect the safety of the system	M	I/D		

Rx59-D4.2-UC2	Control functionalities should not make the robot move dangerously (for itself and for operators)	M	I		
R60-D4.2-UC2	Control functionalities should be able to define Exclusion Zones to avoid machine parts and other selected areas	M	D		
R61-D4.2-UC4	Use case 4 should execute the motion of the robot arm in the hand-guidance regime in a smooth way and without exhibiting unwanted vibrations or jerky movements	S	I	The control software translating the haptic device signals to the commanded motions transmitted to the robot should respect possible flexibility in the kinematic chain formed by the operator's hand, haptic device and the robot arm itself. The goal is to provide a smooth experience for the operator without exhibiting unexpected jerky movements, which could lead to collisions.	T4.3
Digital twin					
R137-D2.3-L2-L4	Data-driven models shall be compared to analytical models and/or validated real robots	S	A	Residual tests, validation test sets, variance evaluation of models	T4.1 T4.2 T4.3 T4.4
R8-D4.1	Load-side motion control requires the usage of additional sensors	S	I	Additional sensors should be mounted to measure the point-of-interest of a machine	T4.4
R17-D4.1	Accurate dynamic models must be automatically captured	C	I		
R18-D4.1	Smart control algorithms must integrate models and adaptation mechanisms within the control loop	S	I	The alternative (fully model-free approaches) may suffer from poor interpretability and performance, while some degree of	T4.3 T4.4

				modeling effort is usually affordable.	
R19-D4.1	Control algorithms must be robust to modelling errors	M	A	If the algorithm were not robust to modeling errors, it could render the closed loop unstable	T4.3 T4.4
R26-D4.1	Although characterization of friction is not required for friction compensation algorithms, a two-mass model of the controlled system is required	S	I	This increases the interpretability of the model	T4.3
R29-D4.1	Model Predictive Control will need feedback of the main d.o.f of the mechatronic system	M	I	If different d.o.f. were used for feedback, a poor model quality would lead to poor performance or even instability.	T4.4
R30-D4.1	For LPV control to be applicable, the scheduling variable must be measured	M	I	The scheduling variable must be measured during training/identification. During operation, the scheduling variable must be (approximately) known	T4.4

Table 4: BB5 Smart control algorithms library requirements

5. BB10 Motion/path planning, collision avoidance and navigation algorithms requirements

ID	Requirement	Priority	Verify	Technical details (SMART)	Tasks
Interfaces and connectivity					
R219-D2.3-B10-sw	The control system algorithms can be integrated in a real HIL testing environment	M	T		T4.5
R220-D2.3	The LIDAR sensor must be suitable for the usage of SLAM	M	D		T4.5
R62-D4.2	Smart control algorithms shall have an input, output and configuration (parameter) interface in SI-units. Additionally, if not covered by the previously mentioned interfaces a diagnostic and/or test interface shall be present.	M	I/D	In mobile systems, physical communication is based internally on bus systems such as CAN or Profinet, as well as on high-speed industry standards such as Ethernet. For the control systems as described in the Imoco project, data rates in the 1M baud range and using visual data via ethernet the Gigabit range is necessary. The latencies should always below 10 ms.	T4.5
R63-D4.2	Algorithms for Path planning and obstacle avoidance have access (input) to a near real time (>5Hz update rate - application dependent) environment map (e.g. resulting from SLAM)	S	D/T		T4.5
R64-D4.2	Algorithms for Path planning and obstacle avoidance on Layer 3 (behavior) shall send motion commands to Layer 2 (control) with a near real-time latency (<0.1s, application specific).	S	D/T		T4.5
R65-sw-D4.2	Interconnection of Radar and Mini-Pc to other Demonstrator components via Ethernet or USB interface	M	T		T4.5 T3.2
Maintainability (modularity, analyzability, testability)					
R242-D2.3-	Algorithms can be tested and verified in a simulation environment with DTs.	M	I	Algorithms like path planning can be tested in a simulation within different	T4.5

B10-sw				scenarios to evaluate their performance. The evaluation is only done on the viewer level in terms of the successful solution of the scenario.	
R239-D2.3-B10-sw	Visual servoing and motion control algorithms related are modular so that these can be ported to other manipulators	W	T	The evaluation can be made on the basis of the adjustable parameters. here, attention is paid to whether the number of parameters is sufficient for porting	T4.5
R227-D2.3-B10-sw	Possible to port different programming languages and operating systems/embedded control systems	M	I		T4.5
R226-D2.3-B10-sw	The libraries and algorithms used must be open source or industrial standard	M	I		T4.5
Performance					
R224-D2.3-B10-sw	Collision avoidance must be possible to execute in real time	M	T	Collision avoidance must work in real time to avoid damage to inventory. This can mean static obstacles such as racks in a warehouse, but also dynamic obstacles such as other vehicles.	T4.5
R223-D2.3-B10-sw	Path planning algorithm must be possible to be done in near-real-time in the control system	M	T	Path planning must be executable in near real time to enable smooth operation of the robots. If the robots are coordinated by an FMS, the high-performance execution of the robot path planning is necessary in order to achieve a timely and efficient operation of the robots.	T4.5
R222-D2.3-B10-sw	Visual servoing for motion control is based on real-time camera systems integrated into the control system	M	T	If the robots are coordinated by an FMS, then the performant execution of the visually guided navigation is necessary to fulfil temporal	T4.5

				assumptions in the fleet coordination and thus enable a performant operation of the fleet.	
R221-D2.3	Enough processing power is needed to work with real-time sensor data (for localisation and navigation calculation)	M	D	The platform must provide sufficient capacity to run the relevant algorithms in real time. Relevant algorithms here are the safety-relevant algorithms, such as collision avoidance, which entails hard real-time requirements.	T4.5
R66-D4.2-P2	Initial work environment scanning and mapping in the mining boom application system must be accurate and fast.	M	T	Environment scanning and mapping is done when the position of the mining machine platform is changed. Accuracy of the environmental model must enable collision free path planning and execution. The scanning and modelling procedure should not take more than a few minutes.	T4.5
R67-D4.2-P2	In boom control, validation of the collision free path should be possible to do before execution of the movement with performance as close as possible to real-time.	M	T	The collision free path must be generated from an arbitrary start position to a given target position before movement can be started. This should not take more than 1 second.	T4.5
R68-D4.2-P4-L3	Path planning and collision avoidance algorithms on the behaviour layer (L3) shall be able to execute in near-real-time (> 4Hz) on the available motion-platform	M	D/T		T4.5
Compatibility (interoperability, co-existence)					
R244-D2.3-B10-sw-SAF	The algorithms must comply with mobile machinery directives	M	T	The algorithms used must take into account the robot specification in order to calculate only valid actions that can be executed by the robot. This can be tested by comparing the calculated movements with the physically possible actions.	T4.5
R241-D2.3-	The implemented motion control algorithms are directly	M	I	Motion control algorithms should be possible to test in	T4.5

B10-sw	interoperable with a HIL toolchain and dynamic DT counterpart of the boom.			DT environment and move to a real machine without or with minimum modifications.	
R225-D2.3-B10-sw	The machine vision algorithms used in visual servoing comprise of ML open-source libraries, i.e. compatible with BB8	S	T	The use of open-soruce libraries enables a form of compatibility between different systems so that subcomponents can be reused	T4.5
R220-D2.3	The LIDAR sensor must be suitable for the usage of SLAM	M	D	The data of the sensor system must correspond to the format expected by the SLAM. In addition, the sensors must not provide too much erroneous data, for example excessive noise.	T4.5
R236-D2.3	The optimised Neural Networks must be able to run on the existing hardware (I.MX), e.g. Nvidia Jetson Or the mini-pc	M	D		T3.3 T3.4
R35-D4.1	Robots managed within the FMS must have access to appropriate on-board sensors to effectively detect obstacles and humans	M	D		T4.5
R69-sw-D4.2	Radar data must be saved as .bin or .csv data	M	T		T4.5
Usability (operability)					
R230-D2.3-B10-sw	Path generation should work automatically with minimal input from the operator	M	T	Path planning should be done without operator intervention to enable automated operation. Minimal intervention is allowed in difficult scenarios or to task the robot.	T4.5
R229-D2.3-B10-sw	The motion control algorithms are intuitive to operate from a usability perspective	M	T	If an operator's intervention is necessary, the operation of the path planning should be intuitive. A graphical representation of the operating elements is preferable.	T4.5

R228-D2.3-B10-sw	The calibration and parametrisation of the algorithms and sensors related must be able to be configured on-site	M	T	Calibration of the sensor technology must be feasible locally, as areas of application can differ slightly at different companies and therefore make fine adjustment of the sensor technology necessary. This requirement can be checked by using the robots in different scenarios.	T4.5
R35-D4.1	Robots must always possess an accurate estimate on their own pose	M	T	The robot must always know its own position as accurately as possible. This information is needed for path planning, collision avoidance and, if necessary, for picking up objects. The localization should not include jumps and drift. In addition, the localization must not show a change in position when the vehicle is at a standstill.	T4.5
R70-sw-D4.2	The user can determine important thresholds and settings from a GUI interface	M	T		T4.5
Reliability (fault tolerance, availability)					
R243-D2.3-B10-sw	The motion control algorithms are fail-safe	M	T	Each motion control algorithm requires an individual means of "fail-safe" implementation / testing. The reliability can be assessed experimentally through different scenarios as well as through a long-term test of the robot in operation.	T4.5
R71-sw-D4.2	Constant False Alarm Rate (CFAR) can be done in range and Doppler domain	S	T		T4.5
Scalability					
R240-D2.3-B10-sw	Algorithms can be adapted/extended to different sensors, robots or different variations of similar systems.	W	T	To use different hardware, possibly given by the use of multiple robots from different manufacturers. Should the algorithms be adaptable to changing	T4.5

				sensors. This can be validated by integrating new sensors.	
Tools/toolchains					
R219-D2.3-B10-sw	The control system algorithms can be integrated in a real HIL testing environment	M	T	HIL system can consist real control hardware similar to a real boom or robot, but there can be also virtual (emulated) HW. Algorithms should be possible to execute and tests in this environment.	T4.5
R72-D4.2	Tools & toolchains (e.g. VR) shall be available for safely testing Path Planning and obstacle avoidance algorithms in simulation / virtual environment (against digital twins).	S	D/T		T4.5
Safety					
R235-D2.3-B10-sw	Measurement outliers and incomplete data (LIDAR data) should not lead to dangerous or unexpected behaviour.	M	T	Incomplete data from the sensor system should not lead to a dangerous situation, but to a safe state by interrupting the current task of the robot if necessary. For example, an interruption of the localisation should not lead to uncontrolled movements of the robot, but rather to a standstill until the localisation provides reliable data again. Incomplete or faulty sensor data can be simulated in test cases.	T4.5
R234-D2.3-B10-sw-SAF	The automatic movements are tolerant to failures of the control system (servo drives, sensors, actuators, software singularities)	M	T	Hardware failures should not lead to a dangerous situation, but to a safe state in which the current task of the robot is interrupted. For example, an interruption of the localisation should not lead to uncontrolled movements of the robot, but rather to a standstill until the localisation provides reliable data again. Incomplete or	T4.5

				faulty sensor data can be simulated in test cases.	
R233-D2.3	Path planning should take into account the presence and movement of human traffic participants and generate cooperative movement behaviour	C	T	A warehouse can also be frequented by people whose intentions are difficult to assess. Based on the interpreted intention of a person, the path planning should calculate a collision-free path while observing additional criteria, such as a minimum distance to the person.	T4.5
R232-D2.3	The short-term future path of the robot should be predictable for human traffic participants	S	D		T4.1 T5.1
R231-D2.3-B10-sw	User can intervene automatic path execution safely	M	T	The user should be able to take control of the boom during the automatic movements any time. Also transition back to the automatic movevent should be safe and flexible.	T4.5
R73-D4.2-P4	User can intervene automatic path execution safety	M	T		T4.5
Security					
R74-D4.2-P2	Control software and the parameters of the control system in pilot 2 must be protected, so that the user or any other person cannot change parameters accidentally or intentionally.	M	T	Using the machine with the wrong parameters can lead to severe safety issues. User permissions should be set correctly to prevent this.	T4.5
Cost					
R237-D2.3	The FPGA hardware shall not cost more than 1500€ and the embedded hardware not more than 500€.	M	D		T3.3 T3.4
R238-D2.3-P5-hw	The target cost of the goods in the visual servoing application for the camera system (excluding servomotors and drives) < 1000€.	M	I		T4.1 T7.1

Table 5: BB10 Motion/path planning, collision avoidance and navigation algorithms requirements

Conclusion

D4.2 provides a second iteration over the requirements specified in D4.1 (Requirements for advanced motion control (first iteration)) [1]. This document provides a full list of the final requirements of WP4 that will need to be validated on future deliverables.

The requirements from both D4.1 [1] and D2.3 [2] are included in this deliverable adding more detail, specially related to their priority in the project and their verification method. Some new requirements have been added, expanding on the needs of the specific technologies that are being developed within WP4 and the pilots, demos and use cases.

The requirements listed in this document are a key input for the technologies being developed in WP4, with a first reporting stage in M21 (May 2023) through deliverables D4.3, D4.4, D4.5 and D4.6. These deliverables will already validate some of these requirements. In later stages of the project, this deliverable will feed validation activities in integrated systems, IMOCO4.E Use Cases, in WP6.

References

[1] Diego Navarro Cabrera, Niceto Rafael Luque Sola, and Eduardo Ros Vidal. "D4.1 Requirements for advanced motion control (first iteration)." Zenodo, 2022. Available online at: https://doi.org/10.5281/zenodo.7575243 (accessed 27 January, 2023).
[2] Sajid Mohamed. "D2.3 Overall requirements on IMOCO4.E reference framework (3.0)." Zenodo, 2022. Available online at: https://doi.org/10.5281/zenodo.7529265 (accessed 27 January, 2023).