I-MECH – Smart System Integration for Mechatronic Applications

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***Abstract*—Emerging mechatronic applications aim to work at limit performance and reliability while their size and operational space is getting restricted more and more. To reach those targets, often fast integration of customized components is necessary, either electronic systems, SW modules, sensors or actuators. Such diverse set of components needs special tool-chains and methods for fast customization and optimization respecting MBSE (model based system engineering) principles. Large-scale I-MECH project is a natural, fully industry driven initiative trying to follow those demands. The purpose of this paper is to describe its core scientific content, report initial milestones and show a variety of application where I-MECH components, so called building blocks, are being applied.**

***Index Terms*—smart system integration, mechatronics, motion control, digital twin, electronics systems, wireless communication, smart sensors, robotics, embedded systems, service oriented architecture, cyber-physical systems**

I. Introduction

Recently, impressive advancements have been reported in diverse fields of control systems design, sensing, actuation model based system engineering [1]–[5] and industrial communications [6]. However, those pieces of technology were developed rather independently to each other in last decades, i.e. not following common direction defined by control system requirements [7]–[9]. Actual issues in high-tech mechatronic systems, specifically their motion control parts, brought completely new needs not just on every part of technology but namely to ability of fast customization and integration. Complex set of technologies that need to be considered is depicted in Fig. 1. Specific challenges worth to highlight are:

- Higher mechanical flexibility of mechatronic systems together with their increased speed caused, among others, increased presence of residual vibrations within the frequency band relevant for feedback control [10]–[12].
- Motion tasks often have recurring signature, hence feedback control strategies must deal with periodic reference signals and disturbances [13], [14].
- The machines and robots are composed by more complex kinematic structures [15] with number of interacting axis and flexible loads [16], hence control HW must be able execute advanced centralized control strategies [17].
- The machines must quickly adapt to new tasks, new product, etc., thus self-adaptation principles are of high importance [18].

Those issues did create main objectives, either scientific and technical (ST) or integration (SI), for common research work under the umbrella of the I-MECH[1] project [19]:

- ST1: To develop techniques for employment of advanced model-based methods for the design, real-time control and self-diagnosis of cyber-physical systems.
- ST2: To develop a smart *Instrumentation Layer* gathering visual and/or sensor information from supplementary instrumentation installed on the moving parts of the controlled system to enhance the achievable performance of the system [20], [21].
- ST3: To develop modular, unified, hardware and software motion control building blocks (BB) implementing a service-oriented architecture paradigm, i.e. smart *Control Layer* [22], [23].
- ST4: To prepare interfaces to State of the Art predictive maintenance platform *(System Behavior Layer)* and develop specific condition monitoring building blocks working at the edge and providing relevant data for System behavior layer [24]–[27].
- SI1: To integrate the developed building blocks into a conceptual open platform for intelligent control of industrial mechatronic systems.
- SI2: To prove the platform deployability on commercial motion control hardware.
- SI3: To prove the platform deployability onto commercial industrial robots (fixed, modular).

This paper describes advances in fulfilling those objectives after reaching first set of milestones (first half of the project duration). The rest of the paper is organized as follows: Section II describes detailed system decomposition of I-MECH objectives into ERP/MES[2] pyramid which is a result of initial project period. Section III provides description of building blocks updated according to hard needs of pilot applications,

[1] full project name: Intelligent Motion Control Platform for Smart Mechatronic Systems

[2] Enterprise resource planning, Manufacturing execution system

which are outlined in Section V. The conclusions and ideas for future work are given in Section VI.

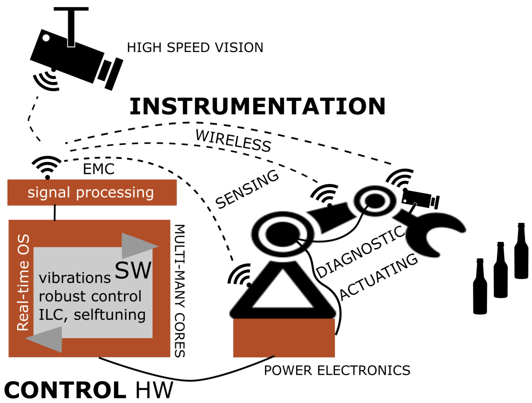

Fig. 1. Identified key enabling technologies (KETs) for smart motion control systems which need high degree of customization in shorter time

II. Ambition and Objectives

The key I-MECH challenge is to integrate technology building blocks summarized in Section IV into complex scenarios and customize them for emerging applications listed in Section V. The first project period showed that the main bottlenecks are in interfaces between subsystems and modules. Unfortunately, due in-sufficient focus recently put into system integration, the technology development was not aware about all issues coming across related domains.

Example 1: advances in wireless communications and sensors did not focus sufficiently on synchronization and low jitter which is necessary to use such sensors in fast feedback control loops;

Example 2: researchers designing multi-many core HW infrastructure often do not care about increasing computational burden of control algorithms which need to be implemented in complex motion control system, etc. There are much more gaps identified and reported in project public deliverables [19].

It was shown that all parts of technology must adopt sort of high-level requirements related to physical machine behavior. In that context, *machine speed* and *precision* were selected and projected to required control loop bandwidth, sampling rates, sensor precision, A/D and D/A resolution and other real-time requirements. Finally, those key performance indicators were mapped into different layers of ERP/MES pyramid, see Fig. 2. Thus every BB in the feedback loop must be able to work with very low signal latency ($< 500\mu s$).

Point out, that a side ambition of the project is to bridge the gap between control system education and industrial countries. The project has a direct influence on the content of master degree courses in the coutries involved [28].

III. Concept and Overall Approach

The main concept behind integration and fast customization is full employment of MBSE state-of-the-art toolchains. Moreover, the I-MECH platform openness and flexibility is an indispensable incubator for a sustainable growth and improvement of model based engineering techniques and tools developed by consortium partners[3]. Hence the envisioned platform together with related model based techniques creates a synergic library for building smart mechatronic systems which can be continuously viewed as beyond the state of the art. The applicability of these techniques was already partially verified on pilot applications described bellow.

The set of techniques covers full rapid prototyping cycle which is usually divided into four stages: Model-in-the-Loop (MIL), Software- in-the-Loop (SIL), Processor-in-the-Loop (PIL) and Hardware-in-the-Loop (HIL). Although meaning of these terms is not fully consistent at global level, all project partners[4] adopted unified viewpoint presented in Fig. 3. In context of modeling toolchains, the research effort under project technical workpackages is pushing the state of the art namely in:

- *Multi-physical component based modeling*, which allows to combine the mechanic and electronic components of mechatronic system. Special focus is devoted to development of proper mathematical models of complex multi-axes systems (tailored to five pilot applications) which could be used for precise feedback or feedforward control. The models should go beyond the traditional concept of rigid multi-body systems. Finite stiffness of machine parts and possible occurrence of mechanical vibrations should be considered to allow realistic modeling.
- *Integration of FEM (finite-element) models* into non real-time simulations together with control system model; development of uncertainty modeling techniques. These techniques will enable a non-conservative robust control design, providing optimal control performance in view of the inevitable uncertainty in the model.
- *Integration of virtual models* of sensors, actuators into plant model and subsequent motion control system optimization in virtual environment.
- *Real-time simulation* of machine models. This implies advanced seamless model reduction techniques and advanced model validation.
- *Identification of model parameters* from data measured on controlled machine and combining results with mathematical physical modeling. It is worth to mention, that such approaches were proven as necessary for underactuated mechanical structures (even unstable), see e.g. [29].

Note, that those hints were concluded after first project phase as elementary for creating reliable digital twin of the machine or production line which 'lives' in real-time with the machine. Development of such digital twins is one of long-term strategic visions of the consortium.

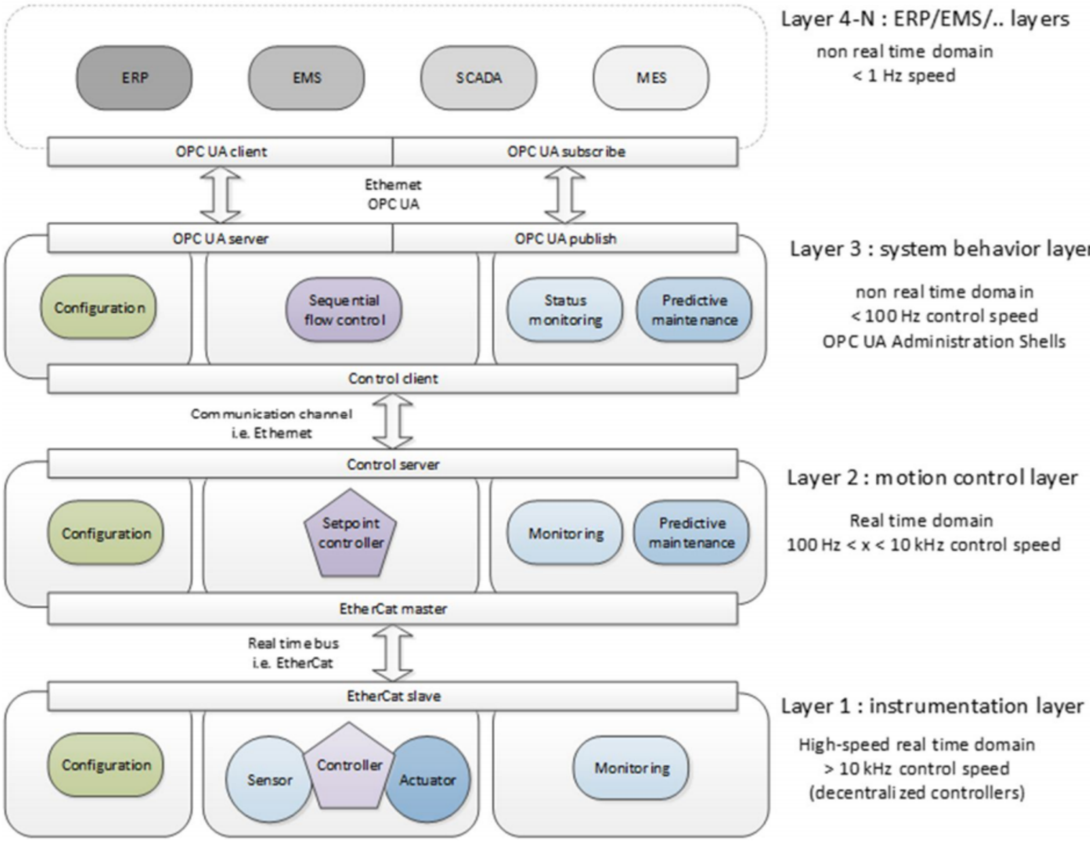

Fig. 2. Motion control system decomposition into Layers with different real-time properties and sampling time demands

IV. I-MECH BUILDING BLOCKS AND METHODOLOGY

In this Section, the set of I-MECH building blocks is described in more detail. Their development is planned in two iterations, where the first iteration is done mainly in MIL schemes (virtual, non real-time environment). Second iteration should deliver final implementations including all HW, SW and electronics. Success stories of the first iteration are reported on the project website [19].

BB1 – Advanced Sensor data processing module

This module forms a common platform for smart sensors which provides high-fidelity information derived from the primary sensor raw data. Considered primary sensors work on various principles – for example optical, including integration of high speed cameras; magnetic; or inertial like accelerometers and gyroscopes. Thus different electrical interfaces are covered, including integration with wireless data transmission system. The SoC+FPGA architecture allows to process raw sensor data with higher sampling rates. The main issue now is integration into SW programming toolchains, namely Matlab-Simulink compatibility.

[3]30 partners from 10 EU countries

[4]Note, that industrial relevance is ensured by companies like Siemens, Reden (www.reden.nl), Open Engineering (www.open-engineering.com).

BB2 – Real-time wireless sensors

As a plugin to BB1, BB2 deals with robust wireless network providing reliable, synchronized, and secure data delivery from sensors to the master node (or central computing unit) in an energy efficient manner. Low latency and fast update rates allow advanced control strategies exploiting auxiliary load-side measurements to be employed. Novel sensing technologies improving measurement precision are available.

BB3 – Robust condition monitoring and predictive diagnostics

This component delivers the capability to monitor performance of a controlled system and to report on its current and predicted condition. It exploits sensed data for acoustic emission and vibration measurement and implements the condition monitoring by means of a set of algorithms. The services/data delivered by this module are presented to Layer 2 both for operation profile modulation (e.g. to reduce the demands on a component that is failing). In Layer 2, the data are merged with those provided by BB6 (information fusion), pre-processed and delivered to Layer 3 MES/predictive maintenance tools for decisions.

BB4 – High speed vision

This module exploits vision systems to deliver sensor data, specifically for feedback motion control. The key concept is implementation of high speed vision with integrated image

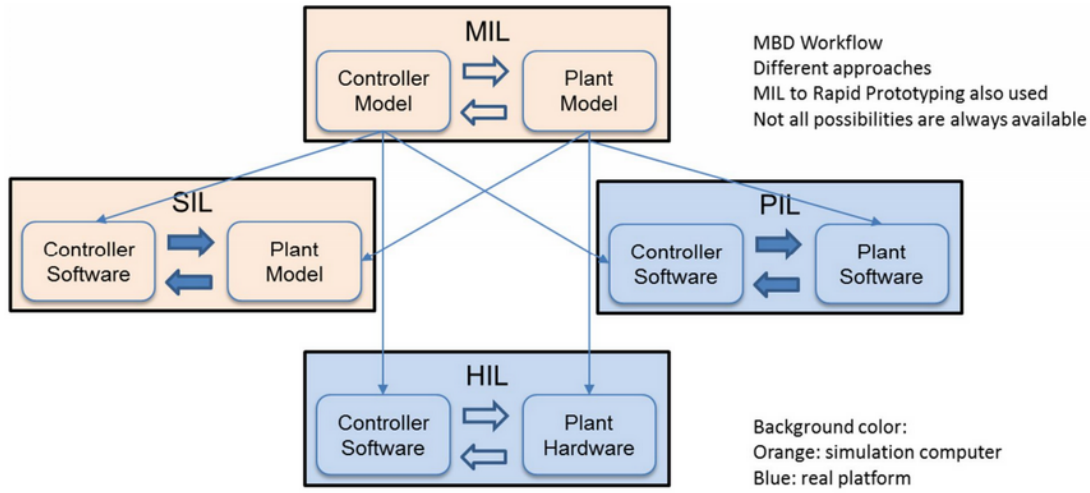

Fig. 3. Methodology of platform customization and deployment to real application (Model based system engineering)

processing towards industrial applications. For integrated, robust, control of production systems and equipment solutions the aim is to develop a system on chip (SoC) architecture. Such a SoC combines capturing raw images, fast image processing, and conversion into required geometric data (e.g. position and velocity of a defined object in the scene) in one device. This device is effectively a novel sensor in Layer 1 that can be used in a machine control setting, it is connectable to BB1.

BB5 – High performance servo amplifier

This BB delivers a high performance, highly configurable current amplifier for servo control application. This provides a flexible low level actuator control in Layer 1 which can be used in high fidelity motion control platforms with stringent performance requirements (e.g. 200-500 Hz position bandwidth and/or mA-current accuracy).

BB6 – Self-commissioning velocity and position control loops

This BB provides the functionality for automatic identification of the controlled system and automatic dynamic tuning of the velocity or position control loop. This allows the control system to be adapted to changing machine dynamics and also potentially plays a role in prognostic and diagnostic activities. It is integrated in the I-MECH motion control platform to facilitate rapid commissioning of I-MECH based systems. BB6 assesses the actual system quality from the Control Layer perspective.

BB7 – Vibration control module

This BB 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). It is intended that this BB be simple pluggable module that can be integrated into any of the demonstrators. Regarding diagnostic services, BB7 provides useful information about actual machine dynamic and can immediately detect changes.

BB8 – Robust model-based multivariable control

This BB delivers the core control methodology feedback loops taking into account all of the data and innovations delivered by the other BBs. It provides a mathematical model of the plant dynamics which can be used either for simulations or a subsequent model-based control algorithm design. Additionally, this BB provides SW algorithms for high-precision motion control of complex multi-axis systems. It utilizes the information about the plant dynamics obtained from previously described mathematical models. Regarding diagnostic services, BB8 can detect any changing deviations between the mathematical model and a real system. It plays a crucial role when system needs flexible adaptation (re-design) and one needs to come back to MIL / SIL stages.

BB9 – Iterative and repetitive control module

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

BB10 – Control Specific Multi-many core Platform

This BB provides a universal HW platform suitable for the implementation of the SW modules developed in terms of the I-MECH project. It will be capable of hosting multiple building blocks by delivering an open, customisable or COTS, multi-many core platform for control systems tasks. In SOA context, it provides a core HW/SW interface to System behavior Layer 3.

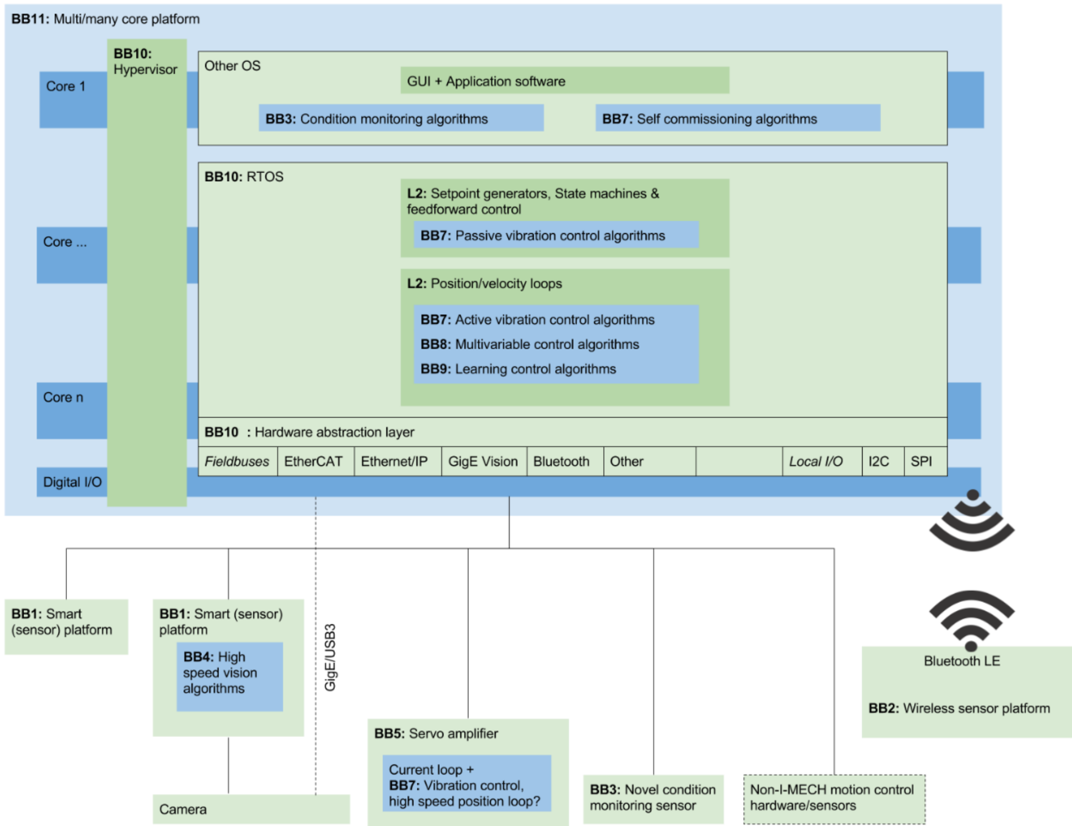

Fig. 4. System decomposition of motion control platform into modules (building blocks)

BB11 – RTOS[5] for multi-many core platform

To enable predictably mastering the parallel computing bandwidth offered by modern computing architectures, it is therefore necessary to extend existing RTOS with scheduling techniques to limit the interference due to the simultaneous execution of multiple activities on different cores, concurring for the access the shared hardware and software resources. On the other hand, industrial application require the possibility to run the existing application code base with little modification, and for this reason we propose the usage of an hypervisor level to isolate different domains trying to provide enhanced guarantees. The main development concerns the hypervisor layer, along with predictable scheduling algorithms and execution models integrated in open source RTOS, will allow ensuring a proper timing isolation among multiple tasks/applications running on different cores.

V. I-MECH PILOTS, USE-CASES AND DEMONSTRATORS

The above described set of BBs will be, after tailoring, integrated with selected Pilot machines, shown also in Fig V. The technology matrix (Tab I) shows which BB is integrated to which pilots briefly described in next paragraphs.

[5]Real-time operating system

Pilot A – Generic substrate carrier.

Vexar is an intelligent substrate transport system (Generic Substrate Carrier, GSC) that is integrated as a module in printing systems. Due to the intelligence of the system, the steel conveyor belt can transport a wide variety of media at high speed and with high accuracy under process modules such as laser and inkjet systems. By means of vacuum the substrate is fixed during transport, as a result of which the print quality becomes almost independent of the mechanical properties of the substrate. The machine benefits mainly from novel current amplifier, repetitive control strategies and fast computer vision that could combine edge and lateral sensing of the belt. Finally, advanced signal processing of encoder signals is of high importance.

Pilot B – 12-inch wafer stage

The 12-inch wafer stage is a key module in the ADAT XF range of small-die-high-volume semiconductor die bonding equipment produced by Nexperia. It offers very high-speed (72.000 units/hour) and high-accuracy (3 micro-meters) positioning of a wafer containing semiconductors to enable high-throughput and high-accuracy component placement in subsequent modules of the machine. The stage requires the coordination of 7 motors, some of which operate in coupled axes.

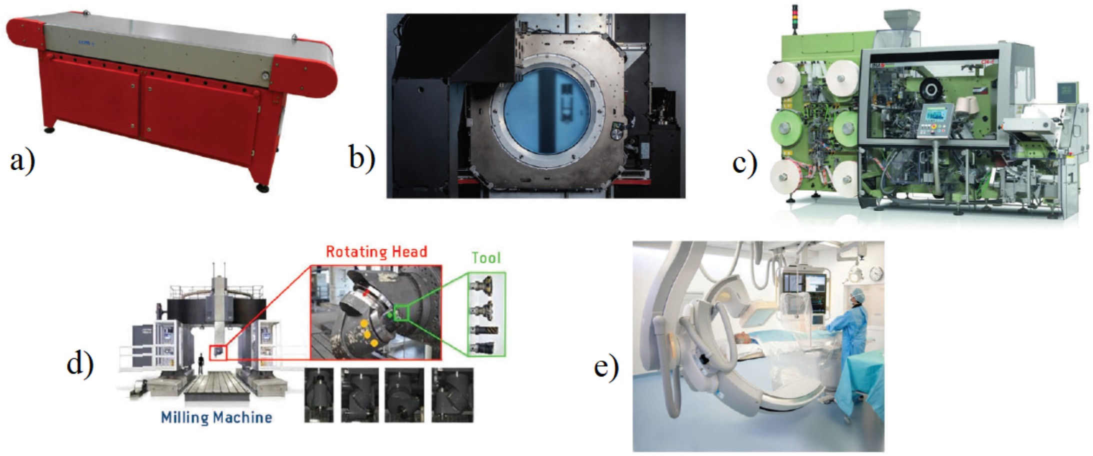

Fig. 5. Examples of application domains where described modules and platform will be implemented: a) Generic substrate carrier, b)12-inch wafer stage, c) High-speed packaging machine, d) Big CNC machine, e) Medical manipulator

Pilot C – In-line filling and stoppering machine, Tea bag machine.

An in-line filling and stoppering machine is used for filling liquid solutions into cylindrical vials and for rubber stopper insertion. Multi-core systems are not sufficiently mature to allow guaranteeing the hard real-time requirements of the addressed setting, due to the mutual interferences of tasks simultaneously executing on different cores, and concurrently accessing shared resources like network controllers, I/O devices, GPU accelerators, and shared data structures. The I-MECH project integrates the latest achievements from the real-time systems community (hypervisor based solutions) 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.

Pilot D – Smart machining tools and milling machines.

CNC milling machines are designed for high-productivity sectors such as aeronautics, mold and dies, energy and capital goods. The milling head is one of the critical components influencing machine performance. A set of wireless smart sensors capable of gathering real-time information about machine's milling head performance will be developed for use in milling heads using I-MECH building blocks. This set will include wireless temperature probes, proximity sensors, accelerometer based vibration sensors and embedded electronics to process the data.

Pilot E – Medical manipulator

Medical manipulators form a class of applications with typical characteristics and specifications. A single set of control parameters cannot cover the whole range of applicable loads. Although the demands in terms of speed and bandwidth may be limited, robustness is extremely important. This robustness has two faces: Robustness with respect to control performance and robustness over a longer period of time (months, years). Both are essential in the medical market. A commercially available medical manipulator with at least 5 degrees of freedom is used for the demonstration of advanced motion control concepts and machine monitoring as developed in terms of the I-MECH platform.

Point out that besides pilots, the BBs are tested e.g. in hoist and crane domain, industrial robotics or metal processing machines, co called project use-cases and demonstrators. More information about all applications can be found at [19].

TABLE I
IMPLEMENTATION OF BBS ON DIFFERENT PILOTS – TECHNOLOGICAL MATRIX

BBs pilots	A	B	C	D	E
BB1	Y	Y	-	Y	-
BB2	-	Y	-	Y	-
BB3	Y	Y	-	-	Y
BB4	Y	Y	-	-	-
BB5	Y	Y	-	-	-
BB6	Y	Y	-	Y	Y
BB7	-	-	-	-	Y
BB8	Y	Y	-	-	-
BB9	Y	Y	-	-	-
BB10	Y	Y	-	-	Y
BB11	Y	Y	-	-	Y

VI. CONCLUSION AND FUTURE TRENDS

It was shown that performance limits in motion control systems are often caused by bottlenecks in fast system integration of highly customized modules (HW, SW, sensors, etc.). Point out, that pilot machines described are already on the market. The demand for novel BBs and toolchains for integration rise up from the need to put those machines on next performance level, i.e., make them competitive on the global market or even leading technology. The authors believe that during next year successful stories of validated performance improvements on every machine will be reported.

Clearly, the technology development is extremely fast. Hence after first half of the project, it is evident that there are already new drivers for consequential cooperation, e.g.:

Employing artificial intelligence at higher levels of control platform including machine learning approaches to support integrated zero-defect production and predictive maintenance; high-fidelity modelling and simulation approaches enabling turning digital twin into full digital thread (full machine lifecycle), multilayer, multi-domain modeling; following XIL standard which could standardize testing of components of large number of different vendors; full integration of novel principal sensors and actuators. Hence there is a extraordinary motivation to continue in cooperation also under *Horizon Europe* framework programm.

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