Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 54 (2016) 53 – 58

www.elsevier.com/locate/procedia

6th CLF - 6th CIRP Conference on Learning Factories

The MTA SZTAKI Smart Factory: platform for research and project-oriented skill development in higher education

Zsolt Kemény[a,*], Richárd József Beregi[a], Gábor Erdős[a,b], János Nacsa[a]

[a] *Fraunhofer Project Center PMI, Institute for Computer Science and Control, Hungarian Academy of Sciences, Kende u. 13–17, H-1111 Budapest, Hungary*
[b] *Department of Manufacturing Science and Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary*

[*] Corresponding author. Tel.: +36-1-279-6180; fax: +36-1-466-7503. *E-mail address:* zsolt.kemeny@sztaki.mta.hu

---

Abstract

Nowadays, the potential of learning factories as test beds and research plants is gaining recognition, and several facilities are extended or built up already with these complementing purposes in mind—among them the *Smart Factory* at the Fraunhofer Project Center at MTA SZTAKI currently completing a major stage of development. The paper presents the structure and key design principles of the plant, and explains how the composition and functionalities of the equipment implement focal principles of the *Industry 4.0* and *Cyber-Physical Systems* concepts. Furthermore, it is shown how the *Smart Factory* provides students with challenges and resources for project-oriented development of their skills, and where these opportunities fit into technical higher education by hosting both individual student projects and courses with a specific structure of progress.

Peer-review under responsibility of the scientific committee of the 6th CIRP Conference on Learning Factories

Keywords: Smart Factory; Industry 4.0; Cyber-Physical Systems; Research test-bed; Project-oriented education

---

1. Introduction

Advances in information and communication technology, semiconductors and manufacturing technologies are setting the stage for a qualitative leap in the interaction of a physical environment and computational resources. The past 1–2 decades witnessed the emergence of systems combining diverse entities, processes and complex interrelations of a physical environment with the ever increasing and heavily networked computational capabilities of virtual resources, referred to as *cyber-physical systems* (CPS) [1,2]. Aside from their resourceful complexity, CPS are marked by profoundly improved observability of physical object states and processes, their representation in virtual resources, and possibilities of exerting influence on the physical environment. The networked fusion of physical and virtual resources is expected to bring about new qualities of the entire CPS—most often, robustness, resilience, fast adaptivity and fault-tolerance, as well as various forms of self-organization (self-configuration, self-repair, "self-*" in general) are cited as the expected emerging advantages [2–4].

With its rich interrelations, constraints and requirements, industrial production is clearly a domain that can benefit from implementing the CPS paradigm [1,5]. Due to the importance of human workforce and cognitive resources, CPS in industrial environments are, sometimes, even viewed as *socio-cyber-physical systems* whose function strongly depends on proper awareness and collaboration of humans taking part in the production processes [6].

The application of various characteristic elements of CPS is already spreading in the manufacturing industry, expected to lead up to a major change, often referred to as the *4th industrial revolution*, bringing about the so-called *Industry 4.0* [1,2,7–9]. Nonetheless, most sources in literature agree that related changes will be gradual. Even if the spreading of cyber-physical technologies is facilitated by competitive pressure, and the evolution of *production networks* intensifies the need for such solutions, much of a system-level background still remains to be elaborated and made fit for industrial requirements by research, development and standardization [1,2,10].

In addition, the incremental transition to Industry 4.0 solution elements and their meaningful integration into existing production environments requires well-conceived, systematic approaches [9,11]. An important part of such methodologies is the transfer of applicable knowledge to the decision makers, technical experts and personnel designing, implementing and coexisting with new solutions. Not less important is the development of confidence, new forms of routine, awareness and collaboration—a mindset suitable for Industry 4.0, in other words. The latter attitude requires a higher level of awareness, autonomy and flexibility due to Industry 4.0 settings no longer

Peer-review under responsibility of the scientific committee of the 6th CIRP Conference on Learning Factories
doi:10.1016/j.procir.2016.05.060

regarding humans as a special form of instructable machines but as participants of production processes endowed with creativity and consciousness which artificial components of a production system do not possess.

Consequently, hands-on experience and self-directed, explorative learning play an increasing role in making people ready for work in an Industry 4.0 production system. While some sources argue that an Industry 4.0 environment can, by itself, support this as an integral part of production in a *work-based learning* setting [12], this is of limited use where Industry 4.0 solutions are not yet in place and will not be implemented unless decision makers and technical staff are made aware of the possibilities and prepared in advance [11].

Meant, among other things, to develop competencies receiving little attention in "conventional" education, *learning factories* have the potential of introducing perspectives and skills needed for Industry 4.0 environments. Learning factories put much emphasis on hands-on experience, development of social skills necessary for collaboration in a working environment, awareness of a situation and its implications in a sociotechnical system, as well as self-directed, explorative learning [13,14]. Learning factories depict real production environments with regard to selected aspects and functionalities to a degree allowing *immersive* learning. A considerable part of such facilities includes aspects that are of key importance in building up perspectives, skills and knowledge needed for Industry 4.0: (i) some form of IT infrastructure is coupled with the physical processes, even if not necessarily in ways prevailing in Industry 4.0 [13–15], (ii) product and process variability and evolution of the manufacturing assets and staff are an integral part of the concept [16], and (iii) in a number of cases, preparation for fitness for Industry 4.0 is explicitly one of the drivers in the concept of the facility and its didactic activities [11]. Often, learning factories also serve as tools or test beds for research—such extended use is particularly important in areas as CPS and Industry 4.0 where much of the theoretical background is still subject to intense research that must remain closely connected to and aware of real-world challenges and demands.

An overview of existing learning factories suggests that many of them already have some characteristics that would support learning processes towards Industry 4.0 knowledge, yet, only a fraction of them exhibits an interesting set of features and approaches: (i) emphasis on the "cyber" structures in higher abstraction levels while retaining bi-directional links to physical processes (i. e., automation with considerable computational power and intelligence in the virtual subsystems), (ii) openness of the physical and IT infrastructure with regard to reconfigurability and interlinking with other, both virtual and physical, systems, and (iii) direct inclusion of autonomous learning and exploration into the design and construction of system components and functionalities.

The paper presents a compact facility which primarily serves as a research and demonstration test bed, yet, it has an important secondary use in augmenting technical higher education. In further parts, the paper is organized as follows: Section 2 explains the purpose and current structure of the facility; Section 3 highlights its current role and future potential in higher education; and Section 4 explains which aspects make the facility an embodiment of the CPS paradigm, and in which regard it can be considered a learning factory specifically for immersive learning of selected concepts in CPS and Industry 4.0.

2. Purpose and structure of the *Smart Factory*

2.1. Purpose and scenario

The design and gradual construction of the *Smart Factory* laboratory at MTA SZTAKI was initiated in 2011, and is managed by the Research Laboratory on Engineering and Management Intelligence (EMI), and the Fraunhofer Project Center PMI at MTA SZTAKI. The current form of the facility is being gradually built up since 2013. The *Smart Factory* is a compact research and demonstration facility which compresses a manufacturing site to the size of a single room and presents key physical and virtual processes of industrial manufacturing in a tangible, explorable way. The *Smart Factory* serves as: (i) a project-independent demonstration platform primarily targeting representatives of the industry interested in deploying innovative IT solutions developed by EMI and PMI; (ii) an experimental platform where Industry 4.0-related concepts can be tested in a scaled-down, safely contained environment allowing the controlled introduction of real-world constraints and disturbances; (iii) a demonstration and publicity tool capable of explaining CPS and Industry 4.0 concepts with the safe inclusion of the general public; and (iV) a facility supporting technical higher education by providing students with hands-on experience and opportunities for self-directed design and construction projects whose outcomes can remain integrated into the equipment.

The physical processes of the *Smart Factory* depict a simplified manufacturing scenario where workpieces of uniform geometry but unique identity, carrying blank cardboard inlays, undergo subsequent processing steps of stamping, punching/drilling, and one more freely configurable human-aided operation. Product diversity is exhibited by different stamping patterns, and additional variation can be introduced by the manual processing step (e. g., with item-specific instructions delivered in-place), or by customizing product data travelling with the workpiece on permanently attached RFID tags. Workpieces are supplied either from high-rack storage or external sources, and processing steps can take place on 4 workstations of identical physical configuration. Ink pads for stamping are implemented as movable resources delivered in place by the material handling components used for the workpieces. Once fully functional, "customers" will be able to place orders, follow the progress of production, and check the correct execution of manufacturing steps upon product delivery. Various operator views will "drill down" deeper into processes of the attached IT system, and it will also be possible to introduce disturbances and resource shortages to test the robustness and resilience of the production system. In addition, provisions are made for coupling the facility with other, possibly remote, systems.

2.2. Manufacturing resources

The core mechanical and control components of the manufacturing resources in the *Smart Factory* are comprised of FESTO Didactic modules. Built of FESTO MPS elements, each of the four identical production cells contains:

- A six-position turntable driven by a stepper motor,
- A pneumatic 2-DOF manipulator for transferring the workpieces to/from the conveyor,
- A pneumatic stamp to test for workpiece presence,

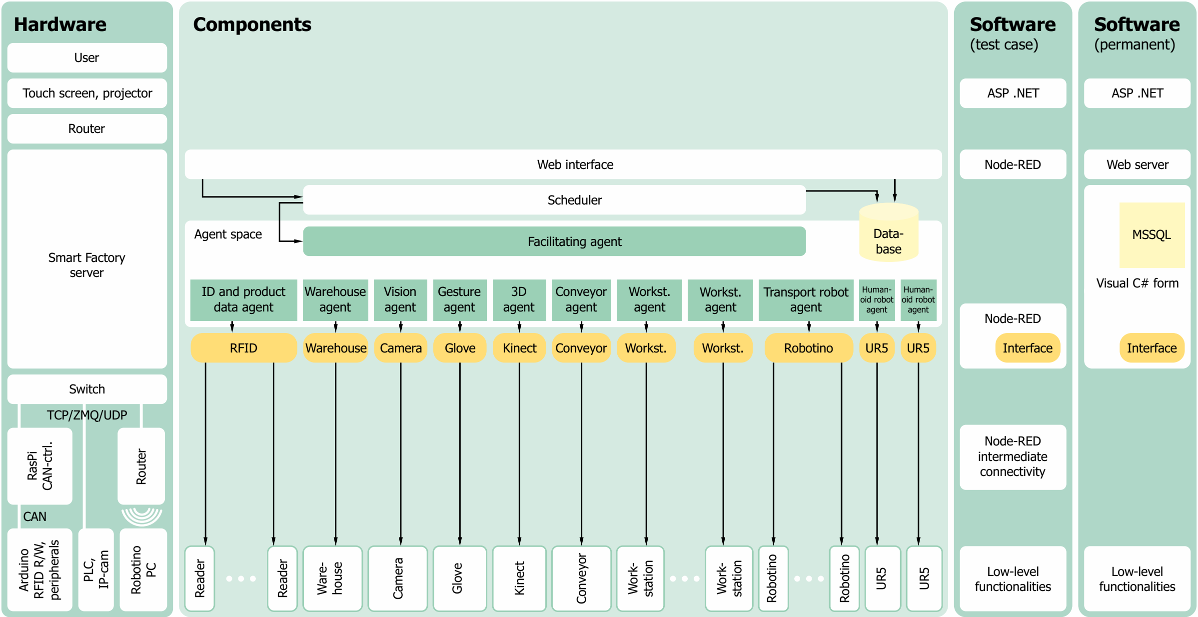

Fig. 1. Simplified architecture of the *Smart Factory*

- An electromagnetic stamp marking the workpiece with a given pattern,
- A slot reserved for a freely configurable manual operation,
- A drilling machine, and
- An electromagnetically actuated flap that can divert the workpiece onto a slide with limited storage capacity.

Each of the production cells (see Figure 2 left) is controlled by a dedicated FESTO PLC that can be accessed via local network and has a number of freely configurable I/O channels to communicate with auxiliary equipment. The workstations are now in the process of receiving RFID readers, human–machine interface elements and other extensions as described further below.

2.3. Material handling

While being custom-designed, the warehouse also relies on FESTO components, such as one more PLC and various pneumatic and electric actuators. The warehouse comprises racks where pallets can be placed on pre-defined locations. Each pallet has four recesses for cylindrical workpieces measuring 26 mm in height and 38 mm in diameter (these are resembling the workpieces commonly used with FESTO Didactic components but are custom-designed two-piece urethane castings to meet dimensional and identification requirements specific to the *Smart Factory*). The pallets remain in the warehouse but can be moved to designated RFID access locations, as well as points of loading/unloading to mobile robots or the conveyor system.

Components of the latter are of the FlexLink X45 family. The facility is served by a closed circle of four, separately driven, conveyor sections. The section containing an access point for robot manipulators is also equipped with a FlexLink X45 stop unit. All X45 modules are currently operating in stand-alone mode, but their addressing over CAN bus is planned for the near future. In addition to the FlexLink modules, bypass units were recently installed to improve material handling reserve and workpiece throughput at the external access points and at the workstations. Design and implementation of the bypass modules are an in-house development: the units have a 3D-printed body and diverting flap, and are actuated by an Arduino-driven stepper motor (Figure 2 right).

The facility is also equipped with several local storage racks for 6 workpieces each. Four of these are located adjacent to the workcells (and are partly accessible by the pneumatic manipulator of the corresponding production cell), a fifth is installed at the robot manipulator access point, and a further rack facilitates handover between mobile robots and a manipulator serving the warehouse pallets (in-house development, see Figure 2 center). Workpieces can be moved between these storage locations by means of 2–3 Robotino mobile robots, each equipped with three omnidirectional wheels, one control unit accessible via wireless network, a camera and a number of optical and inductive sensors facilitating alignment with the pre-defined material handling points. Each mobile robot can move one workpiece at a time.

Among the most recent additions to the facility are two Universal Robots UR5 6-DOF manipulators, each equipped with a Robotiq model 85 adaptive two-finger gripper, and a 6-axis force/torque sensor. The conveyor path is within the workspace of both robots, while one of them also has access to one of the aforementioned intermediate storage racks and the access point at the conveyor-mounted stop unit.

2.4. Sensors and interfaces

In addition to the optical and electro-mechanical sensors used locally by the system components, the *Smart Factory* also relies on a number of sensors to ensure outward process transparency and interaction with human personnel.

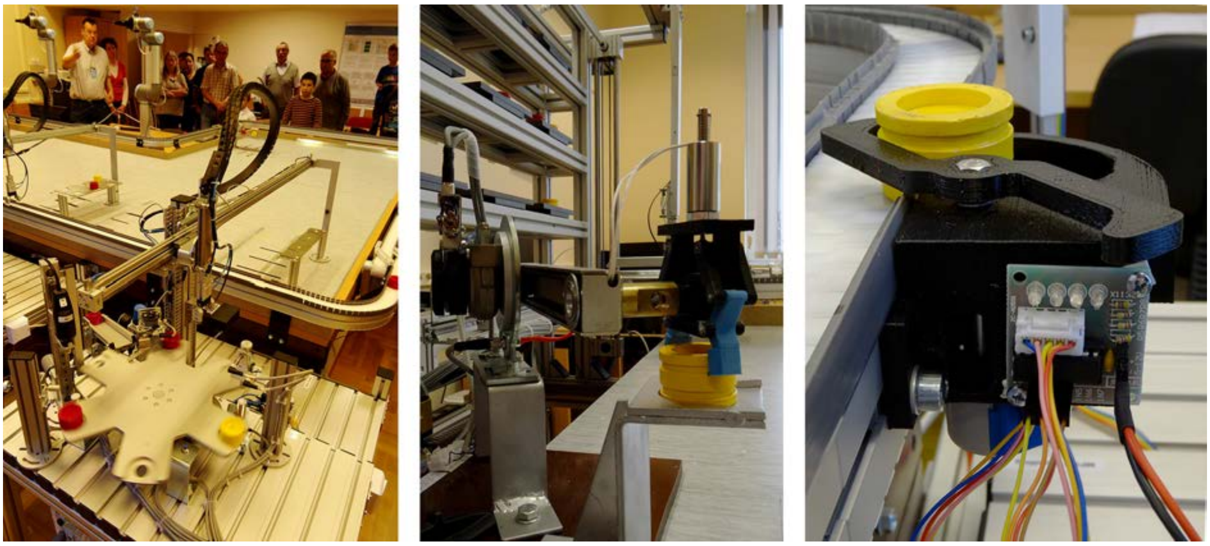

Fig. 2. Views of the *Smart Factory*: one of the workstations and the mobile robot service area during a public presentation (left); warehouse transfer manipulator developed in a student project (center); bypass unit developed in a student project and manufactured on a student-built 3D printer (right)

Tracking and unambiguous identification of workpieces relies on NFC tags (Mifare Classic 1K) embedded in the workpiece castings. In addition to a unique identifier, the tags also accommodate 752 bytes of additional memory for product data. This particular type of tags was chosen due to: (i) costs of tags and transceiver equipment being a fraction of that of industrial-grade alternatives, and (ii) compatibility with numerous smart phones, facilitating the development of product data access applications, also for possible use in presentations open to the general public where the visitors themselves can install access software on their own smart phones and inspect product data by themselves. In the current configuration, NFC transceivers are connected to Arduino-like microcontroller boards which will also control bypass units associated with some of the readers. Each workcell has its own microcontroller board accessing 2 (optionally 3) NFC readers and controlling the bypass unit of the cell. In addition, two more boards will be installed at the warehouse, and at the manipulator access point, respectively.

Due to its compact size and clear arrangement, much of the facility area can be observed by a single ceiling-mounted wide-angle IP camera. This will serve the purpose of global surveillance of the state of facility components and occupied workpiece locations via image processing, and can also form partial input to telepresence solutions with remote locations latching into the processes of the *Smart Factory*.

While the force and torque sensors of the UR5 robots do support human–machine interaction during physical contact at workpiece handover, it is also important to be aware of humans not engaging in contact. To this end, two Kinect devices were recently installed, observing the vicinity of the UR5 robots from two different viewpoints—their point cloud data can be merged on demand. Kinect devices are supplied with powerful processing and recognition tools that allow the matching of assumed skeletal models to point cloud features, as well as recognition of basic gestures. These are planned to be deployed in future experiments and solutions for human–machine interaction, including scenarios where robots and human operators perform shared manipulation tasks.

A specific class of interaction is the provision of personnel with relevant information, primarily via visual interfaces. While this is, nowadays, typically conveyed via a screen of limited size and fixed location, the seamless merging of large visual interfaces and work surfaces has already been proposed as a means of suggestive and efficient feedback to the human personnel. To this end, a ceiling-mounted projector has been installed which can project visual content onto the desk surface shared by the two robot manipulators and a human operator.

2.5. Connectivity and IT background

The connectivity architecture of system components is largely determined by two factors: (i) available communication channels of the individual components (LAN, WLAN, CAN, SPI, or simple I/O) impose technical constraints on direct access, necessitating the addition of interfacing units as needed, and (ii) direct connection of components should preferably be laid out keeping in mind reliability and isolation of possible communication disturbances.

As mentioned before, the PLCs assigned to the workcells and the warehouse are connected via LAN, and are thus easily accessible by a host computer running high-level execution control. NFC readers, additional sensors and bypass units are connected to microcontroller boards that accommodate an on-board CAN interface. It is, therefore, easy to connect them with a CAN bus which will also be accessed by a CAN-card-equipped Raspberry Pi that has a LAN connection with the high-level host. While it appears to be less than optimal to serve the workcells via two separate communication channels, one must also keep in mind that the microcontroller boards are to be one of the main areas for experiments, and must be safely contained to limit the effect of possible faults on the entire system. The clean separation of subsystems is also the reason for the pending installation of a second CAN bus dedicated to accessing the X45 modules of the conveyor system.

Connection to further major components is typically solved with LAN access—this applies to the high-level host, the manipulator controllers, and the ceiling camera. The two mobile robots are, as mentioned before, accessed via WLAN over a dedicated router. High-level access to external clients will be provided via web interfaces.

A core piece of the "cyber" level is an agent container running on the central host, accommodating software agents representing the physical components of the facility to a level of detail required by their functionality. In its current implementation, the agent layer is the outcome of a longer, comprehensive student project that recently led up to an MSc thesis [17]. At the time of writing this paper, an in-depth evaluation of the findings of this project is taking place, whereafter software tools and frameworks will be selected for a long-term implementation of the agent space. Functionalities on higher abstraction levels, such as planning and scheduling, are also subject to further design and implementation decisions. Nevertheless, standardization of interfaces will allow a modular composition of the IT components, and a suitable structure will facilitate the safe containment (or separate testing) of experimental areas before their live deployment and full integration in the IT infrastructure.

Figure 1 shows the overall architecture of the *Smart Factory* facility in three different perspectives. To the left, the composition of main hardware components is shown, with an emphasis on connectivity (note that this is merely a highly simplified excerpt of all connections and components, omitting several parts that currently undergo installation). In the middle, the functional components are shown, centered around an agent framework, while the far right lists the main software components deployed at the corresponding abstraction levels.

3. Role in education

Inclusion of students in activities regarding the *Smart Factory* has received attention since the beginning of the project. While this is, in part, a natural consequence of the strong ties between MTA SZTAKI and the Budapest University of Technology and Economics (also shown by the high share of former Technical University students among young academics at the institute), raising students' interest in being involved in the *Smart Factory* is also addressing the growing need for researchers and engineers who have hands-on experience, comprehensive knowledge and a sound view of the world in areas leading up to Industry 4.0. Some of the design decisions regarding the *Smart Factory* were made in favor of easy student participation, lowering potential deterrence often posed by (i) perceived high value of equipment, (ii) apparent complexity of problems to be tackled in a single step, (iii) the possibility of knock-on effects of failed experiments impairing the entire system. In order to overcome these problems, several component groups can be isolated as a safe "sand box", or replicated as a disjoint test object for first steps. The use of the *Smart Factory* facility in education at the Technical University (in close collaboration with the Department of Manufacturing Science and Engineering, DMSE) is following two different patterns:

Individual student projects—From early on, the facility has been hosting individual, open-ended student projects aimed at designing and implementing functional additions to the equipment. In these cases, students have much freedom in selecting their intended problem area, and are gradually included into the *Smart Factory* community, strengthening the social skills needed by professionals in industry and research—nevertheless, no strict didactic methodology is followed, and directing the students' work is largely up to the individual decisions of the student's supervisor. Some of these projects have led up to MSc [17] and BSc theses [18–20], and have contributed much to the facility gaining a "maker space" character.

Inclusion in the Mechatronics Project course—As a rather recent—and methodologically more specific—development, the *Smart Factory* has become one of several infrastructural environments for the *Mechatronics Project* course, beginning with the spring semester of 2016. For the course, groups of 3–4 students are formed who act together as a "company" developing mechatronics solutions. The supervisor allocated to the group acts as the client, and also inspects the progress of the students in all key phases of the design and development span. The course is comprised of 5 main phases: (i) agreement on the problem to be solved (equals to initial negotiation with the client), and elaboration of a project plan including manpower assignment and budget allocation for the hardware required; (ii) high-level specification, market survey for sub-components, and detailed specification; (iii) construction and separate testing of sub-assemblies, leading up to milestone 1 and the first written report; (iv) integration of sub-assemblies, fine-tuning and integrated system tests; (v) final delivery and report (milestone 2). While the *Smart Factory* is not the only environment providing problems and infrastructure for their integrated solution, it clearly is the only one at DMSE's disposal that presents integration-related constraints (e. g., adaptation to "legacy" subsystems, or constraints resulting from the processes in the facility as a whole) in tangible, meaningful, and systematically explorable or documented form, coming close to comparable integration problems in real-life industrial cases.

4. Discussion

Having presented the *Smart Factory* and its relevance in technical higher education, this section will recapitulate the characteristics that make the facility (i) an example of a *cyber-physical system* and an implementation of the *Industry 4.0* principles, and (ii) a *learning factory* of a less conventional kind that still supports autonomous, immersive learning as part of a technical higher education curriculum.

CPS and Industry 4.0—The *Smart Factory* comprises a simplified environment that still retains a physical representation of relevant processes found in the manufacturing industry, including material handling, transformation of goods, product diversity, resource constraints, and planning and execution control in higher abstraction levels of the IT infrastructure. The facility consists of components that exhibit context-awareness, autonomy, and allow the interaction and mutual representation of physical and virtual entities in the IT infrastructure and the physical subsystem, respectively. Interaction is bi-directional—sensors and interfaces allow the exact, real-time acquisition of states and process characteristics, and actuators influencing the processes are accessible by the virtual subsystem. The latter is also characterized by a networked infrastructure of interacting autonomous virtual entities (agents). Remote access and advanced human–machine interfaces will allow the coupling of the facility to remote systems, as well as human operators and users of various skill levels. *In its structure and architectural* *characteristics, the Smart Factory can already be considered a scaled-down representation of an Industry 4.0 production environment.* Once reaching an appropriate level of completion, the facility is also expected to exhibit the robustness, resilience and self-organization attributed to Industry 4.0 production systems.

Learning factory—The role of the *Smart Factory* in education is twofold. The facility hosts individual student projects in a "maker space" manner, providing technical and social background for synthesizing a practice-oriented view of the world from existing explicit knowledge, newly gained knowledge related to their specific problem, tacit knowledge and social skills. The problems solved convey aspects relevant in professional work, but are detached from immediate constraints. The *Smart Factory* is also hosting the work of several student groups of the *Mechatronics Project* course at DMSE. Here, a solution to a mechatronics problem is elaborated, implemented and evaluated in the context of the production facility. First experience has shown that the tangible and comprehensible presence of integration constraints posed by the production environment is to the benefit of students interpreting the problem in an industrial context. The size of the facility does not suffice for all student groups taking part in the course, yet, *the Smart Factory is capable of functioning as a scaled-down learning factory, and can be a prototype for similar sites to be established primarily for education.*

5. Conclusion and outlook

The paper presented the architecture and key design principles of the *Smart Factory* at the Fraunhofer Project Center at MTA SZTAKI. It was shown that the composition and functionalities of the equipment implement focal principles of the *Cyber-Physical Systems* and *Industry 4.0* concepts in a simplified manufacturing scenario. The paper also highlighted the inclusion of students in the design and construction of the facility, emphasizing architectural characteristics that remove several burdens students may perceive when they take first steps in automation and IT-related domains in an Industry 4.0 setting. Since the spring semester of 2016, the facility is also offered as one of several sites of the *Mechatronics Project* course. Although the dimensions and capabilities of the facility do not come close to those of a full-fledged learning factory, it was shown that a smaller number of students still can acquire valuable skills and hands-on experience, both in individual projects and courses of specific structure. At the time of writing this paper, the *Smart Factory* is still pending completion but plans are already outlined for the future: external connectivity is to receive increased focus, and further opportunities are expected to open up to the benefit of technical higher education.

Acknowledgement

Work presented in the paper has been supported by the Hungarian National Scientific Research Fund under grant No. OTKA K113038 "Basic research for supporting the realisation of cyber-physical production systems", and by the grants of the Highly Industrialised Region in Western Hungary with limited R&D capacity: "Strengthening of the regional research competencies related to future-oriented manufacturing technologies and products of strategic industries by a research and development program carried out in comprehensive collaboration", under grant No. VKSZ_12-1-2013-0038.

References

[1] J. Lee, B. Bagheri, H.-A. Kao, A cyber-physical systems architecture for industry 4.0-based manufacturing systems, Manufacturing Letters 3 (2015) 18–23.

[2] L. Monostori, Cyber-physical production systems: Roots, expectations and R&D challenges, Procedia CIRP 17 (2014) 9–13, variety Management in ManufacturingProceedings of the 47th CIRP Conf. on Manufacturing Systems.

[3] J. Jatzkowski, B. Kleinjohann, Towards self-reconfiguration of real-time communication within cyber-physical systems, Procedia Technology 15 (2014) 54–61, 2nd Int. Conf. on System-Integrated Intelligence: Challenges for Product and Production Engineering.

[4] M. Mikusz, Towards an understanding of cyber-physical systems as industrial software-product-service systems, Procedia CIRP 16 (2014) 385–389, product Services Systems and Value Creation. Proceedings of the 6th CIRP Conf. on Industrial Product-Service Systems.

[5] P. Wright, Cyber-physical product manufacturing, Manufacturing Letters 2 (2) (2014) 49–53.

[6] E. M. Frazzon, J. Hartmann, T. Makuschewitz, B. Scholz-Reiter, Towards socio-cyber-physical systems in production networks, Procedia CIRP 7 (2013) 49–54, forty Sixth CIRP Conf. on Manufacturing Systems 2013.

[7] T. Bauernhansl, Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration, Springer Fachmedien Wiesbaden, Wiesbaden, 2014, Ch. Die Vierte Industrielle Revolution – Der Weg in ein wertschaffendes Produktionsparadigma, pp. 5–35.

[8] D. Spath, O. Ganschar, S. Gerlach, M. Hämmerle, T. Krause, S. Schlund, Produktionsarbeit der Zukunft – Industrie 4.0, Fraunhofer Verlag Stuttgart, 2013.

[9] A. Bildstein, J. Seidelmann, Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration, Springer Fachmedien Wiesbaden, Wiesbaden, 2014, Ch. Industrie 4.0-Readiness: Migration zur Industrie 4.0-Fertigung, pp. 581–597.

[10] J. Otto, S. Henning, O. Niggemann, Why cyber-physical production systems need a descriptive engineering approach—a case study in plug & produce, Procedia Technology 15 (2014) 295–302, 2nd Int. Conf. on System-Integrated Intelligence: Challenges for Product and Production Engineering.

[11] C. Faller, D. Feldmüller, Industry 4.0 learning factory for regional SMEs, Procedia CIRP 32 (2015) 88–91, 5th Conf. on Learning Factories.

[12] G. Schuh, T. Gartzen, T. Rodenhauser, A. Marks, Promoting work-based learning through Industry 4.0, Procedia CIRP 32 (2015) 82–87, 5th Conf. on Learning Factories.

[13] E. Abele, J. Metternich, M. Tisch, G. Chryssolouris, W. Sihn, H. El-Maraghy, V. Hummel, F. Ranz, Learning factories for research, education, and training, Procedia CIRP 32 (2015) 1–6, 5th Conf. on Learning Factories.

[14] H. ElMaraghy, W. ElMaraghy, Learning integrated product and manufacturing systems, Procedia CIRP 32 (2015) 19–24, 5th Conf. on Learning Factories.

[15] U. Wagner, T. AlGeddawy, H. ElMaraghy, E. Müller, The state-of-the-art and prospects of learning factories, Procedia CIRP 3 (2012) 109–114, 45th CIRP Conf. on Manufacturing Systems 2012.

[16] D. Plorin, D. Jentsch, H. Hopf, E. Müller, Advanced Learning Factory (aLF)—method, implementation and evaluation, Procedia CIRP 32 (2015) 13–18, 5th Conf. on Learning Factories.

[17] R. Beregi, Design of a prototype production control system to the Smart Factory, Master's thesis, Department of Manufacturing Science and Engineering, Budapest University of Technology and Economics (2015).

[18] A. Szobonya, Optimizing the internal logistics of the Smart Factory pilot system, Bachelor's thesis, Department of Manufacturing Science and Engineering, Budapest University of Technology and Economics (2016).

[19] K. Abai, Complex expansion of a pilot production system, Bachelor's thesis, Department of Manufacturing Science and Engineering, Budapest University of Technology and Economics (2015).

[20] Á. Benke, UR5 industrial robot based solution of a packing problem, Bachelor's thesis, Department of Manufacturing Science and Engineering, Budapest University of Technology and Economics (2015).