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Work Package	Deliverable ID
WP2, Business requirements and reference system architecture	**D2.1, Updated state of the art and enabling technologies of motion control solutions for smart mechatronics and robotics systems**

Executive summary

The I-MECH project aims to design and implement a widely applicable, modular, open motion control platform and related smart components. An initial set of 11 building blocks will be developed for the I-MECH platform. These building blocks will focus on smart and wireless sensors and actuators, high performance servo drives, high speed vision, multivariable and self-learning control, self-commissioning and condition monitoring and multi/many core computing for motion control.

The I-MECH pilots, demonstrators and use cases span a wide range of applications and industries, ranging from the semicon and industrial printing industry to the packaging industry and healthcare. This report analyzes the needs of I-MECH pilot, demonstrator and use case applications related to motion control, especially regarding the first 11 I-MECH building blocks, and their needs related to “smart manufacturing”/Industrie 4.0. Furthermore, an inventory has been made, where applicable, of the state-of-the-art of technologies used in industry and academia regarding the gathered requirements and I-MECH building blocks.

The contents of this deliverable will be further extended in deliverable D2.2 and serve as input of the definition of the architecture of the I-MECH platform, which will be published in deliverable D2.3 and D2.4.

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Keywords
Instrumentation, Sensors, Actuators, Drives, Vision, Control, Dynamics, Vibrations, Bandwidth, Observers, Learning, Repetitive, Robustness, Trajectory, Filters, Multi-Many-Core, OPC UA, RAMI 4.0

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ECSEL Joint Undertaking
Electronic Components and Systems for European Leadership

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(Open) Issues & Actions

Open Issues (and related actions) that need central attention are part of a file called "IAL - Issues & Action List – WP2" which can be found in the Google Drive Partner Zone.

ID	Description	Due Date	Owner	IAL ID
OI-0011	COTS platform section in requirements table is still quite empty.	Ask partners for extra input for D2.2	WP2 - Task leaders	WK1744.03
OI-0012	Several requests for contributions to this document are still open and certain topics require more elaboration	Ask partners for extra input for D2.2	WP2 - Task leaders	WK1744.03
OI-0016	Significant parts have been copied 1:1 from the FPP. This is not the intention and should be corrected for the next revision/D2.2	Next revision	WP2 - Task Leaders	WK1744.01

Document Revision History

Revision	Status	Date	Deliverable leader	Description of changes	IAL ID / Review ID
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Contributors

Revision	Acronym of Partner	Contributor	Description of work
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		Petr Blaha	Small contributions to requirements table
	EDI	Kaspars Ozols	Inventarisation state-of-the-art wireless sensors
	EMCMCC	Mart Coenen	Various contributions
	FAGOR	Carlos Rodriguez de Yurre	Specification Use Case 1.2 in requirements table
	GEFRAN	Davide Colombo	Specification Use Case 1.1 in requirements table
	GMV A&D	Joaquin Estremera	Specification Use Case 2.1 in requirements table
	IMA	Giacomo Collepalumbo	Specification Pilot 3 in requirements table
	Nexperia	Gijs van der Veen	Various contributions
		Tom Kampschreur	Various contributions
	PHI	Rens Berkhof	Specification Pilot 5 in requirements table
	REDEN	Jakko Nieuwenkamp	Contribution to modeling and identification
	Sioux CCM	Arend-Jan Beltman	Various contributions
		Rob Pulles	Specification Pilot 1 in requirements table
		Thomas Lembrechts	Various contributions
	TU/e	Gert Witvoet	Contributions to state-of-the-art (de)centralized control
		Dip Goswami	Various corrections
	UCC	Javier Torres	Small contributions to requirements table
		Michael Walsh	Small contributions to requirements table
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Document control

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Gert Witvoet (TUe)	Leading D4.4		X						
Dip Goswami (TUe)	Leading D3.7, D4.6		X						

File Locations (cross reference to I-MECH documents)

Via URL with a name that is equal to the document ID, you shall introduce a link to the location (either in Partner Zone or CIRCABC)

URL	Filename	Date
2017102001R01	I-MECH Requirements Table	21-OCT-2017

Abbreviations & Definitions

Abbreviation	Description
AC	Alternating Current
BB	Building Block
BLDC	Brushless Direct Current Motor
CNC	Computer Numeric Control
COTS	Commercial off the Shelf
DCS	Digital Communication System
DC	Direct Current
EC	European Commission
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
EMI	Electromagnetic Interference
FPP	Final Project Proposal (of the I-MECH project, which is described in the I-MECH Grant Agreement)
HIL	Hardware in the loop
(I)IoT	(Industrial) Internet of Things
MIL	Model in the loop
MIMO	Multiple Input Multiple Output
NRZ	Non Return to Zero
PHY	Physical Layer, the lowest layer of the OSI model of computer networking [1]
PoE	Power over Ethernet
PWM	Pulse Width Modulation
RF	Radio Frequency
RTOS	Real Time Operating System
SerDes	Serializer/Deserializer
SIL	Software in the loop
SOA	Service Oriented Architecture
SPI	Serial Peripheral Interface
TRL	Technology Readiness Level
UI	User Interface
UPS	Uninterruptible Power Supply
UWB	Ultra-WideBand
VEP	Virtual Execution Platform
VFD	Variable Frequency Drive

VMM	Virtual Machine Manager
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network
WWAN	Wireless Wide Area Network
WSN	Wireless Sensor Network

Definition	Description

1 About this document

This deliverable (D2.1) is a part of work package 2 of the I-MECH project. Figure 1.1 shows the planned approach for work package 2. The approach consists of 12 steps which lead to publishing of 4 deliverables. Google Docs was used to collaboratively gather information and work on documents together with all 31 partners participating in the I-MECH project.

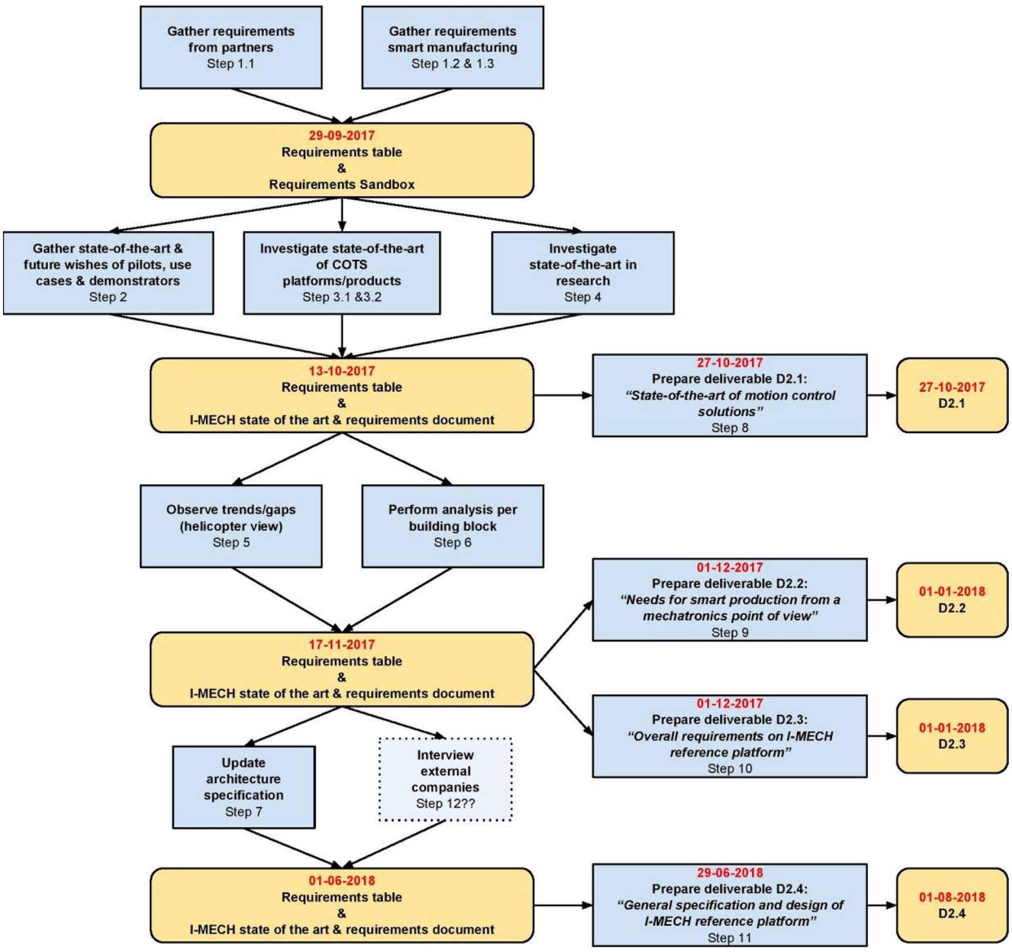


Figure 1.1: Approach to I-MECH Work Package 2

Partners were asked during step 1 (1.1, 1.2 & 1.3) to contribute general functional and nonfunctional requirements for the I-MECH platform and its building blocks based on personal experience and information gathered from public documents of other 'smart manufacturing' or mechatronics related projects funded by the European Commission as part of e.g. H2020. These requirements could be entered into a Google Docs spreadsheet (which is part of this deliverable as appendix A) or, for some non-functional requirements, as a text document in case requirements could not be stated appropriately in a single cell of the 'requirements spreadsheet'. However, public documents of other EC-funded projects provided disappointingly few relevant and useful facts and potential requirements for the I-MECH platform.

Public documents of several potentially relevant projects were nonetheless gathered and stored in a public folder of the I-MECH consortium as potential information source for other I-MECH work packages. A list of investigated projects can be found in appendix B. The 31 partners of the I-MECH consortium participate in a large number of these projects. This will enable knowledge and experience transfer of other EC-funded projects to the I-MECH project, despite the poor information content of publicly shared documents of these projects.

The requirements gathered in step 1 were used as input for step 2, 3 (3.1 & 3.2) and 4. Exact specifications for the gathered requirements were determined for these requirements. Step 2 gathered specifications of the current I-MECH pilots, use cases and demonstrators and their future wishes, while step 3 and 4 investigated specifications of COTS platforms and modules and motion control implementations at participating universities with respect to the gathered requirements. The gathered specifications were collaboratively added to the ‘requirements spreadsheet’ and related text documents on Google Drive.

The gathered information was evaluated and processed into a readable document, to be published as deliverable D2.1, during step 8. The remaining steps of the plan will be used to analyze the gathered data further and propose a reference architecture of the I-MECH platform. These analyses and concepts will be published as deliverables D2.2, D2.3 and D2.4.

2 Introduction

The I-MECH project, funded by the ECSEL-JU program, aims to design and implement a widely applicable, modular, open motion control platform and related smart components for applications where dynamics and precision of the controlled motion and easy reconfigurability are crucial. Examples of such applications could be high-performance pick & place machines in the semiconductor industry, medical imaging devices, CNC-machining, industrial robots and industrial inkjet printing. The platform is intended to bridge the gap between the latest research results and best industrial practice. The I-MECH consortium consists of 31 participants, ranging from small to large enterprises from industry to research organizations and universities from various countries in Europe, collaboratively developing the I-MECH platform. The I-MECH platform will rely on the usage of model-based development methods, a smart instrumentation layer and modularization using hardware and software 'building blocks' to achieve its goals.

A wide variety of "commercial off-the-shelf" automation and motion control platforms is already available on the market. Siemens, Beckhoff Automation, B&R Automation, Bosch Rexroth, ABB, Rockwell, Kollmorgen, ACS Motion Control, dSPACE, National Instruments, Yaskawa, Omron, Bachmann, ProDrive, Aerotech, Sanyo Denki and Mitsubishi are a few examples of the long list of suppliers of COTS motion control & automation platforms. However, looking back into the last decades of industrial automation, many dedicated, custom solutions have been developed for motion control systems, mostly with proprietary solutions and specific applications in mind, despite the availability of a wide array of COTS solutions. This trend can also be observed in the (motion control) requirements and current specifications of pilots, demonstrators and use cases participating in the I-MECH project, as many of the requirements for (motion) control are dedicated to specific applications and most I-MECH pilots and use cases currently use an in-house developed motion control solution.

Some of the, not necessary valid, reasons for companies to develop their own custom motion control platform instead of using a COTS platform could be:

- lack of customizability of hardware of COTS motion control platforms,
- lack of availability of 'advanced' control algorithms, based on recent academic results, on COTS motion control platforms (e.g. algorithms for MIMO control, learning control, control of very non-linear processes, vision-in-the-loop, system identification & controller tuning),
- limitations in customization of control algorithms and other software due to lack of openness of COTS motion control platforms,
- limitations in the development environment (e.g. lack of model-based development using MIL/SIL/HIL for virtual commissioning and parallel development),
- limitations in the software/ hardware architecture limiting the performance needed for advanced, high-performance control systems,
- desired independence of the COTS motion control platform supplier with respect to costs, required cooperation for implementation of new functionality & protection of intellectual property,
- insufficient documentation and support of the COTS motion control platform,

As WP2 will force the consortium to extensively investigate existing COTS solutions, features (both positive and negative!) that thus far were not discovered, might be revealed.

One of the tasks of Work Package 2 of the I-MECH project is to inventorize and identify the gaps between the state-of-the-art in motion control in industry, the state-of-the-art of motion control in research and the needs of the 'smart' manufacturing industry in Europe. The pilots, use cases and demonstrators participating in the I-MECH project, ranging from the CNC machining, packaging, production line automation, industrial printing and semiconductor industry to the healthcare industry and applications involving industrial robots, were used as a representative cross-section of the state-of-the-art and needs of the European manufacturing industry. This report presents an investigation into the needs of the European manufacturing industry related to smart motion control and an investigation of modern state-of-the-art technologies that could be applicable during implementation of the I-MECH motion control platform.

The aim of the I-MECH project is to find a set of requirements for a (more) open motion control platform for the future, which enables faster developments and improve maintainability with respect to the latest developments in research. Typical requirements and specifications (in smart performance figures) for motion control in manufacturing applications throughout Europe and specifications of modern COTS motion control platforms were gathered in a 'requirements table' presented in appendix A. Selected topics and requirements of this table were investigated in further detail in chapter 2 of this report. Chapter 3 reflects on the identified topics and requirements and their implications for the general motion control structure of the I-MECH platform. Chapter 4 reflects specifically on model based development approaches in I-MECH. The modular I-MECH platform will be constructed out of building blocks. The consortium will start with implementing an initial set of 11 building blocks. Chapter 5 analyzes the implications of the state-of-the-art technologies and identified requirements on each planned building block.

3 Requirements

The I-MECH platform will use a 3-layered architecture for the motion control platform (figure 3.1). Layer 1, the instrumentation layer, represents the interaction between the system and the physical environment within which it exists. This interaction is achieved by means of transducers that transform the energy from a power source into a delivered mechanical and/or electrical effort, while sensors provide information from the system and/or material being processed and provide feedback about the actual state of the moving parts. Layer 2, the control layer, represents the algorithmic to manipulate the physical environment via the instrumentation layer (Layer 1). Layer 3, the system behavior layer, defines a system behavior 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.

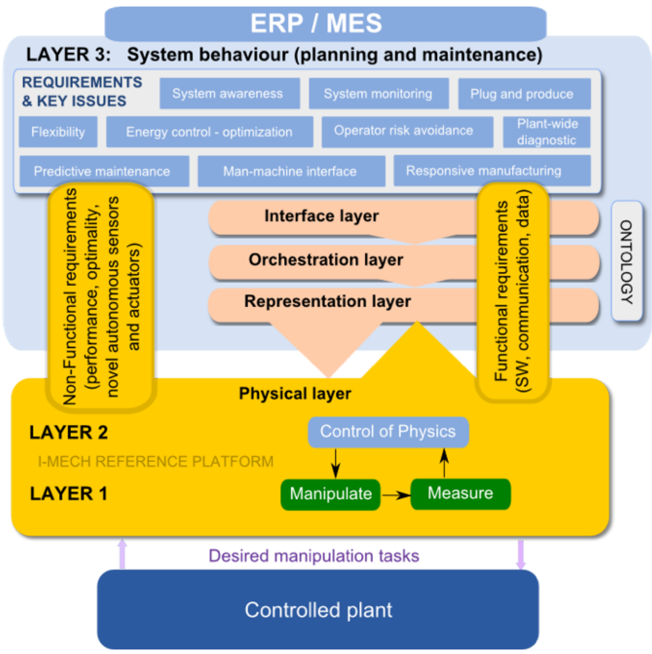


Figure 3.1: I-MECH architecture, featuring 3 layers, and showing context with Industry 4.0 with primary research focus highlighted.

This chapter presents requirements and topics organized per layer in which they are expected to be relevant for the I-MECH platform. The "requirements table", presented in appendix A (Requirements Table) was used as one of the inputs of this chapter. This table shows the specific requirements and specifications of pilots, use cases and demonstrators participating in the I-MECH project.

Additionally, requirements need to be subdivided into 'functional' and 'nonfunctional' requirements. Functional requirements serve the 'needs' of the automation task for e.g. Printing, Semicon, Packaging, Manufacturing, Medical as the system requirements. The nonfunctional requirements can for example be found in the domain costs, speed, volume, (human) safety and machine damage requirements or up-time. For example, some of the pilot systems have to run 24/7 autonomously, like the substrate carrier, 12" wafer stage, teabag machine while other systems will remain partly autonomous or human controlled, like CNC machines and medical manipulators. Environmental requirements can matter, for example requirements regarding contamination in cleanrooms, floor vibration and humidity. Sensors could be exposed to disturbing elements like e.g. the magnet flux of permanent magnets (typically for linear motors), radio fields of wireless power transfer, etc. Such 'type of requirements' can have a significant impact on the definition of the I-MECH platform.

3.1 Layer 1: Instrumentation

Layer 1 concerns measurement and manipulation of the physical environment. In I-MECH, smart drives and smart wired/wireless sensors will be developed. These developments will consider the state of the art and improve upon it based on demands from I-MECH partners and other end-users.

In the requirements list a nice overview is given for what **is available and used** in the motion market already, where deviations are regarding the requirements for sensor resolution, speed (refresh rate) but no change in the PHY being used, either 0-10 volts or Ethercat and some go for SPI for the sake of speed and overhead. The use of non-industrial interfaces like Ethernet or USB(3) will be supported in this project. The usage of the signal interfaces determine the wiring needed to be used. For analogue signals wires with PVC can be used. With high speed digital signals, shielded (twisted) pairs insulated by nylon, polyamine or even (foam-based) teflon shall be used. These shielded pairs can also be used for high-end differential analogue signalling. As 0-10 volt signalling is mostly asymmetric (common-return) balancing these analogue signalling is typically not foreseen (though easy to apply).

The higher the data rate, bandwidth e.g. when using raw vision data > 1 Gb/s, the connectors (and their pinout) shall be optimally selected with the wiring to ensure signal integrity over the full signal path. Smart vision, smart sensor and smart drive system may reduce the data (and thus the required data rate) down to the essential data i.e. control loop speed required.

Furthermore, each sensor, wired or wireless, suffers from latency: μs → tens of ms. The physical property has to be transferred into the electrical domain, mostly with an analogue signal representation. Then further signal conditioning has to be applied, either in the analogue and/or digital domain. The analogue signal is mostly converted into the digital domain, using an ADC with serial or parallel outputs. When the analogue or digital signal is available, it needs to be transferred over wires at max. with a fraction: 60-80% of the velocity of light after being put through a serdes and provided with error coding. At the wired receiver side it will be decoded and used for further processing.

With wireless, the analogue or digital signal (after non-return-zero (NRZ) and error conditioning) needs to be modulated on a RF carrier and will then be transmitted at the speed of light. Due to the many metal parts in machinery, multiple reflections and multipath signals will result which require proper decomposition of the signals at the receiver side, not to mention the Doppler effect which will result in case of sensors, i.e. fast transmitting/ receiving antenna movements yielding frequency (phase) shifts.

Short message wireless sensors will use Zigbee alike protocols for the sake of low energy consumption. The main pitfall for Zigbee, Bluetooth and other wireless protocols using the 2.45 GHz band is that the 2.45 GHz is an industrial free frequency band which can be utilized for many purposes like (food and material) heating. Other ‘free’ industrial frequency bands are: 433, 868 MHz. The GSM, DCS, GPRS, 3G, LTE (4G) and 5G bands are restricted or even forbidden to be used other for services than following the defined protocols. Low and high band UWB (ultra-wideband) will suffer from WiFi at either the 2.45 or 5.2 GHz as well as vice versa WiFi will suffer from nearby used UWB. New operations will go the to X-band: 8.0 – 12.0 GHz or even higher to the WPAN band: 57 - 66 GHz, where smaller sized antenna and phased-array beam forming can be used.

For some sensor purposes contactless power or even energy harvesting can be used to minimize the wiring in-between the sensors and the motion control system. In particular when the mechanical strain from cables needs to be minimized, this will be an alternative. So far, TE-Connectivity offers a contactless digital data link plus power transfer up to 12 Watt. With VanderLande Industries conveyors are provided with contactless power @ 20 kHz which can deliver an instant power of 600 Watt. In semiconductor cleanroom environments, contactless powered foups are transporting wafers and reticles along an overhead rail systems to and from the production machines.

The motion control system outputs need to be available in the same way as inputs, analogue or digitally. Either analogue signalling is used: 0-10 volt and/or differential digital interfaces for which there are too many non-compatible protocols available. Communication can be done in parallel, using multiple point-to-point (input and) output ports or via a bus structure e.g. using Ethercat, Profibus or many of the other protocols.

W.r.t. to actuator amplifiers/drives, the power requirements will differ from a few Watt up to several kW. The quest is to squeeze more conversion power at ever higher control bandwidth into less a volume. Unfortunately, faster switching results typically in more switching losses for which heatsinks or other means of cooling are required and higher RF emission i.e. noise for which filtering at either the supply or load/actuator side will be required. As such, thermal issues need to be resolved either at the drive (+ filtering) or at the actuator by eddy-current losses.

Either (smart) setpoint-driven amplifiers/drives applications which have an internal closed loop with a sensor/encoder are used or the motion is continuously dictated by data from the motion control system in either feedforward and/or feedback or a combination thereof. In Paschen critical applications (low vacuum), special care shall be taken regarding overvoltages occurring between actuators: linear, rotating, piezo in that vacuum environment.

N.B. With linear levitated motor applications static magnetic fields of >1 Tesla can be expected at the levitation level which will drive most inductive components e.g. DC/DC converters used in that environment into saturation.

3.1.1 Smart actuators and drives

Amplifiers or drives are used to excite the actuators in motion control systems. A distinction shall be made between analogue and pulse width modulated (PWM) drives. Both drive systems can be used to drive solenoids, DC and AC rotation and linear motor systems or stepping motor systems. In case of brushless motor applications nowadays 3-phase PWM drives are used: brushless DC or BLDC systems with or without encoder and commutation via EMF-feedback.

Analogue amplifiers can be used in various configurations, dependent on the linearity and efficiency required. However when energy and space efficiency needs to be optimized, PWM drives are more favorable when the necessary filtering at the supply and load side aren't considered.

PWM drives compared to analogue drives typically result in high conductor and eddy-current losses in the actuator as the high frequencies do not provide energy to the motion itself. These losses shall be considered with the thermal constraints of motion design or filtering shall be applied to limit the heating of the actuator and absorb the RF-energy in a (sine filter) at the output of the PWM drive.

Two types of PWM drives are commercially available of which the fixed frequency with variable pulse width is most commonly used, though variable frequency drives (VFD) presently comprise the most used systems to feed low voltage industrial motors in applications that involve speed variation.

Either way, the fast switching in combination with long(er) motor cables results in overvoltages which affect the insulation withstand requirements for the electrical windings of the actuator. Long cables represent capacitance which inherently can cause overcurrent load conditions for the PWM drives. Cables in-between PWM drives and actuators need to be shielded of which the shield is grounded at both ends to the actuator housing and the PWM drive. Measures need to be taken similar to the wiring of the sensor/encoder systems such that all signals are confined within a shielded cable on the inner wiring and no signal currents are running over the shields, then the actuator cable will be optimized for minimal emission to elsewhere in the motion control application.

Both active and passive filtering techniques are commercially available for such conditions but better and/or more compact solutions need to be developed with the I-MECH project.

If, the sensor cable is applied according the measures stated in 3.1.1 and the motor cable is applied as stated above, no physical separation will be necessary between these cables in a common flex cable tray as nearly no crosstalk will result.

3.1.1.1 EMC requirements

PWM motion control systems are well known to produce a lot of unintended RF emissions (EMI) either conductively or by radiation. Smart motion drives will be developed functionally for which these requirements are not (yet) specified: WP3.6. Within smart open motion control systems, sensor and encoder systems might be adversely affected or even hampered by such nearby emission effects.

One of the aims of I-MECH is to (co-)develop active EMI noise canceling circuits/concepts which will reduce the need for bulky filters at either (AC/DC) supply side and the load side of the motion control system such that cables used to provide power signals to the actuators might be used in addition to transfer encoder signals back to the drive without the need for separate cables. Having these noise cancelling solutions will also provide a means to merge power and small signal cables into a single cable caterpillar without any need for separation i.e. without any threat for crosstalk. Having proper noise canceling (at the source) will also reduce the need for well-shielded cables which are often mechanically (too) stiff to be used with fast motion control systems.

Such an active EMI noise cancelling approach is useful to reduce the amount of wiring, other than to use wireless interfaces in parallel to power and might be a concept for interconnectability which is not standardized yet i.e. will not be in conflict with all existing small signal PHY's. It will lead to other connection techniques as the power cables need to be physically applied to allow 'power-line communication' over these power cable interfaces too.

The cancelling i.e compensation technique foreseen will reduce both the low actuator i.e. motion frequencies excited by the motion control system as well as the PWM switching frequencies used to generate these motion signals and the combinations thereof. Do note that the total amount of RF noise generated can be as high as 10% of the total power required by the motion control system. Drawback is that electronics need to be added on both supply and load side of the motion control system to be able compensation i.e. cancellation of these EMI signals effectively. These cancelling i.e compensation solutions need to be scaleable to suit the various power levels as used with the application foreseen.

3.1.1.2 Commutation/alignment methods

The commutation/alignment of drives has serious impact on the start, stop and movement profiles of the actuator. The commutation required is restricted by the load condition of the actuator when starting to move and when needed to stop (other than hitting an end-stop). Hitting an end-stop typically has the transfer of motion energy into electrical energy in return as the actuator will momentarily behave as an electrical generator due to the lasting magnetic field. The PWM stages and the PWM drive supply have to be able to handle the instantaneous energy feedback.

Applying an instantaneous high voltage to an inductive actuator will do nothing as the actuators' inductance will prohibit the current to ramp up fast. Opposite, as the actuators' inductance will show stray capacitance over its windings, high peak currents, with no benefit for the motion required, will result. Smooth commutation will be required though if a high torque is necessary, high startup currents will be inevitable. For every actuator-load condition, an optimal commutation profile can be determined with various directions for optimization: acceleration, energy efficiency, etc.

3.1.1.3 Amplifier condition monitoring

Amplifier condition monitoring can be used two ways: checking the performance of the drive and/or checking possible wearout of the actuator driven. Even when the drive and actuator are well specified and 'calibrated' and the load can be considered in a reference condition, even the internal temperature changes of the actuator windings can be measured by measuring the energy losses in the actuator as part of the losses are proportional with the temperature of the windings. Aside this approach, also the status of the bearings can be continuously analyzed on metal particles or the presence of water in its grease. These kind of 'big data' generation can be used to monitor entire systems and indicate preventive maintenance when necessary.

3.1.2 Sensors

Physical process and control parameters have to be transferred into the electrical domain to enable closed loop processes. The following domains may be considered:

Time	Space	Force	Temperature	Acoustic	Vision	Electrical	Other
Time	Distance	Friction	Temperature	Sound pressure	1D	voltage	alpha, beta, gamma, X-ray
	Displacement	Force/strain		Sound frequency	2D	current	Light, photons
	Speed	Thrust			3D	power	Humidity
	Acceleration	Pressure				energy	Viscosity
	Angular velocity	Torque				E-field	Biological
		Weight				H-field	pH
		Gravity				charge	Magnetic field

3.1.2.1 Absolute vs Relative

Most sensors and encoders are restricted in their use and need calibration or homing prior to their application. Absolute sensors have the advantage that they will start from any moment in time onwards (when powered) but are typically restricted in resolution. Both absolute and relative sensors need calibration of their min-max values/ranges, sometimes with values in-between to allow more accurate interpolation (if nonlinear). Causes which affect the transfer function between the physical quantity measured and the electrical readout value are typically: temperature and supply voltage (and with analogue readout; the signal load conditions). Other environmental influences on the transfer function may be moisture, vibration, light, EMI, finite stiffness or non-infinite flexible dynamic links.

3.1.2.2 Auto-calibration and auto-offset.

The general aim for new sensor developments is to develop auto-calibrating and auto-offset sensors and encoders which require one-time only alignment within its application. Here too, the upper and lower bounds for the application need to be known and set to the motion control system being responsible for the many physical processes it needs to control as listed in the sensor overview above. Motion will be critical with most processes that require (autonomous) control loops e.g. piezo motors to adjust the errors in optical lens system used with satellites, down to energy harvesting systems following the position of the sun to obtain maximum PV cell efficiency.

3.1.2.3 Dynamic range, bandwidth and refresh rate

There is not one sensor/encoder that can cover the whole dynamic range of a physical parameter at once. It may be such that the dynamic range requirement is extending the requirement of the application foreseen. Changing from the analogue to the digital domain (by using analogue-to-digital conversion inside or outside the sensor/encoder) introduces granular responses due to the discrete amplitude-step limitations. High resolutions: 16, 24, 32 or even 64 bits may be achieved at the cost of bandwidth, sampling rate, throughput and refresh rate. Supply source stability and electrical noise in the front-end of the sensor or encoder system become a crucial factor.

3.1.2.4 Sensor supplies and their interfacing

Most sensor systems are DC supplied having an internal DC/DC converter, this to correct for the external supply voltage fluctuations and/or to derive the various internal voltages as used by the sensor system. In parallel, wired or wireless interfacing will be present. One exclusion will be HART-interfaces and 4-20 mA applications, where the supply voltage is combined with the analogue/digital signal interfacing. Other applications are the ASI-, E-, or home-bus, where supply and digital communication is combined over a non-shielded 2-wire system. Data rates on non-shielded cables are limited. Other options are the use of coaxial cables, where the analogue (even RF carrier-modulated) or digital signals are superimposed on the supply voltage, by using NRZ-coding for the digital signals e.g. Ethernet CAT-V systems, carrying both analogue as digital modulated signals and DC power.

Other sensor and encoder systems require 4-wire solutions, like USB, CAN, Modbus, Profibus up to PoE. The main aim is to minimize the number of cables in-between the sensor systems and the motion control system and to avoid ground loops. To avoid ground loops for signal and supply, even if the sensor/encoder is within a conductive enclosure, the sensor system shall be galvanically separated from the enclosure but RF-grounded to that enclosure (to minimize the local E-field i.e. capacitive coupling inside the sensor system).

Most sensor/ enclosure systems qualified to be CE-compliant for safety and EMC are tested without closing an electrically conductive loop through the sensor housing back to the motion system to which these are mechanically and electrically connected. Furthermore, no formal EMC requirements apply for frequencies below 150 kHz i.e. the frequency band where most active sensors operate as well as most power converters: DC/DC, AC/DC, UPS, PWM drives, LED drivers, etc.

When all signals are confined within a shielded cable on the inner wiring and NO signal nor supply currents are running over the outer shield(s), then the sensor cable will be optimally immune to disturbance signals from elsewhere in the motion control application.

Sensor/encoder systems selected and developed in this I-MECH project shall at least follow this requirement. A better alternative will be to supply through wiring only and wireless for the communication or supply by energy harvesting and wireless for communication, like Wireless sensor networks (WSNs), when energy-wise and reliability-wise allowed.

3.1.3 Smart sensors

In the context of I-MECH smart sensors refer to sensors with built-in intelligence and/or processing capabilities. By default, wireless sensors could be considered “smart” (e.g., think of the reliability and data redundancy aspects relating to wireless protocols). These smart functions could for example be used for estimation of unmeasured variables, condition monitoring and smart data reduction purposes. Finally, these sensors may be self-powered and directly translate signals to standard digital protocols (e.g. SOA oriented). A special class of smart sensors relates to vision technology, in particular “Vision in the loop”.

3.1.3.1 Wireless sensors and protocols

Already mentioned that wired and wireless interfaces suffer from latency, chapter 3.1. Many wireless technologies are currently available in the market suited for various industrial applications - whether it is a high-data rate video streaming, low-power and short duty-cycle wireless sensor data transmission or harsh environment long-range data transfers. There is (in most cases) no need for long range communications for wireless sensor applications in I-MECH Layer 1. This is however just one aspect of the whole parameter spectrum that describes wireless communication. A wide range of applicable wireless technologies was reviewed – both standalone wireless standards for custom solutions and ready-to-use products for industrial wireless sensor networks (WSN) and internet-of-things (IoT) applications (wireless solutions integrated with analog/digital inputs for sensors) - as I-MECH pilots and demonstrators show interest in the usage of wireless sensors but either do not yet have specific requirements for wireless communication in mind, or already have a nearly complete design ready.

Licensed and unlicensed wireless bands

Most of the products developed in the electronics industry use wireless communications that operate in the industrial, scientific and medical (ISM) radio bands (Table 3.1). The ISM bands are part of the frequency spectrum that can be used without a license and are not occupied by government institutions and telecommunication corporations. The use of these frequency bands may differ between countries due to differences in national regulations. The most appropriate wireless bands for the I-MECH use case are 868/915 MHz and 2.45 GHz, since these correspond to short/mid range radio communications intended for low power devices. The 5.8 GHz standards were not analyzed since these are intended for high data rate transmissions, but not for energy efficient battery powered embedded devices. It is expected, based on requirements from I-MECH pilot applications, that wireless sensors used in I-MECH layer 1 will be implemented frequently on moving parts, for example on moving parts of a CNC machine, where no power source is available. Hence, a ‘universal’ platform using 5.8 GHz standards would be relatively unsuited for such applications.

The use of licensed instead of unlicensed ISM band wireless technologies in consumer electronics is nevertheless present - e.g. “NarrowBand IoT” (NB-IoT). These standards, part of the range of Mobile IoT (MIoT) technologies, are standardized by the 3rd Generation Partnership Project (3GPP) and use LTE and GSM bands, which are not applicable for short range wireless communication, which is the I-MECH layer 1 use case.

Table 3.1: ISM frequency bands

Center frequency	Use
6.78MHz	Wireless power transfers
13.56 MHz	Near field communication
27.12 MHz & 40.68 MHz	Not often used, long range possible
433.92 MHz (Region 1)	Long range data transfers
868 MHz (Region 1) & 915 MHz	Mid-range data transfers
2.45 GHz	Short-range data transfers
5.8 GHz	Short-range, high data rate transfers
24.125 GHz, 61.25 GHz, 122.5 GHz, 245 GHz (Subject to local acceptance)	High data rate transfers, radar detectors

Wireless standards for I-MECH layer 1

A comparison of wireless standards currently available in industry is shown in figure 3.2. It should be noted that some (modern) standards are missing in this figure and some of the shown standards are deprecated. For example, an updated version of 802.11(b,g), 802.11n, low power WiFi, 802.11ah and Bluetooth LE 5.0 are not included in this picture as they were released recently, while WiMedia and the Ultra Wide Band (UWB) radio communication scheme are deprecated and nowadays rarely used. The standards are divided in the categories WPAN (Wireless Personal Area Network), WLAN (Wireless Local Area Network), WMAN (Wireless Metropolitan Area Network) and WWAN (Wireless Wide Area Network) [2]. Standards categorized as Wireless Personal Area Networks (WPANs) and Wireless Local Area Networks (WLANs) are implemented for wireless radio use in manufacturing/ robotics industry, which is a case of the I-MECH Layer 1, since they define communication up to (Line-of-Sight): 10 m or 100 m, accordingly, which is sufficient for this type of use cases. Standards categorized as Wireless Wide Area Networks (WWANs), implemented on licensed band cellular networks such as GSM or LTE, are not particularly suited for I-MECH Layer 1. WWAN technologies are designed for long range, low data rate communications making it not applicable for real time sensor data streaming over short ranges.

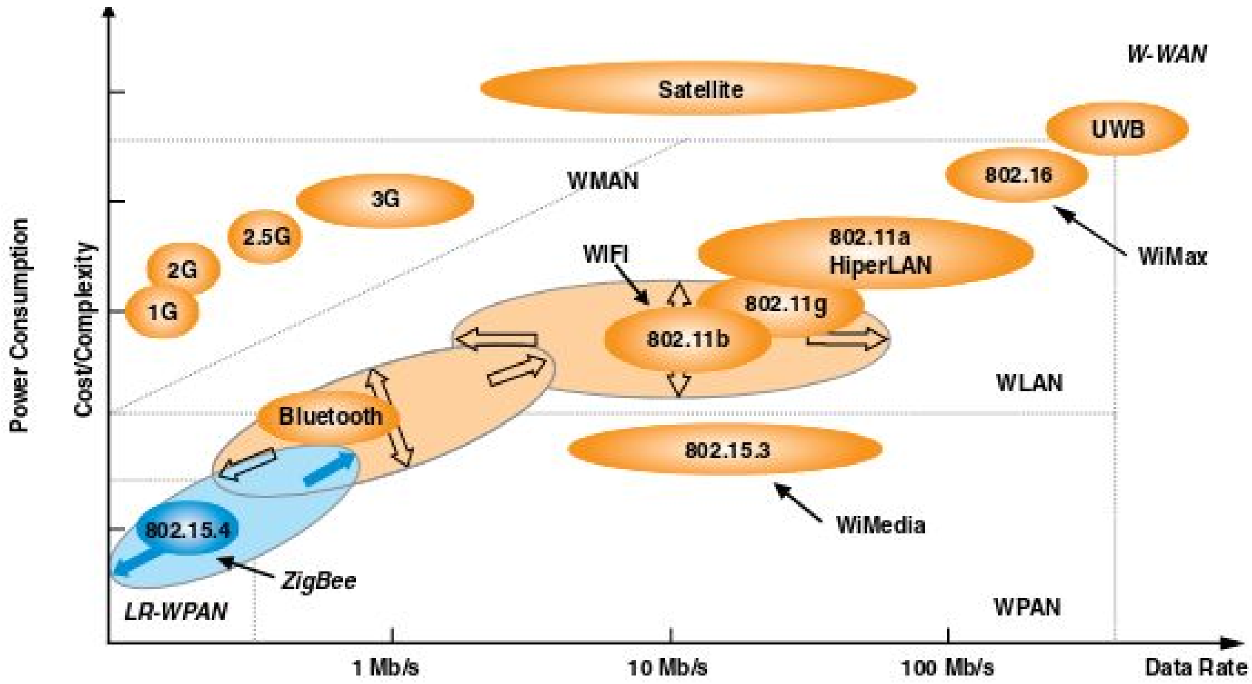


Figure 3.2: Wireless standards compared in terms of data rate and complexity of implementation [3].

WPANs and WLANs contain multiple wireless standards that utilize 868/915MHz and 2.4GHz unlicensed frequency band - 802.15.4 (Zigbee, Xbee etc.), 802.11ah and WiFi 802.11n, Bluetooth LE 5.0 (802.15.3) correspondingly. The WiMax (802.16) standard, illustrated in figure 3.1, is a solution meant for long range data transfers with fixed stations, therefore not appropriate for deployment on moving parts.

The 868/915 MHz ISM band is relatively narrow and this limits the maximum data rates, but is better than higher frequency bands when obstructions such as shelfs, industrial robots and other equipment in manufacturing facilities are in the Line-of-Sight. 2.45GHz standards are typically used in applications requiring higher data rates in close range - voice, video and other intensive data communications (e.g. up to 300 Mbps for 802.11n).

Table 3.2 sums up the main properties of the wireless standards that are most suitable for use in different I-MECH Pilots and Demonstrators, while table 3.3 compares a few COTS wireless sensor networks.

Table 3.2: Comparison of manufacturing/robotics industry suitable wireless standards

Standard	**WiFi(802.11n)** [4]	**802.11ah** [5]	**802.15.4 (ZigBee, Xbee)** [6]	**BLE LE 5.0 (802.15.3)** [7]
Frequency band	2.4 GHz	868/915 MHz	2.4 GHz and 868/915 MHz	2.4 GHz
Modulation	QSPK/QAM	QPSK/QAM	PSK/QPSK/ASK	GPSK

Coding Scheme	DSSS/OFDM	OFDM	DSSS	AFH
Number of channels	14	N/A	16 @ 2.4GHz 10 @ 915MHz 1 @ 868MHz	79
Max.Data rate	50-200 Mbit/s	347 Mbit/s	400 Kbit/s	2 Mbit/s
Network size (nr of nodes)	Up to 250	Up to 250	~1000	7 active, while 248 sleep
Range	Up to 70 m	Up to 1000 m	Up to 8 km, typ. 100 m	Up to 200 m
Max. Tx. power	20 dBm (100 mW) OFDM 18 dBm (63 mW) DSSS	20 dBm (100 mW)	20 dBm @ 2.4 GHz 27 dBm @ 915 MHz 27 dBm @ 868 MHz	20 dBm (100 mW)
Tx. current	243 mA Tx @ 10 dBm [1]	N/A	6.1 mA Tx @ 5 dBm [2]	8.5 mA TX @ 0 dBm [3]
Topology	Star	Star	Start, Mesh	Star

Ready-to-use Wireless-sensor products for I-MECH Layer 1

Multiple ready-to-use wireless sensor nodes are available on the market. Few examples with a list of their main specifications are given below:

1. V-Link®-200 Wireless 8 Channel Analog Input Sensor Node from LORD, MicroStrain® Sensing Systems; [8]
2. SG-Link® -LXRS® Small, Low-power Two-channel Analog Sensor Nodefrom LORD, MicroStrain® Sensing Systems; [9]
3. NI WSN-3202 from National Instruments; [10]
4. TEDIASENS SN-X from ELOVIS GmbH; [11]
5. V-Mon 4000 from Inertia Technology; [12]
6. Wzzard Intelligent Edge Node from B+B SmartWorx; [13]
7. GP-AP81 from OleumTech; [14]

Table 3.3: Comparison of COTS ready-to-use wireless sensor nodes available on the market, see the list above for references to products

Specifications	**Product name by number**						
	1. (V-Link)	**2. (SG-link)**	**3. (NI WSN)**	**4. (Tediasens)**	**5. (V-Mon)**	**6. (Wzzard)**	**7. (GP-AP81)**
Number of analog inputs	8	2	4	3	4	3	2

Resolution (bits)	18	12	16	24	12	12	24
Max. sample rate (kHz)	4* 8**	0.5* 4**	0.001	13	10	0.001	Not specified
Indoor wireless range (m)	250	50	300	138	30	100	Not specified
Radio frequency (GHz)	2.4	2.4	2.4	2.4	2.4	2.4	0.9/ 2.4
Protocol: 802.15.4 802.11g 802.15.4e	+	+	+	+	Not specified	+	Not specified
Max. TX Power (dBm)	20	16	17	Not specified	10	8	0/ 0/ 8
Data rate (kbps)	250	250	250	1000	4000	250	9.6/ 115.2 /250
Internal battery capacity (mAh)	2400	250	Not specified	2600	2600	2400	Not specified
Operating temperature (°C)	-40 to 85	-20 to 60	-40 to 70	Not specified	-50 to 60	-40 to 80	-40 to 85
Dimensions (without antenna) WxHxD (mm)	129x 83x 31	58x 50x 21	86x 124x 42	71x 114x 37	66x 117x 40	95x 116x 65	140x 193x 111

** Continuous sampling*
*** Periodic burst sampling*

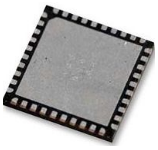
The following conclusion can be made based on table 3.2 and 3.3:

- 802.11n [15] is great solution for extensive data streaming, but has a high power consumption, making it not suitable for autonomous wireless sensor applications which is case of I-MECH Layer 1.

Microchip's ATWINC1510 [16,17], an example COTS product using the 802 standard, "is a low-power consumption 802.11 b/g/n IoT module, whic specifically optimized for low-power IoT applications". This module consume mA when transmitting @ 6 Mbps, which is 6 times more compared Bluetooth 5.0 solution. However, a 6 Mbps or even 54 Mbps data rate will be more than needed for usage in I-MECH Layer 1, where data is transmitted between only a few sensors.

- 802.11ah [16] is a great solution for industrial applications (long range, high data rate and presumably low power), where extensive data exchange between sensor/camera and gateway is needed (the case of I-MECH Layer 1). However, use of this standard cannot be recommended at this moment as hardware is still scarcely available.

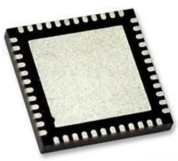
- 802.15.4 [15] is suited for certain cases when there is a demand for low power. Disadvantage of the standard is the relatively low data rate (typically 400 kbps).



An example of a 802.15.4 implementation in the 2.4 GHz frequency ba the Texas Instruments CC2531F256RHAT [18]. This solution has a maxi data rate of 250 kbps, but compared to Bluetooth 5.0 still a relatively power consumption of 29 mA @ 1 dBm.

The 868/915 MHz frequency band is mostly used for applications requir larger range. The Xbee 868LP [19] module is an example of a sol applying the 802.15.4 standard in this frequency range. It can transmit ι 112 meters indoors or 8.4 km outdoors, but has relatively small maximum rates, only up to 80 kbps, compared to Bluetooth 5.0.

- Bluetooth LE 5.0 (802.15.3) [20] can be implemented in those cases when there is a limited power source availability. Since it supports up to 2 Mbps data rate, it can be used for extensive data transmission of sensor data. The maximum transmit range of ~60 m indoors and about 200 m outside is sufficient for industrial environments. The combination of the relatively high data rate, good range and very low power consumption makes this standard a great solution for I-MECH Layer 1 wireless communication. Furthermore, Bluetooth LE 5.0 has the advantage of the capability of bypassing a lot of interference with other RF communications in the same bandwidth by using Gaussian Minimum Shift Keying (GFSK), which is a method for modulating available spectrum efficiently, and Adaptive Frequency Hopping, which is used to hop between 79 channels at 2.4 GHz and avoid any “bad” channels.



An example product applying the Bluetooth LE 5.0 standard is the Silicon EFR32BG12 Blue Gecko Bluetooth SoC [6]. This module has a low p consumption (8.5 mA TX current @ 0 dBm and 10.0 mA RX current a GHz @ 95 dBm sensitivity) and a relatively high (compared to 802.15.4) rate of 2 Mbps (1 Mbps in real life scenario). It is expected that this shou sufficient for deployment in I-MECH layer 1 pilots, where data from ser deployed on moving parts of industrial robotics equipment need t transferred to a gateway in the nearby distance (< 10 m). 1 Mbps is a sui data rate for the proposed sensor use in I-MECH pilots pro (accelerometer, gyroscope, magnetometer and temperature sensors), a pilots indicate that a 400 kbps data rate, at maximum, is needed.

Summary

The most suitable wireless solution for I-MECH Layer 1 is Bluetooth 5.0 LE, based on the presented analysis. This solution has a low power consumption [15] while having a relatively high data rate (1 Mbps) has major advantages. However, the Bluetooth 5.0 LE standard ‘wastes’ excessive power on transmission range, as 200 m communication distance is a lot more than needed in I-MECH Layer 1. A custom solution might therefore still be relevant in case there is a demand for a lower power and higher data rate technology.

3.1.3.2 Vision Sensors

Please refer to chapter 5, section 5.4: BB4: High speed vision.

3.1.3.3 Sensors dedicated for Condition Monitoring

Although condition monitoring is a Layer 2 functional block in I-MECH, it requires technology at the instrumentation level in Layer 1.

Various measurements to detect degradation and wearout can be used. Either the voltage i.e. current is used (big data: determined by the sampling rate i.e. parameters stored) to verify during a known repetitive movement the power i.e. friction encountered. Due to mechanical friction, temperatures may rise which can be easily detected.

Inside bearings, the color i.e. transparency of the grease can be checked optically (SKF). In oil lubrication based machines, the amount of metal can be detected using a magnet in the flow which collects the metal parts and causes contact when a certain level (metal height) on top of the magnet is exceeded.

Other degradation and wearout measurement techniques are under development.

Inside motion control systems, dust on forced cooling elements, heatsinks are the most common artifacts. Temperatures of processing chips and power stages need to be kept low enough (also with LEDs used for illumination) to ensure their lifetime (MTBF). External temperature over 70 degrees shall be avoided whereas the internal die temperature may not exceed 125 degrees, typically.

3.1.3.3.1 Vibration and temperature monitoring

Typical requirements on sensor interfacing for condition monitoring are listed in the requirements table. Furthermore, the reference platform should facilitate processing sensor data with the particular requirements below.

Vibration severity measurement
- Low noise MEMS accelerometers / miniature piezo accelerometers
- >20 g range, configurable
- >5 kHz self-resonance frequency
- < 40 ug/√Hz
- sufficient processing power to perform noise reduction by sensor fusion

Shaft unbalance diagnostics
- Low noise MEMS accelerometers / miniature piezo accelerometers
- Bandwidth dependent on shaft frequency
- < 40 ug/√Hz
- Configurable analog or DSP tracking filter (Q > 20)

- > 1 update per shaft rotation

Gear(box) diagnostics

- Low noise MEMS accelerometers / miniature piezo accelerometers
- >1 kHz bandwidth
- sufficient processing power to perform signal processing, PCA

Bearing/lubrication diagnostics

- High frequency accelerometer, AE sensor (ultrasonic emission)
- Detection based on resonance and/or broadband emission
- > 10 kHz bandwidth
- > 50 kS/s

Acoustic diagnostics

- MEMS accelerometers
- >20 kHz bandwidth
- >50 kS/s
- 16/24 bit resolution
- SPI/PDM interface or analog voltage

Temperature diagnostics of power electronics and overload power management

- RTD, semiconductor or thermocouple
- 10 Hz update
- sufficient processing power to estimate model-based temperature distribution

3.2 Layer 2: Control

The control layer considers motion control algorithms, as well as the modelling, programming and identification tools required to design and commission these algorithms. The control algorithms may combine centralised and decentralised strategies for control of multivariable systems. The I-MECH reference platform should provide the capabilities to execute these algorithms in real-time using an open architecture with sufficient processing power and an open architecture. Condition monitoring forms an integral part of Layer 2. Layer 2 communicates with the behavioral layer via industry 4.0 compliant paradigms and interfaces.

3.2.1 Centralized and decentralized control.

Centralized versus decentralized control is ongoing. smart actuators: motors with built-in drives which can be CAN, Profibus or Ethercat controlled are common, similar to the 6-DoF robotic systems which are fully integrated with the robotic system and only requires geometrical data either as cartesian or spherical coordinates.

The same applies for sensors, where either the raw data is obtained and transferred rather than first conditioned and reduced to ensure a minimum amount of bus utilization as only the significant data is being transferred. A typical example is interpretation of multiple analogue signals of an optical sensor head; usually an FPGA takes care of this and puts the result on an industrial communication bus.

Having all raw sensor data and actuation parameters locally accessible with centralized systems will enable specific optimization for certain application but also means that the amount of data being transferred to and from the centralized system will be orders higher than with decentralized systems where only the most relevant data is transferred.

3.2.1.1 Components of feedback control

3.2.1.1.1 PID controllers

(Proportional-Integral-Derivative) PID controllers are nowadays the standard in industrial applications. The control action is composed by three different parts: one proportional to the control error (that is, to the present control error), one proportional to the integral of the control error (that is, to the past control error) and one proportional to the derivative of the control error (that is, to the future control error). The tuning of the PID parameters in process control is a well-known topic, but in mechatronics the available tuning techniques still need to be improved.

3.2.1.1.2 Filters (Notch, Low-pass, Lead-lag, Biquadratic, ...)

In real industrial applications, a filtering action is sometimes necessary to reduce the noise in sensor measured signals. Furthermore, filtering can be used to avoid the excitation of some resonant frequencies of the system.
The tuning of the filter coefficients is not trivial in general and it is only based on the level of the experience of the operator. A method for the automatic selection of the filter parameters should be adopted in order to decrease the setup of the machine and to reach a higher level of robustness.

3.2.1.1.3 Integrator anti wind-up

The use of an integral action in the controller can yield large overshoots and low frequency oscillations of the output when controller variable saturates because of the actuator physical constraints. Different types of anti-windup strategies are available in literature: conditional integrator, back calculation, automatic reset, preload etc.
The choice of the anti-windup strategy and its related parameters can be automatically done by considering the already defined control parameters.

3.2.1.1.4 Cascade control

Cascade control is the typical control structure that is used to control mechatronics systems. This structure, in fact, can be employed every time that the system to control is composed by parts that have different order of the time constants. Usually, due to the large variety of the mechatronic systems, the tuning of the loops control parameters is done by experts on the specific field in a sequential way (the inner loop controller is tuned before the outer loop controller). It is therefore useful to have an automatic procedure for the autotuning of the systems in order to simplify the controller design phase and in order to reduce the commissioning time.

3.2.1.1.5 Loop shaping control design

Rather than classical (time-domain) tuning of PID and filter parameters, the use of loop shaping is common in high-performance motion control industries. In loop shaping control design, the frequency response of the controlled process is measured. Subsequently, the controller parameters are tuned to obtain a specific shape of the loop gain in the frequency domain. A PID controller structure is still often used, although other structures can be used. The aims are to 1) achieve sufficient phase margin at the crossover frequency, 2) achieve low-frequency disturbance rejection and tracking performance (high gain) and 3) achieve high-frequency roll-off, to avoid control action at frequencies where noise and uncertain dynamics dominate.

3.2.1.1.6 Non-LTI controllers

Standard controllers, as the ones mentioned above, are linear time-invariant (LTI), which means they can be described by a linear differential equation (or difference equation in the digital domain) with constant parameters. Most common automated controller synthesis techniques also return LTI controllers. In case LTI controllers are not able to meet the requirements of a specific application, several alternative controller structures could be employed.

3.2.1.1.6.1 Gain scheduling

Gain scheduling is a well-known technique for the control of non-linear systems. Nowadays the standard gain scheduling technique uses a set of predefined controller parameters that are statically defined. The choice of the appropriate set of parameters is based on a linearized model of the system and depends on the operating point. For time-variant systems this strategy can lead to a decrement in performance. That is why an intelligent gain scheduling based technique needs to be developed.

3.2.1.1.6.2 Auto-tuning position control loops

The tuning of the external loop of the motion control system, that is the position loop, is mainly performed by the operator after the setup of the velocity loop. The tuning of the position controller is important because, as it is possible to see in the literature, it can bring the overall system to the instability. Due to this fact, an automatic procedure of the position controller parameters estimation has to be done by considering, for example, requirements on the maximum overshoot or on the minimum phase margin required.

3.2.1.1.6.3 Adaptive control

For some applications variations in either plant dynamics and/or external disturbances can be so large, and hard to quantify a priori, that it is impossible to meet the requirements in all situations. In such cases adaptive controller techniques might be beneficial, such as linear parameter varying (LPV) system descriptions and control, least mean squares algorithms, and model reference techniques. Developments are needed to make such techniques applicable to motion systems and to make the algorithms sufficiently long-term stable.

3.2.1.1.7 Observers and state estimation

Observers are model based components that are commonly used to have an estimation of the system physical quantities like position, velocity, acceleration etc. Typically, observers are used in order to obtain the initial conditions of a system (for example, those of friction models that take into account the temperature of the mechanical transmission), when the measurement of some physical quantities is affected by noise, or when it is not possible to have a measurement directly from a sensor.
A relevant example of observer is the Kalman filter, which can be used, for example, for the estimation of the motor current or, in other cases, of the motor acceleration, velocity, and position. Furthermore, an observer based strategy can be effectively adopted in order to have an estimation of the position of the load for systems endowed with an elastic (or for overhead cranes) or to implement virtual force sensors for robot manipulators.

3.2.1.1.8 Flexible control algorithm

The control algorithm should be software-reconfigurable, for instance to depart from a fixed PID control structure as is common in many industrial controllers. This is necessary to facilitate the implementation of more complicated or hybrid feedback control schemes.

3.2.1.1.9 Auxiliary feedback control

Using both motor and load-side feedback has been shown to improve closed-loop dynamics and robustness. Available algorithms can be deployed thanks to the processing power in current FPGAs and DSPs or CPUs.

3.2.1.2 Robust (de)centralized control

Complex multi-dimensional motions are often required in applications such as robotics or CNC machining. One common approach to control such motions is to decompose the spatial motions from the machine coordinate system into the contribution of the individual machine axes by performing an inverse kinematic transform (or geometric decoupling) in the motion planning layer. The resulting commanded trajectory for each axis is then followed by the individual control loops. This type of approach to multiple-input-multiple-output (MIMO) systems is referred to as “independent” or “decentralized” control, as it neglects eventual dynamical interactions between the individual loops. This concept works well when the level of mutual disturbances and mutual dynamic interactions is low and the individual loop controllers manage to follow the commanded motions with sufficient precision.

Highly dynamical systems with irreconcilable interactions between the individual loops require the employment of coordinated (or “centralized”) control methods to obtain stable closed loops while achieving acceptable tracking performance. In such cases the performance with decentralized control can be limited, hence the requirements necessitate a centralized approach. The control algorithm computes appropriate actuator commands based on the feedback from all of the system parts, forming a single multivariable feedback loop instead of a series of independent single input-single output loops. This imposes additional requirements on the controller implementation, where all sensor variables and actuator outputs have to be accessible in a centralized manner, which might be difficult or even impossible to implement in commonly available COTS general purpose motion controllers, due to the limited capability for control algorithm customization. Development of a custom motion control platform which supports general (state space) implementation of complex multi-axis motion control strategies is therefore desirable.

Synthesis of centralized controllers typically depends on a mathematical model of the system to be controlled, often obtained via control-relevant modelling and (advanced) system identification procedures, but the actual performance is highly dependent on the quality of such models. In standard synthesis techniques, performance requirements and knowledge of disturbances and setpoints are often formalized by means of weighting filters. Moreover, robustness (in terms of closed-loop stability and performance) is typically taken into account by explicitly modeling the uncertainties in the system. In practice, however, these techniques are difficult to apply or require expert control knowledge; sufficiently reliable and accurate system models are hard to obtain, uncertainties are difficult to quantify within the required framework, and weighting filters are not intuitive to formulate. Hence, developments are needed to provide truly applicable robustness concepts and designs, by bridging the gap between the mathematical toolsets and real applications.

3.2.1.3 Trajectory generation

Trajectory generation and its use in feedforward control is an essential component in most high-performance mechatronic systems. While mass (acceleration), friction (velocity) and stiffness (static) feedforward are common, current (jerk) and voltage (snap) feedforward are less common. The latter may be necessary to improve performance when the current control loop limits performance. Tuning feedforward controllers is a challenging and time consuming task, since it depends on a good system description (model) and since the parameters are often task and operating-point dependent.

3.2.1.3.1 Input shaping

Input shaping is effective for the open-loop control of oscillatory mechatronic systems. The technique is based on the superposition principle for linear systems, generating a series of oscillatory responses that cancel each other out, giving a final non-oscillatory response.
Input shaping technique parameters are relatively easy to be found, as they are based only on the measure of the natural frequencies and the damping of the system. Input shaping techniques are applicable to multi-frequencies system, and robust techniques exist.
A limit of input shaping techniques is the dependence of the minimum actuation time on the natural periods of the system.
Various studies on complex input shaping techniques exist. However, they rarely find application in industry. Therefore, a simple and user-friendly module for the use of input shaping techniques in industrial applications is needed.

3.2.1.3.2 Friction feedforward

Feedforward actions are nowadays used for several purposes, and one of the main one in mechatronics is for friction compensation. It is in fact known that, in order to obtain a better positioning precision, friction has to be properly compensated. Due to the fact that friction is a complex nonlinear phenomenon, and the positioning precision requirements are more and more restrictive, the usually used Coulomb plus viscous friction model is often not sufficient to obtain the required performance. Thus, an automatic procedure for the friction model identification has to be developed and, in order to fulfil the positioning precision requirements, and an automatic setup of the feedforward for the friction compensation has to be done. Further, the model has to be continuously adapted in order to cope with the friction variations (for example, because of changes in the temperature).

3.2.2 Modelling and identification

Modeling of a system that has to be controlled is done for two reasons. First, before the actual system is built, a model of the system is used to virtually test the system and predict its real life performance. This model can be used during the design phase to optimize the design and investigate design options. Second, once the system is built, a model of the system is built to be used in the controller (feed forward loop, state observer, condition monitoring). This model should ideally be the same or derived from the model used during the design phase to reduce the modeling effort.

Simple linear lumped element models do often no longer suffice in order to model system behavior with sufficient details to determine achievability of increasingly challenging specifications on speed and accuracy, although they provide great insight during the concept phase of the engineering process. Furthermore, usage of more detailed and accurate models will, at least in theory, result in better machine performance when they are used in the control loop. Finite element models are able to capture the physics that are affecting the system performance, e.g. hysteresis, geometric/material nonlinearity and higher mode dynamics if 3D physics. However, a finite element model is typically too slow to be used in a real-time controller of an actual system. It is therefore frequently necessary to apply model reduction techniques to reduce computational complexity of finite element models before they are used in a real-time controller. These techniques are well known for linear systems, but not yet fully adopted by commercial companies. Moreover, model reduction techniques for nonlinear multivariable systems are even more challenging and not at the TRL for general commercial use.

In order to evaluate the accuracy of model reduction techniques on a flexible multi-body dynamic system, we can compare the solutions obtained with the complete model and a numerically less complex model that is derived from the complete model using model reduction techniques. The resulting reduced order model can then be used in a 0D simulation software like LMS Amesim [21], that also permits definition control loop and simulation of the controlled system, when the deviation between both models is acceptable. This solution has the great advantage that it results in reduced simulation times. However, the general accuracy of the solution can suffer from a relative lack of accuracy of the reduced order model with respect to the 3D finite element model it has been generated from. Furthermore, unacceptable deviations between actual behavior of the system and behavior expected based on the model can occur when a complex nonlinear system is linearized around a single workpoint to reduce numerical complexity of the model with certain model reduction techniques. Hence, model reduction techniques that can preserve the nonlinear behavior of a system when a nonlinear 3D FEM model of the system is reduced to a 0D representation could be valuable.

If the two solutions lead to the “same” results on several representative cases (ideally with experimental measurements on them to qualify the accuracy of the models), it will permit us to be convinced that model reduction technique can be extensively used in the framework of the I-MECH project at two levels:

- in a 0D simulation tool like LMS Amesim for the design of controllers before the system is built (virtual prototyping)
- in the controllers themselves when the system is built (feedforward loop, …)

An alternative to losing model accuracy to reduce computational complexity would consist in combining the description of the controller together with the 3D finite element model in a monolithic resolution strategy inside a 3D simulation software like OOFELIE: Multiphysics [22]. This method would lead to no compromise on numerical solution accuracy but would necessitate strong computing resources and an accurate model of the controller. Usage of a multi or many core platforms for model based motion control, reserving cores specifically for FEM model solving could result in gains in the time required to solve complex models. However, commercial FEM software is often not particularly optimized for the usage of many cores such that the increasing the number of cores at a certain point does not result in gains in solving speed [23–26]. It remains however always recommended to simplify models as much as possible, as one often quickly gives away a lot of computation power to unnecessary detailed simulations.

System identification is a step needed to be able to tune the controller. The behavior of the actual system is identified during system identification by measuring the behavior of the system. This is often done by subjecting the system to disturbances, for example by exciting it with an impulse hammer or injecting noise into the system with a ‘shaker’ or, which is ideal for tuning of a controller, via the actuator in the system of which the controller needs to be tuned. System identification is ideally combined with parameter estimation, where the value of parameters of a model of the system are estimated based on measurement result obtained during system identification. It is very valuable to also be able to estimate the uncertainty of estimated parameters. Not all control strategies are equally robust for system changes. The question is how to find the most robust control strategy taking into account the uncertainty of system parameters. The system identification and parameter estimation steps can be cumbersome and currently require a lot of time and expertise. There is a need to simplify and even automate the identification and subsequent parameter estimation procedure.

System identification does not end at the deployment of the system, since some system parameters may change over time e.g. due to wear of the system, changes in conditions of the environment of the system, exchange of components of the system or changes in materials the system is handling. The controller should in such cases be re-tuned at regular intervals to keep system performance high. Furthermore, the condition of a machine can be monitored and breakdowns can be predicted by performing system identification and parameter estimation on a regular basis for a system. Extension of the retuning and service intervals in general (by structural health monitoring) are ways to reduce operating costs.

3.2.3 Vibration control

3.2.3.1 Residual Oscillation Compensation

Residual oscillation is an undesired phenomenon that can occur every time that a load is connected to its actuator by means of an elastic transmission. The presence of residual oscillations leads to an increasing of the total actuation time, an increasing of operative costs, a less accurate positioning and sometimes to an increase of hazards (e.g. for overhead cranes). Several techniques are already present in the literature, but there is still a concern in the use of closed loop techniques in industrial fields because of the difficulty in placing a sensor on the load side. Moreover, open loop techniques like input shaping and/or input-output inversion are used but, as it usually happens in practice, these techniques are based on simplified models that cannot take into account the complete dynamics of the systems. It is therefore necessary to investigate more reliable and simpler to use techniques.

3.2.3.2 Vibration compensation

Vibrations are generally one of the most critical problems that affects mechatronic systems. It is in fact known that vibrations can cause different undesired effects such as positioning errors, mechanical stress and actuation wear. To compensate for the vibrations, different filtering actions can be adopted (notch filtering, low pass filtering, etc.), but, most of the times, the tuning of the filter parameters is difficult. That is why an automatic procedure for the resonance frequency identification has to be developed in order to guarantee an automatic (and possibly adaptive) procedure for the selection of the filter parameters.

3.2.4 Learning control

3.2.4.1 Iterative learning control

Iterative learning control can be used effectively, for example in robotics, when the same task (starting from the same initial conditions) have to be performed many times. In fact, the set-point for the control system is changed at each iteration in order to compensate for the control error attained at the previous trial. This allows to reach some end-effector positions by automatically compensating gravity, joint compliances etc. The effectiveness of this technique is proven in the literature, but in industry it is not yet usually employed because there are some critical parameters to tune in order to obtain a monotonic decrement of the error at each iteration. Thus, the gap between theory and practice has to be reduced by devising suitable robust design techniques.

3.2.4.2 Repetitive control

Repetitive control can be used to reject periodic disturbances that occur when performing a repetitive task. As for iterative learning control, which presents similar issues, the effectiveness of this technique is proven in the literature, but in industry it is not yet usually employed because there are some critical parameters to tune in order to obtain a monotonic decrement of the error at each iteration. Also in this case, the gap between theory and practice has to be reduced by devising suitable robust design techniques.

3.2.5 Monitoring and diagnostics

Condition monitoring and predictive diagnostics will require performance data as well as physical measurements (acquired in the instrumentation layer) to be collected by the platform. This data, based on measuring physical signals, should be processed to provide diagnostics.

3.2.6 Many-multi-core platform for high-performance motion control

The need to increase the computing power of CPUs is nowadays frequently achieved by increasing the number of processing cores of the CPU instead of increasing the clock-speed, moving from single core to multi-core or even manycore designs. This is in particular advantageous for tasks that can be computed in parallel. Manycore processors a class of multi-core processors specifically optimized for a high degree of parallel processing with a high number of cores, at the cost of lower single thread performance, while multi-core processors are usually optimized for executing both parallel and serial code efficiently [27]. The transition from single core to multi or many core processors has been going on for quite a while in scientific and home computing [28,29]. The power of multi- and manycore processors has however also come available since the last few years in COTS motion control platforms. TwinCAT from Beckhoff automation is for example capable of running on many-core platforms using up to 256 cores [30]. The usage of a multi/many core processor also enables efficiently executing multiple operating systems on a single processor. This is valuable to integrate (legacy) software that was developed for a different operating system. The COTS automation & motion control solution from B&R uses a hypervisor to allow running of other operating systems beside the RTOS of B&R [31].

BB11 aims at developing innovative technologies for mixed-criticality systems. In particular, it aims at the concurrent execution of different OSs with heterogeneous criticality levels (e.g., a certified RTOS for safety-critical and/or real-time tasks and a general-purpose OS for non safety-critical tasks). This objective will be achieved through the usage of a hypervisor (like, e.g., Xen, Jailhouse, tzvisor, etc) for enforcing the isolation of the different domains.

It is therefore important that the underlying processing unit of the COTS platform (i.e., CPU or SoC) has an instruction set capable of executing virtualized instructions. In practice, the following requirements are needed:

- Intel x86 CPUs:
    - 64-bit instruction set
    - Intel: VMX, VT-D, EPT (extended page tables), unrestricted guest mode, preemption timer
- ARM SoCs:
    - ARMv7 with virtualization extensions or ARMv8

Additionally, the processing unit must have at least 2 physical cores to let running the safety-critical tasks on an isolated core, reducing the interference from the non safety-critical part.

The Hypervisor must support at least the following guest Operating Systems: VxWorks 6.9+ (at least 2 instances), any real-time Linux kernel and potentially Windows.
Moreover, it should guarantee full and real-time access to PCI and PCIe peripherals, exclusive access to the I/O space (e.g. serial ports) and should provide an efficient and reliable inter-core communication system. The 'multi-many-core' ambition will be closely aligned with the needs to process data of vision sensors. (see section 3.1.3.2 Vision Sensors)

3.3 Layer 3: System behavior

The primary reason for the inclusion of layer 3 in this document is to ensure compatibility of layer 2 with industry-standard interfaces. For the pilots and demonstrators we will investigate the impact of their applied standard (e.g. ISA 95 [32,33] for J&J Vistakon) in the context of compatibility with Industry 4.0.
The second reason is the I-MECH ambition to discover to what extent a model-based approach (like discussed in 3.2.2 Modelling and identification) can be applied here. The complexity of the behavior in Layer 3 is usually high (many exceptions to be directed without introducing e.g. race conditions or deadlocks). Tools like Dezyne [34] could help us to improve management of the creation process of this type of software.

3.4 Industry 4.0 compatibility

At Hannover Messe 2015, the Platform Industrie 4.0 (I4.0) announced a reference architecture model for Industrie 4.0 (RAMI 4.0) [35]. RAMI 4.0 is a unified architecture model that serves the purpose of a common understanding, which standards, use-cases, standards etc. for I4.0 are necessary, and allows discussing associations and details. In RAMI 4.0 I4.0 components are defined in their structure and functioning. Thus, it enables cross-company networking and integration across value-added networks. Where meaningful, RAMI 4.0 builds on existing and relevant standards. I-MECH embraces this initiative and in the course of the project, the consortium will strive for maximal compatibility. We will be in contact with 'Productive 4.0' [36] to align this ambition with other EU projects.
For those partners involved with the I-MECH project as well as Industry 4.0, the aims and pace must be held with the developments in Industry 4.0 to ensure compatibility (to avoid divergence) for the outcome achieved and targets set.

3.4.1 Condition monitoring

Conditioning monitoring is provided by layers 1 and 2. During I-MECH, the pilots will specify which information needs to be interpreted and logged. It can be expected that the information density is high. Thus demanding for traffic on communication busses and storage capacity of hardware.

3.4.2 Performance assessment

Performance monitoring and assessment in the process control field is a well-established topic that has received a big impulse in the Industry 4.0 framework because of the availability of a large amount of data. The data can be used to establish the status of the process (e.g. in order to evaluate the need of maintenance) or to evaluate if the controller needs to be re-designed, because a change in the process dynamics has yielded a significant decrement of the performance.

This concept should be transferred also to motion control systems. In particular, it is important to have methodologies that allow the verification of the performance of the controller, which might be degraded because of many factors, like for example a change in the friction characteristics. Techniques should be developed in order to assess automatically when the controller needs to be redesigned and how this can be done, by taking into account that, for example, in the usual cascade control structure, there are the position/velocity PID controllers, feedforward controllers and filters.

3.4.3 Communication for Industry 4.0

The OPC Unified Architecture seems to be (one of) the most popular communication protocols for 'Industrie 4.0', machine-to-machine communication and IoT applications based on an inventarisation of several EC-funded projects related to smart manufacturing (e.g. OpenMOS, PLANTCockpit, IMC-AESOP, DAEDALUS) and availability of implementations of the protocol in modern COTS motion control and automation platforms (e.g. Beckhoff Automation, Siemens, Bosch Rexroth & B&R). Moreover, OPC UA is the communication technology used in the Industrie 4.0 reference architecture RAMI4.0 [35].

OPC UA provides a vendor and platform independent communication protocol for industrial automation applications. The platform-independence is one of the main advantages of the communication standard. The basic implementation of the protocol uses a client-server approach. It can be used for horizontal communication in a manufacturing environment, for communication between devices, and vertical communication, communication between devices and SCADA/MES/ERP systems and even the cloud. The standard OPC UA protocol is not suited for communication with real-time requirements. However, the OPC foundation is working on making the protocol suited for real-time communication in the form of OPC UA TSN (Time Sensitive Networking) [37,38].

The OPC UA standard is freely available on the website of the OPC foundation for registered users and standardized as IEC 62541, with test tools and laboratories for testing and certifying available. Several open source as well as commercial implementations of OPC UA clients and servers are available. OPC UA can in theory be implemented in all languages. The OPC foundation freely provides the OPC UA stack in Ansi C/C++, .NET and Java including sample applications [39].

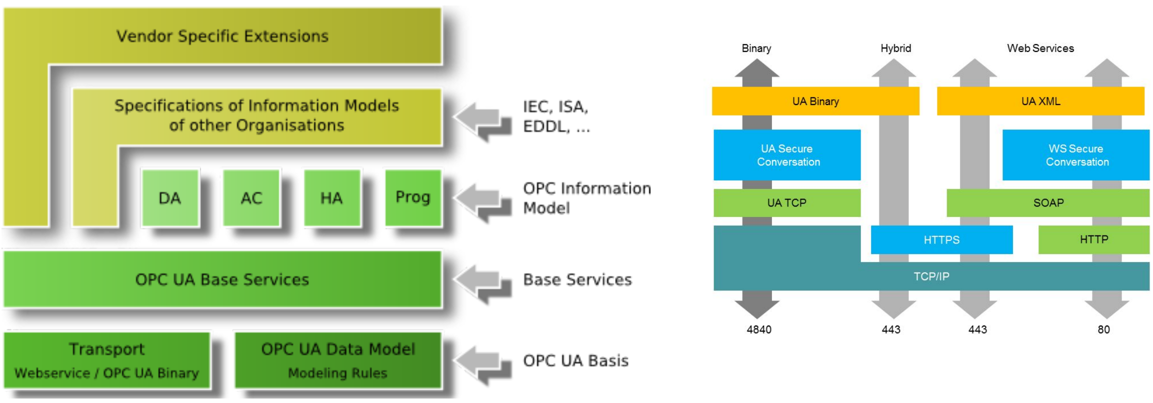


Figure 3.3: OPC UA architecture

The OPC UA protocol is modular. All implementations require a few basic functionalities, specified in the OPC UA standard [40]. OPC UA models data as objects that can have variables, methods and events. A set of fixed OPC UA services, defined by the OPC UA foundation, can be used to access those objects and for example read and write data in a variable, e.g. a measured value, call a method or receive events, e.g. alarms, from the object [41]. There are also services to subscribe to data, request 'historic' data, discover OPC UA servers, browse servers, etc.. Using a fixed, universal set of services ensures that OPC UA works 'plug-and-play'. The set of objects that an OPC UA server makes available to its clients is called its 'address space' [41]. OPC UA uses so called 'Information Models' to structure and relate the information in an address space in such a way that it represents standard systems, processes or even entire plants [42]. Several 'standard' information models are made available by the OPC foundation. It is possible to define new information models as external party [40]. The PLCopen foundation has for example made an information model available to be able to access data on PLCs using OPC UA.

OPC UA information can be transported over different protocols. Every application is required to implement at least the 'UA Binary protocol', implementation of other protocols, e.g. using web services, is optional. A publish/subscribe communication model was added to OPC UA to facilitate bandwidth-efficient many-to-one, one-to-many communication, relevant to SOA applications [43]. OPC UA provides furthermore mechanisms for identification and notification of OPC UA-capable devices and functions within a network using intelligent, configuration-less procedures.

OPC UA provides secure data transfer and authentication at user and application level. User identification can take place upon connection using X.509 certificates, Kerberos, or a user/password combination, which enables support for common user administration systems like Microsoft Active Directory, while OPC UA applications can identify themselves using software and application instance certificates [44]. Messages sent via OPC UA are signed, which prevents tampering with messages by unauthorized parties [44].

The OPC UA communication protocol is very modular, which makes the protocol scalable. Scaling is done using 'profiles' that describe the available functions of a OPC UA server [45]. OPC UA scales from a small 15kB footprint suited for small, low power devices with single threaded processing, like smart sensors, to implementations on PLCs, implementations with many options and functions suited for high power platforms on industrial PCs and even implementations in the cloud (e.g. Amazon AWS or Microsoft Azure) [43].

4 Reflection

After reading section 3 of this document, it becomes clear that algorithms (and the accompanying computing hardware) for domesticating the physics of the partners' 'plants' are dominant in I-MECH. However, several 'nonfunctional' requirements need to be addressed explicitly.

4.1 In search for a standard

The requirements to be considered should be turned into 'standardized requirements' to enable modular design for those parameters NOT included in the model(s) but assumed to be fulfilled by design. That is why there is a single I-MECH requirements table for all Pilots, Use Cases and Demonstrators. As this standardization in the field of building block modelling is a new unsolved challenge, it is a great opportunity for the I-MECH partners to be filled in. The same applies for other electrical parameters which are at present not covered (but assumed to be fulfilled) by the various existing electrical and safety related standards (Defined per Pilot, Use Case and Demonstrator). This opportunity needs to be a collaborative effort by academia and industry.

4.2 Don't get disturbed!

Motion control systems are still based on classic design w.r.t. their hardware design (e.g. design of cabinets) to enable the control systems based on (again) classic placement and cable routing techniques using e-cad or other wiring design schemes. These cabinets are truly connected node-by-node but mostly without considering signal 'return' paths which are often not even indicated on the wiring scheme/diagram. There is a huge gap between mechanical design and electrical design w.r.t. grounding, bonding and filtering. Electrically, the grounding symbol is an indication that something must be grounded but no indication is given where. Mechanical engineers and installation engineers have no perception where this 'optimal' grounding must take place.

When power wiring in installations is also considered for powerline alike communication (to save extra wiring), shielded multi-wire cables can be used but terminal connections e.g. like the Phoenix connector blocks or Harting power connectors and pin assignments have to be reconsidered or re-thought to enable RF based signal communication on these power wires too.

With most of the motion control systems, the grounding structures are considered as the ultimate 'equipotential' structure through which currents may flow. The opposite shall be challenged: there shall be NO current running through the grounding structures: NO DC or mains frequency (leakage currents) nor any other RF frequencies unless in a wiring fault condition. The grounding structure should not be a part of the signal path and ALL sensor, supply and actuator signals should run over the wires assigned as intended.

4.3 Model Based approach

Part of I-MECH emphasizes the ambition to improve the 'classical' way of engineering towards a direction that is envisioned by e.g. INCOSE [46], the international council on systems engineering, (e.g. T4.2, Unified framework for model-based design of motion control systems) and T4.3, Modeling & Identification of complex multivariable systems) How does this ambition affect the WP2 implementation? At this point in time, the leader of T4.2 has started an inventory among the pilot, use case and demonstrator owners. We have to learn whether existing (or emerging) 'tools' will support a model-based approach at behaviour level (Layer 3), control level (Layer 2) and at instrumentation level (Layer 1). We have to learn to what extent the interfaces between different modelling tools (e.g. between partners) are standardized.

4.4 Relation with ECSEL-JU goals

ECSEL-JU has published a roadmap, the Multi Annual Strategic Plan 2017, describing the goals and key enabling technologies for the European industry in the coming 10 years [47]. Several trends observed and objectives stated in the ECSEL roadmap, especially for topics like smart production, smart systems integration and Cyber Physical Systems, are also present in requirements for the I-MECH platform derived from participating pilots, demonstrators and use cases.

The I-MECH platform will obviously directly contribute to one of the ECSEL main objectives to move towards more digitized and highly automated production. Examples of other needs and objectives that can both be found in the ECSEL roadmap and needs from participating I-MECH pilots are for example the need to be able to simulate systems and various related needs, up to the need to be able to simulate entire factories for optimization and virtual commissioning purposes. The need for flexible production and customization is explicitly stated, amongst others, by IMA regarding their food packaging I-MECH pilot application. This need for reconfigurability is also recognized in the ECSEL roadmap. I-MECH intends to introduce customizability by using configurable building blocks. Needs for smart maintenance stated by ECSEL are especially the focus of the Philips Healthcare pilot and will result in the development of a specific I-MECH building block for condition monitoring of machines. The needs of the big CNC machining pilot from Nicolàs Correa match closely with ECSEL's goals on real time sensing and networking in challenging environments. Finally, a need for more and better standardization was clearly identified during inventorization of I-MECH requirements. Better standardization is another crucial objective of the ECSEL strategic plan as "standardization will drive the development of interoperable products/methods and tools addressing several fragmented markets" [47].

It is clear that the needs and objectives identified by the ECSEL strategic plan and the needs from I-MECH pilots and the objectives of the I-MECH initiative match on many aspects. It remains therefore of importance to remain monitoring the progress of other ECSEL initiatives during the course of the I-MECH project to ensure that relevant facets of the ECSEL and I-MECH roadmap remain aligned. This is of particular importance regarding standardization, like standardization of communication protocols and methods and tooling for model based development. The ECSEL roadmap expects for example in the coming years significant progress regarding an “open simulator platform” for multi-domain and multi-physics simulation with linking from and to different simulators and engineering tools, suited for simulation of the entire product life cycle, plant wide optimization and control optimization and developments in model based system development including automatic code generation. Developments in these areas are of large relevance to the I-MECH platform. It is therefore unfortunate that the quantity and quality of information about methods and tooling shared by other EC funded projects seems to be rather poor.

5 Requirements for Building Blocks

Eleven building blocks have been defined. Figure 5.1 visualizes which blocks are related to which part of the I-MECH reference model.

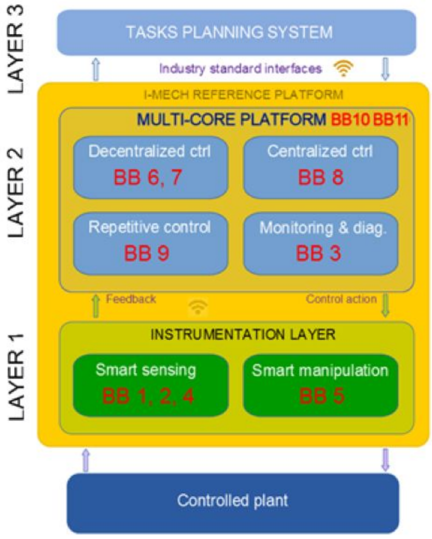


Figure 5.1: Layered I-MECH architecture showing the allocation of I-MECH building blocks

Table 5.1 explains where the building blocks will be applied in the I-MECH pilots and demonstrators. It shows the relation with the pilot projects. In the subsequent sections, the BBs will be further clarified based on the content of the FPP and extended with new insights. Although the best performance will only be achieved through the platform as a whole, the individual building blocks can be offered as standalone products suitable for integration with existing legacy solutions in the market.

Table 5.1: Expected applications of I-MECH building blocks in I-MECH pilots and demonstrators.

	BB 1 Platform for Smart Sensors with Advanced Data Processing	**BB 2** Real-time wireless sensors	**BB 3** Robust condition monitoring and predictive diagnostics	**BB 4** High speed vision	**BB 5** High performance servo amplifier	**BB 6** Self-commissioning velocity and position control loops	**BB 7** Vibration control module	**BB 8** Robust model-based multivariable control	**BB 9** Iterative and repetitive control module	**BB 10** Control Specific Multi-many core Platform	**BB 11** RTOS for multi-many core platform
Pilot 1: GSC	Encoder signal processing of an interrupted ruler		Predict when the belt needs cleaning	Measure belt-edge	Replace amplifiers for reluctance actuators	Autotune & Commission the belt translation	Vibration damping of machine frame	Verify if this approach can improve the GSC performance	Verify if this approach can improve the GSC performance	Existing solution (CPU) is too expensive. I-MECH platform will meet this challenge.	
Pilot 2: 12-inch wafer stage	The combination of BB1 and BB5 could result in a next generation control and amplification unit.	Real-time wireless force sensing in small volume: pickup/handover /attach force measurement on bondheads	Improve RAMS: Reliablity, Availablity, Maintainablity and Serviceability with the outcome of BB3 and BB6	E.g. next generation platform for machine vision. (should replace centralized solution of existing platform)	The combination of BB1 and BB5 could result in a next generation control and amplification unit.	Improve RAMS with the outcome of BB3 and BB6. Exclude human factor in tuning methods		The outcome of this BB should make the existing solution more robust. For this BB is interested in multivariable identification and deployment on a motion platform.	Verify to what extend this could improve conventional system lay out the industrial foundation. Get ILC out of the research corner.	The combination of BB10 and BB11 could be very interesting, since Nexperia relies on exploiting centralized control in existing systems too.	
Pilot 3: High speed Packaging										The combination of BB10 and BB11 is significant, ensure always-on, deterministic, Hard Real-Time Motion Control System with tighter control loop and therefore more efficient CPU utilization	
Pilot 4: Big CNC machining	Proximity sensors, accelerometers and temperature sensors will be processed in a single, advanced control unit	The pilot requires safe and secure communication in a hostile environment(vibration, metallic, interferences, dust and liquids)	Enable life monitoring, decen. decisions and execution of a smart factory. Several param. have to be monitored and trigger an alarm signal if potential risks are foreseen.			Reduce mach. commiss. time and operation expertise. Essential to handle the information provided by modules BB1,2 and convert it into a valuable input for BB3.		Large amount of data from BB1, 2 (temperature, rel. position, accelerations) can be processed into useful information with the help of robust multivar. control approach.			
Pilot 5: Medical manipulator		Sensors could be useful. Key is their reliable operation and (low) cost.	Improve RAMS: Reliablity, Availablity, Maintainablity and Serviceability	Could be useful in e.g. patient and medical staff position assessment in collision avoidance algorithms.		Improve RAMS. Faster development cycle and more robust behavior.	Can be useful to e.g. stabilize images or as measurement tool for vibration relating to RAMS.	The dependency between the orientation of different axes of a medical robot is extensive. Elaborating on a model base approach is welcome. Key is the robustness.	A medical manipulator in many cases executes repetitive movements. Such control, if stable, will improve performance.	Cost effective decoupling of RT demands between app. SW and RT control SW. Provides interface between the FPGA and application.	Fully decoupling RT control needs from the app. and offers synchronisation possibilities. Maintainability of the RTOS is an important issue.
Demonstrator 1 - MagneMotion LSM	Data contextualisation and data for BB3 (analytics)	Key sensing for Magnemotion electrical power consumption, location and kinematics. Product process tracking	Data analytics for electrical power consumption, LSM carrier degradation and preventative maintenance analytics	Part tracking and kinematic modeling of Magnemotion system (in conjunction with wireless sensing)	Improvement over current Magnemotion controllers, power losses, greater efficiency			Model Magnemotion loops for improvement of the loop control and kinematic optimisation			It may be interesting if a problem of communication between the Magnemotion and current control systems was found.
Demonstrator 2 – Injection mold industry		Useful on mold injection plastic in order to retrieve data, e.g. prevent failure in critical components during the injec. process.		Identification of small components in molds (e.g. In-Mold-assembly).							

5.1 BB1: Platform for Smart Sensors with Advanced Data Processing

This building block forms a common platform for smart sensors which provides high-fidelity information derived from the primary sensor raw data. Considered primary sensors operate on various principles - for example optical, including integration of high-speed cameras (BB4); magnetic; or inertial like accelerometers and gyroscopes. Also, different electrical interfaces will be covered, including integration with wireless data transmission system (BB2).

All application cases briefly described above share several common requirements:

1. Advanced data processing algorithms:
    a. Raw data from primary sensors usually cannot be directly used in higher control system levels.
    b. In smart sensors, the data processing covers not only basic operations like time decimation and filtering, but especially complex mathematical models which provides for example precise estimations of position, velocity and acceleration of physical objects.
    c. Such algorithms have to be executed in real-time, with very low latency, to allow building high quality fully closed control loops based on such sensors.
2. Flexible and high-performance interfaces to primary sensors:
    a. A wide range of primary sensor interfaces will be covered: high speed analog-to-digital converters, high-precision time measurements, high-data-throughput camera image interfaces, low-latency wireless transceivers.
3. Flexible interfaces for integration with higher level layers (SOA based):
    a. Distributed control systems interfaces: High-performance ethernet-based communication systems like EtherCAT or Profinet IRT.
    b. Standard servo drives and motion control systems interfaces: Open digital sensor communication protocols like BiSS-C / vendor-specific digital communication protocols like DRIVE-CLiQ / quadrature encoder signal simulation.
    c. Time synchronization: In high-speed control loops, precise time synchronicity spanning all layers is a clear requirement. This can be covered by ethernet-based communication, but also physical input and output synchronization signals have to be often deployed.

5.2 BB2: Real-time wireless sensors

Apart from conventional position encoders, several additional sensors such as gyroscopes or accelerometers can be attached to the moving machine body. This additional feedback information enables novel robust control strategies which can significantly enhance the overall performance [48–51]. The additional instrumentation is often installed at places with difficult access for wired connection due to the motion of the working mechanism. Therefore, it is more convenient to use wireless sensor networks (WSN). However, the state of the art WSN have several limitations that affect operation efficiency, including power restrictions, limited computational ‘smart’ power, storage restrictions, transmission ranges, etc. [52]. At present, many researches focus on micro-node WSN in energy-constrained applications which can handle real-time data transfer in the case of moderate performance requirements (low bandwidth and tolerable delay) e.g. in temperature, pressure and humidity monitoring [53]. However, state of the art wireless systems do not allow high sampling rates, low latency and sampling synchronization which are essential in time-critical high-fidelity motion control systems [54–57]. These issues will be addressed by the I-MECH platform which will offer a low-latency, secure and reliable wireless transmission system fulfilling stringent performance requirements of motion control applications in multi-path (electromagnetically reflective) application environments. Besides that, the new generation of sensors - pull-in time accelerometers [58] (where time measurements are performed instead of capacitive measurements) will be developed as they achieve very high resolution compared to conventional sensor types.

High-resolution MEMS inclinometers based on the pull-in voltage measurement will be also be considered [59]. There is a variety of positioning technologies that can be used for tracking and motion analytics [60,61]. One technology which lends itself to solving these challenges is Ultra Wide Band (UWB) beaconing systems [62]. Hybrid Systems combining radios and Inertial measurement sensing technology provide low-latency, calibration-free precision monitoring capabilities giving <0.1m accuracy in the Non Line Of Sight (NLOS) case with minimal infrastructure requirements [63,64].

5.3 BB3: Robust condition monitoring and predictive diagnostics

Commercially available motion control products do not typically offer any advanced functions addressing condition monitoring, diagnostics and predictive maintenance of drive systems, at least in the low-power range. Usually only simple measurements of temperature, current or voltage are used in the detection of actuator malfunction. The high computational power available in today‘s hardware platforms allow the integration of advanced diagnostic algorithms directly into drive firmware at reasonable cost. Recent advances in MEMS technology enable miniature vibration and acoustic sensors together with advanced signal processing techniques to be used, enabling new levels of reliability and safety in motion controlled systems.

The topic of condition monitoring, fault detection and diagnostics has been an active research domain for more than 30 years. Despite that, it still remains an open issue, as can be demonstrated by the number of publications on the subject in recent years. Conferences often contain special sessions on this topic. Joint special section on Modern Diagnostics Techniques for Electrical Machines, Power Electronics & Drives was issued in IEEE Transaction on Industrial Electronics and in IEEE Transactions on Industrial Informatics (the top rated journals in the field) in the spring of 2014.

Due to the long history of this research field, there exist many papers providing summaries or overviews of existing methods. Current trends in fault detection in electrical motors can be found in [65]. Methods for fault detection of AC induction motors were reviewed in [66]. [67] is interested in broken bar detection in induction motors. MEMS sensors are nowadays very natural components of consumer electronics. Their utilization in industrial applications is relatively rare. Vibration analysis using MEMS in industrial motors was presented in [68–70] and others. Monitoring and diagnostics of the cutting process during CNC machining is reported in [71–73]. Our aim is to combine model-based fault detection and diagnosis algorithms with results from MEMS sensors to improve existing industrial drives. This approach will extend the set of algorithms running in inverters’ controllers which are nowadays capable to realize these computations. The price of MEMS sensors is low and will not significantly increase the price of electrical drives. Apart from drive monitoring system, machine tools specific diagnostics with the utilization of novel sensor types will be considered as well.

5.4 BB4: High speed vision

Utilization of visual feedback is emerging in many recent motion control applications. The goal is to extract feedback information from a vision sensor and use it to control the motion of a working mechanism. Many different control concepts are known in the field of visual servoing. (e.g. pick and locate load via vision and place at corrected position) Visual Servoing control techniques are broadly classified into the following types: Image-based Vision System (IBVS), Position/pose-based (PBVS), Hybrid approach, see [74,75] for introduction into this wide field.

Depending on the specific application and requirements, many different types of vision systems and optical layouts are found, e.g. [76,77]. Performance of the vision components is continuously improving, especially the image chip. This opens up possibilities that were previously not feasible, also towards control and feedback for industrial application. For example, optical coherence tomography (OCT) microscopy technology has been developed into vision solutions for industrial inspection to achieve zero-defect manufacturing [77,78]. Increasing vision system capabilities push the possibilities for vision based servo solutions.

The basic principles of processing the image data that receive most attention are: image-based methods, which work directly with the error between current and desired features of the image whereas position/pose-based methods estimate the motion of the object of interest from the visual data. Both approaches require fast processing (< 1 ms) of the (megapixel) visual information and rapid (< 100 us) synchronization with the motion control system. This is difficult to achieve using standard off-the shelf components. The goal of the I-MECH project is to develop an industrially integrated solution which can be easily incorporated into the open-architecture motion control platform. Striving for a generic approach, yet dedicated to the common needs for industrial visual servoing, is a significant challenge that will enable a wide scope of industrial applications without the need to repeat similar developments for each application case over and over.

The focus is on integrated image processing, delivering fast capturing to facilitate vision-in-the-loop applications, with a low cost.

5.5 BB5: High performance servo amplifier

This BB will deliver a high performance, highly configurable current amplifier for servo control applications. This provides a flexible low-level actuator control in Layer 1 which can be used in high-fidelity motion control platforms with stringent performance requirements (e.g. 200-500 Hz position bandwidth and/or mA-current accuracy). It is expected to be applied in pilots 1 and 2. In a generic integration scenario, BB5 is connected to control HW (BB10) and exchanges – among feedback control signals – also diagnostic data further communicated to Layer 3 using industry 4.0 standards like OPC UA.

There are a very limited number of suppliers of amplifier-only designs/components that can be integrated into a customized control solution and most products incorporate non-current-control functions, which

makes the solution less cost-effective. Of this set of suppliers, even fewer offer full flexibility in the definition of control architecture and/or the related parameters. This requires a digital amplifier backbone with high speed feedforward control.
The goal is to develop highly efficient servo amplifiers for current (torque/force) control which can be integrated in high performance motion control platforms. This BB can be realised both as a stand-alone entity and it can be easily embedded (incorporated) into a printed circuit board which will be interfaced to the multi-many core control board (BB 8).

5.6 BB6: Self-commissioning velocity and position control loops

The vast majority of commercial motion controllers have adopted the conventional three level cascade control structure for electrical drive systems.

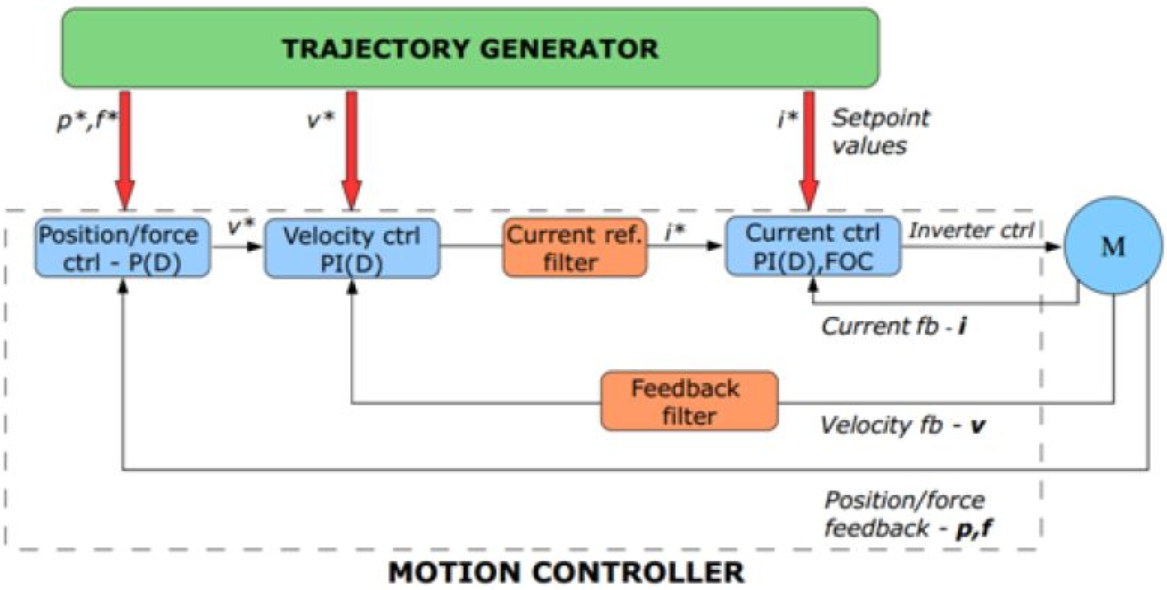


Figure 5.2: Thee level cascade control structure

The innermost current loop controls the generated torque or force (which is proportional to motor current) by driving the power-electronics components of the actuator, typically a voltage-source three-phase inverter. A higher level velocity loop controls the speed of motion by setting a current/torque setpoint for the inner loop. The last outer loop performs position (or eventually force control) and generates velocity commands for the speed controller. Linear PID type algorithms are predominantly used in the individual levels. Various feedback or reference shaping filters may be used to improve measurement noise attenuation and excitation of high-frequency dynamics of the mechanical load.

The reasons for the extensive employment of this control scheme include the possibility of gradual closing of the individual loops, low number of user-specified parameters which can be adjusted manually and simple introduction of physical limitations of the actuator [79]. Advanced control strategies based on the recent results of control theory can significantly improve achievable performance in high-end applications [80–82].

However, many commercial products usually do not allow any modifications of the control algorithms beyond the conventional cascade PID scheme. The user is only allowed to parametrize the given structure offering very limited freedom in controller design. Some manufacturers offer support for the implementation of user-defined instructions in the form of algorithms designed in Matlab Simulink, C(++) or IEC 61131-3 (e.g. Beckhoff, Siemens, B&R, Delta Tau) . However, there is no standardized suitable framework available for development of complex algorithms or a software library implementing the latest motion control concepts.

Most of the industrial motion control applications use only the position and/or velocity feedback information acquired from a motor encoder. Therefore, the control algorithm does not have any direct information about the actual motion of the attached mechanical load which may differ considerably from the motor-side behavior and which is essentially the true object of interest (this is why it is sometimes called as a semi-closed loop approach). This problem is emphasized in the case of highly dynamic motions with a mechanically compliant load which may cause elastic deformations in the individual parts of the kinematic chain. This issue is typically solved by installing a second load-side mounted position sensor which transmits the true position/velocity of the controlled load. However, this information is not used in an optimal way in most of the commercial motion controllers. The prevalent solution is to simply substitute the motor side feedback signal by the load sensor data in the conventional cascade structure leading to suboptimal performance.

A systematic utilization of both motor and load-side feedback is necessary to considerably improve achievable dynamics and robustness of the system leading to a so called fully-closed loop approach. Several research results are available showing the importance of the additional load-side feedback with respect to the overall system performance, especially when dealing with mechanically compliant systems [83–85]. Employment of auxiliary load-side measurement is treated in [86] which proposes a special eddy current sensor providing load-side acceleration feedback. Installation of accelerometers or gyroscopes has been proposed for particular robot types [87,88]. Employment of MEMS accelerometers in machine tool control is considered in [73]. Again, development of automated user-friendly routines remains an unresolved issue for practical applicability of these novel control methods in industrial practice.

A fundamental issue of load-side position sensing is measurement precision. Standard sensor types for position measurement in such applications are incremental encoders. The key encoder parameter which determines the measurement precision is resolution, usually expressed as pulses-per-revolution (PPR). Although there are very high resolution (one million PPR and more) encoders available on the market, they are often not suitable or available for load-side measurement applications. It can be due to the harsh environment, limited space or mechanical coupling problems. In such cases, standard low-resolution (ten thousand PPR at max) encoders or even gear tooth induction sensors (a few hundred PPR at most) have to be used. Precise measurement of position, velocity and acceleration from such sources is a challenging problem with no adequate solution available on the market.

The encoder signal evaluation problem and its wide range can be illustrated by many academic publications from last decades, such as [89–93] which describe several advanced algorithms for velocity and acceleration information extraction from encoder signal. However, we do not know about the application of any of such algorithms in today‘s general purpose motion control systems. Another proof of problem significance can be an algorithm called microstepping embedded in the EL5151 IO module [94] offered by Beckhoff Automation, which is based on linear interpolation of time stamped encoder position measurements. Although this is a far less advanced technique than published algorithms mentioned above, it is probably the best of the very few solutions commercially available in this area.

Modern FPGA-based hardware allows rapid sampling and high-performance signal processing, and as it became cheaper and powerful in last years, more advanced algorithms can be deployed in this application area for significant improvements of measurement precision.

5.7 BB7: Vibration control module

The increasing demands for precision in motion controlled systems along with new types of lightweight mechanical designs and the use of compliant components in the driven mechanism leads inevitably to the inducement of unwanted mechanical vibrations. The problem of transient or residual motion induced oscillation is recognized as one of the most limiting factors on achievable performance [95–97].

The best way to avoid vibration problems is proper adjustment of the system mechanics in order to shift the resonance dynamics towards higher frequencies out of the range of target system response. However, this cannot be done in many cases and some corrective action must be taken by means of the control system and its algorithms. The majority of commercial products address this problem by introducing various frequency filters with notch or low-pass characteristics which shape the spectrum of the excitation forces/torques injected by the actuators. The goal is to limit the power of excitation around the critical resonance frequencies at which the compliant system tends to oscillate. While this approach works well for high-frequency oscillations, it is totally inadequate when the target bandwidth overlaps with the system resonances (which is often the case when trying to achieve ultimate performance).

Special adjustment of the control algorithm and employment of advanced control methods such as input shaping or active vibration damping is needed in such cases [98,99]. A minority of commercial products offer some support for vibration damping. However, their performance is still limited compared to the latest research results.
Many advanced algorithms have been proposed for the motion control of mechanically compliant systems ranging from PID control [96] to resonance ratio control [100], model-predictive control [101], sliding-mode control [101,102] or nonlinear methods [103,104]. However, direct implementation of these methods in actual applications is problematic. Deep understanding of control theory and utilization of complex numerical routines is often required making them unacceptable for a wide range of industrial users. Development of proper software tools for assisted commissioning of motion control loops which hide the mathematical background, offer physically intuitive user-specified tuning parameters (e.g. drive stiffness/bandwidth, amount of damping) and allow performing the controller synthesis procedure almost automatically are needed for the successful transfer of the latest theoretical results into industrial practice.

5.8 BB8: Robust model-based multivariable control

This building block will deliver the core control feedback loop taking into account all of the data and innovations delivered by the other BBs. It provides a mathematical model of the plant dynamics which can be used either for simulations or a subsequent model-based control algorithm design. Additionally, this BB provides SW algorithms for high-precision motion control of complex multi-axis systems. It utilizes the information about the plant dynamics obtained from previous described mathematical models. Regarding diagnostic services, BB8 can detect any changing deviations between the mathematical model and a real system. It plays a crucial role when the system needs flexible adaptation (re-design) and one needs to come back to MIL / SIL stages. In the real-time regime, BB8 is typically executed under BB10 and BB11 which provide a full interface to Layer 3.

Robust multivariable control strategies will be developed based on the high-fidelity mathematical models describing the dynamics of the controlled plant. Experimental identification of models is preferred over numerical modeling in industrial applications since precise geometric data are not available in many cases. The conventional approach applied in commercial motion control products is to neglect all dynamical interactions in the system and consider it as a parallel chain of independent single input-single output subsystems or to employ an idealized rigid multibody model which ignores finite stiffness of machine parts. This can lead to poor performance in the case of highly dynamic motions which emphasize the multivariate nature of the controlled system and the possibility of oscillatory behavior. The goal is to develop procedures exploiting high-fidelity models which can be acquired from system identification experiments. The models will be utilized in developing robust multivariable control for automated motion and vibration control. They will serve either for simulation (SIL/HIL) or control design purposes. BB8 will serve as the platform to host BB3.

5.9 BB9: Iterative and repetitive control module

This BB explicitly addresses controlled systems which perform iterative/repetitive functions to treat them as repetitions of simple behavior rather than as continuously novel actions. It provides a set of algorithms implementing advanced repetitive control schemes with a self-commissioning feature which can be used for various motion control tasks that have a periodic nature. When damping known periodic disturbances, it can detect their changes (via control quality monitoring) and provide information to Layer 3. It is a pluggable module in the I-MECH architecture. In the real-time regime, BB8 is typically executed under BB10 and BB11 which provide a full interface to Layer 3.

Execution of repeating motion sequences or compensation for periodic disturbances are problems that arise in many practical motion control applications. Learning-type control methods which iteratively adapt the generated motion can be employed in such cases to significantly improve various performance objectives (e.g. tracking error or energy consumption). The iterative control scheme may take the form of an adaptive feedback controller or a variable feedforward generator. Although some significant results have been achieved in the theoretical research, there is a very limited support of these powerful techniques in industrial motion control products.

The state-of-the-art research in repetitive and learning algorithms suffer from limitations such as high sensitivity to variation, lack of robustness and flexibility and are often sub-optimal. Novel repetitive and learning algorithms will be developed in the context of the I-MECH platform aiming for enhanced models, higher control accuracy and low experimental cost targeting high-precision mechatronics systems. The focus will be on iteratively improving the performance by continuously updating the model and the controller in view of factors such as tracking error, execution time, energy consumption etc.

5.10 BB10: Control specific multi/many core platform

The exponentially increasing transistor density predicted by Moore's law is leading to a consistent growth in the number of cores in a chip, allowing modern systems to increase their computing performance while keeping the operating frequency and power consumption at reasonable standards. Multi-core platforms are already commonplace components of most computing systems, both in the general-purpose and in the embedded computing domain. Real-time control systems will no longer be immune to such a trend. While current industrial controllers still feature single-core processors, there is a strong interest in developing multi-core solutions to enable increased performance for next-generation motion control applications. The main problems lie in the need to reuse legacy code and standards built for single core devices, as well as in difficulties of providing predictable timing guaranteeing to performance-critical control applications when multiple tasks/cores may simultaneously contend for shared computing components, concurrently accessing shared memory, buses, caches, I/O and external devices. The timing delays due to the blocking and interference experienced by critical activities on shared resources are detrimental to the stability and performance of control loops. Hence, very few industrial applications adopt multi-core technologies for critical control systems. These considerations clash with the current hardware market trends. All main chip producers feature almost exclusively multi-core platforms.
Commercial-off-the-shelf (COTS) platforms with hundreds or more cores are being conceived (e.g., Kalray [105]), along with accelerators for GP-GPU computing featuring thousands of cores (e.g. Nvidia [106]). For these reasons, many application providers adopt multi-core platforms (for the cheaper prices due to massive scale production, longer life-cycles and maintainability), but they disable all cores but one in order to predictably limit the timing interference from concurrently running activities. Of course, this practice does not allow fully exploiting the computing power of multi-core systems, keeping the performance to single core standards.

The I-MECH project will exploit recent advancements in the real-time research community aiming at providing predictable timing guarantees on multi-core platforms without sacrificing performance (i.e. predictability) and near-zero inter- and intra-core interference among the concurrently running applications (i.e. composability). It will collect meaningful results from ongoing projects that developed useful software tools, operating systems and middleware to increase the predictability and composability of both COTS and dedicated multi-core platforms, exploiting and extending them to satisfy the needs of next-generation motion control applications.

For the COTS platforms, I-MECH will evaluate and extend recently proposed hypervisors to allow running multiple applications onto different cores, ensuring the different partitions do not interfere among each other. This will allow system designers to integrate multiple modules (e.g., motion and control modules) onto the same chip, with positive repercussions in terms of product cost and size, also allowing when needed to maintain the software structure similar to those used in single cores. A hypervisor, also called Virtual Machine Manager (VMM), is a combination of software and hardware components that allow emulating the execution of multiple virtual machines upon the same computing platform by properly arbitrating the concurrent access to shared hardware resources. Most of the available open source hypervisors are specifically tailored to server applications and cloud computing. In these areas, hypervisors are mainly designed to provide isolation, load balancing, server consolidation and desktop virtualization within the managed virtual machines. However, the emerging of new potential areas call for cost-effective solutions ever more require sharing an on-board computing platform among different applications with heterogeneous safety and criticality levels, e.g., a human interface module on one side, and a critical control module on the other side. These domains are independent, with different period, deadline, safety and criticality requirements. However, they need to be properly isolated with no mutual interference, or a misbehaving module may endanger the timely execution of a high-criticality domain, affecting safety qualification. In order to provide real-time guarantees, hypervisors either dynamically schedule virtual machines according to a given on-line policy, or they statically partition virtual machines to the available hardware resources. An example of the first category is Xen [107], which implements a hierarchical virtual machine scheduler managing both real time and non-real time workloads using the Global Earliest Deadline First (G-EDF) algorithm. On the other hand, statically partitioned solutions tend to isolate virtual machines onto dedicated cores, with an exclusive assignment of hardware resources. An example of this approach is given by Jailhouse [108], which does not allow multiple virtual machines to share the same core. An advantage of this latter approach is that the resulting hypervisors have a typically smaller code footprint, implying much lower certification costs. Indeed, reducing the code size is a prominent characteristic of other recent VMMs, like NOVA [109] and bhyve [110].

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Along the line of dedicated multi-core platforms, I-MECH will evaluate and extend the CompSOC [111,112] (Shubhendu Sinha, 2015) platform in the context of high-precision motion control applications. CompSOC offers predictable and composable virtualization technology using the concept of Virtual Execution Platform (VEP). The idea of a virtual resource is to reserve a part of a resource for an application according to its allocated budget. The resource can be a processing unit, communication, storage or energy. Predictable arbitration ensures that a virtual resource offered by a single resource has a minimum guaranteed performance as specified in the budget. Composable arbitration ensures that (the performance of) a virtual resource is independent of other virtual resources on the same resource. A CompSOC platform can run multiple VEPs concurrently, without any interference between them, i.e. composedly. Recent literature has shown the potential of such dedicate predictable and composable platform to implement high-performance control applications [113,114]. The predictable timing is exploited in the controller design to achieve a higher performance. The CompSOC will be further extended for the high-performance high-precision motion control applications, the developed techniques will be implemented and evaluated with respect to COTS implementation within I-MECH.

5.11 BB11: RTOS for multi/many core platform

Current operating systems targeting multi-many core platforms are not suitable for advanced control applications requiring to elaborate a large amount of data. In many industrial settings the lack of predictability of the legacy software run on multiple cores is a limitation to the applicability of new algorithms and applications. In fact, the current state of the art does not allow mixing different applications on the same multi-many core platform without either affecting the real-time requirements, or under-utilizing the computing platform. The reason is that there are different hardware resources that are inherently shared by the various cores in the system, like caches, buses, shared memory, I/O devices. A core accessing any of these shared components may cause a blocking delay to any other core that requires accessing the same component. In SOA context, it ensures timely processing of requests coming from System Behavior Layer 3.

To enable predictably mastering the parallel computing bandwidth offered by modern computing architectures, it is therefore necessary to extend existing RTOS with scheduling techniques to limit the interference due to the simultaneous execution of multiple activities on different cores, concurring for the access the shared hardware and software resources. On the other hand, industrial application require the possibility to run the existing application code base with little modification, and for this reason we propose the usage of an hypervisor level to isolate different domains trying to provide enhanced guarantees.

The main idea is that the hypervisor layer, along with predictable scheduling algorithms and execution models integrated in open source RTOS, will allow ensuring a proper timing isolation among multiple tasks/applications running on different cores. In particular in the project we will explore how recently proposed techniques in the real-time community can be applied to the industrial test-cases of I-MECH.

As for the open source RTOS, special attention will be given to the integration of Linux with minimal real-time operating systems such as ERIKA Enterprise (provided by partner Evidence) [115]. Depending on the requirements, ERIKA Enterprise will be extended providing support for additional features and libraries to be able to execute the I-MECH uses cases applications. To be independent from closed-source implementation, we will consider implementing a real-time version of existing communication protocols adopted in the automation domain. For control applications requiring very high precision one or more software layers may be omitted as needed.

6 Conclusion

The inventory, besides the question what future smart production and/or manufacturing requires from emerging mechatronic technologies, has confirmed the description of the final project proposal (FPP).

To summarize, the main shortcomings of the available commercial off-the-shelf products include:

- *Fixed control structure with limited parameterization and customization opportunities. The majority of commercial motion controllers implement conventional decentralized cascade PID velocity and position control schemes which cannot meet the high performance requirements of complex mechatronic systems. There is usually no low-level access to the control logic, which limits the possibilities for smart control engineering.*
- *Commercial suppliers of motion control do not facilitate modeling of detailed plant physics. The available products do not offer sufficient support for the automatic identification of the controlled plant dynamics and consequent tuning of controller parameters. Standardization is required. In real world deployments manual tuning is often performed, leading to long commissioning time and suboptimal performance.*
- *Traditional motion control concepts assume rigid-body dynamics of the controlled system.*
- *Severe degradation of performance occurs with mechanically compliant loads. Conventional motion controllers rely only on indirect feedback information provided by the sensors installed in/on the actuators. The true objective is to control the motion on the load side so load feedback would significantly improve overall performance.*
- *Significant achievements in MEMS technology over the last decade have brought a wide variety of affordable motion sensing devices which could be integrated in intelligent motion control systems. A particular difficulty is wired or wireless transfer of the feedback information in situations where installation of additional sensor wiring is not feasible. Efficient methods for robust, safe and fast wired and wireless transfer of sensor data have to be employed to allow their utilization in real-time control system with fast update rates, low jitter and latency.*
- *Utilization of advanced fault monitoring and predictive maintenance methods is still rare in motion control systems. Usually only simple measurement of temperature, voltage, current and vibration is used to detect malfunctions.*

All these issues are addressed by I-MECH. When the limitations above are addressed, more innovative ideas can physically push roots into an industrial environment. The progress beyond the state of the art is achieved by means of the I-MECH platform building blocks (BB):

- *Employment of advanced model-based design techniques for the development of smart robust control strategies both for decentralized single-loop problems and centralized solution for complex multivariable systems (BB6, BB8)*
- *Development of automatic procedures for the acquisition of plant dynamics models and the consequent choice of a proper control structure for tuning of the controller parameters (BB6, BB7, BB8, BB9)*

- *Development of high-fidelity models of mechanical systems (beyond the traditional simplifying assumptions of rigid-body mechanics) enabling a significant performance enhancement for systems with flexible dynamical behavior e.g. dynamic stiffness control (BB7, BB8)*
- *Integration of the additional sensory information about load-side motion to the advanced control schemes (BB1, BB4)*
- *Development of robust protocols for wired and wireless data transmission suitable for high-speed real-time operation of motion control elements focusing on energy efficiency, security and reliability (BB2)*
- *Development of advanced cost-efficient solutions for monitoring, diagnostics and predictive maintenance of the electromechanical components of motion control systems allowing safe, robust, accurate and reliable operation (BB3)*
- *Development of open architecture HW platforms capable of execution of the co-developed software modules allowing easy scalability and reconfigurability according to specific user requirements (BB5, BB10, BB11)*

The interfacing between the various BBs is given in the figure 5.1. What has been found during the inventory with our I-MECH partners, during the course of WP2 (at this moment in time!), is that the BBs defined in the FP were just a ‘tip of the iceberg’, considering the multi-page length of the ‘I-MECH Requirements Table’ presented in appendix A.

The defined objectives can only be achieved through the coordinated effort of all of the consortium members integrating the latest theoretical results with the various engineering disciplines involved in motion control system design. The pilots will offer support as a ‘platform’ to align this process. The proposed approach will be able to deal with the complexity associated with accurate modeling and control of complex mechatronic systems, and as such enable significant performance enhancements in comparison with the state of the art. This brings tremendous possibilities for applications on a huge market of manufacturing equipment, robotics and motion control systems. The availability of the product for immediate commercial exploitation will be verified through specific demonstrators that will show the application of developed technology to the actual practice of industrial partners involved in I-MECH. So during the course of these activities, partners aim to enable a path to commercially available, scalable, flexible products following a standardized architecture ready to be exploited by industry which can be extended by academia.

In more detail, the main target of I-MECH is to provide a fully functional, open motion control platform for applications where the dynamics and precision of the controlled motion and easy reconfigurability are crucial. The platform will consist of a library of functional blocks implementing the developed algorithms, as well as hardware capable of real-time execution of the developed software modules. The requirements table as listed per October 16, 2017 needs to be filled in by ALL partners involved and might even result in more items and parameters to be considered to obtain a full overview over what is required by industry, what is made available by academia and where the pitfalls and gaps are. In the coming months, the decomposition of the different control architecture of the pilots (and demonstrators) will be elaborated in more detail. Thus the commonality will appear and direct the interface definitions between layers and/or building blocks.

In 3.2.2 Modelling and identification has been addressed the challenge to organize a decomposition of your modelling framework, that facilitates practical simulation times, whilst offering sufficient representation depth of involved physical behavior. In the course of I-MECH, Task 4.3 will investigate this challenge and propose a way of working, hopefully supported by state-of-the-art modelling tools that are are prepared for such use.

During the creation process of the (final) project proposal, we have introduced 2 deliverables for making an inventory of the 'actual status'. It appeared more practical, not to subdivide into separate documents. Deliverable D2.1 can be considered as a first revision of a document that will hold both 'Updated state of the art and enabling technologies of motion control solutions for smart mechatronics and robotics systems' and 'Needs for future smart production (manufacturing) in Europe from the mechatronics and robotic point of view' In the next month we will update this document and call it D2.2. This will mainly be the result of reflecting how task deliverables shall be incorporated into pilots, use cases and demonstrators.

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Appendix A

The ‘requirements table’, containing requirements of I-MECH pilots, demonstrators and use cases for the I-MECH platform and the state-of-the art of selected COTS solutions and academic implementations regarding these requirements, is included as PDF document and XLS document as attachment inside this PDF document. You can view the attachments of this PDF by using Adobe Acrobat (https://get.adobe.com/reader/).

Appendix B

EC Project/Initiative	Likely relevant for	Consortium partner(s) involved in project/initiative
H2020/ECSEL/**R5COP**	BB4: High speed vision BB8: Multivariable control	Eindhoven University of Technology, Brno University of Technology
FP7/Artemis/**R3COP**	BB4: High speed vision BB8: Multivariable control	Eindhoven University of Technology, Brno University of Technology
FP7/Artemis/**ASTUTE**	BB3: Preventive diagnostics	IK4-Tekniker
FP7/Artemis/**D3COS**	?	-
FP7/Artemis/**CAMMI**	?	-
FP7/Artemis/**POLLUX**	BB10: Many core platform BB11: Many core RTOS	Brno University of Technology, Nexperia
FP7/Artemis/**EMC^2**	BB10: Many core platform BB11: Many core RTOS	Brno University of Technology, Eindhoven University of Technology, TNO, Nexperia
FP7/Artemis/**eSCOP**	BB3: Preventive diagnostics BB6: Self-commissioning BB8: Multivariable control	University of West Bohemia
FP7/Artemis/**HoliDes**	BB3: Preventive diagnostics	Brno University of Technology
FP7/Artemis/**eSONIA**	BB3: Predictive diagnostics BB8: Multivariable control	Brno University of Technology
FP7/Artemis/**DEWI**	BB2: Wireless sensors BB10: Many core platform BB11: Many core RTOS	Nexperia, Elektronikas un datorzinātņu institūts, Eindhoven University of Technology, IK4-Tekniker
FP7/ENIAC/**SAFESENS**	BB2: Wireless sensors	University College Cork, Nexperia
IMS2020/Roadmap	General	-
Manufuture/Roadmap	General	-
EFFRA/Roadmap	General	-
PPP Factories of the Future/Roadmap	General	-
PPP SPIRE?	General	-
ENIAC/MOTORBRAIN	BB3: Preventive diagnostics BB10: Many core platform	Brno University of Technology, Nexperia, TNO
ECSEL/3CCAR	BB3: Preventive diagnostics BB10: Many core platform	Brno University of Technology, Nexperia, Eindhoven University of Technology, Elektronikas un datorzinātņu institūts, TNO
CIDAM	BB6: Self-commissioning BB7: Vibration control	University of West Bohemia, Brno University of Technology

	BB8: Multivariable control	
CAK	BB3: Preventive diagnostics BB4: High speed vision BB5: Servo amplifier	University of West Bohemia, Brno University of Technology
CHAMELEON	BB6: Self-commissioning BB7: Vibration control	Fagor Aotek, IK4-Tekniker
EFFIC	BB1: Smart sensors BB4: High speed vision	Sioux CCM
NEO-GNC	BB1: Smart sensors	GMV Aerospace & Defence
EXPRESS	?	IKERLAN-IK4
GATEONE	?	IKERLAN-IK4, University College Cork
SMARTER-SI	?	IKERLAN-IK4, University College Cork
FP7/ESTOMAD	BB3: Predictive diagnostics BB6: Vibration control BB8: Multivariable control	
FP7/IMPROVE	BB3: Predictive diagnostics BB8: Multivariable control	Siemens
T-CREST	BB10: Many core platform BB11: Many core RTOS	Eindhoven University of Technology
CREMA	BB3: Predictive diagnostics BB6: Vibration control BB8: Multivariable control	IKERLAN-IK4
MEMAN	BB1: Smart sensors BB6: Self-commissioning BB9: Iterative control	IKERLAN-IK4
EMC2	BB2: Wireless sensors	Nicolas Correa
PROMARE	BB3: Predictive diagnostics BB6: Vibration control BB8: Multivariable control	Nicolas Correa
ROMISY	BB2: Wireless sensors	Open Engineering S.A.
Projects related to specific application/manufacturing process		
MEGAROB http://cordis.europa.eu/project/rcn/105485_en.htm	Machining of very large workpieces	-
NU-WAVE	Novel production machines for textile	-

http://cordis.europa.eu/project/rcn/94689_en.html	industry	
Symbionica? http://cordis.europa.eu/project/rcn/198346_en.html	Reconfigurable Machine for the new Additive and Subtractive Manufacturing of next generation fully personalized bionics and smart prosthetics	-
BOREALIS? http://cordis.europa.eu/result/rcn/196373_en.html	Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts	-
FAB2ASM http://cordis.europa.eu/project/rcn/94309_en.html http://www.fab2asm.eu/	Efficient and Precise 3D Integration of Heterogeneous Microsystems from Fabrication to Assembly	-
COMET http://cordis.europa.eu/project/rcn/95706_en.html	Adaptive control of industrial robots for plug and produce components	-
HYPROLINE http://cordis.europa.eu/project/rcn/104393_en.html		-
Projects related to layer 1: Instrumentation		
HARCO? http://cordis.europa.eu/project/rcn/94813_en.htm	Layer 1: Adaptable smart components	-
3SMVIB	BB2: Wireless sensors	Open Engineering S.A.
FP7/IMC-AESOP	Layer 3: SOA/CPS	-
FP6/SOCRADES	Layer 3: SOA/CPS	-
FP7/PLANTCockpit	Layer 3: SOA/CPS	-
Projects related to layer 2: Control		
APROCS? http://cordis.europa.eu/project/rcn/207853_en.html	Layer 2: Automated Linear Parameter-Varying Modeling and Control Synthesis for Nonlinear Complex Systems	-
CLOVER? http://cordis.europa.eu/project/rcn/206521_en.html	Layer 2: tuning of controllers + robustness	-
Projects related to layer 3: System behavior, SOA, connection to MES/ERP/SCADA		
ReCaM? http://cordis.europa.eu/project/rcn/198385_en.html	Layer 3?: tools for reconfiguring production systems	-
FoFdation	Layer 3: Universal manufacturing information system for smart factory architecture.	-
POPJIM	Layer 3: Self configuring, tuning and	-

http://cordis.europa.eu/project/rcn/95707_en.html	optimizing modules + wireless plug and produce	
sCorPiuS http://cordis.europa.eu/project/rcn/193437_en.html	European Roadmap for Cyber Physical Systems in manufacturing	-
Daedalus http://cordis.europa.eu/project/rcn/205469_en.html	Distributed control and simulAtion platform to support an Ecosystem of DigitAL aUtomation developerS	-

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