Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 23 (2018) 105–110

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

8th Conference on Learning Factories 2018 - Advanced Engineering Education & Training for Manufacturing Innovation

Human–robot collaboration in the MTA SZTAKI learning factory facility at Győr

Zsolt Kemény[a]*, Richárd Beregi[a], János Nacsa[a], Csaba Kardos[a], Dániel Horváth[a]

[a]*Centre of Excellence in Production Informatics and Control at the Institute for Computer Science and Control, Hungarian Academy of Sciences, Kende u. 13–17, H-1111 Budapest, Hungary*

Abstract

In recent years, interest has grown in environments where humans and robots collaborate, complementing the strengths and advantages of humans and machines. Design, construction and adjustment of such environments, as well as the training of operating personnel, requires thorough understanding of the nature of human–robot collaboration which previous automation expertise does not necessarily provide. The learning factory currently being constructed by MTA SZTAKI in Győr aims to provide hands-on experience in the design and operation of facilities supporting human–robot collaboration, mainly in assembly tasks. The work-in-progress paper presents design principles, functionalities and structure of the facility, and outlines deployment plans in education, training, research and development in the academic and industrial sectors.

Peer-review under responsibility of the scientific committee of the 8th Conference on Learning Factories 2018 - Advanced Engineering Education & Training for Manufacturing Innovation.

Keywords: Human–robot collaboration; industrial production; assembly

1. Introduction and related work

Recent years have witnessed the appearance and maturing of technologies that allow humans and robots to work in the same space, and even simultaneously perform operations of the same task in a coordinated manner, mutually aware of each other's actions, intentions and plans. This allows the strengths and advantages of machines and humans

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

2351-9789
Peer-review under responsibility of the scientific committee of the 8th Conference on Learning Factories 2018 - Advanced Engineering Education & Training for Manufacturing Innovation.
10.1016/j.promfg.2018.04.001

to complement each other, which is of high practical value in tasks requiring capabilities that none of robots and humans would deliver alone [18, 19]. The practical feasibility of safe and efficient human–robot collaboration (HRC) has opened up new prospects in industrial manufacturing, promising advantages in production responsiveness, flexibility, and resilience [20]. Collaborative workstations introduce new aspects in layout design, lifting the strict separation of humans and robots in time and space. Several layout design approaches have been presented to date [20], and an amendment (ISO/TS 15066) proposed for robot safety standards (ISO 10218) puts forth modes of safe collaborative operation in a shared safeguarded area (safety-rated monitored stop, hand guiding, speed and separation monitoring, power and force limiting). In this regard, it is important to point out that ISO 10218 and ISO/TS 15066 already take an integrated approach with the compound of control, robot, end effector, workpiece and task being simultaneously subject to safety assessment in a collaborative setting. Mental, emotional and social aspects of HRC receive less representation in today's standards. ISO 10075 specifies that the mental stress on a human must be optimized within a preferred range, however, much of the emotional and teamwork-related dimensions (mutual awareness, situation awareness, team alignment, rewards, fairness) are still subject to research [12].

It is anticipated that the importance and penetration of HRC will undergo considerable growth and qualitative development in the coming years, and much of the promised success will depend on the readiness of shop-floor personnel and the engineering community for the adoption of the HRC paradigm. Much hands-on experience and room for risk-free experimenting are required to thoroughly explore aspects that were hitherto not represented in live industrial environments. Also—as it is typically the case with new and promising technologies—engineers and decision makers have to develop a sober judgement for introducing a collaborative solution vs. keeping to established patterns of purely manual or purely automated task execution. Learning factories with special focus on HRC and its integration in a wider industrial environment can play an important role in shaping the views and enhancing the knowledge of future—and already practicing—engineers, shop-floor personnel and decision makers [14]. Moreover, leaving an HRC-focused learning factory simultaneously open for experiments and knowledge exchange is also expected to help keeping R&D close to the industrial community.

One should also stress that HRC is only one among several recent trends that are predicted to change the character of industrial production [17]. Due to their impact, all of these developments likewise have their justified place in learning factories [15, 16], in fact, their clean separation may even contradict the evolving reality of the industry which students and employees are educated and trained for. Thus, it is reasonable to include increased process transparency, bi-directional interaction of virtual and physical resources, execution structures with local autonomy and intelligence, as well as advanced connectivity into the features of an HRC-oriented facility. This is all the more valid, as the aforementioned aspects—also attributed to Industry 4.0 / cyber-physical production systems (CPPS)—are often part of the very fundaments of HRC. (For further details regarding HRC, the reader is also referred to [22, 23, 27], while differences of the learning factory and the teaching factory paradigms can be obtained from [24, 25, 26].)

The in-progress paper presents a learning factory being constructed with the goal of bringing HRC, specifically in industrial assembly, closer to students and professionals. Built and operated by MTA SZTAKI at the premises of Széchenyi University in Győr, the facility is to start education in September 2018, and will, simultaneously, remain a laboratory open for demonstrations to industry and experiments advancing the state of the art of industrial production, robotics and automation. In further parts, the paper is organized as follows. Purpose and general design principles of the facility are presented in Section 2, key components and main system architecture outlines are presented in Section 3. Deployment plans—both in education and R&D—are outlined in Section 4, with concluding remarks in Section 5.

2. Purpose and design principles

2.1. Purpose of the facility

Providing hands-on experience for university students in HRC is among the key purposes of the facility, however, other groups and activities are targeted as well. Given the strong presence of the automotive industry in the vicinity of Győr, the site presents itself as an ideal location for technological demonstrations, knowledge transfer and training held for industrial representatives, as well as for R&D work, partly in response to industrial needs. Therefore, the learning factory is also intended to serve the industry and the research community, and is kept open regarding access and equipment to answer changing demands.

Many industrial operations can benefit from HRC, yet, a learning factory of limited size (in this case, 150 m^2 shop-floor and 75 m^2 lecture / office rooms) has to remain within a given focal range of the full spectrum. The site in Győr has selected industrial assembly as its main application context, where components and sub-assemblies remain within the dimension of up to a few ten centimeters, and their weight ranging up to a few kilograms. All components used in the courses are planned to be re-usable upon disassembly. The equipment of the learning factory is not dedicated to fixed assembly operations of specific workpieces (even though a palette of typical geometry-based task types is currently under elaboration), therefore, measurement, 3D imaging and prototyping capacities are also accommodated. Operations performed during education and training are not directly meant to create commercial value, even though services can be offered on a commercial basis at a later time. Since collaborative workstations can differ substantially from today's industrial practice, it is important that both students and professionals gain opportunities of direct comparison to conventional solutions serving similar purposes. In the facility at Győr, this is granted by its co-location with automation equipment representing the current industrial mainstream (see Figure 1 for a general layout).

2.2. Design principles

HRC is expected to deliver most benefits where adaptivity to new tasks and unforeseen situations is required, and collaborative workstations are likely to become highly reconfigurable in industrial deployment. Given the rapid development of the field, it is also difficult to predict how HRC and its deployment will develop in the coming years. Thus, *an HRC learning factory must be kept flexible enough to adapt to the evolving demands*. Moreover, *layout design* for HRC may substantially differ from conventional automation practice, due to the (partial) lifting of human–robot separation (see ISO/TS 15066). HRC-oriented layout design is, thus, a core topic for courses, and the *equipment has to be highly reconfigurable* regarding layout of major components, and assignment of tools, sensors and human–machine interface elements. Several tools have multiple gripping adapters and *serve humans and robots likewise*.

HRC is likely to prevail in assembly areas with high task and product diversity. This is best represented in *independently operating cells* connected by intra-logistics services, rather than processing stations planted along a conveyor system. *Supported collaboration patterns should be as diverse as possible* with regard to collaboration participants (human–robot and robot–robot collaboration must be equally possible), and their multiplicity.

Given the recent trends in industrial production, HRC workstations are expected to function in *an environment with high connectivity*, which is further amplified by the data-intensive nature of planning and executing certain collaborative operations in which relevant data cannot remain within a limited vicinity of the workstation.

3. Components and system architecture

3.1. Core equipment of the HRC-centered facility

Corresponding to the design principles outlined in the previous section, the facility has a number of independent workstations. Four of these are built around a central stand carrying a UR5 or UR10 collaborative manipulator. Their location is laid out so that each can be conveniently populated by operators and further equipment, and maneuvering space is left for AGVs serving the stations. A fifth support is available with a set of mounting pads at different angles for building a dual-arm workstation. The layout of each station can be freely configured using pre-fabricated frames with solid mounting surfaces (see Figure 1). The frames provide storage and mounting room for robot controllers, host computers and other equipment below the table surface. Working surfaces have no built-in compliance, and thus do not provide a fully collaborative environment—however, this trade-off allows reconfigurability in a lightweight, cost-efficient way. Since only the robots have built-in safety limits, the resultant safety of the entire station has to be assessed by a supervisor before a given station configuration goes live.

Intra-logistics is served by two AGVs, (in addition to material handling by human workforce). One of the AGVs is also equipped with a UR3 robot arm to facilitate loading / unloading operations at the workstations. Navigation of the AGVs is aided by on-board laser scanners, as well as an indoor positioning system.

A pool of end effectors and sensors is available for freely chosen assignment to robots and workstations. Currently, this includes several parallel-jaw grippers, a dexterous three-finger gripper, force / torque sensors, cameras (optionally in conjunction with laser pointers), 3D imaging devices (time-of-flight, structured-light, and triangulation scanners).

Some of the imaging devices, as well as additional tools, are suited for use by both humans and robots, and equipped with appropriate gripping adapters. Human–machine interfaces (HMI) play a key role in collaborative environments—also these are provided as components that can be relocated and combined as required. Worker identification and gesture recognition are served by cameras and 3D imaging sensors (primarily Kinect for whole-body gestures); microphones, headphones, keypads and screens are also available for coupling to a host computer assigned to the workstation. While hardware for HMI is already available, development and integration of HMI software components are still underway, and continuous refinement will extend into the operation span of the facility.

3.2. Communication, control and modeling

The communication infrastructure closely follows the workstation-oriented organizing structure of the facility. A given degree of autonomy and local computing capacity is present on several abstraction levels, reflecting increased local autonomy of the CPPS paradigm. Each station has a *field control level* built around one or more robot controllers—these handle peripherals further down the hierarchy, and connect to a local SCADA (supervisory control and data acquisition) node further up. The latter connects via TCP to a PC host—once software development is complete, this will accommodate a "cockpit" with complex presentation capabilities for advanced user interfaces (virtual reality, augmented reality including spatial manipulation by a human operator), and sufficient computing power for processing data-intensive inputs (e.g., 3D point clouds and camera images for gesture recognition). An industrial-grade switch is assigned to each workstation, and connection to a facility-level MES (manufacturing execution system, still under construction) and facility monitoring functionalities. A separate server room is available for hardware running the functionalities of the top hierarchical level, and maintaining connections to the world outside the facility boundaries. Still in progress is also the creation of models for the entire facility and its components. This is planned to follow the *digital twin* principle—the physical system and the model closely follow each other's changes in a bi-directional way, in several functionality layers.

3.3. Additional equipment and capacities

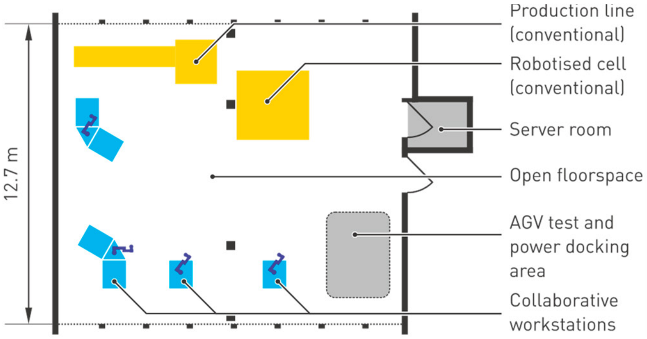
The HRC learning factory shares its space with conventional automation equipment, owned and operated by Széchenyi University. This consists of a production line performing assembly operations, a palletizing station with a tripod robot, and a conventional robotic cell with two 6-DOF industrial robots. This provides the opportunity of a side-by-side comparison of collaborative and non-collaborative solutions of similar assembly tasks.

The HRC learning factory is also augmented by office space where lectures or instruction sessions can be held to small groups, and product and cell layout design can take place using dedicated design suites. Procurement of product prototypes and new equipment components (e.g., end-effector adapters for dual-usage tools, mounting pads for sensors and appliances) is supported by an FDM (fused deposition modeling) 3D printer installed in the office room.

4. Planned deployment

Deployment of the facility will follow two major tracks, with cross-links of problem and knowledge sharing between them. After going live in September 2018, a longer period of refinement of the learning and knowledge transfer content is expected, therefore, the two tracks will be presented here in their current, conceptual form.

The *industrial track* embraces needs of the industry in problem solving, research, knowledge transfer and training. Here, problems or solution ideas are taken up from the industry and elaborated to a presentable solution or adoptable proof-of-concept within the premises of the HRC learning factory. Development efforts, hardware contribution, and benefits are shared with the industrial partner by contract. By assigning their own manpower to collaborate in the solution process, industrial partners can participate in an active transfer of relevant knowledge. If the contribution of new components is found beneficial for the facility, these can remain installed as part of the contractual reciprocation for the R&D efforts. With the HRC learning factory being open to any industrial client, this scheme is expected to ensure that (1) the problems solved and demonstrated to further audience represent real industrial needs, and (2) the diversity of contributors avoids that the facility becomes locked into an exclusive technological ecosystem and potentially falls behind the state of the art.



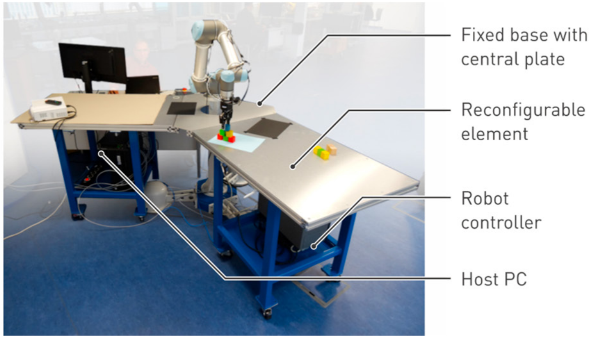


Fig. 1. Architectural scheme of the HRC learning factory (left), and workstation configuration example (right).

The *educational track* exploits the facility in the strict sense of a learning factory. Beginning with the fall semester of 2018, a comprehensive "narrative" spanning product design, process and workstation layout design, and process execution will gradually be assembled, centered around an HRC-related assembly problem where partial solutions can either be provided beforehand or left to be elaborated by groups of students in a modular manner. The distinct elements of the narrative will be: (1) product design with criteria and constraints, (2) procurement and separate feasibility tests of assembly operations on workpieces in a test environment especially built up for the workpiece, (3) workstation layout and process design using HRC where beneficial for the entire production, (4) ramp-up and production with HRC involved. The requirements of the given curriculum and targeted student group will determine which of these elements are elaborated by the students, and which are provided as-is. First runs are planned to be held for technical manager students, while later on, mechanical engineering students will be integrated into the same course, solving problems that suit their area of education.

The overall scenario can also be adapted for collaboration in a larger, cross-site scheme—in this regard, first plans have already been outlined with the learning factory sites operated by TU Wien.

Aside from the two major deployment tracks, the facility remains open for individual projects, one-shot sessions and research not directly connected to specific industrial problems, too.

5. Conclusion and outlook

The growing impact of human–robot collaboration (HRC) on industrial production is raising the demand for shaping the mindset of decision makers, engineers and shop-floor personnel for accepting and understanding the characteristics of HRC in its proper place and context. Existing practical experience in conventional automation is not always sufficient, implying a need for learning factories with special focus on HRC.

The learning factory currently being constructed by MTA SZTAKI in Győr aims to provide hands-on experience in the design and operation of facilities supporting HRC, mainly in assembly tasks. The work-in-progress paper presented key purposes, design principles, functionalities and structure of the workstation-oriented facility. A deployment roadmap was presented, composed of two main parts: an industrial track taking up real-life problems from the industry and returning solutions and knowledge transfer, and an educational track with the plan of a modular course in which problems can be selected for solution in accordance with curriculum requirements. Closer collaboration regarding course content and exchange is planned with the two learning factory sites operated at TU Wien.

Acknowledgements

Research in this paper has been supported by the GINOP-2.3.2-15-2016-00002 grant on an "Industry 4.0 research and innovation center of excellence", and by the European Commission through the H2020 project EPIC (https://www.centre-epic.eu/) under grant No. 739592.

References

[1] L. Bochmann, T. Bänziger, A. Kunz, K. Wegener, Human–robot Collaboration in Decentralized Manufacturing Systems: An Approach for Simulation-based Evaluation of Future Intelligent Production, Procedia CIRP, 62 (2017), 624–629

[2] A. Cherubini, R. Passama, A. Crosnier, A. Lasnier, P. Fraisse, Collaborative manufacturing with physical human–robot interaction, Robotics and Computer-Integrated Manufacturing, 40 (2016), 1–13

[3] V. Gopinath, F. Ore, K. Johansen, Safe Assembly Cell Layout through Risk Assessment—An Application with Hand Guided Industrial Robot, Procedia CIRP, 63 (2017), 430–435

[4] E. Matsas, G.-C. Vosniakos, Design of a virtual reality training system for human–robot collaboration in manufacturing tasks, International Journal on Interactive Design and Manufacturing, 11(2) (2017), 139–153.

[5] X. V. Wang, Zs. Kemény, J. Váncza, L. Wang, Human–robot collaborative assembly in cyber-physical production: Classification framework and implementation, CIRP Annals, 66(1) (2017), 5–8.

[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.

[7] M. Brettel, N. Friederichsen, M. Keller, M. Rosenberg, How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective, International Journal of Mechanical, Industrial Science and Engineering, 8(1) (2014), 37–44.

[8] K. F. Seitz, P. Nyhuis, Cyber-physical production systems combined with logistic models—a learning factory concept for an improved production planning and control, Procedia CIRP, 32 (2015), 92–97.

[9] Zs. Kemény, J. Nacsa, G. Erdős, R. Glawar, W. Sihn, L. Monostori, E. Ilie-Zudor, Complementary research and education opportunities—a comparison of learning factory facilities and methodologies at TU Wien and MTA SZTAKI. Procedia CIRP, 54 (2016), 47–52.

[10] F. Ranz, V. Hummel, W. Sihn, Capability-based Task Allocation in Human–Robot Collaboration, Procedia Manuf., 9 (2017), 182–189.

[11] A. Jäger, W. Mayrhofer, P. Kuhlang, K. Matyas, W. Sihn, TU Wien Learning & Innovation Factory for integrative production education, in: V. Hummel (Ed.), The Learning Factory—An Annual Edition from the Network of Innovative Learning Factories, ESB Business School, Reutlingen Univesity; Next Level Interactive UG, Frankfurt am Main, (2015), 14–25.

[12] A. Aly, S. Griffiths, F. Stramandinoli, Metrics and benchmarks in human–robot interaction: Recent advances in cognitive robotics, Cognitive Systems Research, Volume 43 (2017), 313–323.

[13] S. Sütő, Z. Forgó, F. Tolvaly-Roşca, Simulation Based Human-robot Co-working, Procedia Engineering, Volume 181 (2017), 503–508.

[14] E. Abele, J. Metternich, M. Tisch, G. Chryssolouris, W. Sihn, H. ElMaraghy, V. Hummel, F. Ranz, Learning Factories for Research, Education, and Training, Procedia CIRP, Volume 32 (2015), 1–6.

[15] M. Dinkelmann, P. Riffelmacher, E. Westkämper, Training concept and structure of the Learning Factory advanced Industrial Engineering, In: Enabling Manufacturing Competitiveness and Economic Sustainability: Proceedings of the 4th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2011), ElMaraghy, H. (eds.), Montreal, 624–629, 2011.

[16] U. Wagner, T. AlGeddawy, H. ElMaraghy, E. Müller, The State-of-the-Art and Prospects of Learning Factories, Procedia CIRP 2012, 3:109–114.

[17] B. Tether, A. Mina, D. Consoli, D. Gagliardi, A Literature Review on Skills and Innovation. How Does Successful Innovation Impact on the Demand for Skills and How Do Skills Drive Innovation? A CRIC Report for The Department of Trade and Industry (2005).

[18] C. Thomas, B. Matthias, B. Kuhlenkötter, Human–Robot Collaboration—New Applications in Industrial Robotics, Proc. of the International Conference on Competitive Manufacturing (COMA), Stellenbosch, 293–299. 2016.

[19] G. Charalambous, S. Fletcher, P. Webb, Identifying the key organisational human factors for introducing human–robot collaboration in industry: an exploratory study. The International Journal of Advanced Manufacturing Technology Vol. 81, no. 9–12 (2015), 2143–2155.

[20] A. Cherubini, R. Passama, A. Crosnier, A. Lasnier, P. Fraisse, Collaborative manufacturing with physical human–robot interaction, Robotics and Computer-Integrated Manufacturing 40 (2016), 1–13.

[21] M. Hermann, T. Pentek, B. Otto, Design principles for Industrie 4.0 scenarios, Proc. of the 49th Hawaii International Conference on System Sciences (HICSS), 2016, 3928–3937.

[22] G. Michalos, S. Makris, P. Tsarouchi, T. Guasch, D. Kontovrakis, G. Chryssolouris, Design considerations for safe human–robot collaborative workplaces, Procedia CIRP, 4th CIRP Global Web Conference—Understanding the life cycle implications of manufacturing, Volume 37 (2015), 248–253.

[23] P. Tsarouchi, J. Spiliotopoulos, G. Michalos, S. Koukas, A. Athanasatos, S. Makris, G. Chryssolouris, A Decision Making Framework for Human Robot Collaborative Workplace Generation, Procedia CIRP, 6th CIRP Conference on Assembly Technologies and Systems (CATS), Volume 44 (2016), 228–232.

[24] L. Rentzos, M. Doukas, D. Mavrikios, D. Mourtzis, G. Chryssolouris, Integrating Manufacturing Education with Industrial Practice using Teaching Factory Paradigm: A Construction Equipment Application, (CMS 2014), Procedia CIRP, 47th CIRP Conference on Manufacturing

[25] L. Rentzos, D. Mavrikios, G. Chryssolouris, A Two-way Knowledge Interaction in Manufacturing Education: The Teaching Factory, Procedia CIRP, 5th Conference on Learning Factories, 7–8 July, Bochum, Germany, Volume 32 (2015), 31–35

[26] G. Chryssolouris, D. Mavrikios, L. Rentzos, The Teaching Factory: A Manufacturing Education Paradigm, 49th CIRP Conference on Manufacturing Systems, 25–27 May, Stuttgart, Germany Volume 57 (2016), 44–48.

[27] S. Makris, P. Karagiannis, S. Koukas, A. S. Matthaiakis, Augmented reality system for operator support in human–robot collaborative assembly, CIRP Annals—Manufacturing Technology, Volume 65, Issue 1 (2016), 61–64.