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| **WP3, Instrumentation Layer Design and Development** | **D3.2 - Instrumentation Layer requirements and specification (second iteration) v4.4** |

From the Use-cases (chapter 3), Pilots (chapter 4) and Demos (chapter 5), presently under development, requirements and specifications are collected which act as constraints for the development of new hardware and instrumentation for Layer 1, especially in the WP3 (chapter 6). The commonality, format, order of the parameters are based on the required interaction with the higher layer levels: 2 and 3 through OPC-UA. These requirements and specifications enable compatibility in-between the layers and then allow for hardware-software co-development SiL/ HiL/ MiL.

The present divergence in hardware layer and software interface requirements and specifications is large, when centralized controlled motion is compared to smart distributed sensing, control and actuation. The level of hardware interfacing is broad, varying from analogue (0-10 volt, 4-20 mA with < 1 kHz bandwidth), to SPI, USB and all kind of other digital interfaces. For I-Mech project the **main backbone communication: EtherCAT** is preferred, which brings the total control loop bandwidth to tens of kHz. Raw video (video-in-the-loop), streamed at Gb/s, even with high frame rates, has to be extracted for control to limit bandwidth (when sent over EtherCat).

The variety in control speed is determined by the motion control applications: Pilot 2 is doing ~70 kU/hour die placement down to container sway control, Use-case 1.1 of a few sub-Hz and collision detect: pilot 5 at a max. delay of a few ms. Wear-out w.r.t. preventive maintenance needs detection over longer periods. The requirements in consumed power are limited by battery or energy scavenging operated sensors systems versus the wired or contactless powered applications.

The main issue is the amount of 'new' data that is required beyond the functional set-point data exchange as used with the conventional motion control systems. 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 (which includes part of the BB-10 (-11) as local intelligence to limit the data exchange bandwidth over the signal interfaces as defined in D2.4 and D6.2).

The I-Mech motion control design platform and architecture needs to be changed accordingly and many of the BBs (chapter 6) defined need to be re-defined (re-developed or adjusted) to predefined formats to enable SiL, HiL, MiL. To obtain an open motion control interface structure, as being one of the **ECSEL-JU** goals, other motion module exchangeability parameters to consider are given in chapter 7, but aren't the prime focus in this first I-Mech project.

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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, SiL, HiL, MiL.**

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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.

| ID | Description | Due date | Owner | IAL ID |
|---|---|---|---|---|
| OI1-18-10 | Use cases 1.3 and 2.2 info is lacking as input. Will be added after Madrid meeting | 2018-11-20 | Zapuni, TECO | |
| OI2-18-10 | Contribution to BB4 is out-of-line with other contributions regarding the Venn-diagram | 2018-11-20 | TUE | |

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| V4.1 | final | 31-10-2018 | Mart Coenen | 2 use cases added. BB matrix updated. Open issues added | |

## Contributors

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|---|---|---|---|
| V4 | EDI | Kaspars Ozols | Enforcing progress, |
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| | Nexperia | Gijs van der Veen | |
| | TUE | Aaron Goswami | review |
| | Ingenia | Francesc Marlasca | review |
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| | UC1.2 | Fagor | All necessary info added |
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| | UC2.2 | Zapuni | Requirements are given in figure 3.4.2 |
| | Demo1 | J&J Vistakon | Graph is updated |

## Document control

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## Literature/ References

| Ref | Name | Publisher | Year |
|---|---|---|---|
| [1] | 'Fieldbus' interface (IEC 61158) | IEC | 2014 |
| [2] | Minimum cycle time analysis of Ethernet-based real-time protocols | https://hal.archives-ouvertes.fr/hal-00714560 | 2012 |
| [3] | Application Guide for AC Adjustable Speed Drive Systems | Nema | 2015 |
| [4] | | | |
| [5] | | | |

# Abbreviations & Definitions

| Abbreviation | Description |
|---|---|
| API | Application Program Interface |
| BB | Building Block |
| DLL | Dynamic Link Library |
| DMA | Direct Memory Access |
| FELV | Functional Electrical Low Voltage |
| IEC | International Electrotechnical Committee |
| HIL | Hardware in the loop |
| MIL | Model in the loop |
| MS | Milestone |
| LDO | Low Dropout (voltage regulator) |
| PC | Personal Computer |
| PLC | Programmable Logic Controller |
| SELV | Safe Electrical Low Voltage |
| SIL | Software in the loop |

| Definition | Description |
|---|---|
| | |

# Task 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 WP7 where the requirements and specifications for the I-Mech pilots, chapter 4, will be implemented. The output of WP6 will be related to the integration of the I-Mech use-cases, chapter 3, and demos, chapter 5 and demands for proper specifications and requirements as given below for the generic motion platform model using unified building blocks: chapter 2. To obtain an open motion control interface structure, as required by the **ECSEL-JU** goals, other motion module exchangeability parameters to consider are given in chapter 7 of this document.

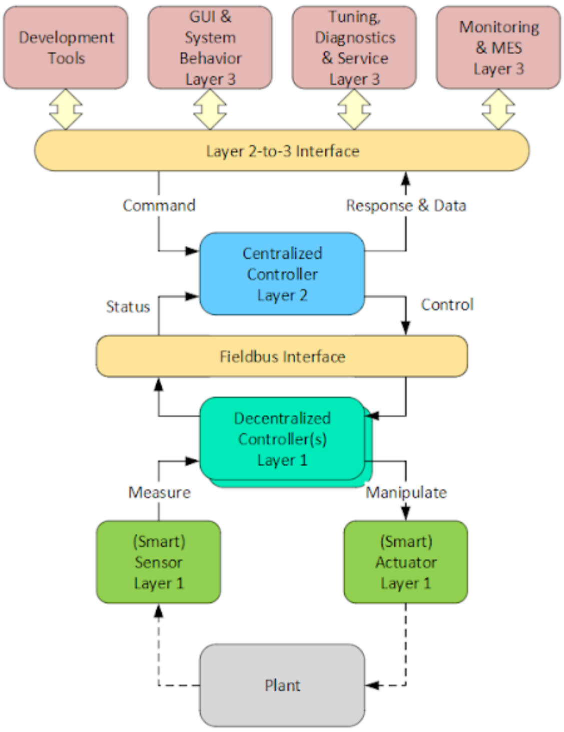



Figure 1 - Generic I-Mech motion platform model

From the overview of the generic motion platform model above, (taken from D6.2) , incorporating all I-Mech layers, it can be seen that the software; Layer 2 and 3 relies on evident hardware of Layer 1. From task 2.1 up to task 6.1, the requirements and specifications are given for their dedicated topics within those work-packages concerned. What is lacking from e.g. the physical sensor i.e. actuator drive needs to be added- on e.g. by using additional sensors and shall be controlled by a decentralized controller which then enhances those conventional sensor and actuator drive systems (with whatever interface) to become (more) smart and suited for the needs of the higher layers of the motion platform w.r.t. measurement, response to data etc. but most of all to minimize the bi-directional data overhead on the 'Fieldbus' interface (IEC 61158) [1], either hard-wired or wireless. Different fieldbuses offer different sets of features and performance. It is difficult to make a general comparison of fieldbus performances because of fundamental differences exist in data transfer methodology. Typical delay i.e. latency is in the order of milliseconds or faster.

| Fieldbus | Bus power | Cabling redundancy | Max devices | Synchronisation | Sub millisecond cycle |
|---|---|---|---|---|---|
| AFDX | No | Yes | Almost unlimited | No | Yes |
| AS-Interface | Yes | No | 62 | No | No |
| CANopen | No | No | 127 | Yes | No |
| CompoNet | Yes | No | 384 | No | Yes |
| ControlNet | No | Yes | 99 | No | No |
| CC-Link | No | No | 64 | No | No |
| DeviceNet | Yes | No | 64 | No | No |
| EtherCAT | Yes | Yes | 65,536 | Yes | Yes |
| Ethernet Powerlink | No | Optional | 240 | Yes | Yes |
| EtherNet/IP | No | Optional | Almost unlimited | Yes | Yes |
| Interbus | No | No | 511 | No | No |
| LonWorks | No | No | 32,000 | No | No |
| Modbus | No | No | 246 | No | No |
| PROFIBUS DP | No | Optional | 126 | Yes | No |
| PROFIBUS PA | Yes | No | 126 | No | No |
| PROFINET IO | No | Optional | Almost unlimited | No | No |
| PROFINET IRT | No | Optional | Almost unlimited | Yes | Yes |
| SERCOS III | No | Yes | 511 | Yes | Yes |
| SERCOS interface | No | No | 254 | Yes | Yes |
| Foundation Fieldbus H1 | Yes | No | 240 | Yes | No |
| Foundation Fieldbus HSE | No | Yes | Almost unlimited | Yes | No |
| RAPIEnet | No | Yes | 256 | Under Development | Conditional |
| Fieldbus | Bus power | Cabling redundancy | Max devices | Synchronisation | Sub millisecond cycle |

Figure 2 - The various latencies of fieldbus related options (EtherCAT is I-Mech preference)

To ensure motion control stability, the foreseen latency with ALL the interfaces i.e. the data collected and transmitted shall be used and corrected for, or the data shall all be time-stamped such that the latency can be corrected for during acquisition.

In the I-Mech project, the specifications and requirements within each work-package, are aligned for a second time, in each general overview and architecture task, 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 generic requirements and specifications will adapt to the developments of the pilot work in progress. With the task 2.1 and 2.4 (I-Mech architecture) up to task 6.1, the requirements and specifications will also be updated a second time after a 6 months period to adapt to the developments of the demos, use-cases and pilots work in progress. In time, even task 7.1 will be updated to follow the directions taken w.r.t. the requirements and specifications.

This deliverable 3.2 will be a guiding document and formally restricted to the requirements and specifications of work-package 3:

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 - (BB10/BB11) Development / selection of control specific multi-many core platform and will be derived from the information provided by the WP-3 tasks, the use-cases, demos and pilots.

By definition of (generic) building blocks, to be used with the I-Mech motion control platform, the building blocks will contain both hardware and software to become exchangeable and interchangeable modules at the boundaries of these building blocks, both in hardware: signals, supply, size, etc. as in software: commands, data exchange, etc, see clause 7. Standardization of the generic i.e. exchangeable parameters, e.g. by using OPC UA, 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 control market and is as such one of the focal points of the ECSEL-JU.

# 1 - Introduction

This document describes the dedicated high-level (architectural) approach for WP3: MS1 and MS3 deliverable D3.2: Layer 1, Instrumentation Layer Requirements and Specifications. The implementation plan given below is taken over from the main WP3 structural plan.

From WP2 (business requirements and the overall reference system architecture), task 2.1, 2.2 and 2.3, the specifications, requirements, preferred architectures: 2.4 and 6.2 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 WP6 (Implementation and integration of I-Mech platform, including 'use cases' and 'demonstrators'), see requirements spreadsheet WP2 as well as WP4 to provide the necessary embedded software for the building blocks considered. A global indication on the software requirements is given in D4.2.

These I-Mech requirements and specifications apply to all 3 levels: **instrumentation** (Layer 1), **control** (Layer 2) and **system's behavior** (Layer 3) where a distinct is made between hardware- and software-oriented activities. The application specific user-interface (UI) software is also within the scope of this I-Mech project too but will be heavily determined by the hardware, hidden by the OS, DLL's, API's and instrumentation drivers to become more unified approachable by the upper software layers e.g. like 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 intrinsic hardware instrumentation layer, development efforts have to be spent w.r.t. further and better standardization i.e. open-systems: WP3 and WP4 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-Dx, RJ-45, 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, supply and signal levels, shielding measures and data exchange protocols. **With the I-Mech project, the main backbone is chosen to be EtherCAT**. As can be seen from figure 1, whatever is behind the EtherCAT controlled smart sensor, smart drive, or decentralized controller is irrelevant (and can be any of those described above) as long as all EtherCAT interface constraints as well as the data format set as required by Layer 2 and 3 can be fulfilled.

The latter also applies for wireless interfaces; Bluetooth, Z-wave, Zigbee, etc., where aside the wireless PHY dedicated software stacks and protocols may or need to be added to make them more robust (which will add delay or latency and affect transparency of the (bi-directional) data flow). These present inconsistencies in solutions jeopardize open-system integration and, in particular, system reliability as well as the implementation of complex algorithms, fed by and driving to the various parts of the motion control system under development in I-Mech.

Suppliers' proprietary and non-industrial interfaces should be avoided (forbidden (?)) in the I-Mech pilots, use-cases and demos as hardware-wise more flexible, modular and open-system oriented architectures are targeted (even though when these proprietary interfaces 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, weight, etc. in the various systems defined in the use cases, pilots and demos. As such, there will NOT be a one-size-fits-all solution to the various needs in motion control. With the definition of the building blocks, the least common denominator requirements and specifications will be depicted to which add-on shells i.e. application specific measures shall be added to make then fit-for use.

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. As stated before, whatever is behind the EtherCAT controlled smart sensor, smart drive, or decentralized controller is irrelevant (and can be any interface) as long as all EtherCAT interface constraints as well as the data format set as required by Layer 2 and 3 can be fulfilled.

The instrumentation interfacing at the *building block* level has to be open-system compliant in many (more) ways as specified in the requirements following in chapter 6. International standardization needs to be and will be done in collaboration with I-Mech WP8.

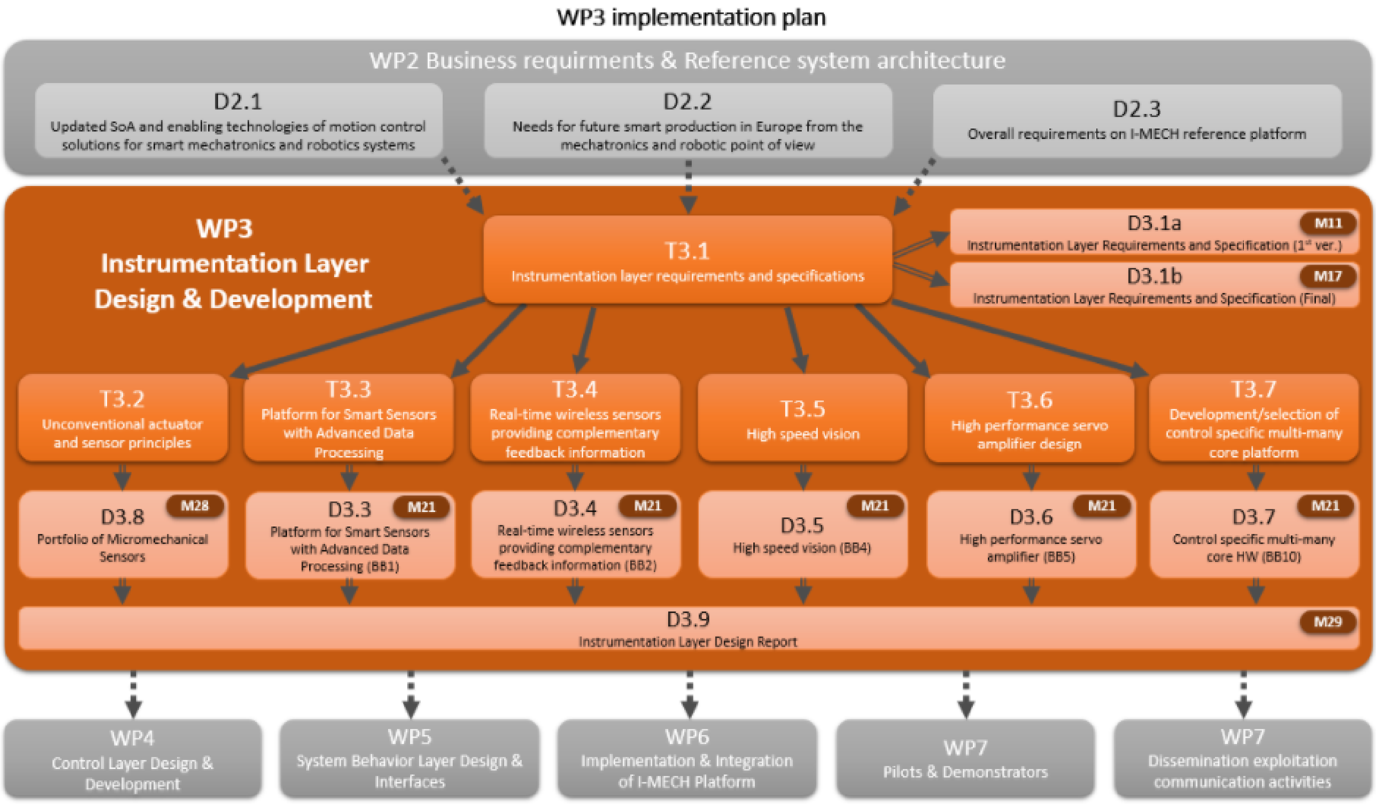



Figure 3.1 - WP3 Implementation plan

The lower-level hardware Instrumentation Layer Requirements and Specifications for the I-Mech Use-Cases, Pilots and Demo's were collected in WP2 task 2.1, 2.2 and 2.3 and submitted as deliverable 2.3. At a high-level i.e. architectural level (also T2.4 and T6.2), choices have been 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 axis, 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 local hardware layer, also the interfacing: analog, digital, wireless needs to be defined while taking into account the signal reliability and the latencies involved and shall be interfaced towards the higher level requirements by using EtherCAT (as an interface of the in-between decentralized control).

With today's complex motion control systems, the expected motion behavior: feedback (PID), feed-forward or a combination thereof, see deliverable 4.2, needs to be simulated and modelled on forehand. For this, the adequate behavior models of all motion control parts used need to be developed and unified for the simulation environment in which it is used e.g. MathWorks Simulink. To ensure suited behavior models, the necessary settling and response parameter formats need to be standardized i.e unified between the providers of the model parts to enable exchangeability.

**This modelling work isn't the responsibility of WP3 and shall be dealt with at the appropriate I-Mech work-package 4, tasks: 4.2 and 4.3. With further simulation developments: SiL and MiL, 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/ exchangeable by the (smart) hardware used and as such the data parameters used both with the hardware, including its API or DLL (being part of Layer 1 and 2), have to be fully aligned with the simulation model; Layer 2 and 3, for the intended hardware to be used. For the exchange of parameters between the models and modules OPC-UA is considered as a conversion option. With virtual 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 and practically need to be simplified to those parameters required by the tools used. With hardware, less parameters will be accessible for the higher layers in the system, unless initially defined during development and added to the wish list of requirements and specifications. To enable this parameter access, predefined data registers, where these properly defined parameters are allocated, is a must. This makes it an I-Mech requirement for Layer 1 and 2, to enable communication with Layer 2 upwards.

**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 and some homing information. 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 or orientation 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 well as overvoltages or overcurrents to protect the drive and/or actuator used for preventing machine damage. Threshold detection will then be sufficient rather than full voltage and current waveshape capturing. For other means of control i.e. diagnostic, wear-out or vibration, dedicated data access might be necessary, or the device has to be made smart with a local algorithm which compress 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 EtherCAT data interface at Layer 1 to become available to the above Layers 2 and 3, for processing and control. These data interface decisions: hardware, format, coding , when standardized to EtherCAT affect the ability to develop generic building blocks which can be used with the I-Mech motion control system.

Motion control system architectures can be diverted in 3 groups:

- **Locally smart** (chapter 2.1 and T3.3) i.e. all signal conditioning will be done locally within the smart sensors, smart actuators and for the algorithms by the smart control systems while minimizing the load on the EtherCAT 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 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), not being 'the' preferred I-Mech approach.
- **Hybrid** (chapter 2.3). What can locally be 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 Netherland d.d. 20-21/02/2018. This approach also serves most of the motion systems installed base.

**The present motion control system diversity determines the non-exchangeability of the various building block implementations foreseen. I-Mech sets requirements on the smartness of the various motion system parts: sensors, motion control, drives, and actuators to enable implementation of these 'above' functional requirements by accessibility of data and unification of the interfacing using EtherCAT as 'the' standardized backbone.**

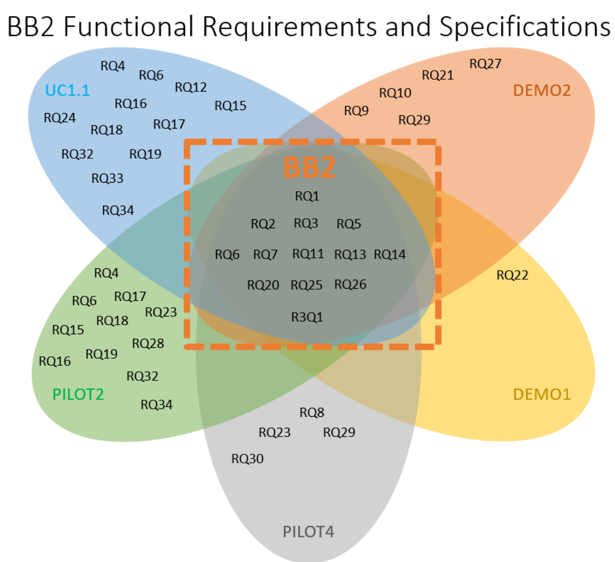



Figure 3.2 - BB example in search for the least common denominator

Different from the smartness i.e. cleverness of the I-Mech motion platform parts, the requirements and specifications set needs to be **SMART.** The letters S and M usually mean **specific** and **measurable**. Possibly the most common version has the remaining letters referring to **achievable**, **relevant** and **time-bound**. On the opposite, the requirements and specifications need to be generic (enough) and suited to most of the BB's, Use-cases, Demos and Pilots to avoid divergence in this already divergent motion control market.

As such, a least common denominator in the specification has to be found i.e. defined for each building block, to which, like with an onion, several shells can (and may) be added to make these (more) suited for their specific application. On the other hand the main signal interface backbone has been defined to be EtherCAT. On the opposite side of the decentralized controller and/or the smart-sensor or smart-drive ANY analogue or digital signal interface may be used at the local level.

For the other ('non-')functional requirements, as indicated in clause 7, no specific SMART requirements can be defined e.g. with supply voltages: 5, 12, 24 or 48 volts DC and its tolerances. A tendency is to aim for the higher DC supply voltages to minimize DC currents which then allow thinner wiring (thus more flexible cable) to be used. The 48 volts DC is again low enough to satisfy the electrical safety requirements which are set to a level of 60 volts DC for a SELV or FELV circuit. The opposite is that distributed local DC/DC converters have to be used throughout the motion control system which all may contribute to the electromagnetic interference (EMI), when implemented as switching power converter. Using local filtering and shielding to overcome the EMI from the local switching DC/DC converters results in volume, weight. Using non-switching LDOs will result in additional power losses i.e. heat, which then require a heatsink, thus additional volume. Both of these power conversion solutions can be influenced by external interferences or even high-level static magnetic fields.

Many hardware instrumentation layer requirements and specifications are given by the various Use-cases, Demos, Pilots, Building Blocks and developments in WP-3 which cannot be easily harmonized to a single set of least common denominator requirements due to the broadness of the motion system applications. Initial focus is given to the data format and data stream i.e. data interfaces to enable easier exchange of modules and to enable (at least) a 'standardized' exchange of data in-between them.

The requirements and specifications are subdivided into 4 groups: functional (F), operational (O), design (D) or Building Block specific (BB) along the Use-cases (UC), Pilots (Pi) and Demos (De).

# 2 - Motion control diversity

The 3 types of presently diverted motion control systems: local, central and hybrid, shall be used to align the developments for the generic Building Blocks defined in the I-Mech FP as well as the Use-Cases, Pilots and Demo's defined in this I-Mech project. The related (high-lighted) 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 and through an industrial communication bus. The data sample rate communicated will be ≥ 10 kHz. The I-Mech preferred interface will be EtherCAT.

- BB-2: Real-time Wireless Sensors (= hardware, L1). Sensors are needed to measure system information that are used for optimizing motion 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.The I-Mech preferred interface will be EtherCAT.

- BB-5: High performance current amplifiers (= hardware: L1). The responsiveness (between actual and requested current value) of amplifier is of importance for the loop gain of the motion controller. High dynamical (e.g. loop gain of 400Hz) require these amplifiers. Data exchange will be limited by the EtherCAT interface structure chosen by I-Mech.

- 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). To enable vibration control, the parameters shall be restricted to those accessible from the hardware.

- 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. To enable SiL and HiL, the parameters shall be restricted to those accessible from the hardware.

- 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.To enable iterative and repetitive control, the parameters shall be restricted to those accessible from the hardware.

- 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. As defined in figure 1, BB-10 can also be used with the decentralized control while using BB-11 for its operation.

- 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 i.e. D3.2. Nevertheless, the interdependence between the other work-packages, building blocks and/or tasks in other work-packages are highlighted in this document too.

**Unfortunately, hardware can't 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 diverted 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-6, 7 and 9 (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 be less 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.

Determined by the local smartness of the hardware (= distributed motion system architecture) used, the 'above' laying functional software: Layer 2 and 3, needs to be divided into subsets at the various smart parts to enable an overall 'above' functionality: WP4 and 5. If all motion control is done centrally, with upfront knowledge of the transfer functions and latency of the sensors/ encoders and drive to actuators AND the necessary data as required is available, this can be done centrally (if the hardware layer 1 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.

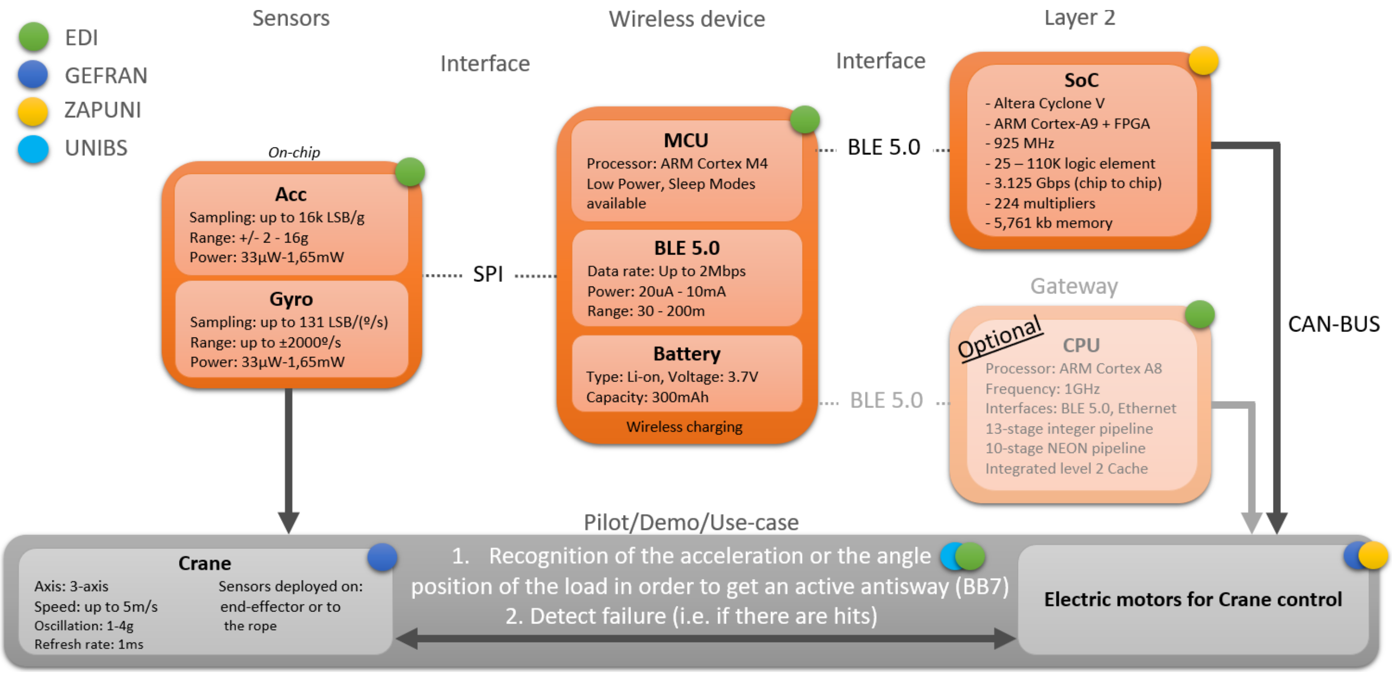



Figure 3.1.1 - Real-time wireless active anti-sway system

The overall system will consist of four main components –

1. Wireless Device with sensors (developed by EDI), (BB-2, T3.4)
2. Layer 2 processing unit, which is based on SoC (ZAPUNI) (BB-1), 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) (BB-7).

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 1,1 kW, with mechanical brake controlled from inverter, sinusoidal encoder, limit switches.
- Trolley: inverter ADV200-1015, asynchronous motor 0,7 kW, 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 - Requirements and specification

Based on the block diagram shown in Figure 3.1.1 and corresponding description, detailed Use-Case 1.1 requirements and specifications are defined in Table 3.1.1.

Table 3.1.1 - Use-Case 1.1 requirements and specifications

| **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 2 g 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 1 kHz 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) | EtherCAT or CAN-BUS | The selection of EtherCat and 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 | < 500 $\mu$s | The latency should be at least less than half of the sampling rate period. To ensure stability in the system, actual value could be < 200 $\mu$s. |
| UC1.1.F17 | Transmit power | < 20 dBm | According to ETSI EN 300 328 standard, the transmission power should not be higher than 100 mW. |
| 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 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. |

| **Operational Requirements** | | | |
|---|---|---|---|
| **Wireless Device** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.1.O1 | Minimum sampling freq. | 1000 Hz | Considering the mechanical scenario of the crane the supposed refresh rate is 1 kHz. The data must be transmitted to the inverter at a rate of 1 kHz to be used for real-time control purpose. |
| UC1.1.O2 | Min. acceleration range | > ±2 g | Based on the Use Case specification, where max. movement speed is up to 5 m/s. |
| UC1.1.O3 | Accelerometer resolution | >12 bit | Based on the Use Case specification, where max. movement speed is up to 5 m/s. |
| UC1.1.O4 | Accelerometer Noise density | <200 | A min. value to ensure necessary precision for Anti-sway, Condition monitoring. |
| UC1.1.O5 | Gyroscope dynamic range/sensitivity | > +/- 2000°/sec | Based on the Use Case specification, where max. movement speed is up to 5 m/s. |
| UC1.1.O6 | Gyroscope resolution | > 12 bit | Based on the Use Case specification, where max. movement speed is up to 5 m/s. |
| UC1.1.O7 | Gyroscope Noise | < 7°/sec | Noise value has to be less than last significant bit value. |
| UC1.1.O8 | Number of sensitivity axis (Acc, Gyro) | 3,3 | To obtain full orientation of the IMU, it is necessary to use 3 axial accelerometer and gyroscope. |
| UC1.1.O9 | Raw sensor data size per one sample | 12 Bytes | Inertial measurement unit with 2 sensors inside, each sensor measures 3 axes. Each axis is represented with 2 bytes of data. |
| UC1.1.O10 | Raw sensor data transmission throughput | 12 kB/s | Is computed as a number of bytes per sample, multiplied by maximum sampling frequency. |
| UC1.1.O11 | Sensor communication interfaces | I2C, SPI, UART | Commonly supported communication interfaces in commercially available sensors and microcontrollers. |

| | | | |
|---|---|---|---|
| UC1.1.O12 | Processor | Low power, sleep modes available | Achieving required performance with low power consumption is a must in automated wireless sensor industrial use cases which also allows to extend the operation time without charging. Sleep mode allows to save power when there is no need to acquire or process any of the data at specific time moment. |
| UC1.1.O13 | Packet routing | Point-to-point | Wireless device is communicating only with Gateway. No other network client. |
| UC1.1.O14 | Wireless Communication range | 100 m | The use-case 1.1 needs about 20 m but considering other I-MECH systems the requested distance is up to 100 m. |
| UC1.1.O15 | Data rate | 104 kbit/s | 2 bytes for every axis (gyro and acc (6 axis in total)) and 1 byte for packet type -> 13 bytes for 1 sample. Sampling at 1 kHz. |
| UC1.1.O16 | BLE 5.0 frequency band | 2.4 GHz | Device must operate in 868 MHz frequency band (ISM-band). |
| UC1.1.O17 | Channel width | 104 kHz | With implementation of simplest modulation, e.g. BPSK (2 signal levels) and data rate of 104 kbit/s, according to Nyquist it is assumed that minimum bandwidth, needed to achieve required data rate, should be at least 104 kHz. |
| UC1.1.O18 | Power supply | Li-Ion battery cell 3.6 V | This is nominal voltage for Li-Ion batteries. Li-Ion batteries provide very high energy density, and are rechargeable, making them suitable for envisioned needs. |
| UC1.1.O19 | Battery re-charging | Type-C USB | Type-C USB connected charging has become as the standard for charging connection for mobile devices. |
| UC1.1.O20 | Software reset mechanisms | Yes | The system will check for faulty data, or no data from the sensors and will trigger system restart |
| UC1.1.O21 | Hardware reset | Yes | Button for hardware reset of the system |
| **Layer 2 SoC processing device** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.1.O22 | Service communication interface | Ethernet, TCP/IP | General interface for non-real-time data, diagnostics and servicing, interface to Gateway in case of architecture with Gateway |
| UC1.1.O23 | Real-time communication interfaces to Layer 2 | EtherCAT, CAN | Integration with I-MECH Layer 2 |
| UC1.1.O24 | Real-time communication period | 1 ms | Matching sampling frequency of wireless device |
| UC1.1.O25 | Real-time synchronization (distributed clock support) | yes | For high-performance feedback control, time synchronization of full system from sensor sampling to control system is required |
| UC1.1.O26 | Wireless Interface | BLE 5.0 | Optional architecture with wireless interface directly on SoC device |

| | | | |
|---|---|---|---|
| UC1.1.O27 | Processor / SoC | ARM Cortex-A9 + FPGA in SoC | FPGA is required for effective implementation of EtherCAT Slave and for precise timing and synchronization management |
| UC1.1.O28 | RAM | 512 MB | For running Linux without limits, RAM is cheap. |
| UC1.1.O29 | Flash memory | 64 MB + SD slot | 64 MB is a reasonable QSPI Flash size for FPGA + optimized Linux and algorithms. Storage should be extendable by (micro)SD card. |
| UC1.1.O30 | Operating system | RT-Linux, RTOS | Real-time optimized Linux with RT patch should be sufficient for 1 ms cycle times; RTOS is an option for more jitter-sensitive tasks |
| UC1.1.O31 | Power Supply | 24V DC | Industrial automation standard |
| **Gateway (optional)** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.1.O32 | Communication with the drive | CAN-BUS/ ETHERCAT | Supported interface by the Gefran drive |
| UC1.1.O33 | Gateway communication interfaces | USB, Ethernet, WiFi, BLE | Interfaces for non-real-time data, diagnostics and servicing and wireless communication with wireless device. |
| UC1.1.O34 | Real-time communication period | 1 ms | Matching sampling frequency of wireless device |
| UC1.1.O35 | Processor | Arm Cortex-A | Gateway is externally powered, therefore affordable high-performance processor can be implemented – ARM Cortex-A series. |
| UC1.1.O36 | Operating system | RTOS, Linux | RTOS or custom compiled and minimized Linux for fast data processing and delivery from wireless sensors to SoC system. |
| UC1.1.O37 | Power Supply | 24V DC | Industrial automation standard |

| **Design Requirements** | | | |
|---|---|---|---|
| **Wireless Device** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.1.D1 | Wireless Device locations | Hook, rope | The wireless device should be deployed on the hook or on the rope. |
| UC1.1.D2 | Wireless Device node size | <200 $cm^3$ < 100 g | Sensor and wireless device block should be as small and light as possible. Less than 200 $cm^3$ and 100 g. |

| | | | |
|---|---|---|---|
| UC1.1.D3 | Mechanical/Electrical/Water protection/robustness | Yes | System has to be vibration/shockproof, waterproof and static electricity proof |
| UC1.1.D4 | Operating temperature (ºC) | -30 ÷ +80 | Typical working temperature for commercial electronic equipment. |
| UC1.1.D5 | Relative humidity (%) | 10 ÷ 100 | Typical humidity range for commercial electronic equipment. |
| UC1.1.D6 | Electromagnetic compatibility | Yes | Wireless Device must be compatible with existing wireless technologies and radiation levels. CE certified wireless communication modules and other components must be used to reduce electromagnetic radiation. |
| UC1.1.D7 | Enclosure | > IP64 | Ingress Protection IP64 or higher, according to EN 60529. Protected from total dust ingress. Protected from water spray from any direction, limited ingress protection. |
| UC1.1.D8 | Antenna placement | PCB antenna | Antennas deployed on PCB would allow to minimize node size and chance of collision with other objects. |
| **Layer 2 SoC processing device** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.1.D9 | Operating temperature (ºC) | 0 to +50 | Should be installed in control cabinet, optional ext. range (-30 to +60) |
| UC1.1.D10 | Enclosure | IP20 | Should be installed in control cabinet |
| UC1.1.D11 | Electromagnetic compatibility | YES | General requirement for all industrial electronic components (CE cert.) |
| **Gateway (optional)** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.1.D12 | Mechanical/Electrical/Water protection/robustness | Yes | System has to be vibration/shockproof, waterproof and static electricity proof |
| UC1.1.D13 | Operating temperature (ºC) | -30 ÷ +80 | Typical working temperature for commercial electronic equipment. |
| UC1.1.D14 | Relative humidity (%) | 10 ÷ 100 | Typical humidity range for commercial electronic equipment. |
| UC1.1.D15 | Electromagnetic compatibility | Yes | Wireless Device must be compatible with existing wireless technologies and radiation levels. CE certified wireless communication modules and other components must be used to reduce electromagnetic radiation. |
| UC1.1.D16 | Enclosure | > IP64 | Ingress Protection IP64 or higher, according to EN 60529. Protected from total dust ingress. Protected from water spray from any direction, limited ingress protection. |

## 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).

### 3.2.2 - Requirements and specification

| Functional Requirements | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.2.F1 | Operation environment | Device ope-rate in typical environment conditions. | The device must operate in typical temperature ranges, humidity levels and interference levels. |
| UC1.2.F2 | Physical parameter measurement | Acceleration and angle position | |
| UC1.2.F3 | Communication between drives and CNC | EtherCAT | Full synchronization of drive and CNC loops through EtherCAT @ 16 ks/s. |
| UC1.2.F4 | Communication between CNC and accelerometers | 4-20 mA | Full synchronization with CNC loops. |
| UC1.2.F5 | Algorithms | Vibration Control<br>ILC<br>MIMO Control<br>Robust Control | Algorithms will be developed in Task 4.4, 4.5 and 4.6. |

| | | | |
|---|---|---|---|
| UC1.2.F6 | Drivers bandwidth | >2 kHz | |
| UC1.2.F7 | Commutation method | | FOC with encoder, motor position sent to CNC in ethercat |
| UC1.2.F8 | Multicore platform | >= 2 cores | x86 platform with hypervisor support |
| UC1.2.F9 | General purpose OS | Linux/Windows 7 embedded | |

| **Operational Requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.2.O1 | Real-time communication rate | 8/16 kHz | Motor drives with ethercat interface and at least 8 kHz sampling rate (16 kHz desired) and commanded in current/torque |
| UC1.2.O2 | Hypervisor | Near 0 latency | |
| UC1.2.O3 | Accelerometer: Resolution | >12 bit | Based on acceleration and speed expected |
| UC1.2.O4 | Accelerometer: Range | ± 4g | Based on acceleration and speed expected |
| UC1.2.O5 | General requirement | | All signals and statuses of the drives shall be traceable for CNC |
| UC1.2.O6 | General requirement | | It shall be possible to tune position, speed and current loop |
| UC1.2.O7 | General requirement | | Drives shall be able to be torque commanded |
| UC1.2.O8 | General requirement | | Any algorithm shall be enabled or disabled at any time |
| UC1.2.O9 | General requirement | | Any sensor shall use industry standard communications protocol |
| UC1.2.O10 | General requirement | | The system will be highly centralized. All the loops will run in the x86 platform (except torque/current and below) |

| | | | |
|---|---|---|---|
| UC1.2.O11 | General requirement | | The BBs will be implemented as C routines for x86 (use of specific functions available, for instance SIMD instructions) in the execution platform |
| UC1.2.O12 | General requirement | | There will be a twin for every algorithm of the BBs in Simulink (desirable with the exact behaviour relating format, etc…) |
| UC1.2.O13 | General requirement | | Frequency and execution order must be explicit for loops and blocks. |

| Design Requirements | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.2.D1 | Accelerometer location | TCP | The accelerometer shall be put near the effector end and connected to the CNC |
| UC1.2.D2 | Drives size | | It shall be possible to install drives into Scara robot structure |

## 3.3 - Use case 1.3: PAC Tecomat - Programmable automation control - modular HW for machinery

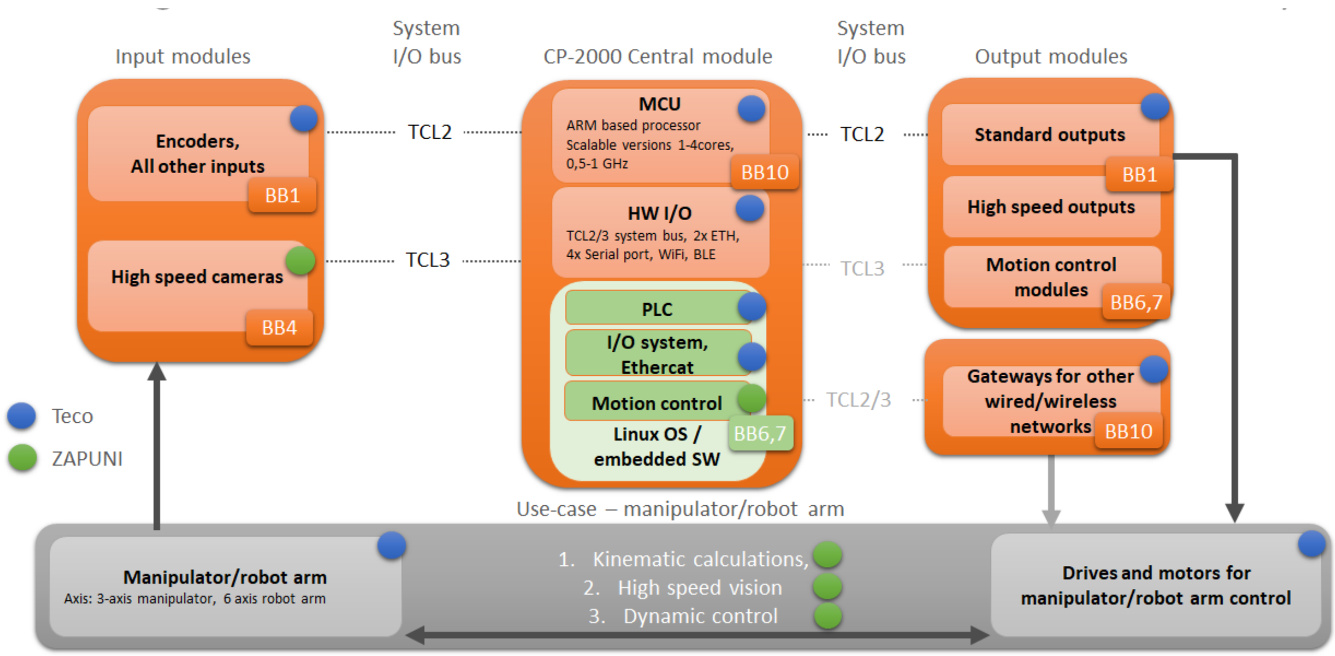



Figure 3.3.1 - Functional diagram PAC base hardware

### 3.3.1 - Functional description

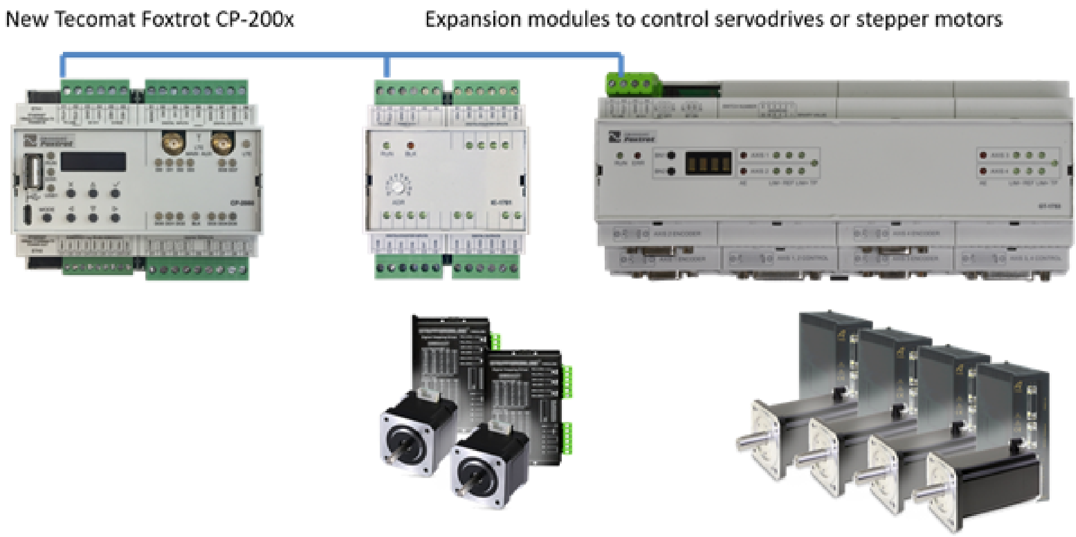



Figure 3.3.1 - Modular Tecomat system

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.

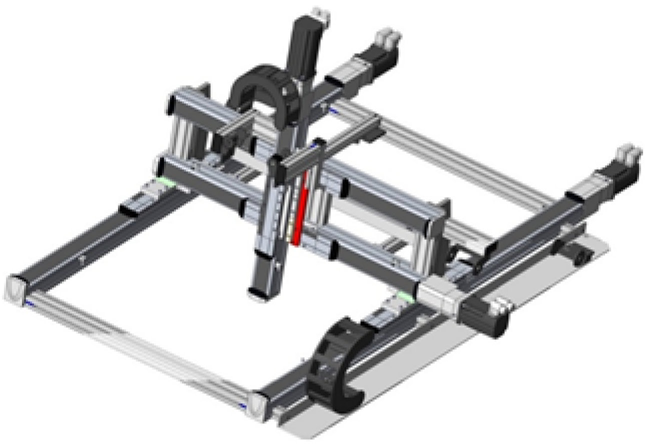


Figure 3.3.2 - Robotic manipulator to test PAC Tecomat Foxtrot

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.

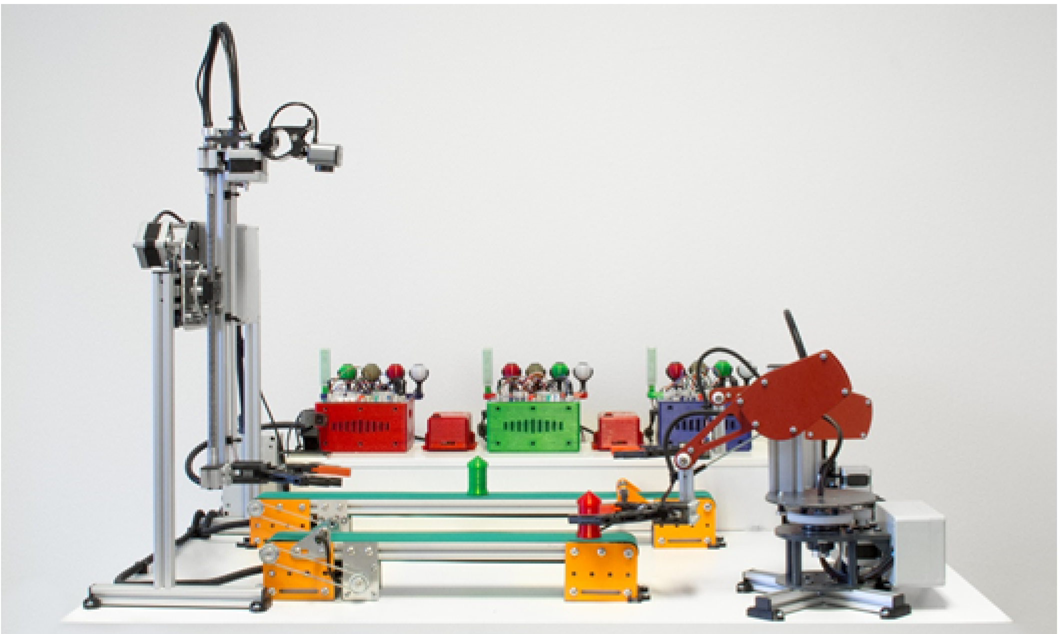


Figure 3.3.3 - Set of robotic manipulators to test cooperation of more PAC together

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.

| **Functional Requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC1.3.F1 | High number of digital I/O | 2 Ethernet, 4 serial/ CAN ports, 2-wire low speed expansion bus, 2 USB ports. | Flexibele interface selection must be enabled |
| UC1.3.F2 | High number of analog I/O through high-speed extension bus | 1 x High speed system expansion bus | |
| UC1.3.F3 | computing capabilities on analog and digital I/O | 32-bits | |
| UC1.3.F4 | Interfaces to communication networks | EtherCat, BT | Wired and wireless |
| UC1.3.F5 | Algorithms | | to make linearization and other high speed tasks like reading encoders or control PWM, stepper motors |

# 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 3.4.1.

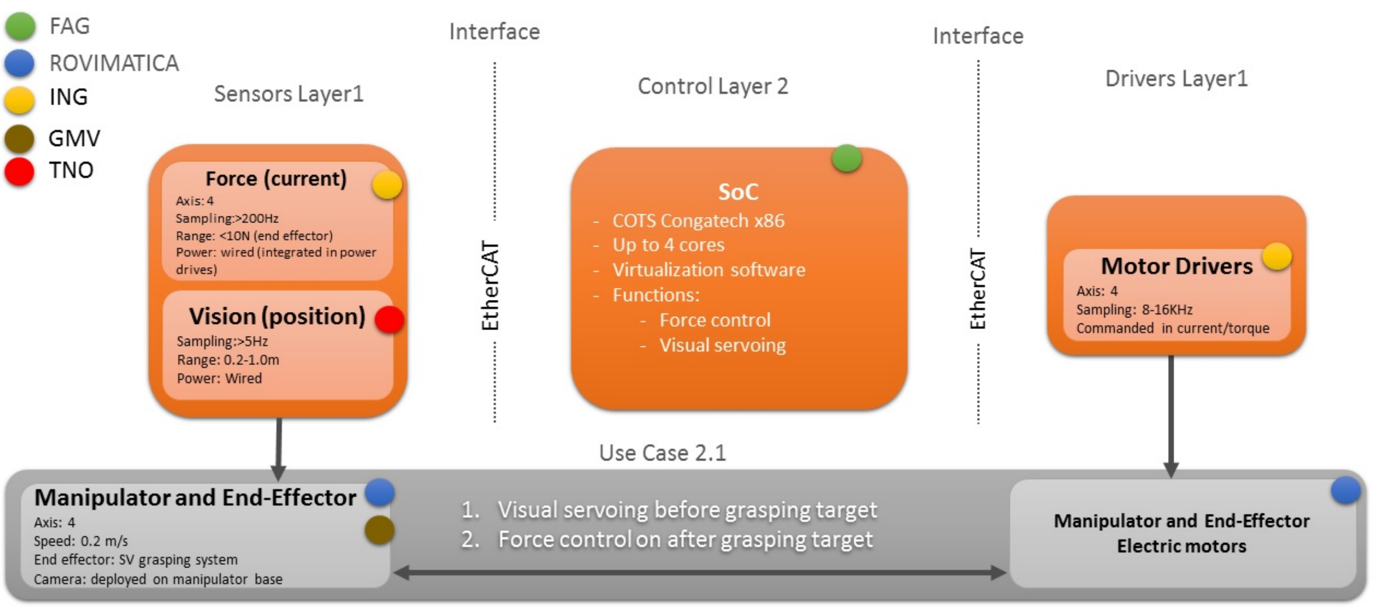


Figure 3.4.1 - On-ground validation of space GNC systems

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 (TNO).
3. Platform art + corresponding systems (GMV).

The motor drives (by ING) 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 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 (TNO) 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. Optionally , the vision processing system could also implement itself visual servoing algorithms and provide position/speed commands directly to the motor drives to minimise latency.

### 3.4.2 - Requirements and specification

Based on the block diagram shown in Figure 3.3.1 and corresponding description, detailed Use Case 2.1 requirements and specifications are defined in Table 3.3.1.

Table 3.4.1 - Use Case 2.1 Requirements and specifications

| **Functional Requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC2.1.F1 | Operation environment | Device operate in typical environment conditions. | The device must operate in typical temperature ranges, humidity levels and interference levels. |
| UC2.1.F2 | Win/Mac/Linux compatible | Yes | System should be able to operate with most popular operating systems for data transferring and reconfiguration |
| UC2.1.F3 | Physical parameter measurement: Force/torque | Force/torque in all (4) manipulator axes. | Force/torque at manipulator actuators shall be measured to implement force/impedance control.<br>Force/torque measurement at 4 manipulator axis shall be performed through current sensing at motor drives. |

| | | | |
|---|---|---|---|
| UC2.1.F4 | Physical parameter measurement: relative position | Relative 2D/3D position manipulator-target | Relative 2D/3D pose between manipulator and target shall be measured to implement visual servoing.<br>Position measurement shall be performed through a vision system including (optionally) markers at the target. |
| UC2.1.F5 | Channel width (vision) | 400-800 Mbps | 400-800 Mbps Bandwidth, for visual servoing system. |
| UC2.1.F6 | Channel width (force) | < 1 Mbps | For current sensing and current commanding |
| UC2.1.F7 | Communication with power drives for manipulator control | EtherCAT | Full synchronization of drive and CNC loops through EtherCAT. |
| UC2.1.F8 | Communication between Camera and Vision processing system | GiGE | GiGE vision Standard protocol used for communication between camera and vision processing system. |
| UC2.1.F9 | Communication between Vision processing system and and Motor drives | EtherCAT | Optionally the vision processing system shall interface the motor drives directly through EtherCAT protocol |
| UC2.1.F10 | Communication between Vision processing system and manipulator SoC | EtherCAT | Vision processing system shall interface manipulator control system through EtherCAT |
| UC2.1.F11 | Force/impedance control algorithms | 4 axis force/impedance control | The system shall implement force/impedance control in the four axis of the manipulator. The manipulator shall be able to exert commanded 3D forces / torque at its end effector. |
| UC2.1.F12 | Position/speed control algorithms | 2D/3D position/speed control (visual servoing) | The system shall implement visual servoing allowing positioning the end effector of the manipulator at commanded pose/speed respect to the target. |

| **Operational Requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| UC2.1.O1 | Force control performances | Force/torque control tolerance below 5%<br>Force range < 10 N,<br>Torque range <10 Nm | Force/torque control tolerance and ranges at end effector |
| UC2.1.O2 | Visual servoing performances | Distance range: 0.2-1.0 m<br>Speed range: <1 cm/s<br>Vision control | Measured magnitude: XY (lateral) position of the marker(s).(2D) Optionally distance, orientation of marker(s)(3D). |

| | | | |
|---|---|---|---|
| | | tolerance: 2 mm (at 0.2 m) | |
| UC2.1.O3 | Force/impedance control bandwidth and sampling frequency | Force control loop, 4 axis: 500 Hz (2 ms)<br>Current loop bandwidth > 2 kHz.<br>Current loop sample rate > 16 kHz. | Current loop per axis implemented by motor drivers.<br>Force/impedance control implemented at SoC. |
| UC2.1.O4 | Visual servoing bandwidth and sampling frequency | Bandwidth per camera:<br>- actual: nominal 150-200 Mbps<br>- desirable up to 400 Mbps - 800 Mbps<br>Vision control loop > 5 Hz (200 ms),<br>Desirable 50 Hz (20 ms) | Visual servoing control implemented at SoC or Vision processing hw. |

## 3.5 - Use Case 2.2: Improved motion of 6-DOF cost effective robot (Zapuni)

### 3.5.1 - General description

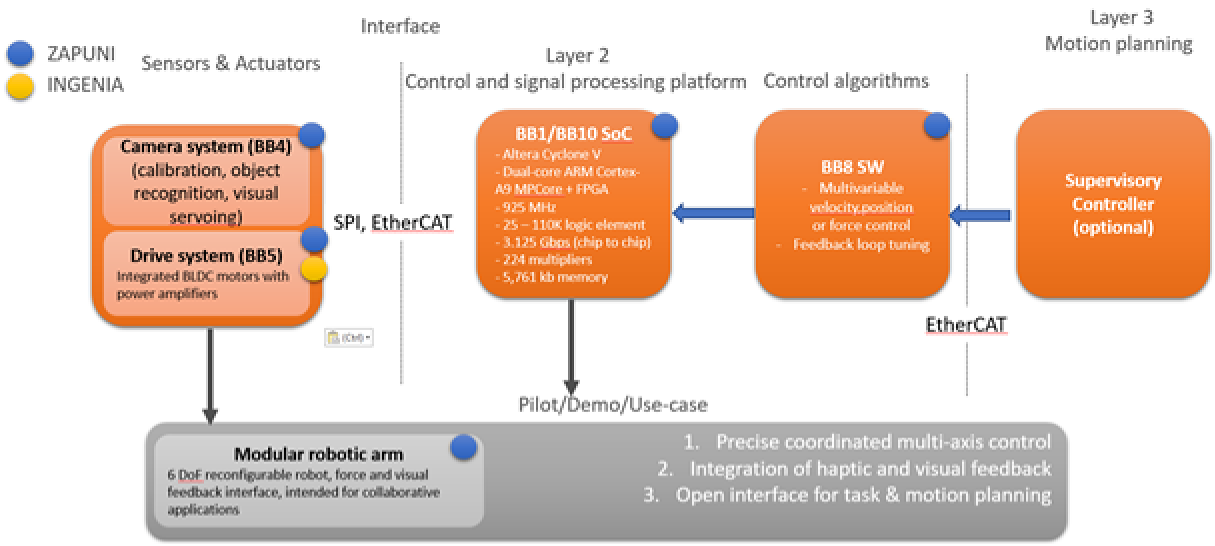



Figure 3.4.1 - Platform validation on open modular robotic arm

**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

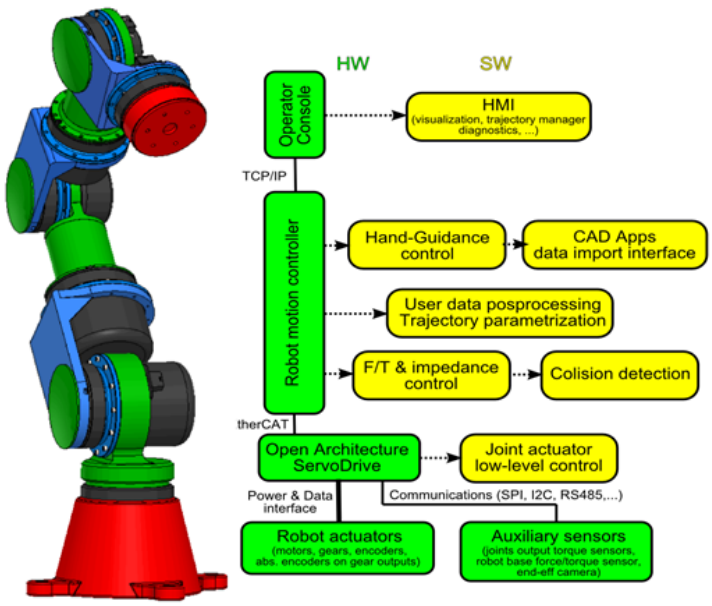



Figure 3.4.2 - Concept of open modular robotic arm

# 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 (GSC)

Information and requirements related to Pilot 1 listed in this document are based on content from deliverable D7.1. D7.1 is the leading document for this information and lists the latest revision of requirements and information. Minimum info has been copied to avoid duplication and maintain readability.

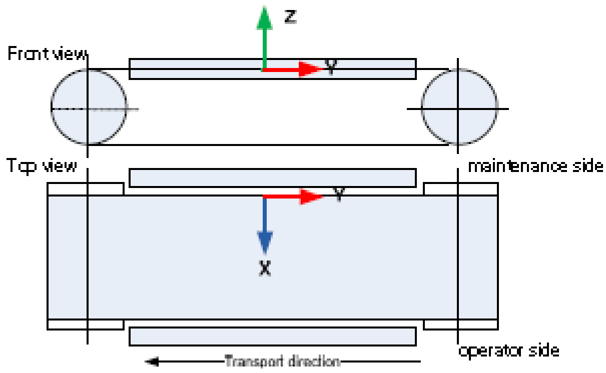



Figure 4.1.1: Direction definitions in a schematic side view of the GSC (above) and a top view of the GSC (below).

## 4.1.2 - Proposed hardware and interfaces

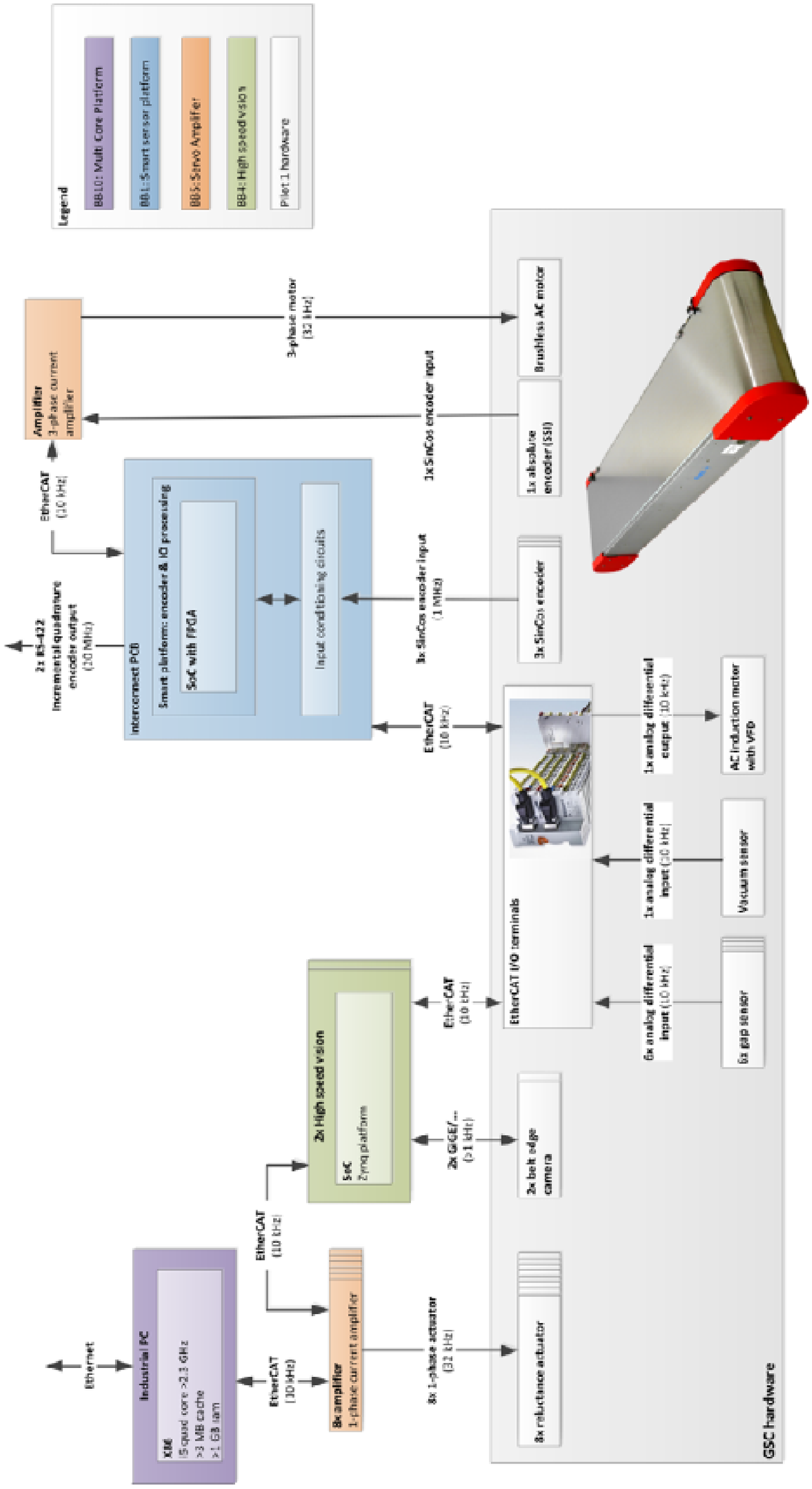



Figure 4.1.2

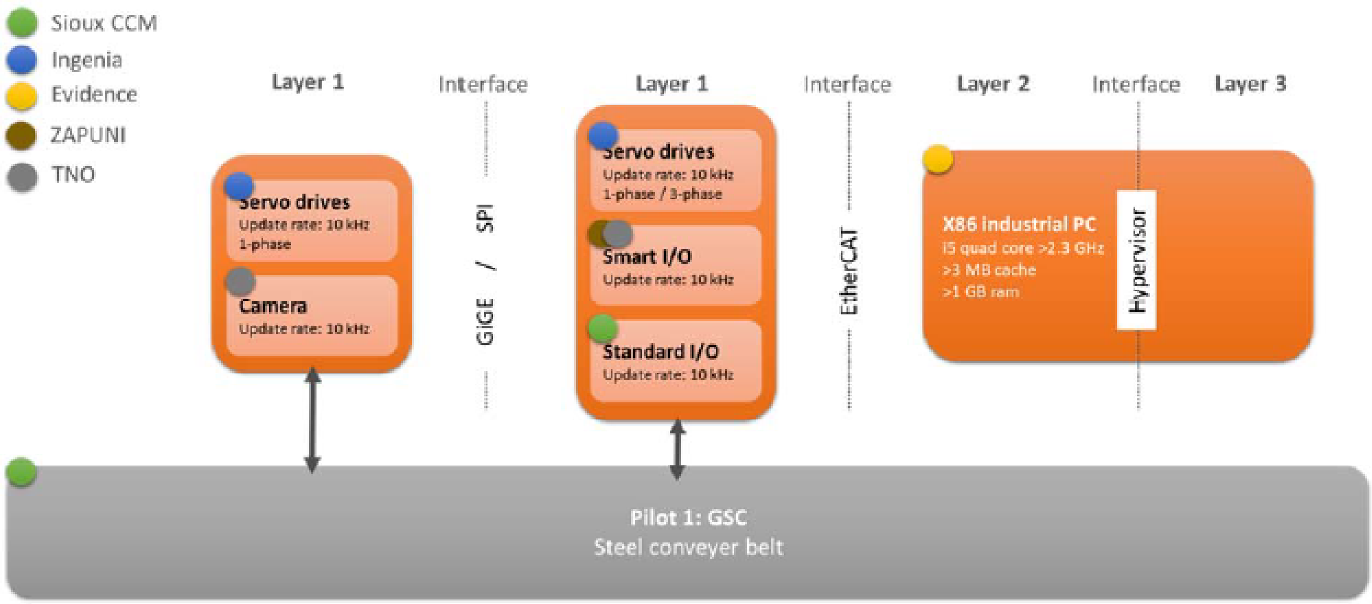



Figure 4.1.3 - Block diagram of the steel conveyor belt application

### 4.1.3 - General Layer 1 requirements

| Req. ID | Parameter/Description | Nominal | Min | Max | Dim |
|---|---|---|---|---|---|
| Pi-1.L1.1 | Main communication bus between layer 1 hardware and the central control layer (layer 2) | EtherCAT | | | |
| Pi-1-L1.2 | Sample rate communication bus[1] | | 10 | | kHz |
| Pi-1-L1.3 | All relevant signals and statuses of L1 devices should be traceable by the central control layer (layer 2) | Yes | | | |

### 4.1.4 - 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.

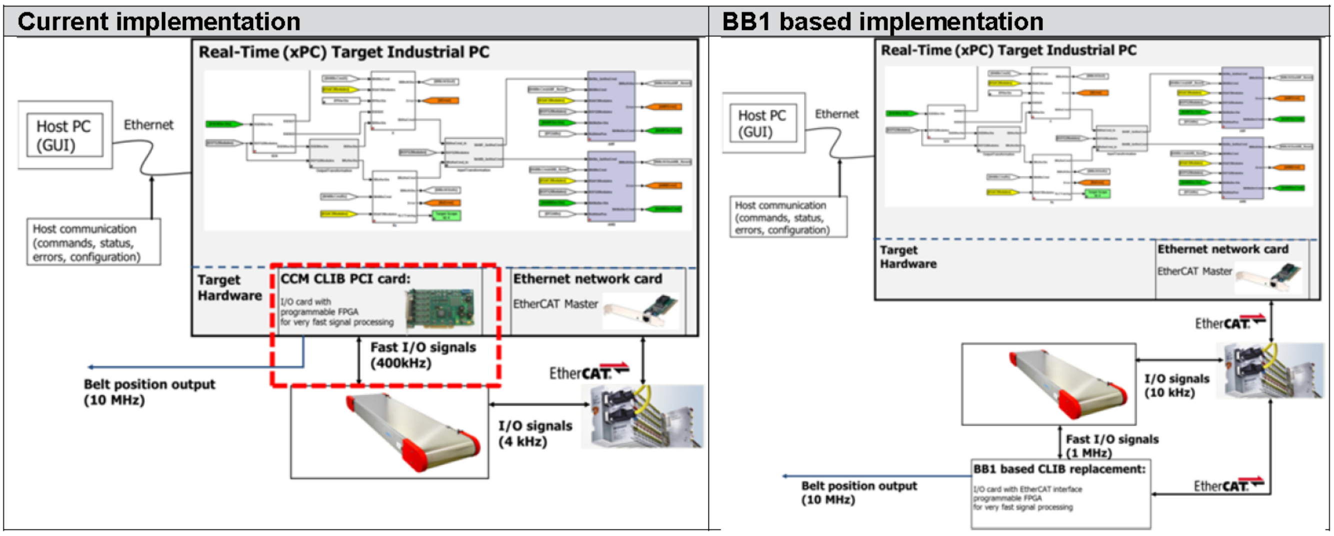



Figure 4.1.6 - Current vs BB-based application

**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.

## 4.1.5 - BB1 – Advanced sensor signal processing module requirements

| Req. ID | Parameter/Description | Nominal | Min | Max | Dim |
|---|---|---|---|---|---|
| Pi-1-BB1.1 | FPGA specs | Xilinx FPGA with sufficient available resources for existing algorithm implementation (currently implemented on an Altera Cyclone EP4CE30F23C7). | | | - |
| Pi-1-BB1.2 | Communication (fieldbus) interface | EtherCAT slave | | | - |
| Pi-1-BB1.3 | EtherCAT sample rate | | 10 | | kHz |
| Pi-1-BB1.4 | Target price | 500 | | | € |
| Pi-1-BB1.5 | Live updatable parameters via EtherCAT:<br>- At Startup (once for initialization)<br>- Low update rate (e.g. 1…100Hz)<br>- High update rate (10 kHz, each sample) | Yes | | | |
| Pi-1-BB1.6 | Firmware upgradable via EtherCAT (FoE) | Yes | | | |
| Pi-1-BB1.7 | *Wish: Integration with BB5 amplifiers* | 8x | | | |
| Belt transport position SinCos encoder inputs | | | | | |
| Pi-1-BB1.8 | Number of analog inputs | | 6 | - | - |
| Pi-1-BB1.9 | Analog input resolution | | 14 | - | bit |
| Pi-1-BB1.10 | Analog input sample rate[1] | | 1 | | MHz |
| Pi-1-BB1.11 | Analog input low pass noise reduction filter passband frequency range<br><br>(As defined in Figure 1.4) | | 0 | 500 | kHz |
| Pi-1-BB1.12 | Analog input low pass noise reduction filter passband gain.<br><br>(As defined in Figure 1.4) | | -0.5 | 0.5 | dB |
| Pi-1-BB1.13 | Analog input anti-aliasing filter | No | | | |

| | | | | | |
|---|---|---|---|---|---|
| Pi-1-BB1.14 | Analog input type | Differential | | | |
| Pi-1-BB1.15 | Analog input voltage range : | | 0 | 5 | V |
| Pi-1-BB1.16 | Analog input differential voltage range | | -0.68 | 0.68 | V |
| Pi-1-BB1.17 | Number of RS-422 digital inputs (encoder index pulse) | | 3 | | |
| Pi-1-BB1.18 | RS-422 digital input (encoder index pulse) sample rate | | 1 | | MHz |
| Belt transport position encoder outputs | | | | | |
| Pi-1-BB1.19 | Number of RS-422 digital outputs[2] | | 4 | | - |
| Pi-1-BB1.20 | RS-422 digital output sample rate | | 20 | | MHz |

| | | | | | |
|---|---|---|---|---|---|
| *Wish: AMSR gap sensor inputs* | | | | | |
| Pi-1-BB1.21 | Number of analog inputs | | 6 | - | - |
| Pi-1-BB1.22 | Analog input resolution | | 16 | - | bit |
| Pi-1-BB1.23 | Analog input sample rate | | 10 | | kHz |
| Pi-1-BB1.24 | Analog input anti-aliasing filter | Yes | | | |
| Pi-1-BB1.25 | Analog input type | Differential | | | |
| Pi-1-BB1.26 | Analog input voltage range : | | -0.5 | 0.5 | V |
| | | | -0.5 | 10 | V |
| Pi-1-BB1.27 | Analog input differential voltage range | | 0 | 10 | V |

[1] This frequency is based on the wish to sample in each quadrant, a 5 m/s belt speed and a 20 $\mu$m encoder pitch
[2] Used for the incremental encoder outputs

### 4.1.6 - BB4 – High speed vision

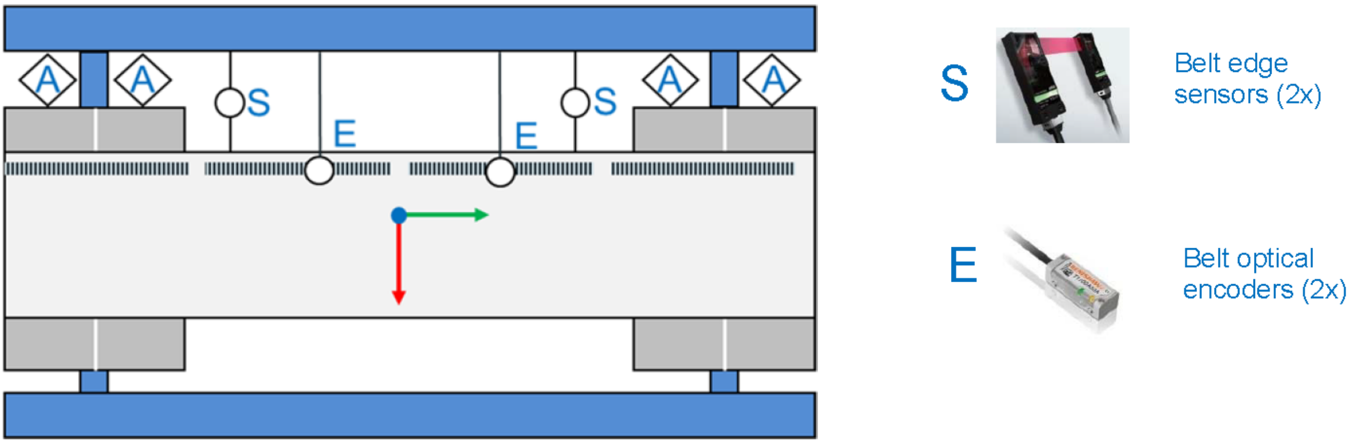



Figure 4.1.7 - Vision sensor locations

**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.

*Note: The belt edge sensors measure the lateral belt position and are used in both X and Rz position control loops*

| Req. ID | Parameter/Description | Nominal | Min | Max | Dim |
|---|---|---|---|---|---|
| Pi-1-BB4.1 | Belt edge sensor output least significant bit[5] | - | 0.1 | - | um |
| Pi-1-BB4.2 | Belt edge sensor accuracy (including optics which is out of scope)[6] | 1 | - | 2 | um |
| Pi-1-BB4.3 | Belt edge sensor sample rate[7] | 10 | 1 | - | kHz |
| Pi-1-BB4.4 | Belt edge sensor measurement range lateral direction (X) | - | -2.5 | 2.5 | mm |
| Pi-1-BB4.5 | Belt edge sensor measurement range transport direction (Y) | - | 1[8] | - | mm |
| Pi-1-BB4.6 | Belt edge sensor (fieldbus) interface | EtherCAT and/or Analog output | - | - | - |
| Pi-1-BB4.7 | EtherCAT sample rate | | 10 | | kHz |

| | | | | | |
|---|---|---|---|---|---|
| Pi-1-BB4.8 | Target price<br>- Processing + 2x (Camera)<br>- Processing + 2x (Camera + optics + illumination) | | | ?<br>2500 | €<br>€ |
| Pi-1-BB4.9 | Vision algorithms programmable/ modifiable by non-FPGA/ VHDL experts | Yes | | | |

### 4.1.7 - BB4 – High speed vision requirements

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

| | | | | | |
|---|---|---|---|---|---|
| Pi-1-BB4.20 | Number of belt transport sensors<br>(Might be combined with belt edge sensors) | 1 | | | |
| Pi-1-BB4.21 | Belt transport sensor output least significant bit | - | 0.1 | - | um |
| Pi-1-BB4.22 | Belt transport sensor accuracy (including optics which is out of scope) | - | 1 | - | um |
| Pi-1-BB4.23 | Belt transport sensor index detection accuracy | - | 1 | - | um |
| Pi-1-BB4.24 | Belt transport sensor sample rate | 10 | 1 | - | kHz |

[1] The target price is based on the assumption that the high speed vision solution will replace both the belt edge measurement system and the belt transport position (encoder) system.
[2] The measurement value should not be truncated unnecessarily. A smooth, although noisy, signal will introduce less disturbances in the feedback control loop.
[3] Sub-pixel accurate algorithms, averaging within the field-of-view and sensor calibration could be used to achieve the required accuracy.
[4] 1 kHz is the absolute minimum sample frequency. The cheapest possible solution capable of a 1 kHz sample frequency and the highest performance solution for the target price are of interest.
[5] A higher range is better to increase robustness against dirt and belt edge damage. The range could also be increased optically.

### 4.1.8 - BB5 – Servo amplifier

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

**Generic amplifier requirements**

| Req. ID | Parameter/Description | Nominal | Min | Max | Dim |
|---|---|---|---|---|---|
| Pi-1-BB5.28 | 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 | | | |
| Pi-1-BB5.29 | It shall be possible to auto-tune the current loop | Yes | | | |
| Pi-1-BB5.31 | It shall be possible to tune the current loop manually | Yes | | | |
| Pi-1-BB5.32 | Minimal functions for human safety | - Safe Torque Off (STO)<br>- Switch back to failsafe outputs on communication loss | | | |

### 4.1.9 - Requirements for amplifier used for reluctance actuators

| Req. ID | Parameter/Description | Nominal | Min | Max | Dim |
|---|---|---|---|---|---|
| Pi-1-BB5.1 | Current loop PI-control bandwidth (with AMSR actuator resistance: 6.8 ohm, Inductance: 49.5 mH @ 100Hz) | | 500 | - | Hz |
| Pi-1-BB5.2 | Number of motor phases | 1 | | | |
| Pi-1-BB5.3 | Current loop sample rate | | 32 | | kHz |
| Pi-1-BB5.4 | Current sensing resolution | | 0.2 | | mA |
| Pi-1-BB5.5 | Current demand resolution | | 0.1 | | mA |
| Pi-1-BB5.6 | Continuous current | | 1 | 3 | A |
| Pi-1-BB5.7 | Peak current | | 2 | 6 | A |
| Pi-1-BB5.8 | Bus voltage | | 24 | 48 | Vdc |
| Pi-1-BB5.9 | PWM frequency | | 32 | | kHz |
| Pi-1-BB5.10 | PWM resolution | | 12 | | bit |

| | | | | | |
|---|---|---|---|---|---|
| Pi-1-BB5.11 | (field)bus interface (also for configuration and update of firmware) | EtherCAT & SPI[9] | | | |
| Pi-1-BB5.12 | Sample rate bus | | 10 | | kHz |
| Pi-1-BB5.13 | Cost price per axis | | | 70 | euro |

### 4.1.10 - Requirements for amplifier used for brushless AC servo motor

| Req. ID | Parameter/Description | Nominal | Min | Max | Dim |
|---|---|---|---|---|---|
| Pi-1-BB5.14 | Current loop PI-control bandwidth (Rph-ph=4,64 Ohm, Lph-ph=24 mH) | | 500 | - | Hz |
| Pi-1-BB5.15 | Number motor phases | 3 | | | |
| Pi-1-BB5.16 | Current loop sample rate | | 32 | | kHz |
| Pi-1-BB5.17 | Current sensing resolution | | 2 | | mA |
| Pi-1-BB5.18 | Current demand resolution | | 1 | | mA |
| Pi-1-BB5.19 | Continuous current | | 10 | | A |
| Pi-1-BB5.20 | Peak current | | 15 | | A |
| Pi-1-BB5.21 | Bus voltage | 325 | 325 | 565 | Vdc |
| Pi-1-BB5.22 | PWM frequency | | 32 | | kHz |
| Pi-1-BB5.23 | PWM resolution | | 12 | | Bit |
| Pi-1-BB5.24 | (field)bus interface (also for configuration and update of firmware) | EtherCAT | | | |
| Pi-1-BB5.25 | Sample rate bus | | 10 | | kHz |
| Pi-1-BB5.26 | Cost price per axis | | | 800 | euro |
| Pi-1-BB5.27 | Encoder input | SSI (absolute) & SinCos | | | |
| Pi-1-BB5.30 | Commutation method | Field Oriented Control | | | |

#### 4.1.11 - BB10 – Multi/many core platform

**Main target:**
Execute non-real-time OS and real-time software on the same hardware with reduced hardware costs.

| Req. ID | Parameter/Description | Nominal | Min | Max | Dim |
|---|---|---|---|---|---|
| Pi-1-BB10.1 | Performance | At least equivalent to:<br>CPU board Intel Core i5 6440EQ - Quad core - Chipset QM170 - 2.7 GHz[10] | | | |
| Pi-1-BB10.2 | Hardware suited for executing EtherCAT master | Yes | | | |
| Pi-1-BB10.3 | Hardware suited to execute compiled Simulink models | Yes | | | |
| Pi-1-BB10.4 | EtherCAT sample rate | 10 | | | kHz |
| Pi-1-BB10.5 | Position loop update rate | 10 | | | kHz |
| Pi-1-BB10.6 | Capable of executing real-time controller and non-real-time operating system (Linux or Windows) simultaneously on platform | Yes | | | |
| Pi-1-BB10.7 | Cost | | | 1000 | euro |

1. The bandwidth of EtherCAT at 100 Mb/s should be sufficient for pilot 1 with a 10 kHz sample rate (a minimum EtherCAT cycle time of about 40-65 us is expected, leaving 35-60 us for time critical calculations). However, we encounter limitations of the EtherCAT-bus for systems with more axes or more extensive logging of data. EtherCAT is currently quite limited with respect to available bandwidth and the maximum achievable sample rate due to delays in slave-to-slave communication. We therefore strongly recommend to investigate support of higher performance communication buses by the I-MECH reference platform.
2. This frequency is based on the wish to sample in each quadrant, a 5 m/s belt speed and a 20 um encoder pitch
3. Used for the incremental encoder outputs
4. An Altera Cyclone EP4CE30F23C7 is used in the current CLIB. Performance of this FPGA is sufficient for the smart encoder processing required by the GSC pilot.
5. The measurement value should not be truncated unnecessarily. An untruncated, although noisy, signal will introduce less disturbances in the feedback control loop.
6. Sub-pixel accurate algorithms, averaging within the field-of-view and sensor calibration could be used to achieve the required accuracy.

7. 1 kHz is the absolute minimum sample frequency. The cheapest possible solution capable of a 1 kHz sample frequency and the highest performance solution for the target price are of interest.
8. A higher range is better to increase robustness against dirt and belt edge damage. The range could also be increased optically.
9. A variant with EtherCAT is prefered for initial testing to ensure independence of other building blocks. A variant with SPI interface is of interest in later stages to be integrated with I-MECH BB1, such that up to 8 amplifiers can be controlled via a single BB1 EtherCAT slave.
10. Applicability of a SoC platform equipped with an FPGA instead of an X86 platform is still under investigation.

## 4.2 - Pilot 2: 12 inch wafer stage

***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.

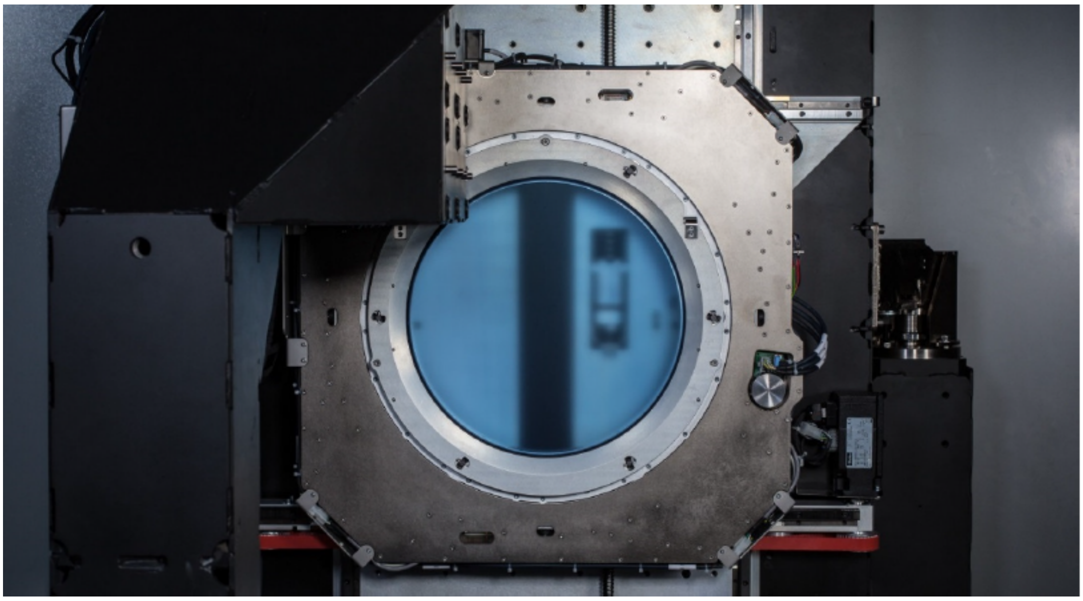


Figure 4.2.1 - Photo of the wafer stage

### 4.2.1 - 12-inch wafer stage properties

Sensors:

- 3 short-stroke encoders
- 4 long-stroke encoders
- additional long-stroke motor 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
- Electromechanical brake on y-axis motor (vertical axis)

Additional sensors:

- High-speed camera for vision-in-the-loop control

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

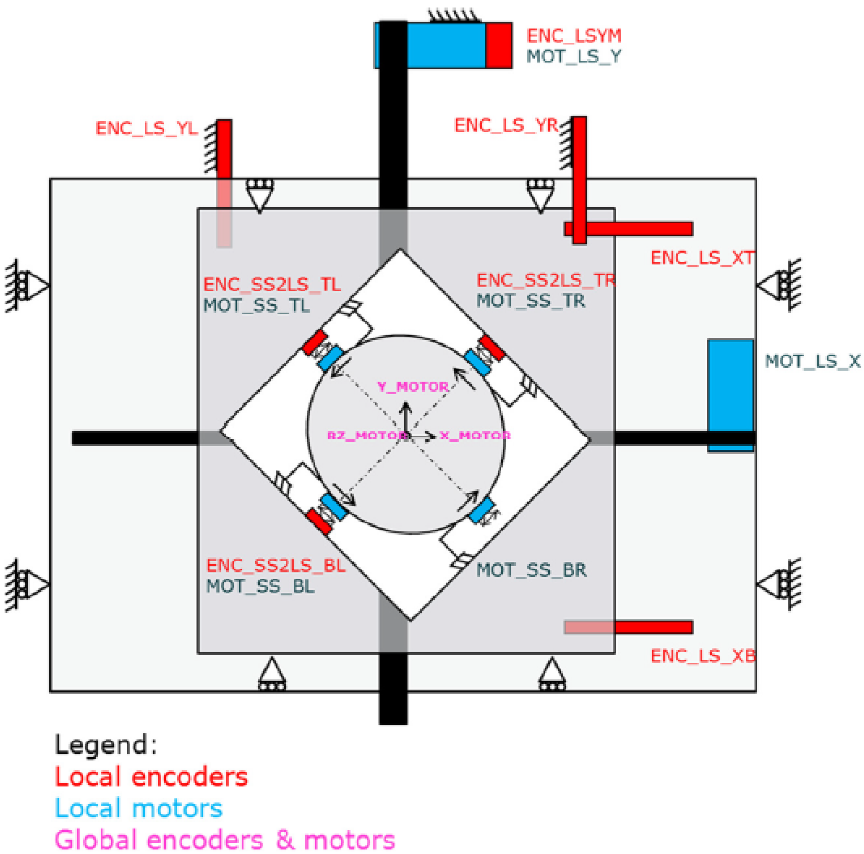



Figure 4.2.2: overview of the motors and encoders

Nexperia currently relies on a a modular motion control platform which 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.

For the purpose of the I-MECH project, it is sufficient to demonstrate a model-based control design workflow based on a centralized control system. Such a system may not currently exceed the performance requirements of the current control platform, but will likely do so in the future when decentralized topologies are also supported. A block diagram of the system envisioned by Nexperia is shown in Figure 4.2.3. Furthermore, the centralized architecture still allows full demonstration of the I-MECH principles.

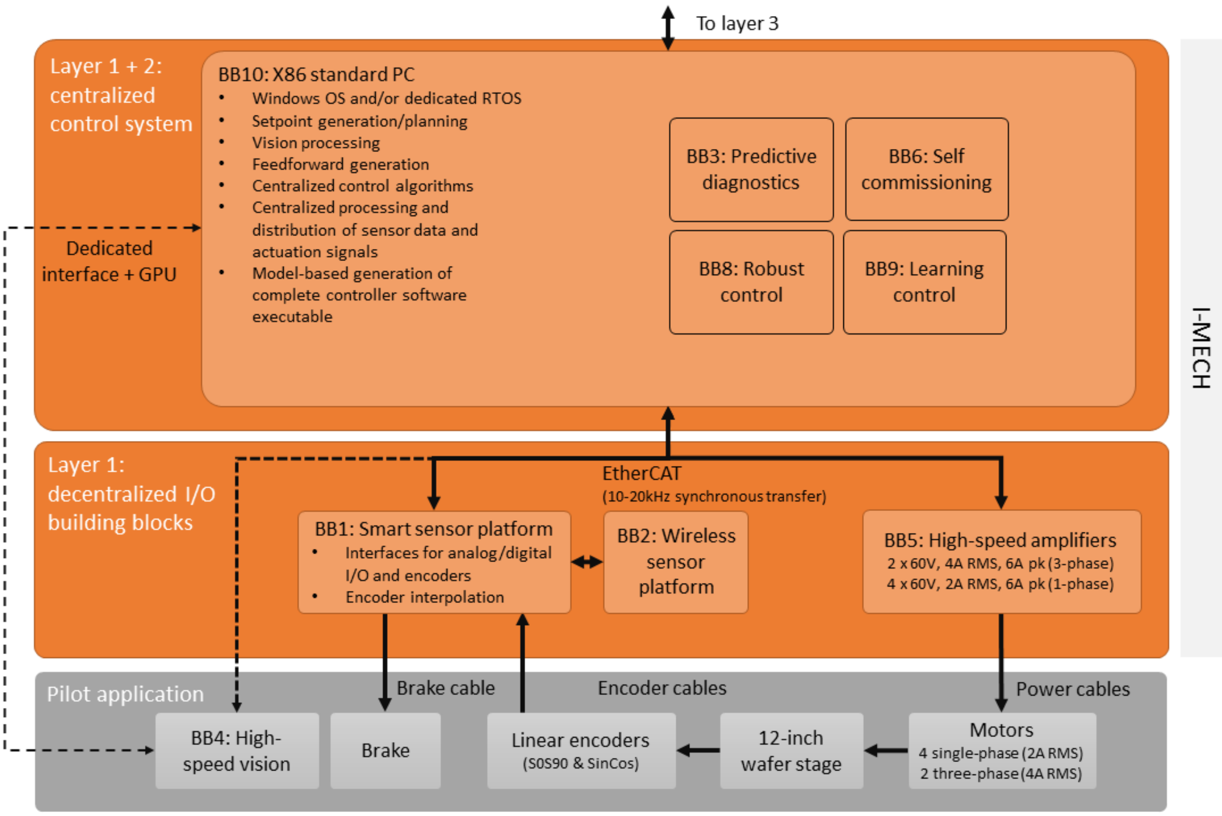



Figure 4.2.3: 12-inch wafer stage motion control

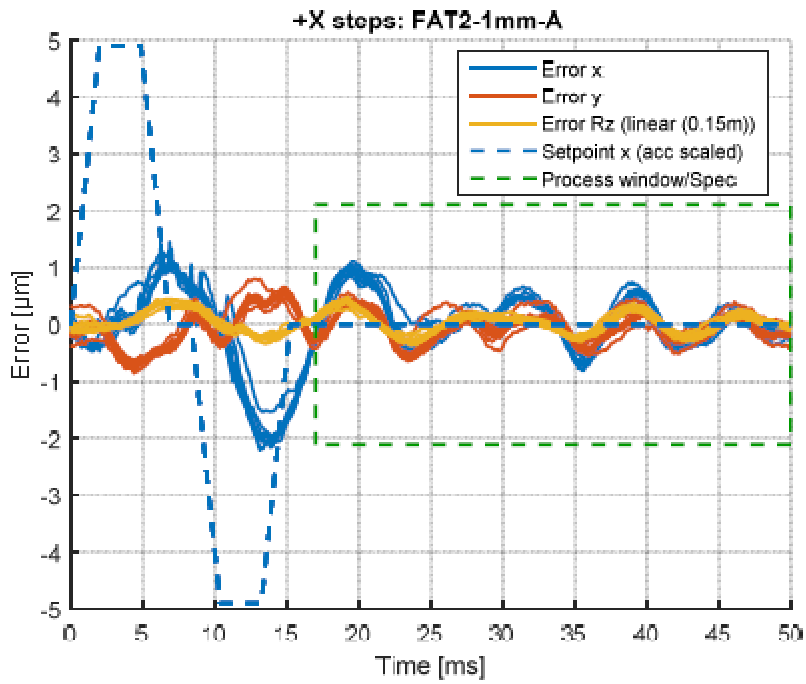



Figure 4.2.4 - Graphical depiction of 12-inch wafer stage settling requirements

## 4.2.2 - Requirements and specification

Based on the block diagram shown in Figure 4.2.3 and corresponding description, detailed Pilot 2 requirements and specifications are defined in Table 4.2.1.

Table 4.2.1 - Pilot 2 requirements and specifications

| **Functional and operational requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| **General hardware** | | | |
| Pi-2-1 | Operating temperature (°C) | +20°C - +24°C | Typical working temperature for semiconductor electronic equipment. |
| **Smart sensor platform (BB1)** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |

| | | | |
|---|---|---|---|
| Pi-2-BB1.1 | Communication interface between layer 2 and BB1/2/5 | EtherCAT | The selection of EtherCat is based on D2.1 - D2.4. |
| Pi-2-BB1.2 | Signal tracing | All relevant signals and statuses of layer 1 devices, 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. | To facilitate debugging, commissioning and maintenance |
| Pi-2-BB1.3 | Latency between the encoders and servo drives. | Depends on sample rate; e.g. for 10 kHz shall not significantly exceed one EtherCAT cycle (100 us) | To obtain decent robustness margins in the servo control loops |
| Pi-2-BB1.4 | Wired firmware upgrades | Yes | Keeping the system up to date without requiring dedicated tools |
| Pi-2-BB1.5 | Live update of parameters via fieldbus:<br>- At Startup (once for initialization)<br>- High update rate (each sample) | Yes | Facilitates online tuning and diagnostics |
| Pi-2-BB1.6 | Integration with BB5 amplifiers | Yes (optional) | Allows closing a control loop (encoder->current) and commutation without latency of the EtherCAT field bus, which is at least one cycle<br>I.e. in this case encoder inputs do not have to pass via layer 2. |
| Pi-2-BB1.7 | Processor / SoC | SoC/FPGA solution | FPGA is required for effective implementation of EtherCAT Slave and for precise timing and synchronization management |
| **Wireless sensor gateway (BB2)** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-2-BB2.1 | OTA firmware upgrades | Yes | So that no dedicated tools are required |

| | | | |
|---|---|---|---|
| Pi-2-BB2.2 | Communication interface between the wireless node and 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. |
| Pi-2-BB2.3 | Physical parameter measurement | Analog force sensors (via ADC) | Analog sensors may be present on the wireless sensor node. |
| Pi-2-BB2.4 | Data encryption | No | There is no particular need to encrypt data |
| Pi-2-BB2.5 | Architecture | Preferably integrated with BB1 to share a common EtherCAT interface | Sensor nodes can then be transparently accessed as if they were wired sensors connected to BB1 |
| Pi-2-BB2.6 | Sampling frequency | 1 kHz | The minimum is 60 Hz (i.e. 2 measurements every machine cycle, which is 33 ms or 30 Hz) |
| Pi-2-BB2.7 | ADC resolution | ≥12 bits | |
| Pi-2-BB2.8 | Raw sensor data transmission throughput | Up to 12 kbit/s | Number of bits per sample, multiplied by maximum sampling frequency. |
| Pi-2-BB2.9 | Sensor communication interfaces | I2C, SPI, Analog | Commonly supported communication interfaces in commercially available sensors and microcontrollers. |
| Pi-2-BB2.10 | Power supply | Wireless power transfer if feasible, battery otherwise | Self-powering saves maintenance |
| Pi-2-BB2.11 | Wireless Communication range | 4 m | Sufficient for all machine topologies |
| Pi-2-BB2.12 | Software reset mechanisms | Yes | The system will check for faulty data, or no data from the sensors and will trigger system restart |
| **High-speed vision / Vision in the loop (BB4)** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-2-BB4.1 | Loop rate | >500 Hz | The main aim is demonstration of vision in the loop technology. Initially, the achievable sample rate is not essential. |
| Pi-2-BB4.2 | Architecture | COTS components | Commercial hardware (camera, GPU) to build a cost-effective system |
| Pi-2-BB4.3 | Position feedback | Yes | Position feedback must be possible based on a simple template match on a recognizable object in 2D. |

| High-performance servo amplifiers (BB5) | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-2-BB5.1 | Signal tracing | 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. | To facilitate debugging, commissioning and maintenance |
| Pi-2-BB5.2 | Current loop tuning | Manually and automatically | Automatic to ease commissioning effort where possible |
| Pi-2-BB5.3 | Minimal functions for human safety | - Safe Torque Off (STO)<br>- Switch back to failsafe outputs on communication loss<br>- Preferably, drive safety can be controlled in several zones, perhaps using an approved (digital) protocol for safety systems<br>Safe speed will require input from an auxiliary encoder/tacho for speed monitoring | Compliance with safety directives |
| Pi-2-BB5.4 | Outputs shall be EMC filtered | Yes | Ideally, unshielded motor cables will not emit harmful interference |
| Pi-2-BB5.5 | Voltage/PWM feed-forward shall be possible | Yes | To bypass delay of current feedback loop (unless current feedback loop is very fast) |
| Pi-2-BB5.6 | Standard protection features (RMS current, I2T power, Max current) | Yes | |
| Pi-2-BB5.7 | Current loop bandwidth | ≥5 kHz | |
| Pi-2-BB5.8 | Current requirements | 2 x 3-ph, 60V, 4A RMS, 6A peak<br>4 x 1-ph, 60V, 2A RMS, 6A peak | To comply with pilot motor specifications |
| Pi-2-BB5.9 | Current resolution | 0.6 A | |

| | | | |
|---|---|---|---|
| Pi-2-BB5.10 | Current loop SNR | 90 dB | To achieve higher dynamic range than currently achievable |
| Pi-2-BB5.11 | Commutation | Field-oriented control | |
| **Layer 2 platform (BB10/11, x86-compatible)** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-2-BB10.1 | Performance | Sufficient to perform servo loop computations for several (MIMO) axes at 10 kHz, including advanced control methods such as ILC | An i5 x86 platform should easily be capable of providing the required performance and memory to satisfy this requirement. |
| Pi-2-BB10.2 | EtherCAT sample rate | 10-20 kHz | |
| Pi-2-BB10.3 | Position control loop update rate | 10-20 kHz | |
| Pi-2-BB10.4 | Control loop latency | Depends on sample rate; e.g. for 10 kHz shall not significantly exceed one EtherCAT cycle (100 us) | To obtain decent robustness margins in the servo control loops |
| Pi-2-BB10.5 | Service communication interface | Ethernet, TCP/IP | General interface for non-real-time data, diagnostics and servicing, interface to host and development PCs |
| Pi-2-BB10.6 | Real-time communication interfaces to Layer 1 | EtherCAT | Integration with I-MECH Layer 2 |
| Pi-2-BB10.7 | Real-time synchronization (distributed clock support) | yes | For high-performance feedback control, time synchronization of full system from sensor sampling to control system is required |
| Pi-2-BB10.8 | RTOS | Real-time OS compatible with Simulink executables | Any RTOS is suitable which is open and extensible and can sustain executables created from Simulink models. |

## 4.3 - Pilot 3: High Speed Packaging

### 4.3.1 - Customer Requirements and Specifications

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 positive in-line 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 - 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 BB-11 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

**Requirements and Specifications**

Table 4.3.1 - Pilot 3 - requirements and specifications

| **Functional Requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-3.F1 | OPC-UA | Yes | HMI communication |
| Pi-3.F2 | OPC-DA | Yes | HMI communication |
| Pi-3.F3 | Modbus-TCP | Yes | HMI communication |
| Pi-3.F4 | Ethercat | Yes | Fieldbus for IO and Motion |
| Pi-3.F4 | Powerlink | Yes | Fieldbus for IO and Motion |
| Pi-3.F5 | Sercos III | Yes | Fieldbus for IO and Motion |
| Pi-3.F6 | MQTT, AMPQ | Alternatively | Machine to cloud communication |

| | | | |
|---|---|---|---|
| Pi-3.F7 | Logging | Yes | Detailed and fine grained diagnostics |
| Pi-3.F8 | Webserver | Yes | Online access to relevant variables and parameters |

| **Operational Requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-3.O1 | Hardware architecture | x86 compatible | Ability to run legacy software and availability of industrial-grade products |
| Pi-3.O2 | Number of CPU cores | At least 4 cores | Pilot requires 3 RealTime OSs and 1 GPOS |
| Pi-3.03 | RealTime OS | VxWorks 6.9.x and 7 | Legacy software and industrial-grade support |
| Pi-3.04 | Minimum scheduling cycle time | 50us | x |
| Pi-3.05 | Motion Control cycle time | 500us | |
| Pi-3.06 | Max Jitter | 1% cycle time | |

| **Design Requirements** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |

| | | | |
|---|---|---|---|
| Pi-3.D1 | RealTime oriented software | Yes | RealTime compatible memory management and IO access |
| Pi-3.D2 | Object oriented C++ API | Alternative to Pi-3.D3 | |
| Pi-3.D3 | ANSI-C API | Alternative to Pi-3.D2 | |

Communication and interface requirements:

- OPC-UA, OPC-DA, Modbus-TCP for HMI communication
- EtherCAT, Powerlink, Sercos-III as fieldbuses for IO and Motion
- MQTT, AMPQ for machine to cloud communication
- Web-Server 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.

Hardware requirements

- X86 platform

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.

### 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 [JN1] .

## 4.4 - Pilot 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.

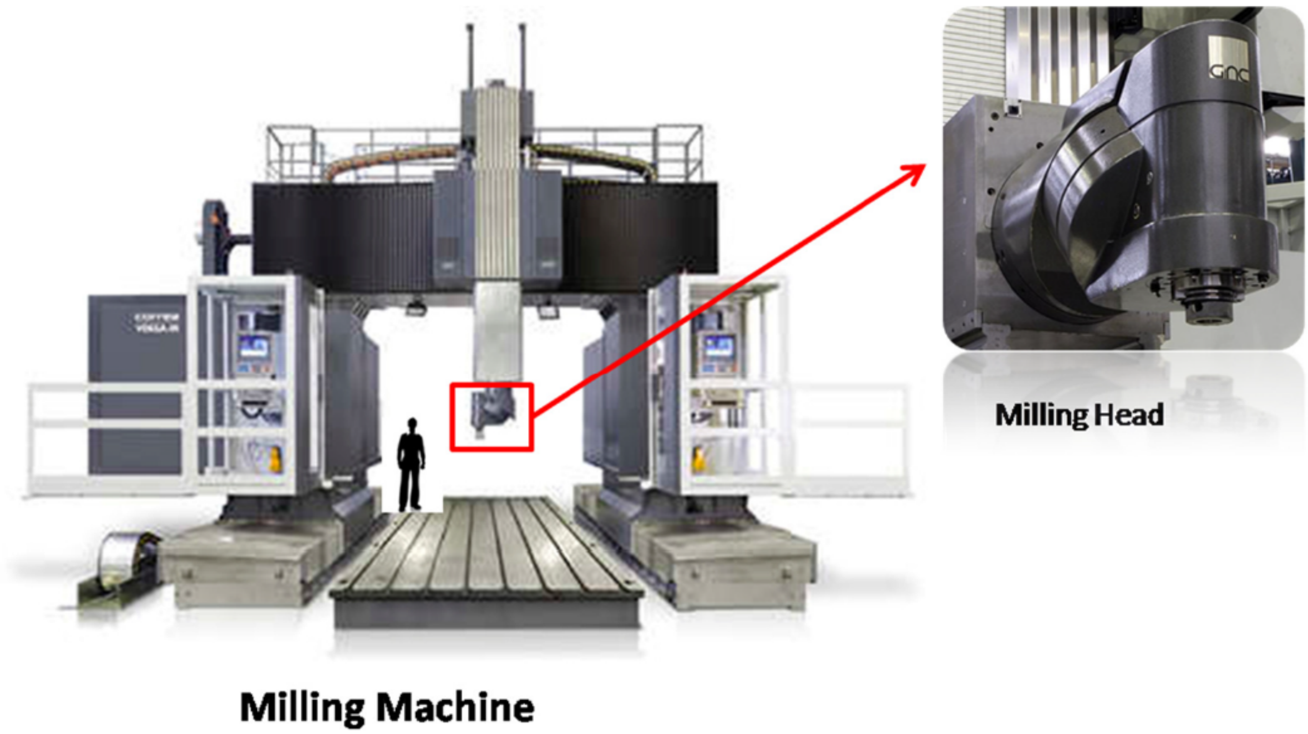



Figure 4.4.1: Example of milling machine and milling head where the I-MECH platform will be integrated in order to monitor important process parameters.

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.

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.

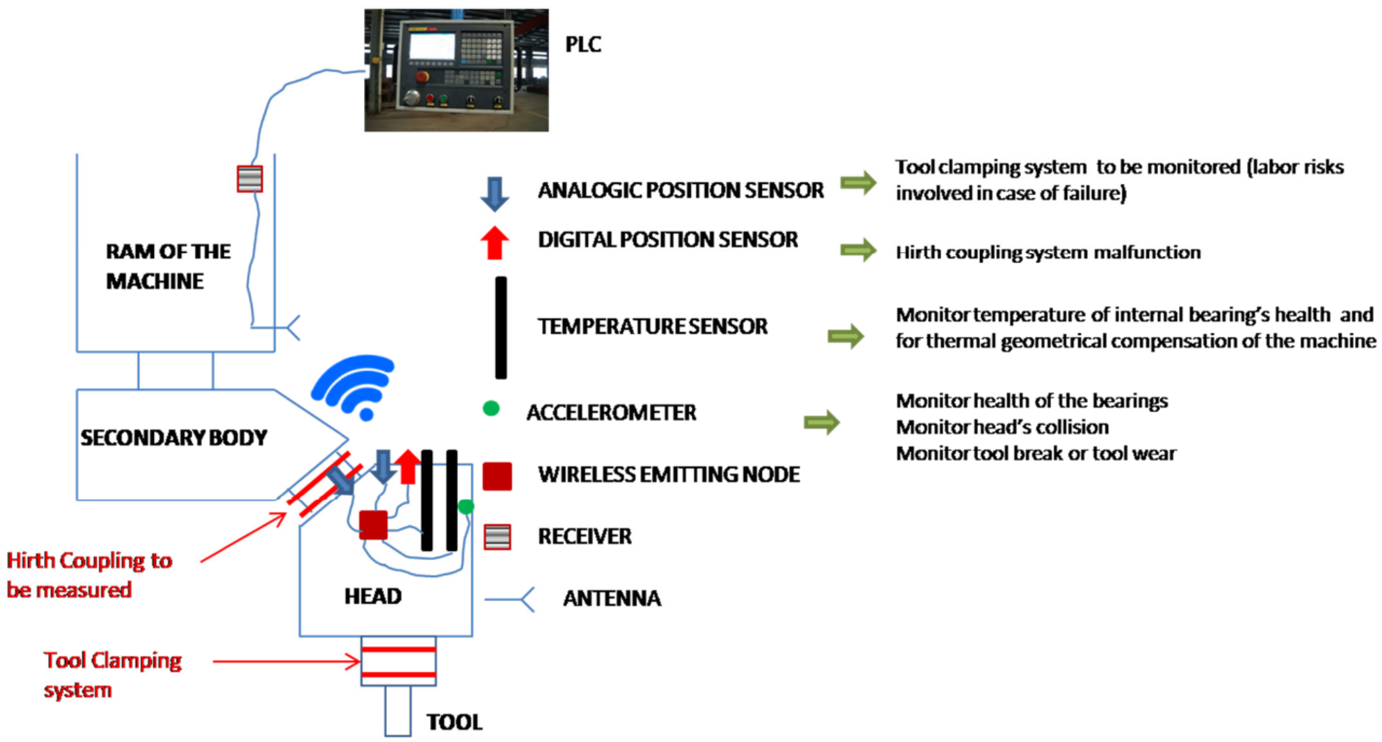



Figure 4.4.2: Illustration of how the I-MECH platform will work once integrated in the mechatronic system.

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.

### 4.4.1 - Software Requirements and Specifications

#### 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 4 m
- Output signals being collected by CNC must be made through[JN1] PROFINET

#### Electronics

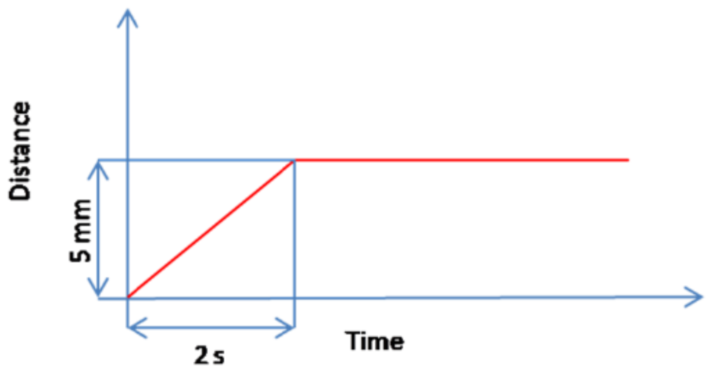
- Node identification system: More than one node can be connected to the same machine, being active only one at a time, but being ready for head change
- Node activation/deactivation from PLC
- Safe energy mode and/or energy harvesting elements to maximize operation lifetime (minimum required 12 months)

### 4.4.2 Hardware Requirements and Specifications

#### Sensors

Analogic Position sensors:

- Output Voltage: 0-5V or 0-10V
- Output Current: 1-5 mA or 4-20 mA
- Input Voltage: 15-30V
- 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 20s
- Trigger an alarm sign if a set point is reached

Accelerometer:

- Acceleration range: 50 g
- Frequency range: 1k Hz
- Resolution: 0.05g

***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 |
| Acceleromenter | 1 digital input and 1 communication port |
| Temperature | 1 communication port |
| ENABLE | 5 digital outputs |
| Total | 5 digital outputs<br>2 digital inputs<br>1 communication port |

**Signal Conditioning Circuitry**

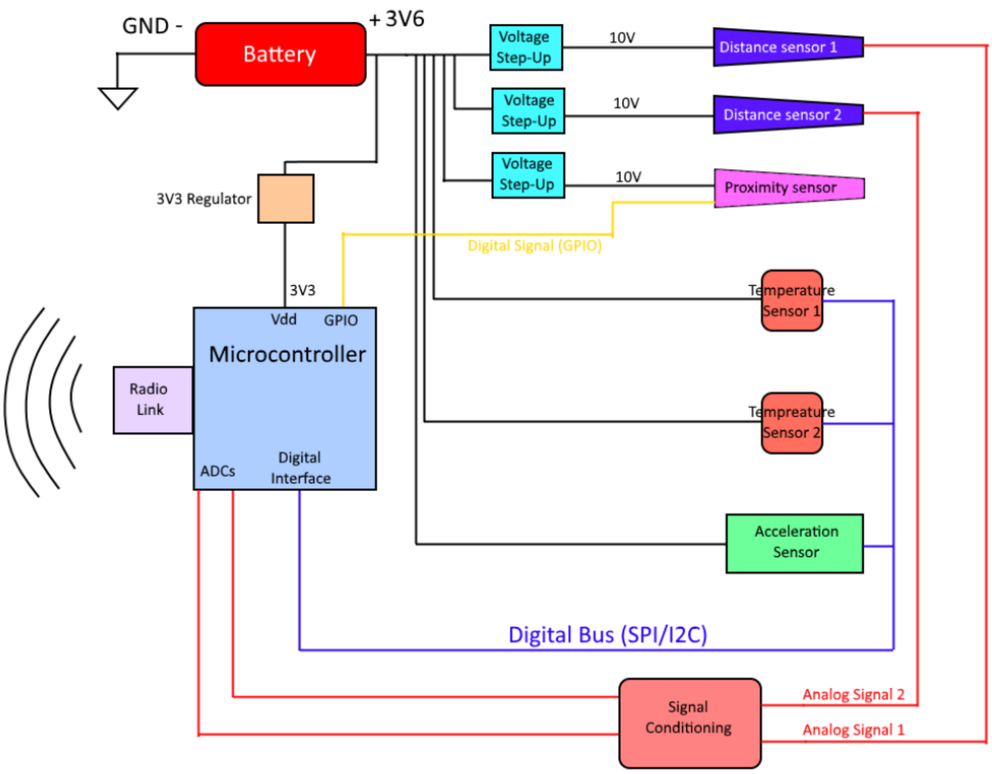



Figure 4.4.3: CNC interface overview

## 4.4.3 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.

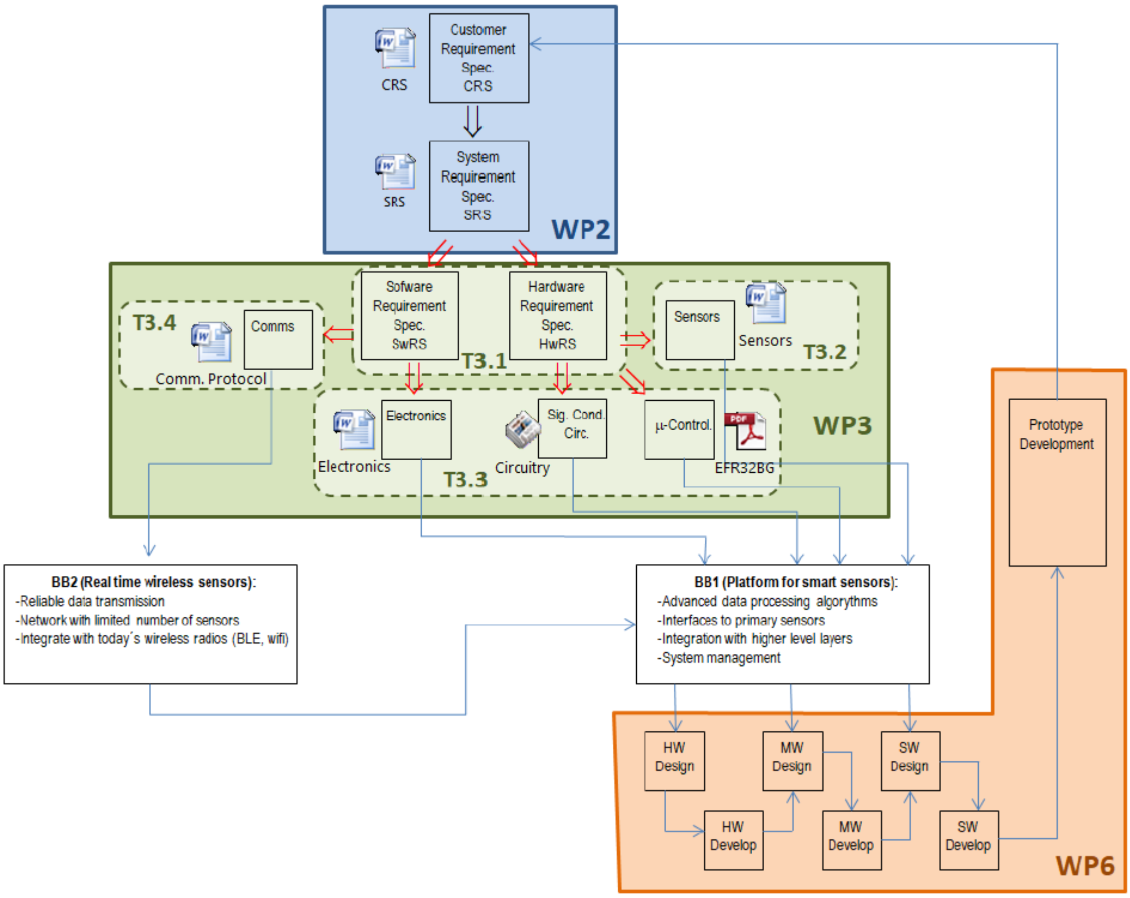



Figure 4.4.4 - Pilot 4 - System Decomposition Overview

## 4.4.4 - Usage of I-MECH Building Blocks

**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.

IKERLAN will integrate all the sensors and electronic components needed for signal conditioning, data processing and data sending in programmable PCBs. 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.

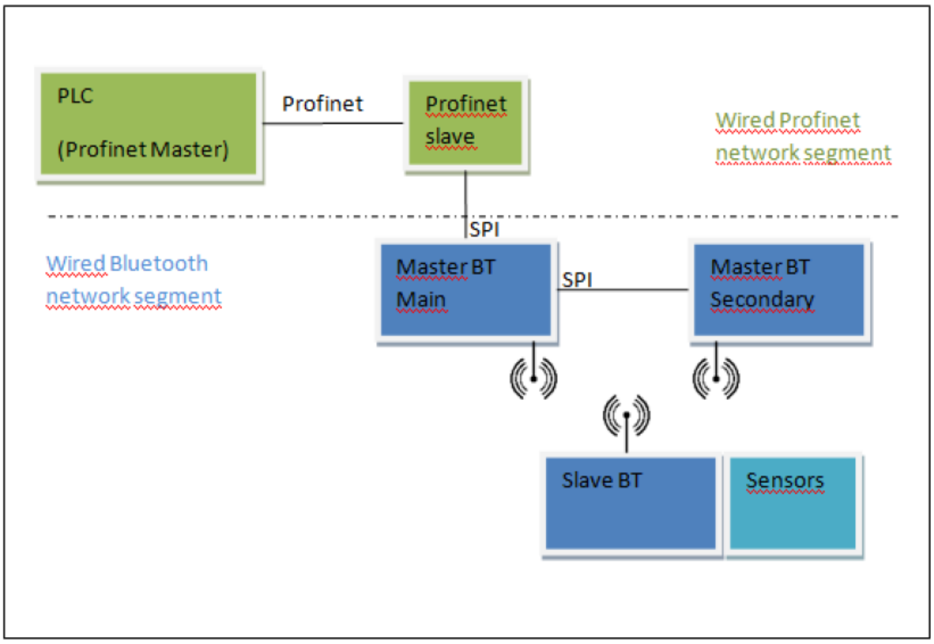



Figure 4.4.5 - Preliminary sketch of the wireless network designed in order to transfer the data collected from the sensors to the PLC of the milling machine.

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.

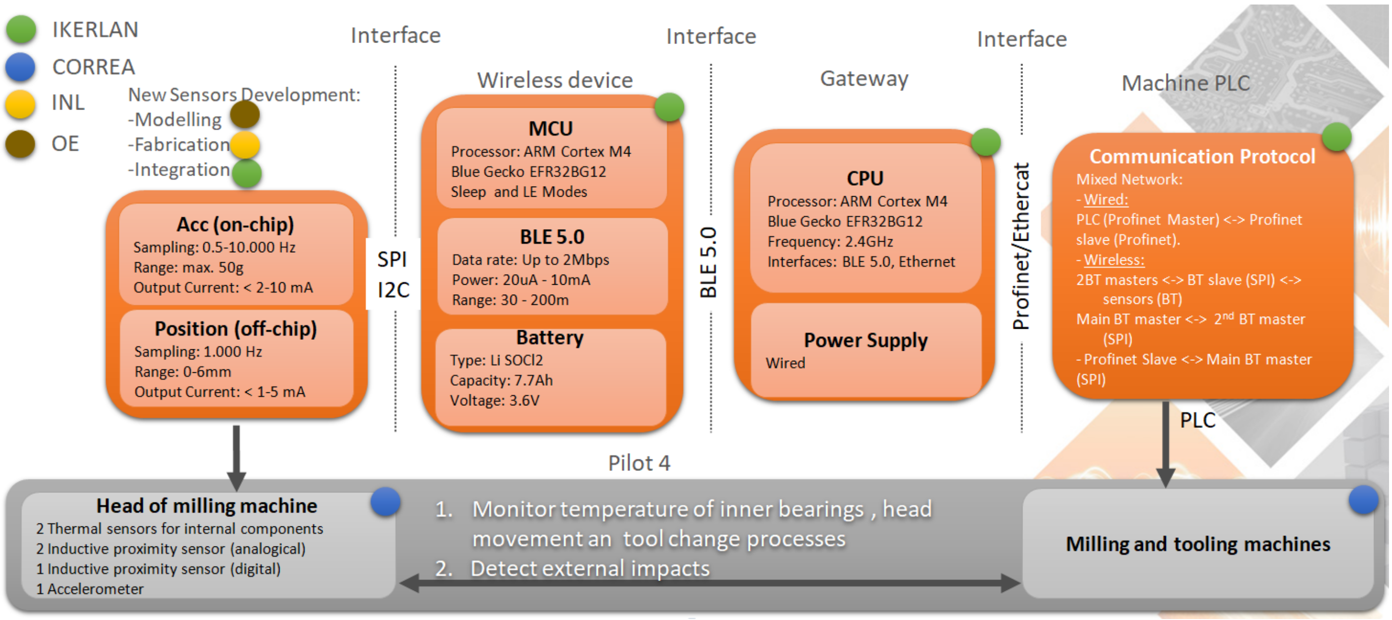



Figure 4.4.6 - Block diagram of the blocks of the milling machine

### Requirements and specification

Table 4.4.1 - Pilot 4 - requirements and specifications

| Functional Requirements | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-4.F1 | Operation environment | Device operate in interference environment conditions. | Metallic particles stemming from the machining process may difficult the communication and damage the device. |
| Pi-4.F2 | Physical parameter measurement | Temperature, relative position and impact strength | |
| Pi-4.F3 | System's operation time without battery change | 2 years | |
| Pi-4.F4 | Data encryption | No | |
| Pi-4.F5 | Visual indicators | Yes | On PLC screen |
| Pi-4.F6 | Physical buttons for device control | Yes | Buttons that allow turning on/off from the PLC |

| | | | |
|---|---|---|---|
| Pi-4.F7 | Data logging locally | Yes | Ability to store data on the device. |
| Pi-4.F7* | Data logging remotely | Yes | Ability to send data to Gateway |
| Pi-4.F8 | Electromagnetic compatibility | Yes | Sensor system must be compatible with existing wireless technologies and radiation levels. |
| Pi-4.F9 | Auto calibration | No | |
| Pi-4.F10 | Mechanical/Electrical/Water protection | Yes | System has to be shockproof |
| Pi-4.F11 | Fast start-up | Yes | System has to turn on and be able to start working in less than minute. |
| Pi-4.F12 | Win/Mac/Linux compatible | Yes | System should be able to operate with most popular operating systems for data transferring and reconfiguration |
| Pi-4.F13 | User Friendly web interface | Yes | System has to be easy configurable |
| Pi-4.F14 | Wired firmware upgrades | No | |
| Pi-4.F14* | OTA firmware upgrades | No | |
| Pi-4.F15 | Wireless debug connectivity | Yes | |
| Pi-4.F16 | Mechanical robustness | Yes | System must be vibration proof. |
| Pi-4.F17 | Communication with PLC | Profinet/SPI | |
| Pi-4.F18 | Communication between Wireless Device and GW | BLE 5.0 | To ensure minimum power consumption for wireless devices, most power effective wireless solution in market should be chosen. |

| **Operational Requirements** | | | |
|---|---|---|---|
| **Wireless Device** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-4.O1 | Minimum sampling freq. | 0.5-10000 Hz | |
| Pi-4.O2 | Min. acceleration range | 50 g | |
| Pi-4.O3 | Accelerometer resolution | 0.05 | |
| Pi-4.O4 | Power supply | Li-SoCl2 | Capacity 7.7Ah to ensure 2 years operation time |

| | | | |
|---|---|---|---|
| Pi-4.O5 | Raw sensor data size per one sample | 12 Bytes | |
| Pi-4.O6 | Raw sensor data transmission throughput | 900 B/s | |
| Pi-4.O7 | Sensor orientation data size | 8 Bytes | |
| Pi-4.O8 | Sensor orientation data transmission throughput | 400 B/s | |
| Pi-4.O9 | Communication latency | Yes | Always alert in a low consume mode awaiting for external signal to start measuring |
| Pi-4.O10 | Wireless communication protocol | BLE | |
| Pi-4.O11 | Wireless Communication range | 1.5-3m | |
| Pi-4.O12 | Encryption algorithms for data communication | AES-128, RSA or similar | |
| Pi-4.O13 | Operating temperature | Temperature (ºC): -30 ÷ +80 | Typical working temperature for commercial electronic equipment. |
| Pi-4.O14 | Relative humidity (%) | 10 ÷ 100 | Typical humidity range for commercial electronic equipment. |
| Pi-4.O15 | Flash memory (storage) | 512 kB | |
| Pi-4.O16 | Electromagnetic compatibility | | CE certified wireless communication modules and other components must be used to reduce electromagnetic radiation. |
| Pi-4.O17 | Software reset mechanisms | Yes | The system will check for faulty data, or no data from the sensors and will trigger system restart |
| Pi-4.O18 | Hardware reset | Yes | Button for hardware reset of the system |
| Pi-4.O19 | Processor | DSP extensions, Sleep modes | |
| Pi-4.O20 | RAM | 128 kB | |
| **Gateway** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-4.G1 | Communication latency | | Always alert in a low consume mode waiting for external signal to start measuring |

| | | | |
|---|---|---|---|
| Pi-4.G2 | Communication latency between wireless sensors | | Always alert in a low consume mode waiting for external signal to start measuring |
| Pi-4.G3 | Processor | Arm Cortex-A | Gateway is externally powered, therefore affordable high performance processor can be implemented – ARM Cortex-A series. |
| Pi-4.G4 | Operating system | RTOS, Linux | RTOS or custom compiled and minimized Linux for fast data processing |
| Pi-4.G5 | communication protocol | TCP/IP | Protocol is used for communication between devices using Ethernet interface. |
| Pi-4.G6 | Power Supply | Wired | |

| **Design Requirements** | | | |
|---|---|---|---|
| **Wireless Device** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-4.D1 | Sensor node locations | 6 | Inside the head of the machine |
| Pi-4.D2 | Sensor communication interfaces | I2C, SPI, UART | Commonly supported communication interfaces in commercially available sensors and microcontrollers. |
| Pi-4.D3 | Sensor node volume | < 588 cm3 | Dimensions given by the free space available inside the head |
| Pi-4.D4 | Isolation | Yes | Protecting housing |
| Pi-4.D5 | Antenna placement | PCB antenna | Antennas deployed on PCB would allow to minimize node size and chance of collision with other objects. |
| **Gateway** | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-4.D6 | Gateway dimensions | | No restrictions |
| Pi-4.D7 | Gateway casing | Yes | Protecting housing |
| Pi-4.D8 | Gateway placement | | 1.5-3 m from the emitting node |
| Pi-4.D9 | Gateway communication interfaces | USB, Ethernet, WiFi, Bluetooth | |
| Pi-4.D10 | Cabling | 1.5 m | From the antenna to the receiver |

## 4.5 - Pilot 5: Medical robotic manipulator

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.

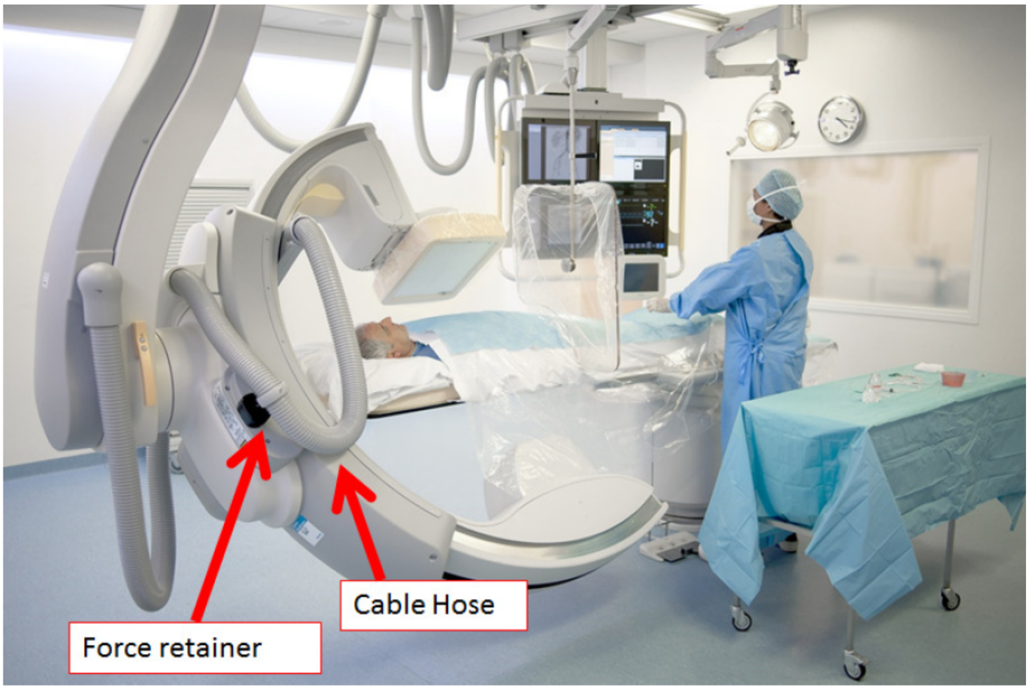


Figure 5.1.1: Cable hose and force retainer – input for model-based control

### 4.5.2 - Customer Requirements and Specifications

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)

### 4.5.3 - System Requirements, Specifications and Constraints

Fieldbus speed : < 1 [kHz]
Control loop bandwidth : < 100 [Hz]

Table 4.5.1 - Pilot 5 - requirements and specifications

| Operational Requirements | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-5.F1 | Operation temperature | +18deg - 30deg | typical working temperature during X-ray interventions |
| Pi-5.F2 | Operating altitude | >3000m | Equipment is used all over the world also on high altitudes |

| **Condition Monitoring (BB3)** | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| Pi-5-BB3.1 | Communication interface between layer 2 and BB3 | EtherCAT | world standard on deterministic real time communication |
| Pi-5-BB3.2 | Signal tracing | All relevant signals from motion controller at layer 1 at sample rate | For debugging and preventive maintenance |

| **Self Commissioning (BB6)** | | | |
|---|---|---|---|
| Req. ID. | Req. title | Value | Rationale |
| Pi-5-BB6.1 | Communication interface between layer 2,3 a BB6 | EtherCAT | world standard on deterministic real time communication |
| Pi-5-BB6.2 | Sample rate | < 4 kHz | Communication between auto-tuner and application HW |
| Pi-5-BB6.3 | Communication between auto tuner and application | Matlab/Simulink | World standard |
| Pi-5-BB6.4 | Signal tracing | All relevant signals from motion controller at layer 1 at sample rate | For frequency response and analyzing (Bode/Nyquist) |
| Pi-5-BB6.5 | Signal injection Noise, Sweep sine, etc | < sample rate | Limited by Ethercat communication |
| Pi-5-BB6.6 | Current loop tuning | Manual | |

### 4.5.4 - 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.

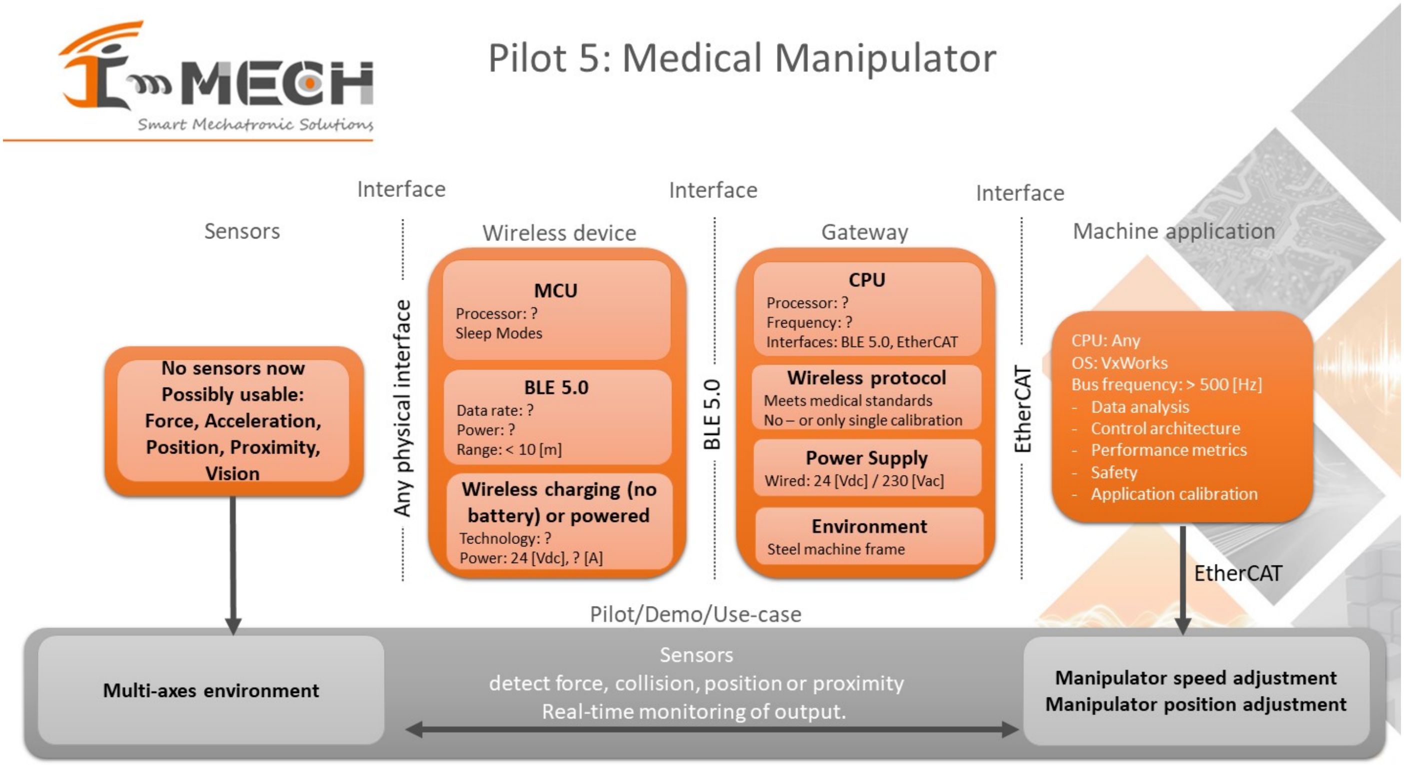



Figure 5.1.2 - Overview Medical robotic manipulator

# 5 - Demos

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

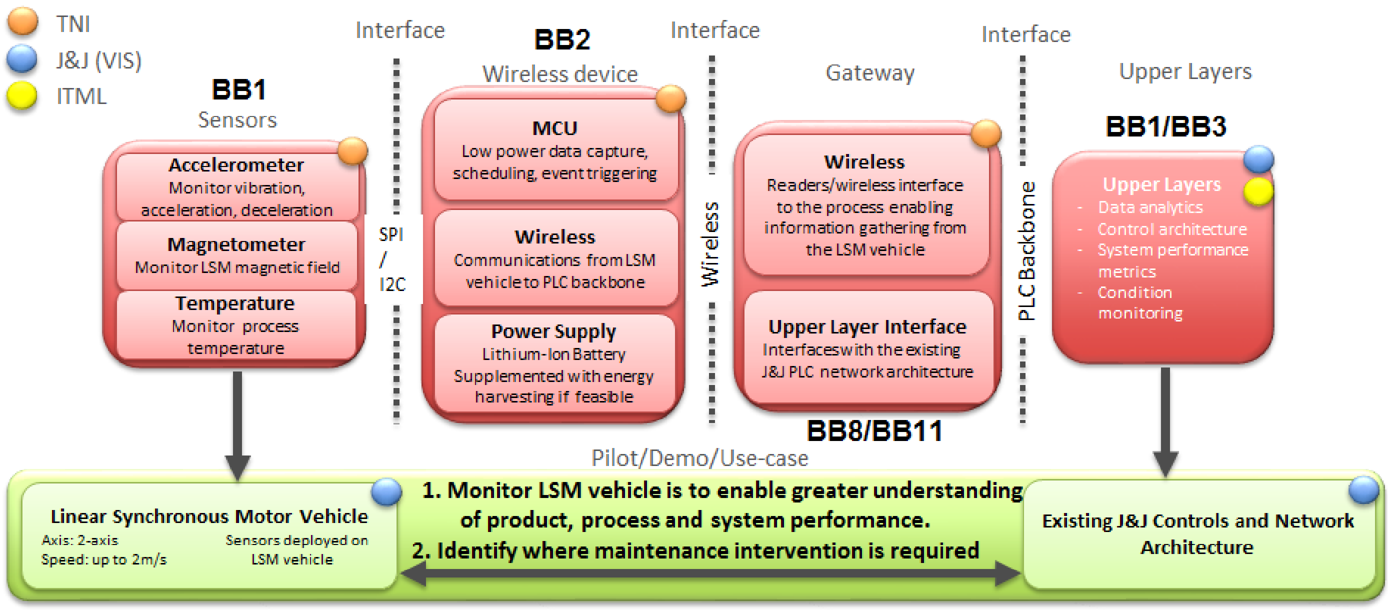



Figure 5.1.1 Condition monitoring platform for Linear Synchronous Motors (LSM) material transfer layer

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

Demonstrator 1 will apply smart sensing and condition monitoring 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 to monitor electro-mechanical parameters and the use of a data analysis platform, developed within I-MECH, to contextualise the data collected.

***Requirements and specification***

Based on the block diagram shown in Figure 5.1.1 and corresponding description, detailed Demo 1.1 requirements and specifications are defined in Table 5.1.1

Table 5.1.1 Demo 1 requirements and specifications

| **Functional Requirements**[K1] | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| De-1-F1 | Temperature Sensor | TC, PT or NTC | Sensor must be able to withstand UV cure temperatures from the range of 20°C to 70°C |
| De-1-F2 | Temperature Sensor | | Sensor must be able to be fitted to the same plane/ area as the product – as close to the product as possible. |
| De-1-F3 | 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 |
| De-1-F4 | 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] ) |
| De-1-F5 | 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. |
| De-1-F6 | Sensor connectivity | | Control input/output shall be Ethernet IP. |
| De-1-F7 | 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** |
| De-1-O1 | General requirements | | Any sensor developed will integrate with the existing MagneMotion controls. |
| De-1-O2 | General requirements | | Any sensor developed will use industry standard communications protocol back to the PLC (J&J preferred standard is Ethernet IP) |
| De-1-O3 | General requirements | | Sensor power will be via own source supply |
| De-1-O4 | 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) |
| De-1-O5 | General requirement | | If battery powered the sensor(s) /sensor block should have a low battery alarm that can be transmitted [WF[5] |

| | | | |
|---|---|---|---|
| De-1-O6 | 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. |
| De-1-O7 | Sensor fitment | | Ideally, sensor(s) should be fitted in the following fallow areas (TBD and agreed between ACoE and Tyndall and MagneMotion.) |
| De-1-O8 | Electrical requirements | | The control voltage will be 24 VDC. ACoE must approve exceptions to 24VDC control voltage. |
| De-1-O9 | 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. |
| De-1-O10 | 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] |
| De-1-O11 | 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. |
| De-1-O12 | Electrical requirements | | All analogue and non-power (signal) cables will be shielded. ACoE must approve all exceptions. |
| De-1-O13 | 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 high temp safety shut-off switch setting. Use MTW wire inside of control panels. |
| De-1-O14 | 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 |
| De-1-O15 | Electrical requirements | | Minimum wire size for wires inside cables shall follow CE, NEC, and NFPA79. ACoE must approve all exceptions. |
| De-1-O16 | 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)

Smart devices are being integrated into tools of injection molding, for example to give feedback on how a mold is (mis-)used and to monitor condition of a mold. This demonstrator will be used to evaluate wireless sensing and smart sensing building blocks, 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.

For this demo, it will be implemented two main functionalities:
i) Incorporation of a corrosion sensor, with the purpose of a predictive maintenance.
ii) Incorporation of a force sensor, with the purpose of force feedback during injection. This will allow to understand the tool health during production, and at same time, indirectly, do a part quality check.

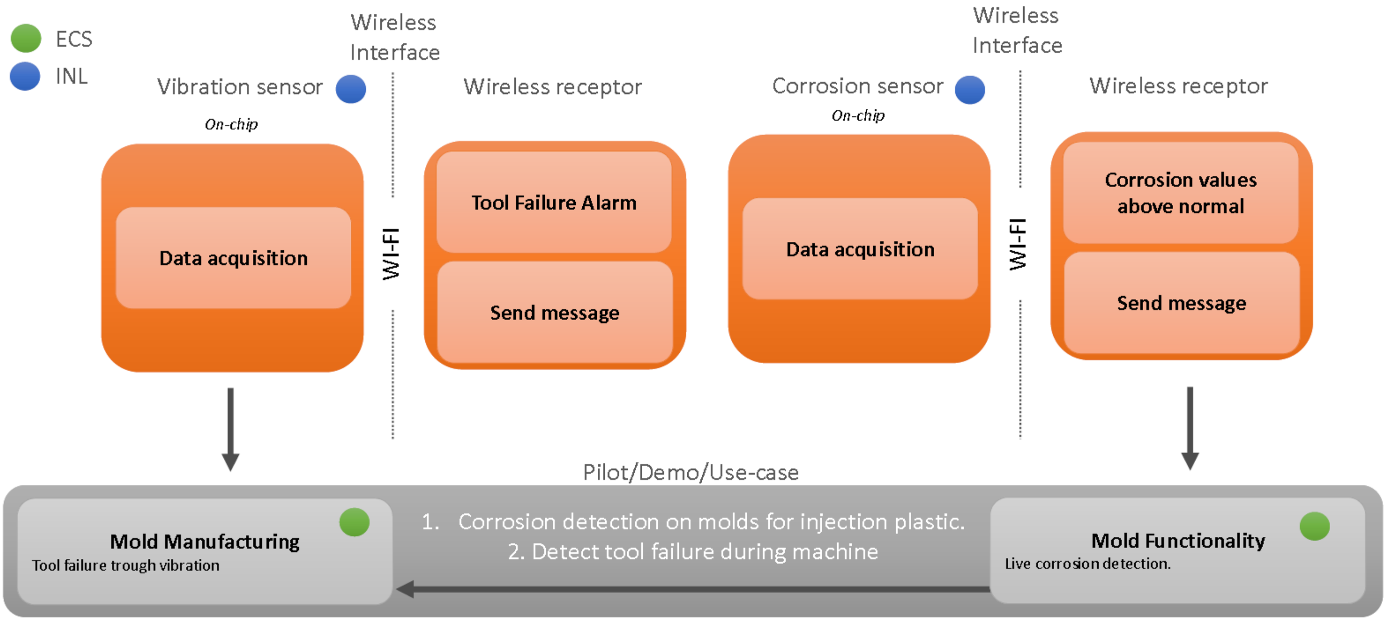



Figure 5.2.1 - Condition monitoring platform for the Injection Mold Tool.

Table 5.2.1- Demo 2 requirements and specifications.

| Functional Requirements[K1] | | | |
|---|---|---|---|
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| FPD2 001 | Force Sensor | 0 – 500N | Sensor must be able to wind stand some quick variations of pressure, in both ways (compression and traction). |
| FPD2 002 | Corrosion Sensor | Calibrated in situ | Sensor must be able to be fitted on the molding area (when possible), or in the nearest area. |
| FPD2 003 | Vibration Sensor | Calibrated in situ | Sensor must be able to detect tool failures. |

Table 5.2.2 - Demo 2 Operational requirements.

| **Operational Requirements** | | | |
|---|---|---|---|
| | | | |
| **Req. ID.** | **Req. title** | **Value** | **Rationale** |
| OPD2 001 | General requirements | In situ | All communication must work on industrial harsh conditions. |
| OPD2 002 | Tool failure | In situ | Communication probably must be wireless, and prepared to work on harsh conditions |
| OPD2 003 | Corrosion detection | In situ | Sensor power will be via own source supply, and the communication must be wireless, and prepare to work on a warehouse storage conditions. |
| OPD2 004 | Force feedback | In situ | Sensor data will generate a output, which will be available to a PLC and/or Injection machine and/or log. |

# 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 | BB 11 (D4.6) [CLICK HERE] RTOS for Multi-many core control |
|---|---|---|---|---|---|---|---|---|
| USE CASES | USE CASE 1.1 (GEFRAN, Davide) | Improved motion of Hoist/Crane | BB1 & UC1.1<br>ZAPUNI Coordinator of Building Block | BB2 & UC1.1<br>EDI Coordination of the Building Block | X<br>X | X<br>X | X<br>X | X<br>X |
| | USE CASE 1.2 (FAGOR, Carlos) | Improved motion of CNC Machine | X<br>X | X<br>X | X<br>X | BB5 & UC1.2<br>INGENIA Coordinator of Building Block | BB10 & UC1.2<br>TUE Coordinator of Building Block | BB11 & UC1.2<br>UNIMORE Coordinator of Building Block |
| | USE CASE 1.3 (TECO, Jaromir) | Improved motion of PLC driven portal robot | BB1 & UC1.3<br>ZAPUNI Coordinator of Building Block | X<br>X | BB4 & UC1.3<br>TNO Coordinator of Building Block | X<br>X | X<br>X | X<br>X |
| | USE CASE 2.1 (GMV A&D, Joaquin) | Improved motion of 6DOF industrial robot | X<br>X | X<br>X | BB4 & UC2.1<br>TNO Coordinator of Building Block | BB5 & UC2.1<br>INGENIA Coordinator of Building Block | BB10 & UC2.1<br>TUE Coordinator of Building Block | X<br>X |
| | USE CASE 2.2 (ZAPUNI, Martin) | Improved motion of 6DOF cost effective robot | BB1 & UC2.2<br>ZAPUNI Coordinator of Building Block | X<br>X | BB4 & UC2.2<br>TNO Coordinator of Building Block | X<br>X | BB10 & UC2.2<br>TUE Coordinator of Building Block | X<br>X |
| PILOTS | PILOT 1 (SIOUX CCM, Rob) | Generic Substrate Carrier | BB1 & P1<br>ZAPUNI Coordinator of Building Block | X<br>X | BB4 & P1<br>TNO Coordinator of Building Block | BB5 & P1<br>INGENIA Coordinator of Building Block | BB10 & P1<br>TUE Coordinator of Building Block | BB11 & P1<br>UNIMORE Coordinator of Building Block |
| | PILOT 2 (NEXPERIA, Gijs) | 12-Inch Wafer Stage | BB1 & P2<br>ZAPUNI Coordinator of Building Block | BB2 & P2<br>EDI Coordination of the Building Block | BB4 & P2<br>TNO Coordinator of Building Block | BB5 & P2<br>INGENIA Coordinator of Building Block | BB10 & P2<br>TUE Coordinator of Building Block | BB11 & P2<br>UNIMORE Coordinator of Building Block |
| | PILOT 3 (IMA, Paolo) | Tea-bag Machine | X<br>X | X<br>X | X<br>X | X<br>X | BB10 & P3<br>TUE Coordinator of Building Block | BB11 & P3<br>UNIMORE Coordinator of Building Block |
| | PILOT 4 (Correa, Jorge) | Milling Machine | BB1 & P4<br>ZAPUNI Coordinator of Building Block | BB2 & P4<br>EDI Coordinator of Building Block | X<br>X | X<br>X | X<br>X | X<br>X |
| | PILOT 5 (PHILIPS, Eric) | Medical Manipulator | X<br>X | X<br>X | X<br>X | X<br>X | X<br>X | X<br>X |
| DEMOS | DEMO 1 (J&J Vistakon, Seamus) | Improved motion of MagneMotion LSM technology | BB1 & D1<br>X | BB2 & D1<br>EDI Coordinator of Building Block | X<br>X | X<br>X | X<br>X | X<br>X |
| | DEMO 2 (Edilasio, Gabriel) | Improved quality of injection molding | X<br>X | BB2 & D2<br>EDI Coordinator of Building Block | X<br>X | X<br>X | X<br>X | X<br>X |

## 6.1 - 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.

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.

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. According, the I-Mech decisions taken, the connection to the main interface backbone shall be through EtherCAT. The actuator/sensor shall be smart (enough) or do its data transfer through a decentralized controller (with EtherCAT interface) to fulfil this constraint.

The sensor system has to be able to cope with a harsh motion environment, including interference, moisture, vibration, see chapter 7.

W.r.t. the unconventional actuators, most interest is in MEMS as well as piezo-stepping motors to enable small displacements.

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 and low power losses.

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.

## 6.2 - 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 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.

The first step is to separate the smart drive from the controller to a separate module aside the controller. This improves the flexibility of choosing a smart drive in relation to the actuation needed. One step further will be the combination/ integration of the drive with the actuator, a single cable interface providing power and data, typically well-shielded will help to minimize the need for local supply filtering. No 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).


Main drawback will be that due to the lack of filtering at the output of the drive, substantially losses will occur locally in the motor due to eddy-current losses in the wiring and the metal caused by the fast PWM switching of the integrated drives. Another challenge will be to integrate filtering which doesn't saturate the inductor cores used to the 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 feedback the response from the actuator to the drive and/or provide that data separately, to the motion controller, or both. Many interface connectors and data protocols are possible. As such, T3.7, the decentralized controller from 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 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. According, the I-Mech decisions taken, the connection to the main interface backbone shall be through EtherCAT. The actuator/sensor shall be smart (enough) or do its data transfer through a decentralized controller (with EtherCAT interface) to fulfil this constraint.

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 determine: time, speed as well as acquire the number plate of the vehicle as minimum data output. No triple high-speed photo will be required to derive the speed violation after which the number plate has to be read back from the photo. Also with pick-and-place machines, vision is used to align to components to their solder pad locations. Not the entire video frame is used but only 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 enhancing the accuracy of the information.

BB1 Functional Requirements and Specifications

| Req.ID | Description | Involved Pilots, Use-Cases, Demos |
|---|---|---|
| RQ1 | Fast start-up, less than 1 minute | Pi1 (), Pi2 (), Pi4 (F11), Uc1.1 () |
| RQ2 | Real-time synchronization (distributed clock) | Pi1 (), Pi2 (), Uc1.1 (O25) |
| RQ3 | FPGA with ~ 100k LEs capacity | Pi1 (BB1.1), Pi2 (BB1.7), Uc1.1 (O27) |
| RQ4 | CPU, ARM Cortex-A class, opt. tightly coupled with FPGA (SoC) | Pi1 (BB1.1), Pi2 (BB1.7), Pi4 (G3), Uc1.1 (O27) |
| RQ5 | EtherCAT real-time fieldbus | Pi1 (BB1.2), Pi2 (BB1.1), Uc1.1 (O23) |
| RQ6 | CAN real-time fieldbus | Uc1.1 (O23) |
| RQ7 | PROFINET real-time fieldbus | Pi4 (F17) |
| RQ8 | Ethernet/IP real-time fieldbus | De1 (F3, O2) |
| RQ9 | Live updatable parameters via EtherCAT | Pi1 (BB1.5), Pi2 (BB1.5) |
| RQ10 | Firmware upgrade via standard protocol (e.g. FoE) | Pi1 (BB1.6), Pi2 (BB1.4) |
| RQ11 | Sample rate on EtherCAT min. 10 kHz | Pi1 (BB1.3), Pi2 (BB1.3) |
| RQ12 | Sample rate on EtherCAT min. 1 kHz | Uc1.1 (O24) |
| RQ13 | Integration with BB5 amplifiers (8x) - optional | Pi1 (BB1.7), Pi2 (BB1.6) |
| RQ14 | Fast tracing of all signals from L1 devices | Pi2 (BB1.2) |
| RQ15 | Ethernet TCP/IP service communication interface | Pi4 (G5), Uc1.1 (O22) |
| RQ16 | Flash memory min 64 MB for OS and applications + SD slot | Uc1.1 (O29) |
| RQ17 | RT-Linux / RTOS for local algorithms / management | Pi4 (G4) Uc1.1 (O30) |
| RQ18 | I/O - Wireless Bluetooth 5.0 | Pi4 (F18), Uc1.1 (O26) |
| RQ19 | I/O - Analog sin/cos encoder input - 3 × 2 channels + RS422, 1 MHz | Pi1 (BB1.8-18) |
| RQ20 | I/O - Digital RS422 output - 4 channels, 20 MHz | Pi1 (BB1.19-20) |
| RQ21 | I/O - Analog inputs 0-10 V - 6 channels, 16 bit, 10 kHz - optional | Pi1 (BB1.21-27) |
| RQ22 | User-friendly web interface for configuration | Pi4 (F13) |
| RQ23 | Sensors integration - temperature, relative position, impact strength | Pi4 (F2) |
| RQ24 | Sensors integration - 3DoF accelerometer + gyroscope (IMU) | Uc1.1 (O2, O5) |
| RQ25 | Sensors integration - temperature, mag. field, vibration | De1 (F1, F4, F5) |
| RQ26 | Tight integration with pre-existing MagneMotion system | De1 (O1, O4, O6, O7) |
| | | |

Note: D3.2 is totally missing Use Case 1.3, Use Case 2.2 which are also involved in BB1

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 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. Typical sensor signal data rates will occur between samples /second to Gb/s. According, the I-Mech decisions taken, the connection to the main interface backbone shall be through EtherCAT. The actuator/sensor shall be smart (enough) or do its data transfer through a decentralized controller (with EtherCAT interface) to fulfil this constraint.

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 1:100, control loop bandwidth versus sampling rate is quite common.

The interrelation between BB-1 and the Use-cases, Pilots and demos is given below.

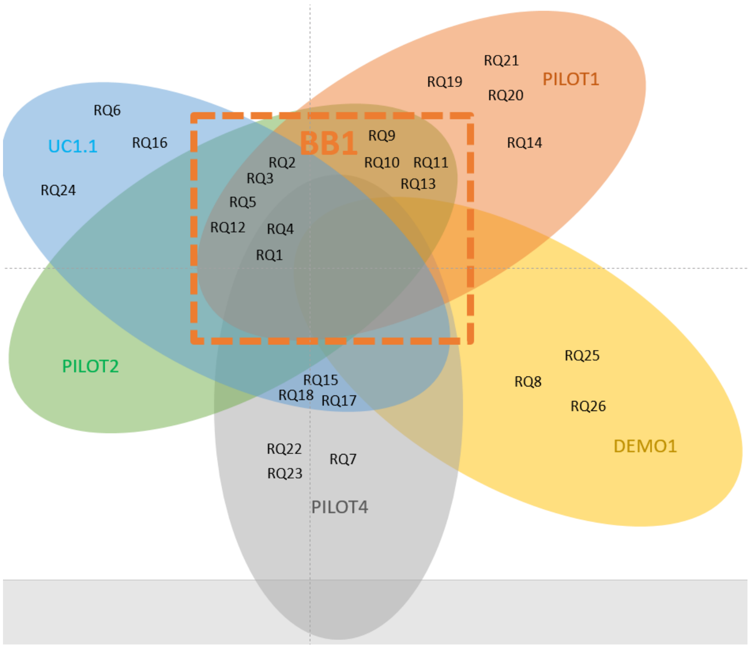



Figure 6.3.1 - Least common denominator BB-1

## 6.3 - 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.

| Req.ID | Description | Involved UCs, Pilots, Demos | Req.ID | Description | Involved UCs, Pilots, Demos |
|---|---|---|---|---|---|
| RQ1 | Capable to operate in industrial environment | UC1.1, Pilot2, Pilot4, Demo1, Demo2 | RQ18 | Wired firmware upgrades | UC1.1, Pilot2 |
| RQ2 | Reliable data transmission | UC1.1, Pilot2, Pilot4, Demo1, Demo2 | RQ19 | OTA firmware upgrades | UC1.1, Pilot2 |
| RQ3 | Network with limited number of sensors simple star topology | UC1.1, Pilot3, Pilot4, Demo1 | RQ20 | BLE 5.0 communication | UC1.1, Pilot 2, Pilot4 |
| RQ4 | Bi-directional operation | UC1.1, Pilot4 | RQ21 | Wi-Fi communication | Demo2 |
| RQ5 | Low Cost HW | UC1.1, Pilot2, Pilot4, Demo1 | RQ22 | RFID communication | Demo1 |
| RQ6 | Low power solution | UC1.1, Pilot2, Pilot 4 | RQ23 | Data transmission distance <10m | Pilot 2, Pilot4 |
| RQ7 | Extend battery lifetime / System's operation time | UC1.1, Pilot2, Pilot4, Demo1 | RQ24 | Data transmission distance >10m | UC1.1 |
| RQ8 | New routing and MAC protocols | Pilot4 | RQ25 | Communication interface between GW/BB1 - EtherCat | UC1.1 , Pilot2, Pilot 4 |
| RQ9 | Novel robust data fusion algorithms | Demo2 | RQ26 | IMU sensor | UC1.1, Pilot4, Demo1 |
| RQ10 | Advanced data aggregation algorithms | Demo2 | RQ27 | Magnetic sensor | Demo1 |
| RQ11 | Real-time data acquisition | UC1.1, Pilot2, Pilot4, Demo1, Demo2 | RQ28 | Force sensor | Pilot2 |
| RQ12 | Low latency solution (<500us) | UC1.1 | RQ29 | Temperature sensor | Pilot4, Demo1 |
| RQ13 | Sensor connection via SPI, I2C and/or UART | UC1.1, Pilot2, Pilot 4 | RQ30 | Distance sensor | Pilot4 |
| RQ14 | Wireless charging | UC1.1, Pilot 2, Demo1 | RQ31 | WSN identification, authentication, activ./deactiv. | UC1.1, Pilot2, Pilot4 |
| RQ15 | RTOS (or accessible via ECAT/BB11) | UC1.1, Pilot 2 | RQ32 | Visual indicators and/or physical buttons | UC1.1 |
| RQ16 | User friendly interface | UC1.1, Pilot 2 | RQ33 | Auto calibration | UC1.1 |
| RQ17 | Data logging locally and/or remotely (or acquisition via ECAT) | UC1.1, Pilot 2 | RQ34 | Fast start-up | UC1.1, Pilot2, |

Table 6.3.1 - Summary of specifications and requirements BB-2

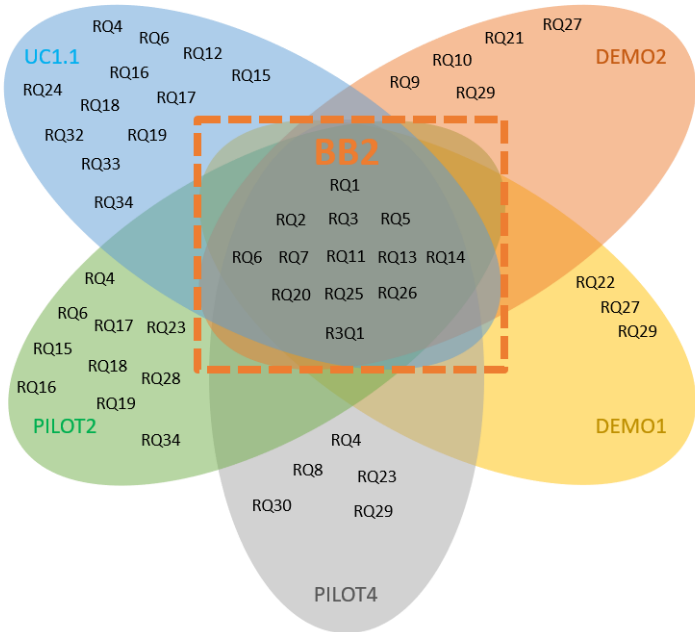



Figure 6.3.1 - Least common denominator BB-2

## 6.4 - Task 3.5 - (BB-4) High Speed Vision

Within I-mech, a Vision In The Loop platform (High Speed Vision BB) is to be developed that allows for high-end mechatronic feedback of motion systems. In order to make VITL applicable in industry, technology must meet both performance requirements as well as implementation boundary conditions such as affordability and maintainability. Compliance to standards and best practices from relevant domains is preferred over reinventing the wheel.

General design requirements (guidelines):
Provide a set of building blocks that can be configured into a HSV solution:

- Without extensive, specific programming
- Make use of open standards and COTS components as much as possible
- Be scalable in performance and cost within the same architectural approach
- Plausible lasting technology development

Application requirements have been derived in line with the I-mech project description (see 20180104.TNO.imech.goals.ppt in Partner Zone Task 3.5 area).
Driving for the I-MECH general ambition, and more specifically the pilots, demos and use cases are 2 types of requirements:

- Throughput and timing: For the sake of low latency from camera and exposure to DA and actuation, and therefore not be limiting in terms of mechatronic performance.
- Interfacing: For I-MECH to be generally applicable, it is preferred to work with state-of-the-art industry standards.

With respect to latency not all pilots, use cases, and demos are demanding the ultimate. However, to make the I-MECH platform fit for future mechatronic control based on Vision in the Loop and widespread use, the HSV architecture should be capable of serving the toughest requirements.

For less demanding applications, the low latency / high performance HSV architecture might be overkill and also unnecessarily expensive. Therefore a low cost solution is required, within the same HSV architecture, but with components that are less expensive and reduced performance.

Functional requirements:

Enable VITL feedback control with at least ~100Hz control bandwidth, with at least 35 deg phase margin. This is based on common servo control practice, taking regular robustness margins into account, and leads to requirements in signal delay < 200 mu-sec. This drives further latency timing budget breakdown below.

Throughput /timing requirements:

- latency : max 200 mu-sec
- camera image: 256 x 256 pixels x 8bit
- camera illumination: 50 mu-sec
- camera with global shutter
- camera output rate: 3Gpixel/sec x 8bit/pixel
- transport time to CPU: 25 mu-sec
- calculation time: 50 mu-sec
- EtherCAT DAC conversion latency < 10 mu-sec

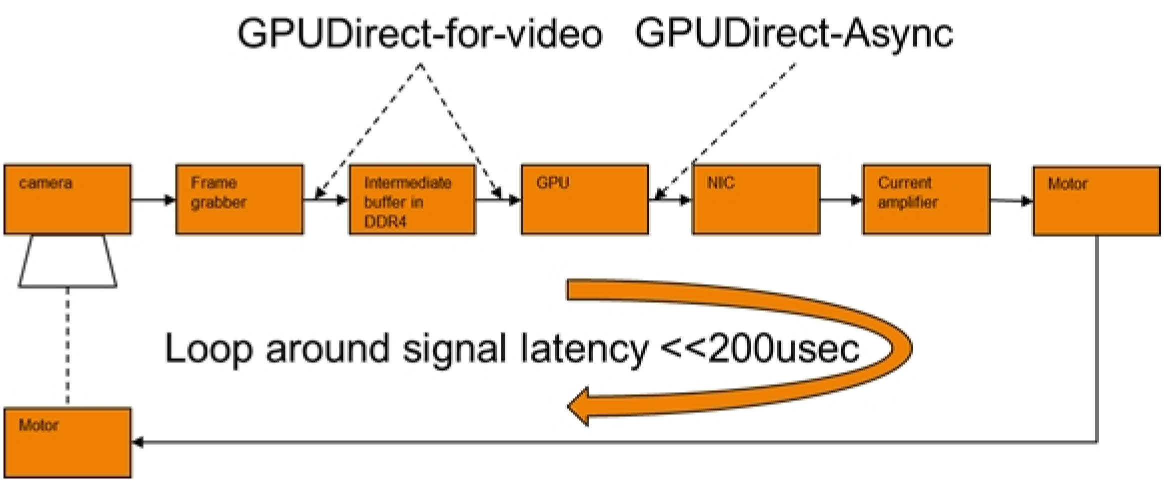



*Figure 6.4.1 closed loop position control with camera over GPU*

Interfacing requirements:

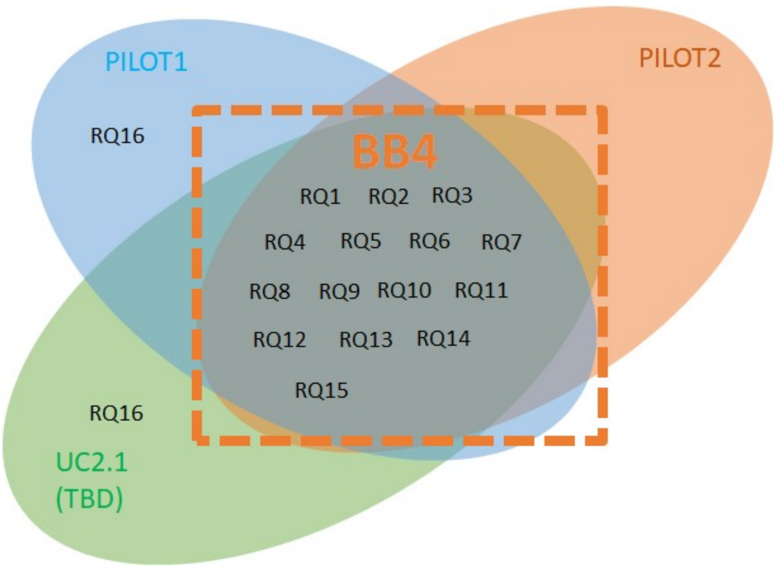
According, the I-Mech decisions taken, the connection to the main interface backbone shall be through EtherCAT. The high speed vision sensor shall be smart (enough) or do its data compression, extraction and transfer through a decentralized controller (with EtherCAT interface) to fulfil this constraint.

- Real-time communication with EtherCAT serving 10 kHz control loop sampling implementation
- Direct to DAC (for minimum latency < 10 mu-sec conversion latency)
- coaXPress 6/12 / Camera link Full Speed image interface
- GigE
- USB3.0

Requirements overview in table format:

| Req.ID | Description | Involved UCs, Pilots, Demos | Req.ID | Involved UCs, Pilots, Demos | Involved UCs, Pilots, Demos |
|---|---|---|---|---|---|
| RQ1 | Capable to operate in industrial environment | Pilot1, Pilot2, (UC2,1) | RQ10 | EtherCAT DAC conversion latency < 10 mu-sec | Pilot1, Pilot2, (UC2,1) |
| RQ2 | Configurable without extensive, specific programming | Pilot1, Pilot2, (UC2,1) | RQ11 | Real-time communication with EtherCAT serving 10KHz control loop sampling implementation | Pilot1, Pilot2, (UC2,1) |
| RQ3 | Use of open standards and COTS components as much as possible | Pilot1, Pilot2, (UC2,1) | RQ12 | Direct to DAC (for minimum latency < 10 mu-sec conversion latency) | Pilot1, Pilot2, (UC2,1) |
| RQ4 | Scalable in performance and cost within the same architectural approach | Pilot1, Pilot2, (UC2,1) | RQ13 | CoaXPress 6/12 / Camera link Full Speed image interface | Pilot1, Pilot2, (UC2,1) |
| RQ5 | Camera image: 256 x 256 pixels x 8bit | Pilot1, Pilot2, (UC2,1) | RQ14 | GigE interfacing | Pilot1, Pilot2, (UC2,1) |
| RQ6 | Camera illumination: 50 mu-sec | Pilot1, Pilot2, (UC2,1) | RQ15 | USB3.0 interfacing | Pilot1, Pilot2, (UC2,1) |
| RQ7 | Camera with global shutter | Pilot1, Pilot2, (UC2,1) | RQ16 | Low cost, reduced latency spec version | Pilot1, Pilot2, (UC2,1) |
| RQ8 | Camera output rate: 3Gpixel/sec x 8bit/pixel | Pilot1, Pilot2, (UC2,1) | | | |
| RQ09 | Transport time to CPU: 25 mu-sec | Pilot1, Pilot2, (UC2,1) | | | |

In graphical form:




## 6.5 - 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.

| Req.ID | Description | Involved UCs, Pilots, Demos | Req.ID | Description | Involved UCs, Pilots, Demos |
|---|---|---|---|---|---|
| RQ1 | Relevant signals traceable | Pilot 1, Pilot 2, UC 1.2 | RQ18 | Sample rate min for bus 10 kHz | Pilot 1, |
| RQ2 | Current loop shall be auto-tunable | Pilot 1, Pilot 2 | RQ19 | SSI encoder (absolute) | Pilot 1 |
| RQ3 | Current loop shall be manually-tunable | Pilot 1, Pilot 2, UC 1.2, UC 2.1 | RQ20 | SinCos encoder | Pilot 1 |
| RQ4 | Must include minimal functions for human safety | Pilot 1, Pilot 2 | RQ21 | Field oriented control commutation | Pilot 1, Pilot 2, UC 1.2 |
| RQ5 | Low Cost HW | Pilot 1 | RQ22 | Bus Voltage 325-565Vdc | Pilot 1 |
| RQ6 | 500 Hz minimum bandwith for PI- control loop. | Pilot 1, UC 1.2, UC 2.1 | RQ 23 | Operating temp 20-24ºC | Pilot 2 |
| RQ7 | Control motors with 1 motor phase | Pilot 1 | RQ 24 | Outputs EMC filtered | Pilot 2 |
| RQ8 | Control motors with 3 motor phases (BLAC) | Pilot 1 | RQ25 | Voltage /PWM feed-forward allowed | Pilot 2 |
| RQ9 | 32 kHz min sample rate | Pilot 1 | RQ26 | I2T, RMS current, Max current standard protections | Pilot 2 |
| RQ10 | 0.6 mA current sensing resolution | Pilot 1, Pilot 2 | RQ27 | Current loop bandwith min 5kHz | Pilot 2 |
| RQ11 | 0.5 mA current demand resolution | Pilot 1, Pilot 2 | RQ28 | Ratings: 60V/4A rms - 3 phases – A peak | Pilot 2 |
| RQ12 | Drive 1-3A continuous current | Pilot 1 | RQ29 | Ratings: 60V/2A rms – 1 phase – 6A peak | Pilot 2 |
| RQ13 | Drive peak current up to 2-6A | Pilot 1 | RQ30 | SNR current loop 90dB | Pilot 2 |
| RQ14 | Bus voltage of 24-48Vdc | Pilot 1, Demo 1 | RQ31 | Sampling rate min 8kHz | UC 1.2 |
| RQ15 | PWM min freq. of 32kHz | Pilot 1 | RQ32 | Shall be possibl to tune velocity, current and position loops | UC 1.2, UC 2.1 |
| RQ16 | PWM resolution of min 12 bit | Pilot 1 | RQ33 | Shall be possible to install drives in the SCARA robot | UC 1.2 |
| RQ17 | EtherCAT interface | Pilot 1, Pilot 2, UC 1.2, UC 2.1 | | | |

Table 6.5.1 - Summary of specifications and requirements BB-5

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

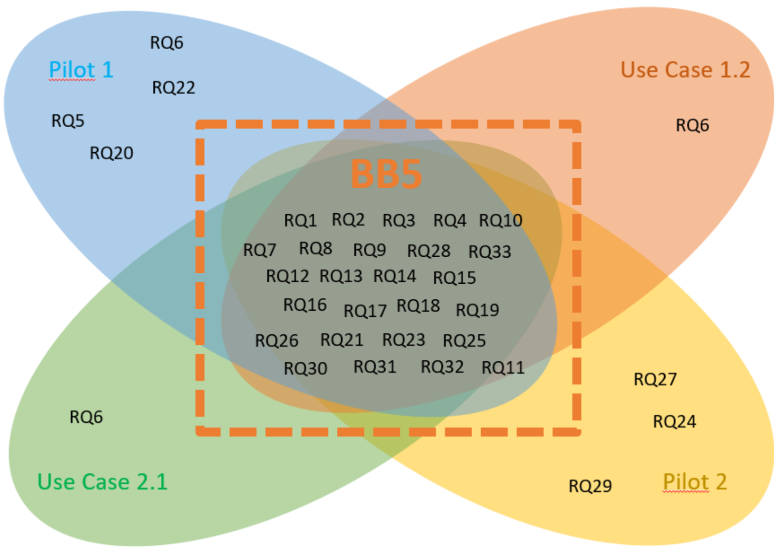


Figure 6.5.1 - Least common denominator BB-5

The interfacing towards the host controller is very broad. Aside the analog interfacing: 4-20 mA, 0-10 volt, the digital interfacing will be broad, varying from RS-232, RS-422/485, Lin-, CAN(open)-, MOD- Profibus, ethernet, EtherCAT, USB, etc. using a variety of connector types. Even wireless control of high performance servo amplifiers are considered by industry. According, the I-Mech decisions taken, the connection to the main interface backbone shall be through EtherCAT. The drive/actuator shall be smart (enough) or do its data transfer through a decentralized controller (with EtherCAT interface) to fulfil this constraint.

## 6.6 - 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 (decentralized) core controller.

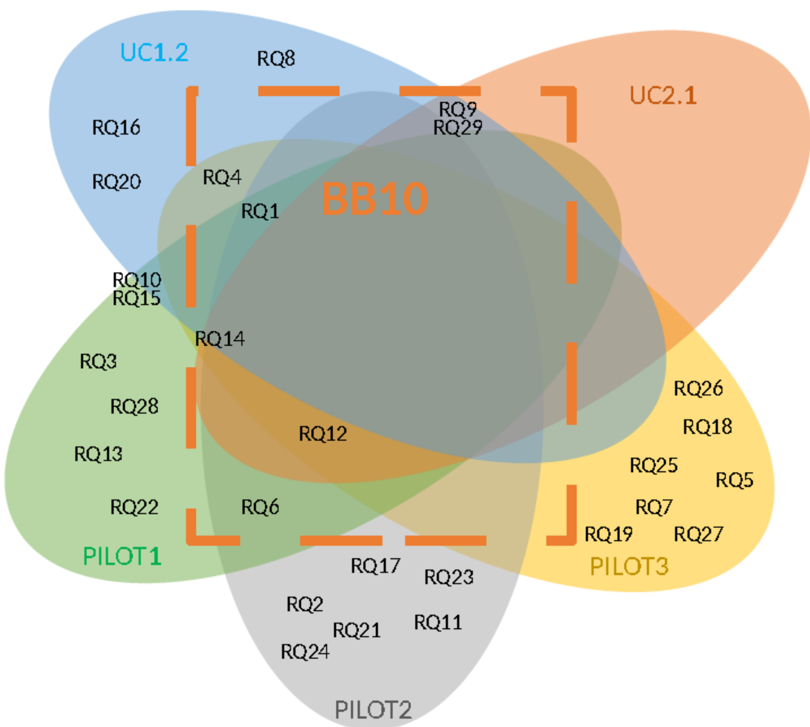



Figure 6.6.1 - Least common denominator BB-10

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.

According, the I-Mech decisions taken, the connection to the main interface backbone shall be through EtherCAT. The data transfer of the decentralized controller shall be with EtherCAT interface to fulfil this constraint.

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.

The interrelation between BB-11 and the Use-cases, Pilots and demos is depicted in Figure 6.6.1 and detailed in §6.6.1 and §6.6.2.

### 6.6.1 - Requirements matrix -- CPU, OS, network

The following table provides the collected list of requirements, where core requirements are underlined.

| ***Req. ID*** | ***Description*** | **UC1.2** | **UC2.1** | **Pi-1** | **Pi-2** | **Pi-3** |
|---|---|---|---|---|---|---|
| *RQ1* | CPU: x86-compatibility | O11 | | BB10.1 | BB10.1 | O1 |
| RQ2 | CPU: performance ≥ Intel i5 | | | | BB10.1 | |
| RQ3 | CPU: performance ≥ Intel i5 6440EQ | | | BB10.1 | | |
| RQ4 | CPU: cores ≥2 | F8 | | | | O2 |
| RQ5 | CPU: cores ≥4 | | | | | O2 |
| RQ6 | Host: Simulink models/executables | | | BB10.3 | BB10.8 | |
| RQ7 | Host: VxWorks 6.9 and 7 | | | | | O3 |
| RQ8 | Host: Linux/Windows 7 Embedded | F9 | | | | |
| RQ9 | Host: Windows/Mac/Linux support | F9 | F2 | | | |
| RQ10 | Host heterogeneity: RTOS+GPOS | O2 | | BB10.6 | | |
| RQ11 | Real time synchronization | | | | BB10.7 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| RQ12 | Network: EtherCAT | | F7 F9, F10 | BB10.2 | BB10.6 | F4.1 |
| RQ13 | Network: EtherCAT master | | | BB10.2 | | |
| RQ14 | Network: EtherCAT w/ sample rate: 10~20 kHz | F3 | | BB10.4 | BB10.2 | |
| RQ15 | Network: EtherCAT w/ sample rate: ~10 kHz | F3 | | BB10.4 | | |
| RQ16 | Network: EtherCAT w/ sample rate: ~16 kHz | F3 | | | | |
| RQ17 | Network: TCP/IP over Ethernet (non RT) | | | | BB10.5 | |
| RQ18 | Network: Powerlink | | | | | F4.2 |
| RQ19 | Network: SERCOS III | | | | | F5 |

### 6.6.3 - Requirements matrix -- application, misc

The following table provides the collected list of requirements, where core requirements are underlined.

| ***Req. ID*** | ***Description*** | **UC1.2** | **UC2.1** | **Pi-1** | **Pi-2** | **Pi-3** |
|---|---|---|---|---|---|---|
| RQ20 | RT communication rate 8~16 kHz | O1 | | | | |
| RQ21 | Loop sample rate ≥16 kHz | | O3 | | | |
| RQ22 | Loop update rate ~10 kHz | | | BB10.5 | | |
| RQ23 | Loop update rate 10~20 kHz | | | | BB10.3 | |
| RQ24 | Loop latency 50~100 $\mu$s | | | | BB10.4 | |
| RQ25 | Scheduling cycle time ≥50 $\mu$s | | | | | O4 |
| RQ26 | Jitter ≤ 5 $\mu$s | | | | | O6 |
| RQ27 | Motion control cycle time ~ 500 $\mu$s | | | | | O5 |
| RQ28 | Cost ≤1 KEUR | | | BB10.7 | | |
| RQ29 | Industrial operation environment | F1 | F1 | | | |

# 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 - (Smart) sensors/encoders (incl. vision)

Sensors & encoders are not on their own but to be used in a motion control system application with other:

- sensors & encoders (acting at near to the same frequencies)
- PWM drives
- switching AC/DC, DC/DC power converters
- UPS
- permanent magnets i.e. stationary magnetic or electric fields,
  moving circuits in H-fields, resulting in dϕ/dt induced voltages
- a common 'mechanical' frame with surface treatments: anodized, powder coated
- internal or external power supply distribution (with internal resonances)

In most modern motion control system, operating frequency management is a prerequisite to enable proper operating systems. Every (sub-)system has its own operating frequency and accompanying bandwidth in which the readout can be affected by external influences.

### 7.1.1 - Functional requirements for sensors/encoders:

a. Unique determination of physical property to be measured (non-confound)
b. Fit for the dynamic range for the physical property to be measured
c. Fit for the speed that the physical property is likely to change: response latency

### 7.1.2 - Operational requirements for sensors/encoders:

a. Known transfer function between the property to be measured and the representative data output. Applies to smart sensors too!
b. Known latency (or time-stamping) between the actual measurement and the moment that the output data becomes available for further processing
c. Behavior model available for advanced simulations
d. Available bandwidth for data transfer e.g. vision sensors

e. Data compression i.e. video data analysis and extraction to reduce data bandwidth on interface backbone

### 7.1.3 - Mechanical requirements for sensors/encoders:

a. Distributed: front-end & signal conditioning ↔ all-in-one
b. Weight (incl. filtering, heatsink)
c. Form fit/ mounting
d. Volume
e. Cable/connector interface, type, size, wired ↔ wireless
f. Power dissipation w.r.t. additional cooling/heating measures required
g. Vibration, moisture, humidity

### 7.1.4 - Electrical requirements for sensors/encoders:

a. Nominal supply voltages and tolerances (PSRR)
b. Higher supply voltage → low current, less IR-drop → thinner cables
c. Hot-swappable; soft-start, inrush current limited
d. PHY: wired/wireless, levels, protocols
e. Power (w.r.t. self-heating) and temperature sensitivity
f. Grounding (if applicable)
g. EMC, both on interface(s), supply and sensor body (DC to daylight)
h. Internally used operational frequencies and bandwidths
i. ESD, EoS.

### 7.1.5 - Additional requirements for sensors/encoders:

a. Serviceability
b. Remote diagnostics
c. Environmental: RoHs, WEEE
d. Safety: human, environment, machine damage
e. BIST
f. (Self-)calibration
g. Identification (self-detection)

## 7.2 - Main motion control system

Similar as with sensors and encoders, requirements can be set for the main motion control systems which are central, while keeping up with the computational efforts for the smart sensors and encoders connected on the one hand and driving the output data towards smart motors and actuators through a pre-defined backbone: EtherCAT.

### 7.2.1 - Functional requirements for motion control systems:

a. Fit for I-Mech selected (smart) sensor and (smart) actuator interface
b. Power efficient
c. Fast enough w.r.t. control loops to be closed
d. Self-detecting i.e. auto-recognition of sensors connected (IoT)
e. Supply (over-)voltage protection/withstand capabilities, data and noise filtering
f. Kind of interface, PHY: analog, differential, high-speed: serial/parallel (SERDES), wireless, aside EtherCAT, alternative I/O mainly applies to decentralized controllers
g. Safety: human, environmental and machine damage
h. Serviceability (remote)
i. Self-diagnostic, BIST

### 7.2.2 - Software requirements for motion control systems:

a. Kind of interface, protocol (SERDES: clock recovery, latency)
b. Data format, error coding, word-length, NRZ, balanced coding, (an-)isochronous self-clocking signals
c. Standardized instruction set e.g. like: SCPI Standard Commands
d. Responsiveness to triggering, latency

## 7.3 - (Smart) drives, motors and actuators

Similar as with sensors and encoders, requirements can be set for the (smart) motors and actuators

### 7.3.1 - Functional requirements for smart drives/ actuators:

a. Unique determination of physical property to be excited versus signal(s) applied
b. Fit for the dynamic range for the property to be excited
c. Fit for the speed that the property needs to be changed: force, torque

### 7.3.2 - Operational requirements for actuators:

a. Known transfer function between the property to be excited and the signal(s) applied. Applies to smart actuators too!
b. Known latency between the actual response and the moment that the signal(s) has/have been applied (taken into account the inertia of the load being driven)

### 7.3.3 - Electrical requirements for (smart) actuators:

a. Supply voltage and tolerances (PSRR)
b. Higher voltage → low current, less IR-drop on cabling
c. Hot-swappable; soft start, inrush current limited
d. PHY: wired/wireless, levels, protocols
   when directly connected to the backbone: EtherCAT
e. Power (w.r.t. self-heating) and temperature sensitivity
f. Grounding (if applicable)
g. EMC, both on interface(s), supply and sensor body (DC to daylight)
h. Internally used operational frequencies and bandwidths

### 7.3.4 - Other Hardware issues: Layer 1

a. Volume: @ device as well as its connector(s)
b. Power dissipation (thermal constraints, heatsink requirements)
c. Supply (over-)voltage protection/withstand capabilities, filtering
d. Kind of interface, PHY: analog, differential, high-speed: serial/parallel (SERDES), wireless
   when directly connected to the backbone: EtherCAT
e. EMC: emission and immunity, both conducted and radiated
f. Safety: human, environmental and machine damage
g. Environmental: RoHs, WEEE, thermal, humidity, vibration
h. Serviceability (remote)
i. Self-diagnostic, BIST
j. Enclosure requirements?

### 7.3.5 - Software issues: Layers 2 & 3

a. Kind of interface, protocol (SERDES: clock recovery, latency)
   when directly connected to the backbone: EtherCAT
b. Data format, error coding, word-length, NRZ, balanced coding,
   (an-)isochronous self-clocking signals
c. Standardized instruction set e.g. like: SCPI Standard Commands
d. Responsiveness to triggering, latency

### 7.3.6 - Simulation issues (WP-4)

a. The behavior models shall include a fixed set of parameters exchanged, including the order of these parameters.
b. The behavior models shall be drop-in replaceable with the ultimate hardware to enable hardware/ software codesign and verification
c. The behavior models shall include all time constants, latency as to be expected from the real hardware.

## 7.4 - Infrastructural requirements with I-Mech motion control systems

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 interface 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.

For local interfaces to a decentralized controllers ALL analog and digital interfaces are allowed to be used. **However, in this I-Mech project, the backbone interface is standardized to EtherCAT, typically provided with RJ-45 or M12 connectors.**

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.

Photo 1 - Various motion interconnection options

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. BLT-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 BLT-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 (CE) compliance as stand-alone device, but 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 re-routing (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'.

## 7.5 - 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; main backbone: EtherCAT. 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 1:10 to 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/ EtherCAT: 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 and D6.2): locally smart or centrally controlled or a hybrid form in-between (to serve an installed base). 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 a clear convergence in the realization (WP-6) of the hardware and its interfacing with motion control systems in general: **EtherCAT**. The diversity of common connector types, connector pin allocation, signal levels, protocols, coding and interface channel capabilities is nearly unbound. It will be the task for BB-10 (for the decentralized controllers) 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. PVC is also forbidden in fire-hazard environments.

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