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A human-cyber-physical system approach to lean automation using an industrie 4.0 reference architecture

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Abstract

The factory of the future requires flexibility and adaptability to satisfy market demands. However, these properties are difficult to ensure when collaborative manipulators are considered. Thus, approaches for integrating these devices, fostering the adoption of new engineering methodologies for augmenting manipulators are studied. In this work we address how integration of human operators with robotic manipulators might accommodate flexibility requirements using a concept of lean automation. To answer this question, we compare the current research in the field, and we propose a design structure which addresses safety, interfaces and design methods. Our results show safety hardware posing considerable constraints on flexibility. The human interface influences the workload perceived by an operator and, Industrie 4.0 reference architectures do not foresee the human and reconfigurable production cells yet. From a design prospective, this study emphasizes the need to take into consideration human and engineering aspects while planning for the factory of the future.

Keywords: Human-cyber-physical system ; lean automation ; human-centred design ; Industrie 4.0 ; RAMI 4.0

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1. Introduction

Robotics has been the constitutional backbone for the manufacturing industry in the last four decades. Innovations in this technology have changed how products are manufactured, moving the manufacturing from a mass standardized production base to a customized one [1]. Therefore, demand for robotic devices has seen a constantly growing trend in the past twenty years [2]. Notably, their demand has been enhanced by the a priori forecasted Industrie 4.0 (I4.0). I4.0 promises increased manufacturing efficiency adopting innovative technologies in conjunction with interconnections [3]. A result of this is a new set of collaborations on the manufacturing floor: human to human, machine to machine and human to machine [4]. From this set of collaborations, a valuable one is coming from the human to machine interaction; it is regularly known with the name of Human-Robot Collaboration (HRC), and it foresees the proximity between robots and human workers while sharing tasks [3]. Although this collaboration is twenty years old already [5], the field now proposes new methods for uniting human and robots (e.g. human-robot teams) [6]. Yet, its adoption is still scarce and moderate [2]. Therefore, researchers identified three barriers of adoption: safety, interfaces and design methods [7]. Of notable importance, in investigating these areas, is the necessity to enhance the robot with multiple devices for accomplishing the research goal. This augmentation of capabilities, using the I4.0 semantics, can be traced back to the concept of Cyber-Physical Systems (CPS) [8]. Although their direct relation to collaborative robots or cobots, CPS are an additional cornerstone in I4.0 for facilitating shop-floor flexibility [9]. More importantly, CPS are seen as one of the key-enablers to lean automation [10]; they can give the necessary degree of flexibility and connection between production processes and business systems [11]. It is within these concepts that a factory of the future (FoF) can be defined. In the FoF each device provides its capabilities as a service while still being able to invoke other services for completing its task [12]. Thereby, extending this concept to human beings, it is possible to foresee an augmentation of this notion to the one

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of Human-Cyber-Physical system (HCPS) [13]. This newly formed combination is considered as the intelligent manufacturing core for the FoF [14]. However, for exploiting the capabilities of a HCPS it is necessary to shift from the concept of the automation pyramid to a more flatten one, as proposed in I4.0 reference architectures (e.g. RAMI4.0, IIRA) [15, 16]. Reference architectures provide common structures when dealing with I4.0 semantics. Therefore, new developments must consider the ensemble of reference architectures and CPS for delivering systems adaptable and re-usable in I4.0 frameworks. This paper proposes a concept for a human-robotic CPS to satisfy needs of I4.0 production scenarios by a proper mapping into a reference architecture. In particular, it wants to define a design which can be used to widespread collaborative robots as flexible helpers for human operators. As long as humans will be part of the system, human aspects are going to be part of the design. Therefore, the concept is articulated following the barriers for adoption of HRC: safety, interface and design methods. To the best of authors' knowledge, the novelty of this research lies in the combination of methods for addressing HRC barriers with an Industrie 4.0 reference architecture in a real industrial scenario. In order to achieve the desired level of complexity, methods from Human-Centred Design (HCD), image analysis, distributed control and standards for reference architectures are employed. The system we derived from the ensemble of these methods is experimentally validated in each of its functions thanks to a proper design of use cases. We demonstrate the performances of the HCPS both quantitatively and qualitatively using a user evaluation with workload measurement and estimation of marker position precision.

The paper is organized as follows: initially, the architecture is defined considering the application to an FoF floor and previous research (Section 2 and 3). Secondly, its implementation is explained considering three possible use cases (Section 4). Finally, the system is evaluated in its three core components (Section 5 and 6).

2. Related work

This work proposes an approach with diverse concepts behind. Therefore, this section gives and overview of existing background.

2.1. Safety

The EC machinery directive (2006/42/EC) [17] dictates what rules a certain machine should obey, whether it is a normal robot, a general machine or a collaborative robot. From this law, the guidelines for collaborative robots of the International Organization for Standardization (ISO) were produced. For collaborative devices, the most important are: ISO 10218-1:2011 [19], ISO 10218-2:2011 [20] and ISO/TS 15066:2016 [21]. Moreover, application of ISO 13849-1:2015 [18] and assignment of performance levels does not apply. Mainly because ISO 13849-1:2015 deals with performance evaluation of safety critical control devices. Which is not the scope of this paper. In this set the newest, the ISO/TS 15066:2016, is of undisputed importance because it targets the robots' operation modes. The collaborative modes envisioned by the ISO are: Safety-Rated Monitored Stop (SRMS), Hand Guiding (HG), Speed and Separation Monitoring (SSM) and Power and Force Limiting (PFL). However, their application requires a meticulous and demanding analysis of every risk before adoption. Therefore, there is the necessity to simplify these processes. As one approach, offline simulation can be performed, evaluating impact forces and dangerous scenarios [22] Berg et al. [23] propose an innovative system to integrate safety elements during the design process of the robotic cooperation. The proposal suggests methods which check safety aspects while the application is being developed. Unfortunately, the authors argue that this approach is not yet usable due to current safety standards. Nikolakis et al. [24] propose how a CPS design can give capability to a robotic system to perceive human operators in its surroundings. In particular, the design detects only human shapes to safely slow down manipulators to avoid dangerous collisions. However, all of these methods do not employ safety hardware necessary for integration into real manufacturing scenarios. Hence, when developing a robotic application for manufacturing scenarios, as in this paper, application of methodologies from the ISO standards is mandatory. Furthermore, Aaltonen et al. [25] underlines how the lack of knowledge in safety of collaborative robots poses a big constraint in their adoption. Hence, for closing this gap, this work proposes and describes a safety approach to protect humans in the FoF.

2.2. Interfaces

User interfaces are the mean of communication between robots and humans. The interface can assume different forms but at the end it will try to target one or more human operator's senses in order to control or receive feedback from the autonomous system. Major breakthroughs in this field must be attributed to the introduction of computer graphics, which are summarized in [26]. But one of the largest outcome to underline is the adoption of digital interfaces by robot manufacturers into their design. With this well-established practice, researchers began focusing augmenting graphical computer interfaces and Human-Centred Design (HCD) was found to benefit the human acceptance of robotic systems [27]. Dragan et al. [28] underline how a legible motion is well perceived by a human compared to a goal-oriented one. Similarly, Hoff et al. [29] underline that interface style is strongly influencing the trust of human operators in robotic system. Following these new trends, researchers started focusing on usability, satisfaction and fluency when using robotic interfaces for smoothing interaction between robot and individuals [30, 31], while also trying to focus on personalization of the experience [32]. Within the study, novel input methods for robotic interaction are investigated. One of these is gaze, which sees the user using his eyes to forward some commands to the robot [33, 34]. However, little effort was taken to evaluate and validate these novel input methods in a manufacturing scenario. Therefore, the goal of this research is to validate the efficacy of gaze as robot interface input method. Moreover, in order to fully consider the usability, a HCD approach is chosen to fine tune the interface design to the best usability using well-know metrics, such as workload.

2.3. Design methods

The span of research decreases when focusing on flexible robotic applications and Industrie 4.0 reference architectures. First of all, flexibility, according to the scope of this research, is intended as mean to perceive and interact with the environment while it alters. The most promising approach is using vision system coupled with Convolutional Neural Networks (CNN) giving robots perception of the environment [35]. From this, CNNs range of adoption has extended to several areas, new forms of robot collaborations which interpret flexibility with acquiescent robot teaching methods are one example [36]. Nevertheless, their transition to shop floors is still restricted to some use cases due to computational intense image analysis. Another approach to flexibility is the usage of Radio-Frequency Identification (RFID) or marker technologies. These technical solutions have an upside compared to the vision approach because they require far less power to run, thus being cheaper. Nonetheless, they preserve precision and reliability of camera approaches [37, 38]. However, limited research has been done to leverage these as context aware knowledge for robotic systems. In particular, this work is going to use markers as characterizers of a certain workspace to give environment information to the HCPS. This information is going to be leveraged to allow flexibly behaviours.

2.4. Shop floor digitalization with RAMI 4.0

Reference architectures promise to provide tools in order to flatten the automation pyramid and give a cyber representation of production resources. In the scope of this research a reference architecture has to be applied to a HCPS. Up to now, the main contributions state that new frameworks are needed to integrate humans into the modern production systems [39]. Yli-Ojanperä et al. [40] argue that researchers are proposing CPS without a common understanding of reference architecture models. Nonetheless, this work uses an established reference architecture to exploit context awareness and enable the representation of flexible HCPS across multiple layers of the FoF architecture. More precisely, RAMI4.0 model is going to be used due to its closeness to European markets [40]. The model is structured in three dimensions: life cycle value stream, hierarchy levels and layers as shown in Figure 1. The first dimension depicts the product life cycle, from initial development and design to end of life. The second, represents the pyramidal hierarchical levels in the factory hardware. Finally, the third, pictures properties and structure of the system and can be used to map how high level activities (e.g. business decisions) drive the manufacturing and its digital services. In the scope of this work, the RAMI4.0 is used for providing information regarding human robotic material handling teams to upper levels of the system (i.e. Business Layer). Therefore, the design structure is encompassing a component necessary to provide such information.

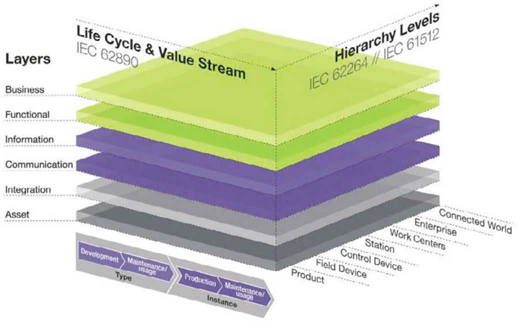


Fig. 1: Reference architecture model Industrie 4.0 [15]

3. Proposed architecture

The architecture described in this paper aims at satisfying the FoF flexibility demand taking a user-centred approach with special regard to safety. The architecture bases itself on the concept of a lean and flexible approach to manufacturing which uses production islands. Those islands are organized in the shop floor, but the value chain from the raw material to finished goods is not a-priori defined as shown in Figure 2. Hence, necessity of a system which allows seamless reconfiguration to every island is necessary. At this point it is fundamental to underline the mapping into the RAMI4.0. Allowing a system to communicate with different islands, is a new concept that is difficult to integrate in standard automation approaches. The concept foresees that this system is integrated at the *Information* Layer. This decision is moved by the system necessity to inform the *Business* and *Function* layers about its location and status. With this information, the *Business* layer can properly plan for production requirements according to market needs and send feedback to the system through the *Functional* layer. Unfortunately, the *Functional* layer of RAMI 4.0 is not ready to forward functions to the system from the *Business* layer [40]. Therefore, the approach results on an architecture which produces information available to the upper layers as shown in Figure 3. The HCPS relates to the production process instance at station hierarchy level. This correspondence is moved by its capability to be part of a manufacturing island once deployed at the shop floor.

The proposed architecture is composed of four modules, as shown in Figure 4. The main units are: environment perception, cobot, interface and enterprise resource planning (ERP). In order to guarantee the sought reliability level, each component of the system has to be designed as stand-alone while being aware of the surrounding systems. Hence, each part is going to have complex internal state machines driven both by internal and external events. Precisely, each stand-alone component in the system should change status upon external events and then elaborate information via internal processes which, at the end, will communicate with the outside systems.

The environment perception is the module giving knowledge about the island and surrounding obstacles. The information is composed of island location, its identification and outer obstacles. This unit must provide this knowledge with a high confidence because the behaviour of other components is island dependent. The approach to this module is going to be tackled with two methods. On one hand, a QR code recognition is going to be used for providing island wise knowledge due to its proven cost effectiveness and reliability as seen in the state if the art. On the other hand, obstacles perception is going to deploy a safe and certified communication channel to properly satisfy demands of safety requirements. Therefore, the environment perception is going to be performed by a safety laser scanner sensor. This was chosen due to its technical feature to define precise space fields were obstacles are monitored. Moreover, safety scanners prove to be widely used when applying safety directives.

The cobot is the core module of the architecture due to its capability to interact with the environment and allow the human operator to allocate tasks. Despite its central role in the architecture, it is important to underline how the cobot is the major source of risks for the application. Therefore, the choice of this device must fall back to specially designed devices which facilitate the risk and safety evaluation. For this purpose a robot with ISO 10218:1 certification has to be chosen. Finally, the cobot must allow connection both through safe and unsafe channels for enabling communication among CPS elements.

The interface is the module to bridge between the digital components and the human operator. Therefore, in this work it is intended as mean of communication between the human and robot. Considering the environment is noisy and the pre-existence of a vast amount of machines with graphical interfaces, an approach with graphical interfaces is chosen. The interface's main goal is to show visual feedback regarding the robot operational status and provide interaction commands for the human operator avoiding increasing the workload on operators. More precisely, the interface uses gaze as input for interaction commands and symbols as feedback of robot status. For uniting these, a HCD approach which tries to empower the human was chosen. This approach, to be undertaken correctly, has to be conducted following the guidelines of ISO 9241-112:2017 [41]. For ensuring that the workload is not increased, user evaluations which incorporate the NASA TLX workload evaluation questionnaire [42] are employed.

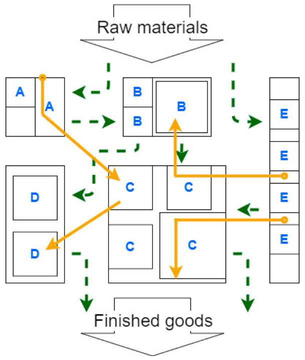


Fig. 2: Concept of island manufacturing. The flow between raw materials and finished good is not a-priori defined. Therefore the HCPS system should be able to adapt to every island at the shop floor.

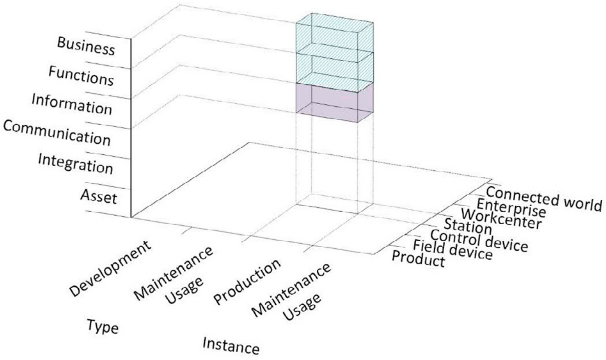


Fig. 3: Mapping of the system into RAMI4.0. The figure shows how the system is related to the *Information*, *Functions* and *Business* layers at the level of production process instance and station hierarchy. The proposed system delivers the information (violet layer) and it is up to the upper level to interpret it and use it (light blue dashed layers).

The ERP is the component to receive data regarding the HCPS. This knowledge is going to be leveraged for assessing performances, resources, schedule production and planning. This unit must bridge between the concept of flexible CPS and the manufacturing schedule. Therefore, it should embed tools and interfaces to allow lean approaches to the manufacturing. However, as previously highlighted, mapping between *Business*, *Function* and *Information* layers is still not clear in RAMI4.0. Therefore, treatment of its design is out of scope for this research. In the proposed architecture, it acts as a passive external device, reading information from the cobot and the environment perception.

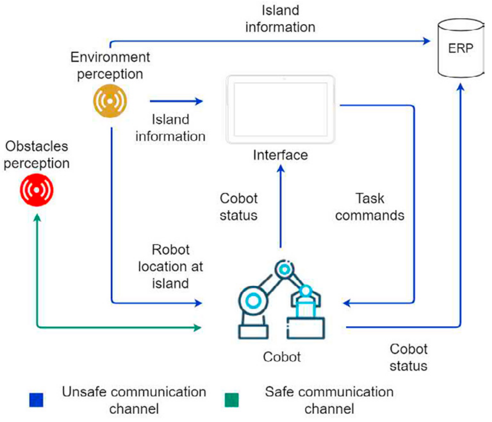


Fig. 4: Architecture of the Cyber-Physical System. The main units are: environment perception, cobot, interface and enterprise resource planning (ERP). Two line of communications are envisioned. One is a safe communication line to promptly communicate obstacle presence. The other is a unsafe one necessary to deliver non-critical control messages for the functioning of the CPS.

Nonetheless, these units need to be driven, controlled and integrate human feedback. Therefore, the architecture needs a distributed control among the modules of the HCPS. Distributed control heavily relies on the sharing of information between the participants. Thus, a suitable communication method has to be chosen. In this case, the transmission of information can be achieved using two channels. The first one is a safe channel between the cobot and the obstacle perception. Using a safe channel, the deliver of important information in time is guaranteed. The second one is an unsafe channel between all the other bodies of the CPS. The unsafe channel is for non critical information and no timing constraint is posed. On one hand, the connection between cobot, interface, environment and obstacles perception is wired through socket connection. This is necessary to standardize among the units. On the other hand, connection to the ERP is wireless through proprietary interface to ERP. This is necessary to guarantee exchange of information while the HCPS is deployed in remote areas.

An equally significant aspect of the design is its mechanical arrangement for accommodating the different units, while retaining flexibility. For this purpose, the design envisions to mount the robot arm on the top of a manually-operated cart, as shown in Figure 5. Moreover, taking safety and usability into account, two modules for obstacle perception are proposed, one in charge of monitoring the front and one the rear. This choice is necessary to guarantee an effective application of the SRMS method on a 360° area as long as the obstacle position is unknown a-priori. For the environment perception just one sensor is selected. This choice is motivated by the sufficient information provided by one marker (identification and position). The sensor is located at the side were the cobot has a maximum extension. Therefore, possibility of interaction with the island is maximized. The last component is the interface. It is envisioned to position the interface at the handler side. In this way the user will be able to monitor the robot's status meanwhile the cart is being moved. Moreover, due to the opposite displacement between the environment perception and the interface, its location is out of reach from the set of robot motions.

The final aspect of the concept is safety. Integration of the safety must follow the regulations. Therefore, considering a general task of HRC, it is identified that three possible risks may arise: collision (high risk), squeeze of human body parts (high risk) and workpiece drop (medium risk). Therefore, it was decided to reduce the risk arising from those through the adoption of SRMS, PFL and a gripper monitoring methods. With these risk reduction techniques, the task was considered safe for human-robot-collaboration.

4. Implementation

Having defined the core components and methodologies in the architecture the implementation has to be considered. Considering the features highlighted in the previous section, especially focusing on safety. It was decided to use a collaborative robot supporting PFL according to ISO 10218 and an Ethernet communication safety protocol, a safety PLC with safe Ethernet communication protocol, a safety laser scanner with safe Ethernet communication protocol, consumer eye tracker, tablet and camera. Therefore, the following were selected: Kuka iiwa™ R820 14, Siemens simatic™ et200sp with Profisafe™, Sick Microscan3™ Pro with Profisafe™, HP™ pro X2, Logitech pro 9000 and Tobii eyeX™. These were allocated according to the concept explained, as shown in Figure 6. However, during the assembly there was an issue with the safety sensor mounting. Due to the cart structure it was not possible to deploy two safety scanners at the proposed locations. Therefore, the design had to be changed and the scanner was mounted in front of the robot arm. Doing so, it was possible for the sensor to monitor the most dangerous area directly in front of the arm. Changed aspect was the introduction of a PLC (Programmable Logic Controller) between the safety scanner and the cobot. This modification was necessary to guarantee the safe communication consistency due to the introduction of a safe module in charge of the low level redundancy checks in the Profisafe™ communication. With this change, it was noticed that selection of the field upon island identifier was not possible. The safety implementation wanted to monitor fields dynamically (e.g. robot arm moves to the right, right part of the CPS is monitored). Therefore, robot arm had to specify its position to the safety controller. In doing so, due to a limitation in the kuka iiwa™ safety configuration, external information (i.e. QR position) was not possible to be integrated. This was mainly due to limitation of the robot safety which can send field signals just through a pre-defined program and not from a custom one. The obstacle detection was tuned to a maximum of 65N and fields of the laser scanner for a well-defined use case were created. The choice to implement these two risk reduction techniques was motivated by the presence of two high-risk scenarios: collision and squeeze of human body parts. Therefore, SRMS was implemented as described to reduce the robot velocity up to halting its motion in order to avoid collision. PFL was implemented to detect abnormal forces, therefore, limiting the damage of

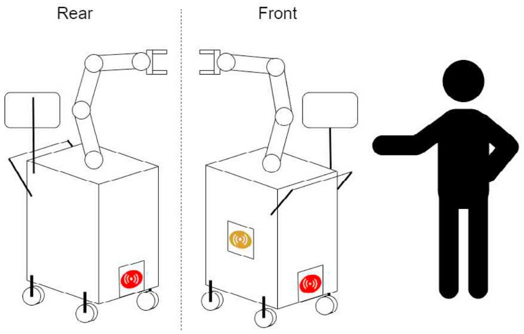
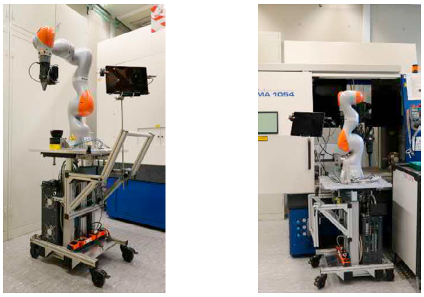


Fig. 5: CPS mechanical arrangement. Two modules for obstacle perception are envisioned (in red), one in charge of monitoring the front and one the rear. This choice is necessary to guarantee an effective application of the SRMS method on a 360° area as long as the obstacle position is unknown. On the other hand, just one sensor for the environment perception (in ocher) is selected. Finally, the interface is envisioned to be dislocated at the handler side. In this way the user will be able to monitor the robot status meanwhile the cart is moved.



(a) Left view (b) Right view

Fig. 6: Assembly of the CPS station. CPS was assembled as specified in the concept. However, the obstacle detection sensors displacement had to be changed due to the cart structure that was not allowing the mounting of two sensors near the base.

possible squeeze scenarios. The effectiveness of safety was evaluated in a special designed use case, as in Figure 10a.

After considerations of these limitations the interface was developed. Referring to the HCD principles the design had to be iterative. Therefore, an initial sketch to understand the evaluation procedure and get feedback on the usage of gaze input with the eye tracker Tobii eyeX™ was obtained. The sketch compromised several buttons which could be activated using dwell time by gaze input and two feedback windows as shown in Figure 7a, buttons are highlighted in colour. With the initial feedback from a small pool of testers it was seen how the gaze dwell input had to be treated with care. More precisely, the pool of users expressed that gaze input was too sensitive and they were afraid to activate buttons just looking at the screen. Moreover, it was seen that the provided instructions for usage were not considered by the evaluators. Due to this feedback three possible other designs were sketched and in the end a minimal design was selected as shown in Figure 7b, buttons are highlighted in colour. Differently from the initial sketch, the number of buttons was reduced from six to five, the gaze input was confined to the central button and a better organization of textual and visual feedback was integrated. As a matter of facts, symbols were created as in Figure 8. The first symbol, see Figure 8a, was necessary to indicate robot was in autonomous mode, thus contact has to be avoided. The second symbol, see Figure 8b, was necessary to indicate that collaboration was possible. Finally, the last symbol, see Figure 8c, was indicating the robot was standing still, thus waiting for a new task. The effectiveness of this interface was evaluated in a special designed use case, as in Figure 10b.

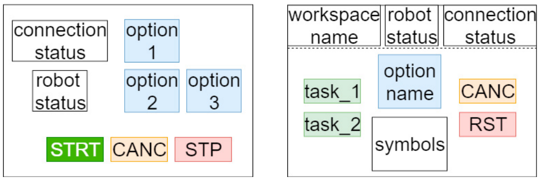
The final component was the unsafe communication and management of the workspaces, including the island recognition and positioning. For this purpose a central program (from now on coreserver) was created to communicate with the different bodies of the CPS. The coreserver was in charge to get the QR position in respect to robot base through the Logitech pro 9000 and forward it to the HMI and the robot. With this information the HMI was then showing tasks island related. Once the operator chose one from this set of tasks the interface communicated back to the coreserver through socket communication and forwarded the information to the cobot along with the QR position. Once the information arrived to the robot main program, it was reinterpreted and a special sub-task was called through a thread giving the end-points location transformed to the QR relative position. Transformation between the input *qrlocation1* to *qrlocation2* was performed using the Homogenous Transformation Matrix and a custom trigonometric method. Choice was driven by impossibility of the robot arm controller to modify frames during program execution. Moreover, during task execution, another thread was opened to send back the robot status to the HMI, following a path through coreserver. The flow of information is depicted in Figure 9. Using this procedure it was possible to implement the gripper monitoring. This strategy was implemented in the HMI which disabled the option to open or close the gripper in certain applications once the cobot communicated its status. This methodology was selected because the risk of workpiece drop was at a medium level, therefore, need for high safety was unnecessary. The effectiveness of coreserver was then evaluated in a special designed use case, as in Figure 10c.

5. Evaluation

Having prepared the uses cases the main components of the design were evaluated.

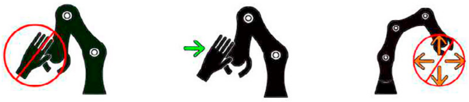
5.1. Safety

With the well defined use case three risks were identified: collision, squeeze and workpiece drop. Therefore, three risk reduction techniques were implemented: SRMS, PFL and grip-



(a) Initial design (b) Final design

Fig. 7: HMI designs. On the left the first design used to get overall feedback for HCD iteration. On the right the final chosen design according to the feedback received. Buttons are highlighted in colour.



(a) Robot in automatic motion. (b) Robot in collaborative mode. (c) Robot halted at position.

Fig. 8: Symbol designs.[1]

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[1] Symbols are taken from [30] and modified after authors' approval.

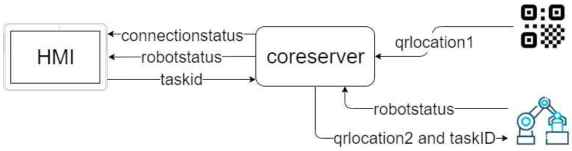


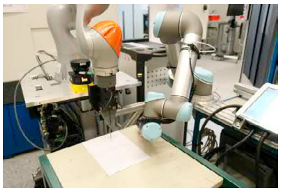
Fig. 9: Data flow between units of the CPS. Coreserver is the central process in the design as long it forwards the data back and forth between the several modules. Connection to the HMI and to the cobot has been achieved using socket communication with properly designed messages.

per monitoring. The evaluation had to assess if the introduction of these three techniques was enough. A procedure to simulate the three hazards was created. For collision and squeeze, the hazards were simulated by entering the dangerous area and obstructing the robot motion. The workpiece drop was simulated by trying to open the gripper during a certain task. The simulation results were obtained as depicted in Table 1. Considering the limits given by the hardware, the outcome was reasonable on a safety point of view.

5.2. Interface

The user interface was evaluated. Or more precisely, the workload perceived by users when engaging with the robot and its interface. For proceeding with the evaluation, a task of collaboration with the robot was identified. In the task, the user had to retrieve a mockup of a manufacturing piece and measure dimensions of two points. After the measurement, he had to write the measures on a sheet of paper. For measuring how the interface was affecting the user, the task was to be performed with three interaction means. The first was the normal interaction mean provided by the robot through a smartpad. The second was the newly designed interface with touch-only input. The last was the newly created interface with gaze and touch inputs. The questionnaire was composed by the NASA TLX scale and a three choice question which was asking what was the preferred interaction mean. In the study participated 19 employees from the research department staff, 15 males and 4 females, M age = 33.57, SD = 13.35. The result can be summarized in Table 2. From the preferred interaction mean the likeness ratio was calculated. The ratio was obtained dividing the number of likes by the number of dislikes. In this calculation it is important to remember that the number of users per interaction mean was the same as the user population. Moreover, a one-way ANOVA was performed to examine the means of interactions workloads and a significant statistical difference was found ($p = 0.002$, Bonferroni corrected). From this it was possible to discover that touch input only interface was the one with the lowest workload, meaning it was the easiest to use.

(a) for safety evaluation. (b) Use case for interface evalutation.



(c) Use case for coreserver evaluation using a supporting robot to calculate ground truth transformations.

Fig. 10: Use cases.

5.3. Design method

The design method was quite complex however, the core component was the island recognition and transformation of coordinates to the QR relative position. Therefore, the evaluation principally focused on this point. For proceeding with the evaluation a tray with a millimeter paper and a QR marker was placed in front of the robot as in Figure 10c. Then, a point was taught to the robot and it was asked to the robot to reach that point after a defined move of the tray. With this method, the goal was to identify downsides of the system in basic transformations, namely in translations along X, Y and rotations around yaw. Motion after tray movement was recorded, and transformation was compared with the ground truth calculated through an additional robot using a three points transformation measurement [43] and a millimeter paper. The results can be summarized in Table 3. On the other hand, the island identification was correctly performed if the QR marker was placed in the camera field of view. Besides the island identification, the design method compromised also the transfer of information between the several units. Effectiveness of this approach was implicitly tested during the user evaluation due to observation of unusual behaviours by the system and direct questions to the participants. At this level, no major drawbacks were identified because the information proved to be reliable. However, a small discrepancy was found when using gaze input. In such cases, if the sensor for eye tracking was not user calibrated, the response to the commands proved to be unpredictable and erroneous motions have been activated.

6. Discussion

The current study investigated and evaluated three design components for a Human-Cyber-Physical System. The first component was safety. In its implementation and evaluation it was found that its integration poses hard constraints on the flexibility of the system. More precisely, during implementation of the SRMS method it was not possible to select a scanner monitoring area upon the island information. With this underlined limitation the degree of adaptability of the HCPS to different islands is strongly limited. Therefore, different safety modalities (e.g. PFL) or use cases with defined position of the HCPS should be used. The second component was the user interface. From the conducted user study it was found that the input method

Table 1: Results of the safety evaluation. The first column describes the type of hazard. The second column reports the deployed safety method to reduce the risk. Finally the last column reports the recorded falls for the employed safety method.

Hazard	Employed safety method	Results
Human enters robot dangerous area	SRMS	Human can enter the dangerous area under the scanner or behind obstacles
Human retrieves a workpiece from the machine	PFL	No risk identified, arm stops at limit
Human stops program when a workpiece is attached	Gripper monitoring	No risk identified, the gripper does not open

Table 2: Results of the user evaluation. The first column represents the interaction typology. The second represents calculated workload mean with standard deviation and median. Finally, the last column represents the likeness ration for the interaction type.

Interaction	Overall workload			Likeness ratio
	Mean	SD	MED	(Y/N)
Normal	16.15	7.22	16.66	0.06
Touch	9.21	3.15	9.00	1.33
Gaze	13.03	5.77	12.33	0.46

Table 3: Results of the design method evaluation. Precision of island position estimation are reported. The second column represents the ground truth movement of the island in respect to the robotic CPS calculated through an additional robot using a three points transformation measurement. The third column reports the transformation calculated by the island position estimation through a QR code.

Transformation	Ground truth	Calculated
X translation mm	-10 mm	-7.36 mm
Y translation mm	+10 mm	+9.87 mm
Yaw rotation rad	-0.069 rad	-0.04 rad

poses different level of workload on the user. In this study it was found that an interface with touch input method was better performing than one with gaze input if workload was considered. Therefore, users interfacing to robot must be supported by easy and understandable input methods. Finally, the design method. It was found that direct communication between ERP and the proposed HCPS is still not feasible due to lack of information regarding the interface between those components. This is due mainly due to the absence of *Functional* layer in RAMI 4.0. Secondly, it was found that QR codes do not fully respect the requirements for island recognition due to poor position estimation capabilities if a low-range camera is used. Therefore, different island recognition methods or cameras should be used. Thirdly, the distributed control proved relevant to integrate different functions while maintaining the core aspects of every component (e.g. safety of the robot arm). However, this poses a strong constraint on the communication channel which should be designed beforehand and properly tested in more scenarios than the one here proposed.

7. Conclusion

Factories of the future will have an important role in delivering personalized items to a large customer base. To do so, they require a level of flexibility never seen before. Therefore, this paper presents a novel approach to flexibility with a conceptual architecture. The design compromises an ensemble of different units, all connected by communication channels. The goal of the architecture is to integrate human-robot-collaboration by addressing: safety, interface and design methods. Implementation of the architecture had to consider limits given by hardware. Of those limits, the most influencing one was given by the safety hardware which was not allowing the required degree of flexibility. Nonetheless it was possible to propose a HCPS which can adapt seamlessly to different islands and accommodate requirements for future production scenarios using the intrinsic adaptability property of operators. However, further elaboration is necessary for ensuring their applicability to larger scale manufacturing due to the necessity of more resilient technologies, interconnected architectures and flexible safety.

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