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I-MECH Smart Mechatronic Solutions

Work Package	Deliverable ID
WP2, Business requirements and reference system architecture	**D2.2, 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 is an update of deliverable D2.1 and serves 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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(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. The list with closed issues, resulting from reviews, is listed as comments in the review forms (of old revisions) of this deliverable available on the Google Drive Partner Zone.

ID	Description	Next steps	Due Date	Owner	IAL ID
OI-0021	Insufficient feedback on questionnaire for external companies about MB(S)E and motion control for publishing in D2.2	Results will be published as part of D2.4	June 2018	Sioux CCM	WK1751.03
OI-0029	Some use cases and demonstrators did not yet give feedback in the requirements table.	Gather and publish relevant requirements as part of D2.4	June 2018	Sioux CCM	WK1751.04

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Contributors

Revision	Acronym of Partner	Contributor	Description of work
D2.1 R01	BUT	Pavel Vaclavek	Small contributions to requirements table
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	EDI	Kaspars Ozols	Inventorisation 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
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	UNIBS	Antonio Visioli	Various contributions
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Document control

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Dip Goswami	Eindhoven University of Technology	x							
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Séamus Hickey & Sonia Ramirez	Johnson and Johnson Vision Care (Ireland)		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
17102001R02	I-MECH Requirements Table (attached as appendix A)	21-DEC-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
CPS	Cyber Physical System
CPU	Central Processing Unit
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
SoC	System on Chip
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 (D2.2) 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.

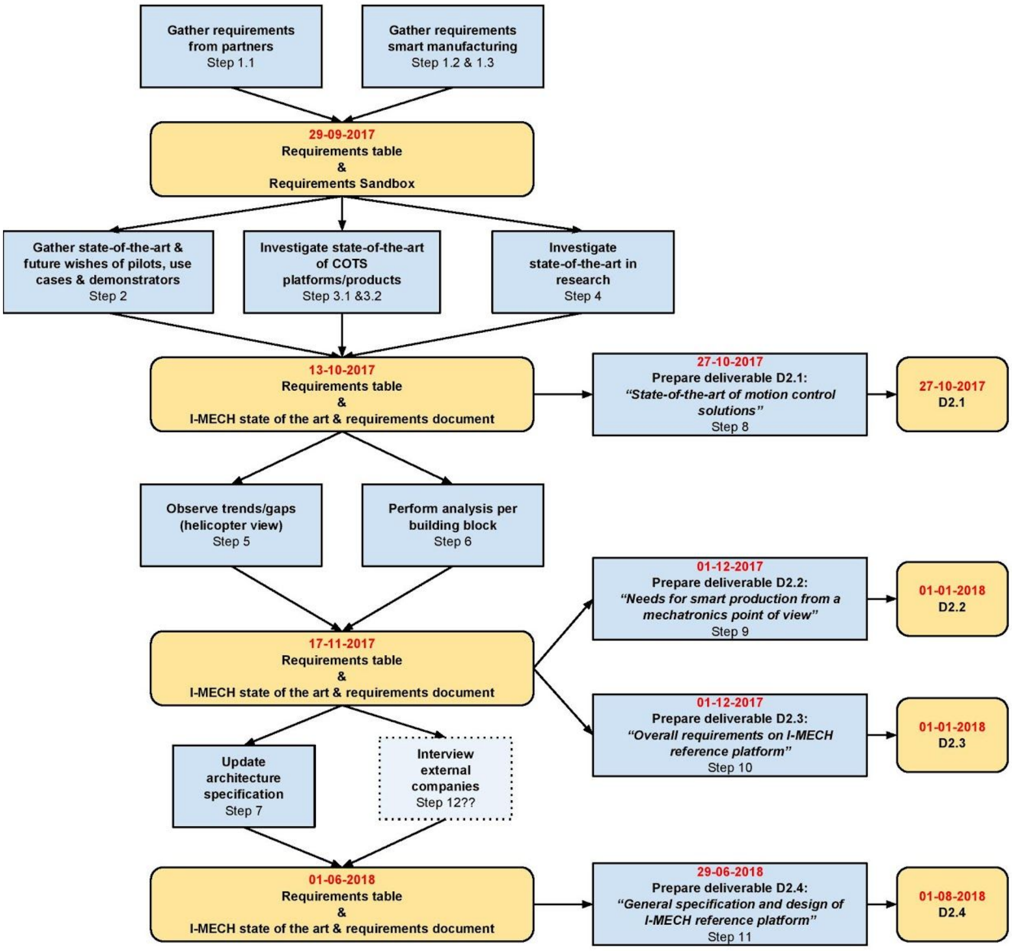


Figure 1.1: Approach to I-MECH Work Package 2

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 most of the 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, and published as deliverable D2.1, during step 8. The structure and content of deliverable D2.1 were improved and slightly extended and are published in this deliverable. An helicopter overview of the requirements and wishes of the I-MECH pilot owners, created as part of step 5, is one of the main new additions with respect to the contents of D2.1. Some pilot owners added new information to the I-MECH requirements table since publishing deliverable D2.1. Step 12, a questionnaire for external companies, has been initiated already, but results will be published as part of D2.4. Deliverable D2.3 will be published together with deliverable D2.1 and contains all requirements gathered as part of D2.1 and D2.2, organized according to the proposed layer and building block structure for the I-MECH motion control platform.

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 3 of this report. Chapter 4 reflects on the identified topics and requirements and their implications for the general motion control structure of the I-MECH platform. Some conclusions are presented in chapter 5. 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. Requirements organized per building block are presented in deliverable D2.3.

3 State-of-the-art

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.

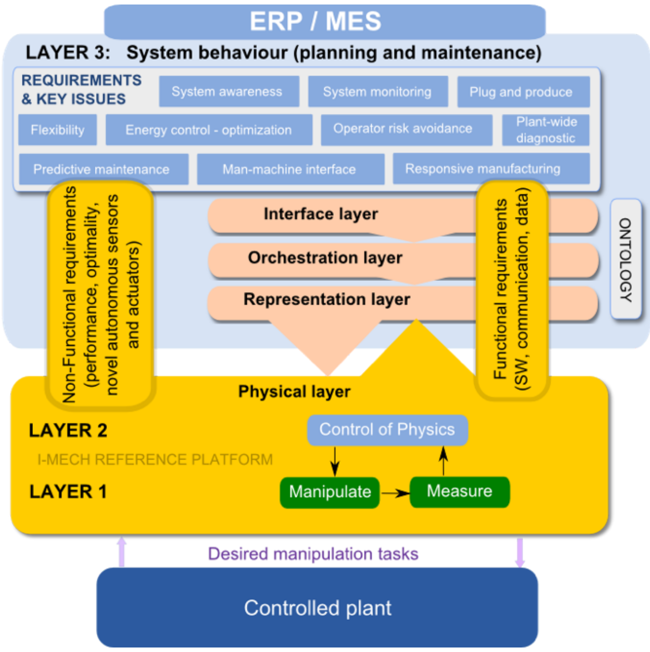


Figure 3.1: I-MECH architecture, featuring 3 layers, and showing context with Industry 4.0 with primary research focus highlighted.

This chapter presents topics organized per layer in which they are expected to be relevant for the I-MECH platform. The “requirements table”, presented in appendix A was used as one of the inputs of this chapter and should be considered as an essential part of this chapter. The table shows the specific requirements and specifications for “the future” of pilots, use cases and demonstrators participating in the I-MECH project as well as their current state of the art, which can be regarded as a quite representative cross-section of the state of the art of the European industry in motion control.

Requirements can be subdivided into 'functional' and 'non-functional' requirements. Functional requirements define what a system is supposed to do, which can often be quantified with a number, while non-functional requirements define how a system is supposed to be, which can often only be described qualitatively. The nonfunctional requirements can for example be found in domains like safety, relation of the system with the environment, reliability, user-friendliness, compatibility, security and system architecture. For example, some of the pilot systems have to run 24/7 autonomously, like the substrate carrier, 12" wafer stage and the tea bag machine while other systems will remain partly autonomous or human controlled, like CNC machines and medical manipulators. Environmental requirements can be very important, for example requirements regarding contamination in cleanrooms, or compatibility with harsh environments, e.g. environments with a high humidity, strong magnetic fields, high temperatures or large vibrations. 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 and implementation of the I-MECH platform. Functional requirements and specifications can mainly be found in the requirements table presented in annex A, while non-functional specifications and considerations are described in this chapter. State of the art of commercial off the shelf products is presented both in this chapter and in appendix A for various topics.

The I-MECH platform intends to develop several 'building blocks' which can be combined together to form the I-MECH reference platform. Footnotes are used at the beginning of sections to indicate for which building blocks the section could be in particular relevant. The following building blocks are planned to be developed during the I-MECH project:

BB1: Platform for smart sensors with advanced data processing
BB2: Real-time wireless sensors
BB3: Robust condition monitoring and predictive diagnostics
BB4: High speed vision
BB5: High performance servo amplifier
BB6: Self-commissioning velocity and position control loops
BB7: Vibration control module
BB8: Robust model-based multivariable control
BB9: Iterative and repetitive control module
BB10: Control specific multi/many core platform
BB11: RTOS for multi/many core platform

Note that specific requirements are mapped to building blocks in deliverable D2.3. D2.3 also list relevance of requirements to tasks within the I-MECH project.

3.1 Layer 1: Instrumentation[1]

Layer 1 concerns measurement and manipulation of the physical environment. Main topics in this area include the sensors and actuators used to measure and manipulate the environment and the communication protocols to transport data between layer 1 and layer 2 (control layer) of the motion control

[1] [BB1, BB2, BB4, BB5]

system. I-MECH will focus especially on 'smart sensors' which can process information locally, wireless sensors, high speed vision and high performance servo amplifiers. These topics will result in separate I-MECH building blocks and will therefore receive attention in this section.

3.1.1 Communication

The requirements table presented in appendix A shows an overview of the current specifications and future requirements for sensor resolution and update rate of I-MECH pilots, demonstrators and use cases. Various physical layers ('PHY', the lowest layer of the OSI model [2]) are currently being used for communication between the control layer and the sensors and actuators in the instrumentation layer. 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. 'Smart sensors' are not yet frequently used, so 0-10 volt analog inputs or digital inputs are still mostly used for direct communication with sensors, with vision as the main exception. The motion control system outputs are made available in the same way as inputs, either analogue or digitally. Ethernet is frequently used for communication layer 2, after conversion of signals to the digital domain, when a centralized control architecture is used. However SPI, PCI and I2C are also currently being used for the sake of speed and overhead. New physical layers are coming available, developed by/for the IT sector, that could in particular satisfy the need for higher bandwidths of digital communication used for motion control. USB3 is an example which is interesting for the sake of data transfer speed. USB3 is at the moment already frequently used for industrial vision applications. 10Gb/s instead of 1GB/s Ethernet could be another alternative. However, one should carefully consider introduction of these kinds of physical layers into a motion control environment, as many of these new 'standards' were not defined with industrial robustness in mind (e.g. applicability in harsh environments).

The chosen signal interface determines which wiring should be used. Special attention should be given to connector (and their pinout) and wiring selection when using a high data rate, e.g. when using raw vision data > 1 Gb/s, to ensure signal integrity over the full signal path. High update rates are generally required when signals are used for motion control purposes. Wires with PVC insulation can be used for analogue signals with only low frequency content. Shielded (twisted) pairs insulated by nylon, polyamine or even (foam-based) teflon should be used with high speed digital signals. 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). A smart vision, smart sensor or smart drive system can be used to intelligently reduce the data amount at the source to limit the required bandwidth for data-transmission and thereby also reduce the requirements on the chosen wiring and connectors. Wiring and connection selection are dependable on environmental and safety requirements. For example, a special case for wiring and actuator selection are Paschen critical applications (applications in a high vacuum environment). Special care should be taken regarding voltages occurring between actuators, e.g. linear, rotating, piezo, and bare conductors in such environments due to the increased risk of electric discharges. None of the I-MECH pilot/use case/demonstrator environments is Paschen critical. The nonfunctional requirements of the I-MECH pilots should nonetheless be kept in mind during selection of connectors and wiring for I-MECH building blocks, as the pilots operate in very different environments and industries which might impose different requirements (e.g. the healthcare sector and semiconductor industry).

There is a (too) wide variety in communication protocols used for transportation of signals between layer 1 and 2 of motion control systems (figure 3.2) [3,4]. Many protocols are unfortunately not compatible with each other and are frequently used to create a kind of ‘vendor lock-in’ by suppliers of COTS motion control platforms. The most popular ‘old’ fieldbus standard is Profibus, which is still widely applied. The market share of industrial Ethernet based fieldbuses is growing and used in particular for high performance applications requiring large bandwidths and minimal latency. The most popular Ethernet based fieldbus in the US is EtherNet/IP, while Profinet, EtherCAT, Modbus-TCP and Ethernet Powerlink are at the moment the most popular standards in Europe. The I-MECH pilots mainly use EtherCAT, although some use cases providing a drive for general motion control purposes strive to support all relevant standards, including standards popular in the US. Industrial wireless communication protocols still have a small market share, but a high annual growth rate. Implementation the modern high performance standards used in Europe, like EtherCAT, Ethernet Powerlink and Profinet IRT will be essential for the I-MECH platform. The possibility to extend this list will be a not negligible factor in the openness of the platform.

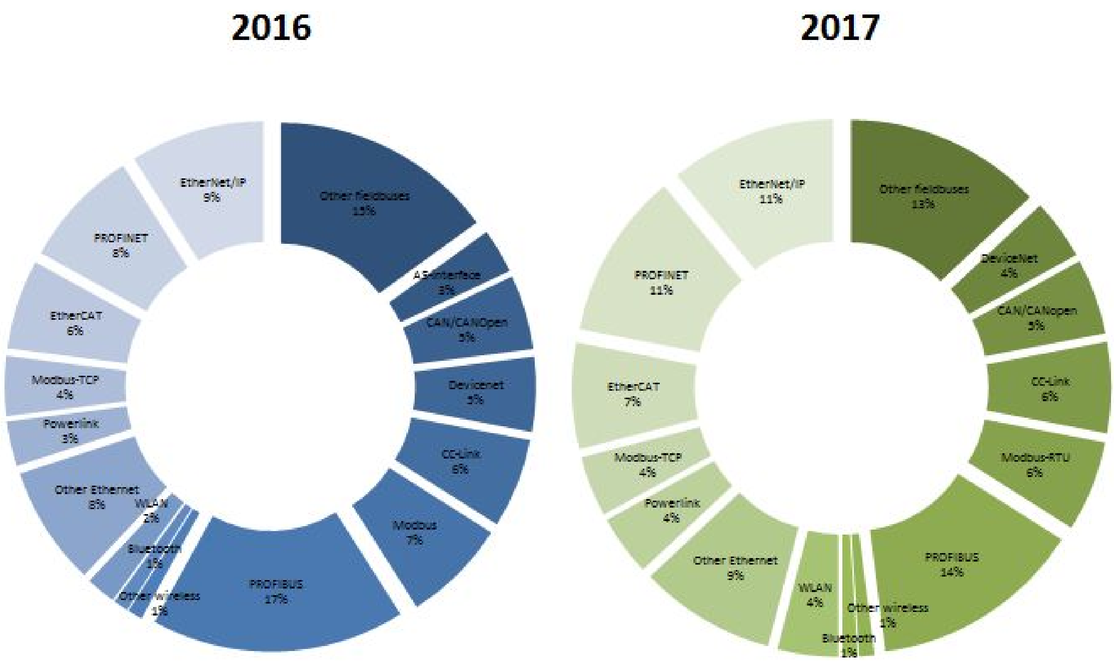


Figure 3.2 Market share of traditional fieldbuses and Industrial Ethernet standards for 2016 and 2017 according to HMS [3,4]

There are comparatively few communication protocols used for machine vision. Camera Link, USB 2.0, IEEE1394, GigE Vision (1.x) and USB 3.x Vision are the most popular standards, of which the latter two are the most modern and best suited for the future. IEEE1394 is becoming obsolete [5,6]. Other high performance protocols for vision are CoaXPress, Camera Link HS and GigE Vision 2.x. GigE Vision 2.x, using 10Gb/s Ethernet, is in particular interesting for very high performance applications requiring a very large bandwidth, precise time synchronization of cameras with a central clock and very precise triggering of the camera via Ethernet. A comparison of the major 6 camera buses is given in figure 3.3 [7]. There is a trend, besides the trend to higher bandwidth communication protocols, towards usage of 'smart' vision systems that process images locally and only send a limit set of parameters towards the central motion control system via standard motion control communication protocols [5].

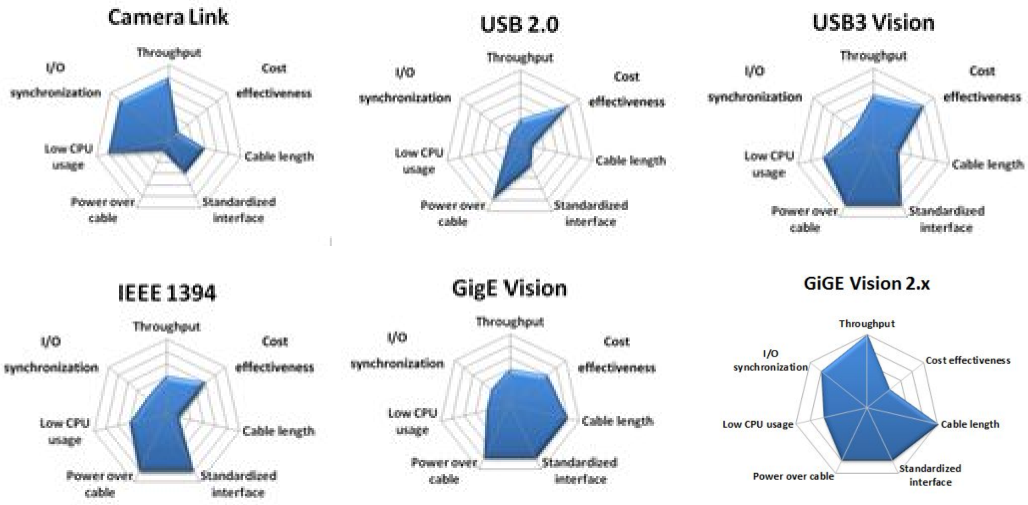


Figure 3.3 Comparison of 6 major camera buses [7,8]

3.1.2 (Smart) actuators and drives[2]

Amplifiers or drives are used to excite and power the actuators in motion control systems. I-MECH pilots mainly make use of brushless AC motors, but some also use AC induction motors or reluctance actuators. There are three methods to drive an electrical motor (depending on the type of motor); either by controlling the current (torque/force control), the voltage (speed control) or the frequency (speed control). I-MECH pilots mainly apply current control. There is a very limited number of suppliers of current amplifier-only designs/components that can be integrated into a customized control solution using a centralized control architecture. Most products incorporate non-current-control functions, which make the solution less cost-effective. Even fewer suppliers offer full flexibility in the definition of control architecture and/or the related parameters of the drive or current amplifier, which is desirable for high performance applications.

A distinction is 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. 3-phase PWM drives are nowadays used for most applications. For example, all I-MECH pilots use PWM drives. Such a drive can in some cases also be used to drive stepper motors, although less expensive solutions are available to drive this type of actuator. 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 are not considered.

Usage of PWM drives instead of analogue drives typically results in higher conductor and eddy-current losses in the actuator, as the high frequencies introduced by the pulse width modulation do not provide energy to the motion itself. These losses should be evaluated with respect to the thermal constraints of the

[2] [BB5]

design of the system and actuator or filtering should 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. The power requirements for actuators and motors used in I-MECH pilots, use cases and demonstrators, differs from a few Watt up to several kilowatts or even megawatts. The challenge for amplifier designers is to squeeze as much power as possible at an as high control bandwidth as possible into the smallest possible volume. A higher control bandwidth also requires a higher PWM frequency. Unfortunately, faster switching results typically in more switching losses. Hence, heat-sinks or other means of cooling are required and higher RF emissions or other noise will occur for which filtering at either the supply or load/actuator side will be required. Fast switching in combination with long motor cables also results in overvoltages, which affects the insulation withstand requirements for the electrical windings of the actuator. Moreover, long cables represent capacitance, which inherently can cause overcurrent load conditions for PWM drives in combination with high switching frequencies. Finally, the high frequent switching of PWM drives often introduces undesired noise in a machine resulting in EMC issues.

3.1.2.1 Controlling EMC of PWM drives

PWM motion control systems are well known to produce a lot of unintended RF emissions (EMI) either conductively or by radiation. Sensor and encoder systems might be adversely affected or even hampered by such nearby emission effects. Motor cables in-between PWM drives and actuators therefore need to be shielded with the shield grounded to both the actuator housing and the PWM drive. Measures need to be taken such that all signals are confined within a shielded cable on the inner wiring and no signal currents are running over the shields, similar to the wiring used for sensor/encoder systems. The actuator cable will then be optimized for minimal emission to elsewhere in the motion control application. When the sensor cable is designed according the measures stated in 3.1.1 and the motor cable is designed as stated above, no physical separation will be necessary between these cables in a common flex cable tray as nearly no crosstalk will occur.

There are more techniques to reduce noise introduced by e.g. PWM drives. Both active and passive filtering techniques are commercially available for such conditions. However, better and/or more compact solutions could be developed as part of the I-MECH project. One of the aims of I-MECH is to (co-)develop active EMI noise canceling circuits/concepts. These circuits will reduce the need for bulky filters at either (AC/DC) supply side and the load side of the motion control system. The noise cancelling solutions will provide a means to merge power and small signal cables into a single cable caterpillar without any threat for crosstalk. The technology might enable using a single cable for transmission of both power and data transmission. An active EMI noise cancelling approach can even be useful to reduce the amount of wiring (other than using wireless interfaces) by enabling communication over power-lines. Having proper noise canceling (at the source) will furthermore reduce the need for well-shielded cables which are often mechanically (too) stiff to be used with motion systems requiring high precision and fast motions.

The cancelling i.e compensation technique foreseen will reduce both the low actuator/motion related 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 to compensate/cancel these EMI signals effectively. Moreover, the technology needs to be scaleable to suit the various power levels as used with the foreseen applications.

3.1.2.2 Commutation

The commutation and alignment method of drives has serious impact on the generated torque/torque ripple and initial movement of the actuator. Trapezoidal, sinusoidal and field oriented control are the most popular commutation techniques for brushless DC/AC motors, ordered by increasing complexity/cost as well as price. Field oriented control requires usage of a digital signal processor. Costs of such an implementation is becoming much less of issue, given the constantly reducing prices DSPs/microcontrollers or FPGA based solutions.

Various methods to determine commutation alignment are available, varying from simple methods using hall sensors to more advanced sensorless strategies using encoder feedback to sensorless approaches [9]. Certain application require that absolutely no movement occurs during system startup, e.g. when used in a medical setting, and therefore use absolute encoders such that alignment for commutation is required only once (in the factory/by design).

3.1.2.3 Smart drives

The availability of computation power within drives enables implementation of smart functionality. Many drives currently have all kinds of functionality for motion control (e.g. PID control, filters, setpoint generators etc.). Most drives do however not yet implement functionality for advanced condition monitoring of the drive electronics or even facilitate monitoring of mechanics attached to the drive. Hence, hardware seems suited for implementation of more smart functionality but software implementation is still lacking. More information about state of the art condition monitoring of servo amplifier electronics in academia can be found in the section about condition monitoring as part of layer 3.

3.1.3 (Smart) sensors[3]

Measurement of several physical quantities can be necessary for control or monitoring purposes in a machine. The domains listed in table 3.1 may be considered, of which the space, force temperature, acoustic, vision and electrical domain are most relevant for motion control and condition monitoring of motion related equipment.

Table 3.1

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

[3] [BB1, BB2]

Angular velocity	Torque	E-field	Biological
	Weight	H-field	pH
	Gravity	charge	Magnetic field

3.1.3.1 Absolute vs Relative

Most sensors and encoders are restricted in their range 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 or costly. Both absolute and relative sensors need calibration of their min-max values/ranges, sometimes with values in-between to allow more accurate interpolation in case of nonlinearities. 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.

3.1.3.2 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. 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 A/D converters (16, 24, 32 or even 64 bits) may be used to achieve the required dynamic range at the cost of required bandwidth and achievable sampling rate. Supply source stability and electrical noise in the front-end of the sensor or encoder system become a crucial factor when a very high dynamic range is required.

3.1.3.3 Sensor supplies and their interfacing

Most sensor 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. This frequently results in problems relating to EMC issues which are discovered very late in the design process or even in the field. Sensor/encoder systems selected and developed within I-MECH project shall at least follow a set of additional requirements and design guidelines, which should be part of the I-MECH methodology, to prevent these kinds of issues. A few examples of design guidelines could be:

- Many sensor systems are DC supplied. Precise measurement systems often have an internal DC/DC converter to correct for external supply voltage fluctuations and/or to derive the various internal voltages as used by the sensor system.
- It is important 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 should 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).

- 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.

3.1.3.4 Smart sensors

Smart sensors refers in the context of I-MECH to sensors with built-in intelligence and/or processing capabilities. Raw data from primary sensors is usually not directly used in higher control system levels. Smart sensors provide high-fidelity information derived from the primary sensor raw data. The data processing covers not only basic operations like time decimation and filtering, but also processing of data using complex mathematical models which provides for example precise estimations of position, velocity and acceleration of physical objects. The smart functions of the sensor could be used for estimation of unmeasured variables, auto-calibration (standard IEEE 1451.4 could be interesting in this regard), condition monitoring and smart data reduction purposes. Many of these 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. Precise synchronization of clocks of the central motion control platform and all smart sensors within the system and time-stamping of acquired data can be valuable for real-time applications, as it allows very precise interpolation and synchronization of data. The IEEE 1588 standard [10] should be a relevant guideline on how to achieve this functionality using standardized methods. In high-speed control loops, precise time synchronicity spanning all layers is a clear requirement. This can be covered by ethernet-based communication, but physical input and output synchronization signals are also often deployed.

Primary sensors can operate on various principles. I-MECH is in particular interested in providing sensory interfaces for high speed analog-to-digital converters, optical sensors (high-speed camera's), digital sensor communication protocols (e.g. for encoders using BiSS-C or DRIVE-CLiQ interfaces), magnetic and inertial sensors like accelerometers and gyroscopes and low latency wireless transceivers. A special class of smart sensors relates to vision technology, in particular for "vision in the loop", as processing vision information generally requires a large amount of computation power. A second special class of smart sensors are wireless sensors (e.g., think of the reliability and data redundancy aspects relating to wireless protocols). Finally, these smart sensors may be self-powered, in case of wireless smart sensors, and directly translate signals to standard digital protocols (e.g. SOA oriented protocols like OPC UA or an industrial ethernet fieldbusses like EtherCAT or Profinet IRT).

3.1.3.5 Wireless sensors and protocols[4]

It is in many situations beneficial to attach sensors such as position sensors, gyroscopes, accelerometers, strain gauges, temperature sensors, etc. to a moving part of a machine. This feedback information can enable more advanced control strategies, like auxiliary feedback control which can significantly enhance the overall performance, or the information can be used to monitor a process locally or monitor machine condition [11–14]. The additional instrumentation is often installed at places which are difficult to access

[4] BB2

for wired connections, due to the motion of the working mechanism. Therefore, it can be more convenient to use wireless communication using wireless sensor networks (WSN).

Many wireless technologies 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 - are currently available on the market. However, the state of the art WSN have several limitations that affect operation efficiency, including power restrictions, limited computational 'smart' power, storage restrictions, limited transmission ranges, large latency etc. [15]. State of the art wireless systems do not allow high sampling rates, low latency and sampling synchronization combined with low power consumption, which are essential in time-critical high-fidelity motion control systems where measurements are used within the control loop [16–19]. It can be observed that motion control suppliers like Beckhoff and Siemens facilitate usage of wireless communication, but that solutions are not optimized for both size, communication speed and power consumption. Conditions within machines pose furthermore challenging requirements for wireless technology, for which most of the COTS technology might not be optimized. Multiple reflections and multipath signals will result due to the many metal parts in machinery, which complicates proper decomposition of the signals at the receiver side. Moreover, the doppler effect will affect data transmission in case of fast movement of the transmitting and receiving antenna relative to each other. The doppler effect will result in frequency (phase) shifts of transmitted RF signals. At present, most research focuses 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), only suited for example for temperature, pressure and humidity monitoring [20].

A wide range of potentially applicable existing state of the art wireless technologies was reviewed for use as part of the I-MECH platform, as I-MECH pilots and demonstrators show interest in the usage of wireless sensors, but nearly all do not (yet) have specific requirements for wireless communication in mind. 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) were investigated.

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 3.2). The GSM, DCS, GPRS, 3G, LTE (4G) and 5G bands are restricted or even forbidden to be used by services not following the defined protocols. 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 the 868/915 MHz and 2.45 GHz frequency bands, since these correspond to short/mid range radio communications intended for low power devices. A pitfall of wireless protocols using the 2.45 GHz band is that the frequency band can be utilized for many purposes, even food and material heating, which can cause interference. Interference can be problematic, certainly when signals are used in a position loop and latency and missing samples can be problematic. For example low and high band UWB (ultra-wideband) communication will suffer from WiFi communication at either the 2.45 or 5.2 GHz as well as vice versa WiFi will suffer from nearby used UWB. The 5.8 GHz standards were not analyzed, although these are intended for high data rate transmissions, because they were not intended 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 quite unsuited for such applications.

The use of licensed instead of unlicensed ISM band wireless technologies in consumer electronics is nevertheless present - e.g. for "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 3.2: 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 3.4. 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) [21]. 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. These standards 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.

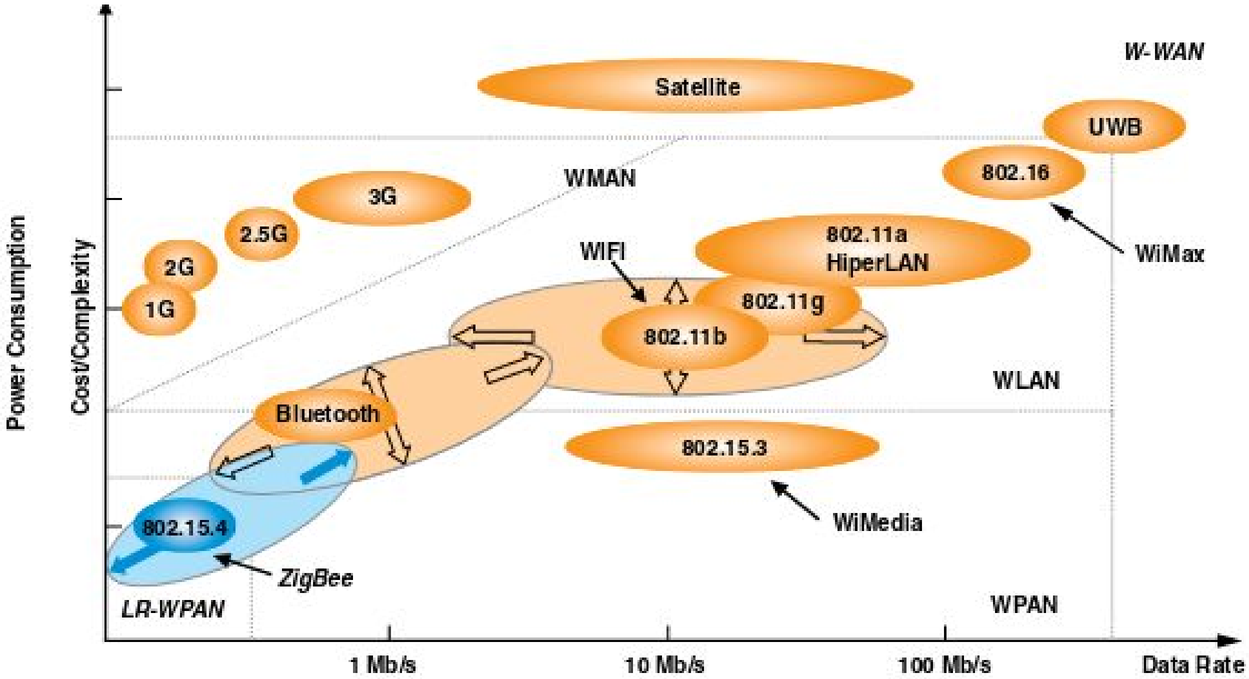


Figure 3.4: Wireless standards compared in terms of data rate and complexity of implementation [22].

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 and 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 3.3 sums up the main properties of the wireless standards that are most suitable for use in different I-MECH Pilots and Demonstrators, while table 3.4 compares a few COTS wireless sensor networks.

Table 3.3: Comparison of manufacturing/robotics industry suitable wireless standards

Standard	**WiFi(802.11n)** [23]	**802.11ah** [24]	**802.15.4 (ZigBee, Xbee)** [25]	**BLE LE 5.0 (802.15.3)** [26]

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; [27]
2. SG-Link® -LXRS® Small, Low-power Two-channel Analog Sensor Nodefrom LORD, MicroStrain® Sensing Systems; [28]
3. NI WSN-3202 from National Instruments; [29]
4. TEDIASENS SN-X from ELOVIS GmbH; [30]
5. V-Mon 4000 from Inertia Technology; [31]
6. Wzzard Intelligent Edge Node from B+B SmartWorx; [32]
7. GP-AP81 from OleumTech; [33]

Table 3.4: Comparison of COTS ready-to-use wireless sensor nodes available on the market, see the list above for references to products

	Product name by number

Specifications	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*

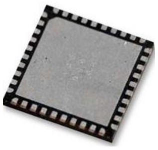
The following conclusions can be made based on table 3.3 and 3.4:

- 802.11n [34] 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 [35,36], an example COTS product using the 802.11n standard, "is a low-power consumption 802.11 b/g/n IoT module, which is specifically optimized for low-power IoT applications". This module consumes 61 mA when transmitting @ 6 Mbps, which is 6 times more compared to a Bluetooth 5.0 solution. However, a 6 Mbps or even 54 Mbps data rate will likely be more than needed for usage in I-MECH Layer 1, where data is likely transmitted between only a few sensors.

- 802.11ah [35] 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.

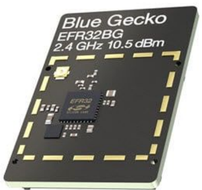
- 802.15.4 [34] is suited for certain cases when there is a demand for low power. Disadvantage of the standard is the relatively low data rate (typically 400 kbps).

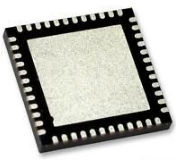


An example of a 802.15.4 implementation in the 2.4 GHz frequency band is the Texas Instruments CC2531F256RHAT [37]. This solution has a maximum data rate of 250 kbps, but compared to Bluetooth 5.0 still a relatively high power consumption of 29 mA @ 1 dBm.

The 868/915 MHz frequency band is mostly used for applications requiring a larger range. The Xbee 868LP [38] module is an example of a solution applying the 802.15.4 standard in this frequency range. It can transmit up to 112 meters indoors or 8.4 km outdoors, but has relatively small maximum data rates, only up to 80 kbps, compared to Bluetooth 5.0.

- Bluetooth LE 5.0 (802.15.3) [39] 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 Labs EFR32BG12 Blue Gecko Bluetooth SoC [25]. This module has a low power consumption (8.5 mA TX current @ 0 dBm and 10.0 mA RX current at 2.4 GHz @ 95 dBm sensitivity) and a relatively high (compared to 802.15.4) data rate of 2 Mbps (1 Mbps in real life scenario). It is expected that this should be sufficient for deployment in I-MECH layer 1 pilots, where data from sensors deployed on moving parts of industrial robotics equipment need to be transferred to a gateway in the nearby distance (< 10 m). 1 Mbps is a suitable data rate for the proposed sensor use in I-MECH pilots projects (accelerometer, gyroscope, magnetometer and temperature sensors), as the 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 [34] while having a relatively high data rate (1 Mbps) as 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.

3.1.3.6 Vision Sensors[5]

Vision is at the moment frequently used for quality inspection purposes, identification of objects and for position/alignment measurements. These applications generally do not have strict real-time requirements. However, utilization of visual servoing is emerging in recent motion control applications. The goal is to extract feedback information from a vision sensor and use it in the feedback loop used to control the motion of a working mechanism. This application of vision does pose strict real-time requirements on acquisition and processing of vision data. Different examples are known in the field of visual servoing, e.g. pick and locate load via vision and place at corrected position which is used in semiconductor pick-and-place machines.

Depending on the specific application and requirements, many different types of vision systems and optical layouts can be found, e.g. [40,41]. Performance of the vision components is continuously improving, especially the image chip. Improvements of the chips with regard to sensitivity to light and read-out speeds open up possibilities that were previously not feasible, for industrial applications like visual servoing, but also other industrial applications. For example, optical coherence tomography (OCT) microscopy technology has been developed into vision solutions for industrial inspection to achieve zero-defect manufacturing [41,42]. Increasing vision system capabilities push the possibilities for vision based servo solutions.

Visual servoing control techniques are broadly classified into the following types: Image-Based Visual Servoing (IBVS), Position Based Visual Servoing (PBVS) and hybrid approaches (see [43,44] for an introduction into this wide field). Image-based methods work directly with the error between current and desired features of the image in 2D, whereas position-based methods estimate the motion and position of the object of interest in 3D based on the acquired (2D) 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 was difficult to achieve using standard off-the shelf components.

Nowadays compact and affordable embedded hardware platforms equipped with FPGAs (e.g. the Zynq platform from Xilinx) can deliver the required computational power to quickly process the acquired images [8,45]. There are also ‘smart’ cameras available with built-in processing power, e.g. the Corsight and GigEPRO cameras from New Electronic Technology with built in Intel Atom CPUs with multiple cores and

[5] [BB4]

an FPGA [46,47] and cameras from Adlink, Omron and B&R with similar features [48–50]. Custom imaging processing software can be programmed by the end user for these cameras. Performance of some of these camera's is in some cases advertised as 'real-time', but not all specific numbers regarding real-time performance like achievable update rate and jitter are specified. The latter approaches are suited for a decentralized image processing approach, which has the advantage that it is very scalable. The solutions can furthermore be dedicated to 1 image processing task, hence there is less to no risk that the image processing task is waiting on other tasks to be completed before processing power comes available. This is a large advantage when vision is used for a real time application like visual servoing. There are also centralized vision processing platforms available which use a very powerful industrial PC for image processing of pictures obtained from a large(r) number of cameras (e.g. from Omron [51]). The PC can communicate the results after processing via an industrial Ethernet fieldbus with a motion control platform. COTS software for all three approaches is however (often) not yet optimized for motion control purposes with hard real time requirements and very high (kHz range) update rates, which is necessary for real visual servoing.

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.

3.1.3.7[6] Sensors dedicated for condition monitoring

Various measurements to detect degradation and wearout can be used (e.g. voltage, current, temperature and (acoustic) vibrations) to verify during a known repetitive movement the required power and encountered. friction. Due to mechanical friction, temperatures may rise which can be easily detected. Inside bearings, the color or transparency of the grease can be checked optically. 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 and heatsinks are the most common artifacts causing 'wear' and reduced performance. Temperatures of processing chips and power stages need to be kept low enough (also with LEDs used for illumination) to ensure their lifetime. External temperature over 70 degrees shall be avoided whereas the internal die temperature may not exceed 125 degrees, typically.

3.1.3.7.1 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, based on academic experience.

[6] [BB3]

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[7]

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 hardware and software architecture with sufficient processing power. Condition monitoring can form a part of layer 2. Layer 2 should communicate with the behavioral layer via industry 4.0 compliant paradigms and

[7] [BB6, BB7, BB8, BB9, BB11]

interfaces. Deliverable D3.1, part of work package 3, investigates possible control strategies, ranging from PID control to iterative learning control in more detail.

3.2.1 Centralized and decentralized control.

Centralized versus decentralized control approaches are both being used frequently. Smart actuators, motors with built-in drives which can be CAN, Profibus or Ethercat controlled are common, similar to 6-DoF robotic systems which are fully integrated with the robotic system and only require geometrical data either as cartesian or spherical coordinates, are examples of very decentralized motion control strategies. The same applies for sensors, where either the raw data is obtained and directly transferred or 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 applications 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. Achieving very high bandwidth servo-loops is therefore easier when using a decentralized control approach. A centralized control approach is better suited for MIMO systems with strong couplings between axes.

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, in particular to tune controllers automatically.

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

A filtering action is often necessary to reduce the noise in sensor measured signals in real industrial applications. Furthermore, filtering can be used to avoid the excitation of some resonant frequencies of the system. The (optimal) 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 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.

The vast majority of commercial motion controllers have adopted a two or three level cascade control structure for electrical drive systems. 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 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. 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 [52]. Advanced control strategies based on the recent results of control theory can significantly improve achievable performance in high-end applications compared to usage of PID based controllers [53–55].

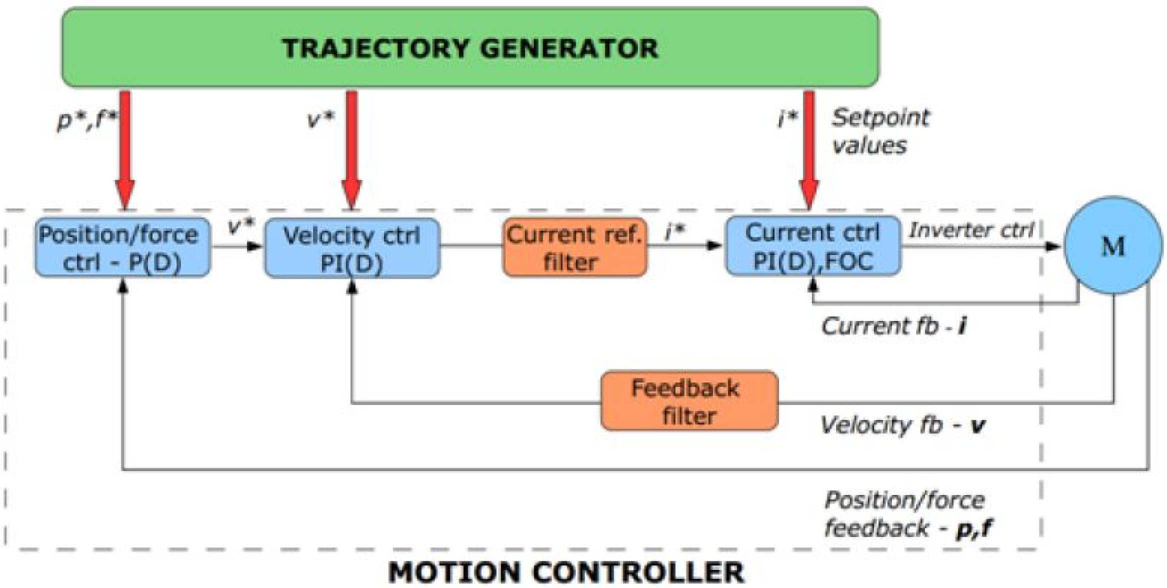


Figure 3.5: Three level cascade control structure

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 nonlinear systems. Nowadays the standard gain scheduling technique uses a set of predefined controller parameters that are statically defined depending on conditions of the system. 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 it determines accuracy, disturbance rejection as well as stability of the system. An automatic tuning method would be beneficial to reduce the dependence on the skill of the operator and decrease commissioning time. 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 coupling (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. 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, Bosch Rexroth, 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 and available computing power for complex algorithms might in some cases be insufficient.

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. Experimental identification of the model of the system is often preferred over numerical modeling in industrial applications, since precise geometric data and knowledge of all available physics is not available in many cases. 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 made 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 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. Nonetheless, the conventional approach applied in commercial motion control products is to neglect many dynamical interactions in the system and consider a system 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.

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 for 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 almost always 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 technology readiness level for general commercial use.

One 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 in order to evaluate the accuracy of model reduction techniques on a flexible multi-body dynamic system. The resulting reduced order model can then be used in a 0D simulation software like LMS Amesim [56], that also permits design of the control loop and simulation of the controlled system (when the deviation between the finite element model and the reduced model 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 a specific 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 [57]. This method would not lead to a compromise on numerical solution accuracy but would necessitate strong computing resources. 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 [58–61]. It remains, in any case, 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 necessarily 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, based on an identification of the system, 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

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, although is essentially the true object of interest (this is why this approach is sometimes called a semi-closed loop approach). This problem is emphasized in the case of highly dynamic motions with a mechanically compliant load which cause elastic deformations in the individual parts of the kinematic chain. Residual oscillations of the load can then occur that are not observable by the controller. 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 these unwanted mechanical vibrations. The presence of residual oscillations leads to an increase of the total actuation time, an increase of operative costs, less accurate positioning and sometimes to an increase of hazards (e.g. for overhead cranes). The problem of transient or residual motion induced oscillation is recognized as one of the most limiting factors on achievable performance [62–64]. Several techniques are already present in the literature to mitigate this problem.

There are three categories of strategies to reduce residual vibrations. 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.

Corrective actions can either be taken in the feedforward path of the controller (passive vibration control), for example by using input shaping, or in the feedback path of the controller (active vibration control) [65,66]. Corrective actions in the feedforward path require precise knowledge of the system dynamics, which can be subjected to variation and change over time. 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.

The majority of commercial products address the 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). A minority of commercial products offer some support for more advanced vibration damping.

A reasonably frequently used method is auxiliary feedback control, where a second load-side mounted position sensor is installed which transmits the true position/velocity of the controlled load. This is unfortunately often not ideal in industrial fields because of the difficulty in placing a sensor on the load side. 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. Although there are very high resolution encoders available on the market, reaching resolutions up to 1 million pulses per revolution (PPR) and more, they are often not suitable or available for load-side measurement applications due to harshness of the 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. Moreover, readings from the secondary sensor are often not used in an optimal way in 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, instead of using information from both signals, 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 [67–69]. Employment of auxiliary load-side measurement is treated in [70] which proposes a special eddy current sensor providing load-side acceleration feedback. Installation of accelerometers or gyroscopes has been proposed for particular robot types [71,72]. 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.

Research results show that there are whole range other strategies available besides auxiliary feedback control. Many advanced motion control algorithms have been proposed for the motion control of mechanically compliant systems ranging from PID control [63] to resonance ratio control [74], model-predictive control [75], sliding-mode control [75,76] or nonlinear methods [77,78]. 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.

3.2.4 Learning control

Execution of repeating motion sequences or compensation of periodic disturbances are problems that arise in many practical motion control applications. Learning-type control methods which iteratively adapt and optimize their performance can be employed in such cases to significantly improve various performance objectives like minimizing the tracking error or energy consumption. Learning control algorithms are used to optimize the control strategy during operation of the machine by measuring system behavior, like position errors and overshoot, and adjusting the control strategy based on these measurements. There are several levels of learning control algorithms. Some approaches are only suited for systems that repetitively perform exactly the same task. More advanced approaches can cope with variation in tasks or even learn by themselves how to perform a novel task. This is for example used in academics to make robots learn new tasks by themselves by means of trial and error [79]. The learning control scheme may take the form of an adaptive feedback controller or a variable feedforward generator. Iterative and repetitive learning control are two strategies well known in academics.

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) has 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 end-effector positions precisely by automatically compensating gravity, joint compliances etc. The effectiveness of this technique is proven in the literature, but in industry it is not yet frequently 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.

3.2.4.3 Current state of learning control

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 suboptimal. Novel repetitive and learning algorithms will have to be developed 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. When damping known periodic disturbances, the algorithms can also be used to detect their changes. This could be relevant for condition monitoring functionality of the I-MECH platform.

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 Multi/Many-core platform[8]

The need to increase the computing power of CPUs is nowadays mostly 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 CPU designs. 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.

The transition from single core to multi or many core processors has been going on for quite a while in scientific and home computing [80,81]. Multi-core platforms are already commonplace components of most computing systems, both in the general-purpose and in the embedded computing domain. Reasonably priced commercial-off-the-shelf multicore platforms with tens of cores (e.g. Intel Xeon processors and AMD Epyc processors) and manycore platforms with hundreds or more cores (e.g., Kalray [82]), along with accelerators for GP-GPU computing featuring thousands of cores (e.g. Nvidia [83]) are available for more specialized applications. This development is in particular advantageous for tasks that can be computed in parallel. Manycore processors are a class of multi-core processors specifically optimized for a high degree of parallel processing with a large 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 [84]. The power of multi- and manycore processors has also come available since the last few years in COTS motion control platforms. TwinCAT from Beckhoff automation is for example capable of running on multi/many-core platforms with up to 256 cores [85].

It is 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: VT-X, VT-D, EPT (extended page tables), unrestricted guest mode, preemption timer
- ARM SoCs:
  - 32-bit ARM (ARMv7) with virtualization extensions
    - Only available for Cortex A7 and Cortex A15 cores
    - Not suited for the Xilinx Zynq platform (ie. Cortex A9)

[8] BB10

- 64-bit ARM (ARMv8): all suited
  - E.g. Xilinx Ultrascale+ (for example used by the AXIOM and HERCULES project [86,87]).

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

3.2.7 Multi/Many core RTOS and related software[9]

Major problems of the transition from single core to multicore computing for motion control reside in the need to reuse legacy code and standards built for single core devices, as well as in difficulties of providing predictable timing guarantees 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, few industrial applications currently adopt multi-core technologies efficiently for critical control systems. These considerations clash with the current hardware market trends. All main chip producers feature almost exclusively multi-core platforms. For these reasons, many motion control systems adopt multi-core platforms (for the cheaper prices due to massive scale production, longer life-cycles and maintainability), but disable all cores but one in order to predictably limit the timing interference from concurrently running activities at the cost of using only a fraction of the available computing power. These issues can be managed by using a hypervisor and RTOS optimized for a multi/many core platform.

It is 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, to enable predictably mastering the parallel computing bandwidth offered by modern computing architectures. 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.

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) [88–92]. 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.

[9] BB11

The usage of a multi/many core processor enables efficiently executing multiple operating systems on a single processor by using a so called hypervisor. 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. The approach allows system designers to integrate multiple modules (e.g., motion and control modules) onto the same chip resulting in benefits regarding product cost and size and possibility of using software structures similar to those used in single cores. This possibility is a valuable method to integrate (legacy) software that was developed for a different operating system on a modern new hardware platform. The COTS automation & motion control solution from B&R is an example of a motion control platform using a hypervisor to allow execution of other operating systems beside the RTOS used by B&R for motion control [93].

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. 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 motion control applications using different modules that share a single computing platform have different requirements for the hypervisor. For example for applications with heterogeneous safety and criticality levels, e.g., a human interface module and a critical control module, have challenging different requirements. These modules 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 or performance qualifications. 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 [94], 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 [95], 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 [96] and bhyve [97].

Along the line of dedicated multi-core platforms, I-MECH will evaluate and extend the CompSOC platform [98,99] in the context of high-precision motion control applications. CompSOC offers predictable and composable virtualization technology using the concept of a 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 [100,101]. 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.

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) [102]. 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.

The hypervisor should 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 [103,104] for Johnson and Johnson Vision Care) 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 is applicable and desirable for the I-MECH platform, based on a questionnaire to external companies. 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 [105] or Capella [106] could help 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) [107]. RAMI 4.0 is a unified architecture model that serves the purpose of a common understanding, which standards, use-cases, standards etc. for Industrie 4.0 are necessary, and allows discussing associations and details. In RAMI 4.0 Industrie 4.0 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. Industrie 4.0 has been about very high level, rather abstract concepts. However, recently a list with requirements to be 'Industrie 4.0' has been published [108]. The guideline with requirements for Industrie 4.0 compatibility will be updated yearly, due to the many ongoing developments and standardization processes and is therefore a

moving target for the I-MECH project. The guideline does however give some indications of requirements that are expected to be introduced in the coming years.
I-MECH embraces the Industrie 4.0 initiative and in the course of the project, the consortium will strive for maximal compatibility. We will be in contact with 'Productive 4.0' [109] 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[10]

Conditioning monitoring data is typically provided by layers 1 and 2 of the motion control system. Layer 2 might preprocess the data, but analyzation of the data is typically performed in the system behavior layer or dedicated software running outside the machine, e.g. in the cloud or as part of the SCADA/MES/ERP tools of a factory. 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 and therefore demanding for traffic on communication busses and storage capacity of hardware.

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. A 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 [110]. Methods for fault detection of AC induction motors were reviewed in [111]. [112] is interested in broken bar detection in induction motors. MEMS sensors are nowadays common components in consumer electronics. Their utilization in industrial applications is relatively rare. Vibration analysis using MEMS in industrial motors was presented in [113–115] and others. Monitoring and diagnostics of the cutting process during CNC machining is reported in [73,116,117]. The aim of the I-MECH project 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

[10] BB3

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.

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[11]

Industry 4.0 is about connecting data and making data available throughout the enterprise or even throughout the supply chain. This is achieved by enabling communication between systems on the same layer in the enterprise hierarchy, e.g. machine to machine communication, and in vertical direction, e.g. machine to MES or ERP or cloud communication. The tendency the last few years was to connect 'everything' to the cloud (the industrial internet of things or IIoT). This does however result in large data flows to cloud services, which can be expensive, and introduce unnecessary delays when data is only used locally within a factory. An intermediary approach using a so called 'edge architecture' seems therefore currently more favorable [118]. An 'edge architecture' uses a local edge server to gather and process data locally, effectively creating a local cloud, and only transmitting preprocessed and selected data to the cloud, for example for archiving purposes. The goal of I-MECH is not to provide the entire Industry 4.0 architecture of automation of an entire factory or supply chain. The I-MECH platform should however be compatible with Industry 4.0 architectures, which mainly means that it should be able to communicate using the expected protocols. Communication protocols found to be relevant for industry 4.0 are listed in table 3.5.

Table 3.5: Communication protocols/standards for Industry 4.0

Protocol	Standard	Purpose	Industry
OPC UA	IEC 62541	Vendor and platform communication protocol, can be transported over other protocols.	Various

[11] BB3

MQTT	ISO/IEC PRF 20922	Publish-subscribe based messaging protocol, mainly of interest for cloud communication & IoT	Various
AMQP	ISO/IEC 19464	“open standard application layer protocol for message-oriented middleware”, mainly of interest for cloud communication and IoT	Various
SECS/GEM	SEMI E30	Used for equipment to host data communication.	Semiconductor industry
ISA 95	ANSI/ISA-95 / IEC 62264	Used for developing an interface between enterprise systems and control systems	Global manufacturers in all industries

3.4.3.1 OPC UA

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 inventorisation 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 standard communication technology used in the Industrie 4.0 reference architecture RAMI4.0 for these kinds of communication [107]. The IIC (industrial internet consortium) can be seen as the US equivalent to the European ‘Industrie 4.0’ platform, except that the IIC focuses on energy, healthcare, public domain and transportation besides manufacturing, which is the sole focus of the Industrie 4.0 platform [119,120]. The IIC had chosen to use DDS (data distribution service) from OMG as standard for communication. The Industrie 4.0 platform and the IIC have however recently agreed to make both standards interoperable and the preferable standard for the manufacturing industry will likely be OPC UA (figure 3.6) [121,122].

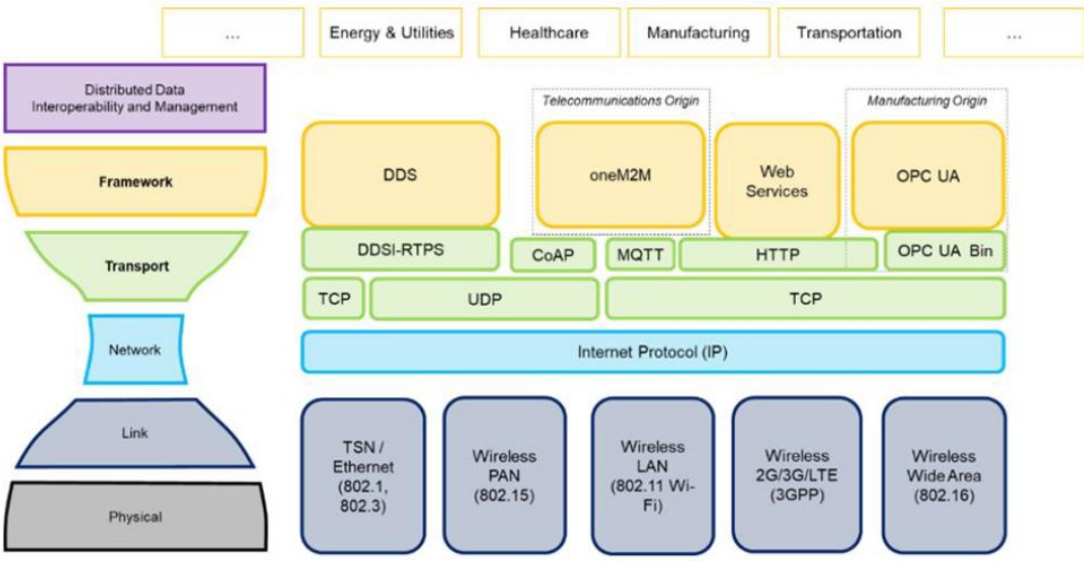


Figure 3.6, standards used for communication as jointly proposed by the IIC and platform Industrie 4.0 [122]

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 idea is that an OPC UA server is able to communicate using proprietary/custom protocols with underlying systems, but is able to transport and present the data in a standardized way to OPC UA clients. It is therefore not necessary to develop very custom drivers for HMIs, data loggers, SCADA/MES/ERP systems etcetera, to enable communication with all kinds of systems, they only have to implement an OPC. The standard OPC UA protocol is not suited for communication with hard 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) [123,124].

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 [125]. Writing your own implementation of an OPC UA server or client based on the OPC UA standard can take many man-years [126]. It is therefore recommended to use an open source or commercial OPC UA server SDK to develop an OPC UA server for either an industrial PC or embedded platform. Matrikon [126] offers an SDK especially suited for development of nano/micro servers for embedded platforms with limited computing capabilities.

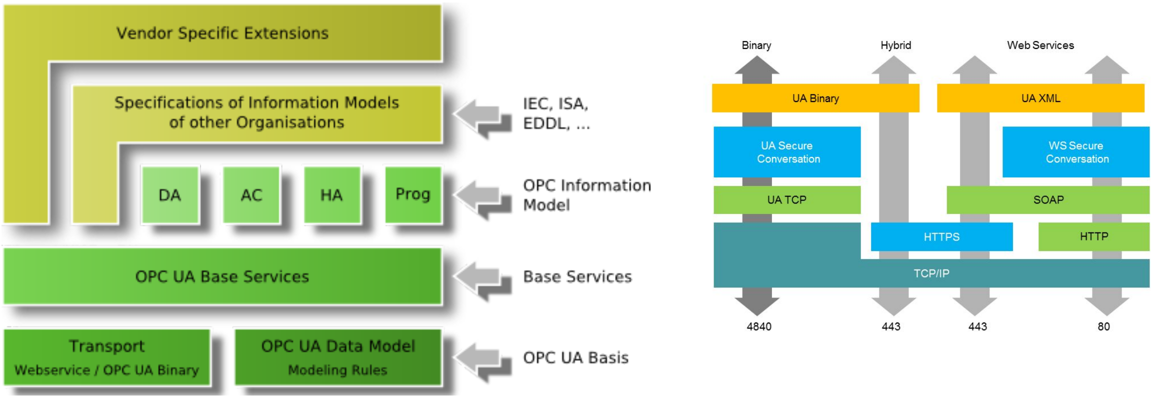


Figure 3.7: OPC UA architecture

The OPC UA protocol is modular. All implementations require a few basic functionalities, specified in the OPC UA standard [127]. 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 [128]. 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' [128].

OPC UA uses so called 'information models' to structure and relate the information in an address space in in a standardized way [129]. Several 'standard' information models are made available by the OPC foundation. It is possible to define new information models as external party [127]. The PLCopen foundation has for example made an information model available to be able to access data on PLCs (equipped with an OPC UA server) using OPC UA in with a standardized structure of the data, mapped according to the software architecture defined in the IEC61131-3 software model [130,131]. ISA-95 is a standard for developing an interface between enterprise systems (SCADA/ERP/MES) and control systems. ISA-95 uses well defined object models to describe information. A standard for an information model for OPC UA to structure data according to the ISA-95 standard is available [132,133].

These standardized information models only define how information is structured. The OPC UA server and client itself take care of the transport of the information between OPC UA client and server. The main effort in writing applications implementing an OPC UA server is (automatically) exposing and structuring parameters and variables used within the application in the address space of the OPC UA server (optionally following a standardized information model). The advantage of using a standardized information model, is that the client can find all the necessary information at an expected location. Hence, when you are a developer of HMIs and design a dial gauge indicator interface element to indicate the measurement value of a sensor, you only have to design the element once by referring to certain parameters related to the measured value, e.g. range and measurement unit, at location within the address space relative to the measured value. This interface element is easily reusable, when another application adheres to the same information model/structure of the address space.

OPC UA information can be transported over different internet 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 recently added to OPC UA to facilitate bandwidth-efficient many-to-one, one-to-many communication, relevant to SOA applications [134]. 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 [135]. Messages sent via OPC UA are signed, which prevents tampering with messages by unauthorized parties [135].

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 [136]. 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) [134].

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. 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.

A general mechanism is needed to support plug and play of the building blocks to enable (re)use building blocks and make them available in different pilots and demonstrators, without adapting the blocks to special cases. A plug and play infrastructure requires elements like:

- A discovery mechanism for building blocks,
- An update mechanism for building blocks,
- Management of state changes of building blocks (installing, idle, operational,…)
- A detection mechanism of layer 1 devices (smart sensing/ smart manipulation) at layer 2,
- A metadata description, describing the sensor/actuator type and working limits
- Status monitoring

4.2 Model Based approach

Part of I-MECH emphasizes the ambition to improve the 'classical' way of engineering towards a model based (systems) engineering direction that is envisioned by e.g. INCOSE [137], the international council on systems engineering. This aspect will be part of multiple tasks of the I-MECH project (e.g. T4.2, Unified framework for model-based design of motion control systems) and T4.3, Modeling & Identification of complex multivariable systems). 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. In parallel a questionnaire was sent to multiple external companies to inventorize their wishes and expectations regarding model based (systems) engineering.

4.3 Analysis state-of-the-art of I-MECH pilots/demonstrators/use cases

This section analyzes the global trends and remarkable deviations observed in the I-MECH requirements table which is included as appendix A. This table list the requirements and wishes from I-MECH pilots, use cases and demonstrators (12 in total, in the next part all referred to as pilots) for a motion control platform/the I-MECH platform. It should be noted that not all pilots provided input on all requirements, hence observations are sometimes based on a rather small sample.

4.3.1 Layer 1: Instrumentation

4.3.1.1 General I/O

The instrumentation layer facilitates communication with sensors and actuators. Pilots in general want the same functionality as they already have regarding analog and digital inputs & outputs and encoder inputs. The number of required inputs and outputs is in all cases not very high, varying between approximately 5-20 analog I/O and at most 50 digital I/O. The possibility to connect hundreds to thousands of I/O, which is possible with some COTS automation/motion control platforms (e.g. Beckhoff, B&R, Siemens), is not required for a typical I-MECH pilot. Update rates of the I/O should preferably be with the same update rate as the servo (position) loops, which should be feasible due to relatively low amount of required I/O. Pilot owners do not yet think they will require special IEPE sensor interfaces. However, these interfaces are frequently used for interfacing with vibration sensors in condition monitoring applications. IEPE interfaces could therefore still be required by applications, as pilot owners in most cases would like to add more advanced condition monitoring to their systems. Standard IEPE interfaces are available from many COTS motion control suppliers (e.g. Beckhoff, B&R and Siemens), which should be simple to integrate into the I-MECH platform as they are also equipped with either EtherCAT, Ethernet Powerlink or Profibus interfaces.

4.3.1.2 High speed vision

Only 2 of the 12 pilots indicate that they are already using machine vision. The update rate of vision systems used in these pilots is not particularly high speed with an update rate of only 50 Hz. This does however not mean that the delay between triggering of the camera and finalizing processing of the acquired image is not required to be extremely short. This aspect was however not considered in the requirements table. The vision data is in both pilots likely used for quality inspection and for low update rate position measurement for alignment purposes and trajectory generation instead of real high speed visual servoing. Both applications will not require much high performance than they already have with regard to high-speed vision in the future, except for small increases in achievable update rate and implementation of new interfaces due to obsolescence of old interfaces or introduction of higher performance interfaces (obsolescence of Firewire and SpaceWire). It should however be noted that the 12’’ wafer stage application uses many high resolution cameras (up to 12). This can still put a significant load on available processing power and communication bandwidth when a central processing solution is used, even when update rates of the cameras are not particularly high. The Space GNC Systems application requires a very unconventional interface (SpaceFibre), mainly used for space applications.

There is one pilot that would like to introduce machine vision in the future, but also with a very modest update rate of 50 Hz. Only one pilot (the GSC) would like to use machine vision for high speed visual servoing purposes in the future using update rates of 5 kHz. The required resolution is however modest, hence existing hardware platforms are expected to be able to provide sufficient computational power for this application.

The large difference in required update rates between the different pilots that wish to use (high speed) vision and number of cameras used in an application might indicate that one single universal solution might not be suited for all pilots. Real-time requirements (e.g. jitter) are much less strict when vision is used with update rates of 50-100 Hz and data is not used for visual servoing. A very high speed vision visual servo application might greatly benefit from the usage of a dedicated embedded platform with an FPGA and highly optimized algorithms to process images in such a way that a fixed processing time in combination with very high update rates can be guaranteed. Processing data from a large amount of cameras with a low update rate might be more cost effective when using a big, high performance multicore PC with one or more high performance video cards for which COTS image processing software can be used. The disadvantage of such a centralized approach is that it is not very scalable.

4.3.1.3 Wireless sensors

None of the pilots is currently using wireless sensors. There is only modest interest in application of wireless sensors. Only the “Big CNC Machining” pilot is definitely interested in application of wireless sensing technology and already knows that Bluetooth Low Energy is sufficient for the application. This technology should also be sufficient for the 12’’ Wafer Stage pilot with respect to the expected required bandwidth. However, it should be verified whether this protocol is suited for time synchronized, real-time data communication. Real-time communication is a requirement for the 12’’ Wafer Stage pilot as the technology will potentially be used for wireless encoders. Standard COTS hardware solutions seem potentially suited for both applications, except that they do not provide the required energy harvesting functionality and use a battery instead.

4.3.1.4 Smart sensors

Nearly all systems do currently not apply smart sensors. There is modest interest in the application of a programmable platform for smart sensors by pilots. One pilot requires a very specific ARM processor based hardware platform, to be used as a platform for wireless sensors. Another pilot is looking for a solution to process decentralized I/O using an FPGA. The third pilot is specifically looking for smart accelerometers, likely to be used for condition monitoring purposes. The application of FPGAs for the smart sensor platform can require usage of complex tooling to program the FPGAs. A solution where standard programming language, also used to program the rest of the motion control algorithms, could be used, would be preferable (e.g. code generation from Simulink models, PLC or C code). This is for example offered by the COTS motion control solution of B&R, but unfortunately vendor-locked to the B&R environment. Optimization of the generated code for maximum hardware efficiency and performance can however be critical for certain applications and current COTS solutions could be improved with respect to this aspect.

4.3.1.5 Servo amplifiers

All I-MECH pilots make use of PWM amplifiers and wish to remain using this type of amplifier in the future. Nearly all pilots use servo amplifiers in current mode and expect to remain doing this in the future except one pilot that would like to be able to use servo amplifiers in current and voltage mode. There is quite some variation in the performance of servo amplifiers currently used by pilots. This is not unexpected, as some pilot systems mainly focus on very precise high speed movements of small masses which requires very high bandwidths, while in other pilot systems motion mostly concerns large masses and relatively low speeds which might need high power amplifiers, but not necessarily a high bandwidth. Pilots that indicated that they would like to use the I-MECH high-speed servo building block in the future currently use amplifiers with a significantly lower performance than some of the other participating pilots regarding bandwidth and precision related features. Pilots that would like to implement the building block indicate that they would in the future like to use field oriented control and have improved PWM frequencies and current loop sample rates. The desired PWM frequencies and current loop sample rates are however quite modest compared to the current performance of certain pilots like the 12’’ wafer stage. However, the 12’’ wafer stage pilot currently applies custom servo amplifiers with proprietary technology, for example for commutation and alignment.

The most frequently used actuator types to be controlled are brushless AC, DC brushed/voice coil actuators and reluctance actuators. Requirements like power rating, voltage and current rating and maximum slew rate are very application dependent. There are large variations in the required power between the different pilots and actuators applied within pilot systems. However, these requirements are not of particular interest for the I-MECH reference platform, as they do not determine what makes an servo amplifier an I-MECH servo amplifier. Features more typical for the future I-MECH platform, like auto-tuning of the current loop and ability to modify the control algorithm are not available on about half of the current systems and desired by most systems that lack these features. Most pilots do not have particular wishes regarding requirements like real-time bus voltage correction, improvements on signal-to-noise ratio and current loop resolution, except pilots that already have very high performance amplifiers. Requirements regarding condition monitoring seem not particularly advanced, in most cases just requiring I2T, over and under voltage and peak current protection, although more advanced strategies based on modeling of servo amplifiers are available in academia. Pilots indicate that it should be possible to support the highest safety level, PLe, when using I-MECH servo drives.

One gets the impression that pilots requiring very high performance servo amplifiers currently use custom high performance servo amplifiers. Applications having more modest performance requirements are looking to improve the performance with respect to what they currently have, but will likely not be prepared to spend much money on these improvements. They would already have chosen for a more expensive custom solution, as the required high performance technology seems available within specialized companies. Hence, there is a group of pilots that is looking for a ‘higher performance’, affordable servo amplifier and a group looking for a very high performance, likely quite costly, servo amplifier to replace currently applied servo amplifiers. The ‘ideal’ servo amplifier for both groups could be similar regarding application of a part of the I-MECH methodology (e.g. possibility to auto-tune the current loop, modify the current loop and trace signals related to the current loop), but could possibly be quite different regarding hardware architecture. Furthermore, a decentralized control strategy instead of a centralized control strategy might be required when using a very high performance servo amplifier to utilize the performance of the amplifier maximally. For example, the 12'' wafer stage pilot currently uses a decentralized control strategy to minimize communication delays between the position and current loops.

4.3.1.6 Communication protocols

EtherCAT is the most popular fieldbus amongst pilots, some use Sercos III, while only one pilot currently requires Ethernet/IP and wishes to remain using this protocol in the future. The requirement for Ethernet/IP results from the required compatibility with Rockwell Automation motion control products. One pilot focussing on a general purpose COTS servo drive already has implemented support for a very wide variety of fieldbus protocols and would like to keep supporting this wide variety of protocols when implementing the I-MECH platform or I-MECH building blocks. Some pilots would like to use a SPI bus and/or I2C bus besides a fieldbus for communication devices in the instrumentation layer. These protocols are however only suited for communication over very short distances and seem therefore mainly suited to connect sensors to a smart sensor platform or to extend a centralized motion control hardware platform with extra I/O. It seems clear that it should be possible to integrate 'any' protocol on the I-MECH platform, given the variety in wishes and variety in protocols on the market. Multiple COTS solutions prove that such support for a wide variety of protocols is possible (e.g. solutions from Beckhoff and B&R). Sufficient attention should be given on how to make the hardware abstraction layer of the I-MECH platform modular and interfaces standardized, such that addition of new protocols remains possible and as much plug and play as possible.

Many pilots would like to double the sample rate of their control layer and therefore also the sample rate of the communication between devices in the instrumentation layer and the control layer of the motion control platform (up to 20 kHz). These pilots indicate initially that they would like to keep using EtherCAT to communicate with I/O in the instrumentation layer, but seem to realize afterwards that this might not be realistic regarding their wishes for an increase in sample rate of communication between the instrumentation and control layer. The 12'' wafer stage pilot currently already has a quite high sample rate of 8 kHz. This is however achieved using a decentralized control approach where the servo position loop communicates via a local DSP bus with the current loop executed on an FPGA. This approach is however not applicable for pilots that would like to use a centralized motion control strategy. It is however not clear from the requirements list whether currently achieved update rates of communication with the motion control layer for a centralized control are limited by the bandwidth of the applied communication protocol or limited by the computation power of the motion control platform.

4.3.1.7 (Electrical) standards

There are a few general standards for machinery to which all systems sold in Europe should comply. Hence, these standards (e.g. the machinery directive and directives regarding EMC, radio frequency emissions, electromagnetic fields and electrical safety) are applicable to all pilots and are relevant for all I-MECH hardware, but application of these standards might not be as stringent in every industry/application. The goal should therefore be that I-MECH hardware and software should be such that it does not prevent a system integrator applying the I-MECH platform from complying to these standards. It should furthermore be noted that one pilot requires conformity to IEC60601-1-2, an EMC standard for medical devices. This requirement is not of particular relevance for the I-MECH platform, as an I-MECH building block should not be required to be compatible with this standard by default. It should therefore be kept in mind that it should be possible to design hardware that meets medical standards when using an “I-MECH methodology”.

4.3.2 Layer 2: Control

4.3.2.1 Control algorithm adjustment

Enabling adjustment of control algorithms in the control layer is an important goal for I-MECH. However, at least 5 of the 12 pilots report already having this functionality and only 1 pilot explicitly states that it does not yet have this functionality. The available and wished methods to adjust the control algorithms vary however, ranging from code generation using Matlab Simulink models to manually programming in C, C++, IEC61131-3, ADA, Python or VHDL code. Some pilots want to keep the same options they already have, while others would like to add more options. There is however no convergence to 1 single, universally preferably programming method for custom control algorithms. It can be observed that generic motion control platforms supplied by for example Beckhoff, B&R and Siemens also support most of these methods to write custom motion control algorithms.

Pilot owners prefer in general that their custom motion control algorithms and software code should run on an X86 CPU. One pilot has no preference for a solution using a CPU or a SoC and another states a preference for a specific programmable automation controller. A few indicate that they would also like to support usage of FPGAs, DSPs or SoCs. Not all pilots do however intent to implement the “entire” I-MECH platform into their system, but only a few building blocks. Some of the used/wished platforms require programming in a very specific programming language. A possible solution to achieve some standardization for the I-MECH platform could be using a development environment that can do code generation for a wide variety platforms such that specific I-MECH building blocks can be implemented on this wide variety of hardware without manually writing or porting the code for each new platform. Simulink from the Mathworks could be suited for this task. This software tool is furthermore already widely used in academia and industry. There are however some concerns regarding optimization of code for speed, efficiency and parallelization on multi/many core platforms and FPGAs when using solutions like Simulink.

4.3.2.2 Control algorithms

All pilots use a motion control platform that support basic SISO PID control in combination with various filters (notch, lowpass, highpass or biquad) and integrator reset/anti windup functionality. Gain scheduling is currently being used by two pilots, but a few other pilots are interested to apply this as well. None of the pilots currently uses real MIMO control, but there is some interest to start applying MIMO control.

Basic feedforward control using static, velocity, acceleration and friction feedforward control is also implemented by all pilots. However, model based feedforward taking cross-couplings into account using an inverse model of the plant is only used by 1 pilot, but there is interest from other pilots to also implement this method of feedforward control.

The GSC pilot is the only pilot already using some kind of learning control (repetitive control). There is interest to introduce various forms of learning control in pilots, but there is clearly not much industrial experience yet in this field of control. Even some of the participating universities indicate that they do not have much experience with these approaches. The goal of I-MECH should therefore not only be to introduce algorithms for learning control in an industrial setting, but also to increase understanding of these kind of learning algorithms within the industry and academia.

4.3.2.3 Commissioning

Frequency response measurements and time domain analysis used for ‘manual’ commissioning of servo axes is already possible on all motion control platforms used by the pilots. However, real-time analysis of the obtained data is not always possible but regarded as preferable. It is neither in all cases possible to trace signals related to the current loop, which can be very useful for tuning of the current loop or troubleshooting. Pilots indicate that they would therefore like to be able to also trace these signals. Automatic tuning of the control loops is not a common feature at all. Only a few pilots indicate that they can already ‘partially’ tune control loops automatically. Only a few COTS motion control platforms indicate that they have functionality for auto-tuning of control loops. However, this is most likely in many cases intended for tuning of controllers suited for process control instead of motion control. There is a wide interest in automatic tuning functionality for motion control purposes by the I-MECH pilots. Functionality for automatic tuning of control loops for motion control, part of I-MECH building block 6, could therefore be a distinguishing feature of the I-MECH platform.

4.3.2.4 Centralized/distributed control

Most pilots prefer a centralized control approach for the position loops. Two pilots indicate that they currently use a centralized approach for trajectory generation but distributed SISO position loops executed on the DSP of the applied servo amplifiers. One pilot intends to remain using this distributed approach, likely to circumvent the communication via a fieldbus between servo amplifiers and the central control which could be a bottleneck for the achievable update rate of the position loop.

4.3.2.5 Trajectory generation

Basic trajectory generation functionality using 3rd order profile generators, jogging, camming & gearing and trajectory generation using inverse kinematics is basic functionality for all pilots. Quite a few pilots use a platform that supports input shaping using model inversion. On the fly updates of the trajectory is however not very common but desirable, which is a bit peculiar as the functionality does not seem particularly difficult to program.

4.3.3 Layer 3: System Behavior

The focus of I-MECH is more on layer 1 and 2 of a motion control system, as layer 3 is in general very application specific.

4.3.3.1 Industry 4.0 concepts

Pilot owners were asked to state their requirements regarding relatively vague industry 4.0 concepts like "system awareness", "plug-and-produce", "operator risk avoidance" and "responsive manufacturing". Some pilots indicate that they either do not know whether they already implement these concepts or that they do not understand some of the concepts, but that they still would like to implement the concept in the future. This makes the validity of some of the responses slightly questionable.

The general tendency is that pilot owners prefer to have less configuration work when commissioning a new system. Hence, software and hardware should have plug-and-produce/play functionality when possible and it should be possible to automate certain tuning and calibration tasks. The latter should be supported by implementation of I-MECH building block 3 "Self-commissioning velocity and position loops". A scripting interface (e.g. for Python) for the I-MECH platform might also be useful to automate commissioning tasks. Implementation of plug-and-play functionality seems however far more complex. This feature requires auto-discovery, metadata descriptions and self-configuration of hardware and software. The platform is required to be able to support a wide variety of communication protocols for communication with devices in layer 1. Many of these protocols might not be particularly suited for plug-and-play functionality. It might be relatively easy for a motion control platform to detect that a new sensor, for example a camera, or a new actuator was attached to the system. However, understanding what this actuator should do or how the sensor signal should be used requires a completely other level of intelligence. The amount of artificial intelligence required to make such deductions automatically seems currently not available. Hence, the wish to have plug-and-produce functionality should be interpreted as a wish to have building blocks, either hardware or software, requiring minimal configuration and with easy to understand interfaces and clear guides on how to execute the necessary configurations.

"Real-time" condition monitoring, performance assessment, potentially used for predictive maintenance is something that all pilots desire to implement in the future. Only a few pilots already have a some limited functionality regarding these features in place. An important requirement for the I-MECH motion control platform itself concerning these wishes is that the platform should be able to expose (preferably all) internal signals to a condition monitoring function that can monitor performance and predict failures by calculating certain KPIs based on the available signals. The I-MECH project however also intends to develop specific algorithms to calculate KPIs used for advanced condition monitoring of servo axes based on models of drives and measurements with vibration and acoustic sensors. This seems more advanced than pilots request, as current, voltage, I2T, following error and temperature are examples of KPIs requested to be available for condition monitoring by pilots. These more advanced measurements and calculations will however be necessary to fulfill the wish of pilots to be able to perform predictive maintenance and not only monitor the condition of their systems, as these measurements and advanced KPIs provide a far deeper insight into the functioning of the system. The I-MECH platform should furthermore have a good logging functionality for internally used signals, which is explicitly requested by one pilot.

4.3.3.2 Communication

Wishes regarding communication between layer 2 and 3 of the control system vary strongly between the pilots. This could be due to a difference in the definition of the functionality of 'layer 3' used by the pilot owners, such that the assumed demarcation between layer 2 and 3 differs between the pilots, or because some pilots use a centralized control strategy and others a decentralized control strategy. Some pilots indicate that layer 2 and 3 are integrated in one centralized controller and would like to keep this approach in the future. Others state that they would like to connect layer 2 with layer 3 either by means of USB 3, EtherCAT, Profinet, Sercos III, DS402, Ethernet/IP or OPC UA. The I-MECH platform intends to use a multi or many core platform such that the RTOS used for motion control as well as non real time operating systems which could be used for the system behavior layer or the GUI can co-exist on the same hardware platform. A fieldbus between layer 2 and 3 would in such case not be required.

Many pilot owners do not specify particular wishes for protocols/standards used for communication between layer 3 and other machines, ERP, SCADA or MES systems used in a factory. One of the twelve pilot prefers implementation of an industry specific protocol (secs/gem, used in the semicon industry), while three prefer more generic standards: MT-connect, ISA-95 or OPC UA (the information models associated with both MT-connect and ISA-95 can be used in combination with OPC UA). OPC UA is a standard strongly associated with industry 4.0 and also supported by most of the larger COTS motion control platforms. OPC UA itself does however only facilitate transport of information between a server and client, but does not standardize structuring of the information. Information structures can therefore vary between applications. An arbitrary OPC UA server and client can therefore exchange data with each other, but not 'automatically' talk with each other without programming effort. The I-MECH platform should therefore preferably implement functionality which makes structuring of the available information for use with OPC UA relatively simple instead of man-months of manual programming work.

4.4 Relation with ECSEL-JU goals

ECSEL-Joint Undertaking 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 [138]. 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 stated by 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 requirements, up to the wish 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 ECSELs 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" [138].

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 high relevance to the I-MECH platform.

4.5 Relation with I-MECH objectives

The I-MECH final project proposal defines several scientific and technological, system integration, operational and exploitation objectives. Table 4.1 briefly relates these objectives to topics described in this deliverable.

Table 4.1: I-MECH scientific & technology, system integration, operational and exploitation objectives

Objective		**relation to deliverable**
ST1	To develop techniques for employment of advanced model-based methods for the design, real-time control and self-diagnosis of cyber-physical systems.	Several considerations regarding modeling and system identification were discussed in section 3.2.2.
ST2	To develop a smart instrumentation layer gathering visual and/or sensor information from supplementary instrumentation installed on the moving parts of the controlled system to enhance the achievable performance of the system.	Several requirements for building blocks were gathered in the requirements table included in appendix A and state of the art solutions were discussed in chapter 3.
ST3	To develop modular, unified hardware and software motion control building blocks implementing a service-oriented	Several requirements for building blocks were gathered in the requirements table included in appendix A and state of the art

	architecture paradigm, i.e. smart control layer.	solutions were discussed in chapter 3.
ST4	Prepare interfaces to state of the art predictive maintenance platform (system behavior layer - layer 3) and develop specific condition monitoring building block providing relevant data for system behavior layer.	Implementation of OPC UA should result in the possibility to connect state of the art predictive maintenance platforms to the I-MECH platform and I-MECH building blocks. The optimal information model to be used in combination with OPC UA for such applications is however not yet clear.
SI1	To integrate the developed building blocks into a conceptual open platform for intelligent control of industrial mechatronic systems	Not applicable for this deliverable.
SI2	To prove the platform deployability on commercial HW – Use Cases 1.1. 1.2 and 1.3	Requirements were gathered for these use cases and are presented in Appendix A
SI3	To prove the platform deployability onto commercial industrial robots (fixed, modular) - Use Cases 2.1 and 2.2	Requirements were gathered for these use cases and are presented in Appendix A
SO1/ SO6	To demonstrate and validate I-MECH pilots in different mechatronic domains (demonstration at machine level - pilots and shop floor level - demonstrators)	Requirements were gathered for these pilots and demonstrators and are presented in Appendix A
SE1	To establish so called I-MECH Center (led by Sioux CCM) which shall ensure sustainable cooperation between consortium partners after the project termination. It will be open also for new interested parties (SME, LE, RTD, UNI) coming outside the I-MECH consortium. Consequently, it is believed that, through such center, I-MECH will become a European solution desk for advanced motion control in cyber-physical systems (see Task 8.4)	Not applicable, though gathered requirements should ensure that the developed platform will matches wishes from the industry.

5 Conclusion

The inventory of state-of-the-art motion control technology available on the market and used by pilots and the requirements for future motion control technology stated by pilot owners, besides the question what future smart production and/or manufacturing requires from emerging mechatronic technologies, has confirmed the description of the I-MECH final project proposal (FPP).

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

- *A default 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 often a possibility to implement more advanced control schemes, but there often is no library with more advanced control strategies. There is furthermore usually no low-level access to the control logic, which limits the possibilities for smart and very high performance control engineering.*
- *Commercial suppliers of motion control often do not facilitate modeling of detailed plant physics. The available products do in particular 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 (auto-tuning) concepts often still 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, hence load-side 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.*

The I-MECH project intends to address all these issues. When the limitations above are addressed, more innovative ideas can physically push roots into an industrial environment. The following progress beyond the state of the art is expected by means of the implementation of I-MECH building blocks as planned in the I-MECH final project proposal:

- *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 acquired using advanced (wireless) sensors, usable for advanced motion control 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)*

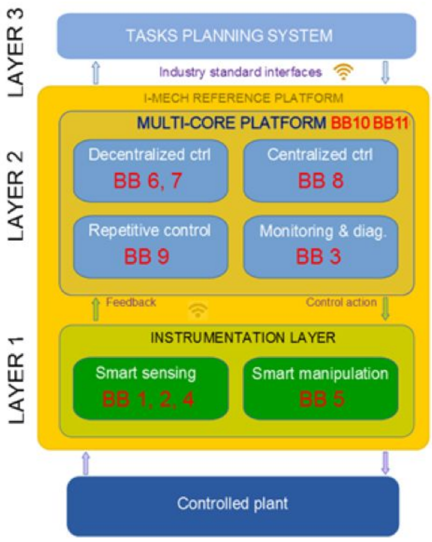


Figure 5.1: Layered I-MECH architecture showing the allocation of I-MECH building blocks

The interfacing between the various BBs, as expected in the FPP, is given in figure 5.1 (a more detailed overview of the expected interfacing is published as part of D2.3). What has been found during the inventory with our I-MECH partners, during the course of work package 2, is that the BBs defined in the FP were just a 'tip of the iceberg'. Other required functions and features are listed in D2.3.

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. 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. 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.

During the creation process of the (final) project proposal, we have introduced 2 deliverables for making an inventory of the 'actual status'. 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'. This document provided a revision of deliverable D2.1 with extra content and more analyses of the gathered content.

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7 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/).

8 Appendix B

EC Project/Initiative	Likely relevant for	Consortium partner(s) involved in project/initiative
IMS2020/Roadmap	General	-
Manufuture/Roadmap	General Smart Manufacturing	-
EFFRA/Roadmap	General Smart Manufacturing	-
PPP Factories of the Future/Roadmap	General Smart Manufacturing	-
PPP SPIRE	General Smart Manufacturing	-
CIDAM: Czech Center of Intelligent Drives and Advanced Machine Control	General motion control	University of West Bohemia, Brno University of Technology
CAK: Czech Center for Applied Cybernetics	General motion control	University of West Bohemia, Brno University of Technology
Projects related to specific smart manufacturing manufacturing process/application		
MEGAROB	Machining of very large workpieces	-
BOREALIS	Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts	TNO
FAB2ASM	Efficient and Precise 3D Integration of Heterogeneous Microsystems from Fabrication to Assembly	-
COMET	Adaptive control of industrial robots for plug and produce components	-
HYPROLINE		TNO, Sioux CCM
EFFIC	Flexible production of solar cells	Sioux CCM
CHAMELEON	Smart devices in machine tools BB6: Self-commissioning BB7: Vibration control	Fagor Aotek, IK4-Tekniker
NEO-GNC	Validation system for space GNC systems BB1: Smart sensors	GMV Aerospace & Defence
SMARTER-SI	Building blocks and concepts for small lot produciton	IKERLAN-IK4, University College Cork
MEMAN	Resource saving in metal industry BB1: Smart sensors BB6: Self-commissioning BB9: Iterative control	IKERLAN-IK4

Projects related to layer 1: Instrumentation		
HARCO	Layer 1: Adaptable smart components	-
3SMVIB	BB2: Wireless sensors	Open Engineering S.A.
ROMISY	BB2: Wireless sensors	Open Engineering S.A.
FP7/Artemis/**DEWI**	Wireless sensor networks 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**	Sensors for enhancing building safety and security BB2: Wireless sensors	University College Cork, Nexperia
ENIAC/**MOTORBRAIN**	Power electronics for drive train for electric vehicles BB3: Preventive diagnostics BB10: Many core platform	Brno University of Technology, Nexperia, TNO
ECSEL/**3CCAR**	Integrated components for control in electrified cars BB3: Preventive diagnostics BB10: Many core platform	Brno University of Technology, Nexperia, Eindhoven University of Technology, Elektronikas un datorzinātņu institūts, TNO
EXPRESS	Smart systems integration	IKERLAN-IK4
Projects related to layer 2: Control		
H2020/ECSEL/**R5COP**	ROS Based Robot Cooperation BB4: High speed vision BB8: Multivariable control	Eindhoven University of Technology, Brno University of Technology
FP7/Artemis/**R3COP**	ROS Based Robot Cooperation BB4: High speed vision BB8: Multivariable control	Eindhoven University of Technology, Brno University of Technology
FP7/**ESTOMAD**	Energy optimal motion control BB3: Predictive diagnostics BB6: Vibration control BB8: Multivariable control	Siemens
APROCS	Layer 2: Automated Linear Parameter-Varying Modeling and Control Synthesis for Nonlinear Complex Systems	TUe
CLOVER	Layer 2: tuning of controllers + robustness	SIEMENS
FP7/Artemis/**POLLUX**	Realtime platform for electric vehicles BB10: Many core platform BB11: Many core RTOS	Brno University of Technology, Nexperia
FP7/Artemis/**EMC^2**	Embedded multicore systems for mixed criticality applications BB10: Many core platform BB11: Many core RTOS	Brno University of Technology, Eindhoven University of Technology, TNO, Nexperia
T-CREST	Multi core architecture for embedded systems	Eindhoven University of Technology, GMV

	BB10: Many core platform BB11: Many core RTOS	
Projects related to layer 3: System behavior, SOA, connection to MES/ERP/SCADA		
EMC2-Factory	Energy efficient production systems BB2: Wireless sensors	Nicolas Correa
FP7/Artemis/**eSONIA**	Service oriented Architecture BB3: Predictive diagnostics BB8: Multivariable control	Brno University of Technology
FP7/Artemis/**HoliDes**	Adaptive human-machine systems BB3: Preventive diagnostics	Brno University of Technology
FP7/Artemis/**eSCOP**	Service Based Architecture BB3: Preventive diagnostics BB6: Self-commissioning BB8: Multivariable control	University of West Bohemia
FP7/**IMC-AESOP**	Layer 3: SOA/CPS	-
FP6/**SOCRADES**	Layer 3: SOA/CPS	-
FP7/**PLANTCockpit**	Layer 3: SOA/CPS	-
ReCaM	Tools for reconfiguring production systems	-
FoFdation	Universal manufacturing information system for smart factory architecture.	-
POPJIM	Self configuring, tuning and optimizing modules + wireless plug and produce	-
sCorPiuS	European Roadmap for Cyber Physical Systems in manufacturing	-
Daedalus	Distributed control and simulAtion platform to support an Ecosystem of DigitAL aUtomation developerS	-
FP7/Artemis/**ASTUTE**	Decision support system for HMIs BB3: Preventive diagnostics	IK4-Tekniker
FP7/Artemis/**D3COS**	Dynamic distribution of tasks based on workload for man-machine systems	-
FP7/Artemis/**CAMMI**	Adaptive cognitive man-machine interfaces	-
CREMA	Cloud based manufacturing BB3: Predictive diagnostics BB6: Vibration control BB8: Multivariable control	IKERLAN-IK4
PROMARE	Pro active maintenance of unique machines BB3: Predictive diagnostics BB6: Vibration control BB8: Multivariable control	Nicolas Correa

FP7/**IMPROVE**	Modeling of production processes (virtual factories) for efficiency optimization BB3: Predictive diagnostics BB8: Multivariable control	Siemens
Projects related to model based engineering		
Enable-S3	Combination of testing of CPS using simulation and real world testing	GMV, Evidence, Philips, TUe, Universtiy of Modena, Reden, TNO

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