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Towards Implementing Safety and Security Concepts for Human-Robot-Collaboration in the context of Industry 4.0

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Abstract. In future industrial environment, mass customized products will be produced through intelligent manufacturing systems. These production systems are characterized through networked, cooperating objects called cyber physical systems (CPS). These systems are unique in a sense that they are able to capture, store, process, and communicate data. Cyber physical production systems form the basis of novel interaction and collaboration opportunities between humans and their working environment. In this context, human-robot collaboration is an application area for the future factory floor and will pave the way for the new dimensions in manufacturing. Due to the diverse capabilities of CPS and the fact that human robot collaborative systems have to address and fulfil industrial safety requirements to a major extent, there is a particular need to systematically guide the development of such cyber physical production systems exhibiting human-robot collaboration in a connected environment. Accordingly, there is need for new methodologies and tool support for developing human-robot collaboration safety and security concepts for industrial working environments. In this paper, the authors propose an integrated approach towards solving intricate issues in the systematic development of safe and secure human robot collaboration in the domain of heavy payload industrial robots. Based upon a real world use case derived from industrial assembly, the outcomes are applicable in order to develop human-robot collaboration in cyber physical production systems in the context of industry 4.0.

Keywords: human robot collaboration, industrial safety, cyber physical systems

1.1 Introduction

System flexibility is the key in the future manufacturing systems to deliver flexibility in products, generally known as mass customization. Many new technology domains are being integrated in manufacturing to support such systems which include Internet of things (IoT), cloud computing, sensor networks, cyber physical systems and big data analytics. The merger of these ICT technologies in manufacturing enable the system to predict properties in operation, maintenance, product design variation and logistics. These futuristic systems are proposed for system flexibility enabling high productivity of customized products and further technology areas to evolve in the umbrella of industry 4.0. Advanced robotics is also an integrated technology in the future manufacturing systems in which the flexibility of artificial intelligence and positioning accuracy of the robots can be beneficial for the industrial manufacturing systems. For this reason, the work share of robots is expected to rise in future smart factories. These self-learning, self-decision making manufacturing systems and robots may limit the future industrial roles for the humans to some extent. It does not mean that the human absence is the future of the manufacturing systems. Human presence would be inevitable but restrict to supervisory roles on the shop floor working closely with the robotic counterparts. This has lead to the evolution of technologies like human-robot collaboration (HRC) in an industrial scenario. Many industrial robot developers have already built coworker robots or cobots with flexible capabilities to support manufacturing tasks.

There are almost one million non-collaborative robots installed in industry worldwide [1]. Replacement of present day conventional robots with the newly developed cobots needs a huge amount of investment by the manufacturing industry. On the other side, new manufacturing processes or assembly lines can easily be designed to work with cobots and possess a lot of revenue potential for cobot manufacturers. In order to save the huge replacement cost, there is a development opportunity to transform the conventional robots into intelligent cobots using the integrated working environment of interconnected sensor network, communication system, data fusion and other technologies. However, due to worker safety issues, the transformation of conventional robots to cobots is more feasible in small and medium scale payload robots. In order to develop such an interconnected system, a cyber physical system (CPS) is envisaged to incorporate requirements of sensors, safety, security, communication and electronics. It is noted that successful transformation in medium scale robotics will trigger research effort in the case of heavy payload robots to enable collaborative tasks. [2][3]

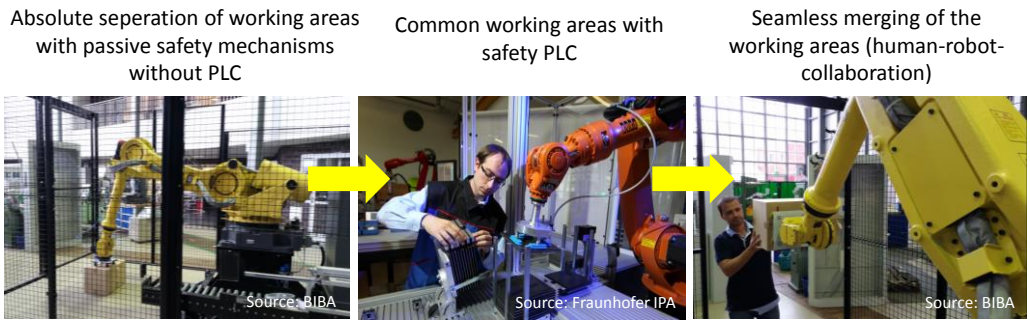


Fig. 1.1. Human-robot-interaction in cyber-physical work environments

There are many cobot examples that are developed to work with human workers and have appropriate safety certifications [1], [4]. These are mostly medium payload (0.5 to 14 kg) cobots developed for mobile phone and electronics manufacturing. The regular features of the cobots are human worker avoidance, speed reduction upon violation of workspace, collision detection and instant hold upon collision and the programmable compliance that they can be trained for different jobs on the shop floor. There are safety and protection measures that needs to be implemented for a cobot-human shared work cell according to the ISO 15066-2016 [5]. However, the safety and security (protection) requirements in the case of heavy payload robotics is still in the infancy stage.

The paper focuses on the development of CPS for the conversion of conventional heavy payload robots into intelligent systems. Together with the other intelligent plant modules, the cyber physical production system (CPPS) [6][7] is comprised of the necessary communication and sensor network, the cyber component (CC), physical component (PC) and the human component (HC). In the future manufacturing systems, there will be a seamless integration of humans and machines and passive safety fencing will be removed (See Fig. 1.1). The increased level of connectivity in future manufacturing systems (CPPS) will affect the concepts of safety and security. Safety and security are both system level properties and must be considered concurrently. As safety physically protects humans from the systems, the security essentially protects the systems from humans as attackers. In this paper, the objective is to systematically identify the risk sources and highlight hazards from the integrated safety and security aspects in the case of a heavy payload robot. The considered heavy payload robot is installed in an automobile manufacturing plant as a vital physical module and works intelligently by developing an external CPPS that enable it to exhibit HRC. The outcome of the paper may contribute towards the development of future HRC capable integrated manufacturing systems in the context of industry 4.0. The next section of the paper introduces a use case of an assembly scenario in the automobile industry proposed for an active HRC. The third section explores the CPPS model for the use-case and the technology requirements according to the designed framework. The fourth section investigates risks based on the integrated concepts of safety and security in a CPPS based heavy payload robot as a vital PC. Section 5 concludes discussion and findings.

1.2 Use Case

Traditional work environments lack the ability to respond intelligently to adapted processes and therefore do not allow dynamic modifications. While this leads to new and improved ways of interaction and collaboration, it places challenges on safety and protection systems. Contemporary protection systems separating the worker from the machine (e.g. through safety fences) are not sufficient for enabling efficient HRC. Context-based systems are required which have to provide active, integrated and omnipresent protection of the human worker. The CPPS work environment needs real time adaptation to situtions and working conditions. This is an active protection concept in addition to the passive protection of injury avoiding construction of robots and machines.



Fig. 1.2 The assembly scenario (Courtesy of ThyssenKrupp System Engineering)

As a representative industrial HRC scenario, an assembly process from automotive industry was chosen where the workspace of an industrial robot and a human worker substantially overlap (Fig. 1.2). The tasks are related to the assembly of motors and gear drives. Under consideration of customer requirements, several potential assembly scenarios were identified. These were analyzed according to qualitative criteria and weighting, thus were

narrowed to eight scenarios. The eight scenarios were subject to a task and cost analysis in order to highlight which of the processes possess the highest economic potential.

In this manner a semi-automatic assembly process focusing upon motor and gear drive assembly was chosen. The main advantage of this particular process lies in the fact that the type and sequence of the tasks significantly resemble the other identified assembly processes. Therefore this process was chosen as an exemplary HRC reference scenario. The scenario is based upon the semi-automatic assembly of the seal ring upon an automobile motor. A heavy payload robot with a gripper, lifts a motor from a workpiece carrier. The motor is then forwarded to the assembly worker and presented in an ergonomically convenient position. The task of the assembly worker consists of screwing on a seal ring on the front end of the motor with a pneumatic screwdriver. This process step can be considered as the intermediate HRC since the working areas of the assembly worker and the robot overlap synchronously. Table 1.1 shows the detailed operation sequence of the representative scenario. Fig. 1.4 shows the phase wise HRC identification for better understanding of the process. It is clear that HRC is exhibiting at two phases out of the 11 phases marked as separate activities in the process.

Table 1.1. Detailed phases of the assembly scenario

No.	Operation sequence
1	Workpiece in workpiece carrier is moved discontinuously on conveyor belt and moved in default position.
2	Robot removes the workpiece from the workpiece carrier by clutching it with gripper.
3	Robot moves the workpiece into the assembly position.
4	Workman removes assembly component cover from the default position.
5	Workman positions assembly component cover on to the workpiece.
6	Workman removes assembly component screws at default position and move it to the assembly position.
7	Workman mounts assembly component screw on the assembly component cover and workpiece.
8	Robot moves the assembled workpiece to the pneumatic screw driver.
9	Pneumatic screw driver tightens (screws on) assembly component cover and assembly component screw to the workpiece.
10	Robot moves the workpiece to the workpiece carrier and gripper declamps assembled workpiece.
11	Robot moves to the default position.

1.3 Cyber Physical Production System Model

According to the main principle of HRC which can be summarized as continuously monitoring the distance between the human and robot combined with the context of an industrial assembly scenario, technical measures can be derived for the appropriate behavior of HRC safety systems. It became evident that the minimum safety distance from the danger position to the detection position within an HRC scenario should be incorporated when choosing the appropriate CPPS components [8]. It has been shown that the integration of virtual commissioning (VC) for CPS-based HRC is an excellent complimentary technique for accompanying the realization of HRC safety concepts, thus for evaluating the functional-safety and interoperability of CPPS components. However, there is a need of more sophisticated data models for describing and visualizing the behavior of CPPS components. For example, the integration of real sensor data from motion tracking systems is possible in visualization tools which are suitable for VC. In this respect it has to be noted that in HRC settings, the HC is a vital part of the CPPS in addition to the other technical components.



Fig. 1.3 Conventional heavy payload robot as PC in CPPS

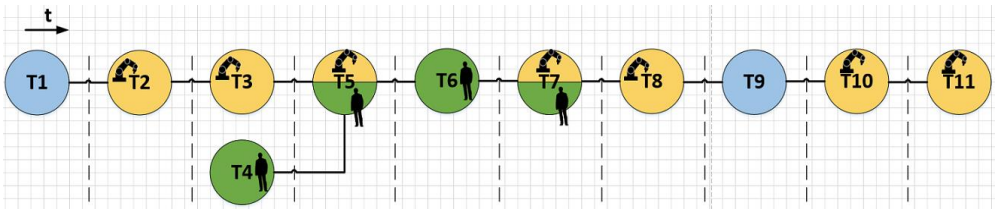


Fig. 1.4 The assembly scenario – phase wise HRC identification

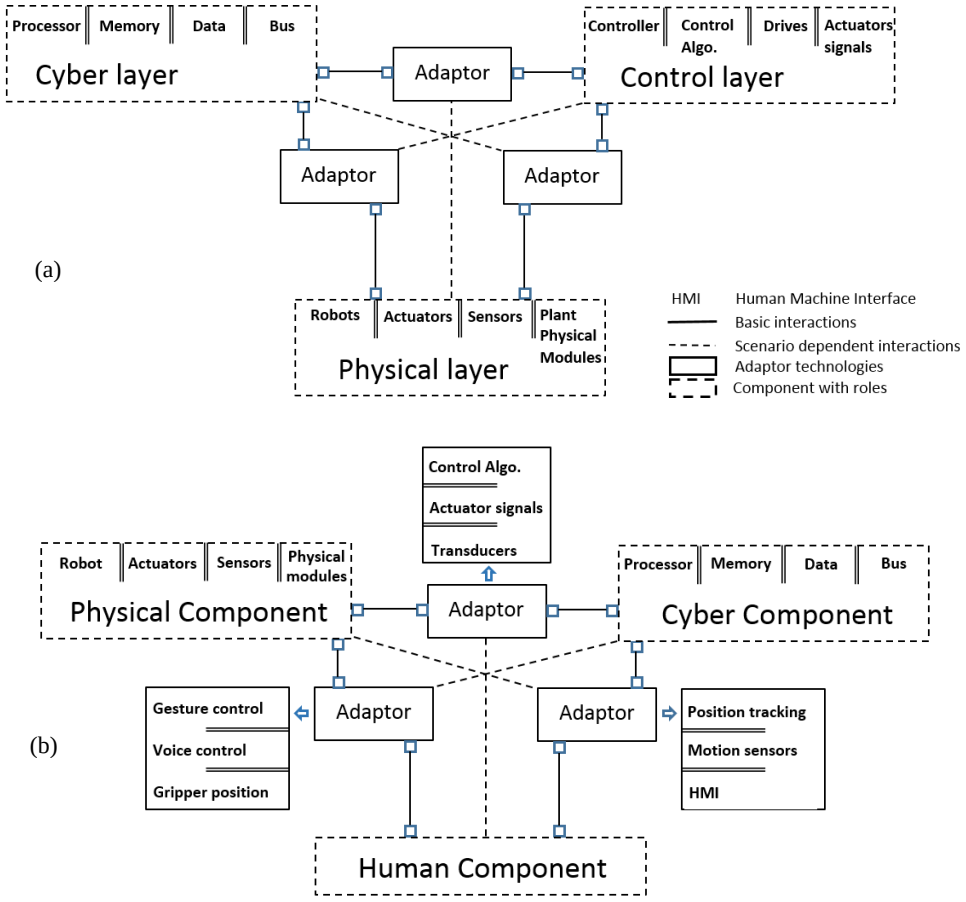


Fig.1.5. (a) Basic CPS definition (b) CPPS Frame work for HRC (Legend given is common)

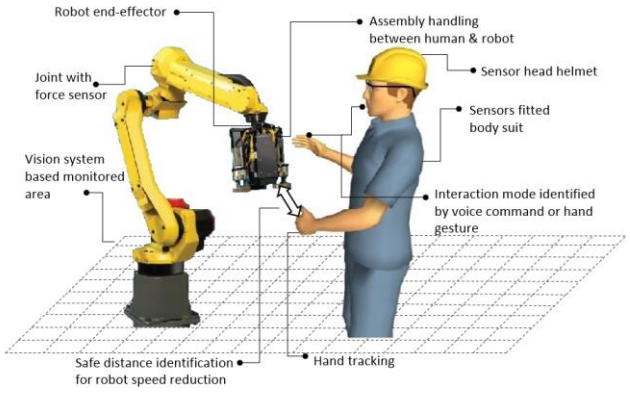


Fig 1.6. HRC technologies involved for transforming conventional robots

In basic CPS definition, (shown in Fig. 1.5-a), it is evident that it is a smart system in which the computational and physical systems are integrated to control and sense the changing state of real-world variables [9]. However, the extended CPPS concept (shown in Fig. 1.5-b) involves the vital HC interacting with other components of the CPPS to exhibit HRC. There are certain adaptor technologies playing an important role between the main components of the CPPS. These adaptors work according to the industrial scenario requirement. Fig. 1.6 shows different adaptor technologies in order to work out the safe HRC. For instance, human worker is equipped with a body suit and helmet that comprised of the motion tracking devices.

A physical research demonstrator of this HRC representative scenario has been implemented with off-the-shelf components. The demonstrator consists of a heavy payload robot from FANUC (R-2000iB 165F), a robot controller (R30iA), an industrial PC (Siemens) with ProfiNet/ProfiSafe interfaces, as well as two safety laser scanners (SICK S3000), two HD cameras and a wearable 3D Motion capturing system. The concept of the demonstrator relies upon a sensor framework which enables the ad-hoc integration of potential cyber-physical components, whereas the sensor data is collected and sensor fusion takes place in the environment of the industrial-PC. Moreover, to verify the industrial HRC scenario in the case study, i.e., only phase no. 5 & 7 in Fig. 1.4, the VC is carried out to test the effectiveness of human avoidance algorithms based on the real time safety

distance calculations. Fig. 1.7 shows a visualization window for the assembly process and to study safety issues in real time.



Fig. 1.7 Virtual commissioning visualization

1.4 Risk Identification

Factories of the Future (FOF) represent demonstrative infrastructures which highlight the strategy implied by "Industry 4.0". These environments are characterized by interconnected cyber-physical components. These infrastructures provide technological challenges regarding security and interoperability, and additionally foster new interaction opportunities for humans with equipment, machines and tools. HRC is a descriptive paradigm and comprises a manifold of technological challenges. As such, an increasing amount of industrial customers of this industrial domain dealing with automatic and semi-automatic assembly processes are highly interested in leveraging their assembly processes to a stage to enable seamless HRC.

The challenges related to an industrial HRC scenario are manifold from a technical point of view, but uniquely address the safety and security aspects. On one hand, the CPPS is designed to meet a single objective of "CPPS-safety", but on the other "CPPS-security" is also an equally vital issue to comprehend. Mitigation approaches for CPPS-security seriouly lack the ability to detect and actively react to the cyber-attack that can advance without restriction, once the cyber layer is compormised. Currently, all the development focus is on the design of an intelligent security cyber attack that includes the penetration enhancement of such attacks through in-depth understanding of the target (CPS) control system. Fig. 1.9 shows a list potential attack methods, targets, effects, and interdependencies between the different CPPS layers.

A CPS possesses different system layers, thus potential attacks are executed at targets placed at diverse system layers. Due to the great amount of the reliance and interdependencies amid CPPS components at different strata, ancillary effects can follow at CPPS elements which have not been openly confronted. These prompted effects can happen at components placed in diverse layers or even linking to different (cyber or physical) domains. Such cross-layer and cross-domain assaults on CPPS are very complicated and hardly understood so far.

The selection of technology for the implementation of defined CPPS for HRC has many technical challenges. The biggest challenge is the computation of safety distance which the robot must establish to avaoid the human working in the production cell. Tight specifications on saftey distance will be translated as the technolgy limit in terms of sensor specifications. Other challenges may include the use of reliable components to develop such a CPPS and a cyber security mitigation plan to counter intelligent cyber-attacks in the connected environment. This security plan must ensure the safe HRC and the security of PC even in the case of a compromised cyber layer of the system. Another physical challenge is to cover all parts of the robot to avoid humans using the safety distance approach [2]. Fig.1.8 shows safety distance calculations with four technology component sensors selected for CPPS application. The data shows that camera systems are the slowest and hence needs largest safety distance. Also, increased human worker speed results in large safety distance. Additionally, the data delay rate of the individual sensor output and communication over the network can cause undesirable results for HRC. By using multiple snesors from different makes can cause 120-150 ms delay using the present day sensor technology and requires sensor fusion techniques to reduce the delay time.

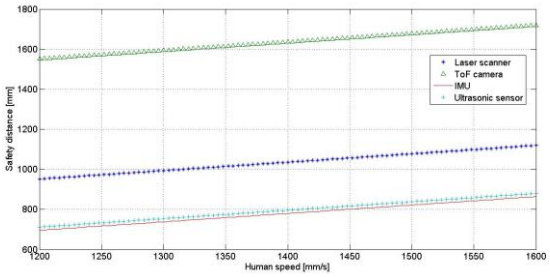


Fig. 1.8 Safety distance versus human worker speed assessment on 4 different sensors

A complete CPPS has many sources of potential hazards due to which the system can malfunction and compromise on safe HRC. The list of these hazards can come from different sources. The three identified hazard sources are due to collaborating robot, the industrial process and due to the CPPS control layer malfunction. Detailed lists of hazards from the three sources are given below.

1.4.1 Hazards from robot during collaboration

1. Hazards from robot characteristics, i.e., speed, force, torque, acceleration, momentum, power etc.
2. Operator dangerous location of working under heavy payload robot.

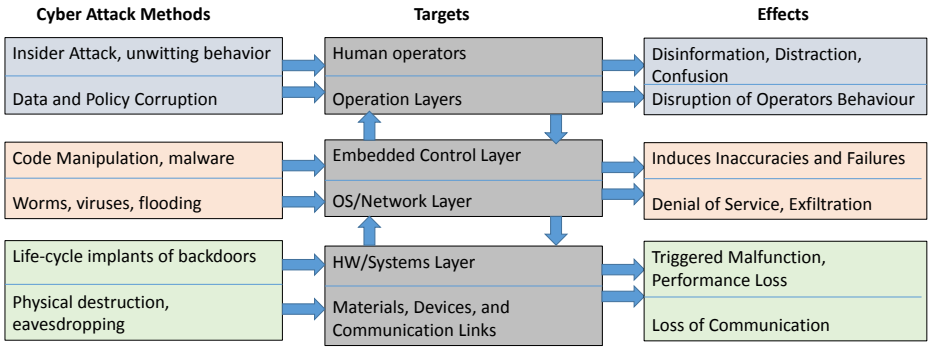


Figure 1.9 Potential Cyber Attack methods, targets, effects, and interconnections between the CPS layers.[10]

3. Hazards from end-effector and work part protrusions.
4. Sensitivity of the parts of the operator body that can come in contact in case of collision.
5. Mental stress to operator due to robot characteristics (e,g., speed, inertia etc.)
6. Hazard from trajectory taken by the robot.
7. Physical obstacles against robot operation during collaboration.
8. Hazard from fast worker approach speed and robot's slow reaction time.
9. Hazard from tight safety distance limit in the collaborative workspace.

1.4.2 Hazards from the industrial process during collaboration

1. Ergonomic design deficiency for operation and maintenance.
2. Time duration of collaboration in the process.
3. Transition time from collaborative operation to other operation.
4. Potential hazards from the industrial process (e.g., temperature, loose parts etc.)
5. Mental stress to operator due to collaborative industrial process.
6. Work material routing during the process.
7. Physical obstacles tackled by worker in order to accomplish process requirement in collaborative workspace.
8. Hazards due to task complexity in collaborative workspace.

1.4.3 Hazards from robot control system malfunction during collaboration

1. Hazards from operator during reasonably foreseeable misuse of the system.
2. Hazards from control layer malfunction and misuse of collaborative system by attacker under a cyber-attack in a connected environment.
3. Physical obstacles in front of active sensors used in the collaborative workspace. (e.g. obstacle in front of camera).
4. Non-provision of transition from collaborative operation to manual system in case of system malfunction.
5. Hazards from multiple workers involvment in the collaborative process.
6. Hazard created due to wrong perception of industrial process completion by the robot.
7. Hazards from obstacles against unobstructed means of exiting the collaborative workspace at any instant.
8. Hazard from visual obstruction for robot in collaborative workspace due to vantage point of operator.

All the three hazard sources are fully effective only to those phases of the selected industrial senario in which the HRC is established. The hazards identified above can effect the HRC at any scale, though the focus in this work is on heavy payload robots. The involved variables at different magnitudes (low, medium, high) during collaboration can be further studied to see the effects on the human worker health and safety, industrial process effectivenesss, quality of collaboration and on the safety and security of collaborative system. These domains can be further expanded to incorporate robustness in HRC process.

1.5 Conclusion

The manuscript proposed an integrated CPPS for the flexible manufacturing industrial environment. The new definition in the CPPS includes the HC that interacts with other CPS components in a fully interconnected system. It is noted that the conventional heavy payload robot can also be part of the futuristic manufacturing systems. In order to see the feasibility of the proposed system, an industrial scenario is selected to visulaize an industrial assembly process using a heavy payload robot. The technolgy selection phase in the CPPS revealed the real challenges which can seriouly hamper the HRC. The

challenges are highlighted from the standpoint of the used robot scale, industrial process complexity, safety distance computation based on existing sensor technology and the malfunction of the control layer in case of cyber-attacks. Overall, it is suggested that any such design activity for such HRC system must include the integrated concepts of safety and security. As in the interconnected environment, both concepts merge to effect on the overall quality of HRC, the industrial process itself and the health and safety of the human operator working with the cobot.

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