Safe Human-Machine Centered Design of an Assembly Station in a Learning Factory Environment

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Abstract

Learning factories allow both, students and professionals, to learn new approaches in production technology in practice. The transition from manual assembly to hybrid assembly towards an almost fully automated assembly can be arranged in learning factories in a practical way. Hybrid assembly specially shows a lot of potential, as it is designed to be adopted in situations with an increasing number of variants or customized products as well as the need for a scalable production system. In the modern view of the fourth industrial revolution (Industry 4.0) in hybrid assembly systems, machines or robots are operating hand in hand with the human worker. This paper provides an approach to human-machine centered design of assembly systems and describes their implementation on a case study in the mini-factory laboratory of the Free University of Bolzano. The paper describes a case study, where a previously only manually produced product is produced in a hybrid assembly system in combination with a lightweight robot. As part of the man-machine interaction this work analyses risks for the safety of the human worker and provides appropriate measures. The work finally concludes with a summary and an outlook for the future.

Keywords
Human-machine interaction, safety, assembly systems, learning factory, small and medium sized enterprises

1. Introduction

Over the past few years, more and more learning factory laboratories were established in universities to promote practical teaching, that supports a direct transfer of know-how from research into industrial practice. The development of Industry 4.0 will be accompanied by changing tasks and demands for the human in the factory. As the most flexible entity in cyber-physical production systems, workers will be faced with a large variety of jobs ranging from specification and monitoring to verification of production strategies, while machines assist them. The Industry 4.0 paradigm, does not only affect M2M (machine to machine) communication, but will also have far-reaching consequences for the interplay of humans and technology. In the factory of the future, people should be integrated into the cyber-physical structure in such a way that their individual skills and talents can be fully realized (Gorecky et al. 2014). Learning factories provide a wide range of possibilities to develop such new methods and innovative technical solutions in a risk-free and close-to-reality factory environment. Examples for such Industry 4.0 technologies for a cyber-physical production system (CPPS) are decentralized planning, control and monitoring methods and systems, human-machine-collaboration as well as technical assistance systems for changeable production systems (Schuhmacher and Hummel 2016). In addition, learning factories allow studying benefits from the use of highly flexible and intelligent micro production units and/or distributed manufacturing systems with new and innovative business model concepts (Rauch et al. 2016).

With the latest trends towards Industry 4.0, many learning factories have aligned their structures in order to demonstrate in their labs applications for new and emerging Industry 4.0 technologies to students as well as specialists from industry in a practical way. The research group IEA (Industrial Engineering and Automation) of the Free University of Bolzano established in 2012 a learning factory titled “mini-factory” with a special focus on lean production and flexible as well as changeable manufacturing and assembly systems for small and medium sized enterprises (SMEs). This research is part of an international research project titled “SME 4.0 – Industry 4.0 for SMEs” with the aim to develop Industry 4.0 solutions for SMEs. Those concepts will then be implemented in the laboratory, named now "smart mini-factory", in order to become a user center of Industry 4.0 for SMEs. It will allow students and SMEs to get to know cyber-physical production systems (CPPS) in a laboratory environment.

This paper first describes the actual situation and infrastructure of the mini-factory laboratory at the Free University of Bolzano and gives an outlook to the planned enlargement of the learning factory. An actual case study of lean and manual assembly explains how the learning factory was used to support teaching. In section 3, the authors describe the integration of a hybrid assembly station for human-robot collaboration in the case study. One specific focus is given to save human-machine interaction using a UR3 lightweight robot and executing a risk analysis for a save integration in the hybrid assembly station. Finally, the paper ends with an outlook for future research and a thorough conclusion.

2. Actual situation in the mini-factory laboratory

2.1 Structure of the mini-factory laboratory

The basic equipment of the mini-factory lab (see Figure 1) includes devices for manual as well as for hybrid or automated assembly.

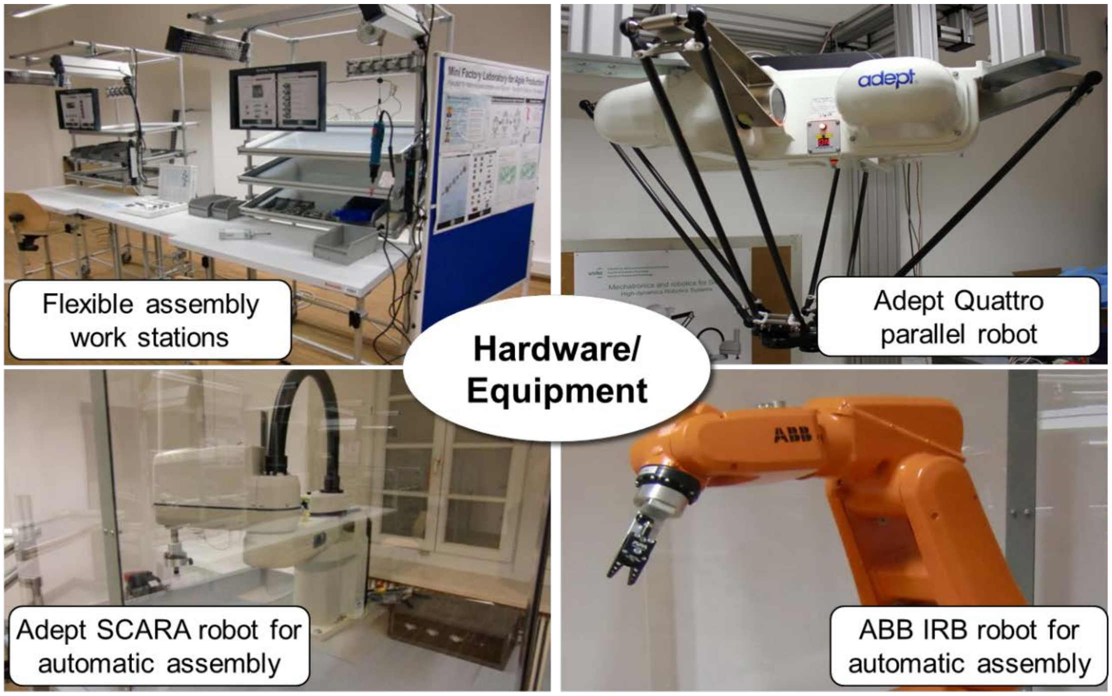

Figure 1. Mini-factory-laboratory – basic hardware equipment and software tools for industrial assembly

In the lab, several manual workstations from Bosch Rexroth are used for industrial small parts assembly. The tables are equipped with modern electric screwdriver systems and grab containers of different sizes. The manual workstations are in part in the Eco-Shape version of Bosch Rexroth – a highly flexible plug-in system of tubular standard frames. Other elements of this mini-factory are lean Kanban flow racks for the application of material commission using the

Kanban concept. Next to a manual assembly, also automated assembly processes can be demonstrated in the lab. The actual automation and mechatronics equipment consists of an Adept SCARA robot (i600 Cobra) for pick -and-place operations, a 6-axis ABB industrial robot (IRB 120) for manufacturing, handling, assembly and packaging jobs, a parallel robot from Adept (Quattro) for packaging jobs and a new lightweight robot from Universal Robots (UR3). To allow also flexible bin picking or picking of sensible products like fruits the robots can be equipped with flexible grippers from Festo and Robotiq. In addition, an easy-to-use, standalone vision-guidance-systems (Adept Sight) and a small parts feeder (Adept Flexbowl) allow picking and handling loose parts in an automated way.

The laboratory is equipped also with several software systems for Virtual Production (see Fig. 2). Manual assembly systems can be created, configured according to the situation and flexibly be arranged by module libraries using MTpro, a planning tool of Bosch Rexroth. RobotStudio from ABB as well as V+ from Adept are used for offline-programming of automated processes. The simulation software FlexSim, which allows a three-dimensional visualization and virtual reality immersion using an Oculus Rift VR head-mounted display system and enables material flow analysis, queuing analysis and bottleneck analysis.

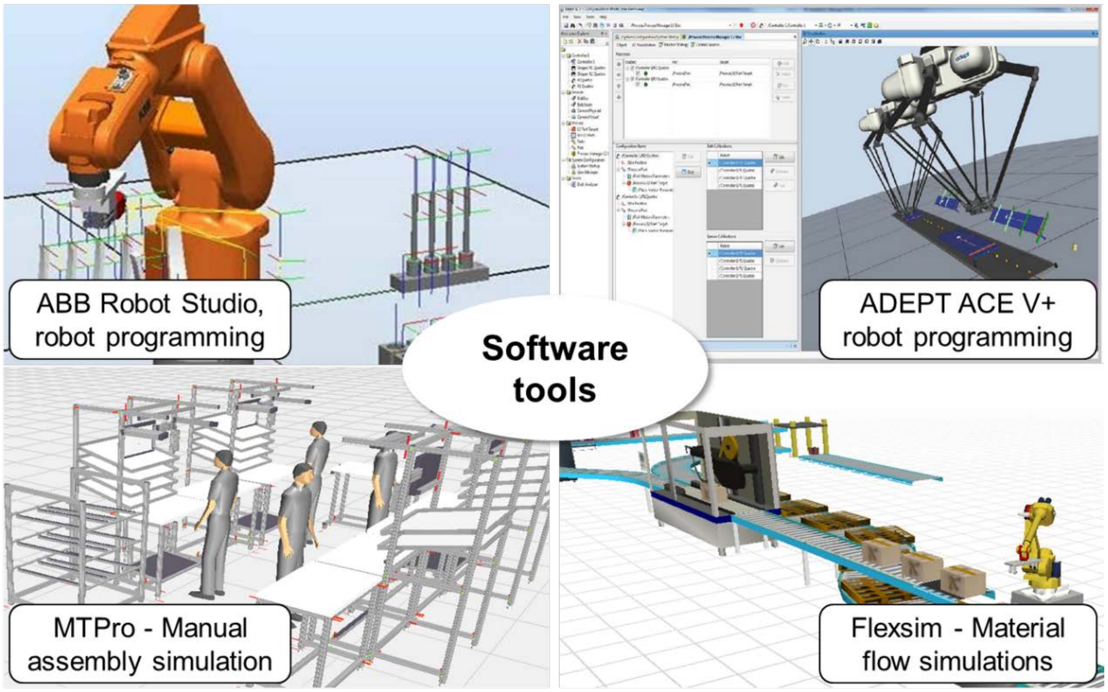

Figure 2. Mini-factory-laboratory – basic hardware equipment and software tools for industrial assembly

2.2. Current case study with manual assembly

The mini-factory is used in different lectures for exercises and practical demonstrations. In one of these, the mini-factory is used to simulate a manual production process for the assembly of pneumatic cylinders. Groups of students have to plan, design and implement a flexible manual assembly system according to lean principles, which is able to produce different product variants. Thus, the aim is to encourage the students to build their assembly system as flexible as possible. In several simulation rounds, the students have to analyze different concepts (object-oriented and process-oriented assembly) and to measure/evaluate cycle times, lead times, inventories with the aim to optimize the assembly line. Effects of the learning curve by an increasing repetition frequency of assembly tasks is checked by means of time measurement. Through the method of video analysis, students train to analyze single assembly tasks and to optimize the distribution of work content, minimizing waiting times on each assembly station and setting the entire cycle time to a minimum (Matt et al. 2014). Figure 3 shows some pictures of the training with students.

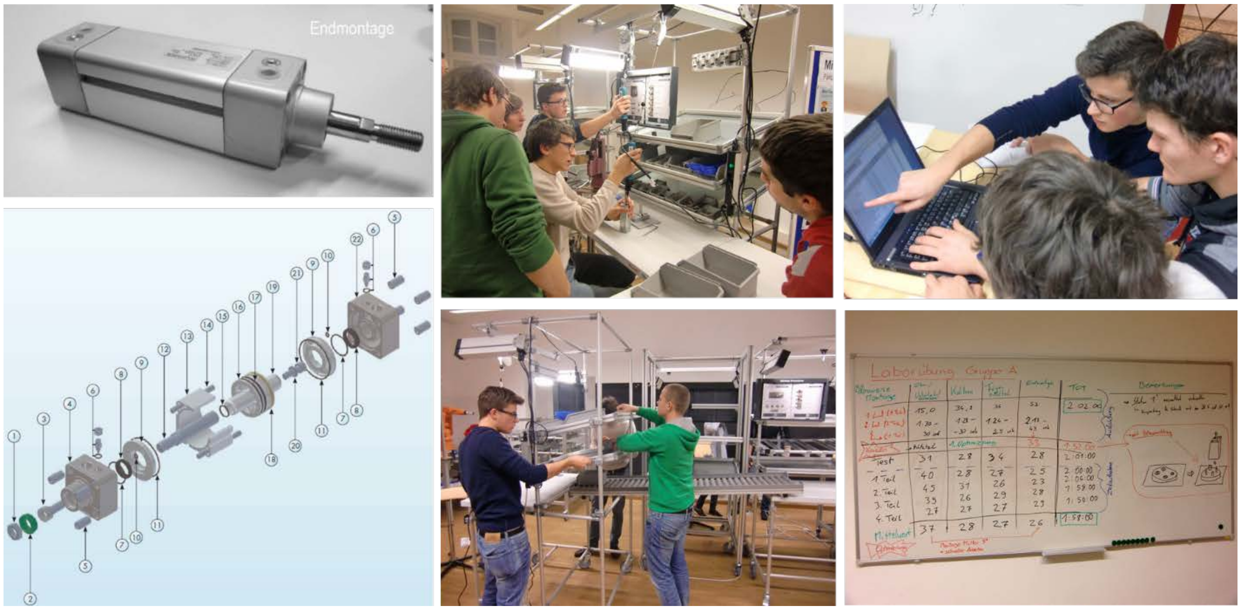

Figure 3. Case study with students: design and optimization of a manual assembly line for pneumatic cylinders

3. Integration of a hybrid assembly station for human-robot collaboration

In the future, the current case study will be extended by a human-machine interaction application. For this purpose, a hybrid workstation was developed, on which employee and robot work almost "hand in hand" and assemble a lot of two pneumatic cylinders. In the following, the integration of a UR3 lightweight robot with its safety functions as well as the developed hybrid assembly station is described. Further, a risk analysis was carried out for the assembly station to analyze and minimize any safety risk for the worker.

3.1. Integration of the lightweight robot Universal Robot UR3

The UR3 is the smaller robot produced by Universal Robots. It is designed for both, assembly and workbench tasks, where the payload does not exceeds 3 kg. It is a 6-axis anthropomorphic robot. Its workspace is almost spherical with a radius of 500mm. The robot is controlled by a Mini-ITX PC with a Linux system installed which runs, as a daemon, the low-level robot controller called URControl. A visual interface is available through a touch screen pendant, providing a Graphic User Interface (GUI) called PolyScope.

The most interesting feature of the UR3 for hybrid assembly is that its design is oriented for safe physical human-robot interaction (pHRI). It was designed according to the standards ISO 10218 and ISO/TS 15066. The first standard, deals with hazards that traditional industrial robots may pose. The second, is a Technical Specification for operation of collaborative robots where a person and the robot share the same workspace. In fact, the UR3 robot has an ergonomic and lightweight design, and its control system makes it a so called "force limited robot", thanks to its build-in capability of collision identification and reaction as well as limitation of dynamical features. The user can configure thresholds for the dynamical properties of the robot and geometric boundaries that, once approached, trigger different handling procedures, as a protective stop to minimize the possibility of injuries. Those thresholds may be configured at four levels. At a general dynamic level, it is possible to set the maximum mechanical power exerted by the robot to the environment (considering the payload as part of the robot), and the maximum generalized momentum of the robot arm. At the level of the dynamics of the end-effector, one can set the norm of its maximum linear speed and the force that it exerts on the environment. At the level of the joints, their maximum speeds and position range may be restricted. Finally, at a geometric level, safety planes and limits on the orientation may be set to the end-effector pose. By default, the robot comes with four levels of safety, which limit four features of the Tool Central Position (TCP) as shown in Table 1 (UR 2015).

Also, be default, the joints velocities are limited to 100 °/s for the shoulder joint and 191 °/s for the other joints, and the positioning of the joint is not limited. The user, including the limits for each safety modality, may modify all these features. However, the modification of the safety configuration requires turning off the robot. To make possible to switch between safety configurations dynamically, to each safety modality it is possible to associate a "reduced mode", which consists in a more restrictive set of constrains for the TCP, which can be switched during the operation of the robot.

Table 1. Safety levels of UR3 lightweight robot (UR 2015)

	Very Restricted	Restricted	Default	Least Restricted
Force	100 N	120 N	150 N	250 N
Power	80 W	200 W	300 W	1000 W
Velocity	0.25 m/s	0.75 m/s	1.5 m/s	5.0 m/s
Momentum	5.0 kg m/s	10.0 kg m/s	25.0 kg m/s	100.0 kg m/s

3.2. Development of a human-machine centered hybrid assembly station

Based on an analysis of assembly activities and cycle times to assemble one of the used pneumatic cylinders in the case study, the assembly activities were divided into manual and automated activities. While the employee is carrying out the pre-assembly and control activities on a rotating table, the robot finalizes the assembly of the pneumatic cylinder by screwing the components together. The rotating table supports an efficient manual and lean assembly, which makes it easier for the employee to prepare the components of the pneumatic cylinder. By means of a workpiece holder on each side of the rotating table the single components can be handled and assembled ergonomically. A lock-function is integrated and has to be deactivated after each assembly step of the cylinder, pushing the cylinder slightly one step down in order to ensure to the worker an ergonomic assembly in the next assembly step at height of the table. Figure 4 shows the developed hybrid assembly station and the used collaborative robot. After the end of the manual preparation a pre-assembly of the single components, the UR3 lightweight robot carries out the final screwing.

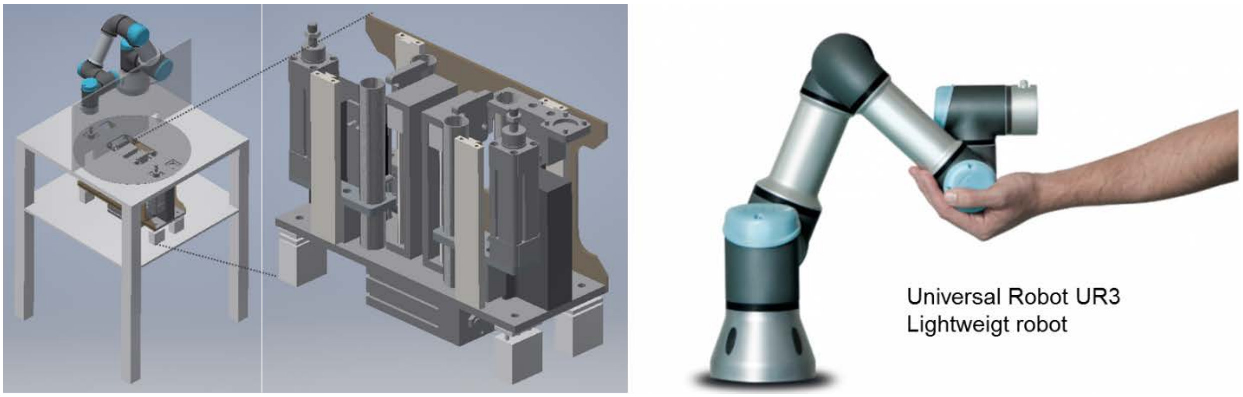

Figure 4. Human-robot interaction in the new developed hybrid assembly station

3.3. Risk analysis for safe human-robot interaction

The UR3 has several certifications that assures the robot as a "force limited robot" (UR 2015). This last term comes from the ISO-10218-1 norm, which defines four types of collaborative applications for robots, and one of them is the so-called "Power and Force Limiting". In these applications, the potential forces exchanges and collisions between the robot and humans are limited through the design of the robot system. However, it is important to note that it is not possible to design inherently safe robots. This is because every application has its particular features. A force limited robot arm may be still dangerous if its application is not correctly designed. By this reason, a risk assessment is always needed before starting a collaborative application. Operating the robot in the default safety configuration with a reduced mode equivalent to the "very restrictive" configuration (see Table 1) we identified three risky situations illustrated in Figure 5.

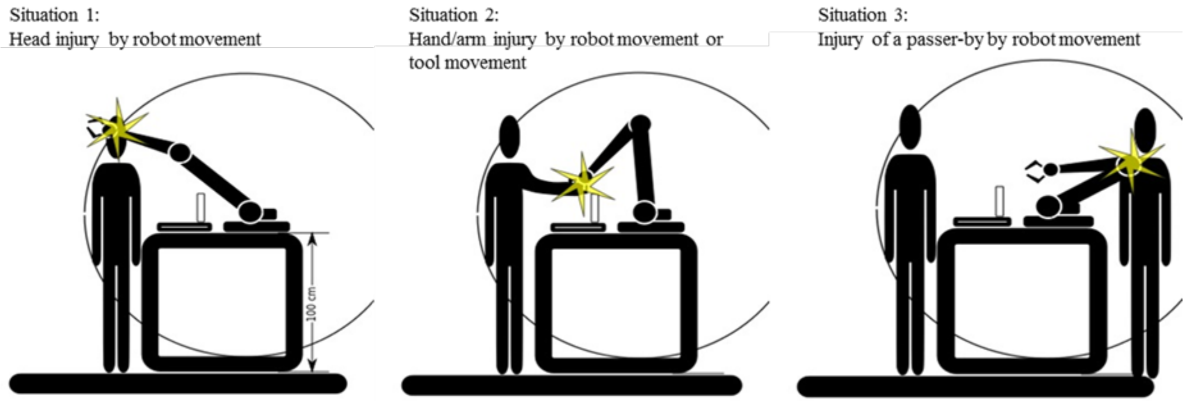

Figure 5. Identified risk situations in the hybrid assembly station

The risk degree of each situation is calculated with the Pilz method (Belanger-Barrette 2016, Cordis 2017), which assigns to each situation a Pilz Hazard Rating (PHR). This rating provides a numerical evaluation of a risk considering four factors: Degree of Possible Harm (DPH), Probability of Occurrence of a Hazardous Event (PO), Possibility of Avoidance (PA) and Frequency and/or duration of Exposure (FE). The Pilz method assigns default numerical values of each the last enumerated factors that can be seen in Table 2.

Table 2. Default numerical values for DPH, PO, PA and FE – Pilz method (Belanger-Barrette 2016, Cordis 2017)

Degree of Possible Harm (DPH)	Possibility of Occurrence of Hazard Event (PO)	Possibility of Avoidance (PA)	Frequency of Exposure (FE)
0.25 - Scratch / Bruise	0.05 - Almost impossible	0.75 - Possible	0.5 - Annually
0.5 - Laceration / cut / mild ill health effect/ minor burns	1.25 - Unlikely	2.5 - Possible under certain circumstances	1 - Monthly
3 - Fracture minor bone – fingers, toes	2.5 - Possible	5 - Not Possible	2 - Weekly
5 - Fracture major bone – hand, arm, leg	4 - Probable		3 - Daily
8 - Loss of 1 or 2 fingers/ toes or major burns	6 - Certain		4 - Hourly
11 - Leg / hand amputation, partial loss of hearing or eye			5 - Constantly
15 - Amputation of 2 legs/hands, total loss of hearing/sight in both ears/eyes			
25 - Critical injuries or permanent illness/condition/injury			
40 - Single Fatality			
65 - Catastrophe			

The numerical value of the hazard rating is given by the following formula:

$$PHR = DPH \times PO \times PA \times FE \tag{1}$$

In situation 1, the operator places some part of his body on the trajectory of the robot and is hit by a link. The nature of this impact depends on the mass and velocities of the robot. Because the velocity of the Tool Center Point is limited

to 1.5 mm/s this represents a negligible injury (Sami et al. 2009). Moreover, it is possible to the operator to avoid contact. On the other hand, the possibility of this event is not negligible and the operator is constantly exposed to it.
In situation 2, the operator gets his or her hand trapped between the tool and the piece. After a first impact, the exchange of forces between the hand and the tool will realize a crushing situation with a cutting device, that will twist. Due to the diameter of the tool, this situation may lead to breaking the phalanx, and making an irreversible damage to the hand. It is possible to avoid this accident, but nevertheless this event is possible and the operator is constantly exposed.

In situation 3, another operator will be hit by a robot link by walking behind the assembly station. As the first situation, this impact is of dynamic nature and because the trajectory of the robot is not particularly harmful, the injury is negligible. Also if this situation is possible, it can be also easily avoided and operators are not constantly exposed to this situation. Moreover, by configuring the UR3 joint limits, we can completely avoid this situation.

The calculated Pilz Hazard Rating ranges from 0 to 9750 where 0 is the lowest (no risk) and 9750 is the highest risk. The complete classification is presented in the following Table 3 (Cordis 2017).

Table 3. Pilz Hazard Rating ranges (Belanger-Barrette 2016, Cordis 2017)

PHR	Risk	Comment
0.005 - 10	Negligible Risk	Presents no risk to health and safety, no control measures required
11 - 20	Very Low Risk	Presents very little risk to health and safety, no significant control measures required, the use of personal protective equipment and/or training may be required
21 - 45	Low Risk	Risk to health and safety is present, but low. Control measures must be considered.
46 - 160	Significant Risk	The risk associated with the hazard is sufficient to require control measures. These measures should be implemented at the next suitable opportunity.
161 - 500	High Risk	Potentially dangerous hazards, which require control measures to be implemented urgently.
501+	Very High Risk	Control measures should be implemented immediately, corporate management should be notified.

The hazard ratings of the identified hazardous situations are presented in Table 4. These values are between 0,005 – 10 and therefore categorized as “negligible risk”.

Table 4. Risk evaluation of identified hazardous situations based on Pilz method

Pilz factor	Situation 1 PHR=1.17	Situation 2 PHR=2.34	Situation 3 PHR=1.17
DPH	0.25 (minor)	0.25 (minor)	0.25 (minor)
PO	1.25 (unlikely)	2.50 (possible)	1.25 (unlikely)
PA	0.75 (possible)	0.75 (possible)	0.75 (possible)
FE	5.00 (constantly)	5.00 (constantly)	5.00 (constantly)

Only situation 2 (injury caused by collision with tool or tool movement) represents a greater risk for the worker compared to situation 1 and 3. This risk could be eliminated introducing a transparent PVC plate between the robot and the worker may or be reduced considerably by a correspondingly safe design of the tool. Further, an interesting approach is modifying the control logic to make the movements of the tool more safe. In fact, the UR3 visual programming tool makes it easy to introduce a "force mode" control that makes it possible to apply a desired force in a defined direction. Because the screwing task does not need an excessive force, we can command the robot for each screw with a gently force. This will additionally minimize the risk of injuries to a simple scratch.

4. Outlook to the new smart mini factory laboratory

A high number of small and medium-sized enterprises characterizes industry in the Province of Bolzano in the North of Italy. The current learning factory of the Free University of Bolzano will therefore become a user center for Industry 4.0 for small and medium-sized enterprises. While Industry 4.0 is still often a topic for mainly large companies, the new and extended learning factory aims to study SME-specific concepts, solutions and technologies. The integration of Information and Communication Technologies (ICT) and Cyber Physical Systems (CPS) with production, logistics and services in the current industrial practices, would transform today's SME-factories into an Industry 4.0 factory with significant economic potential (Olle and Clauß 2017). An objective for further research should be to point out specific entry points for Industry 4.0, that allow SMEs in particular to see direct and transparent benefits for themselves (Olle and Clauß 2017). To achieve this goal the Free University of Bolzano makes part and coordinates an international research project funded by the European Union and titled "SME 4.0 – Industry 4.0 for SMEs". The results of this research project can then be implemented and tested in a dedicated laboratory environment.

The new smart mini factory lab will be extended to 300 m². The aim is to create a learning factory for the development of Industry 4.0 solutions and technologies in a multidisciplinary engineering approach with a focus on cyber-physical production systems, automation and the needs of local SMEs and SMEs in general. The laboratory will be a platform for research and teaching bringing together researchers, students and professionals from SME industry.

5. Conclusion

With regard to the development towards smart factories of the future, new challenges arise for companies as well as for young engineers. The increasing sales volumes of lightweight robots and their increased use in industry forces both universities and companies to train their students and employees in human-machine interaction. In this context, a hybrid station for the human-machine interaction was developed in the learning factory "smart mini-factory" of the Free University of Bolzano. In addition to the manual assembly according to Lean principles, students can also test a safe integration of automated tasks into common assembly processes in the lab environment. In order to ensure a safe cooperation between humans and the robot, an analysis of the safety functions of the robot as well as a subsequent risk analysis and derivation of design requirements for the assembly station were carried out. The main goal of this case study research was to provide a workstation in a realistic industrial lab environment, where students can learn, practice and test how a safe human-machine workplace should be designed. The approach how to analyze the risk of a workstation with man-machine interaction based on the PILZ method can be applied in many situations and industries. Especially in situations where assembly tasks should be fulfilled by workers and robots or automated stations, this approach helps to evaluate the improvement of a redesigned workstation from the safety viewpoint. There are still limitations of the current work in testing the PILZ method in a case study. The main limitations lie in the number of case studies itself. Thus, future research should be done by conducting more case studies and by developing a software application to do such an analysis in a user-friendly way directly at the workstation.

Acknowledgements

The project "SME 4.0 – Industry 4.0 for SMEs" has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 734713. The Smart Mini Factory laboratory of the Free University of Bolzano has received fundings for the extension from the Autonomous Province of Bolzano, Italy.

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Biographies

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