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Generative design in the development of a robotic manipulator

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Abstract

The emergence of cyber physical production systems has brought with it an increased utilization of robotics in collaborative manufacturing environments. An approach to meet this demand is to democratize robotics by making cheaper more customizable robots that can be implemented by small and medium enterprises. To tackle this problem this research looks at using rapid prototyping techniques for the development of customizable robotic manipulators which can be implemented in cyber physical production systems. This research therefore contributes an approach for designing connected and rapid prototyped robotic manipulators. This approach considers both the software and hardware development required for implementing a robotic manipulator. Furthermore generative design, an evolutionary and artificial intelligence based approach, is used to design the link modules between the robot joints. This component has been identified as the ideal to be designed with this approach as it benefits most of the generative design approach coupled with rapid prototyping. This paper also explores a robotic manipulator control structure based on Ethernet control technology for implementation within cyber physical production systems.

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Keywords: Robotics; Design; Artificial intelligence.

1. Introduction

1.1. Cyber Physical Production Systems

CPPS consist of autonomous and cooperative elements (e.g. Smart Machines) and sub-systems (e.g. Smart Factories) that are connected with each other in situation dependent ways, on and across all levels of production, from the processes level up to factory and production levels [1].

One of the main drivers for the implementation of CPPS is the need for continuous adaptability and evolution of the production system [1]. Evolving production system requirements can trace their origin in volatile customer behavior and evolving products [2].

The need to adapt to customer requirements has implied that production systems utilize technologies and machines which provide high levels of efficiency whilst being adaptive to the needs of the manufacturing environment. Since robots provide high efficiency and precision, whilst not sacrificing flexibility, the emergence of cyber physical production systems has brought with it an increased utilization of robotics. That said, trends in robotics are changing with the emergence of collaborative and connected robotics. This trend has also been highlighted at the World Economic Forum in Davos, which identifies advanced robotics as one of the main technological drivers behind Industry 4.0.

1.2. Collaborative and Connected Robotics

That said, this does not mean that humans will be completely eradicated from the shop floor. In fact based on detailed studies and experimentation conducted, Pfeiffer [3] argues that human experience will be still needed on the future shop floor. Based on this, the need for humans and robots to collaborate together on manufacturing operations will increase in the coming years [4]. To substantiate this claim Bloss [4] carried out discussions with key managers of robot companies and based on this concludes that collaborative robotics technology “will become the dominant robot technology in decades to come”.

In response to this growing need, it can in fact be seen how all major robot manufacturers are introducing to their lineup

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collaborative robots who are capable of working hand-in-hand with human operators.

In order to be implemented into CPPSs these robots need to be easily connected to the control system which manages the manufacturing operations. A characteristic which is central to CPPS is the decentralized, or glocalized control. This vision of glocalized CPPS [5] is achieved by using machines that have embedded processing and networking capabilities. These capabilities allow the possibility for the third characteristic of distributed and cognitive control. This distributed control is gaining further popularity with the capability to use cognitive processing to analyze data gathered from machine sensors which allows for the decentralization of the CPPS control.

The need for continuous adaptation has also driven the development of approaches that implement the concept of plug-and-produce. Plug-and-produce allows for different elements of a production system to be added and removed from the production system depending on the needs of production.

This concept of plug-and-produce also allows for the development of modular production systems. As explained by several authors, Schleipen et al [6], Onori [7] and Maeda [8], the concept of plug-and-produce must be supported not only from a mechanical function, but also by the development of new and improved software and control paradigms.

1.3. Democratization of Robotics

Large companies have dedicated development teams and also the investment potential to implement such technologies. As has been reported by the International Federation for Robotics [9], 2015, has seen an increase of worldwide robot sales of 15% to 253,748 units, the highest level ever recorded for one year.

The same take up of these advanced manufacturing technologies cannot necessary be said of Small and Medium Enterprises (SMEs), even though SMEs make up a largest percentage compared to large companies [10]. Therefore if as described by Sommer [10], SMEs are not to be the first victims of Industry 4.0, then there is a need to democratize the use of robotics.

Democratization of technology refers to the process by which more people rapidly gain access to technology. An approach to meet this need is to facilitate the implementation of robotics by developing cheaper and more customizable robots that can be easily implemented by small to medium enterprises.

Since the readiness to invest in Industry 4.0 technologies by SMEs is low [10], providing cheaper robots would possibly increase the take up of robotics. Moreover making robots easy to connect and train would also address any reservations by SMEs on the use and implementation of robotics. These approaches together with providing the possibility of a single robot platform which can be customized for the widely varying needs of SMEs would also increase the take up of robotics and Industry 4.0 technologies.

1.4. Research Aims

To tackle these challenges this research aims to utilize rapid prototyping techniques for the development of customizable robotic manipulators which can be implemented in cyber physical production systems. To minimize the weight and cost of the robotic manipulator this approach utilized a generative design technique to design the links between the robot joints. Generative design is an evolutionary and artificial intelligence approach and is further discussed in Section 2. Other state of the art approaches which tackle similar challenges are then presented in Section 3. Section 4 describes the methodology utilized to develop the robotic manipulator. Section 5 then presents the prototype design and implementation. The conclusions and future work relating to this research are presented in Section 6.

2. Generative Design

Generative design is not a new concept, and is sometimes referred to by the term evolutionary design with reference to the search techniques and evolutionary algorithms which are used in this computational process. In [11], Bentley and Wakefield describe a prototype design system which uses a genetic algorithm to evolve new conceptual designs from scratch. In this approach the prototype system creates new designs and iteratively optimizes these designs using a genetic algorithm. Genetic algorithms utilize the principles of evolution found in nature to first generate a population of solutions, and then 'reproducing' the fittest solutions. Offspring are generated by combining the genotypes of these fit parents using random crossover and mutation operations. The design system contributed by Bentley and Wakefield [11] consists of three elements:

- A suitable representation of solid objects to allow the computer to manipulate candidate designs effectively during the design process.
- A modified genetic algorithm to *evolve* such represented designs from scratch.
- Evaluation software to guide the evolution process.

As explained by [12] the process of conceptual design can be presented as an optimization process. In order to arrive to a solution and identify a set of rules is required to evaluate the fitness of a solution to a particular design problem. These type of approaches make the best use of the inventiveness of evolutionary computation in order to discover solutions which may have not been found by human designers. Hence such design techniques may be used to enhance design exploration support for human designers whilst maintain the designer at the center of the design process [13]. This co-development approach is also described by Krish in their generative design process [14]. Krish explains how the designer explicitly defines the constraint envelopes within which define the geometric viability of solutions. As explained by Sun et al. [15], the use of such evolutionary techniques for design automation can lead to not only an improvement in the functionality of the designs but also to a reduction in the development time and thus reduction in cost, especially when designing complex components.

3. State of the Art

In this section the authors present the state of the art relating to the topics of this research. Generative design is used. An application of generative design is that explained by [16] in the design of a typical micro ball end mill with relatively complex features. This product has been analyzed by the generative design method to generate the number and properties of needed motion axes. This analysis was then used by this research in the design of a novel five-axis laser machine.

Another application is the use by Lee [17] of an evolutionary system for automatic robot design. This work explores different design problems, from evolving simple behavior controllers for robots, to complex behavior controllers, and finally to accomplishing a complete robot system including its controller and physical structure.

An interesting application of generative design is that applied by Saravanan et al. [18] to obtain the optimal geometrical dimensions in the design of robot grippers. Based on the success of their experiments the authors of this research conclude that this work opens the door for further investigations on how the intelligent techniques can be used to solve complex engineering optimization problems [18].

Generative design has also been utilized for optimization of 3D printing applications. One such approach is that employed by Asadi-Eydivand et al. [19] for 3D printing scaffolds in bone tissue engineering. Evolutionary algorithms were successfully used by this research to explore different 3D printing parameters.

As explained by Onal et al. [20], the ability to print robots introduces a fast and low-cost fabrication method to modern, real-world robotic applications. The 3D printing method is used to develop robots based on the origami structure. Whilst these robots do not currently have a suitable industrial application, they demonstrate the usefulness of 3D printing to print complex structures in a cost effective manner, whilst opening the door for new innovative designs.

A similar approach was also implemented by Bulgarelli et al. [21] for the development of a low-cost and open source 3D printable dexterous anthropomorphic robotic hand. An interesting approach adopted by this research is the fact that both the hardware and software developed are provided online to promote further improvements from the community. The open source community in order to facilitate the democratization of robotics. Armesto et al. [22] in fact argue this point by stating that the wider availability of 3D printing technologies gives the robotics community the opportunity to reach a much wider public. This research [22] in fact presents the design of a low-cost printable robot for use in engineering education.

From the literature review carried out the authors can conclude that there is no approach which combines 3D printed robots designed using a generative design approach for use in CPPS. As argued in Section 1, such an approach would decrease implementation costs and therefore sustain the democratization of robotics hence supporting SMEs in implementing CPPS.

4. CPPS Generative Design Supported Process

To support the plug-and-produce concept of CPPS, an approach needs to be utilized that that takes into consideration both the Physical and Cyber perspectives. Hence a methodology is required in order to develop such systems. During this research several design methods were reviewed [23], [24], [25]. Whilst they all highlight the multiple perspectives of CPPS, none of these illustrates the design process from requirements to the final design. This lack of CPPS design methods has also been highlighted by Fisher et al. [25]. A systematic design process derived from Roozenburg's basic design cycle [26] was therefore developed. This design process, which is illustrated in Fig. 1, was therefore used during this research in order to develop the cyber connected robotic manipulator.

This design process for a CPPS device describes the design cycle from goal (the requirements) to means (the approved design). During this design process the designer may employ generative design techniques which utilize artificial intelligence to automate the design synthesis, simulation and evaluation activities. That said, this does not eliminate the designer from the design process. The design process being contributed by this research is a human-in-the-loop system. Therefore whilst some activities of the design process may be automation, it is still the designer who makes the final decision to approve the design.

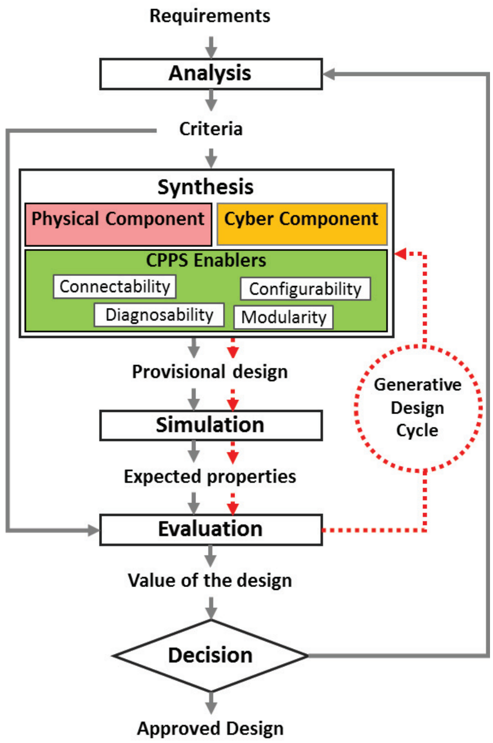

Fig. 1. Generative design cycle for a CPPS device.

Moreover the design cycle illustrated in describes how both physical and cyber components have to be considered during the synthesis design of CPPS. Moreover to meet the system requirements, CPPS devices must also make use of enabler technologies such as configurability, modularity, diagnosability and connectability.

5. Prototype Design and Implementation

5.1. Physical Component Design

The physical component design process results in the physical interface of the robotic manipulator. The physical system design utilizes a set of robotic joint modules, some of which are connected by a link module. Once produced and assembled, the robotic manipulator is essentially an articulated robot as shown in Fig. 2. The manipulator is driven with the use of stepper motors in the joint modules.

5.1.1. Design for Configurability

In order to meet the requirements of being customizable for different industrial applications, the physical robotic manipulator design is configured by selecting, adding and removing joint and link modules. The main configuration of the robotic manipulator is the one illustrated in Fig. 2, and which employs six degrees of freedom. This means that the robotic manipulator is made up of six joints, each of which is a revolute joint. The six degrees of freedom ensure that the end effector can reach any position and orientation within the workspace of the manipulator. Different stepper motor sizes and gear ratios are used in order to lift a 1.5 kg load at maximum extension.

5.1.2. Design for 3D Printing

Since this robotic manipulator was intended to be mostly rapid prototyped, several factors and constraints needed to be taken into account during production of the prototype. Fused Deposition Modelling (FDM) and Stereolithography (SLA) were used as the processes of rapid prototyping. The process was chosen based on the geometry of each part. Parts which had important geometry on one of their sides were 3D printed using SLA, such as the specially designed gears. Placing the side with the important geometry away from the support material was important for the preservation of said geometry.

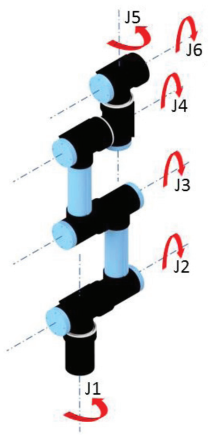

Fig. 2. Assembly model of the robotic manipulator.

On the other hand, parts which have a flat surface on one of their sides were printed using FDM, with that side being placed on the printing bed. The use of FDM was also encouraged when 3D printed parts required support material in internal and unreachable parts. Soluble support was used in these cases, making the support material easily removable during post-processing.

In designing for 3D printing, an important factor considered was the minimization of weight. While modelling using CAD, several parts were designed to have the minimum wall thickness possible. This first step led to the search for other possible means of weight reduction. This included reduction in the diameter of the joints modules which led to all the internal parts also being smaller, and thus lighter.

5.2. Generative Design

Another way to achieve weight reduction was through the creation of holes in parts with unnecessarily large volumes. Hence as mentioned in section 1.4, the link modules which connect the robot joints was selective as an ideal case-study for demonstrating the use of generative design. The implementation of the generative design exercise was carried out using the shape generator function within the Autodesk Inventor CAD system.

5.2.1. Build Volume and Design Constraints

The first step is to create a build volume or approximation of the part model. A cylindrical shape was used as the original build volume for the link module. With the build volume defined, the next step was to define keep out zones. The generative design process will not modify these zones when creating the guide shape. Finally the constraints and forces to be applied to the part were specified. These criteria are then used during the automated simulation of the provisional design solutions to evaluate the capability of each solution to meet the design requirements. Based on the design of the robotic manipulator, for this case study the criteria utilized is the force which can withstood be by the link on the central axis.

The model illustrated in Fig. 3 illustrates the initial build volume and design constraints which were applied to the link module. Important to note for this physical component design are the keep out zones which were required in order to pass the wiring for the electric drives.

5.2.2. Shape Generation

With the design criteria specified, a Shape Generator Study was run within Autodesk Inventor. The algorithm generated a mesh as illustrated in Fig. 4.

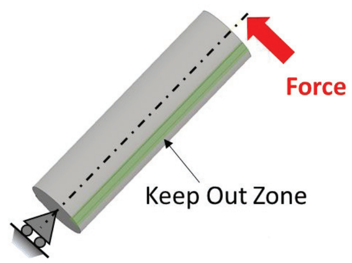

Fig. 3. Generative design constraints.

Fig. 4. Mesh resulting from generative design process.

The mesh serves as a guide for the designer to make modifications to the build volume model using cuts, extrusions and other feature edits. The designer's edits transform the generative design shape from an approximation into a component design.

5.2.3. Result

The result of the generative design exercise is illustrated in Fig. 5. This design maintained the same structural integrity, but minimised significantly on both weight and build time and hence on the overall cost of the robotic manipulator.

5.3. Cyber Component Design

5.3.1. Requirements

The design goal for the control system of this device is for it to encourage integration with other systems and to encourage further development by system integrators. Integration must be done in a simple and rapid manner, on both the hardware and software domains. The system must be based on standardized or open source software control and development tools. To maintain a democratic design, the control hardware must be based on commercially off the shelf parts (COTS), enabling a low cost solution.

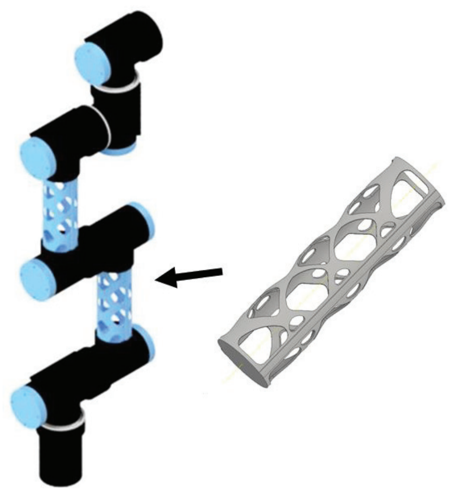

Fig. 5. Result of Generative Design Exercise.

5.3.2. Industrial Ethernet

An industrial network based on Ethernet hardware shall serve as the backbone of the control system. There are multiple relevant industrial Ethernet protocols, the one selected for this solution is EtherCAT.

EtherCAT is an industrial network based on the standard Ethernet physical layer (Ethernet PHY). The network is deterministic, and can be used in a real-time environment. It supports shorter cycle times than other industrial networks, which make it suitable for motion control applications. Apart from the suitable performance EtherCAT provides, there are other factors which make it suitable for a system intended for the democratization of robotic technologies.

When networks are based on the Ethernet PHY, they would typically require a managed network switch, every EtherCAT device has two Ethernet PHYs which enable them to be connected via a daisy chain configuration, eliminating the need for a network switch if a ring network topology suffices. Furthermore, EtherCAT slave devices are responsible for controlling the timing of the network, without the need for a specialized master network controller. Therefore, the master device in an EtherCAT network can use common COTS Ethernet network interface cards (NIC), keeping the cost of implementing an EtherCAT network even lower. The use of a standard NIC allows for the implementation of an EtherCAT master through the use of any suitable device with basic Ethernet capabilities, this includes using a Raspberry Pi should the developer see fit.

EtherCAT is an open source technology, encouraging the development of hardware and software to work with this technology.

5.3.3. Robot Controller

As illustrated in Fig. 6, the robot controller was based on the ATMega2560, developed through Arduino/Genuino development platforms. Apart from the low cost required for developing solutions with Arduino, the vast user base contributing to various projects shortens and simplifies the microcontroller development cycle.

As illustrated in Fig. 6, the microcontroller was interfaced to the EtherCAT network via Microchip's LAN9252 EtherCAT controller for slave devices using SPI communication. A COTS add-on (shield) to the Arduino platform based on the LAN9252 is produced by AB&T Srl. The robot controller receives the joint positional data from its EtherCAT master and subsequently translates from joint position to the required pulses to drive the stepper motor.

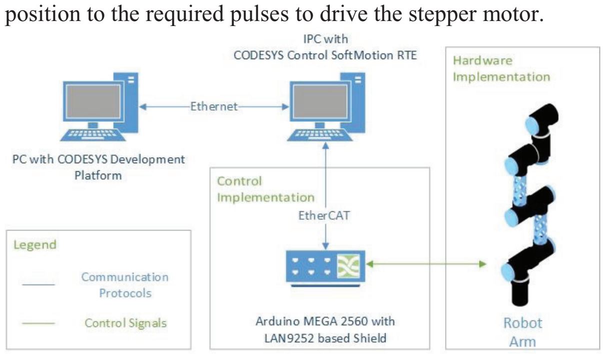

Fig. 6. Robotic Manipulator Control.

5.3.4. Master Controller

To support the flexibility required in the control system to adapt to different robot kinematic parameters, a real-time soft PLC was used. The soft PLC implemented was CODESYS Control SoftMotion RTE, it is developed using the IEC 61131-3 compliant CODESYS V3.5 development environment. The CODESYS development environment is free of charge, it also includes non-real-time versions of the soft PLC systems.

Once again, the low cost of the system enables the democratization of the control software and hardware. As of the time of writing, the real-time versions of the soft PLC systems can be downloaded and used without a license for a limited time before requiring a restart. CODESYS SoftMotion also has the inbuilt functionality to derive robot kinematics by defining the robot's Denavit-Hartenberg parameters (DH parameters).

6. Conclusions

This research therefore contributes an approach for designing connected and rapid prototyped robotic manipulators. This approach considers both the software and hardware development required for implementing a robotic manipulator. Furthermore this approach demonstrated the use of generative design, an evolutionary and artificial intelligence approach, to design the links between the robot joints.

This link module was identified as the ideal component to be targeted to utilizing the benefits of generative design coupled with rapid prototyping. This paper also explored a robotic manipulator control structure based on Ethernet control technology for implementation within cyber physical production systems.

Future work will involve the testing of the robotic manipulator in order to determine the system's accuracy and repeatability and identify areas of further improvement.

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References

[1] Monostori L. Cyber-physical Production Systems: Roots, Expectations and R&D Challenges. Procedia CIRP 2014;17:9–13.

[2] ElMaraghy HA. Changing and Evolving Products and Systems – Models and Enablers. In: ElMaraghy HA, editor. Chang. Reconfigurable Manuf. Syst., Springer London; 2009, p. 25–45.

[3] Pfeiffer S. Robots, Industry 4.0 and Humans, or Why Assembly Work Is More than Routine Work. Societies 2016;6:16.

[4] Richard Bloss. Collaborative robots are rapidly providing major improvements in productivity, safety, programing ease, portability and cost while addressing many new applications. Ind Robot Int J 2016;43:463–8.

[5] Verl A, Lechler A, Schlechtendahl J. Glocalized cyber physical production systems. Prod Eng 2012;6:643–9.

[6] Schleipen M, Lüder A, Sauer O, al et. Requirements and concept for Plug-and-Work: Adaptivity in the context of Industry 4.0. Autom AT 2015;63:801–20.

[7] Onori M, Lohse N, Barata J, Hanisch C. The IDEAS project: plug & produce at shop-floor level. Assem Autom 2012;32:124–34.

[8] Yusuke Maeda, Haruka Kikuchi, Hidemitsu Izawa, Hiroki Ogawa, Masao Sugi, Tamio Arai. "Plug & Produce" functions for an easily reconfigurable robotic assembly cell. Assem Autom 2007;27:253–60.

[9] IFR. Executive Summary World Robotics 2016 Industrial Robots. International Federation for Robotics; n.d.

[10] Sommer L. Industrial revolution - industry 4.0: Are German manufacturing SMEs the first victims of this revolution? J Ind Eng Manag 2015;8:1512–32.

[11] Bentley PJ, Wakefield JP. Conceptual evolutionary design by a genetic algorithm. Eng Des Autom J 1996;2:119–31.

[12] Stankovic T, Stosic M, Marjanovic D. Evolutionary Algorithms in Design. Proc. Des. Conf. - Des. 2006, Dubrovnik - Croatia: 2006.

[13] Singh V, Gu N. Towards an integrated generative design framework. Des Stud 2012;33:185–207.

[14] Krish S. A practical generative design method. Comput-Aided Des 2011;43:88–100.

[15] Sun J, Frazer JH, Mingxi T. Shape optimisation using evolutionary techniques in product design. Comput Ind Eng 2007;53:200–5.

[16] Cheng X, Huang Y, Zhou S, Liu J, Yang X. Study on the generative design method and error budget of a novel desktop multi-axis laser machine for micro tool fabrications. Int J Adv Manuf Technol 2012;60:545–52.

[17] Lee W-P. An evolutionary system for automatic robot design. 1998 IEEE Int. Conf. Syst. Man Cybern. 1998, vol. 4, 1998, p. 3477–82 vol.4.

[18] Saravanan R, Ramabalan S, Ebenezer NGR, Dharmaraja C. Evolutionary multi criteria design optimization of robot grippers. Appl Soft Comput 2009;9:159–72.

[19] Asadi-Eydivand M, Solati-Hashjin M, Fathi A, Padashi M, Abu Osman NA. Optimal design of a 3D-printed scaffold using intelligent evolutionary algorithms. Appl Soft Comput 2016;39:36–47.

[20] Onal CD, Wood RJ, Rus D. Towards printable robotics: Origami-inspired planar fabrication of three-dimensional mechanisms. 2011 IEEE Int. Conf. Robot. Autom., 2011, p. 4608–13.

[21] Bulgarelli A, Toscana G, Russo LO, Farulla GA, Indaco M, Bona B. A Low-Cost Open Source 3D-Printable Dexterous Anthropomorphic Robotic Hand with a Parallel Spherical Joint Wrist for Sign Languages Reproduction. Int J Adv Robot Syst 2016;13:126.

[22] Armesto L, Fuentes-Durá P, Perry D. Low-cost Printable Robots in Education. J Intell Robot Syst 2016;81:5–24.

[23] Khalid A, Kirisci P, Ghrairi Z, Thoben K-D, Pannek J. A methodology to develop collaborative robotic cyber physical systems for production environments. Logist Res 2016;9:23.

[24] Lee J, Bagheri B, Kao H-A. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manuf Lett 2015;3:18–23.

[25] Fisher A, Jacobson CA, Lee EA, Murray RM, Sangiovanni-Vincentelli A, Scholte E. Industrial Cyber-Physical Systems – iCyPhy. In: Aiguier M, Boulanger F, Krob D, Marchal C, editors. Complex Syst. Des. Manag., Springer International Publishing; 2014, p. 21–37.

[26] Roozenburg NFM, Eekels J. Product Design: Fundamentals and Methods. John Wiley & Sons; 1995.