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Workpackage	Deliverable ID
WP5, System Behaviour Layer Design and Interfaces	**D 5.2 System behavior layer integration and connectivity requirements and specification (final iteration)**

Summary

This deliverable compiles the final requirements and specifications for the system behavior layer (Layer 3) interfaces used in the I-MECH platform. The requirements are compiled from the Pilots, Demonstrators and Use-Cases of the I-MECH project where the I-MECH methodology and Building Blocks (BB's) are applied. The focus for Layer 3, the system behaviour layer, for I-MECH is on the interfaces between sensors and actuators as part of the instrumentation layer and the motion control layer.

In this stage of finalising requirements, partners inputs are compiled and aggregated with a focus on the final I-MECH platform and the tools required for it to function.

This report is among the concluding steps in mapping the final I-MECH system architecture developed in D2.4 General specification and design of I-MECH reference platform [Van der Veen, 2018]. Using D2.4 as a guide, the outcomes of this deliverable align the Layer 3 requirements to the overall architecture of the I-MECH platform.

The requirements featured will contribute to the development of BB3 Condition Monitoring and BB6 Control Layer Self Commissioning as part of WP 5. The Building Blocks will form components of the I-MECH platform to be tested and implemented in WP6 and WP7.

There is no activity from Pilot 4 in this deliverable because Correa decided to skip activities in WP5 and to move their effort to other WPs. Pilot 4 does find it useful to use results of BB3 and BB6 which are mainly prepared in WP5.

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Keywords
Acoustic emission, auto-tuning, cloud, condition monitoring, diagnostics, feedback, feedforward, interfaces, motion control, OPC UA, performance monitoring, predictive maintenance, real-time, SCADA, self-commissioning, stability, system behaviour layer, temperature diagnostics, vibro-diagnostic, wireless sensor.

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1 Table of contents

Document Revision History

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Contributors

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Abbreviations & Definitions

Abbreviation	Description
AMPQ	Advanced Message Queuing Protocol
BB	Building Block
CAN	Controller Area Network
CNC	Computer Numerical Control
CPU	Central Processing Unit
DSP	Digital Signal Processor
ERP	Enterprise Resource Planning
GSC	Generic Substrate Carrier
GSM	Global System for Mobile communication
HMI	Human Machine Interface
HTTPS	Hypertext Transfer Protocol for Secure communication
ICP	PCB's piezoelectric sensors with built-in microelectronic amplifiers. (ICP® is a registered trademark of PCB Group, Inc.)
IO	Input Output
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LAN	Local Area Network
MEMS	Micro Electro Mechanical Systems
MES	Manufacturing Execution Systems
MIMO	Multiple Input Multiple Output
MQTT	Message Queuing Telemetry Transport
OPC	Open Platform Communication
OPC UA	Open Platform Communication Unified Architecture
OSI	Open Systems Interconnection
PC	Personal Computer
PDM	Pulse-Density Modulation
PID	Proportional Integral Derivative (controller)
PLC	Programmable Logic Controller
PWM	Pulse Width Modulation
RMS	Root Mean Square
RTD	Resistance Temperature Detectors
RTOS	Real Time Operating System
SCADA	Supervisory Control And Data Acquisition
SECS/GEM	SEMI Equipment Communications Standard/(Generic Equipment Model
SISO	Single Input Single Output
SOAP	Simple Object Access Protocol
SPI	Serial Peripheral Interface
TDM	Time Division Multiplex
WAN	Wide Area Network
WP	Work Package

3 About this Document

This deliverable is related to Task 5.1 and describes the final system behaviour layer connectivity and interface requirements for the I-MECH platform. It builds on the initial Layer 3 interface and connectivity requirements reported in Deliverable 5.1 (Link to 5.1). It carries on from the general requirements gathered in Tasks 2.1, 2.2 and 2.3, which have been reported in the I-MECH requirements table, in Deliverable 2.1 "I-MECH State-of-the-art & Requirements", Deliverable 2.3 "Overall requirements on I-MECH reference platform" and Deliverable 2.4 (Link to 2.4).

This document particularly focuses on system behaviour layer requirements and presents the current industrial control protocols for communications and interfaces for automated systems. Moving focus from pilots to I-MECH platform. These protocols provide platform independent service-oriented architecture that integrates all the functionality of the individual subsystems and are a key factor in integrating disparate control and instrumentation layers being investigated as part of the ECSEL JU.

This deliverable serves therefore as a reference for the activity of WP5 "Behaviour layer design and interfaces", which aims at developing communications and interface strategies between the industrial management systems and the production layer for mechatronic systems in I-MECH. WP5 provides input for BB3 "Robust condition monitoring and predictive diagnostics" and BB6 "Self-commissioning velocity and position control loops" which are directly connected to work package 5 as they deal with operations that span both the control layer and the system behaviour layer. All BBs related to the topics discussed in this report are referenced as a fundamental focus for efforts within I-MECH.

4 Introduction

The finalisation of interface and connectivity requirements for Layer 3 refines the work undertaken previously in D5.1 and focuses on the tools and building blocks which gather data representing the actual status of mechatronic systems, in particular its control and instrumentation components. Specifications and developments in Building Blocks 3 and 6, which reside within WP5, are outlined and the tools and methodologies applied within them are presented. Automatic self-commissioning of motion control loops based on the experimental identification data acquired from the instrumentation layer is contained within BB6 and advanced diagnostics / condition monitoring of electrical drive systems and the algorithmic data analysis utilities located in Layer 3 are shown in BB3.

Considering the importance of a standardised system architecture for the I-MECH platform the open source OPC UA platform [OPC UA, 2018] is presented in the I-MECH context and the developments relating to the data communications architecture are outlined.

The Layer 3 interface and connectivity requirements will provide the structure for the excellent work conducted in Layer 1 and Layer 2 in the area of instrumentation and control to be integrated with the MES/ERP layer for final decision making and greater factory level automation and efficiency.

4.1 Requirement coding scheme

The coding scheme for requirements was retaken from D2.3 [Kampschreur et al., 2018]. Each requirement ID is prefixed with rq- (for requirement), the deliverable ID (in this case D5.2) and the abbreviation of the domain:

- rq-D5.2-XXX: XXX abbreviation of the domain
- rq-D5.2-BBx: building block x
- rq-D5.2-Dx: deliverable x
- rq-D5.2-UCx: use case x

We thus joined the initiative proposed in D2.3 [Kampschreur et al., 2018] to use the same coding scheme, implementing at least the "rq-D#.#-" part to ensure that requirement IDs are unique and can be found easily in documents.

The requirement verification method is also indicated. Two methods are foreseen:

- T: test/validate
- I: inspect/demonstrate

A requirement can be:

- R: required (must-have)
- O: optional (nice-to-have)

- Layers L1, L2, L3
- List of BB: BB1, BB2, …., BB11
- Type: HW, SW, sensor, algorithm, …
- (Purpose: structural, subsystem, communication, …)
- Origin: A-application (coming from pilots, UC and D), P-platform (coming from tasks)
- Application: pilots P1, ...P5, use cases UC1.1, …, demonstrators D1, D2.

5 System behaviour layer communications platform and systems architecture

Layer 3 (System Behaviour Layer), defines a system behaviour in terms of the desired motion trajectory. It addresses the fundamental demands which originate from the management layers of production systems. In addition, functionality such as user interaction, sequence and/or exception management can also be found in Layer 3. The primary focus of I-MECH in relation to Layer 3 is the standardised communication protocols and interfaces between it and the control layer (Layer 2) and instrumentation layer (Layer1).

As part of Deliverable 5.1 [Seamus, 2018], OPC UA [OPC UA, 2018] was identified as the preferred platform independent system architecture for standardized communication protocols between the control layer, Layer 2, and Layer 3. There are, however, challenges with the implementation of OPC-UA for existing systems within I-MECH. Among some of the challenges are that OPC UA is not currently a real time architecture and this presents problems for real time closed loop control and while companion specifications are being developed for a wide range of applications there are gaps for others that prevent compatibility with the open source architecture.

With these challenges in mind OPC UA as a system architecture is still an aspiration for I-MECH and will be demonstrated within a number of the Pilots, but it will not form a core element of the I-MECH building blocks. An example of OPC UA being demonstrated between Layer 2 and Layer 3 in Pilot 1 Generic substrate carrier (GSC) (Sioux CCM) is shown in Figure 1.

This example shows the use of MathWorks Simulink and an intermediary server (AxChange Server) [AxExchange, 2018] between Layer 2 and Layer 3 to present data in the form of XML name space definitions in accordance with OPC UA. This tool enables the data generated in Simulink to be communicated in compliant form with the protocols outlined.

OPC UA, and its utilisation within the I-MECH platform, is addressed in further detail in Task 5.2 as part of Deliverable 5.5.

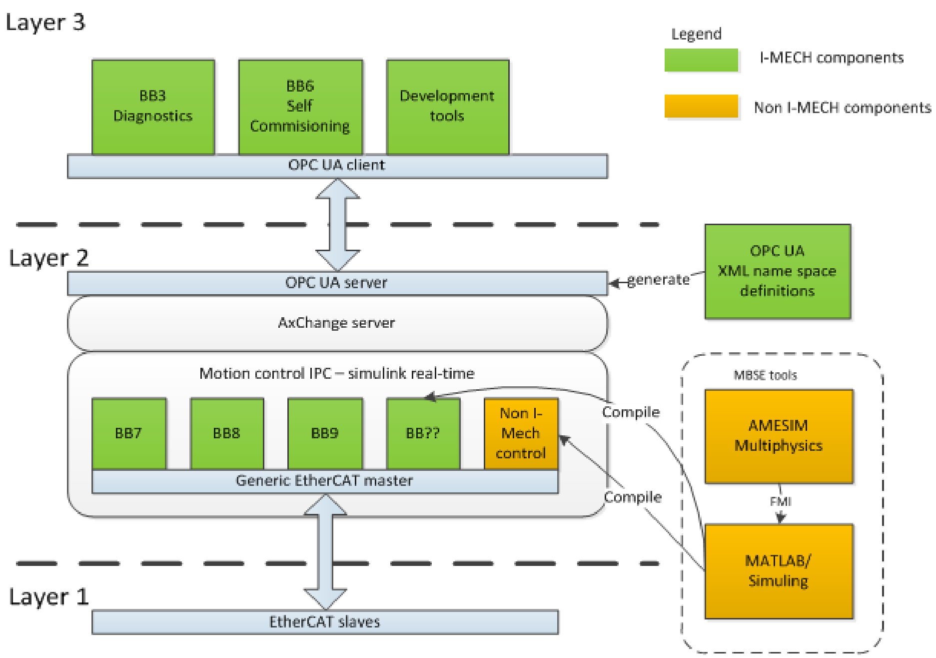


Figure 1 Demonstration of OPC UA architecture within Pilot 1 Generic substrate carrier (GSC) (Sioux CCM)

6 Work package 5 building blocks

Part of the scope of Work Package 5 System Behaviour Layer Design and Interfaces is the development of Building Blocks for the I-MECH platform. The development of a state-of-the-art predictive maintenance platform in I-MECH, as outlined in the projects' scientific and technological development objectives, necessitates a dedicated condition monitoring building block (BB3) to track and predict system health along with a corresponding self-commissioning control loop (BB6) to implement an action at the control layer, Layer 2, and instrumentation layer, Layer 1.

6.1 Building Block 3 Robust condition monitoring and predictive diagnostics

BB3 will contain both, hardware and software components for condition monitoring and predictive diagnostics. The software components can use data either from existing hardware, already incorporated in the system, usually for the purpose of the control, or intentionally added hardware to make the condition monitoring and predictive diagnostics simpler. This intentionally added hardware creates hardware components of BB3. This hardware will be developed mainly in Task 5.3, but also in WP3 as wireless sensors for predictive maintenance.

The example of the first category can be current sensors which are normally used for current feedback control loop. The currents relate with generated torque and thus with power consumption. Monitoring the trends in current can help to detect increased mechanical losses due to malfunction or wear. The BB3 component is in this case software, a set of algorithms which operate with normally measured quantities. Software components of BB3 will try to share and realise the ideas of I-MECH platform which is openness and ease of use in different applications. BB3 components will cover green field applications but they will also give the possibility to spread into brown field solutions which will be demonstrated in Pilot applications and which can be viewed the step beyond the existing solutions.

The example of the second category is a vibration sensor. It is inserted into the system for the purpose of monitoring but mainly for the purpose of predictive diagnostics. This is a typical example of hardware component of BB3. Such a sensor can be equipped with different, more or less complex software (algorithms) which are the software components of BB3. This software can run directly in the sensor. Then we talk about intelligent sensors. It can also run in upper layer, based on provided data. The standardized, preferably open communication interface enables simple integration also in brownfield solutions. There are two aspects which make this sensor beyond state of the art. Firstly, it uses MEMS devices which are cheap and the achievable performance is comparable with piezoelectric ones which enables to realise the tasks of long term predictive diagnostics. Secondly, it uses two MEMS sensors which enables data fusion, increase of the precision and self diagnostics of sensor itself.

Another illustrative example is temperature sensor. These are usually used for runtime monitoring of the motors. They can influence the maximum achievable performance by derating the controller to prevent damage of the system. Long term monitoring of temperatures, taken from different sensors, can be used for deeper condition monitoring and potentially to predictive diagnostics. The outcome for BB3 is again set of advanced algorithms in a form of complete documentation and also software realization.

The possible BB3 components are summarized in following points:

Hardware components

- sensors,
- intelligent sensors,
- hardware for signal measurements and analysis for exclusive use in condition monitoring and predictive maintenance tasks,
- fault injection hardware

Software and algorithms components for

- Data Reduction (DR),
- Condition Monitoring (CM),
- Predictive Maintenance (PM),
- visualization, data manipulation,
- supporting tools for DR, CM and PM,
- models for testing DR, CM and PM tools.
- fault injection software

BB3 development will be fully in line with general requirements (approaches) I-MECH reference platform which are defined in Deliverable 2.4. The software components will be developed as blocks in MATLAB Simulink using model-based design. The design will be mainly based on MIL in MATLAB Simulink - Model Based Design.

Later stage of development will use either SIL or PIL. HIL simulation will be used for verification and validation. The blocks will be collected in the Simulink library. The blocks will be optimized by their design for efficient C code generation using Simulink Coder. They will be supported with the documentation. Special attention will be payed to description of inputs and outputs as well as to description of tuneable parameters (e.g. thresholds, frequencies of interest, …).

The hardware components will conform I-MECH reference platform in standardized interface. EtherCAT slave connection will be provided directly into developed sensors or it will be realized by additional bridging hardware. The EtherCAT slave will come together with description of communication parameters in corresponding .xml file. All BB3 components will be tested during the design and also in WP6 so they will follow test benchmarking strategy proposed in [R. de Yurre et al., 2018].

In depth analysis and decomposition of BB3 was realized in the first year of project solution. Possible locations of BB3 components was discovered inside of I-MECH structure as can be seen in Figure 2.

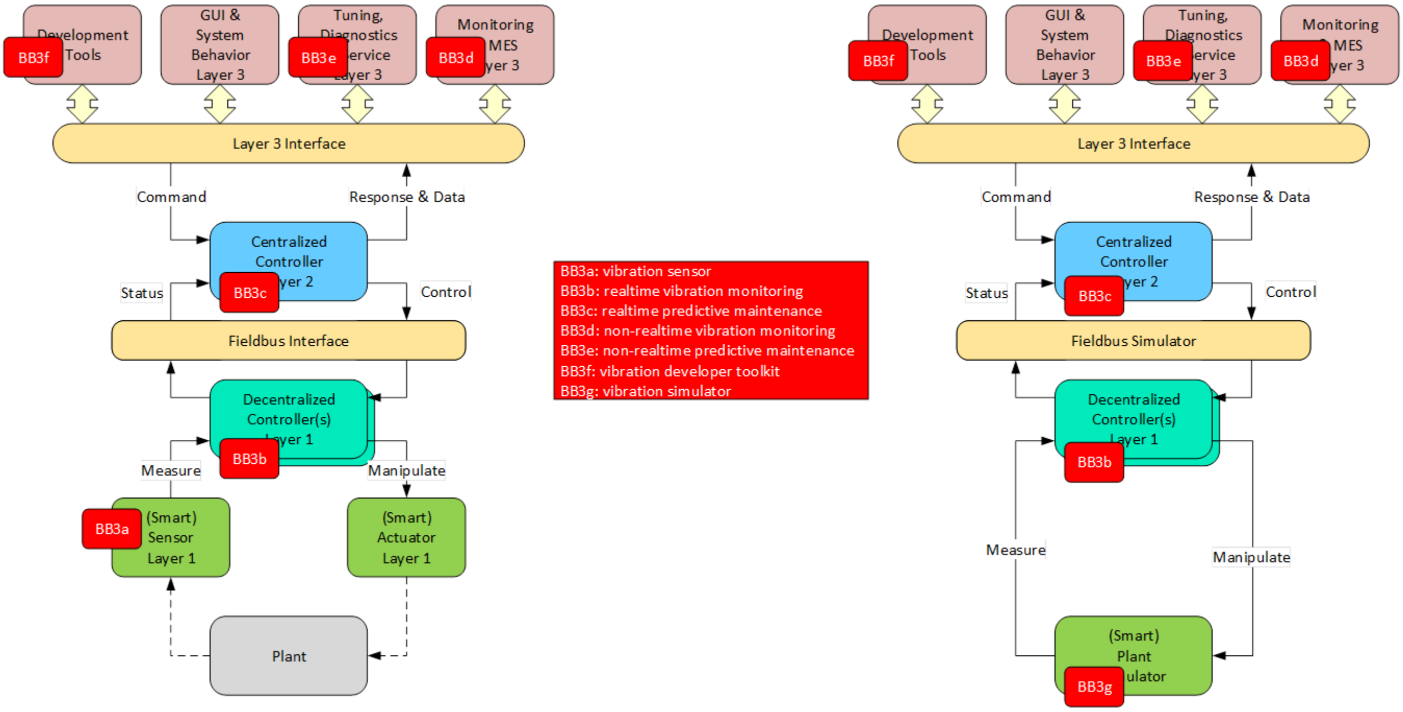


Figure 2 BB3 decomposition in Layers of I-MECH architecture

After the BB3 decomposition, the content was specified, and the potential providers and consumers of individual decomposed parts were searched for. The following paragraph shows the results.

BB3a: sensor, data reduction (DR) algorithms (pattern detection) in smart sensors, data preparation for communication with upper layer
(WP5: BUT), (Other WP: WP3), (Pilot, UC, D: P2, D1, UC1.1)
BB3b: real time vibration, temperature, acoustic, current data condition monitoring (CM), data reduction algorithms, data preparation for communication with upper/lower layer
(WP5: BUT, GEF), (Other WP:), (Pilot, UC, D: P1, P2, P5, D1, UC1.1)
BB3c: real time vibration, temperature, acoustic, current data predictive maintenance (PM), data reduction algorithms, data preparation for communication with upper/lower layer
(WP5: BUT, GEF), (Other WP:), (Pilot, UC, D: P1, P2, D1, UC1.1)
BB3d: trend-based vibration, temperature, acoustic, current data condition monitoring, data storage and visualization
(WP5: ITML), (Other WP:), (Pilot, UC, D: P1, P2, P5, D1, UC1.1)
BB3e: trend-based time sensor data predictive maintenance, data storage and visualization, data preparation for communication with lower layer
(WP5: BUT, ITML), (Other WP: WP4), (Pilot, UC, D: P1, P2, P5, D1)
BB3f: condition monitoring developer toolkit, data preparation for communication with lower layer
(WP5: T5.2), (Other WP:), (Pilot, UC, D: P1, P2, P5, D1)
BB3g: simulation/emulation of plant deterioration for MIL, SIL, HIL testing of DR/CM/PM algorithm
(WP5: BUT), (Other WP:), (Pilot, UC, D: P2)

Outputs of BB3 a-g are addressed and expanded in Task 5.3, specifically in the Deliverable 5.6 report.
After collecting the requirements from pilots, use-cases and demonstrators, common requirements were identified. They are collected in the following table. First column shows how many pilots, use-cases and demonstrators are asking for given topic. There are two numbers total number of partners and in bracket there is a number of partners

which are covered by GA. It also shows which Key Performance Identifier (KPI) in project proposal are connected with the topic. The rows in the table are sorted with descending weight. Most wanted topics are on the top.

Table 1 Analysis of requirements for the BB3 implementation

Weight	Requirement ID	Requirement number	Topic	Coming from	KPI in PP
8 (5)	rq-D5.2.BB3.1	rq-D5.2-P1-BB3.2 rq-D5.2-P2.D1 rq-D5.2-P3.D1 rq-D5.2-P5.BB3.1 rq-D5.2-D1.CM1 rq-D5.2-D2.D2(CM2) rq-D5.2-UC1.CM3 rq-D5.2-UC2.CM1	Data logging at fast sampling frequencies	P1 P2 P3 P5 D1 D2 UC1.1 UC1.2	Partly 1
6 (3)	rq-D5.2.BB3.2	rq-D5.2-P1-BB3.1 rq-D5.2-P3.D1 rq-D5.2-D1.CM1 rq-D5.2-D2.D2(CM2) rq-D5.2-UC1.CM3 rq-D5.2-UC2.CM1	Data logging at low sampling frequencies	P1 P3 D1 D2 UC1.1 UC1.2	Partly 1
6 (3)	rq-D5.2.BB3.3	rq-D5.2-P1-BB3.3 rq-D5.2-P2.D2 rq-D5.2-P3.D2 rq-D5.2-P5.D2 rq-D5.2-D2.D1 rq-D5.2-UC2.CM1	Scope - Real time access to all parameters	P1 P2 P3 P5 D2 UC1.2	Partly 1
4 (4)	rq-D5.2.BB3.4	rq-D5.2-P1-BB3.15 rq-D5.2-P2.CM1 rq-D5.2-P5.BB3.2 rq-D5.2-D1.CM1	Functionality to set one/multiple thresholds/alarms	P1 P2 P5 D1	Partly 1
3 (3)	rq-D5.2.BB3.5	rq-D5.2-P1-BB3.9 rq-D5.2-P5.CI1 rq-D5.2-UC1.SW1	Script interpret like MATLAB or Phyton (IEC 61131-3 for UC1.1)	P1 P5 UC1.1	Partly 1
3 (2)	rq-D5.2.BB3.6	rq-D5.2-P1-BB3.10 rq-D5.2-P2.CM2 rq-D5.2-P3.CP1	Utilization of actual and history data for computation of KI (Key Indicator)	P1 P2 P3	Partly 2
2 (1)	rq-D5.2.BB3.7	rq-D5.2-P1-BB3.13 rq-D5.2-UC2.CM1	Report deviations & warnings to operator	P1 UC1.2	Partly 1 and 2
2 (1)	rq-D5.2.BB3.8	rq-D5.2-P5.BB3.3 rq-D5.2-D2.CM1	Generate event-alarm on thresholds crossing	P5 D2	Partly 1 and 2
2 (1)	rq-D5.2.BB3.9	rq-D5.2-P2.CP2 rq-D5.2-P5.CP1	Monitoring tooling should have functionality to monitor: • settling time • overshoot • following error as a function of time (e.g. deterioration over time)	P2 P5	Partly 1
2 (2)	rq-D5.2.BB3.10	rq-D5.2-D1.CM1 rq-D5.2-UC1.CM2	Predictive capabilities to identify component degradation before an event.	D1 UC1.1	1

BB3 is linked with P1, P2, P5, UC1.1, D1 (there also used to be P4 but they skipped activities in WP5 and thus also in Task 5.3). The requirements were gathered also from P3, D2, UC1.2. The requirements which are required only by one brownfield solution are not inserted in this table.

6.2 Building Block 6 Control system self-commissioning unit

BB6 is related to the self-commissioning of the velocity and position control loops.
In detail, the control structure to automatically tune is the one in Figure 3. The considered control structure has been defined during the meetings of the BB6/Task 5.4 group.

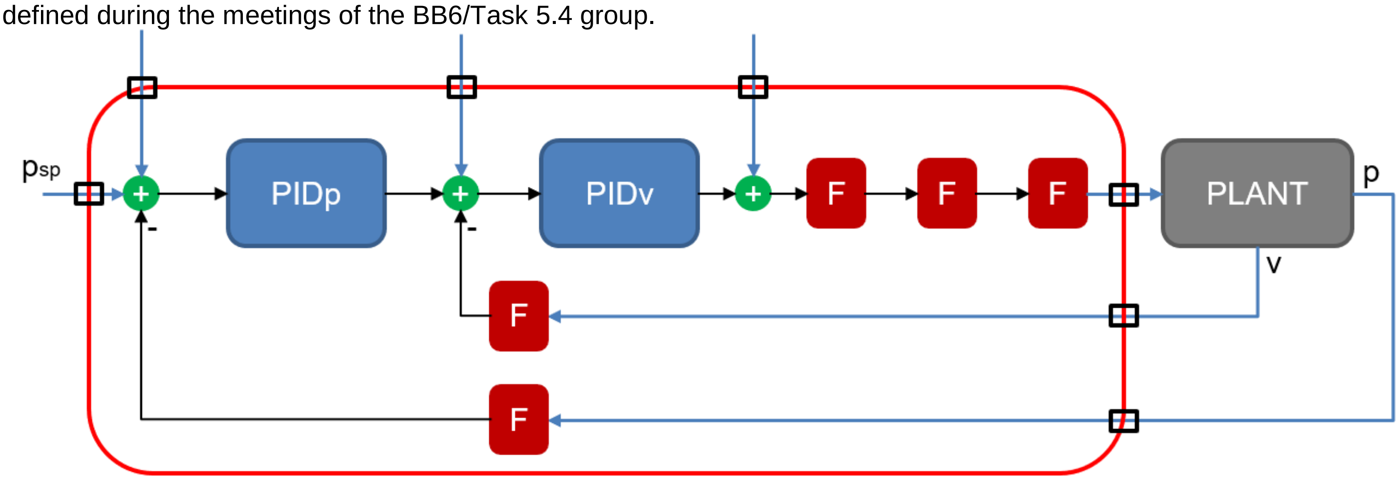


Figure 3 BB6 considered control structure for auto-tuning

BB6 is divided in 4 main parts:

a) Automatic controller commissioning interface (Layer 3)
b) Trajectory manager (Layer 2)
c) Data acquisition module (Layer 2)
d) Tuning manager (Layer 3)

that communicate to each other as shown in Figure 4.

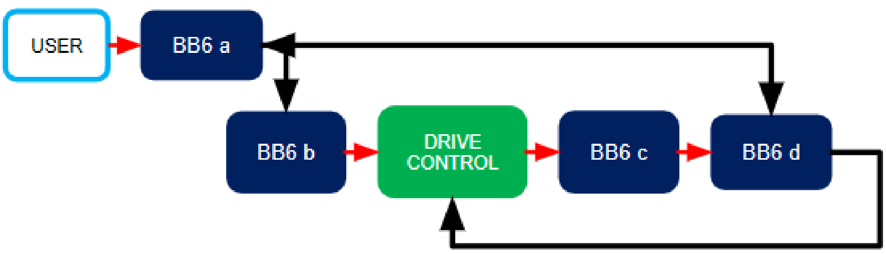


Figure 4 Interconnection between BB6 subparts

The subparts of the BB6 are located in both Layer 2 and Layer 3 as shown in Figure 5.

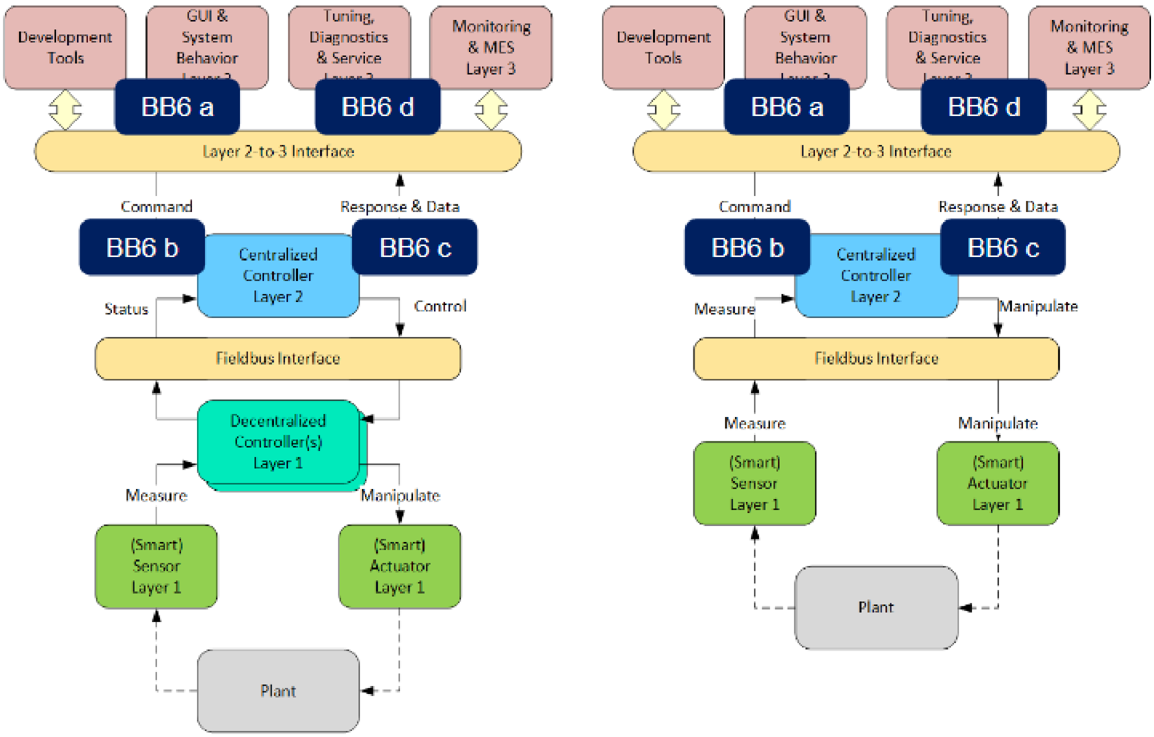


Figure 5 BB6 decomposition in the I-MECH framework

The common requirements of the Pilots for the BB6 implementation are shown in Table 2, while in Figure 6 the BB6 core definition is represented.

Table 2 Requirements of the Pilots for the BB6 implementation

RQ id	Description	Pilots
rq-D5.2.BB6.1	Engineering programming language	P1, P2, P5
rq-D5.2.BB6.2	Feedforward commissioning	P1, P2, P5
rq-D5.2.BB6.3	Feedback commissioning	P1, P2, P5
rq-D5.2.BB6.4	Respect predefined constraints	P1, P2, P5
rq-D5.2.BB6.5	Live tracing (time and freq. domain)	P1, P2
rq-D5.2.BB6.6	Stability monitor	P2
rq-D5.2.BB6.7	Performance monitor	P2
rq-D5.2.BB6.8	Manual stop of the procedure	P5
rq-D5.2.BB6.9	SISO systems (decoupled for autotuning)	P1, P2, P5

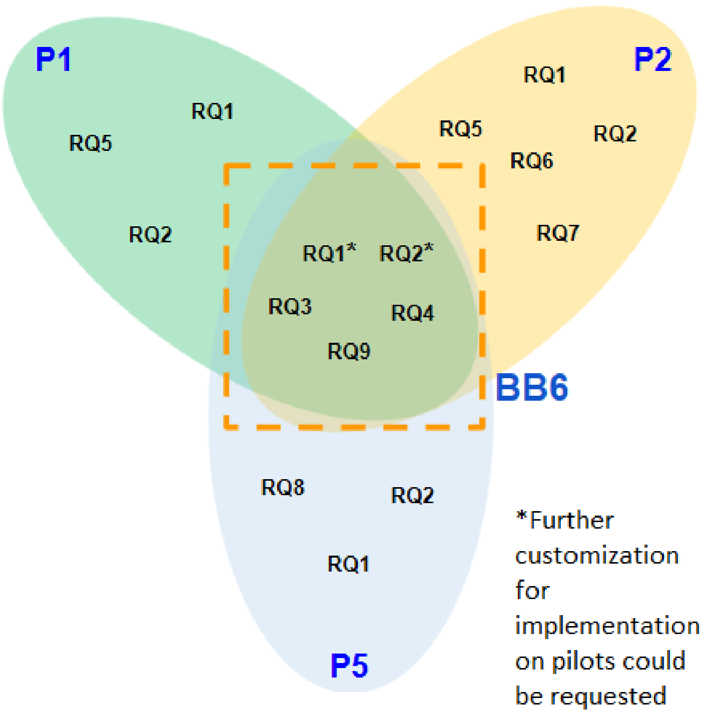


Figure 6 BB6 Requirements definition

As it is possible to notice, from a first analysis of the requirements, the requirements that should be fulfilled to create BB6 are:

- Modified version of RQ1
- Modified version of RQ2
- RQ3
- RQ4
- RQ9.

It is important to remark that a deeper analysis of the requirements for the creation of BB6 will be defined in the upcoming deliverable (D5.3).

Different automatic tuning methodologies have been developed during the last years, but all of them have a common disadvantage: the constraints of the systems, that are for example the Torque/Force, Position and Speed limits, are not considered. Other issues include the necessity of closed-loop identification (e.g. for unstable plants with hanging loads) which requires a special treatment during the signal processing phase in order to avoid systematic errors, this is typically not supported by off-the-shelve HW/SW. Furthermore, the common tuning rules that can be easily found in the literature give only a starting point for the controller tuning. In fact, if a more performing tuning is desired, an operator needs to manually modify the controller parameters.

In addition, the time required currently for the controller tuning needs to be reduced in order to decrease the overall setup time of the machine avoiding time-demanding manual tuning by human operators and, therefore, the costs. In BB6 these limitations have been explicitly considered in order to obtain a more robust and performing tuning strategy, without the intervention of the operator and by reducing the setup time of the machine.

BB6 also utilises optimized excitation trajectories allowing to improve signal to noise ratio, excitation bandwidth and required stroke, while the use of new theoretical advances in design methods for fixed-structure low-order controllers such as PIDs meets a need which is not supported by standard control theory and produces complex controllers of high order that are inherently difficult to implement in practice. Finally, the utilization of the model uncertainty information for the synthesis of robust controllers in BB6 serves as an alternative to relying on a single nominal model which in practice always differs to some extent from the physical reality.

7 Specifications for the I-MECH platform behaviour layer interface and connectivity

The objective for this deliverable is to provide the final requirements and specifications for the system behaviour layer connectivity and interfaces as part of the I-MECH platform. With this in mind the updated requirements and specifications from the participating pilots and use-cases are collated into one common set with the aim of outlining the Layer 3 interface and connectivity platform for I-MECH. The requirements are divided into functional and non-functional requirements to cover both the motion system behaviour and operation respectively.

7.1 Functional requirements

Functional requirements define specific behaviour or functions of the system, they describe what a system is supposed to accomplish. The functionality of the behaviour layer in the I-MECH context focuses on the interfaces between the Layer 2 control layer and Layer 3 system behaviour layer and not the hardware associated with information communication and storage. The following subsections detail the communication and interface, data processing and management, and software requirements for the I-MECH system.

7.2 Communication and interface requirements

ID	Original Requirement.	Obligat-ion	Additional refinement/ requirement detail.	Layers	Type (HW/ SW)	Application	Task/ BB
	Communication and interface requirements						
rq-D5.2-IC.C1	Multi-client interface with parallel access for scripting/GUI.	R	Commonly used scripting tools like Phyton, MATLAB, … are preferred.	L1 L2	SW	P1, P2	T5.2
rq-D5.2-IC.C2	OPC UA.	R	Mainly for the communication between layer 2 and layer 3.	L2-L3	SW	P1, P2, P5	T5.2
rq-D5.2-IC.C3	Scripting.	R		L2, L3	SW	P1, P2	T5.2
rq-D5.2-IC.C4	ISA 95 standard for automated interface between enterprise and control systems.	R		L2-L3	SW	all	T5.2
rq-D5.2-IC.C5	Ethernet IP/EtherCAT.	R	Have enough bandwidth in case of condition monitoring data logging at upper layer, e.g. 500 kbit/s up to 20 Mbit/s.	L1, L2, (L3)	HW, SW	P1, P2, P5, UC1.1	T5.2, T5.3, T5.4
rq-D5.2-IC.C6	OPC UA Wireless sensors connection to PLC or upwards to	R		L1-L2 (-L3)	SW		T3.4/ BB3

	Level 3 or above wireless sensor data transmission to PLC.						
rq-D5.2-IC.C7	Compatibility with communications protocols and wireless frequency (x Hz).	R		L1-L2 (-L3)	SW		T3.4/ BB3

7.2.1 Data processing and management requirements

ID	Original Requirement.	Obligat-ion	Additional refinement/ requirement detail.	Layers	Type (HW/ SW)	Application	Task/BB
	Data processing and management requirements						
rq-D5.2-IC.DP1	Data logging.	R	Enough bandwidth and storage capacity to be able to transfer and store long term (historical) diagnostic data.	L3	SW	T WP5	5.2
rq-D5.2-IC.DP2	Real time access to parameters in the control layer.	R		L3	SW	T WP5	5.2
rq-D5.2-IC.DP3	Process data of raw data outside the condition monitoring measurement module.	R	High performance requirements to be able to do signal pre-processing, data reduction, features extraction and trend/history analysis.	L3	SW	T WP5	5.2

7.2.2 Software requirements

ID	Original Requirement	Obligat-ion	Additional refinement/ requirement detail	Layers	Type (HW/ SW)	Application	Task/BB
	Software requirements						
rq-D5.2-IC.SW1	Compatibility with MATLAB Simulink.	R	Simulink creates the bridge to FMU.	L1, L2, L3	SW	T WP5	5.2
rq-D5.2-IC.SW2	Ability to write custom communication layers to interface with factory automation.	R	For the simplification of the connection with brown field applications.	L3	SW	T WP5	5.2

7.3 Non-functional requirements

Updated for revised partner inputs. In systems engineering, a non-functional requirement is a requirement that specifies criteria that can be used to judge the operation of a system, rather than the functional requirements which are specific to system behaviour. The following subsections detail the condition monitoring, novel autonomous instrumentation, control layer self-commissioning and control layer performance requirements for the I-MECH system. Revise subsections for application/implementation in I-MECH platform, connecting with WP 6.

7.3.1 Condition monitoring

Revised description of condition monitoring for WP5, with focus on the I-MECH platform. Taken from [Seamus, 2018], the International Organization for Standardization deals with condition monitoring programme for machines in following ISO standards. Their aim is to provide general guidelines for condition monitoring to identify and avoid principle cause of failures [ISO 17359, 2011].

- ISO 17359, Condition monitoring and diagnostics of machines — General guidelines
- ISO 13373, Mechanical vibration and shock - Vibration condition monitoring of machines
- ISO 13379, Data interpretation and diagnostic techniques which use information and data related to the condition of a machine.
- ISO 13381, Condition monitoring and diagnostics of machines – Prognostics

BB3 with its condition monitoring should rely on these standards. BB3 will play a key role in Pilots 1, 2, 3 & 5, Demonstrator 1 & 2, as well as Use Cases 1 & 2. Dedicated condition monitoring module with close connection to sensorics and interfaced to the main control system where time domain data can be easily transferred can be located in layer 1. In layer 2, the main control system with reduced diagnostic data throughput and loading, more difficult connection to diagnostic sensorics in the presence of high electrical noise environment should be designed, possible use of smart sensorics could reduce additional loading of main control system. Positioned in L3, batch processing, offline analysis of historical data, no immediate notifications. No evaluation of data in real-time.

Finalised requirements for condition monitoring are summarized in following table.

ID	Original Requirement	Obligation	Additional refinement/ requirement detail	Layers	Type (HW/ SW)	Application	Task/ BB
	General functionality of the condition monitoring module						
rq-D5.2-CM.G1	Functionality to set thresholds/alarms.	R	This functionality should be available at all layers based on requirements on speed of response of the whole condition monitoring system to non-critical or severe diagnostic events.	L1,L2,L3	SW	T WP5	T5.3
rq-D5.2-CM.G2	Possibility to calculate KPIs based on	R	Sensor fusion and/or historical data availability required.	L3 (L2)	SW	T WP5	T5.3

	multiple variables & history.						
rq-D5.2-CM.G3	Functionality to predict/extrapolate.	O	Historical data required.	L3 (L2)	SW	T WP5	T5.3
rq-D5.2-CM.G4	Database with standard functions/fingerprints to detect failure of commonly used systems.	R	Database should be based on historical data and should contain enough patterns for normal conditions, abnormal conditions and failure conditions of the analysed system.	L3	SW	T WP5	T5.3
rq-D5.2-CM.G5	Use of standardized interface to interface with condition monitoring tooling.	R	Standardized OPC UA information model is expected.	L2/L3	SW	T WP5	T5.3
rq-D5.2-CM.G6	Trend analysis on selected features (e.g. RMS value).	R	Main procedure for continuous on-line condition monitoring of drive mechanics. Evaluation of vibration severity can be guided by ISO 10816-3 standard. Analysis of additional features can be considered in specific application cases.	L1 (L2)	SW	T WP5	T5.3
Rq-D5.2-CM.G7	Analysis during transition states.	O	The system must allow measurement and analysis in the intermediate transition states of the rotating mechanical system during its normal operation, where the typical transition states are run-up and slow-down. These transition states could be also initiated by diagnostic unit in case of serious suspicion of mechanical failure.	L1	SW	T WP5	T5.3
	Condition monitoring of electrical drive mechanics and electronics						
rq-D5.2-CM.D1	Monitoring of mechanical unbalance and shaft misalignment.	R	Monitoring of RMS value in frequency band defined by ISO standard (10 Hz – 1kHz). Analysis at fundamental rotational	L1	SW	T WP5	T5.3

			frequency (1st harmonics). For large unbalances also 2nd harmonics analysis beneficial. For shaft misalignment also, analysis at 3rd harmonics necessary.				
rq-D5.2-CM.D2	Monitoring of bearings failure or wear (early detection).	O	Very early detection of bearing wear using ultrasonic (acoustic) emission necessary. In case of evolvement of wear acceleration envelope analysis sufficient – need to filter out low frequency components, later on spectral analysis of vibration velocity required – detection at specific bearing failure frequencies (outer/inner ring, rolling elements, cage).	L1	SW	T WP5	T5.3
rq-D5.2-CM.D3	Monitoring of gearbox teeth wear.	O	Passband or spectral analysis at specific frequencies related to rotational speed and number of gearbox teeth.	L1	SW	T WP5	T5.3
rq-D5.2-CM.D4	Monitoring of winding electrical failure.	O	Analysis of acceleration signals at specific frequencies induced by magnetostriction and torsional vibrations related to fundamental frequency of power network and number of pole pairs induced by eccentricity of stator/rotor (sheets shortcut), winding shortcut, asymmetry of rotor cage in asynchronous drives.	L1	SW	T WP5	T5.3
	Required interfaces to sensorics and signal processing modules.		Sampling frequency and measurement strategy for each component strongly depends on application and selected features, which is planned to be monitored.				
rq-D5.2-CM.S1	Low level digital interface for modern vibration and acoustic sensors.	R	Digital interfaces for modern vibration and acoustic sensors – PDM, TDM, I2S. PDM interface requires digital clock frequency in MHz range (1MHz – 4,8 MHz).	L1	HW	T WP5	T5.3, T5.2

rq-D5.2-CM.S2	Interface for temperature sensors.	R	Temperature measurements with low sampling rate is expected (~1Hz). Analog interface with unified output voltage/current level, or more preferably direct digital interface (e.g. I2C, SPI) of the sensor.	L1	HW	T WP5	T5.3, T5.2
rq-D5.2-CM.S3	Digital interface for modern vibration and acoustic sensors.	R	Serial synchronous digital interface with enough data rate to transfer all output values inside one sample cycle (1Mbit/s up to 10 Mbit/s), e.g. SPI.	L1	HW	T WP5	T5.3, T5.2
rq-D5.2-CM.S4	Low level analog interface for classical vibration and acoustic sensors.	R	General vibrodiagnostic measurements with lower sampling frequency (~10 kHz). Analog sensor interface with pure voltage output or with IEPE using current excitation of the sensor.	L1	HW	T WP5	T5.3, T5.2
rq-D5.2-CM.S5	High bandwidth analog interface for acoustic (ultrasonic) emission sensors.	O	Early detection using high frequency acoustic emission components needs high sampling frequency (>500 kHz).	L1	HW	T WP5	T5.3
rq-D5.2-CM.S6	Digital interface for digital incremental encoders.	R	Classical TTL based encoder input or advanced digital interface (e.g. EnDAT).	L1	HW	T WP5	T5.3, T5.2
rq-D5.2-CM.S7	Analog interfaces for analog output rotational rate sensor or analog resolver.	R	Enough bandwidth to cover expected rotational rates, e.g. incremental sinusoidal signals, sin-cos signals.	L1	HW	T WP5	T5.3, T5.2
rq-D5.2-CM.S8	Digital interface to smart sensors with integrated electronics (RS-485).	R	Synchronous/asynchronous serial digital interface with enough data rate to transfer all pre-processed output data from smart sensors within one expected sample cycle (4Mbit/s up to 20 Mbit/s). Interface with high noise immunity.	L1	HW	T WP5	T5.3, T5.2
rq-D5.2-CM.S8	High level communication interface (process bus) to signal processing and analysis module.	R	In case of signal processing and analysis in dedicated measurement module, data rate can be highly reduced to transfer only warnings, failures or low frequency diagnostic information (e.g.	L1/L2	HW	T WP5	T5.3, T5.2

			vibration severity ~ effective values).				
	Measurements and analysis hardware needed for condition monitoring methods						
rq-D5.2-CM.M1	Measurement of speed and position of rotation.	R	General requirement for vibration diagnostics and mechanical system condition monitoring. Rotational speed and shaft position information.	L1	HW	T WP5	T5.3
rq-D5.2-CM.M2	Hardware for vibration severity measurement – overall fault detection.	R	One low noise acceleration sensor (MEMS or miniature piezo) with 3-axis, sensor self-noise less than 40 ug/Hz and resonant frequency higher than 5 kHz, acceleration range up to 20 g, sampling rate of at least 4 kS/s, measurement in extended ISO bandwidth (1/10 Hz up to 1 kHz), analog or preferably digital interface to the signal pre-processing and effective value calculation.	L1	HW	T WP5	T5.3, T3.2
rq-D5.2-CM.M3	Hardware for vibration diagnostics - unbalance	R	One low noise acceleration sensor (MEMS or miniature piezo) with 3-axis per bearing (typ. two sensors needed), self-noise less than 40 ug/Hz, sampling rate of at least 4 kS/s, frequency range higher than 10 Hz, depending on shaft speed, analog or preferably digital interface to the signal pre-processing and following analysis. Filtering on rotational frequency with analog or digital tracking filter with quality factor better than 20. Measurement of rotation rate and shaft position with one speed sensor.	L1	HW	T WP5	T5.3, T3.2

rq-D5.2-CM.M4	Hardware for vibration analysis – gears and gearboxes faults.	O	Acceleration sensor (MEMS or piezo), one sensor per gearbox shaft, sampling rate of at least 4 kS/s, measurement bandwidth >1 kHz, depending on gear type. Analog or preferably digital interface to the signal pre-processing and following features extraction.	L1	HW	T WP5	T5.3, T3.2
rq-D5.2-CM.M5	Hardware for vibration diagnostics of bearings/lubrication - early fault detection/prediction.	O	High frequency accelerometer, AE sensor (ultrasonic emission), one sensor per bearing, one sensor per system (with advanced DSP), resonance sensors or broadband detection sensors, measurement bandwidth up to 1 MHz (depending on bearing type), typical sampling rate higher than 1 MS/s. High performance pre-processing is needed.	L1	HW	T WP5	T5.3, T3.2, T3.3
rq-D5.2-CM.M6	Hardware for acoustic diagnostics - noise emission, squeak and rattle.	O	One MEMS microphone per system (with advanced DSP), measurement bandwidth up to 20 kHz, sampling rate of 50 kHz, digital interface with SPI/PDM.	L1	HW	T WP5	T5.3, T3.2, T3.3
rq-D5.2-CM.M7	Hardware for temperature diagnostics of power electronics.	R	One or more temperature sensors (RTD, semiconductor, thermocouple), virtualization or model-based temperature distribution approach in case of one sensor, sampling rate of 10 S/s model-based temperature distribution.	L1	HW	T WP5	T5.3, T3.2

7.3.2 Control layer self-commissioning

Revised description of control layer self-commissioning for WP5, with focus on the I-MECH platform.

Final requirements for self-commissioning are summarized in the following table.

ID	Original Requirement	Obligation	Additional refinement/ requirement detail	Layers	Type (HW/ SW)	Application	Task/ BB
	Tracing						
rq-D5.2-SC.T1	Functionality to set thresholds/alarms.	O	Number of thresholds shell be selectable with different alarm levels.	L2, L3	SW	T WP5/6	T5.4
rq-D5.2-SC.T2	Live tracing in time and frequency domain (bode & Nyquist) of all parameters within control system.	O	For manual commissioning and troubleshooting.	L3	SW	T WP5/6	T5.4
rq-D5.2-SC.T3	Triggering functionality for traces.	O	Like real scope.	L2, L3	SW	T WP5/6	T5.4
rq-D5.2-SC.T4	Auto tuning approach should allow the use of "proprietary" instrument for tracing (like scope) that are generally available in commercial drives.	R	The tuning method through "standard" language will define the approach for identification steps and signals that can be used to trigger scope system. The tracing instrument should provide the data collected through open-language (like txt, xml).	L2, L3	SW	T WP5	T5.4
	Auto tuning / Control architecture						
rq-D5.2-SC.AT1	Auto tuning application/function/library/interface that works with a wide range of control algorithms, both feedforward and feedback (not only PID). E.g. I-MECH control algorithms of BB7,8,9 should specify their tunable parameters and tuning strategy to the auto tuning application/function. The auto-tuning function should provide generic optimization functions, parameter	R	Task 5.4 will be used as collector for auto-tuning approaches that have to be developed on BB7, BB8, BB9 (Task 4.4, 4.5, 4.6).	L2, L3	SW	T WP5/4/3	T5.4 T4.4 T4.5 T4.6 T3.6

	estimation functions, noise generation functions, ...						
	System limits						
rq-D5.2-SC.SL 1	Auto tuning functionality should respect configurable torque, position & velocity limits.	R	These limits are dependent on the I-Mech application, and it should be defined at the beginning of the identification steps.	L2, L3	SW	T WP5	T5.4
rq-D5.2-SC.SL 2	Limits should be configurable for all axes.	R	General approach will be based on SISO system, but compatible also for MIMO system.	L2, L3	SW	T WP5	T5.4
rq-D5.2-SC.SL 3	A sequence should be specifiable.	R	Optionally via scripting interface to get system in right configuration for auto-tuning.	L2, L3	SW	T WP5	T5.4
	System identification						
rq-D5.2-SC.SI1	Tools should be suited for system identification & parameter estimation purposes.	R	Expected contributions from Task 4.3.	L2, L3	SW	T WP5/4	T5.4 T4.3
	Feedforward						
rq-D5.2-SC.FF 1	The self-commissioning function should be able to fit basic model to identified system and be able to commission feedforward controllers based on fitted model for: -friction compensation -mass compensation -spring compensation -gravity compensation -passive vibration compensation (input shaping).	R	Expected contributions from Task 4.3 and 4.4.	L2, L3	SW	T WP5/4	T5.4 T4.3 T4.4
	Scripting						
rq-D5.2-	It should be possible to use self-commissioning	R	Compatibility with standard language like MATLAB, Python.	L2, L3	SW	T WP5/6	T5.4

SC.SC 1	functionality in combination with scripting.						
	Validation						
rq-D5.2-SC.V1	Validation signals and approach should be defined.	R	It shall be possible to check the performance of the auto tuning parameters.	L2, L3	SW	T WP5	T5.4

7.3.3 Control layer performance

Description focusing on I-MECH platform control performance. The placement of control layer performance monitoring in a view of the I-MECH concept is similar to self-commissioning. It also belongs to the Control layer or Layer 2. It serves as a data reduction (data pre-processing) algorithm which passes to the upper level only some indicators or classifiers.

ID	Original Requirement	Obligation	Additional refinement/ requirement detail	Layers	Type (HW/ SW)	Application	Task/ BB
	Stability						
rq-D5.2-CLP.S 1	Monitoring tooling should have functionality to calculate and monitor stability and robustness margins of feedback loops as well as self-learning algorithms from BB9.	R		L2, L3	SW	T WP5	T5.3 T4.5
	Performance						
rq-D5.2-CLP.P 1	Monitoring tooling should have functionality to monitor: -settling time -overshoot -following error as a function of time (e.g. deterioration over time).	R		L2, L3	SW	T WP5	T5.3 T5.4

8 I-MECH pilots – Requirements specification

8.1 Industrial printing - Generic substrate carrier (GSC) (Pilot 1- Sioux CCM)

A description of the pilot system and the context of the listed requirements can also be found in D7.1. D7.1 is considered as the leading document for the latest revision of all requirements and information related to pilot 1.

ID	Original Requirement	Obligation	Additional Refinement/ Requirement Detail	Verification	Layers	Type (HW/ SW)	Task/ BB
	Communication and interface requirements						
rq-D5.2-P1-L3.1	The platform shall support Ethernet communication.	R	For communication between layer 3 and rest of the world.	I D7.1	L3	SW	T5.2
rq-D5.2-P1-L3.2	Multi-client interface with parallel access between layer 3 and rest of the world.	R		I D7.1	L3	SW	T5.2
rq-D5.2-P1-L3.3	Automation programming language.	R	The controller architecture should provide possibility for scripting automated sequences in an interpreted high-level programming language like Python, which allows for easily changing the scripts.	I D7.1	L2, L3	SW	T5.2
rq-D5.2-P1-L3.4	OPC UA server.	O	• Easy interface to configure server.	I D7.1	L1, L2, L3	SW	T5.2

			• Preferably with automatic code generation to make variables and parameters used in underlying control/instrumentation layer available on the server and create methods/alarms/…. Automatically. • With encryption/user rights management.				
	Data processing and management requirements						
rq-D5.2-P1-BB3.1	Automatic logging (tracing) of long-term effects at low frequency sampling (1Hz) which are saved on host PC.	R	Examples of long-term effect signals: forces, temperatures, pump speeds, number of revolutions.	I D7.1	L2, L3	SW	T5.3
rq-D5.2-P1-BB3.2	Automatically save relevant trace data the of last 10 seconds when a system error occurs (e.g. maximum tracking error exceeded).	R	Examples of relevant trace signals: setpoints/tracking errors/forces.	I D7.1	L2, L3	SW	T5.3
rq-D5.2-P1-BB3.3	Remote diagnostics & logging.	R	Controller architecture should provide possibility for remote access/control.	I D7.1	L3	SW	T5.3
	Condition monitoring						
rq-D5.2-P1-BB3.9	Engineering Programming Environment[1].	R	Should provide possibility to create and run (interpret) text editable recipes for scripting automated sequences. Preferably in an engineering programming language like Python or MATLAB. This allows for easy creation and modification of sequence scripts by engineers without having to re-compile any software.	I D7.1	L3	SW	T5.2/ T5.3
rq-D5.2-P1-BB3.10	Detect (required) or predict (optional) deviations from expected behaviour that	R		T D7.1	L2, L3	SW	T5.3

[1] E.g. AxChange python scripting interface, capable of easily creating and performing test routines which are typically a combination of programmable machine actions, parameter access and modification, signal monitoring and tracing, calling data analysis routines, generate user (operator) feedback (could also be a report).

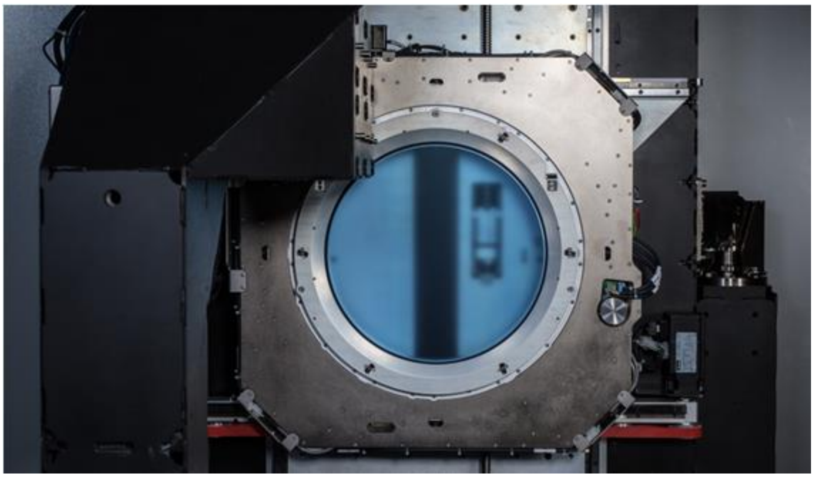
	indicate system pollution or wear, preferably using sensor and controller signals already available in the system. **Typical GSC KPI's to monitor**[2] KPI to monitor Average print overlay error per second (based on position error) Motor torque vs Vacuum pressure Vacuum motor speed vs Vacuum pressure Motor temperature vs motor torque Standard deviation of X, Y, Rz controller output Periodic errors of belt edge sensors Encoder signal quality		Issue to detect Decrease in quality of printer output Ink spill / contamination below belt Sliding bearing of belt damaged / moved Obstruction/leakage of vacuum system Failure of motor cooling Instability of controllers Contamination of belt edge Errors in encoder alignment Contamination of encoder				
rq-D5.2-P1-BB3.10a							
rq-D5.2-P1-BB3.11	System self-tests at start-up / check-up on demand in order to easily create and perform self-tests using Engineering Programming Environment to help find (imminent) system failures prior to operation or during/after service actions. **Typical GSC self-tests:**[3] Test Verify gap sensor output at rest Verify noise on belt edge sensor at rest Verify system dynamics Sensor/actuator tests **Generic self-tests:**	O	Note: This is an extensive check-up, a sequence that checks relevant dynamics, sensors, actuators, accuracy etc. This function is to be used when there is a suspicion that the system is not working correctly. Issue to detect Gap sensors broken Belt edge sensor light cover present Mechanical changes to system Sensor or actuator failure, mechanical obstructions.	T D7.1	L3	SW	T5.3

[2] These are examples of typical KPI's specific for the GSC system, only a subset of them will be developed to prove the principle. Preferably the most generic KPI's that are also useful for other Pilot systems.
[3] These are examples of typical self tests specific for the GSC system, only a subset of them will be developed to prove the principle. Preferably the most generic self tests that are also useful for other Pilot systems.

	Test Verify stability and robustness margins of feedback loops and learning feedforward algorithms		Issue to detect • System component failure • System modifications • System environment modifications				
rq-D5.2-P1-BB3.12	BBs (e.g. BB5 amplifiers) should have a self-test and be able to report their status.	O		I D7.1	L1, L2, L3	HW, SW	T5.3
rq-D5.2-P1-BB3.13	Report deviations & warnings to operator such that operator is warned in time to perform maintenance.	R		I D7.1	L3	SW	T5.3
rq-D5.2-P1-BB3.15	Functionality to set thresholds/alarms.	R	Prevention of false errors due to changes in setpoints, etc.	I D7.1	L1, L2, L3	SW	T5.3
rq-D5.2-P1-BB3.18	Database with standard functions/fingerprints to detect failure of commonly used systems.	O		T D7.1	L3	SW	T5.3
	Control layer self-commissioning						
rq-D5.2-P1-BB6.1	Engineering Programming Environment [AxExchange, 2018].	R	This environment should provide possibility to create and run (interpret) text editable recipes for scripting automated sequences. Preferably in an engineering programming language like Python or MATLAB. This allows for easy creation and modification of sequence scripts by engineers without having to re-compile any software.	I D7.1	L3	SW	T5.4
rq-D5.2-P1-BB6.2	Feedback control loop commissioning.	R	• 3x position control, • 2x velocity control, • optional: 1x Pressure control (very slow system dynamics). Fully automated identification and commissioning of at least the following feedback structure parameters: PID + 3 generic purpose filters.	T D7.1	L2, L3	SW	T5.4
rq-D5.2-P1-BB6.3	Feed forward commissioning.	R	Fully automated identification and commissioning of at least	T D7.1	L2, L3	SW	T5.4

			the following setpoint feed forward parameters: • acceleration, • static friction, • viscous friction.				
rq-D5.2-P1-BB6.4	Automatic controller commissioning functions/toolbox Application optimization criteria and constraints shall be configurable. • Application optimization examples: o Accuracy o Bandwidth o Sensitivity… • Application constraints examples: o Hardware limits o Position, velocity, torque limits	R	Should be applicable to a wide range of control algorithms, both (learning) feedforward and feedback (not only PID). The automatic controller commissioning function should therefore provide generic optimization functions, system identification and parameter estimation functions, noise generation functions, etc.	I D7.1	L2, L3	SW	T5.4
rq-D5.2-P1-BB6.11	Roller reluctance actuators / sensors calibration.	O	Fully automated measurement, parameter calculation and verification sequence.	T D7.1	L2	SW	T5.4
rq-D5.2-P1-BB6.12	Roller encoder eccentricity calibration.	O	Fully automated measurement, parameter calculation and verification sequence.	T D7.1	L2, L3	SW	T5.4
rq-D5.2-P1-BB6.13	Roller motor position dependent force calibration.	R	Fully automated measurement, parameter calculation and verification sequence.	T D7.1	L2, L3	SW	T5.4
rq-D5.2-P1-BB6.14	Roller un-roundness calibration.	R	Fully automated measurement, parameter calculation and verification sequence.	T D7.1	L2, L3	SW	T5.4
rq-D5.2-P1-BB6.15	Belt edge calibration.	O	Fully automated measurement, parameter calculation and verification sequence.	T D7.1	L2, L3	SW	T5.4

8.2 Semiconductor production - 12-inch wafer stage (Pilot 2 – Nexperia)



ID	Original Requirement	Obligation	Additional Refinement/ Requirement Detail	Verification	Layers	Type (HW/ SW)	Task / BB
	Communication and interface requirements						
rq-D5.2-P2.CI1	Multi-client - Multi client interface with parallel access for scripting/gui etc. -> via OPC UA?	R	Use of OPC UA is not essential.	T WP5	L2, L3	SW	T5.2
	Data processing and management requirements						
rq-D5.2-P2.D1	Logging - Data logging functionality, log resolution should be the same as update rate of control system.	R	Appears to require functionality across layers.	T WP5	L1, L2, L3	SW	T5.2
rq-D5.2-P2.D2	Scope - Real time access to all parameters in control layer/instrumentation layer with scope functionality with nice GUI.	R	Appears to require functionality across layers.	T WP5	L1, L2, L3	SW	T5.2
	Software requirements						
rq-D5.2-P2.SW1	Compatible with control layer written/modelled in MATLAB Simulink.	R		T WP5	L3	SW	T5.2
rq-D5.2-P2.SW2	Ability to write custom communication layers.	R	e.g. a SECS/GEM interface to factory automation.	T WP5	L3	SW	T5.2
	Condition monitoring						
rq-D5.2-P2.CM1	Alarms.	R	Functionality to set thresholds/alarms.	T WP5	L3	SW	T5.3

rq-D5.2-P2.CM2	KPIs.	R	Possibility to calculate KPIs based on multiple variables & history.	T WP5	L3	SW	T5.3
rq-D5.2-P2.CM3	Standardized interface - Use of standardized interface to interface with condition monitoring tooling.	R	Possibly via a standardized OPC UA information model.	T WP5	L3	SW	T5.3
	Control layer self-commissioning						
rq-D5.2-P2.SC1	Tracing - Live tracing in time and frequency domain (bode & Nyquist) of all parameters within control system (for manual commissioning and troubleshooting).	R	Triggering functionality for traces (like real scope).	T WP5	L2, L3	SW	T5.4
rq-D5.2-P2.SC2	Auto tuning - Auto tuning application/function/library/interface that works with a wide range of control algorithms, both feedforward and feedback (not only PID).	R	E.g. I-MECH control algorithms of BB7,8,9 should specify their tuneable parameters and tuning strategy to the auto tuning application/function. The auto-tuning function should provide generic optimization functions, parameter estimation functions, noise generation functions, ...	T WP5	L2, L3	SW	T5.4
rq-D5.2-P2.SC3	System limits.	R	Auto tuning functionality should respect configurable torque, position & velocity limits. Limits should be configurable for all axes. A sequence should be specifiable (optionally via scripting interface) to get system in right configuration for auto-tuning.	T WP5	L2, L3	SW	T5.4
rq-D5.2-P1.SC4	System identification.	R	Tooling should be suited for system identification & parameter estimation purposes.	T WP5	L2, L3	SW	T5.4
rq-D5.2-P2.SC5	Feedforward - The self-commissioning function should be able to fit basic model to identified system and be able to commission feedforward controllers based on fitted model for: • friction compensation • mass compensation	R	We are also interested in jerk and snap feedforward, but this is not a requirement.	T WP5	L2, L3	SW	T5.4

	• spring compensation • gravity compensation						
rq-D5.2-P2.SC6	Scripting.	R	It should be possible to use self-commissioning functionality in combination with scripting (e.g. using Python).	T WP5	L3	SW	T5.4
	Control layer performance						
rq-D5.2-P2.CP1	Stability Monitoring tooling should have functionality to calculate and monitor stability and robustness margins of feedback loops as well as self-learning algorithms from BB9	R		T WP5	L3	SW	T5.4
rq-D5.2-P2.CP2	Performance - Monitoring tooling should have functionality to monitor: • settling time • overshoot • following error as a function of time (e.g. deterioration over time)	R		T WP5	L3	SW	T5.4
	Functional Testing						
rq-D5.2-P2.FT1	Virtual testing and calibration process.	R	Functional testing and calibration must rely on virtual testing (S-function or FMI MiL OPC/UA HiL) prior to commissioning.	WP 4/5	L1, L2, L3	SW	T5.1, T4.2, T4.4, T4.6

8.3 High speed packaging - In-line filling & stoppering machine, Tea bag machine (Pilot 3 – IMA)

ID	Original Requirement	Obligation	Additional Refinement/ Requirement Detail	Verification	Layers	Type (HW/ SW)	Task/ BB
	Communication and interface requirements						
rq-D5.2-P3.CI1	OPC-UA, OPC-DA, ModbusTCP for HMI communication.	R		T WP5	L3	SW	T5.2
rq-D5.2-P3.CI2	EtherCAT, Powerlink, SercosIII as fieldbuses for IO and Motion.	R		T WP5	L2-L1	SW	T5.2
rq-D5.2-P3.CI3	MQTT, AMPQ for machine to cloud communication.	R		T WP5	L3	SW	T5.2
rq-D5.2-P3.CI4	WebServer for online access to relevant variables and parameters.	R		T WP5	L3	SW	T5.2
	Data processing and management requirements						
rq-D5.2-P3.D1	Detailed and fine-grained logging.	R		T WP5	L3	SW	T5.2, T5.3
rq-D5.2-P3.D2	Online access to relevant variables and parameters.	R	E.g. Motion control parametrization and diagnostic).	T WP5	L3	SW	T5.3
	Software requirements						
rq-D5.2-P3.SW1	Designed to match Hard Real-Time requirements.	R		T WP5	L2	HW/ SW	T5.2, T5.3, T5.4

rq-D5.2-P3.SW2	Designed to handle multiprocessor systems with Hard Real-Time requirements in mind.	R		T WP5	L2	HW/ SW	T5.2, T5.3, T5.4
rq-D5.2-P3.SW3	VxWorks 6.9.x and 7 compatibles.	R		T WP5	L2	SW	T5.2, T5.3, T5.4
	Control layer performance						
rq-D5.2-P3.CP1	Performance monitoring tool, for monitoring task-level performance.	R	Actual cycle time, jitter, response latency…).	T WP5	L3	SW	T5.3
rq-D5.2-P3.CP2	50 us minimum scheduling cycle time with 1% jitter.	R	Not related to minimum Motion Control cycle time, which is 500 us.	T WP5	L2	SW	T5.3

8.4 Healthcare robotics - Medical manipulator (Pilot 5 - PHI)

ID	Original Requirement	Obligation	Additional Refinement/ Requirement Detail	Verification	Layers	Type (HW/ SW)	Task/ BB
	Communication and interface requirements						
rq-D5.2-P5.CI1	Multi-client interface with parallel access for scripting/GUI etc.	R		T WP5	L2-L3	SW	T5.2

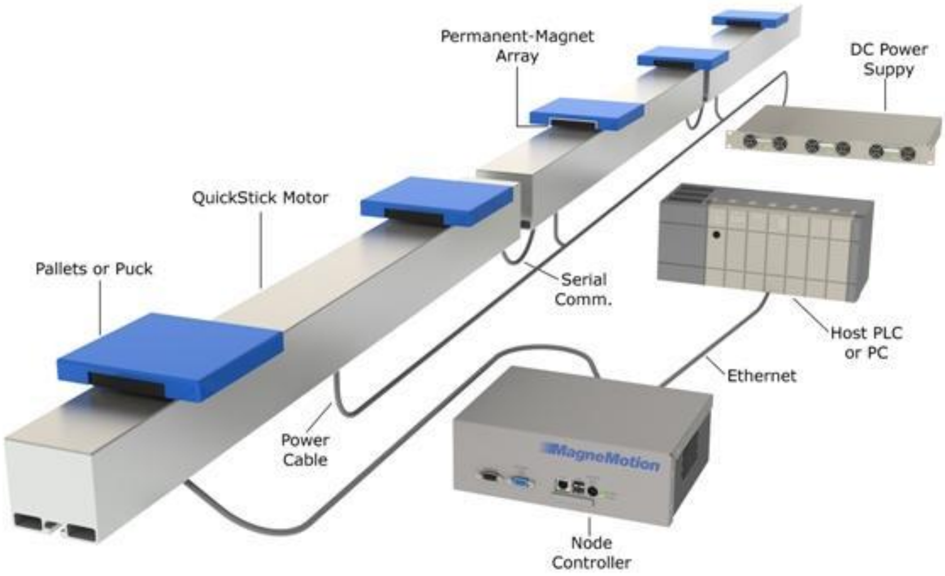
rq-D5.2-P5.CI2	All output is in MATLAB Simulink code or DS402 protocol messages	R		T WP5	L2-L3	SW	T5.2
	Data processing and management requirements						
rq-D5.2-P5.BB3.1	Logging - Data logging functionality,	R	Maximum log resolution is equal to the update rate of the position loop. Triggering functionality for traces.	T WP5	L1-L2	SW	T5.3
rq-D5.2-P5.D2	Scope - Real time access to all parameters with scope functionality with functional GUI.	R	The access shall be in control layer as well as in instrumentation layer.	T WP5	L2-L3	SW	T5.3
	Software requirements						
rq-D5.2-P5.SW1	Communication between the auto-tuner and the application is in MATLAB or Simulink.	R		T WP5	L3	SW	T5.2, T5.4
	Condition monitoring						
rq-D5.2-P5.BB3.2	Functionality to set multiple threshold/alarm levels.	R		T WP5	L3	SW	T5.3
rq-D5.2-P5.BB3.3	Generate event when threshold is surpassed	R		T WP5	L2	SW	T5.3
rq-D5.2-P5.BB3.4	Handshake mechanism on event generation and event reset.	R		T WP5	L2-L3	SW	T5.3
	Self-Commissioning of controller						
rq-D5.2-P5.BB6.1	Frequency analysis (Bode/Nyquist), including coherence output of predefined transfer functions, based on output as provided by rq-D5.2-P5.BB3.1.	R		T WP5	L3	SW	T5.4
rq-D5.2-P5.SC1	Auto-tuning works for a predefined feedback control structure (see *partner_zone/project_breakdown/ WP1/Task1.3/Meetings/F2F Alignment 20feb2018/ OutputMeeting/Questionaire Secretaries-BB6.pptx*). Auto-tuning of the current loop (excluding commutation)	R	The auto-tuning function must provide optimal parameter settings based on initial performance criteria.	T WP5	L3	SW	T5.4

	Feedforward auto-tuning output sets the parameters for effects of viscous friction, coulomb friction, hysteresis, motor efficiency, gravity and inertia.						
rq-D5.2-P5-L1	Auto-tuning signals are generated and transferred to control loop.	R	Signals include: (swept) sinewave, white noise etc. with filter possibilities Hanning, Hamming and Gaussian and measurement averaging.	T WP5	L2, L3	SW	T5.4
rq-D5.2-P5-L2	Generated Auto-tuning signals can be superimposed on application movement commands.	R		T WP5	L2, L3	SW	T5.4
rq-D5.2-P5-L3	Signal injection can only be performed on fixed entry points (to be defined)	R	Injection at Position-, speed-, force setpoint	T WP5	L1, L2	SW	T5.4
rq-D5.2-P5.SC2	Auto-tuning output includes optimization of output of various auto-tuning runs under varying geometrical conditions of the application.	R		T WP5	L3	SW	T5.4
rq-D5.2-P5.SC3	It should be possible to use self-commissioning functionality in combination with scripting with MATLAB.	R		T WP5	L2-L3	SW	T5.4
	Control Performance						
rq-D5.2-P5.CP1	Monitoring tooling must be present and capable of measuring: ● Position settling time ● Position overshoot ● Position- and Speed following error ● Motor current and feed forward current based on output from rq-D5.2-P5.BB3.1.	R	FFT, Coherence, Phase margin, Amplitude margin	T WP5	L3	SW	T5.3
	Safety						
rq-D5.2-P5.S1	Auto tuning functionality must respect configurable torque-, position- & velocity limits. Limits should be configurable for all axes.	R	A sequence should be specifiable (optionally via scripting interface) to get the system in right configuration for auto-tuning.	T WP5	L3	SW	T5.4

Rq-D5.2-P5.S2	The auto tuning process can be terminated manually.	R		T WP5	L3	SW	T5.4

9 I-MECH Demonstrators – Requirements specification

9.1 Contact lens automated transport layer (Demonstrator 1 – VIS)



ID	Requirement	Obligation	Additional Refinement/ Requirement Detail	Verification	Layers	Type (HW/ SW)	Task/ BB
	Communication and interface requirements						
rq-D5.2-D1.CI1	Ethernet IP Rockwell automation - Communications as to Rockwell Magnemotion control protocols.	R		T WP5	L2, L3	SW	T5.2
rq-D5.2-D1.CI2	OPC UA Wireless sensors connection to PLC or upwards to Level 3 or above Ambition: wireless sensor data transmission to PLC.	O	DIN SPEC 16592.	T WP5	L1, L2	HW, SW	T5.2
rq-D5.2-D1.CI3	Wireless sensors - Must be compatible with communications protocols.	R	RAMI 4.0 standards IEC 62714, 61784, 62541.	T WP5	L1	SW	T5.2

	Data processing and management requirements						T5.2
rq-D5.2-D1.D1	Cloud and Edge cloud - Potential for both as part of I-MECH.	R		T WP5	L3	SW	T5.2
rq-D5.2-D1.D2	Mining data from level 2 SCADA system (Rockwell Factory Talk) - connect to internal edge cloud direct to level 2 systems (SCADA).	R		T WP5	L2, L3	SW	T5.2
rq-D5.2-D1.D3	Mining data from level 2 SCADA system (Rockwell Factory Talk) - connect to external cloud to level 2 systems.	R		T WP5	L2, L3	SW	T5.2
rq-D5.2-D1.D4	Cyber security requirements are significant for any data leaving J&J networks (current standard PC Duo probably not suitable for cloud system).	R		T WP5	L3	SW	T5.2
	Software requirements						
rq-D5.2-D1.SW1	Rockwell SCADA Factory Talk - Interfaces to PLC, SCADA databases.	R		T WP5	L2	SW	T5.2
rq-D5.2-D1.SW2	Ethernet IP - Sensors to PLC. SCADA to cloud potentially	R		T WP5	L3	SW	T5.2
rq-D5.2-D1.SW3	OPC UA - Sensors to PLC (preferred Ethernet IP) SCADA to cloud potentially.	O	DIN SPEC 16592	T WP5	L1, L2, L3	SW	T5.2
rq-D5.2-D1.SW4	Direct I/O (digital, analog) to PLC - To Rockwell AB PLC spec.	R		T WP5	L1	SW	T5.2
rq-D5.2-D1.SW5	RFID - Magnemotion carrier identification to PLCX.	R		T WP5	L1	SW	T5.2
	Condition monitoring						
rq-D5.2-D1.CM1	Functionality to set multiple threshold/alarms.	R		T WP5	L2	SW	T5.3
rq-D5.2-D1.CM1	Predictive capabilities to identify component degradation before an event.	R		T WP5	3	SW	T5.3
rq-D5.2-D1.CM1	Condition history for product traceability.	R	Historian data base compatible with Rockwell Factory Suite software.	T WP5	3	SW	T5.3

9.2 Injection mould tool (Demonstrator 2 – ECS)

ID	Original Requirement	Obligation	Additional Refinements/ Requirement Detail	Verification	Layers	Type (HW/ SW)	Task/ BB
	Communication and interface requirements						
rq-D5.2-D2.CI1	Wireless communication.	R		T WP5		HW/ SW	T5.2
rq-D5.2-D2.CI2	GUI to visualizing status.	O		T WP5		HW/ SW	T5.2
rq-D5.2-D2.CI3	Sending GSM messages (probably).	O		T WP5		HW/ SW	T5.2
	Data processing and management requirements						
rq-D5.2-D2.D1	Real-time viewing.	R		T WP5		SW	T5.3
rq-D5.2-D2.D2	Data acquisition frequency dependent on the application.	R		T WP5		HW/ SW	T5.3
	Condition monitoring						
rq-D5.2-D2.CM1	Alarms – On deviation from normal parameters.	R		T WP5		SW	T5.3
rq-D5.2-D2.CM2	Data recording to create a database (probably).	R		T WP5		SW	T5.3

10 I-MECH Use Cases – Requirements specification

10.1 Power electronics for hoist and crane sector (Use case 1.1 – GEF)

ID	Original Requirement	Obligation	Additional Refinement/ Requirement Detail	Verification	Layers	Type (HW/ SW)	Task/ BB
	Software						
rq-D5.2-UC1.SW 1	Script should be implementable in IEC 61131-3 in alternative the algorithm for Self-commissioning or Condition monitoring could be developed through field-bus connection like (CAN-BUS or EtherCAT).	R	The layer where to apply the algorithms should be “flexible”. According to the kind of complexity could be implemented directly in the drive layer (so = 1) or in alternative by using a gateway or PLC in layer 2 and monitoring/setting could be done in layer 2 (PLC/Gateway) or 3 (Standard PC directly connected (TCP/IP) or a network system (OPC/UA)).	T WP5	L1, L2, L3 *(see notes left side)	SW	T5.2
	Condition Monitoring						
rq-D5.2-UC1.CM 1	Algorithm should be defined to evaluate the general status of the application and collect information about the process Performance of the inverter should be monitored in order to check the performance of the inverter and to compare the real situation with that was foreseen. The collected information should be used to improve the performance of the control algorithm and to check the sizing of the inverter.	R	The layer where to apply the algorithms should be “flexible”. According to the kind of complexity could be implemented directly in the drive layer (so = 1) or in alternative by using a gateway or PLC in layer 2 and monitoring/setting could be done in layer 2 (PLC/Gateway) or 3 (Standard PC directly connected (TCP/IP) or a network system (OPC/UA)).	T WP5	L1, L2, L3 *(see notes left side)	SW	T5.3
rq-D5.2-UC1.CM 2	Monitoring of the drive should help to prevent unwanted situation and to create the basis for a predictive diagnostic and maintenance.	R	The algorithm should be developed in order to have a predictive diagnosis of the system and to prevent as much as possible any stop and delay in Work cycles. The monitor could be done by PLC (layer 2) or external device (layer 3).	T WP5	L2/L3	SW	T5.3

rq-D5.2-UC1.CM3	Normally the main operation of the industrial application is managed by a PLC system. The developed algorithm should be able to transmit data from drive to PLC/Gateway through standard fieldbus connection.	R		T WP5	L2	SW	T5.3
rq-D5.2-UC1.CM4	Detection algorithm like (as example) the unwanted touch of the load or excessive oscillation of the load should be implemented and should be monitored. In this situation the control should be able to compensate or to limit the effect i.e. adapting the control gains.	R	Compensative approach should be selected as reaction of “unexpected” behaviour. As example a possible approach could be the reduction of system bandwidth or a trajectory modification.	T WP5/6	L2	SW	T5.3
	Self-commissioning						
rq-D5.2-UC1.SC1	Position limit - Auto-tuning approaches has to consider applications limit that allows: Max. and min. position limit; Max. and min allowed speed; Max and min allowed acceleration; Max and min allowed Jerk.	R	The GUI should be able to accept this type of data from the user in easily way.	T WP5	L2/L3	SW	T5.4
rq-D5.2-UC1.SC2	Actuator limit - According to the type of installation, motor and system auto-tuning has to consider: Max and min Torque limit; PWM (actuator) frequency; Control loop sampling time.	R	The GUI should be able to accept this type of data from the user in easily way.	T WP5	L2/L3	SW standard (i.e. cloud based)	T5.4
rq-D5.2-UC1.SC3	Application model - The following application characteristics will be taken in account: Inertia (constant or variable); Resonances - Low frequency (oscillation), High frequency (vibration); Friction; Back-lash; Unbalance / Cam; Repetitive noise.	R	Algorithm could be implemented directly in the drive SW or in a PLC/Gateway system (ref. rq-D5.2-UC1.SW1)	T WP5	L1/L2	SW	T5.4
rq-D5.2-UC1.SC4	The identification method should have the minimum duration of the experiment and energy consumption.	R	-	T WP5	L1/L2	SW	T5.4
rq-D5.2-UC1.SC5	Performance should be evaluated in order to validate the tuning algorithm. Metrics like response time; under and	R	Monitor of the data could be done locally by using the PLC/Gateway or in the	T WP5	L2/L3	SW	T5.4

	over shoot should be evaluate.		network (i.e. cloud based / OPC-UA).				
rq-D5.2-UC1.SC6	Interface - Limit of controller like: • Memory usage; • Computability should be taken in account.	R	The use of memory/data of algorithm should be evaluated to identify if the solution could be implemented in the drive SW.	T WP5	L1/L2	SW	T5.4, T3.7
	Functional testing						
rq-D5.2-UC1.FT1	Virtual testing & calibration process.	R	Functions testing and calibration must rely on virtual testing (Sfunction or FMI MiL, OPC/UA HiL) prior to commissioning.	WP4/5	L1, L2, L3	SW	T5.1, T4.2, T4.3

10.2 Compact control + HMI unit for CNC machines - Fagor Aotek controllers (Use case 1.2 – FAG)

ID	Original Requirement	Obligation	Additional Refinement/ Requirement Detail	Verification	Layers	Type (HW/SW)	Task/BB
	Condition Monitoring						
rq-D5.2-UC2.CM1	The CNC must provide all the information that it can access from the drives connected to the motion buses (CANOpen, Sercos, SercosIII, EtherCAT), mainly data related to torque, power, speed…	R	In L2 for additional higher order control loops.	T WP5	L2-L3	SW	T5.2, T5.3
rq-D5.2-UC2.CM1	The CNC must provide all the errors, warnings and messages coming from those drives or from the CNC and PLC programs.	R		T WP5	L3	SW	T5.2, T5.3
rq-D5.2-UC2.CM1	The system should be able to monitor high frequency signals in short periods of time and eventually store them (oscilloscope) for diagnosis.	R	With the limit of control loop frequency.	T WP5	L2	SW	T5.2
rq-D5.2-UC2.CM1	The system should be able to store specific information from data and events during the running time (at lower rates) for condition monitoring and diagnosis.	R		T WP5	L3	SW	T5.2

rq-D5.2-UC2.CM1	The PLC must be able to provide information from all relevant information coming from devices connected to the I/O bus or local bus (for instance, power monitors connected to a CANOpen bus, intelligent sensors, analog inputs…).	R		T WP5	L3	SW	T5.2
rq-D5.2-UC2.CM1	The CNC must provide all the information related with the operational state of the program running on channels (G-function codes present, program running, subroutines, line…) for diagnosis purposes.	R		T WP5	L3	SW	T5.2, T5.3
rq-D5.2-UC2.CM1	The CNC and PLC must provide information on the state of peripherals and, specifically, on the tool used and related information.	R		T WP5	L3	SW	T5.2, T5.3
rq-D5.2-UC2.CM1	Events could be time stamped for better precision or polling must be fast enough (compromise).	R	Time stamp could be the loop counter.	T WP5	L3	SW	T5.3
rq-D5.2-UC2.CM1	When available, all internal relevant data should be gathered by the CNC or the PLC and/or collected by a logger and stored or sent.	R	(temperature of motors, drives, encoders, spindle head…) that are usually transmitted on the drive bus.	T WP5	L3	SW	T5.3
	Self-commissioning						
rq-D5.2-UC2.SC1	The CNC software (whether included or external) must have at least an integrated multichannel oscilloscope to plot the tuning relevant signals (torque/current, speed, position, acceleration…) both for command and feedback paths.	R		T WP5	L2-L3	SW	T5.3
rq-D5.2-UC2.SC2	The CNC software should have means to calculate and plot the relevant frequency transfer functions (Bode) relevant for tuning purposes. There are several approaches, being “white” noise over a constant command signal one of the	O	This can be done from external tools.	T WP5	L3	SW	T5.4

	most used, but also chirp signals, etc… can be used.						
rq-D5.2-UC2.SC3	It is highly desirable that the system has an application to (semi)automatically calculate the control loop constants, as well as the non-linear compensators parameters (backlash, friction…).	O		T WP5	L3	SW	T5.4
rq-D5.2-UC2.SC4	Ideally, every loop, compensation, observer… should have a corresponding way of auto tune it integrated in the tuning application.	O		T WP5	L3	SW	T5.4
rq-D5.2-UC2.SC5	It is desirable that the system, included digital drives and fieldbus, can automatically detect connected devices and configure topology.	O		T WP5	L2-L3	SW	T5.4
rq-D5.2-UC2.SC6	It is desirable that the CNC-PLC system has meanings to issue messages, warnings and errors (as different levels of severity on anomalies). It is also desirable that this alarm system be able to work with complex conditions (if (a>b) && c then warning).	O	That warnings and errors could trigger some messages to a customer (E-mail, SMS, application).	T WP5	L2-L3	SW	T5.3
	Data fusion and integration						
rq-D5.2-UC2.CM1	It is highly desirable to have a standardization of data coming from sensors through different buses and software stacks to make it available at different control levels (from mechatronics to process control to condition monitoring, loggers, etc…	R		T WP5	L2-L3	SW	T5.2, T5.3
rq-D5.2-UC2.CM1	Specifically, in the CNC-PLC system, an integrated approach to access data from different sources like spindle drives, acceleration or vibration sensors, etc… should lead to better condition monitoring algorithms.	R	The information should be ideally timestamped.	T WP5	L2-L3	SW	T5.3
rq-D5.2-UC2.CM1	It is highly desirable that the CNC systems allow the	R	Provided these algorithms are well-behaved, i.e. don't	T WP5	L2	SW	T5.2

	execution in real time of third-party control loops or algorithms with access to all the gathered information.		get stuck and hung the CPU...				
rq-D5.2-UC2.CM1	The information should be exported or published in standard formats. These standards are, for a machine tool, OPC-UA with the machine tool companion standard (VDW, 7-2017) or MT-Connect.	R	Other companion standards defined in I-MECH will be considered.	T WP5	L3	SW	T5.2
rq-D5.2-UC2.CM1	Where justified by performance reasons, proprietary formats could be preferred (for instance for local resident algorithms as described just before).	R		T WP5	L2	SW	T5.2
rq-D5.2-UC2.CM1	The non-standard information must be published to the client applications.	R		T WP5	L3	SW	T5.2
rq-D5.2-UC2.CM1	For real time integrated algorithms (usually process control), the calling format and application structure will be that of the Simulink environment (inputs, outputs, step (cycle) and integrator updating).	R	From the last discussions, this req. should be removed.	T WP5	L2	SW	T5.4
rq-D5.2-UC2.CM1	It is desirable that the communication from the CNC could be served to several clients under several protocols at the same time.	O		T WP5	L3	SW	T5.2
rq-D5.2-UC2.CM1	The CNC must be able to upload information to the company net or to the cloud and be provided with state-of-the-art security software (and/or hardware).	O		T WP5	L3	SW	T5.2
rq-D5.2-UC2.CM1	It is desirable that the CNC system allows for communication protocols included by the customer (for instance MQTT protocols, or proprietary modules).	O		T WP5	L3	SW	T5.2

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