Human-Computer-Machine Interaction for the Supervision of Flexible Manufacturing Systems: A Case Study

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Abstract: Production is moving from mass-production to 'mass-customization' and 'personalization' (lot-size-one). Accordingly, modern manufacturing systems must become more agile and responsive to changing global markets and closer to customers. Industry 4.0 technologies have the premises to face these changes in the production paradigm. However, technologies must be supported by methodological approaches focused on the process to be optimized, digitalized, and made more flexible. In this paper, we propose a seamless Human-Computer-Machine Interaction (HCMI) architecture for supporting the supervision activity of the operator in the context of flexible manufacturing systems. The suggested interaction is implemented and validated using a lab case study where we demonstrate how the proposed HCMI architecture, in line with the Industry 4.0 architectural design principles, enables 'close-to-real-time' supervision of the manufacturing system in its self-adaptation to production changes.

Keywords: Human Operator Support, Adjustable Autonomy, Adaptive Autonomy, Hardware-in-the-Loop, Modeling, Simulation, Flexible Manufacturing Systems, Reconfigurable Manufacturing Systems, Manufacturing Operations, Process Supervision.

1. INTRODUCTION

Nowadays, production is moving from mass-production to *mass-customization* and *personalization* (lot-size-one) (Hu, 2013). Manufacturing companies are facing fierce pressure to cope with rapidly changing market demands for high product variety, small-lots of (mass-)customized products, and quick delivery requirements (Mindas & Bednar, 2016). Furthermore, the 'economic-sustainability' of manufacturing companies is based on the combination of high-performance and high-quality products within cost-effective productivity. Therefore, reconfigurable-, adaptive-, and evolving- factorie*s* are necessary for achieving small-scale productions in an economically viable way (Dotoli et al., 2019).

Even if modern *Flexible Manufacturing Systems (FMSs)* can potentially 'self-configure' and 'self-adapt' to product and environmental changes (Lee et al., 2015), the integration of human operators into the production processes is considered as a key aspect (Nelles et al., 2016). In FMSs, *human operators* are expected to assume the role of 'flexible' problem-solvers and supervisors of the ongoing activities (Gorecky et al., 2014). In performing their tasks, human operators receive support by appropriate *Industry 4.0 technologies* in order to exploit their full potential and become *Operators 4.0* (Romero et al., 2016). *Industry 4.0 paradigm* is defined as a combination of modern technologies and novel methodological approaches for the resolution of current and (near-)future industrial challenges (Lu, 2017; Romero et al., 2018). The present research work focuses on *Virtual Commissioning (VC) simulation technology* (see Koo et al., 2011), and the *Virtual Operator (VO) method* (see Romero et al., 2016) in order to support the supervision activity in FMSs. VC and VO are among the Industry 4.0 tools for which the explanations follow.

Virtual Commissioning (VC) is a technology for the evaluation of the system's functionality, performance and safety before its physical assembly and commissioning (Lee & Park, 2014). VC is performed by connecting a virtual model that reproduces the behaviour of the physical plant to the hardware or emulated controller which contains the 'control logic' to be validated. Concerning the *Digital Twin* technology, VC does not use any form of automated data exchange between the physical plant and the digital model, and manual dataflow is applied in between the two domains (Kritzinger et al., 2018). In production systems, the VC simulation model constitutes the basis for its digital twin (Lechler et al., 2019).

Human-Computer-Machine Interaction (HMCI) is defined as the use of simulation for supporting the operators in performing their tasks. Established interaction technologies and metaphors from the consumer goods market are generally adopted for HCMI (Papcun et al., 2018), along with industrial standard communication protocols (Wittenberg, 2016). In this context, the *Virtual Operator (VO)* is defined as a smart and skilled operator that interacts with advanced simulations of realistic scenarios for optimized decision-making and training activities by means of interactive virtual reality technologies (Romero et al., 2016). For the sake of simplicity, we will refer to the VO as “the operator”.

In this work, a seamless *Human-Computer-Machine Interaction (HCMI)* is proposed for supporting the ‘supervision activity’ of the operator through the VC simulation. Here, the operator is responsible for triggering the production after the result of the ‘manufacturing activity’ has been *validated* by means of a VC simulation. Next, we demonstrate how the proposed *HCMI architecture* enables ‘close-to-real-time’ supervision using the lab case study of an industrial robot which performs a cutting operation.

The paper is structured as follows: Section 2 describes the state-of-the-art, and the proposed HCMI approach is introduced in Section 3. Section 4 implements the proposed approach to a lab case study. Obtained results are discussed in Section 5 and eventually, Section 6 presents the conclusions and set the directions for future work.

2. STATE-OF-THE-ART

Different manufacturing systems paradigms have been proposed for dealing with the ‘mass-customization’ and ‘personalization’ production challenges. Examples are *Flexible Manufacturing Systems (FMSs)* providing ‘generalized flexibility’ designed or anticipated variations and built-in a priori (Jovane et al., 2003); *Focused FMSs* delivering a ‘customized flexibility’ for specific production problems (Terkaj et al., 2009); and *Reconfigurable Manufacturing Systems (RMSs)* offering ‘customized physical and logical flexibility on-demand’ by means of modularity, integrability and convertibility (Koren, et al., 1999).

The *Virtual Factory (VF)* concept was first introduced in Onosato & Iwata (1993) and then defined as “an integrated virtual environment supporting the design and management of all the factory entities, ranging from a single product to the network of companies, along with all the phases of the factory lifecycle” by Sacco et al. (2010). Several research projects have studied the opportunity to use *Industry 4.0 digital and virtual technologies* for the implementation of the VF concept.

Relevant R&D examples include: ‘Modular Plant Architecture’ (MPA)[1], ‘A Configurable Virtual Reality System for Multi-purpose Industrial Manufacturing Applications’ (IRMA)[2], ‘Digital Factory for Human-oriented Production System’ (DiFac)[3], and the ‘Virtual Factory Framework’ (VFF)[4].

As the most flexible entity in a production system, the operators are faced with a large variety of jobs and tasks ranging from specification(s) and monitoring to verification of production strategies. Therefore, *Human-Machine Interaction (HMI)* is considered as a key factor for managing flexible production. A recent analysis of the state-of-the-art in human-machine interaction in the Industry 4.0 domain is shown in Krupitzer et al. (2020). However, the analysed works only deal with Human-to-Machine (H2M) and Machine-to-Human (M2H) communication without considering the role of the *simulation* in this interaction.

The development of the Digital Twin technology enhanced the research topic of integrating the simulation within the human-machine interaction. The *Digital Twin (DT)* represents an evolution of the ongoing research on the ‘virtual factory’ since it includes a real-time synchronization with the physical system, thanks to which the user or the autonomous system can make the right decision about the actual and the future production, based on a wide range of available information (Negri et al., 2017). Different works have shown the potentials of the digital twin for monitoring, maintaining, and optimizing production systems (Barricelli et al., 2019; Cimino et al., 2019). However, the use of the DT for supporting the *supervision* activity of the operator has not been investigated yet in detail. Considering that the VC is the precursor of the DT, in this paper, we explore the role of VC for supporting the operator in supervision tasks.

Research in VC has been directed to different areas (Lechler et al., 2019). In the studies on the interaction between the ‘virtual model’ and the ‘operator’, VC has been utilized in *Hybrid Manufacturing Systems (HMSs)* also known as ‘soft robotics’ (Beumelburg, 2005). These soft robotics systems are enabled through human-machine collaboration, and combine benefits of manual and automated systems (ibid.). In HMSs, the human is a critical validation factor and must be included within the VC simulation model. Real-time mirroring of the operator into the virtual environment is known as *Human-in-the-Loop (HITL) commissioning* and is investigated by means of motion capturing and/or virtual reality technologies. Some examples can be found in Bönig et al. (2013), Dahl et al. (2017), and Metzner et al. (2018).

In the context of *hard robotics*, VC is mainly performed for optimizing the control algorithms during the development phase (q.v., Schluse & Rossmann, 2016; Grinshpun et al., 2016). However, the literature lack studies on the use of the VC for supporting the supervision activity of the operator. Given this, in this paper, we propose to use the VC simulation through an HCMI architecture in order to support the operator to verify whether the control logic fulfils defined production requirements.

3. PROPOSED HUMAN-COMPUTER-MACHINE INTERACTION ARCHITECTURE

Here we propose a seamless integration among the Human (i.e., the operator), the Computer (i.e., the VC simulation), and the Machine (i.e., the production plant). The proposed *HCMI solution* applies to a production environment characterized by high product variety and small-lots of customized products.

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[1] https://cordis.europa.eu/project/rcn/53080/factsheet/en
[2] https://cordis.europa.eu/project/rcn/51633/factsheet/en
[3] https://cordis.europa.eu/project/rcn/79403/factsheet/en
[4] https://cordis.europa.eu/project/rcn/97739/factsheet/en

Fig. 1 illustrates the proposed *HCMI architecture* for supporting the 'supervision activity' of the operator in the context of flexible production.

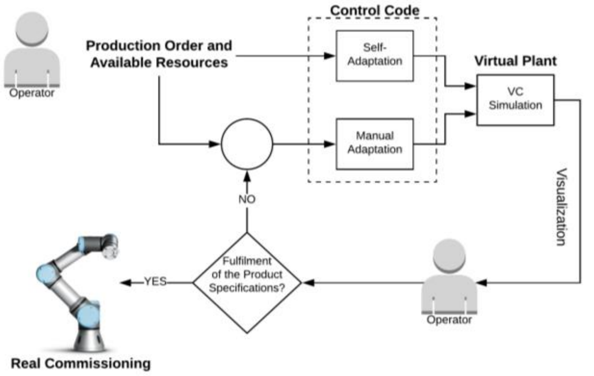

Fig. 1. Proposed Seamless HCMI Architecture

The process starts with the input from the operator, which refers to production order and the resources available for conducting the manufacturing operation. Then, the controller automatically 'self-adapts' its control logic using adjustment-loops to find the parameters to fulfil the production order with the available resources. Once the controller has completed the operation, a *VC simulation* is started for the validation (see Fig. 1). The simulation virtually reproduces the results of the manufacturing activity and is visually supervised by the operator. The operator checks the fulfilment of the product specifications and the viability of the operation (e.g., collisions, etc.).

The verification by the operator will lead to two possible scenarios. In the first scenario, the manufacturing operation is viable and the manufactured products fulfil the specifications defined in the production order. In this case, the operator triggers the production. In the second scenario, the product specifications are not fulfilled or the manufacturing operation is not viable. In this case, the *self-adaptation* operation has failed, and a *manual adaptation* of the control logic to the production change is necessary. The VC simulation model is saved, along with the control logic code, the production order, and the available resources. Next, this information will be used by a software engineer for the design of a new control logic (code) aiming for the fulfilment of the production specifications. Once the software engineer completes the development of the new control logic, a new validation cycle will start.

The information concerning what was the occurred failure would be useful for the manual adaptation operation. However, how to send this information from the operator to the software engineer will be a matter of future work.

4. CASE STUDY

In this section, the HCMI architecture proposed in Section 3 is first instantiated and then applied to a case study for its validation. A *Universal Robot (UR)*[5] simulating a cutting operation is used for this purpose. *Polyscope* software is utilized for programming the robot and *Polyscope User Interface (UI)* for the Human-Machine Interface (HMI). The VC simulation environment is built by interfacing the software *UR Sim* with *Experior*. Polyscope, Polyscope UI and UR Sim are provided by the UR vendor, whereas Experior is a VC simulation software developed by Xcelgo A/S[6]. *UR Sim* is responsible for simulating the robot movement, while *Experior* mirrors the robot configuration built-in UR Sim for reproducing its interaction within a manufacturing environment. It is necessary to include the interface of both software since the UR Sim only simulates the robot movement but not a virtual manufacturing environment. Eventually, a server is created using *XAMPP*[7] (Apache distribution) for saving the VC simulation model, the control logic code, the production order and the available resources in case of a failure in the self-adaptation operation.

Among the available types of VC simulations (Lee & Park, 2014), *Hardware-in-the-Loop (HITL) commissioning* is selected in order to implement a 'seamless' HCMI architecture, where seamless (interoperability) refers to the meaningful information exchange between human, computer, and machine. Here, the simulation model of the physical plant is interfaced with the real controller since the UR controller is connected to a Personal Computer (PC), which runs UR Sim and Experior. The UR controller and the PC are interfaced with an *Ethernet* cable and communicate through the *TCP/IP* protocol. The *Real-Time Data Exchange (RTDE)*[8] interface is also applied since it works with a standard TCP/IP connection and synchronizes the PC with the UR controller without breaking any real-time properties.

The *instantiation* of the proposed *HCMI architecture* (see Fig. 1) is presented in Fig. 2. The production order and the available resources are inserted by the operator through the HMI. Then, the UR controller receives the input parameters and automatically calculates the trajectory that the robot should follow to fulfil the input specifications. Once the robot trajectory has been computed, a pop-up is displayed on the HMI through which the operator will indicate the outcome of the self-adaptation operation. Next, the UR controller triggers the UR Sim simulation that moves the virtual robot using the trajectory generated in the UR controller. The robot movement is mirrored in Experior, and the manufacturing operation is simulated. Meanwhile, the operator inspects the Experior simulation and then selects an option on the previously generated pop-up. If the virtual production was successful, the operator presses the 'CONTINUE' button and the physical robot implements the defined trajectory. Otherwise, the 'STOP PROGRAM' button is selected and the VC simulation model, as well as the control code, the production order, and the available resources, are automatically sent to the server.

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[5] https://www.universal-robots.com

[6] https://xcelgo.com/

[7] https://www.apachefriends.org/index.html

[8] https://www.universal-robots.com/how-tos-and-faqs/how-to/ur-how-tos/real-time-data-exchange-rtde-guide-22229/

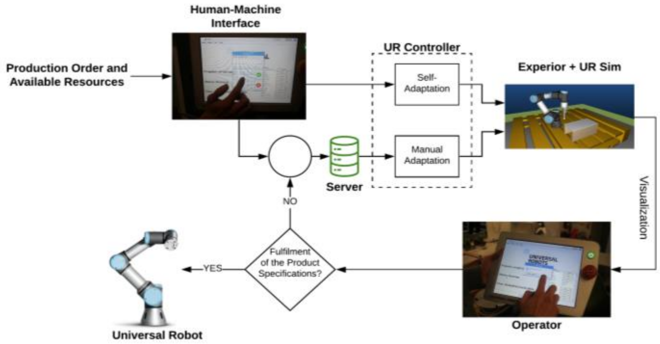


Fig. 2. Instantiation of the proposed HCMI Architecture

Given above, the proposed HCMI architecture is applied to a robot, simulating a cutting operation in order to be validated. The experimental setup is illustrated in Fig. 3. A board marker is inserted in the hand effector of a *Universal Robot UR3* and the cutting operation is simulated by writing on a whiteboard. Then, the following production scenario is implemented:

- Production Order:
  - # 2 sheets of 7.5cm x 15cm
  - # 1 sheet of 15cm x 15cm
- Available Resources:
  - # 1 sheet of 15cm x 30cm

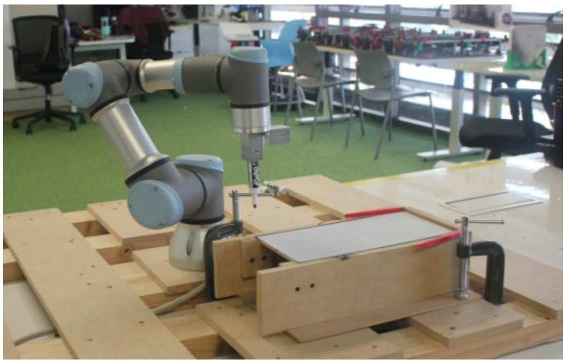


Fig. 3. Experimental Setup for the Simulated Cutting Operation

To start the above production, first, an Experior model is created in order to mimic the spatial configuration of the experimental setup (see Fig. 4). Then, the operator feeds the inputs, i.e., the production order and the available resources through the HMI. This information is received from the UR controller which implements a grasp optimization algorithm in order to identify the corners necessary for manufacturing the required sheets (Martínez et al., 2015). Next, the identified points are interpolated for the generation of the robot trajectory, and the UR controller triggers the UR Sim and Experior simulations while the operator analyses the virtual manufacturing operation. If the manufacturing operation is viable and the manufactured products fulfil the specifications defined in the production order, the operator presses the 'CONTINUE' button on the HMI and the manufacturing process starts. Otherwise, the 'STOP PROGRAM' button is pressed, and the VC simulation in addition to the control logic (code), the production order and the available resources are automatically sent to the server.

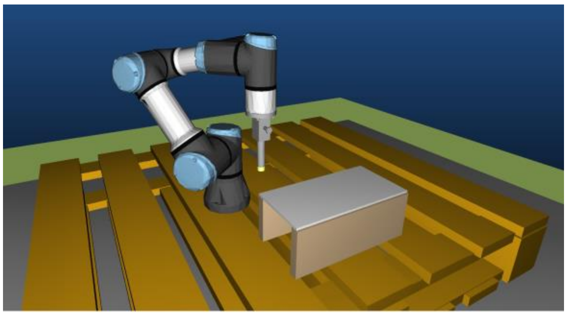
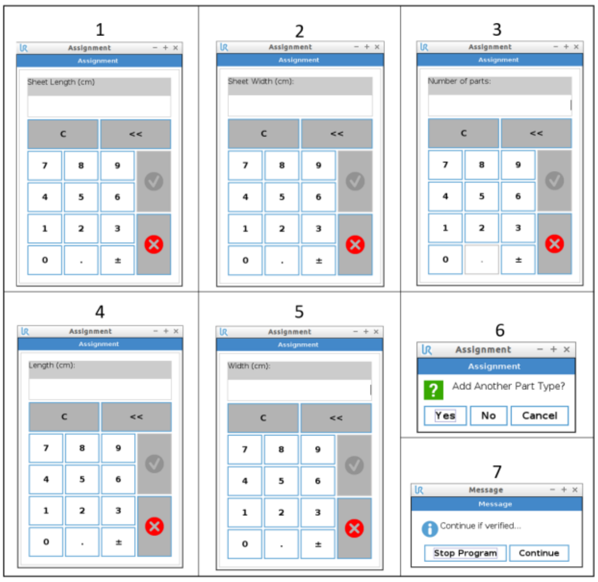


Fig. 4. Experior Simulation Model of the Experimental Setup

5. RESULTS AND DISCUSSION

In this section, the results of the proposed *seamless HCMI architecture* are shown. A video illustrating the implemented case study is also available to the reader[9].

The developed HMI is depicted in Fig. 5. The bold number on top of each image represents the sequence of operations/ activities performed by the operator in its interaction with the robot (i.e., human-machine interaction). The available resource and the production order are first inserted (Activities 1 to 6). Then, 'Activity 7' is used either to trigger the manufacturing operation or to communicate the need for a manual adaptation of the control code in response to the production change.



Add Another Part Type?

Continue if verified...

Fig. 5. Human-Computer-Interface for the Robot Case Study

After inserting the input of the production order and the available resources, the operator verifies the production scenario by inspecting the VC simulation; i.e., *human-computer interaction*. The results of the VC simulation performing the production scenario in Section 4 are shown in Fig. 6. Since the manufacturing operation was viable in the given case and the manufactured products fulfilled the specifications defined in the production order, the operator pressed the 'CONTINUE' button (see Fig. 5, Activity 7) and triggered the production.

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[9] https://www.researchgate.net/publication/340952485_Video_Case_Study_of_Human-Computer-Machine_Interaction_for_the_Supervision_of_Flexible_Manufacturing_Systems

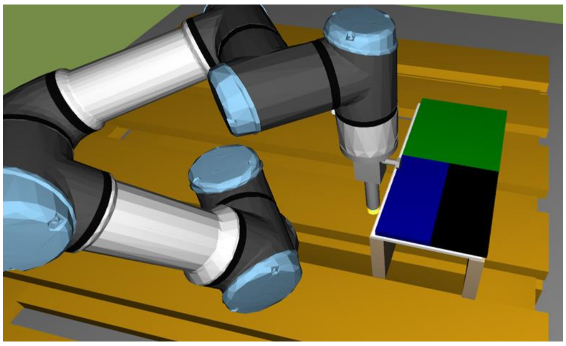

Fig. 6. Virtual Commissioning Result

Once the 'CONTINUE' button was pressed, real commissioning was implemented. The result of the obtained simulated cutting operation is shown in Fig. 7.

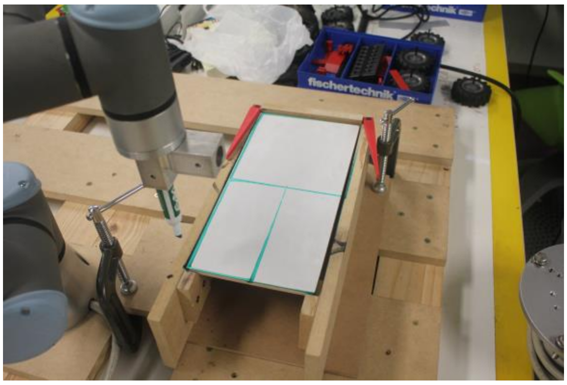

Fig. 7. Real Commissioning Result

The 'master' actor that manages the implementation of the *HCMI architecture* is the UR controller. In fact, it receives the inputs of the operator through the HMI and triggers the VC simulation through its communication with the PC. Eventually, it makes the robot perform the production after the confirmation from the operator. It can be noticed that the involved actors *seamlessly communicate* without any extra implementation over-head.

Furthermore, the proposed *HCMI architecture* allows to quickly evaluate the system adaptation to production changes through the use of a VC simulation. This functionality allows *close-to-real-time supervision* of the operator, thereby enabling increased flexibility in the manufacturing system.

Nevertheless, it should be noted that the proposed approach and its benefits can be achieved given that the simulation model is capable of mimicking the behaviour of the physical plant. In the implemented case study, this condition occurred since the whiteboard was positioned with a fixed orientation (see Fig. 7) generating a scenario in which the system was reactive to *production changes* but not to *environmental changes*. However, in a real production environment, the workpiece sheet may be positioned in a different orientation. This condition may generate inconsistencies between the simulation and the real environmental scenario. Therefore, it is essential to detect the orientation of the workpiece before the implementation of the physical model. Consequently, it can be concluded that in order to make the proposed architecture responsive to both production and environmental changes, the implemented unidirectional communication (from the simulation model to the production plant) must be transformed into a bidirectional communication, i.e., enhancing the proposed HCMI architecture from a *VC-type* to a *DT-type*. However, this topic is part of future investigations.

6. CONCLUSIONS AND FUTURE WORK

In this work, an *HCMI architecture* is designed for supporting the supervision activity of the operator in accordance with FMSs objectives. The proposed interaction is implemented and validated in a case study – viz. a robot simulating cutting operation. The obtained results confirm how the proposed HCMI architecture allows for *seamless interaction* among the operator, the computer and the machine (i.e., the robot). Additionally, the proposed HCMI enables *close-to-real-time supervision* of the manufacturing system in its self-adaptation to production changes.

Notably, the proposed *HCMI architecture* constitutes a preliminary production scheme that in the future can be further improved. Some future works identified are:

- *Recommendations for the manual adaptation,* when 'self-adaptation' to production changes is not achieved, the information concerning the occurred failure would be useful for the manual adaptation operation. A solution for sending this information from the operator to the software engineer will be investigated.
- *Evolution of the VC-type HCMI architecture into a DT-type* will make the proposed HMCI architecture responsive to both production and environmental changes. To achieve this, 'bidirectional' communication should be established between the production plant and the simulation model.
- *Usability test from real operators* must be performed in order to validate the proposed approach and to evaluate its future scalability in a real production environment.

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