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Work Package	Deliverable ID
WP3, Instrumentation Layer Design and Development	**D3.1 - Instrumentation Layer requirements and specification (third iteration)**

Summary

From the Use-cases, Pilots and Demos obtained, global requirements can be derived which will serve as constraints for the development of new hardware and instrumentation Layer 1 and based upon the interaction with the higher layer levels: 2, 3, it also poses requirements in the embedded software stack to enable compatibility and hardware-software co-development.

From the information acquired, it can be noted that the divergence in requirements is large, in particular when centralized controlled motion is compared to smart distributed sensing, smart distributed control and smart distributed actuation. Also the level of interfacing is broad, varying from analogue (0-10 volt, 4-20 mA), to SPI, USB and all kind of other digital interfaces. The main backbone communication is via Ethernet or EtherCAT.

The variety in control speed is large too: Nexperia doing 100 kU/hour down to sway control of a few Hz. The requirement in consumed power are limited by the battery operated sensors systems versus the wired or contactless powered applications.

What is an open issue is the amount of ‘new’ data that is required beyond the functional set-point data exchange. This kind of data will be required for BB-5 to BB-9 and needs to be developed i.e. integrated in new hardware layer designs.

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

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Keywords: open motion control platforms, hardware and instrumentation requirements, building blocks, central versus distributed control, smart sensors, smart drives, wireless communication, hardware, embedded systems,

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Electronic Components and Systems for European Leadership

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(Open) Issues & Actions

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

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Document Revision History

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R02	Draft	05-03-2018	Mart Coenen	Initiate	

Contributors

Revision	Affiliation	Contributor	Description of work
R04	EDI	Kaspars Ozols	Contribution to Section 1, Section 2, Section 3.1., Section 4.2, Section 6. In addition overall deliverable construction and review.
R05	CCM	Arend-Jan Beltman	Request to change the specifications and requirements from too specific into vague enough to be accurate
R06	WP3 & pilot leaders	Various	Comments, specifications and requirements added and processed, figure added in Ch-6
R-08		Various	Use-case 1.3 added + links to

Document control

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Arend-Jan Beltman	Coördinator	X	X	X	X				
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Literature

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Abbreviations & Definitions

Abbreviation	Description
BB	Building Block

Definition	Description

3.1 - Technical requirements at Building Block level

0 - Reader

With the I-Mech consortium, it has been decided that all work-packages incorporate a general overview and architecture task with requirements and specifications. The final prove of the pudding will result from WP-7 where the requirements and specifications for the I-Mech pilots will be implemented. The output of WP-6 will be related to the integration of the I-Mech use-cases and demos. From task 2.1 up to task 6.1, the requirements and specifications are given for their dedicated topics within those work-packages concerned.

The intent is to align within each work-package, in each general overview and architecture task, its requirements and specifications to those of task 7.1 (which is ultimately what shall be delivered as output from the I-Mech project). As task 7.1 will develop/ evolve during the runtime of the project, the achieved and/or reachable requirements and specifications will adapt to the developments of the pilot work in progress.

With the task 2.1 up to task 6.1, the requirements and specifications will be updated after a 6 months period to adapt to the developments of the demo, use-case and pilot work in progress.

This deliverable 3.1 will be a guiding document and is restricted to the requirements and specifications of:

Task 3.2 - Unconventional actuator and sensor principles
Task 3.3 - (BB-1) Platform for Smart Sensors with Advanced Data Processing
Task 3.4 - (BB-2) Real-time wireless sensors providing complementary feedback information
Task 3.5 - (BB-4) High Speed Vision
Task 3.6 - (BB-5) High performance servo amplifier design
Task 3.7 - (BB-10) Development / selection of control specific multi-many core platform

as given in chapter 6 and will be derived from the information provided by the use-cases: chapter 3, pilots: chapter 4 and demos: chapter 5. In chapter 7, the open-items are highlighted which need to land somewhere in the tasks of the I-Mech project, most likely WP-6, which deals with integration.

R1: However, when it comes to the definition of a (generic) building block to be used with the I-Mech motion control platform, the building block will contain both hardware and software to become an exchangeable module at the boundaries of that building block, both in hardware: signals, supply, size, etc. as in software: commands, data exchange, etc.. Standardization of the generic parameters will be a prerequisite to make the I-Mech project a success i.e. a step-up w.r.t. the existing and diverging motion market.

1 - Introduction

This document describes the dedicated high-level (architectural) approach for WP-3: M1.1 deliverable D3.1: Layer 1, Instrumentation Layer Requirements and Specifications. The implementation plan given below is taken over from the main WP-3 structural plan.

From WP-2 (business requirements and the overall reference system architecture), task 2.1, 2.2 and 2.3, the specifications, requirements, preferred architectures and the gaps between academia and industry have become clear. Furthermore, in the combined tasks 2.1, 2.2 and 2.3 a detailed overview i.e. inventory is made by means of a requirements spreadsheet of the state-of-the-art as perceived by industry whereas many academic solutions are off-the-shelf available for industrial implementation.

On the opposite side, the efforts within the I-Mech consortium will (at least) be focused to the 'pilots' chosen in WP7 in conjunction with the efforts of WP-6 (Implementation and integration of I-Mech platform, including 'use cases' and 'demos'), see requirements spreadsheet WP-2 as well as WP-4 to provide the necessary embedded software for the building blocks considered. A global indication is given in deliverable 4.1.

This applies to all 3 levels: **instrumentation** (L1), **control** (L2) and **system's behavior** (L3) where a distinction is made between hardware- and software-oriented activities. The application-specific (UI) software is within the scope of this I-Mech project too, but will be heavily determined by the hardware, hidden by the OS, DLL's and API's to provide a more unified view seen by the upper software layers e.g. ICL, ACSPL+, Logosol, Mint, CPL, TML, TwinCAT NC, MPL, etc. up to the use of drivers which can be linked to: C /C++, Delphi & Visual Basic, Pascal and many other programming languages like Matlab with Simulink or Python.

For the hardware instrumentation layer, development efforts have to be spent w.r.t. further and better standardization i.e. open-systems: WP-3 and WP-4 w.r.t. the PHY-layer, the data exchange protocols and most of all in the use of the hardware interfaces, still varying from sub-Dxy, RJ45, M12, Lemo, Industrial USB, HDMI, DP and many other (non-)industrial and (non-)standardized shielded and unshielded connector types with even worse not-standardized wiring interfaces, shielding measures, etc. The latter also applies for wireless interfaces; Bluetooth, Z-wave, Zigbee, etc. where aside the wireless PHY dedicated software stacks and protocols may be added. These inconsistencies jeopardize open-system integration and, in particular, system reliability as well as the implementation of complex algorithms, fed by and driving the various parts of the motion system.

Suppliers' proprietary interfaces should be avoided (forbidden) in the pilots, use-cases and demos of I-Mech as hardware-wise more flexible, modular and open-system oriented architectures are targeted (even if these were optimized with motion system reliability in mind). Various different interface requirements may exist due to power, operational voltages as well as volume restriction or e.g. vacuum use, serviceability, etc. in the various systems defined in the use cases, pilots and demos.

The approaches have in common that the many different sensors, encoders and/or vision systems are used to determine by what needs to be done (from 'ist' to 'soll'), versus the reaction of the motion system that needs to be given to the process by the various actuators driven. Data latency, processing speed and closed loop bandwidths and the required resolution determine the overall process control loop speed (and its consumed power), also taking into account the responsiveness i.e. latency of the processes itself needs to be controlled.

The instrumentation interfacing at the *block level* has to be open-system compliant in many ways as specified in the requirements following in chapter 6. International standardization needs to be and will be done in collaboration with I-Mech WP-8.

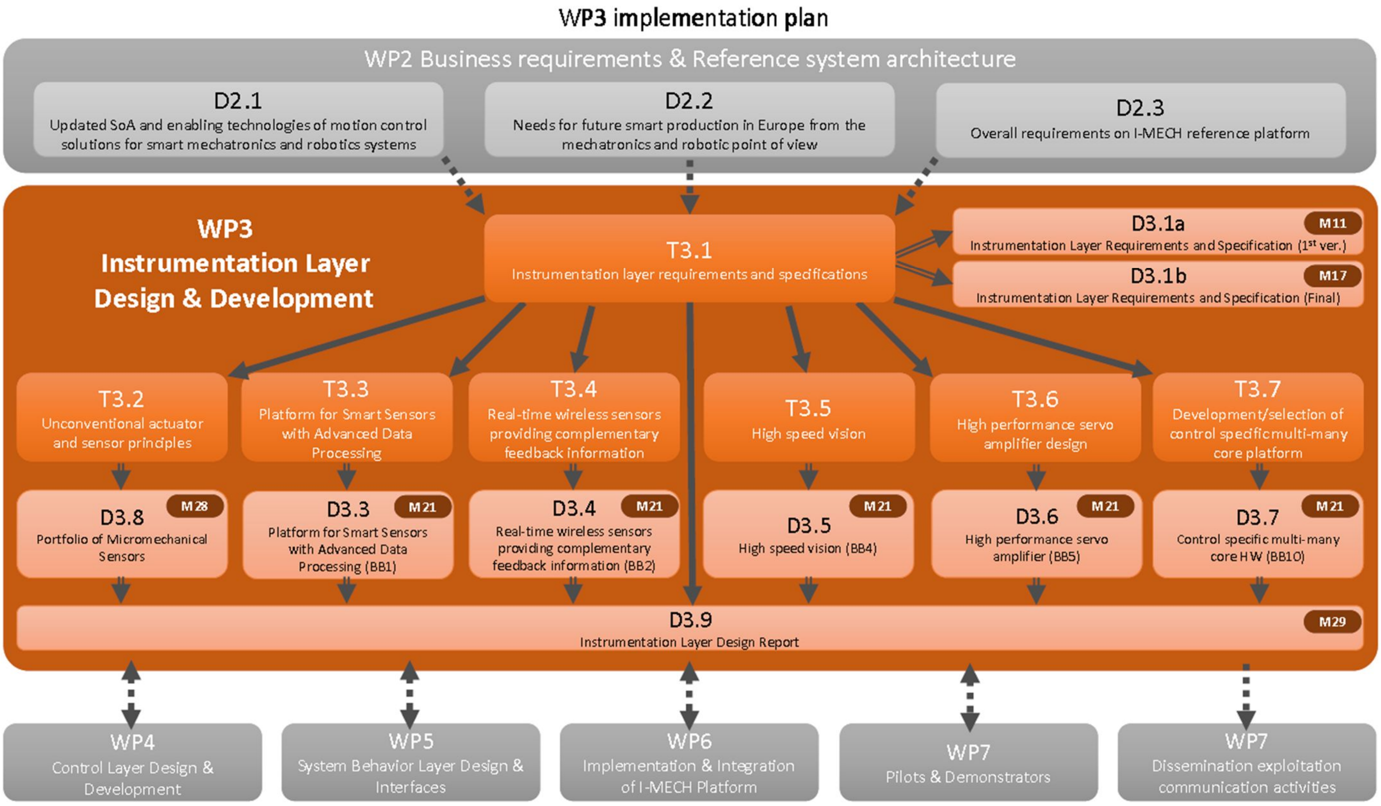


Figure 1.1 - WP3 Implementation plan

The lower-level hardware Instrumentation Layer Requirements and Specifications for the I-Mech Use-Cases, Pilots and Demo's were collected in WP-2 task 2.2, 2.3 and 2.4 and submitted as deliverable 2.3. At a high-level i.e. architectural level (also T2.4), choices have to be made w.r.t. the implementation approach for motion control systems at the modelling, design and realization phases. These functional, operational and design requirements determine the choices: which motion(s) one wants to control: how many axes, how fast, how accurate, settling time, ranges and other boundary conditions and will result in a selection of sensors, actuators and control system options to select from. W.r.t. the hardware layer, also the interfacing: analog, digital, wireless needs to be defined while taking into account the signal reliability and the latencies involved.

With today's complex motion control systems, the expected motion behavior: feedback (PID) or feed-forward or a combination thereof, see deliverable 4.1, needs to be simulated and modelled on forehand. For this, the adequate behavioral models of all motion control parts need to be developed and unified for the simulation environment in which they will be used e.g. MathWorks Simulink. To ensure suitable behavioral models, the necessary setting and response parameter formats need to be standardized (i.e unified) between the providers of the model parts. This modelling work isn't the responsibility of WP-3 and shall be dealt with in the appropriate work package 4, task: 4.2 and 4.3. With further simulation developments, hardware-software co-simulations: hardware-in-the-loop (HiL) must enable verification of developments and realizations step-by-step. As such, the used simulation model has to be inter-replaceable by the hardware used and as such the parameters used with both the hardware, including its API or dll (being part of Layer 2), have to be fully aligned with the simulation model of the intended hardware to be used. With simulation models, the parameters selected at the API or dll interface are close to infinite to be defined as all internal parameters are mathematically known with the simulation model. With the hardware, less parameters will be accessible for the higher layers in the system, unless initially defined during development. For this access, to predefined data registers for which the properly defined parameters are allocated, is a must. This makes it a requirement for Layer 1, to enable communication with Layer 2 upwards.

R2: The 'above' functional data exchange of the motion control e.g. HW/SW co-simulation, diagnostics, etc. determine the hardware and software interface requirements for each hardware module i.e. layer 1 building block.

With the simulation of motion, the (reference) coordinates, the velocity, acceleration and jerk are all identifiable with the model, where at the hardware interface, these parameters are only accessible from the electrical parameters like voltages and current as a function of time. Considering hardware-in-the-loop (HiL), the simulation models used shall be one-on-one interchangeable with the hardware considered. Gathering the mechanical responses as a function of time will result in large amounts of (big) data, but also measuring the actuator voltages and currents as a function of time results in huge amounts of data whereas measuring the position track of the motion might ultimately be sufficient for the motion to be controlled. Voltages and currents are already being sensed in the motor drive to monitor motion as overvoltages or overcurrents to protect the drive and/or actuator used from machine damage. Threshold detection will then be sufficient rather than full voltage and current waveshape capturing. For other means of control i.e. diagnostic or vibration, dedicated data access might be necessary to satisfy latency requirements, or the device has to be made smart with a local algorithm which compresses the dedicated data to limited data strings, representing the essentials of the data to be used in time (!) as latency counts.

To control the functional as well as the additional flow of data parameters in a motion control system, decisions have to be taken w.r.t. the data interface complexity at Layer 1 to become available to above Layers

2 and 3, for processing and control. These data interface decisions: hardware, format, coding immediately affect the ability to develop generic building blocks which can be used with the motion control system.

R3: The architecture and building blocks as developed by the I-Mech consortium shall distinguish themselves from the 'commercial-off-the-shelf (COTS)' (building blocks) designs and (architectural) approaches. The main distinction will be in the area of: modularity and interchangeability, data interface layer openness, confined (as BBs comprise hardware and software as well as the interface), while being motion system simulatible on forehand with predictable behavior while including other (environmental) parameters.

Motion control system architectures can be divided into 3 groups:

- **Locally smart** (chapter 2.1 and WP-3.3) i.e. all signal conditioning will be done locally within the smart sensors, smart encoders, smart actuators and for the algorithms by the smart control systems while minimizing the load on the signal interfaces. Smart sensors provide only the necessary data to the control system and the smart actuator is provided minimum data to make to required movements happen (and may have its own internal or local feedback loop).
- **Centrally controlled** (chapter 2.2). Raw sensor data is preferably collected by the central controller and preconditioning for the drive actuation (with corrections) is preferably done centrally, requiring high-speed data transfer and powerful processing capabilities at the central controller (e.g. Pilot 1 approach)
- **Hybrid** (chapter 2.3). What can be locally done effectively (smart) shall be done locally and what needs to be done centrally shall be done centrally. This latter approach is most commonly used as expressed during the Pilots 2 and 5 meetings in The Netherlands d.d. 20-21/02/2018.

R4: Motion control diversity determines the various building block implementations and sets requirements on the smartness of the various motion system parts: sensors, encoders, motion control, drives, and actuators to enable implementation of these 'above' functional requirements by accessibility of data.

1.1 - The link to the overall I-MECH objectives

1.1.1 -General Objectives / Broad Challenge

The broad I-MECH challenge is to bridge the gap between the latest research results and best industrial practice in advanced mechatronic motion control systems. Software and Hardware building blocks, featuring standardized interfaces, will be developed to deliver a complete I-MECH reference platform. The building blocks will embed the latest thinking from the academic community and, moreover, can be enhanced in future with new research results. The project will deliver a flexible, scalable, future-proofed and fully functional product architecture to be exploited in industry in high-performance motion control applications. These project goals are enabled through a specific set of four Scientific and Technological objectives (ST), three System Integration objective (SI), six System Operational objectives (SO), and one System Exploitation (SE) objectives which are summarized in the FP. The general description, the inter-relation to other building blocks and functional requirements w.r.t. the developments in WP-3 are given.

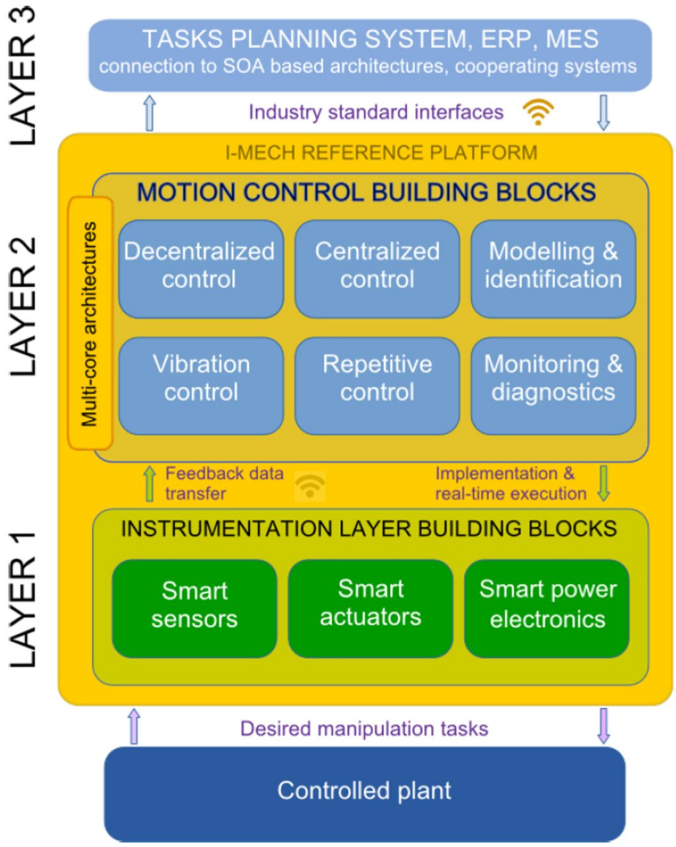


Figure 1.1 - Zoomed view on the I-MECH reference platform with key RTD modules – future Building blocks

1.2 - The link to the overall ECSEL-JU goals

The ECSEL call stated that Smart Systems Integration (SSI) shall address the system itself, enabled by heterogeneous (3D) integration of new building blocks for sensing, data processing, actuating, networking, and smart powering from battery or external supply or energy scavenging and managing. SSI also addresses the integration of the systems into their target environment. To this end, I-MECH work packages are considered to be absolutely aligned with the ECSEL calls' objectives. Focusing on the field of motion control, I-MECH aims to design and implement Smart Systems to bridge the gap between latest research results and industrial practice. The new building blocks as stated in the ECSEL call will comprise of lower layer blocks of robotic control systems in I-MECH made smart(er) by dedicated software. The functionalities in order to maintain and to improve competitiveness will be provided through a cutting edge platform for applications where the dynamics and precision of the controlled motion and easy reconfigurability are both crucial. The extension of the world leadership of European Smart Systems companies will be verified through particular demonstrators that will show the application of developed technology to the actual practice of industrial partners involved.

2 - Motion control diversity

The 3 types of diverted motion control systems: local, central and hybrid, shall be used to align the developments for the generic Building Blocks defined in the FP as well as the Use-Cases, Pilots and Demo's defined in this I-Mech project. The related Building Blocks (BB) are:

- BB-1: Advanced sensor signal processing module (= hardware, L1). Multiple signals (e.g. generated by optical encoders) need a processing speed of more than 100 MHz. This building block can be connected to an industrial communication bus. The data sample rate communicated will be ≥ 10 kHz.

- BB-2: Real-time Wireless Sensors (= hardware, L1). Sensors are needed to measure system information that are used for optimizing the control. Sensor readings occur on rotating and/or moving parts that prohibit wiring.

- BB-3: Robust condition monitoring & predictive diagnostics (= hardware, L1 and all other levels). The system holds numerous signals (e.g. position error, current error, current values) that can reveal the actual condition. Which type of readings are valuable? How can they be collected? Which algorithm(s) do I need to identify which [near future] failure mode?

- BB-4: High speed vision (= hardware, L1). Vision technology is becoming an enabler, due to the rapid improvements of camera features. In (high speed) motion applications, vision can be applied for 'in flight' geometric feature recognition. This can be used as input for motion control and/or positioning improvement. Smart high speed vision only transfers the relevant detail data. Raw high speed data can be several Gb/s.

- BB-5: High performance current amplifiers (= hardware: L1). The responsiveness (between actual and requested current value) of amplifier is of much importance for the loop gain of the motion controller. High dynamical (e.g. loop gain of 400Hz) require these amplifiers.

- BB-6: Auto-tuning & Self commissioning (= hardware, L1 and all other levels). Manual tuning and commissioning is time consuming activity and will not always result in the most optimal setting. Existing (COTS) auto-tuning algorithms can NOT meet the requirements, due to limited use of higher-order plant dynamics.

- BB-7: Unified solution for vibration control (= hardware, L1 and all other levels). This building block provides suppression of unwanted motion induced oscillations in a mechanically compliant driven load. Experimental identification of the controlled system can be followed by an automatic tuning of velocity or position control loop specifically tailored for oscillatory systems (i.e. smart service).

- BB-8: Robust model-based multivariable control (= hardware, L1 and all other levels). It is believed that model based control will enable more robust multivariable control approach. High-fidelity mathematical models, describing the dynamics of the plant, shall be derived and verified experimentally.

- BB-9: Iterative and repetitive control (= hardware, L1 and all other levels). It provides a set of algorithms implementing advanced repetitive control schemes with a self-commissioning feature which can be used for various motion control tasks that have a periodic nature.

- BB-10: Multi-many core for control (= hardware, L1). This building block COULD provide as a universal HW platform suitable for the implementation of the SW algorithms developed in terms of the I-MECH project. It will be capable of hosting multiple building blocks by delivering an open, customizable, multi-many core platform on an FPGA substrate for control systems tasks.

- BB-11: RTOS for Multi-many core control (= hardware, L1 and all other levels). It COULD provide a real-time solution for mixing applications on the same multi-many core platform, without under-utilizing the computer platform.

The above red marked Building Blocks are the ones which belong to the main responsibility of work-package 3. Nevertheless, the interdependence between the other work-packages, building blocks and/or tasks in other work-packages are highlighted in this document too.

R5: Unfortunately, hardware cannot run without the (embedded) software (and the applications above) but software, without the underlying 'open' hardware providing the essential data and being responsive to the instructions given, doesn't make sense either.

Considering the 3 types of motion control systems: local, central and hybrid, the implementation and realization of the building blocks will (most likely) not be identical i.e. interchangeable considering the availability of the required signals at each interface level for the data at their boundaries.

As examples, BB-3, 6, 7, 9 and 11 (all outside the scope of work-package 3) may become a local interaction between the drive and the actuator without the intervention of the overall control system, but (most likely) with the need of additional sensing of the voltage and current data from the drive (D3.6) or from data obtained from additional local sensors. Local confined algorithms need to be developed which can additionally run distributed on the smart drive without the loss of functional performance. Also BB-6, the self-commissioning, can be done through the smart sensors and smart drives if similar techniques as DHCP (Ethernet) are used by the local motion controller and all motions parts connected support this kind of open exchange for recognition. Nevertheless, this recognition option demands from the hardware to be able to provide the info required to the (software) request posed.

BB-10 and 11 will not be an issue if all fast data acquisition and processing is done locally in the smart sensors and smart drives: T3.3 and only set-point calculations will be required for the motion sequences by the motion controller, PC or PLC. Additional signal transfer bandwidth in the interface channel can then be used for additional parameter data upload and downloading, dependent on the features required e.g. BB-3: predictive diagnosis.

The same holds for BB-4 (T3.5), high speed vision, as where raw HD vision data can be transferred at Gb/s capturing frames at rates > 10 k/s, to the processing and controlling motion host through DMA or the raw data is analyzed with the smart vision sensor and based on the algorithms initially send to the smart vision sensor decimated to kB/s of data (T3.3, T3.4). The latter is at the cost of a FPGA/ processor with each vision system at the advantage of easier interfacing to the motion control host. True, the power consumption with each smart high-speed vision will increase due to the local data acquisition required at the advantage of interfacing and high-speed DMA capabilities at the controlling motion host. When the high-speed vision sensor system becomes smart, it can be treated like most of the other sensors of the motion control platforms without the need for DMA.

R6: Determined by the local smartness of the hardware (= distributed motion system architecture) used, the ‘above’ laying functional software needs to be divided into subsets at the various smart parts to enable an ‘above’ overall functionality: WP-4 and -5. If all motion control is done centrally, with upfront knowledge of the transfer functions of the sensors/ encoders and drive to actuators AND the necessary data as required is available, this can be done centrally (if the interfaces used allow this).

3 - Use-cases

3.1 - Use-case 1.1: Power electronics for hoist and crane sector

3.1.1 - General description

To enable an active anti-sway feature in the Gefran Hoist and Crane scenario, a real-time wireless sensor system will be developed. The proposed system will be able to recognize acceleration and angle position of the load, thus will allow to improve displacement time; provide ability for non-skilled operator to use the machine safely and with higher performance; and eliminate load oscillations. Block diagram of the proposed system is shown in Figure 3.1.1.

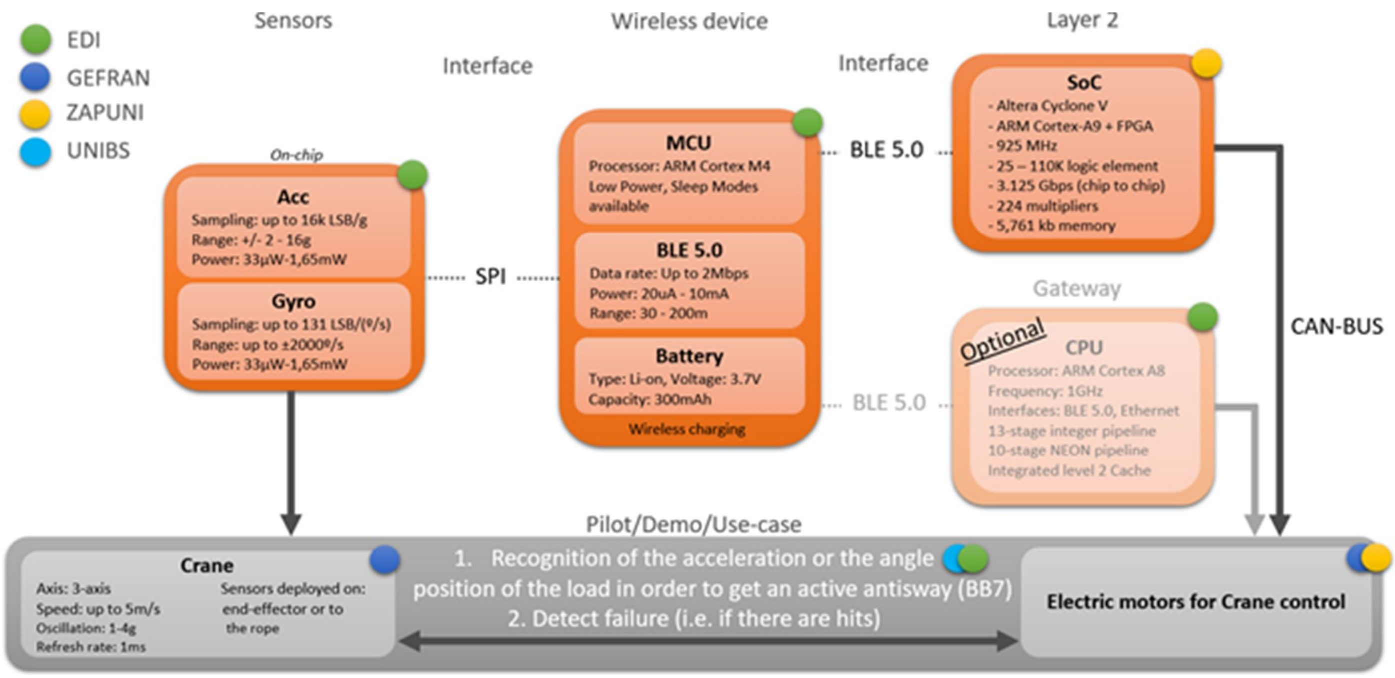


Figure 3.1.1 - Real-time wireless active anti-sway system

The overall system will consist of four main components –

1. Wireless Device with sensors (developed by EDI), (BB2)
2. Layer 2 processing unit, which is based on SoC (ZAPUNI) (BB1), or optionally Gateway (EDI), for simpler applications,
3. Crane + corresponding systems (Gefran) (drives and mechanical parts),
4. Algorithms (control the residual oscillation of an overhead crane) (UNIBS) (BB7).

The Gefran inverters can manage electric motors with or without speed sensor (encoder) and can control all the system movements, both hoisting and travelers (hoist, gantry, trolley). The crane test setup uses 2 axes:

- Hoist: Inverter ADV200-2075 with brake resistor, asynchronous motor 1,1kW, with mechanical brake controlled from inverter, sinusoidal encoder, limit switches.
- Trolley: inverter ADV200-1015, asynchronous motor 0,7kW, limit switches.

Pendant command control is connected to the drive. For the hoisting test a 900 kg load will be used (the load capacity of the crane system is 1600 kg). Beside the physical test-bench some checks and validations will be conducted on a virtual simulator.

The concept will be evaluated through simulation based on Matlab/Simulink and/or Amesim (for plant simulation) in order to analyze the behavior of the algorithm for anti-sway. The activity will be done in the Task 4.4 (vibration control module).

3.1.2 - Relation to Building Blocks

BB-1 - in order to receive and process BB2 data from the crane and provide computational power for BB7, BB1 (Platform for Smart Sensors with Advanced Data Processing) will be used. BB-1 will be FPGA based SoC, thus ensuring high performance and energy efficiency. BB1 will provide modular hardware, including wireless link transceiver module to interface with BB-2 and CAN bus interface to Inverter. Optionally, EtherCAT Slave or Master will be implemented on BB-1 for communication with Inverters in extended setups. Thanks to ARM CPU cores (part of SoC) and large RAM (1 GB) available in BB-1, advanced algorithms for anti-sway control can be implemented with computation time suitable low for real-time feedback control, as the Inverter embedded controller could have lack of resources for such task.

BB-2 - in order to be able to measure and process the data from the crane in real time, BB2 (Real-time wireless sensors) will be used (custom HW&SW). In this case, inertial sensors will be used to recognize acceleration and angle position of the load and wireless communication link (between BB2 and BB1) to provide the data for real time processing in BB7. Specific attention will be paid to ensure high precision, robustness, low-latency, etc. For this purpose, BB2 Simulink model will be developed and MiL setup will be tested. After MiL testing, HiL and Crane In The Loop (CiL) setups will be developed, tested and validated.

BB-7 - in order to control the residual oscillation of an overhead crane, BB7 (Vibration control module) will be used. In particular, a model predictive control (MPC) approach which exploits the feedback of the angle of the rope of the overhead crane will be developed in order to track the operator velocity command with no residual oscillations of the payload by taking into account constraints on the maximum velocity and torque of the motor. The method will be tested first in simulation with Simulink (Simscape Multibody). Then, an available Hardware-In-the-Loop (HIL) setup (made by Gefran) will be used to evaluate the (feedback) control law. Finally, the real crane system will be employed to demonstrate the effectiveness of the methodology. To achieve this, BB2 sensor data via BB1 will be used. A comparison with open-loop techniques (input shaping, input-output inversion) will be also performed.

3.1.3 - Functional requirements

Functional Requirements			
Req. ID.	**Req. title**	**Value**	**Rationale**
UC1.1.F1	Operation environment	Industrial environment	The device must be able to operate in typical industrial environment conditions - temperature ranges, humidity levels and interference levels.
UC1.1.F2	Physical parameter measurement	Acceleration and angle position	The expected acceleration of the system for anti-sway control is linked to the position of the load (length of the rope). The results will be evaluated on Task 4.4. In order to get an initial hypothesis for sizing the accelerometer and gyroscope, it is supposed to have a typical acceleration of 2g and the load position can have a typical angle deviation of +/- 10°. There is a possibility for a collision of the load (material can touch a wall) so the sensors should be able to resist in that condition. Anyway, it is not expected a direct collision with the sensor (there should be designed some protection part).
UC1.1.F3	System's operation time without battery change	5 years	5 years of system's operation time without battery change is reasonable period for easy maintenance.
UC1.1.F4	System's operation time without wireless charging	1 day	Battery recharging should be accomplished in automatic way. No operation should be required by operator.
UC1.1.F5	Wireless charging	Yes	The Wireless Device must support Wireless charging, to be in line with the physical dimension restrictions (use of small battery).
UC1.1.F6	Data encryption	No	There is no particular need to create data encryption, but the protocol must be robust to avoid conflict with other wireless devices.
UC1.1.F7	Visual indicators	Yes	Provides visual information about the state of the system for the user.
UC1.1.F8	Physical buttons for device control	Yes	Buttons that allow turning on/off, restarting and reconfiguration of the device.

UC1.1.F8	Data logging locally	Yes	The system should be able to store data locally. The data must be transmitted to the inverter at a rate of 1kHz to be used for real-time control purpose. In order to achieve the possibility to use the sensor for condition-monitoring purpose it could be needed that the data is "preprocessed" in the device and can be requested asynchronously by the inverter.
UC1.1.F9	Data logging remotely	Yes	The system should ensure data storage on the Gateway/SoC.
UC1.1.F10	Fast start-up	Yes	System has to turn on and be able to start working in less than minute.
UC1.1.F11	Auto calibration	Yes	System has to maintain precision parameters by itself.
UC1.1.F12	Wired firmware upgrades	Yes	User must be able to download latest firmware and upgrade the system.
UC1.1.F13	OTA firmware upgrades	Yes	User must be able to download latest firmware and upgrade system through wireless connection (Over the Air). Including Wireless debug connectivity.
UC1.1.F14	Communication interface between the wireless device and SoC or GW	BLE 5.0	To ensure minimum power consumption for the wireless devices, the least power consuming wireless solution should be selected. As state-of-the-art and market analysis in D2.1/D2.2 shows, BLE 5.0 is the best trade-off for this specific application.
UC1.1.F15	Communication interface between SoC/GW and electric motors for crane control (Drive)	CAN-BUS	The selection of CAN-BUS interface is based on D2.1/D2.2/D2.3. It is also available on the Gefran Drive.
UC1.1.F16	Communication latency between the wireless sensors and motor control platform	< 500us	The latency should be at least less than half of the sampling rate period. To ensure stability in the system, actual value could be <200us.
UC1.1.F17	Transmit power	<20 dBm	According to ETSI EN 300 328 standard, the transmission power should not be higher than 100mW.
UC1.1.F18	Operating system	RTOS	The system should support RTOS to ensure real-time data acquisition and processing without additional delay.
UC1.1.F19	Authentication	Yes	Necessary for device coupling and targeted data exchange.

UC1.1.F20	Win/Mac/Linux compatible	Yes	System should be able to operate with most popular operating systems for data transferring and reconfiguration
UC1.1.F21	User Friendly web interface	Yes	System has to be easily configurable.
UC1.1.F22	Algorithms	Anti-sway, Condition monitoring	The Anti-sway algorithm will be developed in Task 4.4: The purpose of this algorithm is to create a control-loop from information gathered from the inverter, motor and wireless sensor in order to reduce the oscillation generated by the load movement. Algorithm for the condition monitoring will be developed in task 5.3. The strategy is to collect a cluster of information from the motor, inverter and sensors that can be used to evaluate the status of the system and to prevent damaging of the system.

3.2 - Use-case 1.2: Compact control + HMI unit for CNC machines

3.2.1 - General description

Use Case 1.2 will consist of a complete mechanical + hardware + software platform according to I-Mech requirements. The complete system will include:

- Scara robot arm (4 degrees of freedom) with suitable motors and encoders.
- Motor drives with Ethercat interface and at least 8 kHz sampling rate (16 kHz desired) and commanded in current/ torque. (Developed and built by Ingenia, T3.6)
- Fagor CNC based on a COTS x86 module with up to 4 cores and virtualization hardware.
- Accelerometers put near the effector end and connected to the CNC through 4-20 mA interface.

This platform and hardware is chosen because it fulfills many of the problems experienced in mechatronic systems as variable inertia seen from the first axis depending on the position of the second axis, elasticity due to harmonic drive reductions kinematics transform between command (cartesian) and actuator (joint).

3.1.2 - Relation to Building Blocks

As fixed in the requirements table (in D 2.1) Fagor CNC already has some I-Mech BBs implemented in proprietary means (mainly C with intrinsic functions for x86). The CNC can control at the same time up to four interpolation paths (channels). Independent axis can be at the same time commanded by the integrated PLC. The mechatronic problems described in the I-Mech project are all applicable to machine tools. Some of the more common problems deal with BB-7 and BB-8, due to big steel masses moved at high accelerations that have usually low frequency structural vibration modes, with very low damping (steel), and varying frequency depending on axis positions.

The Fagor CNC is based on an x86 CPU architecture and this will be a requirement. Improvements of the actual hardware and software platforms as described in BB-10 and BB-1 are a result of the I-Mech project. But, as a real machine tool is usually not available for demonstration, some of the partners of the Spanish consortium will build a prototype where the important concepts of the BBs will be demonstrated under the specific requirements of this document. For this, Use-Case 1.2 will consist of a complete mechanical + hardware + software platform according to I-Mech requirements. The complete system will be integrated by Rovimatica and consist at least of:

- Scara robot arm (4 degrees of freedom) with suitable motors and encoders.
- Motor drives developed and built by Ingenia as described in **BB-5** (D 2.3.5) with ethercat interface and at least 8 kHz sampling rate (16 kHz desired) and commanded in current/ torque, providing the feedback data as needed by the algorithms for anti-sway and collision/ obstruction detect.
- Fagor CNC based on a COTS x86 module with up to 4 cores and virtualization hardware according to **BB-10**. (D 2.3.11).
- Accelerometers put near the effector end and connected to the CNC (desirable through Ethercat bus at the same rate)

3.2.2.1 - BB-5: High-performance servo amplifier:
- Current loop bandwidth > 2 kHz (the above application)
- Current loop sample rate : >= 16 kHz.
- Commutation method: FOC with encoder, motor position sent to CNC in ethercat,
- Full synchronization of drive and CNC loops through Ethercat
- Provide the feedback data as needed by the algorithms for anti-sway and collision/ obstruction detect

3.2.2.2 - BB-10: Control specific multi/many core platform:
- 2 cores minimum, 4 cores highly desirable
- Sample rate: 8 kHz (16 kHz desirable) in at least one core
- Sample rate: 1 kHz (4 kHz desirable) in another core
- x86 platform with hypervisor support

3.2.4 - Functional requirements

Requirements referred to implementation depend heavily on the control approach taken and the hardware platform decided.

- The system will be highly centralized. All the loops will run in the x86 platform (except torque/current and below).
- The connection to the drives will be ethercat.
- System fully synchronized, all the loops and also between drive loops (pwm, current…) and speed, position and other loops.
- The BBs will be implemented as C routines for x86 (use of specific functions available, for instance SIMD instructions) in the execution platform.
- There will be a twin for every algorithm of the BBs in Simulink (desirable with the exact behaviour relating format, etc…)
- Frequency and execution order must be explicit for loops and blocks.

- This applies also to reading inputs, output application and updating of integrators. All these parts of control loops should be callable independently.

3.3 - Use-case 1.3: PAC based modular HW for machinery – TECO PACs

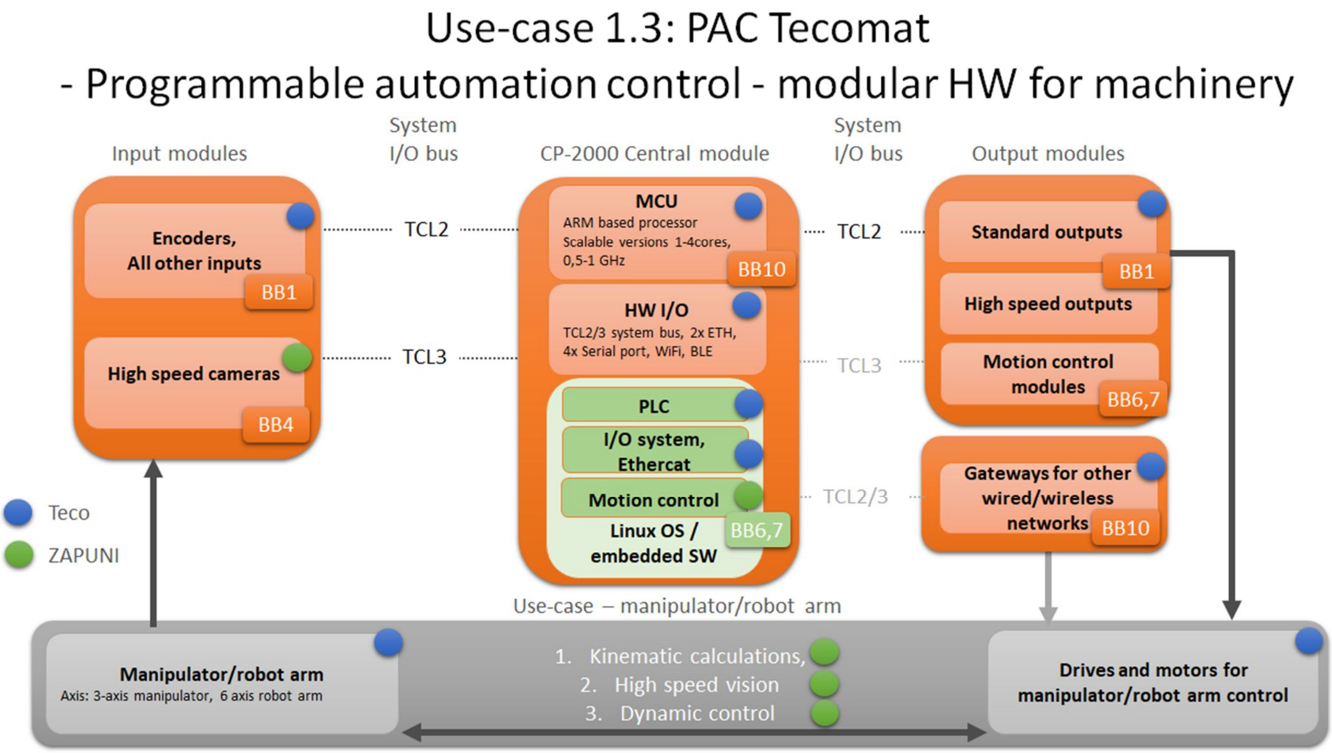


Figure 3.3.1 - Functional diagram PAC base hardware

3.3.1 - Functional description

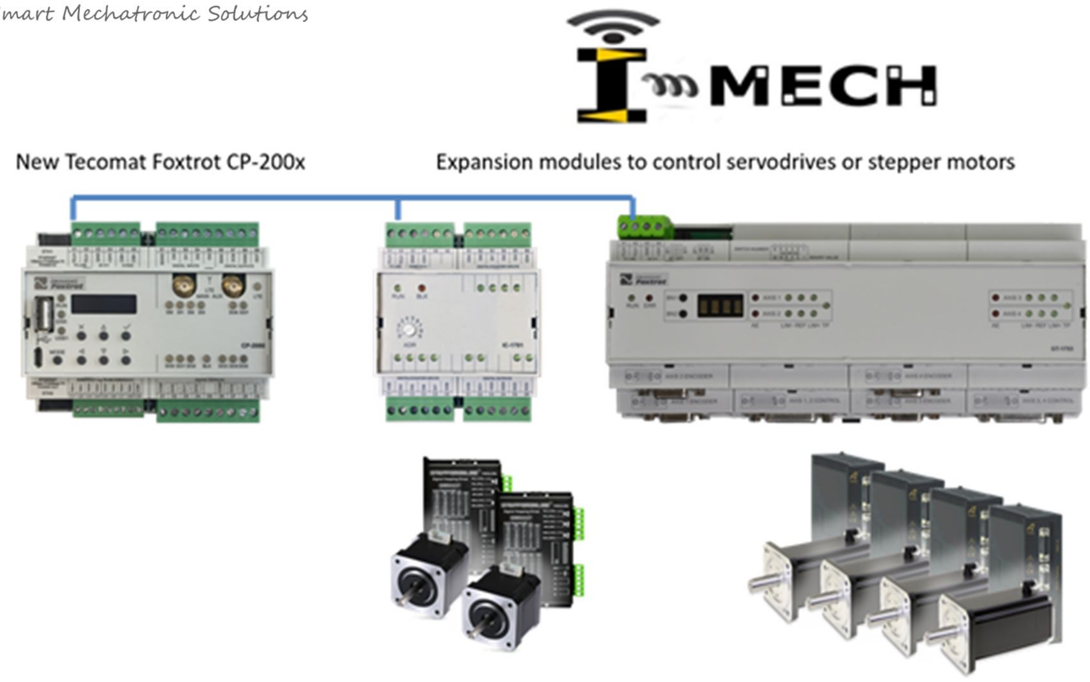


Figure 3.3.1 - Modular Tecomat system

Use case 1.3 will consist of new generation of Tecomat controller i.e. HW and SW platform of the modular system which has to be fully SW compatible with the previous models and IEC 61131-3 programming standard. At the same time it has improve the computing capacity of CPU which will be based on ARM processor. The scalability from the low end 1 core to 4-cores is on the roadmap, going towards I-MECH ambition in **BB-10**.

Tecomat Foxtrot is “small” modular system by Teco currently developed, soon should come “big” modular system working name: Tecomat TC800 with different form factor enabling higher density of I/O per module but the HW concept will be the same as the Foxtrot.

The motion control task developed for Tecomat will be proven on models of 3 axis manipulator. The more axis model like robotic arm would be an option. The right servo-drives or stepper motor drives will be determined. Special Motion control modules for 1, 2, 3 or more axes will be developed if necessary for control optimization, model based chain proposed in WP4 will be applied.

3.3.2 - Relation to Building Blocks

The base unit consist also variety of serial interfaces: 2 x Ethernet, 4 x serial/CAN ports, 1 x High speed system expansion bus, 1 x 2-wire low speed expansion bus, 2 USB ports. High speed expansion bus is dedicated to add either parallel Analog/Digital I/O modules (smart one, each with its own 32 bit computing capability to filter the signals, to make linearization and other high speed tasks like reading encoders or control PWM, stepper motors, This modules corresponds with the **BB-1**. On this bus also, communication modules as masters of different communication networks wired/wireless. This concept makes PAC Tecomat open for practical any current as well as new standards/protocols.

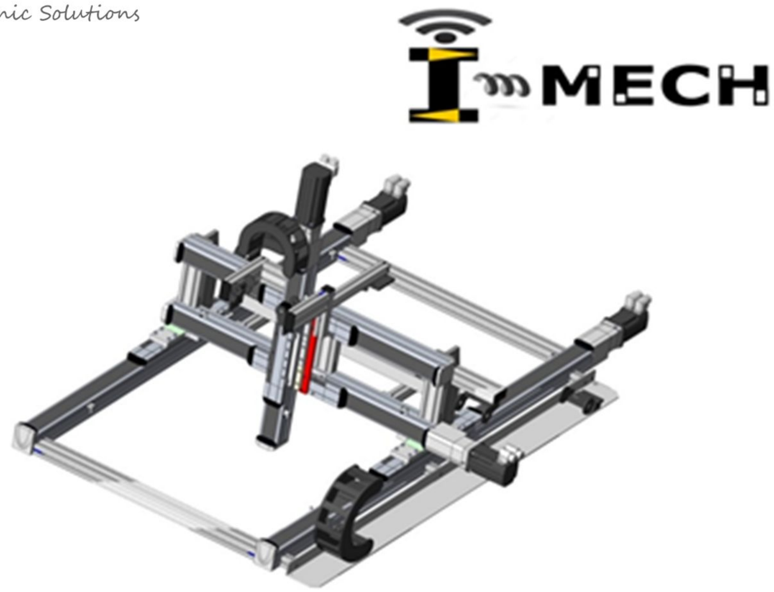


Figure 3.3.2 - Robotic manipulator to test PAC Tecomat Foxtrot

As the current basic modules Tecomat can be networked together in the LAN to create more distributed configuration and/or multiply computing capacity also new generation will enable the same at least. This is the way how processing images from cameras **(BB-4)** can be included in the system if the higher performance of main basic module will be required. The same processor will be fully dedicated for image processing.

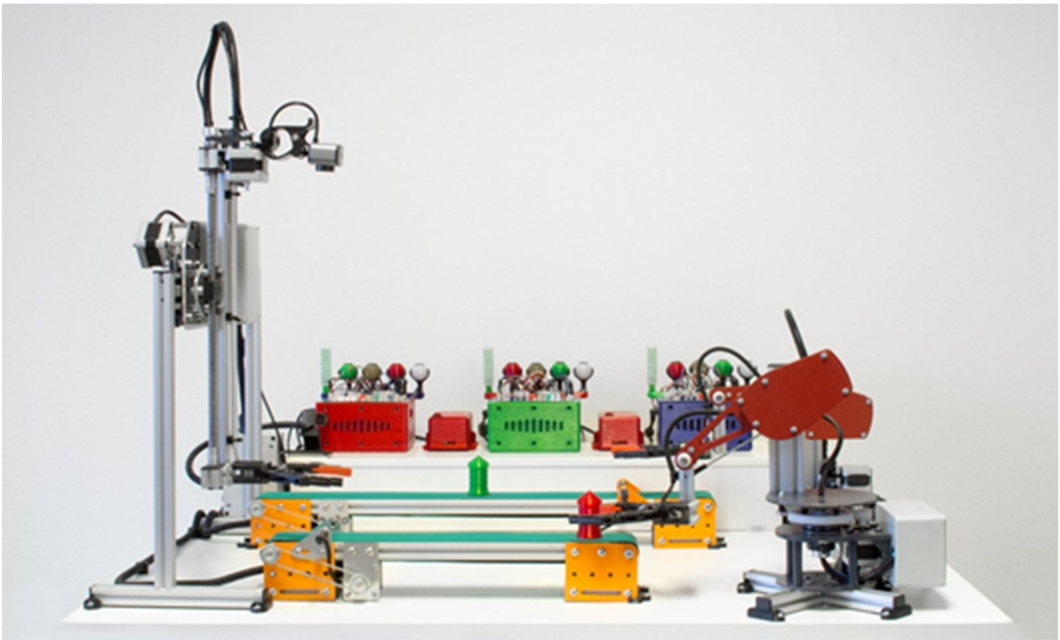


Figure 3.3.3 - Set of robotic manipulators to test cooperation of more PAC together

SW platform of PAC Tecomat is based on Linux enabling handle with more cores (aligned with **BB-10**) as well as with more tasks. On Teco side will be the PLC task and I/O system task – configuring the "**BB-1**" modules/ sensors/ drives layer. It enables to run other tasks developed within I-MECH standard platform. Especially Motion control tasks solved by ZAPUNI. Interface among PLC and Motion control tasks will be

issue as well to expand PLC capability with the state of art encapsulated function blocks form ZAPUNI or other partners, developed within WP4 (**BB-6**, **BB-7**). Also Ethercat master implementation is expected on Ethernet port to enable full compatibility with this standard.
The inherent part of PLC tasks are also http, Mqtt, 104, NTP, SNMP, SMTP and other protocols already, since the compatibility with previous versions of Tecomat. Via those connection capabilities, connection to WP5 is expected.

3.3.3 - Functional requirements

The condensed requirements i.e capabilities of the PAC Tecomat are: 2 x Ethernet, 4 x serial/CAN ports, 1 x High speed system expansion bus, 1 x 2-wire low speed expansion bus, 2 USB ports. High speed expansion bus is dedicated to add either parallel Analog/Digital I/O modules (smart one, each with its own 32 bit computing capability to filter the signals, to make linearization and other high speed tasks like reading encoders or control PWM, stepper motors. Interfaces to different communication networks wired/wireless are available too. This concept makes PAC Tecomat open for practical any current as well as new standards/protocols.

3.4 - Use Case 2.1: On-ground validation of space GNC systems through the use of robotic devices (GMV)

3.4.1 - General description

The most general use of platform-art © (defined as I-MECH Use Case 2.1) is the simulation of activities that include the precise approximation and contact between space vehicles in tasks like rendez-vous, space debris removal, automatic assembly of large structures, etc. Current platform-art © setup has two main lacks:

- Delays in the control of manipulators (due to industrial manipulator controller) prevent accurate force control during contact operations.
- Visual servoing is currently not available.

In order to overcome these lacks, the following solution is proposed:

- A manipulator equipped with a gripper is installed on top of the platform-art © chaser manipulator, allowing full access to the low level control, parameters configuration, path planning, etc.
- Visual servoing is implemented in order to allow precise approximation of the gripper to the target, which is equipped with visual markers (before grasping).
- Force control is implemented in this manipulator, allowing precise, fast control of the forces exerted on the target during contact (after grasping).
- Both the platform-art © chaser manipulator and the force/vision controlled manipulator are controlled jointly to allow for precise force control and visual servoing throughout the overall platform workspace

Block diagram of the proposed system, is shown in figure 3.3.1.

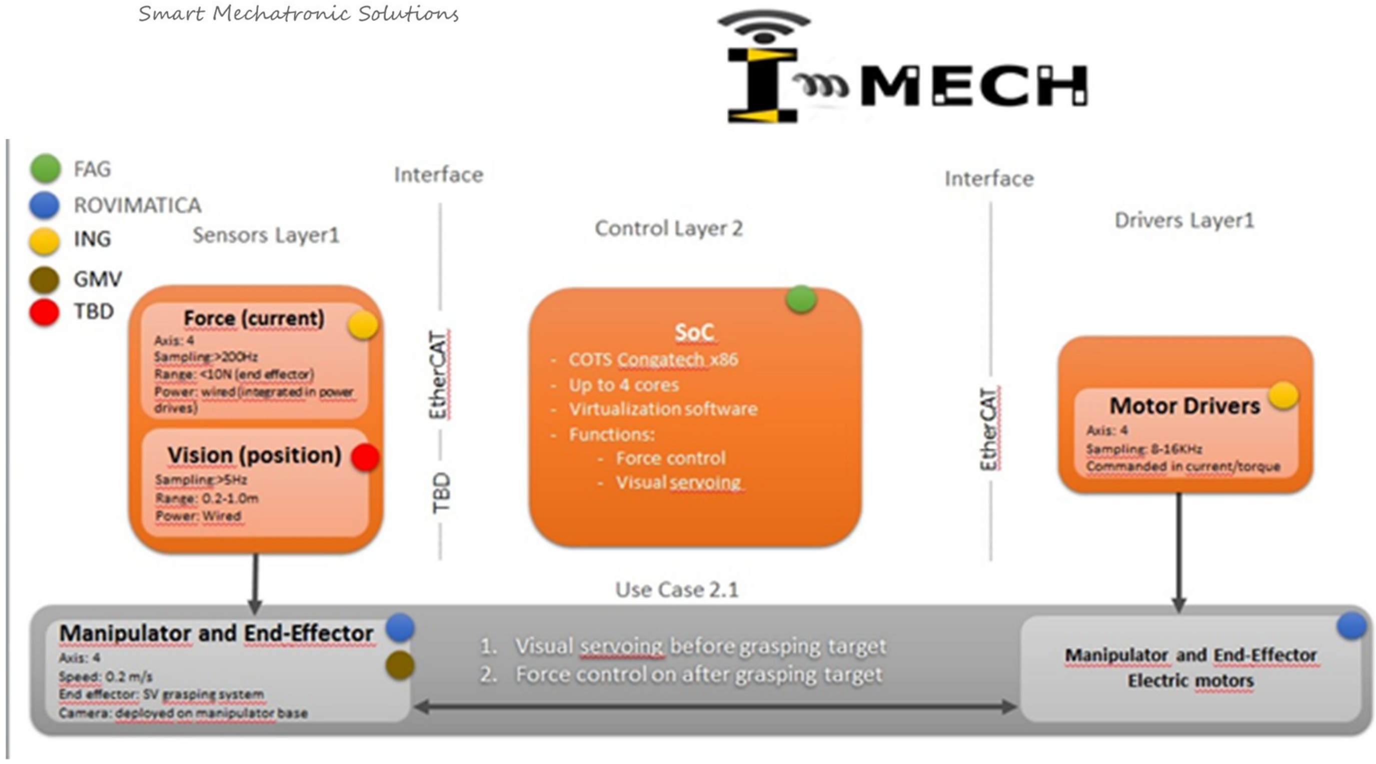


Figure 3.3.1 - On-ground validation of space GNC systems

Note The interface between the sensing and the SoC will be defined by the sensors chosen w.r.t. the signal i.e. data bandwidth required. At this time, no decision has been taken yet w.r.t. the vision system, see below.

3.4.2 - Relation to Building Blocks

The overall system will consist of a complete mechanical + hardware + software platform according to I-Mech requirements, composed of the following elements:

1. Manipulator demonstrator (developed by ROV, FAG, TEK, ING). Same demonstrator as for Use case 1.2 (FAG).
2. Vision system (TBD) **BB-4**.
3. Platform art + corresponding systems (GMV).

The motor drives (by ING: **BB-5**) allow current measurement needed for sensing the joint torques/ forces in the demonstrator manipulator, and they can be commanded in torque (current) mode. The control system **BB-10** included as part of the demonstrator (FAG) implements the algorithms (TEK) needed for controlling the force/torque in the manipulator end effector during contact and grasping operations.

A vision system (to be defined, **BB-4**) is expected to measure the relative position between the manipulator end effector and a visual marker mounted on the target. This measurement is the input allowing visual servoing oriented to approximate with precision the end effector to the target in preparation for the grasping, during the last meter of approximation. A vision processing module (not represented in Figure 3.3.1 could be needed in case the vision system does not include it), in order to provide position commands to the SoC.

3.4.3 - Functional requirements

Functional Requirements			
Req. ID.	**Req. title**	**Value**	**Rationale**
UC2.1.F1	Force current measurements	4 axis, sampling rate 200 Hz,	to measure force: < 10 N
UC2.1.F2	Vision sensing	sampling > 5 frames/s	to obtain object position on short range: < 1 meter
UC2.1.F3	Multi-core	≥ 4 cores	to enable parallel processing for vision and force control
UC2.1.F4	Motor drives and actuators	4 axis, sampling rate 8 /16 kHz	commands in current and torque rather than position

No further specific functional requirements are given in this stage of the project.

3.5 - Use case 2.2 I-MECH platform validation on open modular robotic arm (ZAPUNI)

3.5.1 - General description

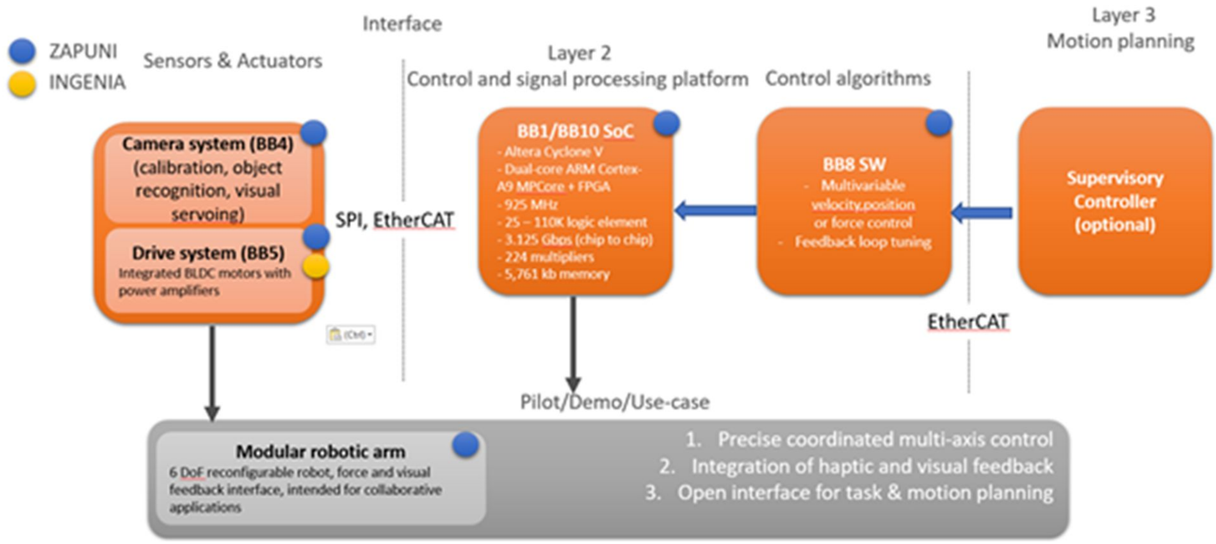


Figure 3.4.1 - Platform validation on open modular robotic arm

Open robotic modular arm will be designed as redundant **7-DoF serial manipulator** with advanced collaborative functions. The robotic arm is considered as fully open architecture regarding the design of the control system (robot controller) as well as the design of the compact actuators forming robot joints with own servo-drives.

3.5.2 - Relation to Building Blocks

The main reasons for developing a fully open robot architecture in comparison with using standard robot architectures (industrial and collaborative robots) are as follows:

- Possibility to introduce **non-standard kinematics**, e.g. the robot under consideration will have 7 independent revolute axes – this concept makes possible to use benefits of redundant robot (dexterity, reduced footprint, etc.) **Task 4.3**
- The **auxiliary sensors** can be easily added (wide range of communication protocols can be managed) **Task 3.2, Task 3.3, Task 3.4, BB1, BB2**
- The **low-level servo-drive control** system can be set and tuned without restrictions steaming from standard servo-control drives (e.g. given regulator structure and tunable parameters) **Task 3.6, Task 5.4, BB5, BB6**
- New **advanced motion control algorithms** can be included directly into the low-level control scheme with a short sampling period (e.g. feedforward/feedback algorithms for vibrations damping, e.g.) **Task 4.4, Task 4.5, Task 4.6, BB7, BB8, BB9**
- Advanced motion control algorithms, especially for collaborative robot control, safety system and intuitive robot motion learning can be integrated to fully open superior robot motion control system (robot controller)

3.5.3 - Functional requirements

The following Figure shows the use case requirements from physical layer perspective

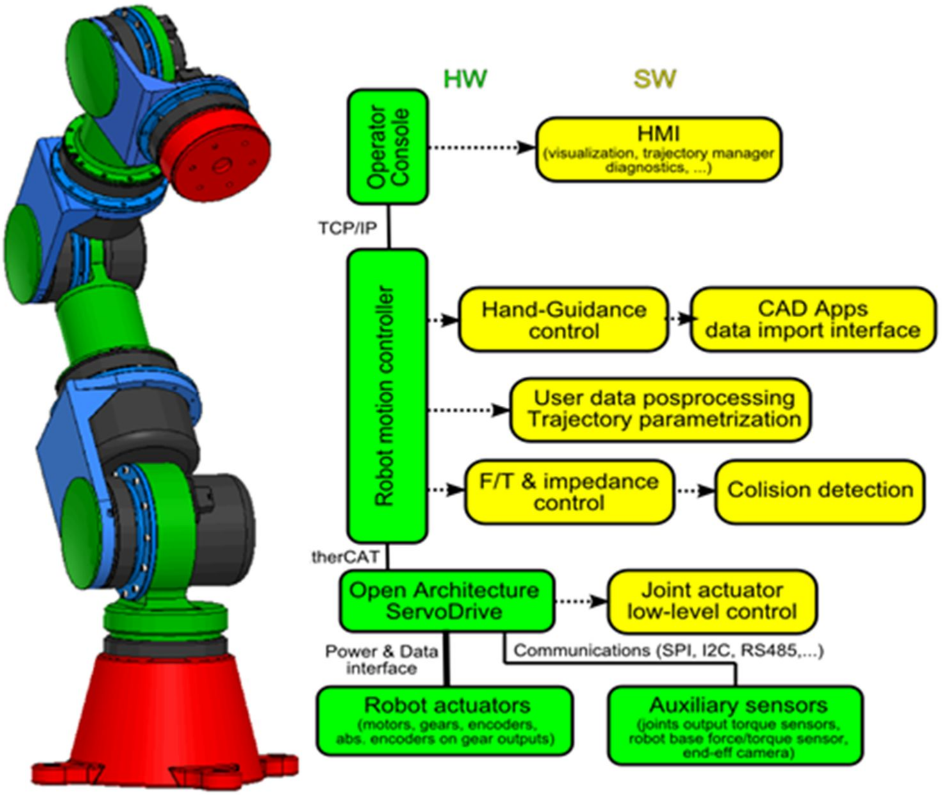


Figure 3.4.2 - Concept of open modular robotic arm

4 - Pilots

In the following pages, the pilots specifications and requirements will be described which are taken from the initial document of task 7.1 which excludes the use-cases.

4.1 - Pilot 1: Generic Substrate Carrier

Information and requirements related to pilot 1 listed in this document are based on content from deliverable D7.1.

4.1.1 - General description

The GSC (Generic Substrate Carrier), developed by Sioux CCM, is a stainless-steel conveyor belt for very accurate transport of substrates. It is capable of transporting practically any kind of substrate, for example paper, cardboard or foils, but also wooden or glass panels. The system is particularly interesting for the industrial inkjet market, which is expected to exploit the GSC for the emerging 1200 x 1200 DPI registration challenge. Manufacturing equipment for single-pass digital printing faces an interesting challenge to deal with the growing productivity demand in combination with rising droplet registration accuracy. Although the administration speed of print-heads is still increasing, high throughput speeds and/or increased print resolution can only be achieved by using multiple heads in series. When using at least 4 different inks the distance between the first and last print-head can become more than 1 meter. The GSC can meet the challenge when the relative registration accuracy over such a distance must be less than 10 micrometer.

The GSC utilizes a stainless-steel conveyor belt in order to eliminate the mechanical (e.g. elasticity) properties of the substrate and prevent deformation of the substrate during transport. The substrate is clamped on the conveyor belt using vacuum technology. Many conventional steel conveyor belts and their steering systems cannot reach the previously mentioned accuracy target. During rotation, a belt will (always) translate axially with respect to the rolls of the conveyor due to limitations in belt and/or roll manufacturing (e.g. accuracy of the weld perpendicularity). The GSC uses movable segmented rollers to actively control and correct the position of the belt without deformation of the belt. This allows accurate control of transported substrates without deformation of the substrate over a large distance, which is ideal for the digital single-pass inkjet industry.

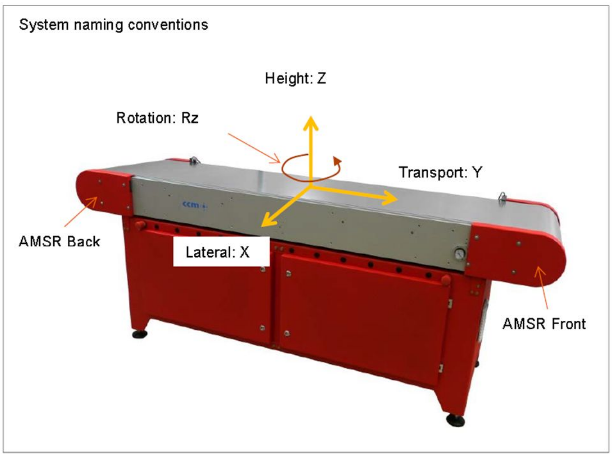


Figure 4.1.1: The Generic Substrate Carrier

The segmented rollers, called “Axially Movable Segments Rolls” (AMSR), allow continuous control of the 3 degrees of freedom of the belt (Y, X & Rz). The belt position in transport direction is controlled by means of rotation of one of the AMSRs using a brushless AC motor. The belt position in X and Rz direction is corrected by moving individual segments of the rolls in axial direction of the roll based on the belt position measured with 2 “belt edge sensors”. Reluctance actuators are used to position the axially movable segments of the rolls. Each roll has two pairs of reluctance force actuators for segment manipulation. One pair is used to position the segments of the AMSR in contact with the belt. The other pair of reluctance actuators is used to actively position an element back to its ‘centre’ position once per revolution when the segment is not in contact with the belt.

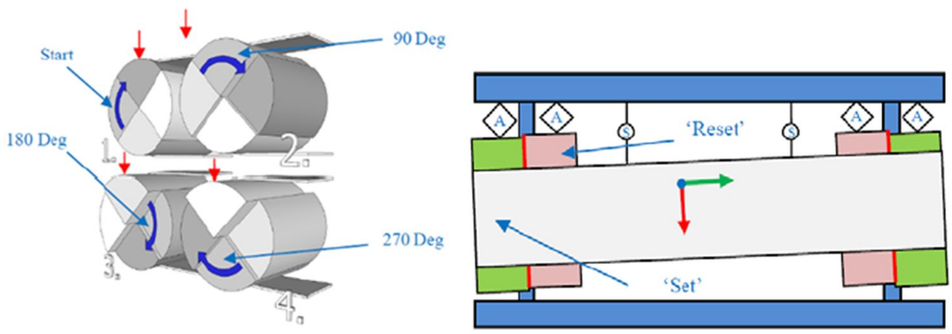


Figure 4.1.2: Principle of steering with AMSRs. “A” represents a pair of reluctance actuators, “S” represents a belt edge sensor.

The relation between force, distance and current is strongly nonlinear for reluctance actuators. Contactless sensors are therefore implemented to measure the gap between the reluctance actuators and the actuated segments. These measurements are fed back to a controller to calculate the current required to exert the desired force on a segment as function of the measured distance. This requires an extremely responsive off-the-shelf current amplifier, especially at higher belt speeds, which does not currently exist in the market. Thus, the performance of the GSC is limited. Furthermore, the existing computing platform (only) employs a single core of the multiple cores available. This limits the sample-time (it is a discrete system) and therefore the responsiveness and performance.

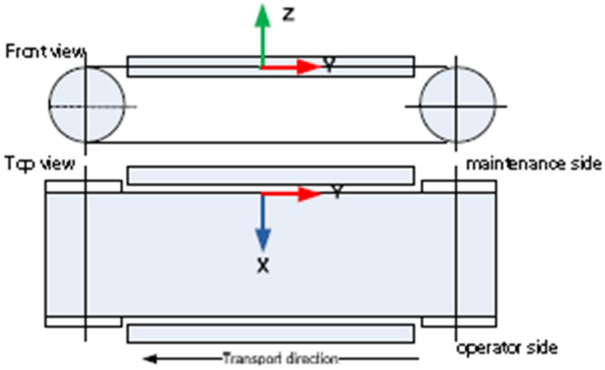


Figure 4.1.3: Direction definitions in a schematic side view of the GSC (above) and a top view of the GSC (below).

<u>Properties of the GSC (pre-I-MECH):</u>

- Total degrees of freedom to control: 8
  - Belt position X
  - Belt rotation Rz
  - Belt position Y
  - 4x AMSR element position
  - Vacuum pressure

- Total number of actuators to control DoFs: 10
  - 2 pairs of reluctance actuators per AMSR, 2 AMSRs per GSC
    - Used for belt steering in X and Rz
    - Each pair of reluctance actuators forms a single SISO axis, because a single reluctance actuator can only exert force in one direction
    - Each reluctance actuator is driven by a 1-phase amplifier
  - 1 Brushless AC motor inside one of the two AMSRs
    - For belt movement in Y (transport direction)
    - Brushless AC motor is driven by a 3-phase amplifier
  - 1 AC induction motor
    - For vacuum generation
    - Induction motor is driven by a 3-phase amplifier

- Total number of encoders/position sensors + vacuum sensor: 12
  - Belt position measurement in transport direction – Y
    - 2 SinCos encoders etched on the belt (fused into 1 encoder signal)
    - 1 SinCos encoder on the motor axis used for commutation of the brushless AC motor
  - Belt position measurement in lateral direction – X & Rz

  - 2 belt edge sensors, possibly replaced by 2 high speed belt edge camera's as part of the I-MECH project
- Distance between AMSR segments and actuator
  - 2 gap sensors per AMSR are used to measure position of the AMSR elements in contact with the belt
  - 1 gap sensor per AMSR is used to measure the position of the AMSR element not in contact with the belt
- Vacuum pressure
  - 1 vacuum sensor
- The 3 encoder sensor heads are sampled at very high speed (400 kHz) and extrapolated to ~10 MHz for usage by the industrial printing systems in which the GSC is integrated.
- The other 9 sensors are connected to analog differential inputs sampled at the position loop sample rate

4.1.2 - Proposed hardware and interfaces

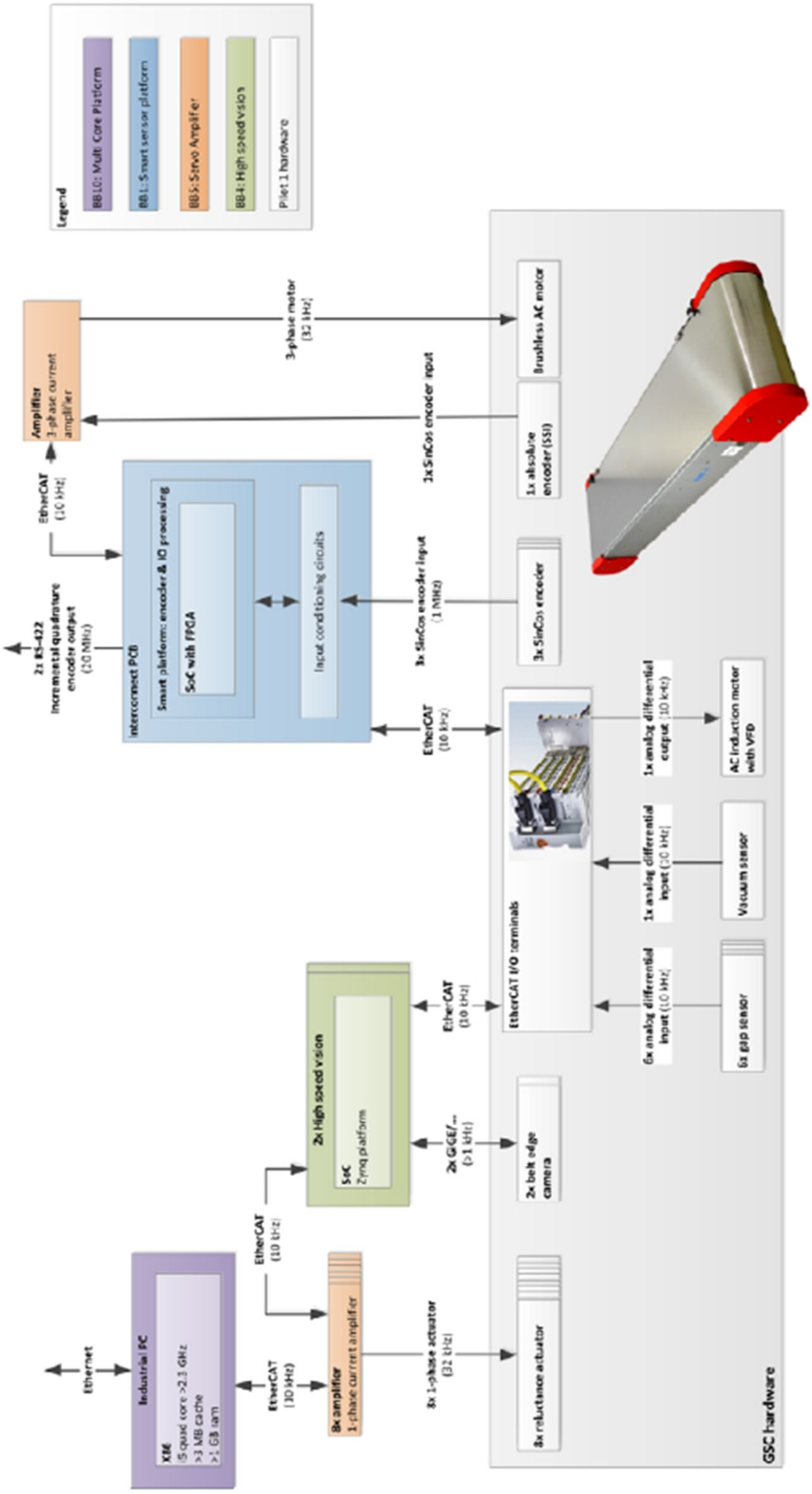


Figure 4.1.4 - Hardware/software interfacing of the steel conveyor belt application

4.1.3 - Relation to Building Blocks

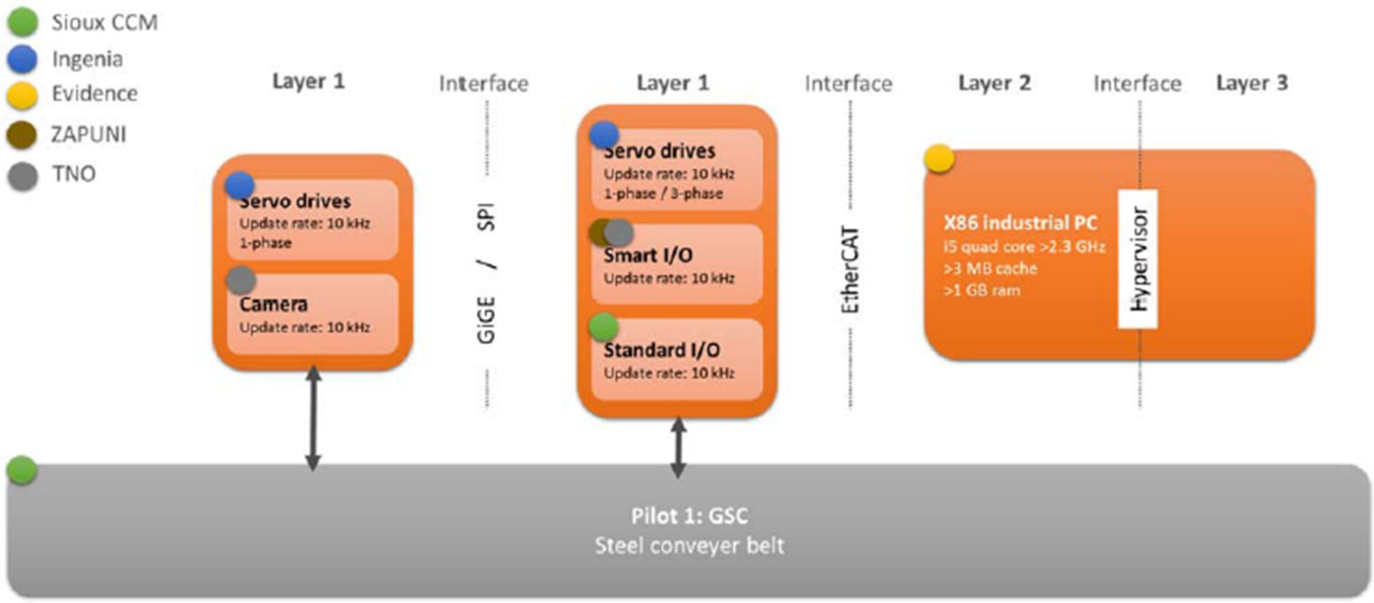


Figure 4.1.5 - Block diagram of the steel conveyor belt application

4.1.3.1 - BB1 – Smart sensor platform requirements

Main target:
Replace CLIB PCI card with de-centralized advanced sensor signal processing module, as indicated in the figure below (to become locally smart). The new implementation should be more compact by not requiring a cumbersome PCI interface and should be less expensive.

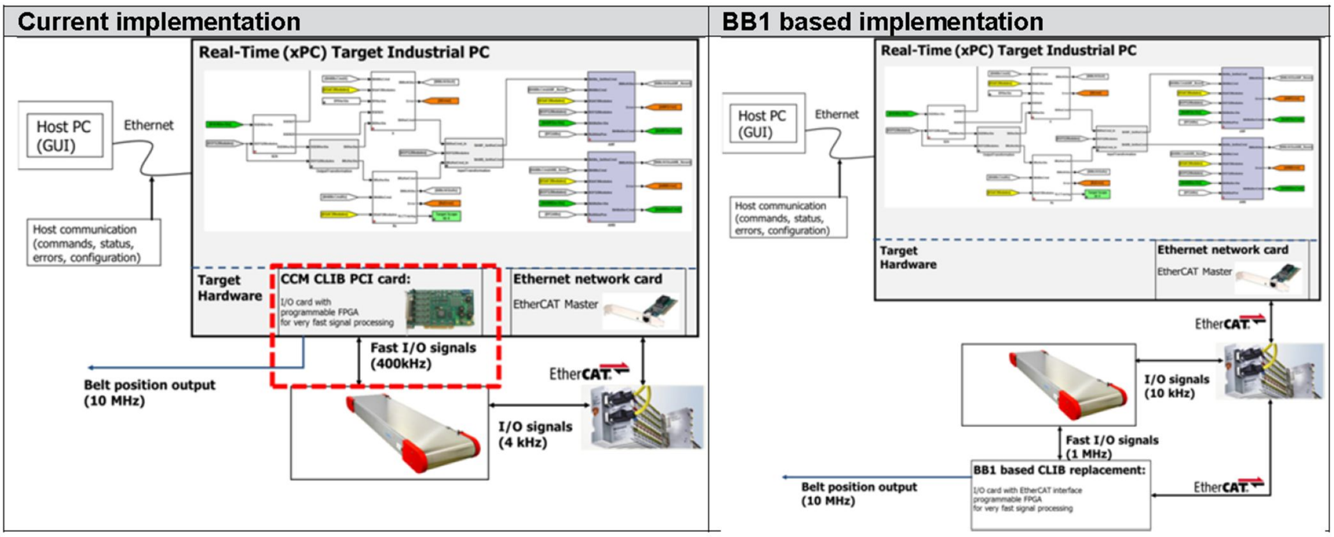


Figure 4.1.6 - Current vs BB-based application

About the current implementation:

The CLIB is used to interpolate 3 analog SinCos encoders, detect the encoder index and output a position to be used by the GSC position loop and two incremental encoder signals with a scalable (virtual) encoder resolution. The CLIB fuses the output of the encoders into a single position measurement and can apply corrections for encoder eccentricity and encoder grating non-uniformity to the SinCos encoder inputs and calculate the quality of the encoder signals. The measured position used by the position loop of the GSC is currently transmitted via the PCI-bus, but should in the future be transmitted via EtherCAT with a 10 kHz update rate. The position signal is extrapolated to a higher sample frequency for the two incremental encoder outputs with each a configurable resolution. These incremental encoder outputs can be used by devices in which the GSC is integrated, for example as inkjet droplet fire trigger. Extrapolation to a very high artificial sample frequency is possible because relevant dynamics and disturbances of the belt are far below the real sample frequency of the SinCos encoder inputs. Some settings of the applied algorithms, like the virtual encoder resolution, are adjustable with low update rates while the system is operational, while inputs for encoder eccentricity should be updated with the sample frequency of the position loops.

4.1.3.2 - BB4 – High speed vision

Main target:

Replace belt edge sensors with high speed vision to mainly achieve a better robustness against dirt and damage to the belt edge, but also a cost reduction using a high speed vision based solution with easily reconfigurable algorithms.

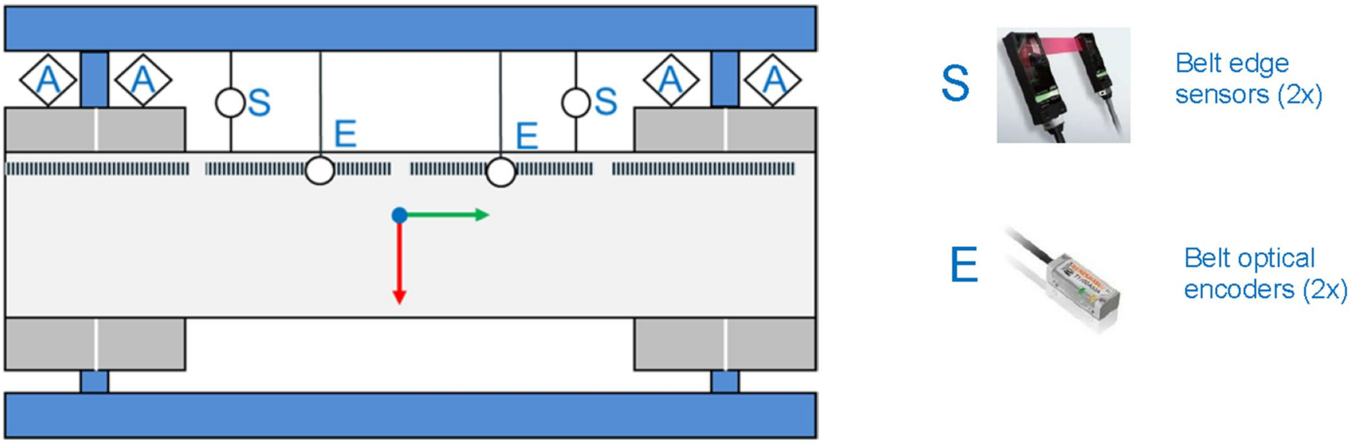


Figure 4.1.8 - Vision sensor locations

4.1.3.3 - BB5 – Servo amplifier

Main target: Replace current amplifiers used for driving the reluctance actuators and the AC servo motor with higher performance current amplifiers.

4.1.3.4 - BB10 - Multi-many core for control

4.1.4 - Functional requirements

The functional requirements are given in chapter 6 as input for the general requirements for the I-Mech tasks and sub-projects under WP-3.

Main target:

- Execute non-real-time OS and real-time software on the same hardware with reduced hardware costs.
- Increase position control sample rate up to 10 kHz.

lot 2: 12 inch wafer stage

4.2.1 - General description

The 12-inch wafer stage is part of the Nexperia ADAT3 pick-and-place platform, used in the assembly of semiconductors. The wafer stage positions a diced (sawn) silicon wafer with semiconductor products (dies). These dies are picked up by the machine and transferred to a package, tape or other carrier.

Pick-and-place in semiconductor assembly requires an accurate alignment of the semiconductor component and pick-up tool at a fixed pick-up position. The 12-inch wafer stage is designed to operate within a 50ms machine cycle (corresponding to 72000 products per hour). The system features a MIMO-controlled short-stroke-long-stroke stage with a patented drive solution designed to achieve high-accuracy positioning (+/-2 um) of a 9 kg wafer stage in extremely short (1 mm) set-points of 17 ms. Control of the stage requires a MIMO control approach, in which several (5) encoder readings are processed simultaneously and control outputs are sent to multiple (6) motors simultaneously. Thanks to this characteristic, the 12-inch wafer stage is an excellent test-bench for demonstrating scalability and the MIMO capabilities of the I-MECH platform.

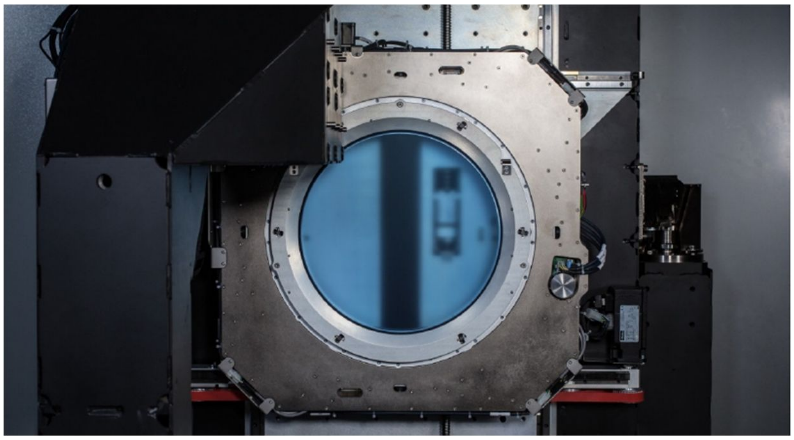


Figure 4.2.1 - Photo of the wafer stage

12-inch wafer stage properties:

- Sensors:
  - 3 short-stroke encoders
  - 2 long-stroke encoders
  - additional long-stroke encoder for the y-axis (vertical axis)

- Actuators:
  - 2 long-stroke motors, three-phase
  - 4 short-stroke motors, single-phase, over-actuated short-stroke stage

- o Electromechanical brake on y-axis motor (vertical axis)

See the figure below for an overview of motors and encoders.

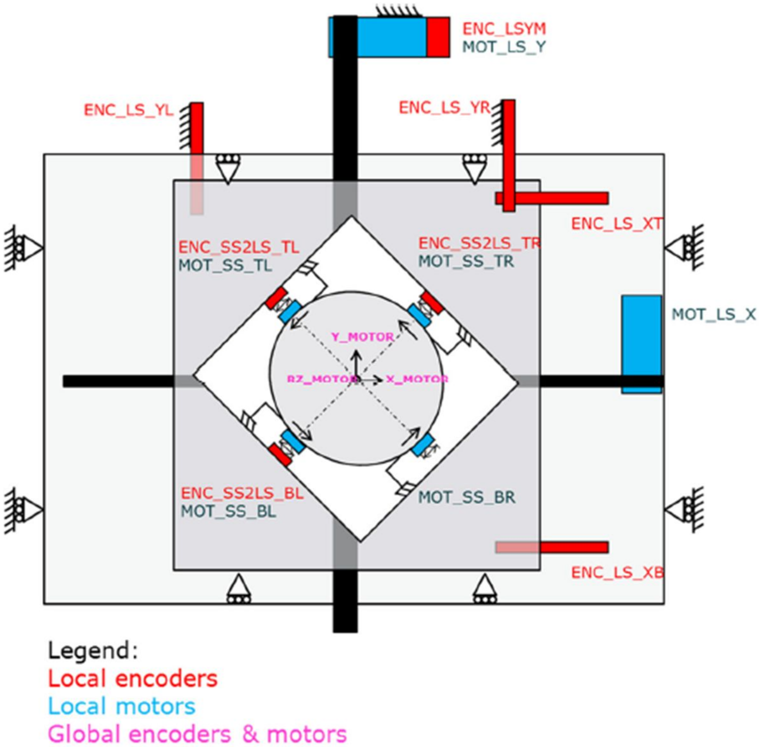


Figure 4.2.2: overview of the motors and encoders

For Nexperia, the main interest is a modular motion control platform. In our view, this combines **local intelligence** in the motion control platform (sensor processing, current control loops, position control loops) with **central intelligence** (coordination, setpoint generation, etc…) in a single, standard PC. In this way, the communication bus is used mainly for streaming of setpoints to controllers and gathering of status data and signal traces. A block diagram of the system envisioned by Nexperia is shown in Figure 4.2.3.

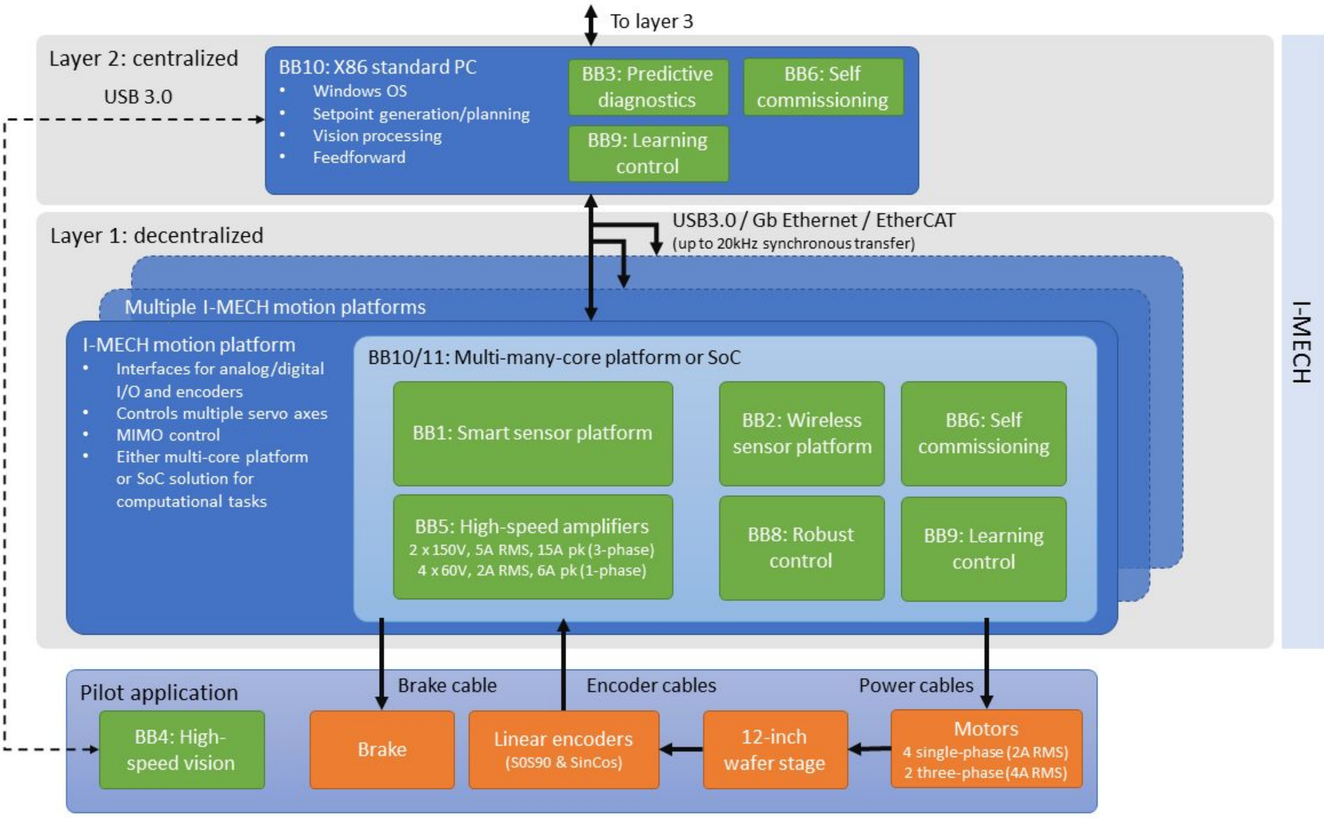


Figure 4.2.3: 12-inch wafer stage motion control

The overall motion control system will consist of four main components:

4.2.2 - Relation to Building Blocks

1. A **standard x86-compatible PC** running Microsoft Windows (i.e. our current platform), performing: all coordination of motion axes, set point generation, vision processing (which could be viewed at as layer 3).
2. Several decentralized **I-MECH motion control platforms**, which are a combination of:

    a. BB-1: Smart sensor platform (including processing to compute position loop controllers)
    b. BB-5: High speed amplifiers
    c. BB-3: Provisions for data acquisition for predictive maintenance
    d. BB-6-9: Self-commissioning and control algorithms
    e. BB-10-11: The main computational framework of the motion controller.

Each control platform manages the position and current control loops for several servo axes, optionally in a MIMO configuration. It is connected via a **standard high-speed PC bus** (USB3.0/ Ethernet/EtherCAT at up to 20 kHz rate) to the central PC to allow set point streaming to the control platforms and signal streaming to the central PC for tracing purposes. It is assumed that for MIMO control cases, the axes coordinated in a MIMO sense (e.g. up to 8) are controlled by a single I-MECH platform, removing the need for very high-rate data exchange among drives.

3. A **wireless sensor gateway**, connected directly to the central PC or to one of the control platforms

It should be possible to connect **multiple motion controllers** to the central PC. This is the reason why an Ethernet/EtherCAT connection would seem favourable from a topology point of view (e.g. using an Ethernet switch).

The subsections below describe how each (layer-1) building blocks' functionality is used in the 12-inch wafer stage pilot.

BB-1: Smart sensor platform

Pilot 2 will use the following functionality offered by BB-1:

- Interfacing of encoders (S0S90 and SinCos)
- Customizable signal processing algorithms (e.g. quadrature interpolation of SinCos encoder signals)
- Interfacing of general digital and analog I/O
- Enabling accurate time-stamping of level-1 I/O signals (possibly with BB-10?)
- Enabling latencies on the order of microseconds (possibly with BB-10?)

BB-2: Wireless sensor platform

Pilot 2 will not use the functionality offered by BB-2 (the possible test-bench for BB-2 is another device), but Pilot 2 could be used to test the principles:

- Reading of several analogue sensors connected to a wireless sensor node
- Contactless energy transfer to the wireless node
- Communication using a low-cost wireless standard

BB-4: High performance current amplifiers

Pilot 2 will use the following functionality offered by BB-4:

- Providing power to 2 3-phase motors (60V, 5A RMS) and 4 1-phase motors (60V, 2A RMS)
- Feed-forward control of voltage
- Automatic tuning of current control loops
- A current loop bandwidth of at least 5 kHz
- EMC filtered outputs
- Safety and drive protection features

BB-5: High-speed vision

Nexperia would like to validate vision-in-the-loop technology on pilot 2. The short-stroke stage has a bandwidth of 150-200 Hz. Pilot 2 can be used to demonstrate:

- X-Y positioning of a die on a wafer on the basis of visual feedback signals
- The achievable bandwidth of such a visual servo system, preferably at least 150 Hz.

BB-10/11: Multi-many core platform for control and RTOS for multi-many core platform

In our view, BB-1 and BB-10/11 will be tightly integrated. Pilot 2 will use the following functionality offered by BB-10/11:

- Achieving accurate synchronization of tasks and devices
- Scheduling multiple, parallel controller tasks such that controllers run at fixed, deterministic rates with limited jitter

- Providing computational power to compute SISO and MIMO controllers as well as more sophisticated algorithms (e.g. ILC)
- Enabling communication to a host PC which streams set points to the motion control platform and receives signal traces from the platform.
- Providing an environment in which the I-MECH control software framework can run, allowing easy adaptation and implementation of user-defined controllers and controller architectures

4.2.3 - Functional requirements

The functional requirements are given in chapter 6 as input for the general requirements for the I-Mech tasks and sub-projects under WP-3.

4.3 - Pilot 3: High Speed Packaging

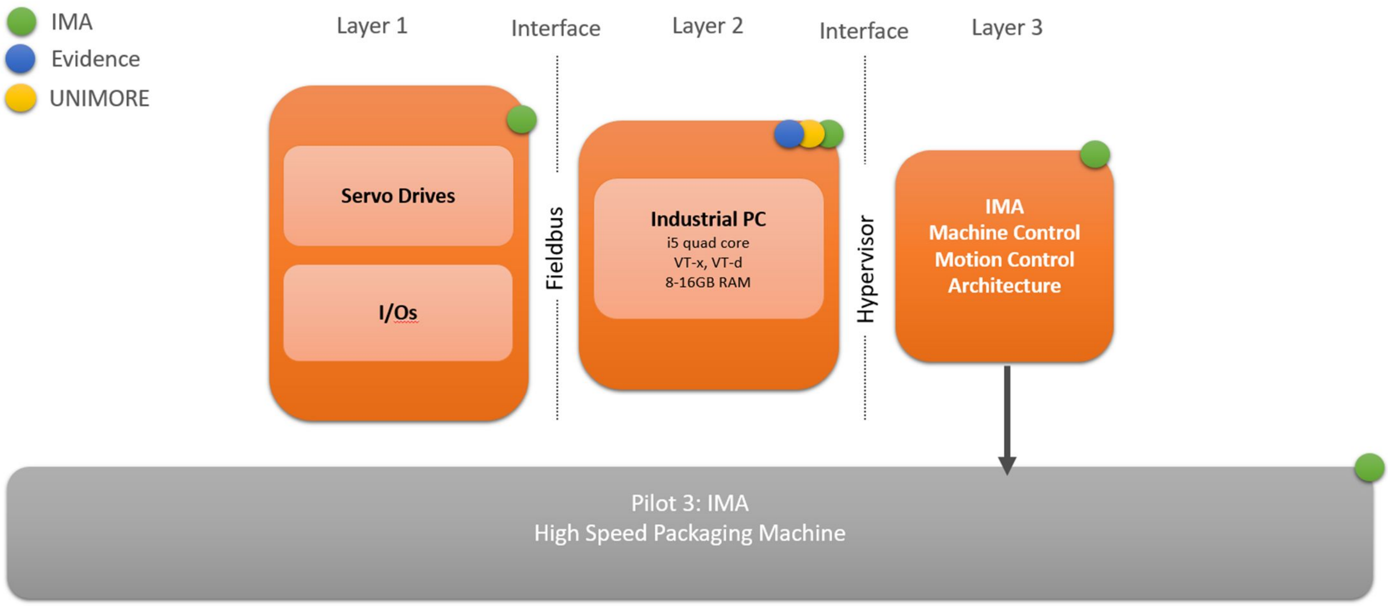
4.3.1 - General Description

IMA is a world leading company in the manufacturing and supplying of machines for packaging in a number of different sectors, such as dairy & food, pharmaceutical, tobacco and tea & coffee. For the scope of the I-MECH Project IMA has selected two machines that are good representatives of its technology: one from the Pharmaceutical sector, the in-line filling & stoppering machine, and one from the Tea sector, the tea-bag packing machine.

An in-line filling & stoppering machine is a machine with continuous motion transport system, that is suitable for filling liquid solutions into cylindrical vials and for rubber stoppers insertion. Thanks to different dosage technologies based on brushless motors, the filling machine can reach a very high accuracy in controlling the actual weight. Each vial is measured by a checkweigher for: one for measuring the tare and one for the gross weight. In this way, the machine is able to check the dosage of 100% of the production up to a speed of 400 vials-per-minute (vpm).

Another type of machine that will be targeted for the demonstration activity is the tea bag packer. The latest generation of tea bag machines has been developed for knot technology and it is the first one able to produce knotted tea bags at a production speed of up to 400 bags per minute ensuring the highest efficiency rates. The idea of the C24-E filter bag, based on a traditional non heat sealable double chamber bag, guarantees optimum infusion and enabling the natural tea aroma to flow out. No metal staple or additional packaging materials are required to fix the bag to the tag and the cotton thread. Fixing is achieved by two simple knots. The machine is also equipped with an automatic splicing system in order to avoid stopping the production.

The future of this type of machinery relies on its flexibility and adaptability to the many different requirements of the customers, with a focus on an increased production speed. This implies imposing a significantly higher performance burden to the machine controller, which is running on an industrial computer. The increase of the clock frequency is reaching its limits and the only way to overcome the issue is to harness the potential of multi-many core hardware architecture.



4.3.2 - Relation to Building Blocks

BB10 – Control specific multi-many core platform

BB10 will address two main objectives: exploring COTS hardware platforms suitable for multi-many core applications and creating a custom but open hardware platform based on FPGA technology for the same kind of applications. Within this context, IMA will participate in the exploration of the COTS component by providing its own requirements and defining its needs so as the most fit platform for the Pilot is found.

BB11 – RTOS for multi-many core platform

In order to address its aforementioned requirements, IMA will make use of the Hypervisor produced by BB11. The Hypervisor will be used to host separate instances of single-core RTOS running the IMA Control System. This way, IMA will be able to tackle its computing load problem by splitting it between different Control Systems, all guests on the same hypervisor, which will be running on the platform chosen by BB10.

4.3.3 - Linkage to I-MECH WPs and Layers

WP3 – Instrumentation layer design and development

IMA, together with pilot-involved partners UMO and EVI, will define the requirements and specification for multi-many-core embedded control hardware. IMA will be involved in Task 3.7, particularly in the definition and characterization of the COTS multi-core platforms available on the market in order to identify the development platform for BB11.

WP7 – Pilots and demonstrators

IMA will exploit the Benchmark suite developed by UMO within BB11 in order to compare the performances of the existing solution with the Hypervisor, also developed within BB11.

The I-MECH Hypervisor, developed by EVI and partners in the context of BB11, will host up to four instances of VxWorks running the IMA Control System configured as described in Architecture 1 and 2 in the "System Requirements and Specifications" section.
Real-Time performances will be measured and carefully reviewed within an industrial-ready setup.

4.3.4 - System Requirements and Specifications

Recent requirements coming from the market address mostly the quality of the final product. In order to satisfy such requirements, the machines have to be equipped with complex quality control systems that must be integrated in its control system. This further increases the computing workload, making it impossible to address with classic single-core architectures. On the other hand, multi-core systems are not sufficiently mature to guarantee the hard real-time requirements of machine control, due to the interferences of tasks that are simultaneously executed on different cores and concurrently accessing shared resources like network controllers, I/O devices, GPU accelerators, and shared data structures.

In the I-MECH project, the consortium will integrate the latest achievements from the real-time systems community in the realization of multi-core Real-Time Operating Systems (RTOS) and execution models to achieve a predictable execution for the two addressed industrial automation settings. In particular, a hypervisor-based solution will be proposed to integrate motion and control modules into a multi-core hardware architecture suitable for industrial production standards, without affecting the real-time requirements of either module. A multi-OS configuration will be potentially adopted to deal with application modules with different requirements (e.g., library/driver support and unmodified execution of legacy code/applications, versus hard real-time guarantees and controlled latency of critical modules). Particular care will be taken in the arbitration of the access to shared hardware and software resources, to ensure a bounded latency of critical tasks.

The Hypervisor produced by BB11 will be used by IMA in its two main system architectures:

Architecture 1. IPC-Based Control System with Distributed IO and Motion Control
- Distributed IO reached via Fieldbus (possibly more than one)
- Brushless Motors controlled via Fieldbus (possibly more than one)

Architecture 2. X86 CoM-Based Control System with Local IO and Motion Control
- Local Analog IO directly used to control Brushless Motors

Some top-tier machines make use of Architecture 1 and up to three instances of Architecture 2. The goal of the Hypervisor within this pilot is to "merge" a case like this in one single hardware component hosting all four instances.

4.3.5 - Functional requirements

Communication and interface requirements

- OPC-UA, OPC-DA, ModbusTCP for HMI communication
- Ethercat, Powerlink, SercosIII as fieldbuses for IO and Motion
- MQTT, AMPQ for machine to cloud communication
- WebServer for online access to relevant variables and parameters

Note: these requirements shall be satisfied by the IMA Control Architecture.

Data processing and management requirements

- Detailed and fine grained logging
- Online access to relevant variables and parameters (e.g. Motion control parametrization and diagnostic)

Note: while these requirements are satisfied by the IMA Control Architecture, they shall be satisfied also by the Hypervisor, for what can be relevant in its context.

Software requirements

- Designed to match Hard Real-Time requirements
- Designed to handle multiprocessor systems with Hard Real-Time requirements in mind
- VxWorks 6.9.x and 7 compatible

Note: these requirements are strictly related to the Hypervisor.

Control layer performance requirements

- Performance monitoring tool, for monitoring task-level performance (actual cycle time, jitter, response latency…).
- 50us minimum scheduling cycle time (not related to minimum Motion Control cycle time, which is 500us) with 1% jitter.

›t 4: Big CNC

Nicolás Correa supplies CNC Milling machines for high-productivity sectors such as aeronautics, mold and dies, energy and capital goods (Figure 4.4.1). These sectors demand increasingly precise machines with more features and increase of productivity in a drastic way.

4.4.1 - General description

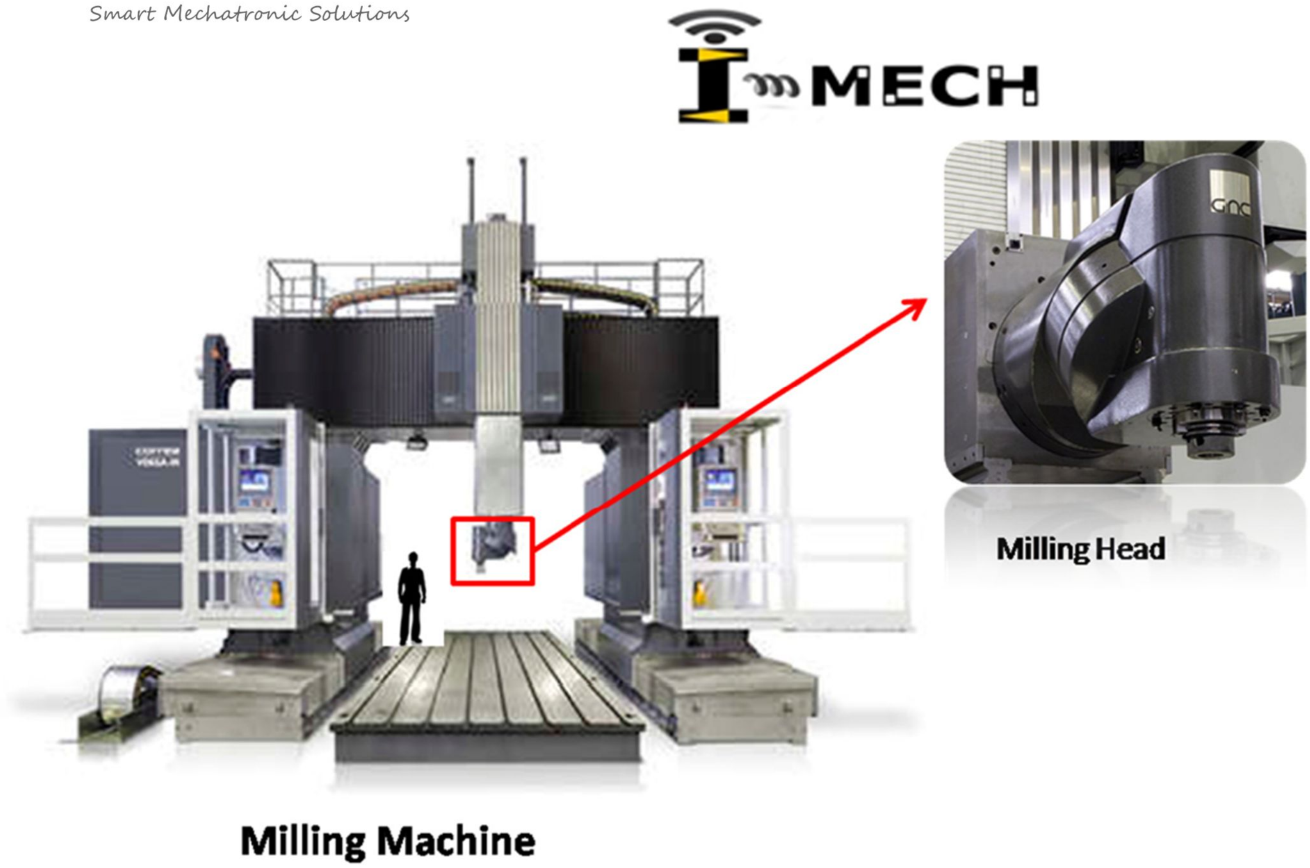


Figure 4.4.1: Example of milling machine and milling head where the I-MECH platform will be integrated in order to monitor important process parameters.

One particular interest is the highest demand in the availability and reliability of machines with reduced maintenance times and advanced capabilities to evaluate in real time, both their health state and the work performance. In case of machine failure, it is currently difficult to identify the source given the lack of operating records. Nowadays, it is not possible to distinguish between an internal error and operator's malfunctioning. This negatively affects the reparation time and hence the machine performance. Most of the failures are due to overheating and breakdown of mobile parts. This can be easily solved with the integration of temperature sensors and precise motion control systems.

One of the main and critical parts of the machine is the milling head (Figure 4.4.1). This part allows machining in different angles positions, roughing and finishing operations on metal components surfaces. The patented Nicolas Correa milling head is a complex component that includes many precise elements and complex mechatronic circuits including gears, bearings, couplings, and refrigeration and lubrication circuits that needs to be monitored in some way.

Classical methods for direct measurements such us wire sensors require intrusion in the process or it is simply impossible to use due to the design itself (mainly because the relative rotation between different bodies of the milling heads makes impossible the continuous electrical connection between the sensors and the data acquisition systems in a reasonable way that do not affect the performance of the milling head). Indirect methods are often complex to use or not reliable. Therefore, the use of wireless sensors opens new possibilities offering clear benefits to the machine owners and builders. The main expected added values are:

- Reduction of machine downtimes due to the monitored critical parts.
- Increase the lifetime of the milling head and its components

- Increase the performance of the machining process due to the ability to improve thermal compensation
- Diagnostic maintenance to avoid failures before occurs
- Decreasing energy consumption in the machining process

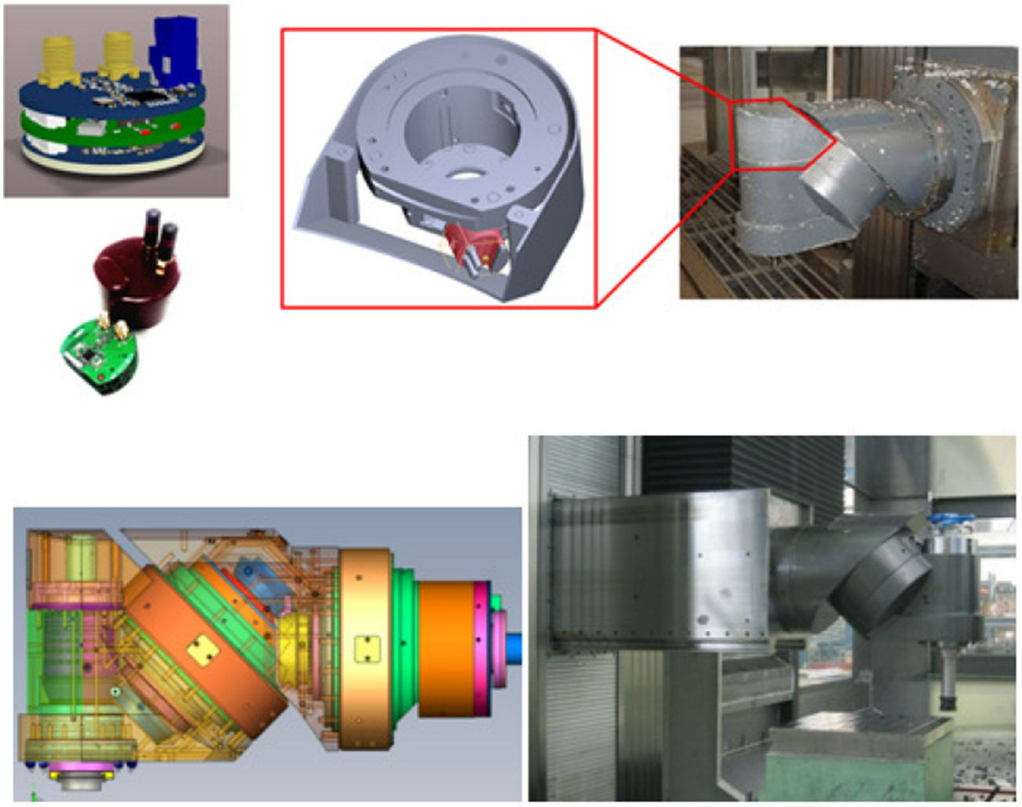


Figure 4.4.2: Potential tentative design of the I-MECH platform and sketch of integration in the mechatronic system

Our approach consists in integrating an electronic node in the head of a milling machine that contains:

- Two temperature probes that will monitor the temperature of internal bearings and whole head
- Two analogue and digital proximity sensors that will monitor the relative position of clamping tool parts.
- An accelerometer will monitor impacts in the head components and machining process
- Embedded electronics that will process all the information.
- A communication module that will send all the information to the central CNC so that this can show an alarm sign if the operating temperature exceeds a certain value, or the motion procedure of the machine is not accordingly followed. In this case the operation is stopped and potential failures are avoided.

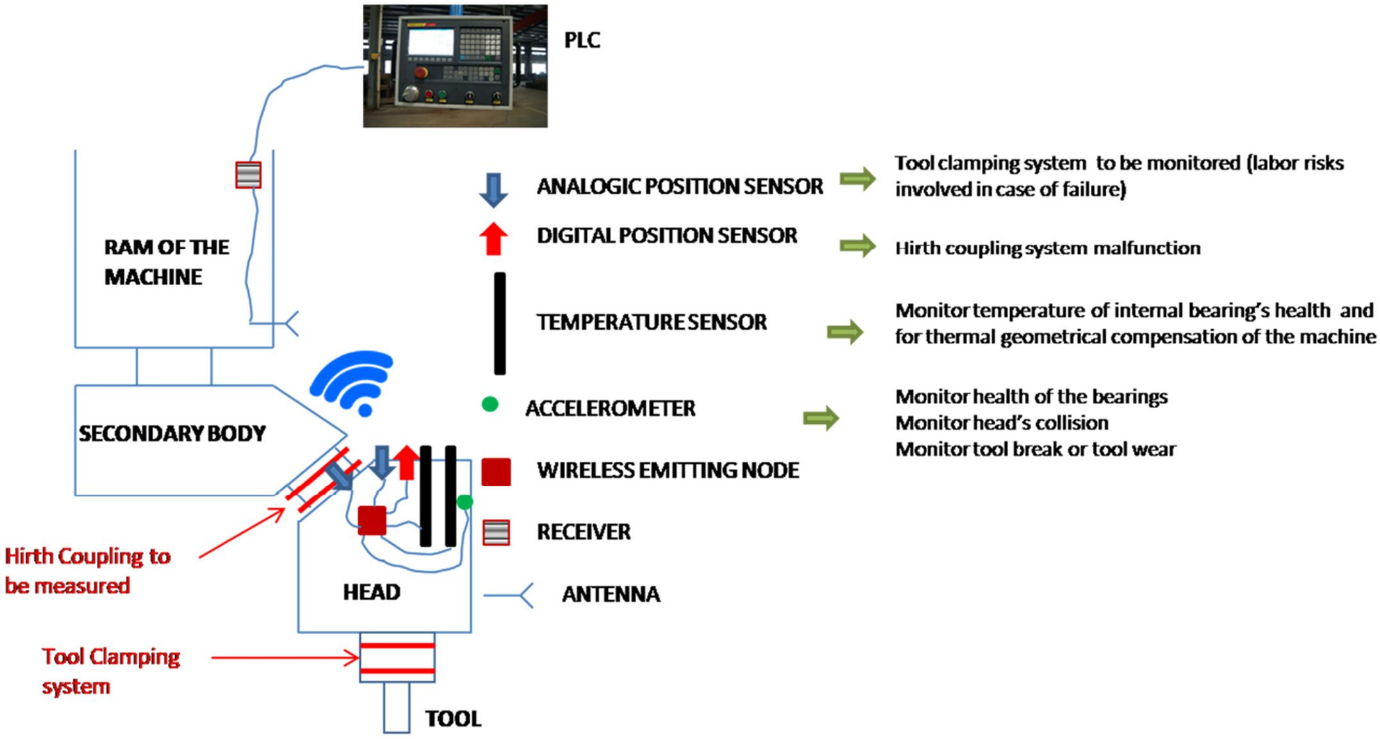


Figure 4.4.3: Illustration of how the I-MECH platform will work once integrated in the mechatronic system.

Once sensors have been implemented into the machine, appropriate control algorithms have to be developed for combining them with the sensors. The aim of this combination of sensors and linked algorithms is:

- To trigger alarms and warnings to the CNC/PLC of the milling machine
- To optimize in an adaptive manner machine aspects such as a proper machine performance during operational stage
- To minimize energy consumption during manufacturing operations.

4.4.2 - Relation to Building Blocks

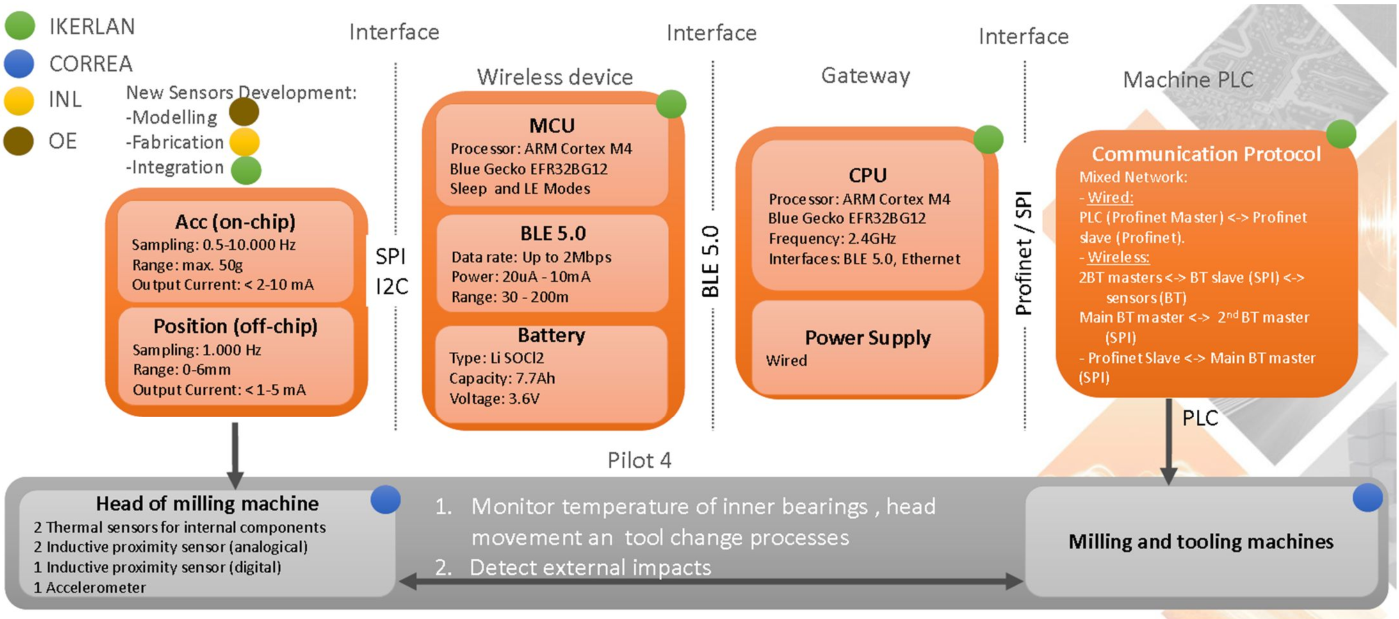


Figure 4.4.2 - Block diagram of the blocks of the milling machine

BB-1 Platform for smart sensors

Pilot 4 will make use of the following BB1 functionalities:

- Advanced data processing algorithms
- Interfaces to primary sensors
- Integration with higher level layers
- System management

We will follow two complementary strategies regarding the sensors needed to monitor the information demanded by the Pilot:

First:
IKERLAN will search the market for commercially available components that fulfil the requirements and specifications given in the sections above. In this way, we already have the following tentative list:

- Analogic Position Sensor: PEPPERL+FUCHS 0.-6mm, 0-5V. SPI/I2C
- Digital Position Sensor: BALLUF, 10-30 VDC
- Temperature Sensor: PT1000 + Dig. Conv. MAX 31865. SPI.
- Accelerometer: SPARKFUN Triple Axis ADXL345. 16G SPI/I2C 16 bit.
- Micro-processor: SILICON LAB EFR32BG12

Second:
- IKERLAN will cross the specifications of the commercially available position sensors and accelerometer and will match them with the requirements of the Pilot. From this matching, we will identify the functionalities that only needed for our Pilot.

- IKERLAN will send these functionalities to INL and OE with the purpose of designing and fabricating ad-hoc components (sensor and accelerometer) with only these specific demanded functionalities focusing on lowering the energetic consumption as much as possible.
- OE will collaborate with INL in the design, modelling and simulating the fabrication and performance of the newly developed components.
- INL will fabricate these components and will send them to IKERLAN for integration in operational devices.

When the new alternative components are delivered by INL and OE, IKERLAN will benchmark them against the commercial ones in terms of required performance and low consumption. The most adequate ones will be integrated in the final I-MECH platform.

BB-2 Real time wireless sensors

Pilot 4 will make use of the following BB2 functionalities:

- Reliable data transmission
- Network with limited number of sensors

IKERLAN will develop the wireless networks to process data from the sensors and send them to the PLC of the milling machine (Figure 4.4.5). IKERLAN will also develop robust protocols with precise synchronization and high energy efficiency transmission for application in harsh industrial environments.

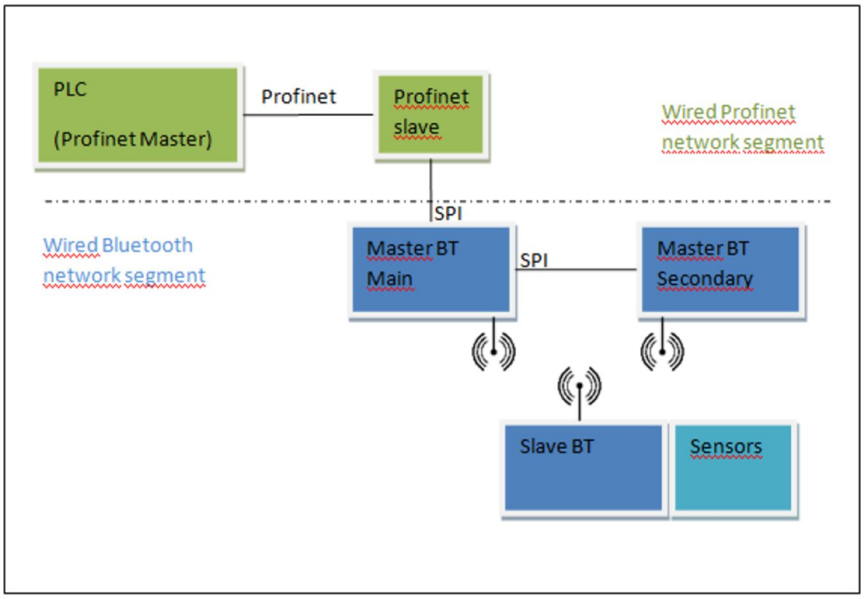


Figure 4.4.6 - Preliminary sketch of the wireless network designed in order to transfer the data collected from the sensors to the PLC of the milling machine.

The tentative network has two different segments: one wireless and one wired.

The wired network segment has the following elements:

- PLC: bus Profinet communication. It receives data from sensors and establishes when proximity sensors have to measure.
- Profinet slave: It receives data from the sensor network and sends it to the PLC through the Profinet bus.

The wireless network segment is formed by:

- A Bluetooth slave: placed at the head. It should take the measurements. All sensors will be connected to this node.
- 2 Bluetooth masters situated closed to the head but in the non-mobile part. They will receive the info collected by the sensing node and send it to the wired net. The main master will have direct communication with the Profinet slave with a SPI communication. The secondary master will only have a SPI communication with the main one.

4.4.3 - Functional Requirements and Specifications

Functional Requirements			
Req. ID.	**Req. title**	**Value**	**Rationale**
P4.F1	Operation environment	Industrial	Wireless sensors must be able to operate in an industrial hostile environment conditions –electromagnetic interferences-.
P4.F2	Transmission range	3.5-4m	Due to the machine layout, the emitter and receiver must be able to communicate within this range
P4.F3	Operation lifetime	1 year	1 years of system's operation time without battery change is demanded for efficient maintenance.
P4.F4	Adapted communication protocol	Yes	Output signals must be integrated in the PLC of the machine through PROFINET and
P4.F5	Temperature sensing and alarm	Yes	Two temperature probes must monitor the temperature of inner bearings and head every 20s, and trigger an alarm if a certain point is surpassed.
P4.F6	Distance sensing	Yes	Sensors must monitor the relative position of clamping tool parts.

P4.F7	Vibration alarm	Yes	An accelerometer must monitor impacts in the machine head and trigger an alarm in case of violent impact
P4.F8	Node identification system	Yes	More than one node can be connected to the same machine, being active only one at a time, but being ready for head change
P4.F9	Node activation/deactivation	Yes	Sensors must be activated from PLC
P4.F10	Low Power	Yes	The device must have a low power mode in order to save energy and a corresponding efficient waking-up system
P4.F11	Output voltage	0-5 V	Position sensors must have an output in this range for an easy integration in the electronics
P4.F12	Output current	1-5mA 4-20mA	Position sensors must have an output in this range for an easy integration in the electronics
P4.F13	Input voltage	15-30V	Position sensors must have an input voltage in this range for an easy integration in the electronics
P4.F14	Accelerometer Specs:	Range: 50g Freq: 1khz Resol: 0.05g	These specs must ensure proper impact detection
P4.F15	Communication interface between the wireless device and the receiver in the machine	BLE 5.0	To ensure minimum power consumption for the wireless devices, the least power consuming wireless solution should be selected. As state-of-the-art and market analysis in D2.1/D2.2 shows, BLE 5.0 is the best trade-off for this specific application.
P4.F16	Communication interface between sensors and wireless device	SPI I2C	Since different peripherals will be connected to the central processing unit, different protocols must be available for external connections

		UART	
P4.F17	Communication between receiver and machine PLC	SPI PROFINET	This guarantees PLC data reception and sensor activation/deactivation

Communications

- Wireless sensors must be operational in an industrial hostile environment (electromagnetic interferences with other equipment, motors, metallic parts, dust and liquids, frequency legislation …)
- Transmission range between 3.5 and 4m
- Output signals being collected by CNC must be made through[JN1] PROFINET

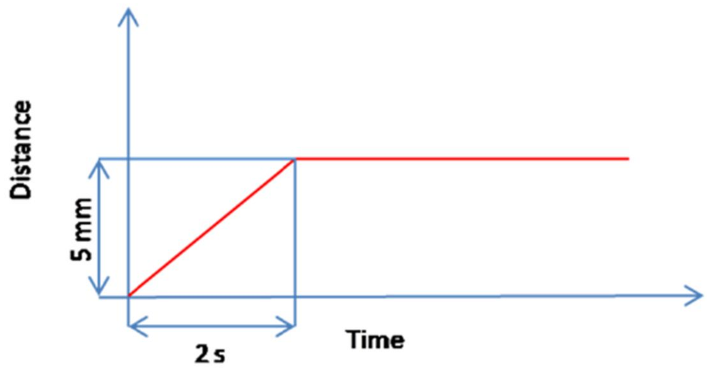
Electronics

- Node identification system: More than one node can be connected to the same machine, being active only one at a time, but being ready for head change
- Node activation/ deactivation from PLC
- Safe energy mode and/or energy harvesting elements to maximize operation lifetime (minimum required 12 months)

4.4.4 - Hardware Requirements and Specifications

Sensors

Analogic Position sensors:
- Output Voltage: 0-5 V or 0-1 V
- Output Current: 1-5 mA or 4-20 mA
- Input Voltage: 15-30 V
- Profile of distances to be measured:



- Values will be read on demand when the order to move the head from the PLC is sent.

Temperature sensors:
- Send values automatically every 20 s
- Trigger an alarm sign if a set point is reached

Accelerometer:
- Acceleration range: 50 g
- Frequency range: 1 kHz
- Resolution: 0.05 g

Microcontroller

- Low energy modes
- External Digitalization with multiples ADCs (3x)

Sensor	Micro-Proccessor Requeriments
Inductive sensor (analogic)	1 communication port
Inductive sensor (digital)	1 digital input
Accelerومenter	1 digital input and 1 communication port
Temperature	1 communication port
ENABLE	5 digital outputs
Total	5 digital outputs 2 digital inputs 1 communication port

Signal Conditioning Circuitry

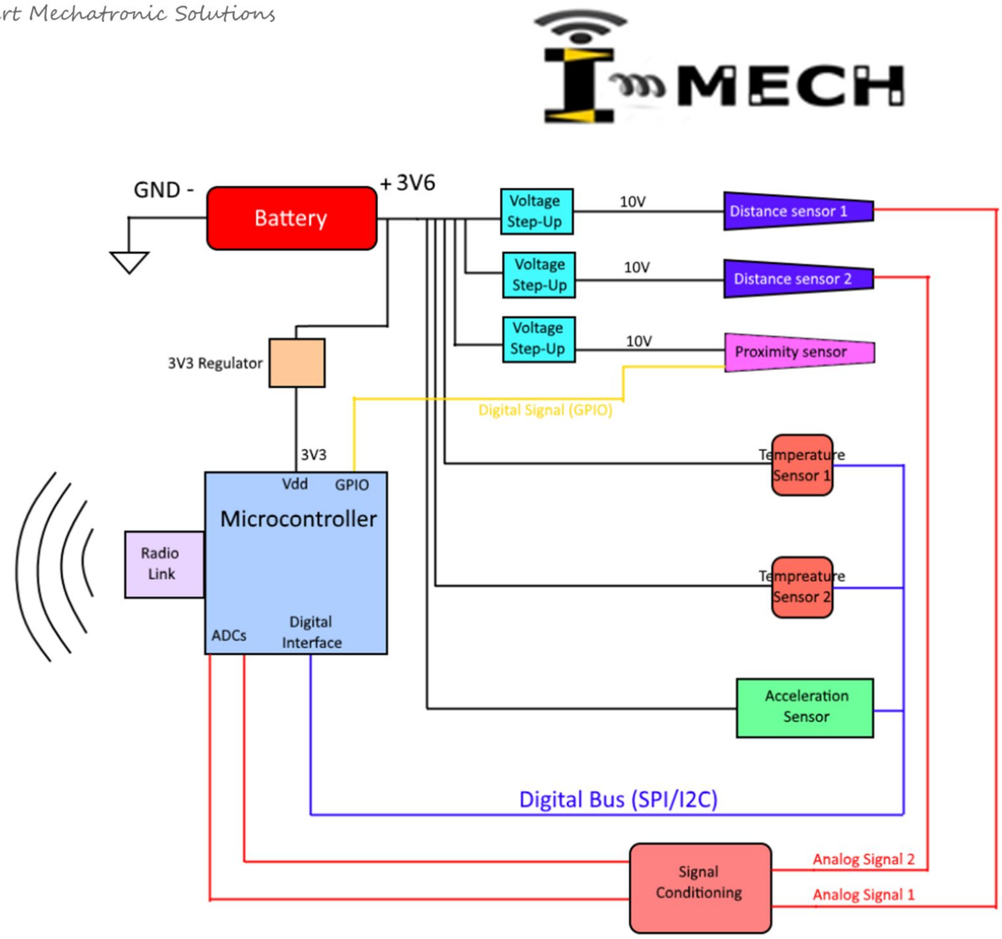


Figure 4.4.4: CNC interface overview

4.4.5 - System Decomposition Overview

With the aim of subdividing the initial complex problem into parts that are easier to handle, we designed the following decomposition diagram shown in Figure 4.4.4. The figure shows the contribution of the I-MECH *Building Blocks* and *Work Packages* that will address the initial requirements and specifications of the Pilot.

The work performed in WP2 mainly focuses on the definition of requirements and specifications. This will be a very valuable piece of information for WP3. With this as an input, within WP3, we will develop the technology at different levels (mainly components, hardware and software design), to accomplish all the communication and electronic demanded tasks.

The result has to be: two functional building blocks that can be easily integrated in an operational device. Every building block will take care of performing different functions.

Finally, WP6 will be responsible for building the operational device and integrate it in the application. In order to do that, hardware, middleware and software have to go through validation, test and evaluation procedures before being deployed as a commercial system by the I-MECH partners.

All these steps are detailed in the following sections.

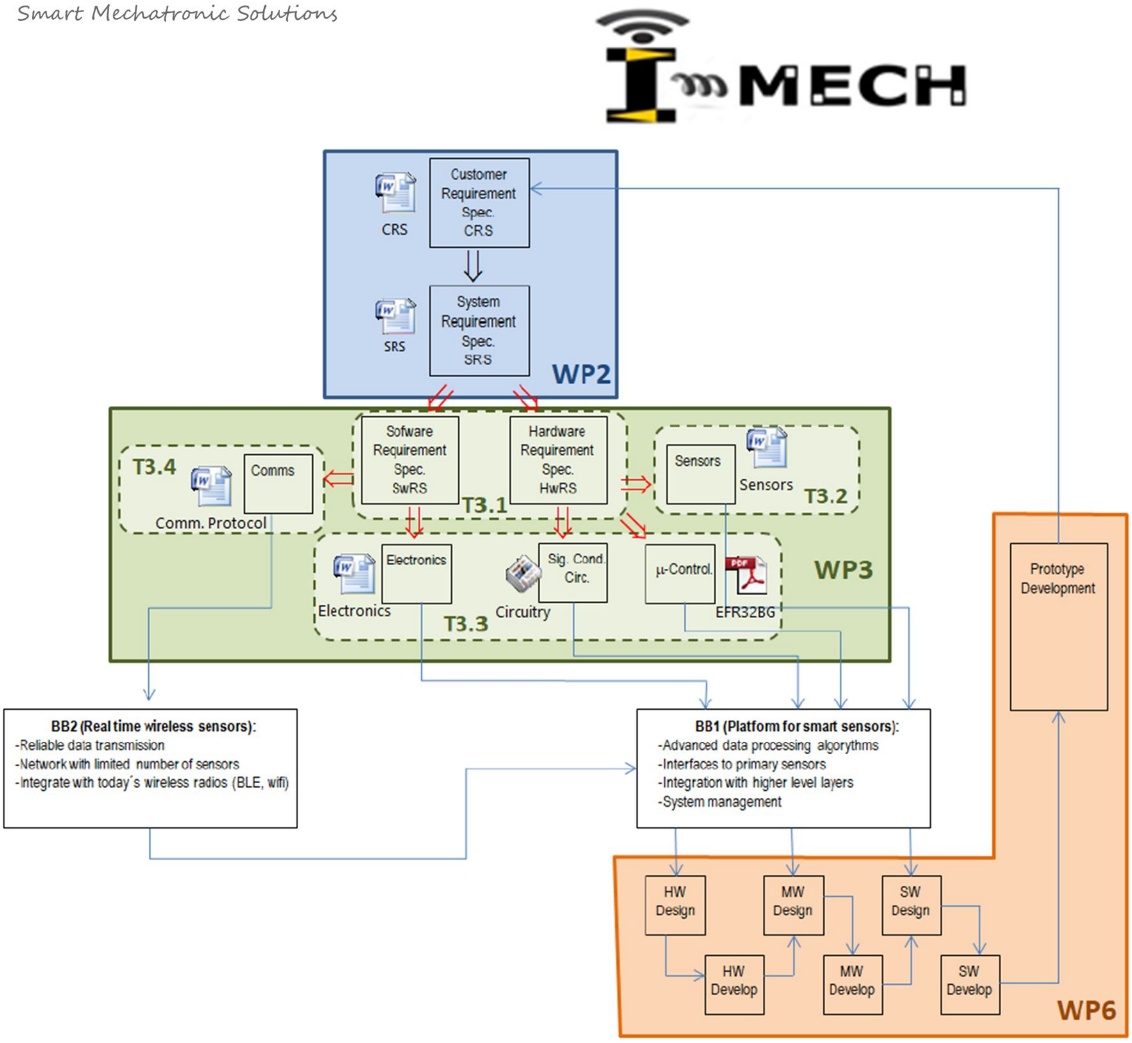


Figure 4.4.5 - Pilot 4 System Decomposition Overview

4.5 - Pilot 5: Medical robotic manipulator

4.5.1 - General description

Two aspects are of main importance in an application like Pilot 5, as intended in the I-Mech project:

1. System variations. Two types of system variations are commonly discerned. The first refers to initial product variations because of differences in manufacturing. In most cases, these variations are dealt with in the design phase by specifying, for instance, deviations from measurable qualifiers like friction force, allowed motor current etc. Secondly, there are variations over time (e.g. due to wear). The medical device as used in Pilot 5 is used intermittently and nearly always suffers from start-up effects (e.g. drive trains almost never reach a stable operating temperature) This leads to non-linear behaviour of lubricants and seals and to variations in the motor force constant. Fretting corrosion becomes a point of attention. This type of variation is atypical of both variation types mentioned and difficult to describe algorithmically.

2. Safety: Pilot 5 primarily operate in an environment where human beings are present. More explicitly, this concerns patients (vulnerable) and medical personnel and this is a critical environment when it comes to safety.

Safety measures mainly rely on manipulator models. One of these models employs motor current as a measure for collisions. The model predicts the required motor current when the manipulator moves. Certain differences between expected (modelled) current and real current are interpreted as a collision between manipulator and environment, with a follow up of appropriate actions. System variations are often non-linear and are typically difficult to model. However, these variations also introduce differences between modelled and real current. Insufficient modelling of these system variations can therefore obscure the conclusion that a collision takes place. To overcome this, each manipulator currently needs to be calibrated to accommodate for non-linear effects that are present at the time of calibration. As these non-linear effects vary over time, the calibration needs to take place regularly. Needless to say that eliminating the need for these calibrations is beneficial for the hospital (less downtime) as well as Philips as manufacturer of the manipulator (less service costs).

Improved modelling, as developed in I-Mech, aims at extending the current manipulator model to a level where recalibration in the field is no longer necessary. I-Mech addresses various modelling activities like model based control, predictive control, robust control, sliding mode control, ILC, adaptive control and repetitive control. Of these, model based control suits the Philips medical manipulator best and is the main focus for pilot 5. The work focuses on showing that a model of a hose with cable bundle and counteracting force retainer of a specific axis can replace/reduce the current calibration actions of that axis.

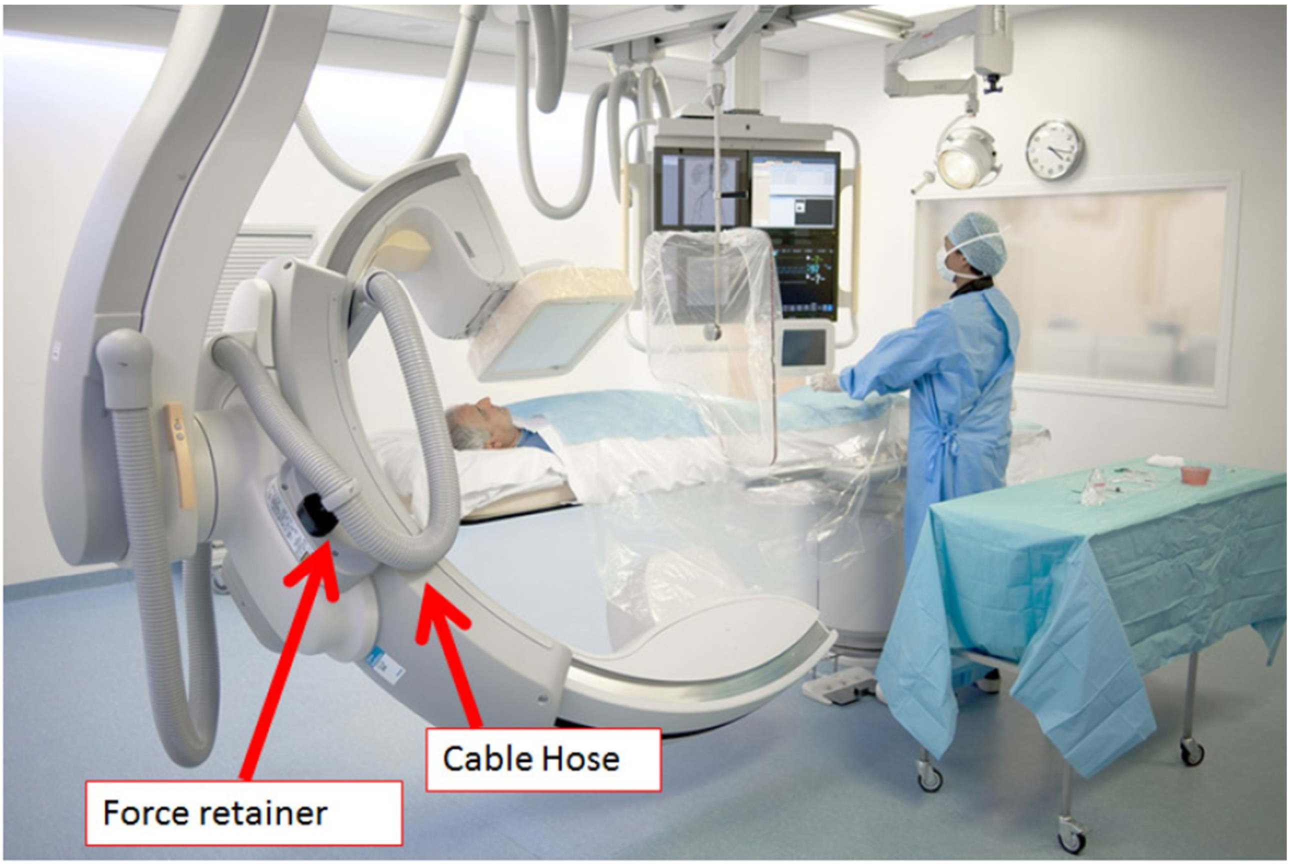


Figure 5.1.1: Cable hose and force retainer – input for model-based control

4.5.2 - Usage of I-MECH Building Blocks

Two building blocks are required to eliminate frequent recalibration of the influence of the cable hose on machine current collision algorithms:

1. Condition monitoring of recalibration data (BB3)
2. Design of the real-time model (BB6).

Both these building blocks are outside the scope of WP-3.

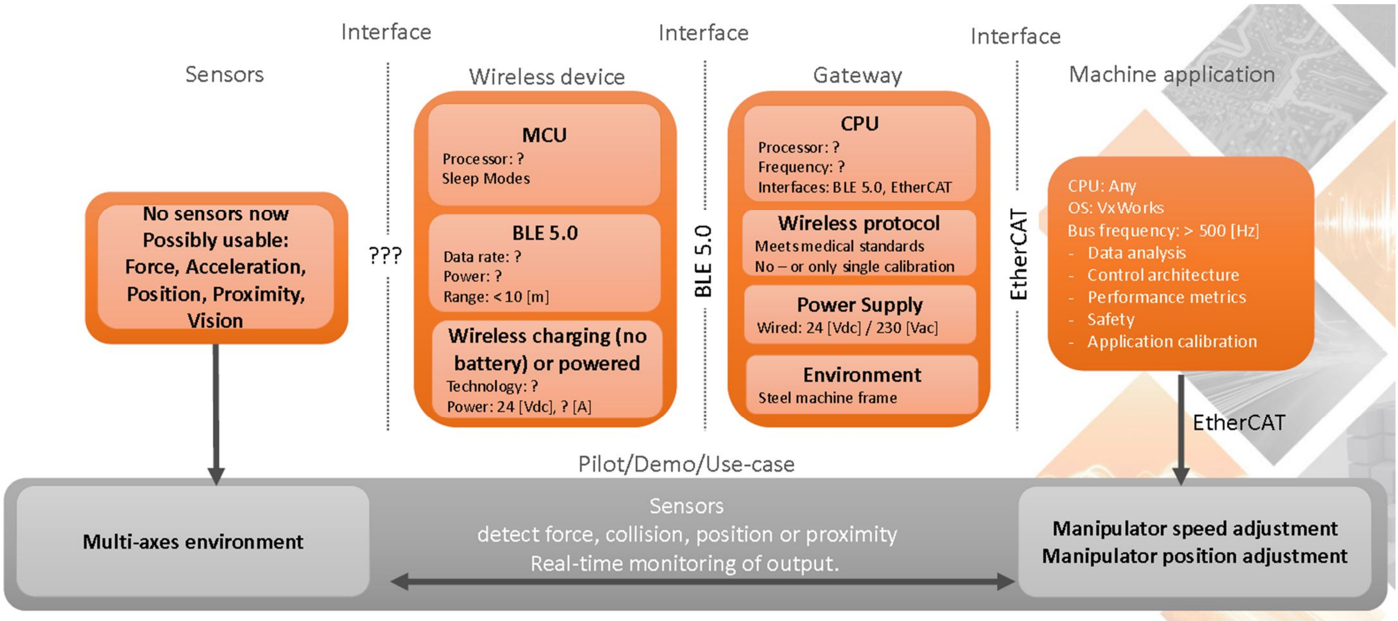


Figure 5.1.2 - Overview Medical robotic manipulator

Note The sensor, interface wireless device and gateway will be defined by the sensors chosen w.r.t. the signal i.e. data bandwidth required. At this time, no decision has been taken yet w.r.t. the sensor system and the derived consequences, see below.

4.5.3 - Functional requirements

Model calculation time	: < 10 [µs] (to be specified)
Model output	: Algorithm, Simulink model or C++ source code
Model calibration frequency	: Never or once
Model accuracy	: > 90 [%] of true physical forces (under discussion)

5 - Demos

5.1 - Demo 1: Process Monitoring and Predictive Maintenance for LSM

5.1.1 - General description

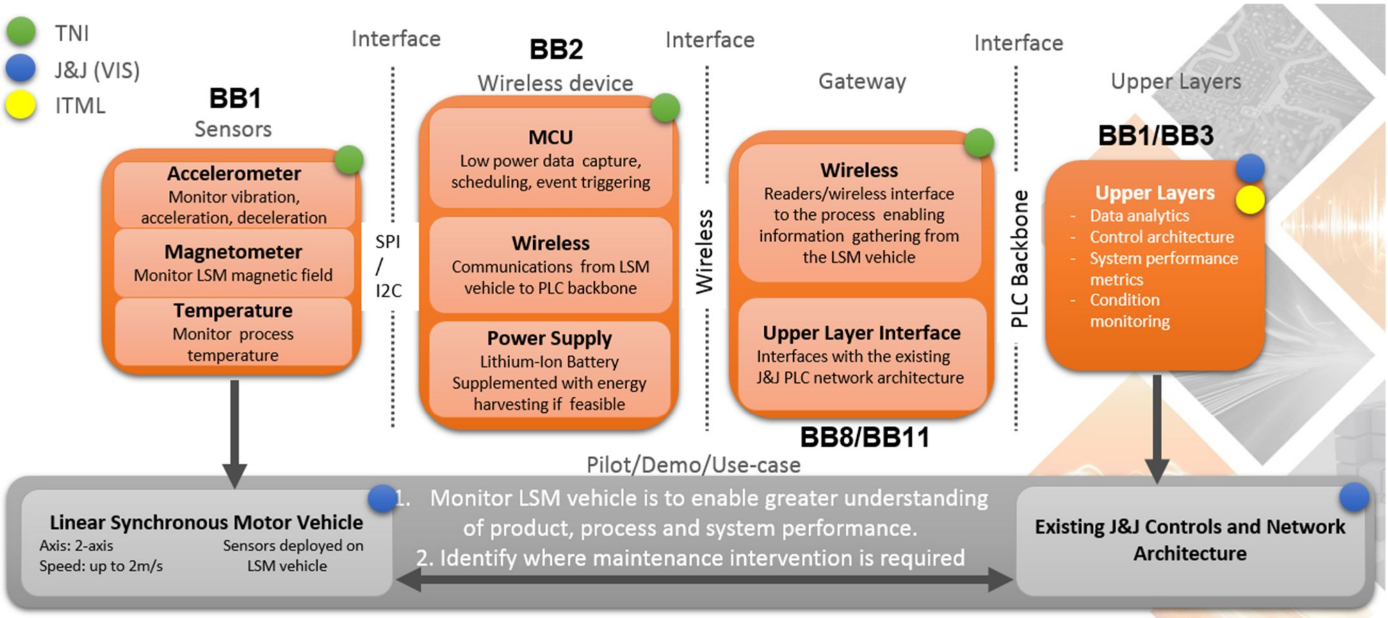


Figure 5.1.1 Condition monitoring platform for Linear Synchronous Motors (LSM) material transfer layer

The overall system will consist of 4 main components:

1. Magnetic field, temperature & vibration sensors
2. Energy harvesting coil to power sensors,
3. Wireless data transmission to PLC,
4. Analytics platform to contextualise and monitor data

5.1.2 - Relation to Building Blocks

Demonstrator 1 will apply smart sensing: **BB-1** and condition monitoring: **BB-6** developed in I-MECH to improve product transfer system performance and implement a predictive maintenance platform to monitor vehicle condition and to address deterioration before failure. This will be achieved with the implementation of wireless sensors **BB-2** to monitor electro-mechanical parameters and the use of a data analysis platform: **BB-10**, developed within I-MECH, to contextualise the data collected.

The requirements for the data analysis will be finalized after the exploratory analysis on the sample data. The challenge is to identify possible correlations between the sensor data in order to design the analysis algorithms to maximize target performance. This process will lead the design of the contextualization modules for the information visualization.

5.1.3 - Functional requirements

Table 5.1.1 Demo 1 requirements and specifications

Functional Requirements[K1]

Req. ID.	Req. title	Value	Rationale
FP 001	Temperature Sensor		Sensor must be able to withstand UV cure temperatures from the range of 20°C to 70°C
FP 002	Temperature Sensor		Sensor must be able to be fitted to the same plane/ area as the product – as close to the product as possible.
FP 003	General Sensor requirement		Sensor resolution will be X10 of the required values (order of magnitude higher resolution). For example, if measuring 20°C to 70°C – the sensor will display/transmit to 20.1°C
FP 004	Magnetic Field Strength sensor		Sensor must be able to measure magnetic field strength of the MagneMotion LSM system between 0.1 – 15 Hz magnetic field frequency and magnetic flux density 50-900 µT (Teslas[WF[2])
FP 005	Vibration sensor.		Sensor will be able to measure vehicle vibration etc. using (technology to be agreed and sensitivity – G loads will come from MagneMotion as to max accel/deceleration.
FP 006	Sensor connectivity		Control input/output shall be Ethernet IP.
FP 007	Sensor connectivity		Sensor data will pass through the existing RFID data transmission to the Rockwell PLC controlling the MagneMotion system[WF[3]

Operational Requirements			
Req. ID.	**Req. title**	**Value**	**Rationale**
OP 001	General requirements		Any sensor developed will integrate with the existing MagneMotion controls.
OP 002	General requirements		Any sensor developed will use industry standard communications protocol back to the PLC (J&J preferred standard is Ethernet IP)
OP 003	General requirements		Sensor power will be via own source supply

OP 004	General requirement		Sensor data will be transmitted back to the main PLC via the same method as current MagneMotion[WF[4] (RFID vehicle reader and data transmission via RFID update)
OP 005	General requirement		If battery powered the sensor(s) /sensor block should have a low battery alarm that can be transmitted [WF[5]
OP 006	Sensor fitment		Sensor / sensors must be able to be fitted to the MagneMotion system without impacting the performance (mechanically or electrically) of the MagneMotion system.
OP 007	Sensor fitment		Ideally, sensor(s) should be fitted in the following fallow areas (TBD and agreed between ACoE and Tyndall and MagneMotion.)
OP 008	Electrical requirements		The control voltage will be 24 VDC. ACoE must approve exceptions to 24VDC control voltage.
OP 009	Electrical requirements		Where DC control voltage is utilized, it will be derived from a regulated power supply with built-in over-voltage and short circuit protection.
OP 010	Electrical requirements		All wires and cables shall be labelled with a label at each point of termination. The label will contain the wire/cable number corresponding to the number shown on the electrical drawings. Machine Controller input/output wires shall be labelled with their respective input/output address. All labels shall be machine printed, permanent, legible and easy to read. [WF[6]
OP 011	Electrical requirements		All other device communications cables should be labelled on each end with two (2) labels. One label indicating the "to" node and one label indicating the "from" node.
OP 012	Electrical requirements		All analogue and non-power (signal) cables will be shielded. ACoE must approve all exceptions.
OP 013	Electrical requirements		Insulation of wires and cables shall meet CE, NEC, and UL ratings. Special attention needs to be given to all high temperature applications. The insulation temperature rating of wiring, cables and terminals in heated areas shall exceed the temperature of the hightemp safety shut-off switch setting. Use MTW wire inside of control panels.

OP 014	Electrical requirements		The minimum wire size for individual wire shall be no smaller than 18 AWG for control wire, and 14 AWG for power wire
OP 015	Electrical requirements		Minimum wire size for wires inside cables shall follow CE, NEC, and NFPA79. ACoE must approve all exceptions.
OP 016	Electrical requirements		A strain relief device consisting of rubber grommets or fibre bushings to prevent damage to insulation shall protect wire/cable passing through the surface of enclosures.

5.2 - Demo 2: Injection mold industry (ECS)

5.2.1 - General description

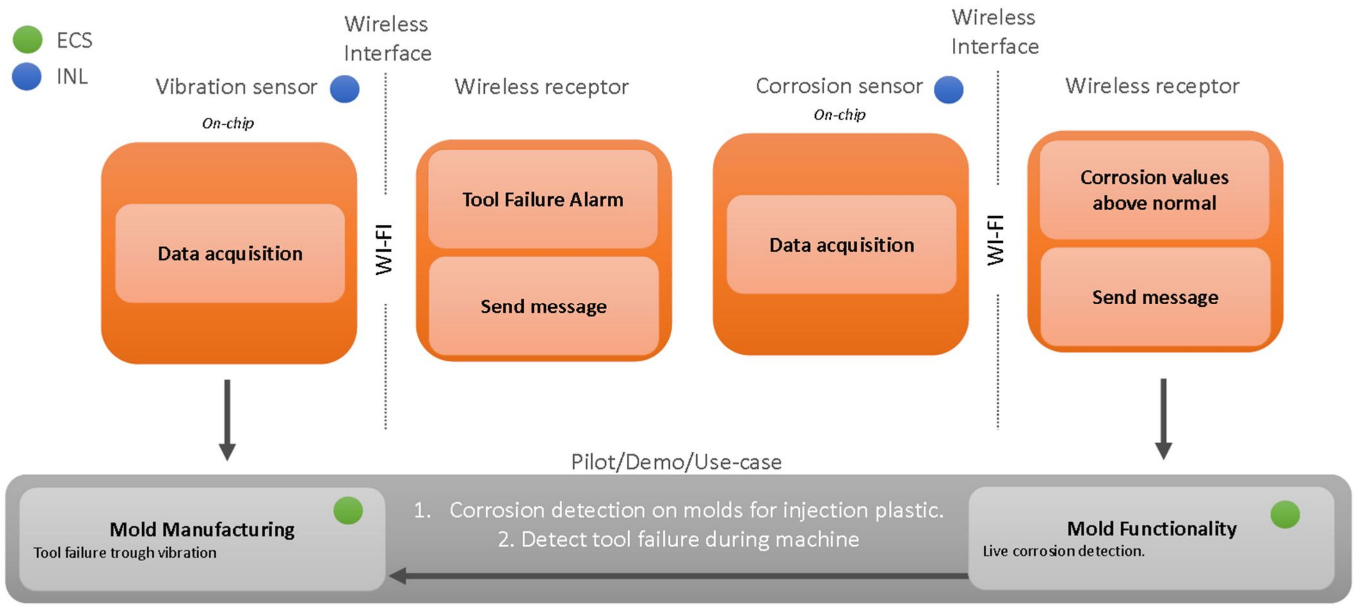


Figure 5.2.1 - Overview Injection mold industry

5.2.2 - Relation to Building Blocks

This demonstrator will be used to evaluate wireless sensing: **BB-2** and smart sensing building blocks: **BB-1**, amongst others, by creating a concept mold with these kind of smart functions, giving to the molding tool a bigger role in terms of functionalities.

It will be divided into 2 parts: Mold manufacturing, and Mold functionality. The first one will be focused on implementation of sensors capable of giving a response during the manufacturing of mold, such as tool failure. The second one will be focused on the functionality of mold, were it will be implemented sensors/actuators capable of interact and acquire data from the tool. In this case, a corrosion sensor that will give me a response on when maintenance should be done. The next diagram explains the main interactions.

5.2.3 - Functional requirements

The functional requirements will be updated with the release of the second version of this document.

6 - WP-3.x (and related BBs) specifications and requirements

With the information as given by the Use-cases, Pilots and Demos, the specifications and requirements for the WP3.x related topics and building blocks are references throughout the I-Mech project and given below.

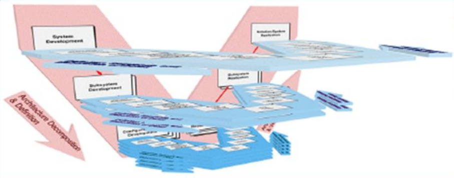
			BB 1 (D3.3) [CLICK HERE] Advanced sensor signal processing module	BB 2 (D3.4) [CLICK HERE] Real-time Wireless Sensors	BB 4 (D3.5) [CLICK HERE] High speed vision	BB 5 (D3.6) [CLICK HERE] High performance current amplifiers	BB 10 (D3.7) [CLICK HERE] Multi-many core for control
USE CASES	USE CASE 1.1 (GEFRAN)	Improved motion of Hoist/Crane	BB1 & UC1.1	X	X	X	X
			ZAPUNI Coordinator of Building Block	X	X	X	X
	USE CASE 1.2 (FAGOR)	Improved motion of CNC Machine	X	X	X	BB5 & UC1.2	BB10 & UC1.2
			X	X	X	INGENIA Coordinator of Building Block	TUE Coordinator of Building Block
	USE CASE 1.3 (TECO)	Improved motion of PLC driven portal robot	BB1 & UC1.3	X	BB4 & UC1.3	X	X
			ZAPUNI Coordinator of Building Block	X	TNO Coordinator of Building Block	X	X
	USE CASE 2.1 (GMV A&D)	Improved motion of 6DOF industrial robot	X	X	BB4 & UC2.1	BB5 & UC2.1	BB10 & UC2.1
			X	X	TNO Coordinator of Building Block	INGENIA Coordinator of Building Block	TUE Coordinator of Building Block
	USE CASE 2.2 (ZAPUNI)	Improved motion of 6DOF cost effective robot	BB1 & UC2.2	X	BB1 & UC2.2	X	BB1 & UC2.2
			ZAPUNI Coordinator of Building Block	X	TNO Coordinator of Building Block	X	TUE Coordinator of Building Block
PILOTS	PILOT 1 (SIOUX CCM)	Generic Substrate Carrier	BB1 & P1	X	BB4 & P1	BB5 & P1	BB10 & P1
			ZAPUNI Coordinator of Building Block	X	TNO Coordinator of Building Block	INGENIA Coordinator of Building Block	TUE Coordinator of Building Block
	PILOT 2 (NEXPERIA)	12-Inch Wafer Stage	BB1 & P2	BB2 & P2	BB4 & P2	BB5 & P2	BB10 & P2
			ZAPUNI Coordinator of Building Block	EDI Coordination of the Building Block	TNO Coordinator of Building Block	INGENIA Coordinator of Building Block	TUE Coordinator of Building Block
	PILOT 3 (IMA)	Tea-bag Machine	X	X	X	X	BB10 & P3
			X	X	X	X	TUE Coordinator of Building Block
	PILOT 4 (Correa)	Milling Machine	BB1 & P4	BB2 & P4	X	X	X
			ZAPUNI Coordinator of Building Block	EDI Coordinator of Building Block	X	X	X
	PILOT 5(PHILIPS)	Medical Manipulator	BB1 & P5	BB2 & P5	X	X	X
			X	EDI Coordinator of Building Block	X	X	X
DEMOS	DEMO 1 (J&J Vistakon)	Improved motion of MagneMotion LSM technology	BB1 & D1	BB2 & D1	X	X	X
			X	EDI Coordinator of Building Block	X	X	X
	DEMO 2 (Edilasio)	Improved quality of injection molding	X	BB2 & D2	X	X	X
			X	EDI Coordinator of Building Block	X	X	X

Figure 6.1 - Relation matrix between only the tasks of WP-3 versus the use-cases, pilots and demos.

In the descriptions below, the overall requirements and specifications for the various building blocks as being developed under the tasks of WP-3 are given. While focussing on the Pilot projects in particular, there is a need for smarter sensors and smarter drives while maintaining, or even enhancing the exchange of data in-between these smarter sensors: **BB-1**, and smarter drives: **BB-5**, and the overall controller: **BB-10**, through wired and wireless interfaces: **BB-2**. Vision in the loop: **BB-4** is considered differently by the projects. The requirements for interfacing of data i.e. set-points range from analog: 4-20 mA or 0-10 volt to digitally with all possible ‘std’ interfaces and protocols to wireless. Considering bi-directional communication between the sensors, encoders, cameras, drives and controller(s), data rates between kb/s to Gb/s are required which put their burden on the wired or wireless interface chosen in these often harsh motion environments, including interference, moisture, vibration.

6.1 - Common I-Mech layer 1 hardware specifications and requirements

An I-Mech compliant motion control platform shall support the use of building blocks as defined. The motion control platform shall be easy accessible for programming, monitoring and upgrading through exchange of an SD-card, Industrial USB, Ethernet, secure WiFi, etc. Programming and upgrading shall only be allowed during development and after installation when in close proximity i.e. visual sight of the motion system. Late configuration of a motion controller could be done by use of RF-ID while leaving the factory /warehouse i.e. configuration of all the I/O ports used according the specifics needs e.g. gain settings, filtering with the specific motion system required. The same kind of post-programming could also be done with the smart sensors and smart drives to pre-program their needs prior to installation.

The hardware layer of the I-Mech compliant motion control platform shall enable the programming and interface optional needs required up to the level i.e. including all the embedded driver stacks to the level that the hardware can be unified accessible by the application software. However, care shall be taken that the multi-options foreseen aren’t becoming a burden to the overall design. Nowadays, most FPGAs have multi-programmable I/O ports by which ports could be USB as well as Ethernet or any other serial or parallel bus.

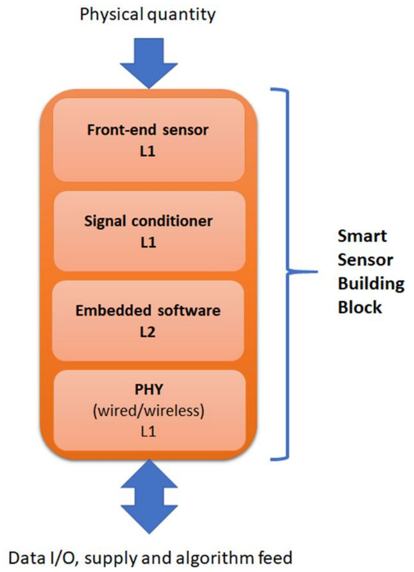


Figure 6.1.1 - Example for a Smart Sensor Building Block

All hardware used with layer 1 of the I-Mech compliant motion control platform shall be compatible with the simulation models to enable hardware-in-the-loop (HiL) system development. I.e. all parameters as required by the software modelling used shall be made available through the layer 1-2 interface of the I-Mech motion platform and requires that embedded software is part of the hardware building blocks as developed.

State-of-the-art I-Mech smart sensors, smart encoders and smart motion controllers **don't use** analog interfaces anymore due to the fact that (most-of-the-time) bi-directional data paths are needed and the fact that the signal required will be sampled at 16 kS/s with 16, 24 or even 32 bits to obtain the resolution required, see figure 6.1.1. Analog interfaces need vast filtering, by hardware and software to eliminate the induced noise on the signal interface down to the LSB resolution required. As such, smart sensors provide the benefit, that all pre-conditioning is done at the sensor and while doing so, the signals can be locally converted to any (serial) digital stream to become more robust and easy to handle both by wired and wireless signal interfaces. The drawback is the need for the local smartness with known latency between the physical parameter being sensed and the digital representation obtained. Sensors with latency need to provide data with time stamping to be able to de-embed the delay between the moment of sampling-and-hold of the physical parameter observed. The bi-directional interface towards the sensor systems are also needed to upload algorithms, filtering or limit points i.e to adapt and optimize the smartness of the sensor system in its application. The burden of this smartness flexibility will be w.r.t. modelling e.g. hardware-in-the-loop. Those software-defined smartness changes affect the behavior model of the sensors i.e. these need to be simulateable too.

Nevertheless, the I-Mech motion platform defined smart sensors and encoders will have bi-directional digital links by which the obtained converted data can downloaded and all kind of algorithms and optimization settings can be uploaded. All signal pre-conditioning and time stamping shall be done within the smart sensor/ encoder hardware.

State-of-the-art I-Mech smart drives and motion controllers **don't use** analog interfaces anymore due to the (most-of-the-time) bi-directional data path needs and the fact that the signal resolution required will be sampled at 16 kS/s with 16, 24 or even 32 bits. Drives will be provided with set-points, with/without feed-forward and will be locally obtain feedback from sensors, encoders or vision-in-the loop to ensure accurate positioning with the settling time frames required. Also here, the time in-between the (software) instructions given and the final displacement 'reached' condition needs to be known.

The bi-directional interface towards the drive systems are also needed to upload algorithms filtering or PID settings i.e to adapt and optimize the smartness of the drive system to its application. The burden of this smartness flexibility will be w.r.t. modelling that those software-defined smartness changes affect the behavior model of the drives when these need to be simulateable too.

Nevertheless, the I-Mech motion platform defined smart drives will have bi-directional digital links by which the set-points can uploaded together with all kind of algorithms and optimization settings. All the re-active feedback from the drive: temperature, currents and voltages as well as the data obtained from the sensors, encoders or vision-in-the loop can be downloaded for further analysis and control: wear-out, collision detect, vibration and sway. All signal pre-conditioning and time stamping shall be done within the smart drive hardware.

Overall, it would be a great advantage if I-Mech motion platform identification would be possible too. Which the parts are involved such that the main controller is able to verify the sensors, drives and actuators used in the I-Mech motion platform system and then is able to adapt the optimal settings accordingly, all within the hardware bounds of the parts of the I-Mech motion platform building blocks used. Drives shall be able to verify their loads i.e. actuators and then act accordingly.

6.2 - Task 3.2 - Unconventional actuator and sensor principles

The unconventional actuator and sensor principles needed by all use-case, pilots and demos analyzed are mainly focussed to an extension of data exchange between the sensors and drive/actuators to enable access to the variables: voltage, current, temperature, pressure, etc. needed for the new building blocks addressing algorithms for corrections. W.r.t. the unconventional actuators, most interest is in MEMS as sensor and actuator as well as piezo sensors and pieze stepping motors to enable measurement of small movements as well as creating small displacements.

The sensors and actuators needed, including MEMS, have to be able to present non-confounded response data which has an unambiguous relation to the physical, optical or chemical property to be measured. To ensure a robust design, the obtained electrical response of the physical, optical or chemical property has to be (signal) conditioned locally before sending it over a wired or wireless interface, when possible with low overall power consumption. Internal compensation techniques will be required to ensure that the sensors provide the signals necessary and the actuators driven arrive at the set-point unconditionally, as fast as possible with low latency (or compensation by using time-stamping) and low power consumption.

For the sake of simple wired connectivity (2-wire applications), the analog 4-20 mA interface is still often used as it has the ability to power up the sensor e.g. single axis accelerometers. For data robustness, a 3- or 4-wire interface is preferred where differential digital (or analog: 0-10 volt) data is running in parallel to the supply voltage needed. With smart(er) sensor development, as shown in figure 6.1, the front-end sensor is extended by signal conditioning hardware and software and it will interface (mostly) in digital formats.

Whether the smart sensor is embodied in one housing or distributed will be determined by the definition of a building block as being part of a modular design. As such, smart (sub-)systems i.e. building blocks are considered modular and interchangeable with limit efforts, both in hardware as in software. Distributed (sub-)systems are unpractical in this sense w.r.t. EMC and other environmental boundary conditions.

For the sake of power efficiency, most of the actuators are driven by pulse width modulated (PWM) signals which cause high levels of interference inside and outside the motion system. sensors might fail to fulfil their performance due to the noise induced by any power converter: AC/DC, DC/DC, UPS or PWM drive. Developments are needed which compensate this interference with a minimum amount of loss, volume and costs. Synchronized compensation is needed by active compensation.

In addition to conventional Si MEMS devices, flexible sensors for pressure, vibration and acceleration are currently being modeled, designed and fabricated.

6.2.1 - Layer 1, Specifications and requirements: New actuator and sensor developments

Pilot-4:

- IKERLAN will cross the specifications of the commercially available position sensors and accelerometer and will match them with the requirements of the Pilot. From this matching, we will identify the functionalities that only needed for our Pilot.

- IKERLAN will send these functionalities to INL and OE with the purpose of designing and fabricating ad-hoc components (sensor and accelerometer) with only these specific demanded functionalities focusing on lowering the energetic consumption as much as possible.
- OE will collaborate with INL in the design, modelling and simulating the fabrication and performance of the newly developed components.
- INL will fabricate these components and will send them to IKERLAN for integration in operational devices.

6.3 - Task 3.3 - (BB-1) Platform for Smart Sensors with Advanced Data Processing

The motion control platform will change from heavy centralized control (taken data from simple sensors) to smart decentralized sensors and smart vision in the loop and smart drives as the amount of communication (bitrate) and the latency (delay) will change from the initial set-point communication to streaming feedback of all kind of parameters to enable the measurement of: wear-out, collision-detect, vibration and sway.

Smart sensors are able to convert the physical, optical or chemical parameters acquired into compressed data with minimum, or in advanced known, data loss and latency. Typical smart sensors are interferometers which convert the modulated optical delay into distance with high accuracy. Other examples are speed cameras (beyond the scope of this project). These speed cameras determine: time, speed as well as acquire the number plate of the vehicle as minimum data output. No triple high-speed photo is required anymore to derive a speed violation after which the number plate has to be read back from the photos taken. Also with pick-and-place machines, vision in the loop (pilot 2) is used to align to components to their solder pad locations. Not the entire video frame is used for processing but only from the corner coordinates and their rotation/ elevation, typically obtained from a contour algorithm. Such in-camera smartness decimates the data on the interface bus which then enhance the accuracy of the information and minimized the data transfer required.

Other sensors need to be smart anyhow in order to de-embed the data necessary from the sensor-to-electrical interface. Opposite, DC-offset in amplifiers used with signal conditioning will be sensitive to local (on-chip) temperatures (even with their on-chip gradients) in case of strain-bridges, Hall-sensors, etc. The output data provided by such a smart sensor is then already 'corrected' for the temperatures measured such that the controller obtains the ' real' data.

Similar as with drives, the variety of interfaces and interface protocols is very broad. Aside the analog interfacing, the digital interfacing will be broad, varying from RS-232, RS-422/485, Lin-, CAN(open)-, MOD-Profibus, ethernet, ethercat, USB, etc. The king of interface required should be selectable by initial software settings. Typical sensor signal data rates will occur between samples /second to Gb/s.

Other sensor smartness will be moving average, elimination of interferences, elimination of outliers, MPEG-4 data compression, etc. All 'smart' data corrections done locally and their impact on the correctness of the original data needs to be known as well as the additional delay which is introduced by the corrections applied.

The smart drives, the smart encoders and the smart sensors are transmitting their data through shared data busses. Using a typical data exchange speed of 10 kHz (or less) allows for time division multiplexing of the signals on the bus. These kind of data exchange speeds are sufficient to enable motion control loops of a few hundred Hz. If one wants to achieve control loops much faster, the data exchange i.e. sampling rate needs to be much faster accordingly. A typical value of 1:10(0), control loop bandwidth versus sampling rate is quite common.

6.3.1 - Layer 1, Specifications and requirements BB-1: Smart Sensors with Advanced Data Processing

Pilot-1:
Replace CLIB PCI card with de-centralized advanced sensor signal processing module, as indicated in the figure below (to become locally smart). The new implementation should be more compact by not requiring a cumbersome PCI interface and should be less expensive.

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot1-BB1.1	FPGA specs	Xilinx FPGA with sufficient available resources for existing algorithm implementation (currently implemented on an Altera Cyclone EP4CE30F23C7).			-
rq-Pilot1-BB1.2	Communication (fieldbus) interface	EtherCAT slave			-
rq-Pilot1-BB1.3	EtherCAT sample rate		10		kHz
rq-Pilot1-BB1.4	Target price	500			€
rq-Pilot1-BB1.5	Live updatable parameters via EtherCAT: - At Startup (once for initialization) - Low update rate (e.g. 1…100Hz) - High update rate (10 kHz, each sample)	Yes			
rq-Pilot1-BB1.6	Firmware upgradable via EtherCAT (FoE)	Yes			
rq-Pilot1-BB1.7	*Wish: Integration with BB5 amplifiers*	8x			
Belt transport position SinCos encoder inputs					
rq-Pilot1-BB1.8	Number of analog inputs		6	-	-
rq-Pilot1-BB1.9	Analog input resolution		14	-	bit

rq-Pilot1-BB1.10	Analog input sample rate[1]		1		MHz
rq-Pilot1-BB1.11	Analog input low pass noise reduction filter passband frequency range		0	500	kHz
rq-Pilot1-BB1.12	Analog input low pass noise reduction filter passband gain.		-0.5	0.5	dB
rq-Pilot1-BB1.13	Analog input anti-aliasing filter	No			
rq-Pilot1-BB1.14	Analog input type	Differential			
rq-Pilot1-BB1.15	Analog input voltage range :				
			0	5	V
			0	5	
rq-Pilot1-BB1.16	Analog input differential voltage range		-0.68	0.68	V
rq-Pilot1-BB1.17	Number of RS-422 digital inputs (encoder index pulse)		3		
rq-Pilot1-BB1.18	RS-422 digital input (encoder index pulse) sample rate		1		MHz
Belt transport position encoder outputs					
rq-Pilot1-BB1.19	Number of RS-422 digital outputs[2]		4		-
rq-Pilot1-BB1.20	RS-422 digital output sample rate		20		MHz

Wish: AMSR gap sensor inputs					
rq-Pilot1-BB1.21	Number of analog inputs		6	-	-
rq-Pilot1-BB1.22	Analog input resolution		16	-	bit
rq-Pilot1-BB1.23	Analog input sample rate		10		kHz

rq-Pilot1-BB1.24	Analog input anti-aliasing filter	Yes			
rq-Pilot1-BB1.25	Analog input type	Differential			
rq-Pilot1-BB1.26	Analog input voltage range :				
			-0.5	10	V
			-0.5	0.5	
rq-Pilot1-BB1.27	Analog input differential voltage range		0	10	V

Pilot-2:

Advanced sensor signal processing module requirements

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot2-BB1.1	Communication (fieldbus) interface	EtherCAT or preferred: Gb Ethernet			-
rq-Pilot2-BB1.2	Field bus sample rate	20	10	20	kHz
rq-Pilot2-BB1.3	Live update of parameters via fieldbus: - At Startup (once for initialization) - High update rate (each sample)	Yes			
rq-Pilot2-BB1.4	Firmware upgradable via fieldbus	Yes			
rq-Pilot2-BB1.5	*Wish: Integration with BB5 amplifiers*	Yes			

Pilot-4:

See project description

6.4 - Task 3.4 - (BB-2) Real-time wireless sensors providing complementary feedback information

Wired interfaces have the drawback of torsion and strain by the interface cables used. Wired interfaces from sensors are often affected by the noise from the motor cables running at short distance (while not being provided with some noise compensation technique. The velocity of the wired interface is known as well as the attenuation per unit of length (when high-speed signalling is used). The use of the insulation material with wired cables determined the maximum data transfer rates possible, which can go up to several Gb/s.
Also, cabled sensors not always can be put on rotating mechanical parts, which limits the possibility to increase the performance of mechatronic systems.

Changing to wireless interfacing, typically does not affect the front-end design of a sensor. Analog or digital data needs to be converted into a serial stream of data which can be transmitted over a wireless link. This will typically be done as a point-to-point connection, different from an WiFi access-point where many users can simultaneously access the interface node. Many standardized and non-standardized protocols and interfaces are known: Zigbee, BLE, Mira-net, Z-Wave, Wireless USB, UWB all having their own limitations and specifications w.r.t. operating frequencies, multi-path robustness (moving nearby metal), data security which have a serious impact on latency. Task 3.4 has to demonstrate the impact of going wireless compared to staying wired w.r.t. latency and system stability.

A remaining topic for wireless sensors i.e. wireless interfacing is the need for power, either from rechargeable batteries or from electrical noise, motion or other means of wireless or contactless energy scavenging to enable the sensor and its real-time wireless interface to operate. These measurements should be transmitted wirelessly with low latency, corresponding speed, refresh rate and distance. In addition, such parameters as energy efficiency, system's operation time without battery change, auto calibration, communication interfaces, synchronization, power supply, mechanical/electrical/water protection/robustness, electromagnetic compatibility etc. should be carefully considered in BB2.

Typically, the higher the data throughput required, the more power is needed. In addition, a sensors which is able to provide Gb/s of data will require power too. The velocity of the object on which the wireless sensor is mounted affects the wireless link as well as the continuous change of the multipath signal transmission in the link, which may temporarily result in a data brown-out.

6.4.1 - Layer 1, Specifications and requirements BB-2: Wireless sensors

Pilot-2:

Wireless sensor platform			
P2.O9	Raw sensor data size per one sample	8 bytes	1 12-bit number per sensor (4x) per sample
P2.O10	Raw sensor data transmission throughput	0.7 kbps – 200 kbps	Depends on continuous sampling (preferred) or intermittent sampling
P2.O11	Sample rate	56 Hz – 8 kHz	Depends on continuous sampling (preferred) or intermittent sampling
P2.O12	Wireless power transfer	NFC for wireless data and power?	No space for Qi wireless charging

P2.O13	Operating temperature	Temperature (ºC): 20 - 30	Typical working temperature for commercial electronic equipment.
P2.O14	Relative humidity (%)	10 ÷ 100	Typical humidity range for commercial electronic equipment.
P2.O16	Electromagnetic compatibility	Yes	CE certified wireless communication modules and other components must be used to reduce electromagnetic radiation.
P2.O17	Software reset mechanisms	Yes	The system will check for faulty data, or no data from the sensors and will trigger system restart
P2.O18	Hardware reset	Yes	Button for hardware reset of the system
Wireless gateway			
Req. ID.	**Req. title**	**Value**	
P2.O19	Communication protocol	USB 3.0 or Ethernet/EtherCAT	
P2.O20	Connection	Preferably directly to central PC	Would a Bluetooth 5.0 dongle, directly connected to the PC via USB be feasible?

Pilot-4:

IKERLAN will develop the wireless networks to process data from the sensors and send them to the PLC of the milling machine (Figure 4.7). IKERLAN. We will also develop robust protocols with precise synchronization and high energy efficiency transmission for application in harsh industrial environments.

Wireless sensor platform			
Req. ID	**Parameter/Description**	**Values**	**Notes**
rq-Pilot4-BB2.1	Sample rate	20 seconds	Temperature sensors
rq-Pilot4-BB2.2	Sample rate	Periodically (event triggered)	Accelerometer and distance sensors

rq-Pilot4-BB2.3	Operating temperature	Temperature (ºC): 10 - 40	Typical working temperature for a workshop
rq-Pilot4-BB2.4	Relative humidity (%)	10 ÷ 100	Typical humidity range for a workshop
rq-Pilot4-BB2.5	Electromagnetic compatibility	Yes	CE certified wireless communication modules and other components must be used to reduce electromagnetic radiation.
rq-Pilot4-BB2.6	Status	Yes	The system will send the status: OK, NOK, Stand-by, low battery
rq-Pilot4-BB2.7	Check	Periodically	Check communications
rq-Pilot4-BB2.8	Range	3,5-4m	
Wireless gateway			
Req. ID	**Parameter/Description**	**Values**	**Notes**
rq-Pilot4-BB2.9	Communication protocol	Profinet	
rq-Pilot4-BB2.10	Connection	PLC	

6.5 - Task 3.5 - (BB-4) High Speed Vision

With non of the use-case, pilots and demos, high-speed high-definition vision frame rates over 10 k/s are considered. Fast smart cameras are needed with pilot 1 and 2. High-speed high-definition cameras are used to trace movements and to acquire the deviations from the intended path foreseen. The main reason for this is that it is not only about the camera (e.g. 1,000,000 frames per second) but also about the processing of the data (direct feedback) and resolution. Increasingly, high-speed vision systems are used to find errors, check quality, inspect and analyze and / or accelerate the production process. The benefits are quick to imagine and the possibilities seem endless. Which technology is the most suitable and what are the different technologies on the challenges. Important challenges are: required infrastructure, frames per second, exposure time and illumination, data stream / processing to obtain the 'best' image.

Vision in the loop can also be used instead of multiple sensors to correct a motion, check products, etc.but then with less speed, though high resolution.

6.5.1 - Layer 1, Specifications and requirements BB-4: High Speed Vision

Pilot-1

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot1-BB4.1	Communication (fieldbus) interface	EtherCAT slave	-	-	-
rq-Pilot1-BB4.2	EtherCAT sample rate		10		kHz
rq-Pilot1-BB4.3	Target price[1]: Processing + 2x (Camera + optics + illumination)			7000	€
rq-Pilot1-BB4.4	Vision algorithms programmable/modifiable by non-FPGA/VHDL experts	Yes			
Belt edge position measurement					
rq-Pilot1-BB4.10	Number of belt edge sensors	2			
rq-Pilot1-BB4.11	Belt edge sensor output least significant bit[2]	-	0.1	-	um
rq-Pilot1-BB4.12	Belt edge sensor accuracy (including optics which is out of scope)[3]	1	-	2	um
rq-Pilot1-BB4.13	Belt edge sensor sample rate[4]	10	1	-	kHz
rq-Pilot1-BB4.14	Belt edge sensor latency	200	-	1000	us
rq-Pilot1-BB4.15	Belt edge sensor measurement range lateral direction (X)	-	-2.5	2.5	mm
rq-Pilot1-BB4.16	Belt edge sensor measurement range transport direction (Y) [5]	-	1	-	mm
Wish: Belt transport position measurement					
rq-Pilot1-BB4.20	Number of belt transport sensors (Might be combined with belt edge sensors)	1			
rq-Pilot1-BB4.21	Belt transport sensor output least significant bit	-	0.1	-	um

rq-Pilot1-BB4.22	Belt transport sensor accuracy (including optics which is out of scope)	-	1	-	um
rq-Pilot1-BB4.23	Belt transport sensor index detection accuracy	-	1	-	um
rq-Pilot1-BB4.24	Belt transport sensor sample rate	10	1	-	kHz

Pilot-2:

6.6 - Task 3.6 - (BB-5) High performance servo amplifier design

The requirements for high performance servo amplifiers are broad for the partners involved in the I-Mech project. All of the high performance servo amplifiers are considered to be digitally controlled. Deviations are made between:

- low power ↔ high power
- low voltage ↔ high(er) voltage
- low current ↔ high current
- with encoder feedback ↔ without encoder feedback
- low bandwidth ↔ high bandwidth
- local closed loop ↔ centrally closed loop
- without in/output filtering ↔ with in/output filtering (active or passive)
- Fixed frequency ↔ variable frequency power conversion
- single phase or DC ↔ 3-phase mains supply
- without I/V feedback ↔ with I/V feedback (scalar vs full waveshape)
- Load dependent ↔ load independent
- No reference signals ↔ reference signals for active noise compensation: motion, mains and PWM

All high performance servo amplifiers are overload protected by temperature, overvoltage and overcurrent sensing (against adjustable limits)

The first step is to separate the drive stages from the controller to a seperate module aside the controller. This improves the flexibility of choosing a drive in relation to the actuation needed. One step further will be the combination/ integration of the drive with the actuator, using a single cable interface providing power and data, typically well-shielded, to minimize the need for local supply filtering. No output filtering will be required between the drive's output and the motor windings as the wiring is short and well shielded by the metal enclosure of the motor housing (and the heatsink for the electronics), if well-designed.

Main drawback will be that due to the lack of filtering at the output of the drive, substantial losses will occur locally in the motor in the wiring and metal due to eddy-current losses caused by the fast PWM switching of the integrated drives. Another challenge will be to assure integrated input filtering and internal power conversion which doesn't saturate the ferrites used due to the high magnetic flux levels: > 1 Tesla (as typical saturation from ferrites occurs from 0,1 T onwards).

Most smart drives have integrated encoders which can provide local feedback to the response of the actuator to the drive and/or provide that data separately, to the motion controller. Many interface connectors and data protocols are possible. As such, T3.6, BB-5 and T3.7, BB-10 shall be equipped with programmable wired I/O interfaces which can handle the variety of digital communication interfaces, if possible over a common I/O socket. Aside the analog interfacing, the digital interfacing will and will be broad, varying from RS-232, RS-422/485, Lin-, CAN(open)-, MOD- Profibus, Ethernet, Ethercat, USB, etc. I2C and SPI-bus are only considered as an internal communication protocol within a module. Even wireless control of high performance servo amplifiers are considered by industry.

6.6.1 - Layer 1, Specifications and requirements BB-5: High performance current amplifiers requirements

Pilot-1:

Generic amplifier requirements

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot1-BB5.1	All relevant signals and statuses of the amplifier, including signals from the current loop, shall be traceable for the central control layer (layer 2) at the sample rate of the bus interface with the central control layer.	Yes			
rq-Pilot1-BB5.2	It shall be possible to auto-tune the current loop	Yes			

rq-Pilot1-BB5.3	It shall be possible to tune the current loop manually	Yes			
rq-Pilot1-BB5.4	Minimal functions for human safety	- Safe Torque Off (STO)[1] - Switch back to failsafe outputs on communication loss			

Requirements for amplifier used for reluctance actuators

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot1-BB5.10	Current loop PI-control bandwidth (with AMSR actuator resistance: 6.8 Ohm, Inductance: 49.5 mH @100Hz)		500	-	Hz
rq-Pilot1-BB5.11	Number of motor phases	1			
rq-Pilot1-BB5.12	Current loop sample rate		32		kHz
rq-Pilot1-BB5.13	Current sensing resolution		0.2		mA
rq-Pilot1-BB5.14	Current demand resolution		0.1		mA
rq-Pilot1-BB5.15	Continuous current		1	3	A
rq-Pilot1-BB5.16	Peak current		2	6	A
rq-Pilot1-BB5.17	Bus voltage		24	48	Vdc
rq-Pilot1-BB5.18	PWM frequency		32		kHz
rq-Pilot1-BB5.19	PWM resolution		12		bit
rq-Pilot1-BB5.20	(field) bus interface (also for configuration and update of firmware)	EtherCAT & SPI[2]			
rq-Pilot1-BB5.21	Sample rate bus		10		kHz
rq-Pilot1-BB5.22	Cost price per axis			70	euro

Requirements for amplifier used for AC servo motor

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot1-BB5.30	Current loop PI-control bandwidth (Rph-ph=4,64Ohm, Lph-ph=24mH)		500	-	Hz
rq-Pilot1-BB5.31	Number motor phases	3			
rq-Pilot1-BB5.32	Current loop sample rate		32		kHz
rq-Pilot1-BB5.33	Current sensing resolution		2		mA
rq-Pilot1-BB5.34	Current demand resolution		1		mA
rq-Pilot1-BB5.35	Continuous current		10		A
rq-Pilot1-BB5.36	Peak current		15		A
rq-Pilot1-BB5.37	Bus voltage	325	325	565	Vdc
rq-Pilot1-BB5.38	PWM frequency		32		kHz
rq-Pilot1-BB5.39	PWM resolution		12		Bit
rq-Pilot1-BB5.40	(field)bus interface (also for configuration and update of firmware)	EtherCAT			
rq-Pilot1-BB5.41	Sample rate bus		10		kHz
rq-Pilot1-BB5.42	Cost price per axis			800	euro
rq-Pilot1-BB5.43	Encoder input	SSI (absolute) & SinCos			
rq-Pilot1-BB5.44	Commutation method	Required: Field Oriented Control. *Wish: Ia/Ib current control for open loop rotation (like a stepper motor)*			

Pilot-2:

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot2-BB5.1	All relevant signals and statuses of the amplifier, including signals from the current loop, shall be traceable for the central control layer (layer 2) at the sample rate of the bus interface with the central control layer.	Yes			
rq-Pilot2-BB5.2	It shall be possible to auto-tune the current loop	Yes			
rq-Pilot2-BB5.3	It shall be possible to tune the current loop manually	Yes			
rq-Pilot2-BB5.4	Minimal functions for human safety	- Safe Torque Off (STO) - Switch back to failsafe outputs on communication loss - Preferably, drive safety can be controlled in several zones, perhaps using an approved (digital) protocol for safety systems Safe speed will require input from an auxiliary encoder/tacho for speed monitoring			
rq-Pilot2-BB5.5	Outputs shall be EMC filtered	Yes			
rq-Pilot2-BB5.6	Voltage feed-forward shall be possible	Yes			
rq-Pilot2-BB5.7	Standard protection features (RMS current, I2T power, Max current)	Yes			
rq-Pilot2-BB5.8	Current loop bandwidth	5			kHz
rq-Pilot2-BB5.9	Current requirements	2 x 3-phase, 60V, 5A RMS, 15A peak 4 x 1-phase, 60V, 2A RMS, 6A peak			
rq-Pilot2-BB5.10	Current resolution	0.6			mA
rq-Pilot2-BB5.11	Current loop SNR	90			dB

rq-Pilot2-BB5.12	Commutation	Field-oriented control, custom			

Pilot-4:

See project description

6.7 - Task 3.7 - (BB-10) Development / selection of control specific multi-many core platform

The specific multi-many core control platform specification is determined by the smartness of the sensors and smart drives connected (as well as high speed vision which need DMA access). This will determine the computational strength required for the core controller.

In addition, the multi-many core control platform must be able to handle a huge amount of I/O interface types, if possible implemented in hard- and software such that RS-232, RS-422/485 (20 Mb/s), Lin-, CAN(open)-, MOD- Profibus, ethernet (100 Mb/s or 1 Gb/s), ethercat (< 100 Mb/s), USB 2 or 3, Firewire, etc. can be handled through a single I/O port, as most of them have a 4-wire interface in common.

As the multi-many core control platform is part of the control loop also here the latency i.e. data throughput from input to output or better from sensing to actuation (full closed loop) needs to be taken into account. Similar as with the wireless interfaces and the smart sensors and smart drives, each smartness will add up in latency and further Pareto analysis will be required to analyze their contributions to the overall latency.

For many motion applications, a PLC or PC (quad or 8-cores) is fast enough to enable control of a motion system, running dedicated algorithms. The need for a dedicated multi-many core control platform may enable parallel processing rather than sequential processing such that multiple axis are driven simultaneously.

6.7.1 - Layer 1, Specifications and requirements BB-10: Multi-many core for control

Pilot-1:

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot1-BB10.1	Performance	At least equivalent to: CPU board Intel Core i5 6440EQ - Quad core - Chipset QM170 - 2.7 GHz[1]			
rq-Pilot1-BB10.2	Hardware suited for executing EtherCAT master	Yes			

rq-Pilot1-BB10.3	Hardware suited to execute compiled Simulink models	Yes			
rq-Pilot1-BB10.4	EtherCAT sample rate	10			kHz
rq-Pilot1-BB10.5	Position control loop update rate	10			kHz
rq-Pilot1-BB10.6	Capable of executing realtime controller and non-realtime operating system (Linux or Windows) simultaneously on platform.[2]	Yes			
rq-Pilot1-BB10.7	Hardware cost target			1000	euro

Pilot-2:

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot2-BB10.1	Performance	Sufficient to perform servo loop computations for several (MIMO) axes[1]			
rq-Pilot2-BB10.2	Ethernet sample rate	20		20	kHz
rq-Pilot2-BB10.3	Position control loop update rate		8	20	kHz

Pilot-3:

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot3-BB10.1	Hardware Architecture - CPU	x86 with VT-x and VT-d support. At least 4 cores			-
rq-Pilot3-BB10.2	Hardware Architecture - Interfaces	PCI, PCI-e, ethernet, serial port			
rq-Pilot3-BB11.1	Supported OSes	VxWorks 6.9.x and 7			

rq-Pilot3-BB11.2	Minimum scheduling cycle time		-	50	us
rq-Pilot3-BB11.3	Scheduling jitter		-	1	% of cycle time
rq-Pilot3-BB11.4	Performance monitoring tool	As per project description			
rq-Pilot3-BB11.5	Communication and interface	As per project description			

Pilot-4:

See project description

7 - Open issues (to be considered too)

Hardware requirements for motion control systems divided into its elements

Modern motion control systems comprise sensors and encoders to provide the input and/or feedback. These sensors and encoders then deliver their signals to the motion control system which then drives the actuators and motors through amplifiers and drives.

7.1 - Infrastructural requirements

Nowadays, most **external** digital signal interfaces are serial: Firewire, Industrial-USB, Ethernet, Ethercat, Profi-, CAN- or MOD-Bus, HDMI, etc. rather than parallel. SPI and I^2C serial busses are intentionally **internal** bus concepts though these appear quite often as in-between bus too. Wired interfaces require suitable cable/wiring with sufficient bandwidth to ensure signal integrity and most likely power integrity (including voltage drop). Cables should also be suited for the motion required e.g. the dynamic link to be bridged i.e. cable caterpillar w.r.t. lifetime. i.e. reliability, stiffness, weight, etc. up to the level of system integration (mounting constraints), installation and serviceability.

Cable selection comes together with the connector i.e. terminal interface to be defined to enable both the functional signals: power and/or high-speed signals and their appropriate shielding to minimize unintended crosstalk e.g. between PWM driving motor cables and small-signal analog or digital sensor and encoder signals . Cable assemblies can be preassembled and molded or need to be assembled in production or at the location of the end installation and adjusted in length. The latter case requires easily to assemble connectors on not too complex cables. In many IT and motion applications, standardized length of cables are used, being too long. Superfluous length of cables are stashed away in cable ducts. Often cable ducts, intended for an mechanical and electrical interface between a control cabinet and the mechanical frame of the machine are kept electrically ‘floating’ from the machine frame and the control cabinet; just used as a mechanical carrier of the cables, instead of being electrically grounded at both ends to machine frame and the control cabinet. Also quite often, 'your' cable tray is (ab)used (as a mechanical carrier) by cables which don't belong there at all.

Determined by the installation, DIN terminal blocks, multi-terminal blocks, Sub-Dxy, LEMO or multi-pin connectors are used as a few are indicated in the photo below. Neither the DIN terminal blocks nor the multi-pin connectors blocks are suited to transfer high-speed signals. Sub-Dxy and LEMO connectors can be used up to about 100 Mb/s if the signal pins are properly assigned, the dedicated round connector as in the center of the photo (Phoenix contact) can do all: power, control and high-speed interfacing up to 1 Gb/s.

Wireless data transfer and their latency (including the data delay and brownout protocol due to multipath signals e.g. from moving metal objects affecting the transmission path) needs to be suited for the motion control system signal interface required. E.g. BT-5.0 (2 Mb/s at low power) is even suited for smart vision applications when the raw data is crunched to a few ASCII-strings i.e. coordinates but will be unsuited for continuous raw-video HD data transfer at high rates e.g. 1 Gb/s. Data manipulation like MPEG-4, where only data from the changing video content is being transferred and all stationary information is transferred only once or even ignored might be possible with BT-5.0 too. This also applies to contour detection algorithms w/wo color detection. New media like 5G will provide sufficient bandwidth but won't guarantee the latency as required in a motion control system. Here again, the choice for the wireless interface: Layer 1, and the protocols necessary to guarantee steaming data up and down with sufficient quality of service (QoS) (Layer 2) will be determined by the overall motion system requirements.

> **The exact figures for the latency of the wired and wireless interface protocols/ solutions needs to be investigated and analyzed, taking into account the data (de-)modulation and/or data protection protocols.**

Wired and wireless connected motion control systems need to be connected in (presently) a harsh environment, vibration, temperature, electrical noise, etc. As the constraints posed on the sensors, motion control system and actuators are tough, similar requirements have to be posed on the infrastructure of the overall motion control system being the electro-mechanical structure to which the motion control system is connected and the wired infrastructure in particular. W.r.t. the wireless interfaces and the presence of movable metal parts, the effects of multipath signal reflections up to even Doppler effects may arise.
The sensors/encoders, the motion control system itself and the actuators/motors driven shall be designed such that NO functional signals require an external cable screen (certainly not a mechanical structure) to enable operation e.g. coaxial cable. All wiring shall be assigned such that the sum of all signal currents on the wires inside a shielded cable add up to 'zero' (for the frequencies of interest, starting at DC). As such, no external currents i.e. flux results which then allows to bundle sensor, actuator and power cables close together in a cable slab or cable tray.

Interfaces and their connector pin assignment shall be chosen such that the above given requirements can be fulfilled and if possible standardized e.g. RS-232 uses pin 2 (Rxd) and 3 (Txd) for communication and pin

5 as being signal reference, the RS-232 cable' outer shield connects to the (metal) enclosures of the subsystems connected but is NO part of the signal interface. The outer shield shall not be continued over a pin but over the conductive connector shell/socket. This could be achieved with USB-2 too, but in most cases the outer cable shield is used in parallel to the ground reference wire (to lower the DC resistance of the cable). USB cable configurations do exist in which the ground reference of USB-2 data lines is implemented as inner shield, insulated from the outer screen (like with FireWire). A similar problem arises with shielded Ethernet, EtherCat where the outer shield can be both assigned for the internal wire pairs as well as it connects to the (metal) enclosures of the subsystems connected.

Another serious issue will be the (power) supply impedances used throughout the system. Single (sub-)systems are characterized for compliance as stand-alone device not as a group or an element of a larger system. Putting many systems together on a supply bus (AC or DC) with cabling in-between bears the problem of multiple resonances in that system due to the power entry filters used. The likely alignment of operating frequencies of sensors/encoders or drives with such resonances will affect the operability of such systems. Extending or shortening cables or even rerouting (in case of non-shielded cables) will affect those resonances. Critically damped power distribution systems can be used to avoid these unforeseen interactions 'by design'.

Pilot-2:

General layer 1 requirements

Req. ID	Parameter/Description	Nominal	Min	Max	Dim
rq-Pilot2-L1.1	Main communication bus between layer 1 hardware and the central control layer (layer 2)	EtherCAT preferred: Gb Ethernet[1] with PTP support			
rq-Pilot2-L1.2	Sample rate communication bus		20		kHz
rq-Pilot2-L1.3	All relevant signals and statuses of L1 devices should be traceable by the central control layer with accurate timestamps (layer 2)				

7.2 - Validation

W.r.t. validation (WP-6), the motion control implementations are very diverse w.r.t the installation: central motion cabinet with multiple drives individually wired to the actuators and parallel the wiring from the encoders back to the control system. Wiring can be done through dedicated multi-functional cables using dedicated connectors or by running multiple cables in parallel.

Another, smart approach is to combine the drive with the actuator locally and to provide the supply of the drives from a shared DC-bus. The smart drives as well as the smart encoders and smart sensors are transmitting their data through shared data busses. Using a typical data exchange speed of 10 kHz (or less) allows for time division multiplexing of the signals on the bus. These kind of data exchange speeds are sufficient to enable control loops of a few hundred Hz. If one wants to achieve control loops much faster, the data exchange i.e. sampling rate needs to be much faster accordingly. A typical value of 1:100, control loop bandwidth versus sampling rate is quite common.

To reduce the overall motion control system costs further, motion drives are further stripped down such that only the output drive and its control are combined with the actuator while the DC-voltage as well as the pre-drive clocking is shared between the drives connected. The main reason is that most actuators with drives don't require power or switch simultaneously (determined by the central drive control host which 'drives' all end-stages). As such the DC power supply can be further reduced and optimized in power, thus size and costs.

Signal interfacing as well as power interfacing can be done through PVC based insulated wiring or PE or PFTE based insulated wiring. Aside the fact that the insulation withstand capabilities of PE or PFTE (or silicone) is much better than PVC, it will be less flexible. Furthermore, the signal channel bandwidth of PE or PFTE base cabling is much higher than of PVC and silicone. As such, for new motion control installations, PE or PFTE based cabling as used with Ethernet: CAT-5 to -8, will be suited for both analogue and digital signals. In addition, the differential twisted wires, preferrably shielded, are suited for analogue signals too: 0 - 10 volt, 4-20 mA, and can be utilized to enhance their immunity to external disturbances i.e. crosstalk from other signals or power. The flexibility of the solid wires, most often used with CAT-5 to -8 can be circumvented too as stranded wire versions are also commercially-of-the-shelf (COTS) available.

8 - Conclusions

1. Setting specifications and requirements for the hardware Layer 1 'parts' is determined by the motion control architecture chosen (D2.4): locally smart or centrally controlled or a hybrid form in-between. This in particular applies for the 'above' functional requirements: anti-sway, diagnostics, collision detect, vibration control.

2. To enable hardware/software co-development and simulation (WP-4/5), the hardware-in-the loop (HiL) parameters are needed at the various levels or interfaces need to be determined. This has direct impact on the Layer 1 ↔ 2 interface as the API or DLL parameters needs to be unified to enable exchange of the building block at the layer 3 level.

3. The implementation of interfaces of all hardware (WP-3): wired or wireless, has a direct impact on the signal bandwidth as well as the latency of the interface link used. As data security and data integrity adds delay to the total latency. These latency effects shall be taken into account, in particular when the ‘above’ functional software becomes distributed and data needs to be exchanged bi-directional.

4. There is no clear convergence (yet) in the realization (WG-6) of the hardware and its interfacing with motion control systems in general. The diversity of connector types, connector pin allocation, signal levels, protocols, coding and interface channel capabilities is nearly unbound.It will be the task for BB-10 to accommodate multi-protocol access through its I/O-ports (without the need for external data translators (which again add latency).

5. High-speed PE/ PFTE based cabling will provide higher bandwidths, more suited for both analogue and digital signals. PVC based cabling will be restricted in bandwidth and unsuited for high-speed interface applications.

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