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Recent advances in learning content and infrastructure development for layout and process planning courses at the SZTAKI learning factories

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Abstract

Two locations maintained by SZTAKI—in Budapest and Győr, respectively—provide infrastructure for learning factory programs, primarily in layout and process planning, and process execution. In addition to project-oriented work successfully hosted by the facilities for several years, the development of repeatable and evolvable learning content began in 2019. A preceding publication presented a roadmap for the development of re-usable courses based on outcomes of one-shot projects which built up an initial infrastructure. This paper gives an in-progress view at selected dimensions of learning content and course development. In view of recent additions to available infrastructure, an extended portfolio of design and scenario choices is presented with suggested sets of options which can be opened up for elaboration by course participants. Complementing these, typical course types are also summarized, with special emphasis on options likely to be deployed in the current operating context of the facilities.

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Keywords: Human–robot collaboration; layout planning; process planning; course development

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1. Introduction

Human–robot collaborative assembly has earned growing attention in the research community and the manufacturing industry due to its potential of combining the strengths of both humans and machines [1]. Nevertheless, human–robot collaboration is predicted to keep evolving over a longer period of time along with the surrounding context of cyber-physical production systems (CPPS) [1,2], and future automation engineers will likely have to pave their own way in currently uncharted domains. In this regard, the ability of learning factories to combine theory with hands-on experience and exploration can play a key role in shaping the mindset of the decision makers, engineers and shop-floor personnel of the coming generation [2,4,5].

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In the past years, the learning factory facilities maintained by SZTAKI [6] have hosted several research, development and education activities, including project work by university students, with human–robot collaboration being among the focal topics. One of the recent individual projects—dealing with collaborative assembly—comprised enough process complexity and configurability to serve as a basis for development of repeatable courses. Preparation of supporting infrastructure and didactic content for courses began in early 2019, and a previous publication proposed a roadmap tailored to the co-dependence of courses and stand-alone projects [6]. This paper gives an in-progress view at the continued development of re-usable infrastructure and didactic content which is planned to have its first open debut within a summer school program scheduled for mid-2020, in collaboration with the Pilot Factory in Vienna maintained by Fraunhofer Austria and TU Wien. In further parts, the paper is organized as follows: Section 2 summarizes infrastructure development, Section 3 presents the targeted tracks of content elaboration, and Section 4 recapitulates refinements of the previously proposed roadmap [6] in view of recent findings. Finally, Section 5 summarizes the current state of course elaboration and highlights upcoming actions.

2. Development of infrastructure and related scenarios

The original assembly station presented in the preceding paper [6] was an outcome of a stand-alone project, and the design choices of the solution were merely meant to efficiently respond to given requirements, without the need of exploring an entire decision space, as would be needed for a hands-on course. Therefore, much effort must be spent on developing building blocks that (1) transform the majority of sub-problems into the abstraction levels represented in the scope of the courses, (2) extend the decision space in the desired abstraction level with alternatives, and (3) allow the comparison and storage of specific choices in a repository of "known good" solutions. In the didactic portfolio targeted by the assembly narrative, layout configurations, sequencing of assembly steps (including synthesis from motion primitives), and allocation of robots/humans to an operation form the main decision dimensions. To this end, the following elements are being elaborated as solution building blocks that can be combined, modified and re-used:

Physical components of the work environment include fixtures; templates for structured component delivery; tool/workpiece adapters for robots and humans (often specific to the task execution); quality control templates; auxiliary components for sensing and task/workpiece identification. Most of these components are exposed to limited mechanical stress and fit well within a 0.1–1 mm tolerance range—therefore, they are implemented as 3D printed parts. Their redesign and repeated procurement can be solved on-site with reasonable effort, therefore, their modification can be opened up as a possible decision dimension if needed by the preferences of the given course instance.

Motion primitives are quickly learned by humans, but their robotic counterparts often require substantial planning and fine-tuning. Systematic approaches do exist [7], although most are dealing with dexterous grasp planning. In this course portfolio, primitives and task allocation choices are elaborated along a simplified classification: (1) simple grasps of rigid workpieces (with special gripper adapter if needed) that can be executed by humans and robots likewise, (2) grasps of rigid pieces requiring grip change (with intermediate placement adapters if needed) with human and robot execution options, and (3) gripping of elastic workpieces preferably performed by humans. The elaboration of motion primitives delivers a suggestion for robot vs. human task allocation alternatives as a by-product that can directly feed into the elaboration of course content (see also Ranz et al. [8] for related considerations).

Process primitives and precedence relations are less diverse in the selected scenario. Nevertheless, alternatives can be opened up by allowing relocation of operations to various production resources, and introducing variation via batch processing and intermediate buffer capacities. These become more pronounced when the preparation of structured delivery is added—this is a sensible extension of the original scope according to findings presented in Section 4. Moreover, the assembly scenario is complex enough to demonstrate advances in (semi-)automatic assembly planning which are likely to become part of everyday design tools in future manufacturing [9].

Digital twins and calibration aids form an important part of the infrastructure due to the cyber-physical aspect of the selected scope. The creation of all infrastructural components goes hand-in hand with a virtual counterpart, allowing hands-on experience in principles that make solution elaboration in CPPS efficient. This will also facilitate an objective comparison of decisions made by different participant teams, which is of key importance if common conclusions are to be found by independently working teams. Solutions and elements elaborated in the virtual model can be transformed into executable robot commands upon calibrating the model with the physical scene—recent advances provide efficient means for this step as well.

3. Evolution of a didactic portfolio

Audience targeted by the SZTAKI learning factories include higher education students, industrial employees, and the general public. While the latter is well-served by a short demonstration, comprehensive content has to be tailored to the needs of the former two groups, in relation to knowledge being acquired and skills being put to use.

Students in higher education receive much theoretical knowledge, but the actual motivations behind a given approach, and their application with "engineering common sense" often remains obscured. This is often overlooked in higher education, and the difficult acceptance of learning factory courses by universities indicates reluctance to address the problem. Therefore, development of didactic content for higher education will follow a "bottom-up" approach: courses retain close ties to previously acquired knowledge but will present practical appeal even outside recognized curricula. This is expected to add more of a practical dimension to the knowledge and mindset of future engineers [10], and recognition by students will likely urge the addition of learning factory courses into higher education. An initial step on the "academic track" [11] of content development is a summer school program in collaboration with the Pilot Factory site in Vienna, operated by Fraunhofer Austria and TU Wien [12,13,14], planned to take place in July 2020. Focusing on various aspects of human–robot collaborative assembly, the course remains within the volume of a summer school, while still giving insight into the focal points to be addressed for a successful university course. Development of didactic content for university courses is planned to integrate feedback from the summer school, under consideration of related findings and methodologies from other learning factories [10,15,16].

Unlike theory-heavy higher education, the opposite bias prevails in the industry: focused on daily survival, engineers often remain within inherited routine. In this case, a key responsibility of learning factories is to place the meaning and impact of theoretical backgrounds and new research results into a more practicable context [17,18]. Programs for industrial employees also tie into a wider "industrial track" [11] enabling combination of training with risk-free piloting of new technologies in a *maker space* way [19]. The industrial use of the facility thus adds a further dimension—namely, piloting—to the learning factory character. A major strength of learning factories is the combination of theory with hands-on experience. While theory and practice can be understood as separate dimensions in the didactic content, it is important to stress their meaningful *synthesis* (see Figure 1), having the potential of combining the usually disjoint domains of higher education and industrial training. While moving course content towards synthesis, sharing the facility and course scenarios also offer the opportunity of bringing industrial employees, future engineers and researchers together to form a common understanding of a domain strongly evolving for decades to come [2,20].

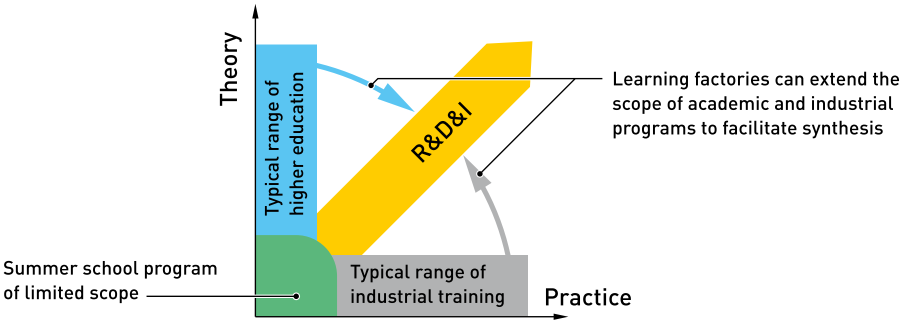

Fig. 1. Relation of targeted learning factory course types to theory and practice.

4. Status of initial roadmap and progress

Previously, a roadmap was proposed for building up repeatable courses with re-usable and evolvable didactic content and infrastructure [6]. As a starting point, the outcome of an individual student project was selected. Such project work has become an established part of the operation of the SZTAKI learning factory facilities, and several of their topics present complexity, evolution potential and relation to focal fields of industrial production to make them suitable as a basis for repeatable courses. The comprises 4 stages, i.e., (1) initial project, (2) assessment of initial project, (3) redesign and implementation, and (4) deployment and evaluation. In the current state of development, phases 1 and 2 have been completed, and phase 3 is approaching completion. Up to this point, the major structure of the roadmap has been confirmed as feasible, however, findings of ongoing implementation suggest some refinement.

The elapsed phases of course development revealed a strong link between advances in the core scenario and elaboration of the infrastructure: scenario choices—including the degrees of freedom open for course participants' decisions—determine the necessary infrastructure to be developed, and findings of the latter process can effect revision of the underlying narrative. The bi-directional nature of the relation between specification and implementation was found to be substantial, resulting in several iterations of the corresponding stages of the course elaboration roadmap.

4.1. Tailoring of diversity to the needs of the didactic portfolio

The individual project serving as a basis for course development dealt with a workstation for assembly of several product classes (ball valves, pneumatic cylinders, and push-buttons), using the same reconfigurable fixture, and kitting pallets following the same delivery and grip assistance principles. Initially, it appeared straightforward that all product classes could be supported by the redesign, and offered as course alternatives. During phase 3 of the roadmap, however, it became clear that continued support for all product classes requires much of the development to run in parallel tracks, with a substantial part of building blocks not being adaptable or exchangeable across product classes. This makes a direct view at cross-product correspondence difficult, with little didactic value (e.g., in a product change scenario).

Enriching the portfolio of choices for a single product class, on the other hand, has a more positive impact, as it frees up development resources for better elaboration of the infrastructure and processes surrounding the assembly of the selected product. With processes connecting to the focal assembly scenario being integrated into the course content, students will experience more of the manufacturing context of their selection of assembly processes (see also Athinarayanan et al. [5] for a wider environment). For these reasons, the product portfolio subject to the course was narrowed down to ball valves (still in 3 different sizes), and instead of elaborating layout and process planning alternatives for assembly only, a connecting group of operations (picking/kitting for structured delivery) was added to the content.

4.2. Integration of parallel outcomes

The SZTAKI facilities host student projects, pilot and demonstration development, and research in parallel. Many of the simultaneous activities rely on common scenarios so that other branches of research and development can contribute with meaningful outcomes to the core scenarios of prospective courses. During the third phase of the course development roadmap, two types of additional outcomes were deemed worthy of integration.

A parallel activity *directly related to the selected scenario* was the development of "passive fixtures" for assembly. The motivation behind this were energy efficiency considerations (the original universal fixture used solenoids with power consumption and thermal issues), and recurring mechanical problems that limited the availability of the initial actuated design. While each passive fixture set serves one given subtype within the product class only, easy prototyping and standardized placement in the assembly scene not only compensate for the loss of quick reconfigurability, but can also open up a further dimension in decision space for a repeatable course (i.e., students themselves can easily procure and test a fixture of their own design). Since this track of development is directly focusing on the assembly of the selected product class, its adoption for the prospective didactic portfolio requires little additional work.

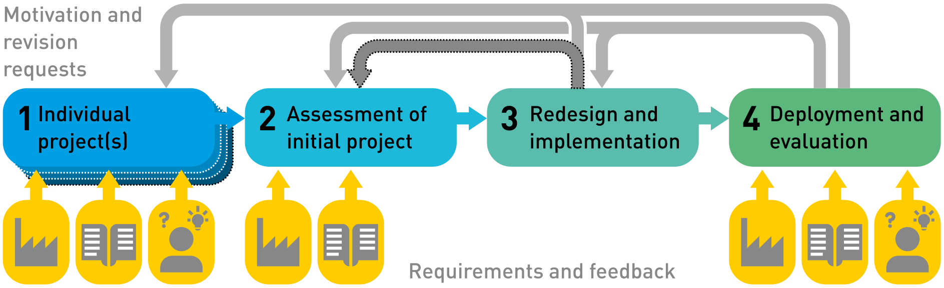

Fig. 2. Modifications to the course development roadmap proposed earlier [6].

Some other tracks of research and development are *not directly connected to the focal course scenario*, but with proper adaptation, they can be meaningfully integrated into the didactic portfolio. One of these examples is a camera-guided bin-picking solution, combining pre-calculation of stable workpiece poses, machine vision, and micro-planning of gripping operations and their sequences. In this scenario, workpieces are picked up from a vibrating table by a robot, and are placed on structured delivery pallets in prescribed poses, allowing—in critical cases, even requiring—a human operator to join in and perform a part of the picking process. While originally designed for other workpieces, the setup can be adapted to selected components of the ball valve, and form a core part of the picking and kitting operations complementing the assembly scenario of the course. In this case, adaptation requires additional attention, and partial redesign may be necessary during the harmonization procedure.

4.3. Refinement of the course development roadmap

In view of the above additions, it proved reasonable to refine the roadmap, especially in phases 2 and 3. Experience regarding development efforts in phase 3 may suggest a reformulation of decision space priorities, requiring a partial reiteration of phase 2. The iterative revision of the scenario will then serve as an evolving common ground for the course portfolio. Also, integration of other outcomes should be cared for. This can be viewed as a confluence of additional one-shot projects with their corresponding iteration of phase 2, feeding into their dedicated development tracks in phase 3. Leaning on the original roadmap scheme [6], Figure 2 shows the roadmap revisions suggested by recent findings—changes are highlighted with dotted lines.

Assessment of didactic content from the perspective of course participants has, understandably, not yet taken place—the first instance of such evaluation is yet to be carried out in phase 4 of the roadmap. Preliminaries, however, do exist. In addition to methodologies already used in other areas [16], structuring of feedback can rely on experience from the existing practice of evaluation forms (as of now, on a voluntary basis) which are already part of lab exercises hosted by the facility in Budapest. With several years of exercise experience already at hand, course assessment will focus on aspects found relevant by students in previous years. Also, it should be noted that development of course content is, to a considerable part, carried out by former participants of lab exercises and individual student projects—their impressions and findings are, in an informal way, already channelled into the development of the initial course content. It is yet to be investigated how much this can apply to comparable course development activities at other institutions using different application narratives and didactic targets. Therefore, pre-existing experience of course development staff has not yet been formally integrated into the roadmap.

5. Conclusion and outlook

The paper presented an in-progress view of course elaboration for layout and process planning topics in the context of human–robot collaborative assembly. A preceding publication summarized the one-shot project serving as a basis for course development and proposed a roadmap of actions in distinct elaboration stages—the current paper reports on recent outcomes of the ongoing process, including infrastructure development, the envisaged didactic and deployment portfolio, and refinements of the roadmap suggested earlier. Based on infrastructure development findings, the diversity of assembly scenarios was tailored to more options of a single product class, and the results of another independent project were selected to be adapted to the core assembly scenario, enriching it by picking and kitting steps. While didactic content is still at a conceptual level, current action plans foresee the inclusion of both "academic" and "industrial" tracks of the learning factories with the possibility of synthesis across targeted audience groups. For 2020, a summer school program is planned whose findings will be integrated into further course content development. Progress with course content has retained its concrete-to-general path, and is planned to remain on this track: elaboration and refinement of both content and methodology will have to remain within the domain of the core scenario. Examination of applicability to other domains will only be considered once sufficient experience is gained with the original collaborative assembly scenario.

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