SSRN
Tomorrow's Research Today

13th Conference on Learning Factories, CLF 2023

Concept of a modular embedded computing platform for automation extension experiments

Zsolt Kemény[a,*], Richárd József Beregi[a], Kristóf Abai[a]

[a] *Institute for Computer Science and Control (SZTAKI), Kende u. 13–17, 1111 Budapest, Hungary*

Abstract

Smart retrofit, one of today's key topics in production-related fields, is also represented in many learning and pilot factories. Limitations along cost–capacity compromises with industrial equipment, however, often move students and researchers alike to more affordable and open "maker-grade" substitutes instead of standard industrial solutions. Certain shortcomings of the current open-source offering still present a gap that may be—especially if frequent reconfiguration is an inseparable part of the didactic or research program—best addressed by a new design of a consistent hardware and software framework for smart retrofit. Summarizing design objectives, architectural features, resource capacities and possible enhancements of the framework, the paper outlines how this strategy has been followed in the SZTAKI Smart Factory, a facility built on industrial core equipment with subsequent non-industrial extensions.

© 2023 The Authors. This is an open access article.
Peer-review statement: Peer-review under responsibility of the scientific committee of the 13th Conference on Learning Factories 2023.

Keywords: Embedded computing; smart retrofit; cyber-physical production systems; peripheral hardware

1. Introduction

The transition to Industry 4.0 is to radically change the character of production [1], yet, fundamental economic and engineering rationality is still certain to preserve validity. Consequently, manufacturers are likely to retain their—still useful—legacy equipment for considerable time, and seek ways of extending their functionality and connectivity by means of a *smart retrofit* to integrate existing equipment into a cyber-physical production system [2]. In view of the durability of production resources, this process is likely to last for several decades to come, making it an important objective to prepare the next generation of engineers for shaping and exploiting a continual evolution of manufacturing resources in an efficient and productive way. While still subject to "engineering common sense," dealing with smart retrofit and its impact on several levels of production does require a different mindset. This includes a growing reliance on autonomous, creative solution finding and critical assessment [3], i.e., capabilities which develop particularly well in hands-on, self-steered learning.

Specific knowledge sets needed to master the new manufacturing paradigm—smart retrofit itself included—differ both by hierarchical level of production and by life-cycle stage of production resources [4], and a systematic presentation of the entire spectrum of challenges and corresponding capabilities is clearly beyond the

* Corresponding author. Tel.: +36 1 279 6180.
E-mail address: kemeny@sztaki.hu

Electronic copy available at: https://ssrn.com/abstract=4469200

scope of the paper. Instead, the case of a specific facility—the SZTAKI Smart Factory [5]—is presented where a smart retrofit framework for simplified automated workstations has to observe budget limitations, as well as needs arising from the types of didactic and research activities pursued with the equipment. The paper summarizes the role and requirements of the platform and their matching with market coverage (Sections 2–3), shows its architecture and key characteristics (Section 4), presents a roll-out roadmap within the application context of the facility (Section 5), and examines its didactic contribution through a specific use case (Section 6). Finally, Section 7 includes an outlook on adoption by other users and anticipated trends influencing future development.

2. Requirements in a didactic perspective

The SZTAKI Smart Factory is a scaled-down physical representation of a manufacturing facility comprising an automated warehouse, workstations, and intra-logistics resources [5]. The warehouse, workstations and fixed conveyors represent conventional automation, currently undergoing a *smart retrofit* enabling (1) integration into a cyber-physical production system (CPPS) [6]; and (2) widening process transparency and design freedom beyond typical industrial limits in instrumentation for education and research. Didactic activities are subdivided into two main types. (1) Repeatable lab exercises of 2–4 hours assume a readily available configuration of the system. The core task corresponds to the question: *How can we schedule operations on workstations to comprise a desired sequence of processing steps?* Smart retrofit adds another question: *How can we use process data to model and improve operation sequences?* (2) In project-based work, spanning an entire semester, student teams extend the automation equipment with further mechatronics solutions. Milestones and timing follow fixed requirements, but the tasks are different every time, and may build upon the results of preceding teams. Here, the main question is: *How can we deliver the specified mechatronics solution under the constraints of the manufacturing environment?* If smart retrofit enters the picture, students either rely on an extended infrastructure as-is, or, if retrofit itself is part of the assignment, elaborate a solution corresponding to the question: *How can we design, prototype, analyze and optimize a smart retrofit solution, given the constraints of the manufacturing environment?*

Project-based teamwork is the core type of student activity in the facility, and is often an "undergraduate forerunner" of follow-up research, or a complement to ongoing R&D&I (research, development and innovation). Emphasized learning targets also correspond well with capabilities needed for future production-related R&D&I. Specifically for a smart retrofit as an assignment, they can be formulated as: ability to autonomously (1) analyze demands vs. capacities; (2) design and construct an instrumentation prototype; (3) critically assess prototype characteristics; and (4) design, construct and validate an optimized solution. More on the socio-technical side, students learn to (5) perform activities (1)–(4) in coherent teamwork; and (6) understand and perform their work in the context of other preceding, simultaneous or follow-up projects hosted by the site. The Smart Factory environment is especially beneficial for meeting (5) and (6) in comparison to the same project work performed in a traditional university lab environment where projects remain largely isolated from each other.

The facility has previously been subject to a number of isolated retrofitting projects, with many of these assigned to student teams. Anecdotal findings from such work show that certain design and construction activities—mostly related to interfacing components—require considerable effort but contribute little to the learning targets, and burden follow-up work with legacy constraints. Under the working assumption that a thorough assessment of long-term extension expectations and standardization of components and interfaces can alleviate the aforementioned problems, it was decided to elaborate a consistent set of smart retrofit components, forming a standardized but open "sandbox" of embedded computing resources for the automated workstations.

3. Comparison of needs to market coverage

Several roadmaps can be taken to build up a retrofitting resource pool. Fully relying on industrial-grade components is possible [7], even if student-initiated extensions are anticipated to go beyond any "closed-world" limits at some point [8]. As pointed out by Zambetti et al. [9], a similar need for open interoperability is expected to gain importance in the industry, and technology providers will likely respond. Nevertheless, the costs of an industrial-grade resource pool will not fit into the budget of the Smart Factory in foreseeable time. Some

Electronic copy available at: https://ssrn.com/abstract=4469200

single-vendor solutions remain in a more affordable price range at the cost of retaining only some industrial characteristics [10], nevertheless, they typically have mechanical limitations that render them unsuitable for the Smart Factory environment. By far most feasible is a blended approach, in which the core of the facility is still built of industrial components, while extensions rely on affordable, often open-source, devices [11]. This still allows industrial design and construction principles to be pursued and demonstrated, but has several advantages: (1) the financial burden of modification remains moderate [12]; (2) motivation thresholds are lowered as students are less deterred by the known value of equipment [13]; (3) open-source communities can be utilized as knowledge sources [14, 15], giving students vital experience in applying engineering principles and critical assessment to compound, previously unknown solutions.

An analysis of available open-source embedded computing ecosystems regarding resource capacities, application potential for the Smart Factory, and community support, two platforms have been selected for use in the retrofitting pool. The *Raspberry Pi* family of single-board computers (SBC) has reached good maturity and community support, and is suitable for higher-level functionalities—CPPS integration and advanced human–machine interfaces (HMI)—in the facility. For lower-level functionalities, the 8-bit range of *Arduino* microcontroller (MCU) boards has been selected. Developer communities and manufacturers of peripheral devices [16, 17, 18] have created a large open ecosystem around the original MCU boards, and community contributions allow easy integration of most of the *AVR* MCU types into the ecosystem [19]. Nevertheless, many of the peripheral devices offered suffer from drawbacks: (1) some low-cost products overstrain components by design, rendering them risky for long-term operation; (2) peripheral "shields" offered for the MCU boards are often designed under the assumption of being the only device connected, and thus curtail extension possibilities; (3) the ecosystem as a whole is far from standardized and consistent, requiring much interfacing effort. These preliminaries have led to the decision to compose a retrofit framework for each workstation containing a *Raspberry Pi* SBC for higher-level functions, and a set of *AVR* MCU boards and peripheral boards built in-house, being interoperable with common *Arduino* solutions but following a more standardized design.

4. Architecture of the hardware platform

The workstation-level embedded computing platform has been designed and implemented as an extensible set of processor and peripheral boards with uniform dimensions and standardized connectors. The 100 mm × 100 mm boards have mounting holes at uniform locations, allowing variable installation on a common mounting frame in a grid pattern. Each workstation is equipped with a mounting frame that can accommodate 4×4 boards in freely selectable configuration. A stand-alone desktop frame for development and testing shares the same basic dimensions. This allows a convenient prototyping of spatial board configuration and wiring arrangement in a less confined environment prior to installation in a more constrained production scene. Under development is also a pool of 3D-printed adapters for local installation of individual boards.

As designed for use with the workstations, the platform is subdivided into four architectural layers. *AVR* MCU boards and peripheral extensions are employed for the (1) *Real-time layer*—handling low-level processes closest to physical resources, often with real-time requirements, typically in the range of milliseconds to seconds, traditionally served by PLC I/O (programmable logic controller input/output) channels; and the (2) *Event-handling layer*—dealing with discrete events as an intermediate-level interpretation of low-level process characteristics and state transitions, along with pre-processing, aggregation, recording or reporting to higher layers. A single *Raspberry Pi* accommodates higher layers: the (3) *Human–machine interaction layer*—human-aware collaboration logic which can have its own dedicated states, behavioral models and human–machine interaction processes; and the (4) *CPPS integration layer*—integrating the workstation into a facility-wide CPPS with an in-house manufacturing execution framework [6], requiring context-aware transformations in data granularity, abstraction level and data exchange protocols. A cross-layer *Controller Area Network* (CAN) bus ensures vertical connection of layers within the range of a workstation, while the SBC running the CPPS integration layer offers both wired and wireless connectivity to the rest of the entire CPPS.

As shown in Fig. 1, the layers of the framework correspond well to a recommended smart retrofit hierarchy [2], with the exception being the place of human–machine interaction. This is understandable in view of a workstation being integrated into the manufacturing system as a whole: in this case, human–machine interrelations within a single workstation have their own autonomy below the level of the CPPS integration interface.

Electronic copy available at: https://ssrn.com/abstract=4469200

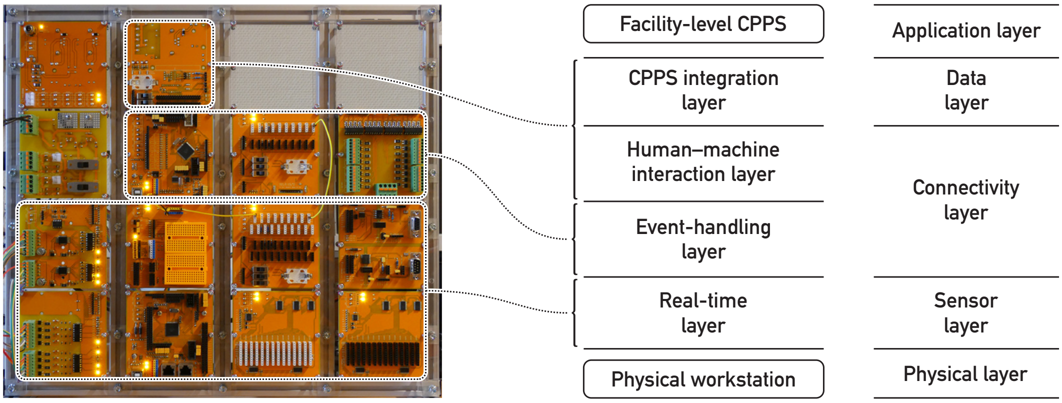

Fig. 1. Hardware component groups of the embedded computing framework on a test stand (left), their correspondence to *architectural* hierarchy of the framework (middle column), and the *functional* smart retrofit hierarchy in [2] (right column).

5. Roll-out roadmap

As of writing the paper, the embedded computing framework is undergoing roll-out. Once the hardware platform instances are fully functional, deployment experience is expected to validate the design and implementation in three subsequent steps: (1) functionality of the basic framework demonstrated with individual benchmark tasks, (2) suitability for integration into an entire CPPS environment demonstrated by at least one integration example, and (3) consistently favorable developer experience during implementation of interconnected projects and experiments. It should be noted that validation steps (1)–(3) cover the entire operation spectrum of the Smart Factory facility, with *a didactic program forming only a part of all these activities*. Allocation of specific tasks to student projects, routine development or R&D&I is being worked out in a rolling-horizon manner as roll-out progresses, and can, therefore, not be reported in advance in full detail.

For initial deployment, five complete sets of boards have been assembled, with surplus copies of some boards serving as backup and as a hardware pool for experiments beyond the workstations. Currently, hardware tests and adaptation of existing software libraries are underway, with testing of the functionality of individual modules already successfully completed. Currently starting is the replication of existing features of additional MCU-driven hardware previously installed at the workstations of the Smart Factory—meeting this goal and replacing legacy hardware extensions will complete step (1) of the validation roadmap. Full integration into the Smart Factory—simultaneous with the construction of a new CPPS environment in a separate project track—is planned to be finished in 2023, upon which validation step (2) can be completed in a number of relevant application examples. Validation step (3) is a long-term goal of the coming years, also connected to further extension of shop-floor instrumentation, and elaboration of an advanced workstation-level HMI operated by the SBC in the hardware framework. While currently on hold due to other project priorities and obstacles in sourcing critical components, development of further hardware modules does remain on the agenda of the coming years, including the goal of a more compact hardware configuration for portable instrumentation in field projects.

6. Didactic use case

In the current stage of the roll-out of the embedded computing platform, it is too early to present a mature case study on its didactic application. Nevertheless, a comparison based on a formerly proposed student project can highlight the expected advantages of the platform.

In previous years, the industrial-grade core equipment of each workstation received an MCU-based extension operating four *Near-Field Communication* (NFC) readers to detect and identify workpieces equipped with NFC tags passing through the workstations. The extension had a rather minimalistic approach to accommodating the readers and operating additional actuators, worked independently of the rest of workstation control (conventional

Electronic copy available at: https://ssrn.com/abstract=4469200

PLC), and transferred unfiltered tag readings to facility-level execution control via a chain of field bus and TCP (*Transmission Control Protocol*) connections. A previously proposed extension would have included a smart retrofit student project, in which the workstation would have been populated by a higher number of NFC readers at locations specified by the students as well as I/O adapters observing PLC behavior, delivering data logs of material movement and process control operations within the workstation. Based on the raw data, students would have determined the minimal number of NFC readers and their optimal location, as well as a minimal set of observed PLC I/O channels to achieve transparency of specified material handling and manufacturing processes at the workstations. The purpose-built and fragmented nature of the existing retrofit solution presented several obstacles: (1) The implementation of the proposed student project would have required a disproportionate amount of routine development giving no essential contribution to meaningful learning targets (see Section 2). It may be enough to highlight that both electrical and mechanical interfacing would have required continuous work of one or several days for each individual instance of adaptation, and it was not guaranteed that the outcomes would be reusable in further projects. (2) The capacity limits of both the existing MCU board and the provided communication channels would have posed serious challenges in forwarding more intense data traffic, potentially requiring workarounds of unforeseen workload, likely to surpass the time frame allocated to the student project. Owing to these shortcomings and further technical obstacles, the smart retrofit student assignment was postponed, along with other similar plans, until a suitable smart retrofit environment becomes available.

The introduction of the embedded computing platform presented in the paper will remove the aforementioned obstacles and make the proposed smart retrofit student assignment realistic. Difficulty (1) will be largely eliminated by more configurable, standardized and widened support for peripheral devices, including native support for up to 28 SPI (*Serial Peripheral Interface*) sensors, i.e., more than the number of NFC readers fitting onto the workpiece path without interference), 8+16 24 V inputs and 8 dedicated 24 V outputs installed by default, and many more low-voltage general-purpose I/O connections available than before. Standardization of component form factor and availability of pre-fabricated adapters will eliminate most routine interfacing work. Difficulty (2) will be largely overcome by the layered architecture enabling local storage/buffering, pre-filtering, and pre-processing of raw data, as well as by the reduction of normal operation-related data traffic due to a systematic separation of data streams for each workstation. The overall consistency of framework components is expected to leverage reusability of results, and establishment of connections to other tracks of development at the same site. Moreover, the infrastructure is kept open for integration of new—possibly third-party—components, which can form the basis of a further class of student projects in the coming years.

7. Conclusion

Durability of legacy equipment is expected to maintain a need for smart retrofit in the transition to Industry 4.0, and higher education has to prepare the coming generation of engineers for tackling related challenges and meaningfully shaping the evolution of retrofit approaches. Supporting corresponding learning targets and encouraging interconnection of several tracks of project work require suitable preparation of a hands-on learning environment, also observing budget constraints, characteristics of market offering, interoperability, and support in developer communities.

The paper presented requirements, preferences and reasonable choices from the perspective of workstation-level smart retrofit in the SZTAKI Smart Factory, a scaled-down physical representation of a manufacturing facility built of a core of industrial-grade equipment with open-source, “maker-grade” extensions. A modular embedded computing framework was presented which is also suited for a didactic program of smart retrofit student projects, eliminating most of the interfacing efforts that contribute little to the key learning targets, and leveraging connections to other student projects and R&D&I tracks. The framework is currently in its roll-out phase with an initial configuration already implemented, and further extensions planned for later phases of its validation roadmap, depending on findings from the entire operation spectrum of the facility, as well as perceived needs and available material supply options.

The hardware framework presented in the paper can be a useful addition to learning factories where reconciliation of hardware-intensive experiments and budget limitations is an issue. Consolidated framework designs, findings and recommendations are planned to be shared within the learning factory community at a later time as far as intellectual property management policies allow.

Electronic copy available at: https://ssrn.com/abstract=4469200

Acknowledgement

Work for this paper was partly supported by the European Commission through the H2020 project EPIC under grant No. 739592, and partly by the Hungarian national grant iNEXT, under grant ED_18-22018-0006 titled "Research on prime exploitation of the potential provided by the industrial digitalisation".

References

[1] X. Yao, J. Zhou, Y. Lin, Y. Li, H. Yu, Y. Liu, Smart manufacturing based on cyber-physical systems and beyond, Journal of Intelligent Manufacturing, 30 (2019) 2805–2817.

[2] D. Jaspert, M. Ebel, A. Eckhardt, J. Poeppelbuss, Smart retrofitting in manufacturing: A systematic review, Journal of Cleaner Production, 312 (2021) Paper ID: 127555.

[3] A. Petrillo, R. Cioffi, F. De Felice, Digital transformation in smart manufacturing, BoD (2018), ISBN 9789535138419.

[4] P. Zheng, H. Wang, Z. Sang, R. Y. Zhong, Y. Liu, C. Liu, K. Mubarok, S. Yu, X. Xu, Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives, Frontiers of Mech. Eng., 13 (2018) 137–150.

[5] Zs. Kemény, R. J. Beregi, G. Erdős, J. Nacsa, The MTA SZTAKI Smart Factory: Platform for Research and Project-oriented Skill Development in Higher Education, Procedia CIRP, 54 (2016) 53–58, 6th CIRP Conf. on Learning Factories (CLF 2016).

[6] R. Beregi, G. Pedone, B. Háy, J. Váncza, Manufacturing Execution System Integration through the Standardization of a Common Service Model for Cyber-Physical Production Systems, Applied Sciences, 11(16), paper ID: 7581.

[7] B. Mayer, D. Tantscher, C. Bischof, From Digital Shop floor to Real-Time Reporting: an IIoT Based Educational Use Case, Procedia Manufacturing, 45 (2020) 473–478, 10th Conf. on Learning Factories (CLF 2020).

[8] I. Singh, D. Centea, M. Elbestawi, IoT, IIoT and Cyber-Physical Systems Integration in the SEPT Learning Factory, Procedia Manufacturing, 31 (2019) 116–122, 9th Conf. on Learning Factories (CLF 2019).

[9] M. Zambetti, M. A. Khan, R. Pinto, T. Wuest, Enabling servitization by retrofitting legacy equipment for Industry 4.0 applications: benefits and barriers for OEMs, Procedia Manufacturing, 48 (2020) 1047–1053, 48th SME North American Manuf. Res. Conf. NAMRC 48.

[10] A. Pechmann, J. Wermann, A. W. Colombo, M. Zarte, Using a semi-automated job-shop production system model to prepare students for the challenges of Industrial Cyber-Physical Systems, Procedia Manufacturing, 31 (2019) 377–383, 9th Conf. on Learning Factories (CLF 2019).

[11] A. Ferrario, M. Confalonieri, A. Barni, G. Izzo, G. Landolfi, P. Pedrazzoli, A Multipurpose Small-Scale Smart Factory For Educational And Research Activities, Procedia Manufacturing, 38 (2019) 663–670, 29th Int. Conf. on Flexible Automation and Intelligent Manufacturing (FAIM 2019), Limerick, Ireland.

[12] L. Louw, M. Walker, Design and implementation of a low cost RFID track and trace system in a learning factory, Procedia Manufacturing, 23 (2018) 255–260, 8th CIRP Conf. on Learning Factories (CLF 2018).

[13] C. Kuhn, D. Lucke, Supporting the Digital Transformation: A Low-Threshold Approach for Manufacturing Related Higher Education and Employee Training, Procedia CIRP, 104 (2021) 647–652, 54th CIRP CMS 2021.

[14] A. Martikkala, J. David, A. Lobov, M. Lanz, I. F. Ituarte, Trends for Low-Cost and Open-Source IoT Solutions Development for Industry 4.0, Procedia Manufacturing, 55 (2021) 298–305, fAIM 2021.

[15] S. Rúnarsson, Open source hardware and software alternative to industrial PLC, Master's thesis, Høgskolen i Sørøst-Norge (2016).

[16] H. K. Kondaveeti, N. K. Kumaravelu, S. D. Vanambathina, S. E. Mathe, S. Vappangi, A systematic literature review on prototyping with Arduino: Applications, challenges, advantages, and limitations, Computer Science Review, 40 (2021) Paper ID: 100364.

[17] M. Matijevic, V. Cvjetkovic, Overview of architectures with Arduino boards as building blocks for data acquisition and control systems, in 2016 13th International Conference on Remote Engineering and Virtual Instrumentation (REV), 56–63.

[18] S. Lang, T. Reggelin, M. Jobran, W. Hofmann, Towards a Modular, Decentralized and Digital Industry 4.0 Learning Factory, in 2018 Sixth International Conference on Enterprise Systems (ES), 123–128.

[19] Laud Media, MCUdude Arduino cores for AVR MCUs (2022), URL https://github.com/MCUdude.

Electronic copy available at: https://ssrn.com/abstract=4469200