Implementing a Human-Robot Collaborative Assembly Workstation

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Abstract— **Over the last decades, the Industrial Automation domain has exhibited an exponential growth of robots' deployment at factory shop floors. The main objective is to increase efficiency and productivity at a reasonable cost, which is lowered thanks to the robot lifespan. But not all the manual tasks, the tasks requiring high-level of dexterity, are yet replaced by robots. In fact, Europe is moving towards the creation of efficient workspaces where both robots and human operators can work safely. In this context, there is a clear intention of achieving solutions that involve collaborative robots, a.k.a. "*cobots*" or co-robots, for permitting a safe interaction between robots and humans working for the same or interrelated processes. Many manufactures started to present their products but those arrived before the industry have clear and several needs of this particular technology. This article presents a human-robot collaborative assembly workstation, composed by the ABB YuMi robot that interacts with a human operation in order to assembly a product box, as a part of a large-scale process. Assembly process, workstation design, implementation and its validation are illustrated. Then, this paper aims to summarize advantages and challenges of implementing cobots by exemplifying a real scenario of collaborative interaction between a cobot and a human operator, feasible to implement at any industrial facility.**

Keywords— Human-robot interaction, Human-robot collaboration, cobots, Industrial applications

I. INTRODUCTION

The industrial revolution represents the changes that occur on the manufacturing systems to address market demand, efficiency requirements, and cost reduction, among others. The key target has been always reaching the maximum outcome from the available resources, equipment and technologies [1], [2]. Within such industrial evolution, the human role has been limited and their presence depleted on manufacturing, due to the increase of the automation level. Nonetheless, the human is still an essential resource at the factory shop floor in several industries due to the high intellect and versatility that human kind hold [3]. Therefore, instead of aiming at fully automated processes, which may increase cost and setup resources [4], a safe mix between humans and robots targeting collaborative manufacturing, might represent an effective technical solution.

In this context, collaborative manufacturing tends to reduce the gap on complex processes in terms of shared tasks between the existing resources at factory shop floor, increasing time and energy efficiency on the process [5]. In turn, collaborative manufacturing could increase the complexity of processes modeling due its dependency between two independently controlled resources (human and robot) while executing tasks.

The Human-Robot Collaboration (HRC) became lately a special division of the collaborative manufacturing. The HRC represents a homogenous skill sharing between the human and the machine in order to achieve tasks more efficiently [6]. More precisely, the human capability of fast cognition and flexibility in kinematic skills, complemented by the high repeatability, accuracy and reliability of the robot provides capability of handling complex processes. Is important to emphasize the collaboration in HRC focuses on parallel task execution by the human and the robot. In addition, the most raised concern about HRC is the human safety at the shop floor. This generates safety concerns, since collaborative robots "*cobots*" might present a revolutionary work architecture, which does not include the use of mechanical barrier methods (fences) [7].

Recently, several research works address the development and evolvement of the HRC. On the other hand, another objective is including the latest advances in the technology to ease and simplify the collaboration. The European Commission presented possibilities for funding HRC project under the Horizon 2020 framework (H2020). This fund was mainly targeting the Factories of the Future (FoF) and the Digitizing and Transforming European industries and services (DT) pillars. In such context, the European funded project titled as Zero Defects Manufacturing Platform (ZDMP) [8] provide funding for this research. ZDMP aims at providing flexible platform for handling defects in products and processes. Consequently, the objective of the presented research is to summarize advantages and challenges of HRC at the shop floor, demonstrated by using an ABB cobot known as YuMi [9] and involving an operator for assembling a box to be used for packaging final products. This use case is part of the assembly process at the Future Automation Systems and Technologies Laboratory (FAST-Lab.) research environment at Tampere University. Additionally, this lab is part of the experimentation and validation facilities for the ZDMP project.

The rest of the document will present topics as follows: Section II provides a view on the state of the art of cobots in the domain of Human Robot Interaction. Section III presents the approach and the pilot for testing and validation. Section IV includes the implementation of the approach in the research lab. Section V provides the discussion. Finally, Section VI concludes the paper.

II. BACKGROUND

A. Human Robot Interaction (HRI)

Definition of robots diverges between authors. Although, many descriptions follow a technical approach based on early robot concepts, motivated to perform applications of industrial automation, by means of automatically controlled, reprogrammable, multipurpose manipulators [10]. Nevertheless, the impact in humans caused by the increasing presence of automated devices and further integration of cognitive features on robotic autonomous systems, made matter of research the interaction and coexistence of both entities in renovated environments, traditionally exclusive for humans. Diverse technical and social aspects from these new environments shaped the current concept of Human Robot Interaction (HRI).

To illustrate HRI as the study of association between robots and humans, several authors compile and categorize its attributes by means of a taxonomy. For instance, A. Yanco, proposed 11 categories including *level of shared interaction among teams, interaction roles, type of human-robot physical proximity, time/space taxonomy* and *autonomy level/amount of intervention* [11]. Each category proposed, allows a general evaluation and understanding about the possible scenarios of humans and robots working together. On the other hand, G. Michalos, gives more relevance to assess the workspace and task participation [12]. Both approaches, gave relevance to categories describing workspace use and active time ratios.

Probably, the most prevalent classification parameters on HRI taxonomy, associate time and space with physical and cognitive interaction. For human-robot collaborative tasks, there is simultaneous coexistence of human-dependent processes. Other cases as cooperative tasks can rank as shifted coexistence of independent processes. In this context, cooperative (shifted) tasks require the robot or human to be on idle state at the time, while the counterpart works. In contrast to collaborative tasks, which require the robot to handle process parts statically or dynamically, while human manipulation is ongoing simultaneously.

General interaction paradigms can also contribute to depict HRI. Interactions controlled by humans as the one presented by H. Tang et al. performing human-robot collaborative teleoperation for reconnaissance robot [13], contrast with autonomous applications as the one presented by L. Rozo et al. about collaborative robot behaviors from human demonstrations [14].

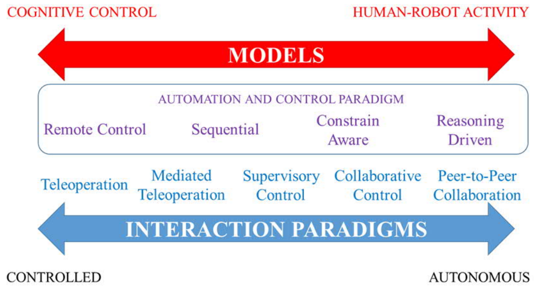

Fig. 1 Interaction paradigms associated to HRI, based on Fig. 71.11 of [15]

Fig. 1 presents a simplified classification of paradigms on HRI, inspired on cognitive characteristics. It allocates collaborative interaction closer to autonomous paradigms, following a model of robot – human activity, commanded under safety constrains for the study case presented on this paper.

Multiple paradigms and attributes of HRI, together with popularization of specialized robots on industrial or service/social purposes, reshaped research goals on robotics. Industrial HRI focused on control, safety for human workers from and process optimization, as seen on [16], [17] and [18], while social HRI, focused on behavioral and social comfort of humans aided by robots, as presented in [19] and [20]. Certain considerations related to psychosocial human behavior might influence industrial HRI. For example, S. Stadler et al. describes in [21] that appearance and expectations of robot users might vary, depending if the robot has a shape of a person (anthropomorphic) or it just look like a machine (functional). This esthetical detail depends on the perception from the user about the robot; people associate anthropomorphic robots as a possible work partner. Another study presented by D. Bortot et al. about human behavior influencing industrial HRI, confirmed the hypothesis that robots moving near humans in rectilinear displacement paths, creates a human well-being perception, since humans feel in control when can determine predictable dynamic situations [22]. This study gives important clues to improve industrial HRI on collaborative work scenarios.

B. *Human on future manufacturing*

In a contemporary industrial environment, large-scale manufacturing tend to rely on automated processes by means of devices such as controllers, instrumentation, robots and interfaces. Social impact of automated robots usually carries the concern about loss human jobs, since technologies implemented in devices and processes as Artificial Intelligence (AI), enhanced its systems to predict and have certain level of reasoning comparable to human capabilities, or sometimes even better.

This situation leaves human skills relegated and obsolete on reasoning, heavy, repetitive or precision tasks [23]. However, this situation is not new on human history. Previous periods known as industrial revolution, included mechanization of manual tasks, inducing a radical change on the productive structure, but giving new opportunities and better living standards to the working class, since population could focus on areas with superior impact. Predictions about the role of humans on future manufacturing augur to be exclusively on creative skills and other occupational areas that might require imperative social intelligence and empathy as education, hospitality, healthcare and tourism [24]. On the other hand, occupational expectancies for technicians are every time closer to the growing demand of experts in robotics and AI.

C. *Partially automated processes*

Supervised robotic processes such as remote ship operation or crane driving require limiting intentionally the mechanical scope of machinery, for safety, quality check or just user comfort purposes. These processes require room for activities exclusively performed by humans. Those cases classify into Partially Automated Processes (PAP), which is the target of survey.

Justify the dependency of humans in manufacturing can be complex, since robots on the market can make look very simple several human mechanical skills. Still, there are clear examples of PAP as *partially automated driving*, a step taken by car manufacturers to get closer around autonomous cars [25].

Because of regulations and technological limitations, safe operation of autonomous cars is not a feature available in commercial models, but major improvements on driving experience are already integrated to new models, as highway pilot, which merges cruise control and lane-keeping systems, creating a combined function automation for assisted driving [25]. Conceptually, partially automated driving can represent a use case of HRI in a partially automated process.

D. Cobots

Collaborative robots are manipulators intended for direct physical interaction with a human operator [18]. On industrial scope, the German Institute of Occupational Safety defines them as *"complex machines which work hand in hand with human beings"* … *"in a shared work process, they support and relieve the human operator"* [26]. Primitive models of cobots relay on humans to overcome quick reasoning and vision guided processes, as explained by car assembly examples on [17]. In that case, a human guided manually a manipulator carrying heavy parts for assembling, while the cobot simultaneously steered the manipulator, restricting its trajectory through predefined surfaces to avoid collisions. Lately, technology covered reasoning and image processing by AI and Machine Vision (MV) applications as the one presented by Lopez-Juarez et al. [27]. However, processing of the aforementioned technologies demanded high use of computational resources, pushing to explore cloud base solutions, but creating a new vulnerability on security, already addressed by S. Olaiya et al. [28].

Then, the goal of cobots was matter of discussion and escalated to be matter of international standardization, since the principles of coexistence and simultaneity with humans prevail among manufacturers and academics. Standards helped to rethink collaborative robotics as descriptive features to comply functional safety, like any other end-user product [29]. The International Organization of Standardization (ISO) released the standard ISO 10218 on 2006 and updated on 2011, for safety requirements on robots (part 1) [30], together with robot systems/cells and applications (part 2) [16], adopted by the American National Standard Institute (ANSI) on 2012 as [31]. This last, specifies the requirements for collaborative operation. Visual indication while the robot is in collaborative operation is mandatory and one or more of the following:

- Safety-rated monitored stop (IEC 60204-1 Category 2): In presence of an operator or obstruction, the robot should ensure stop-motion, keep the electrical motor drives on and resume motion after the obstruction clears, without any additional action. Additional methods of stop should be available in case of stop condition violation.
- Hand guiding (Emergency stop and enabling device): The robot should stop in presence of the operator and wait for enabling to activate the motion leaded by the operator through direct interface. In this way, the operator can sculpt poses or teach spatial targets. Non-collaborative operation can continue after the operator leaves the workspace.
- Speed and separation monitoring: Separation distances should be monitor by scanners, vision systems or proximity sensors. Robot speed directly correlates to separation or distance between the operator and manipulator. Predefined zones in function of speed of both (human and robot), reaction time of the robot/ detection system, intrusion distance capability (extend extremities), position uncertainty for both; can dictate the maximum allowable speed of the manipulator. Moreover, stop condition should activate, following the Safety-rated monitored stop requirements.
- Power and force limiting: Operation of robot is limited in energy to avoid harm on the operator. The manipulator design eliminates pinch points, sharp edges or any other physical characteristic hazardous for human direct contact. The robot should be able to detect and react at direct contact. This part requires risk assessment, since depending the part of the human body where the effective force is applied, hazard threshold may vary. Application can influence drastically the power and force limiting, by changing postures and avoiding sensitive body areas.

Lately, ISO/TS 15066:2016 carried out the standard specifications for industrial collaborative robots, based on discussions from [30], about variations on energy, speed thresholds and contact areas to avoid pain or injury on humans during incidental contact [32]. Nonetheless, concerns about the impact on production efficiency from complying safety arouse, especially because limiting energy on manipulator, also might limit productive characteristics as payload, disabling the robot to execute other functions different from collaborative.

E. Previous work on collaborative robotics

Several experiments on automation and ergonomics focused on assess the capabilities and suitability of collaborative robotics on manufacturing scenarios. I. Makrini et al. presented on 2017 a technological structure for human-robot assembly tasks, including gesture recognition for control purposes, face recognition together with human-like robot behavior to integrate ergonomic metadata facilitating intuitive interaction and visual inspection for manufacturing process improvement. A Baxter dual arm cobot was used in this experiment to validate the structure [33].

Another experiment, carried by A. Cherubini et al. on 2015, assessed the use of cobots to assemble a car homokinetic joint (Rzeppa joint) able to transfer power between drive shafts trough a variable angle but constant speed, limiting mechanical friction and play. This task includes the insertion of spherical parts, which was in charge of operators, but it might generate Musculoskeletal Disorders (MSD) in long term, due the positions and loads manipulated on the process. Implementation included a work cell equipped with a collaborative robot (KUKA LWR IV) aided by machine vision application and following the standards available for speed monitoring besides power and force limitation. The experiment demonstrated that even the process cycle was longer, the burden for operators was lower, decreasing drastically the costs related to MSD, and opening the possibility of having rapid return of investment by improving the process speed in future works [34].

Collaboration between humans and robots analyzed by V. Villani et al. on 2018 presented safety, intuitive programing and interaction methods as the biggest limitations in the matter. In addition, the importance of increase the penetration of collaborative robots on manufacturing should guide future research on the field. While performance-oriented solutions can address current issues, such as safety, the costs of robots and capability to upgrade older technologies to collaborative features can be an opportunity to small and medium-size companies. Finally, a prospect to improve cognitive processing skills and shared autonomy capabilities can enable cobots to assist human workers not only by mechanical means but also cognitive effort reduction [35].

III. RESEARCH PILOT

A. *Manufacturing process in the FAST-Lab.*

The FAST-Lab owns an experimental environment where automated devices are set up to operate in multiple demonstrative industrial manufacturing processes. The laboratory is equipped with robots such as a Mobile Industrial Robot (MIR), a dual-arm robot, a collaborative robot (ABB YuMi) and multiple stationary articulated robotic arms, merged into the existing manufacturing cells in both, the FASTory and FESTO production lines. The latter are production lines based on material handling.

One of the core research topics in the FAST-Lab is the application of integration technologies to enable the coordinated operation of assorted manufacturing devices, based on industrial communication standards. The idea behind including various types of robots in FAST-Lab. is to have an automated system demonstrative and scalable, where researchers can implement interoperability scenarios, following innovative technologies and architectures, demonstrating concepts of usability. All of this, without being forced to use one-type technologies from same service providers and manufacturers.

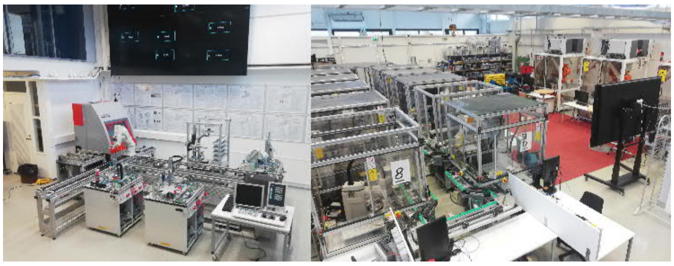

Fig. 2 FAST-Lab facilities. Left: FESTO line. Right: FASTory line

In the context of this research, the implemented process starts by feeding raw material into a pallet. Materials are stored in a rack, reachable by a dual arm robot, then, an orchestrator system lead the pallet over a closed loop conveyor system, running through 11 workstations, where is possible to order 729 product variants out of 3 components, with 9 different characteristics (3 models in 3 possible colors). After production, the pallet returns to the initial cell, where the same dual arm robot picks the product and loads it into a transport basket. FAST-Lab bases its coordinate interoperation by using an orchestrator system, which is a software component in charge of execute services and provide information about the status of the automated system [36]–[38]. The orchestrator system checks if the order requested is completed or the basket is fully loaded in any of the last cases it processes a service requirement for a mobile robot, to transport the product basket to the next stage.

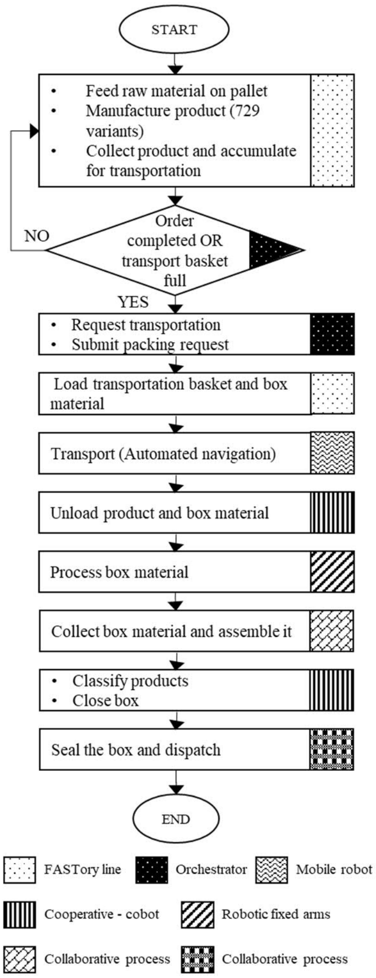

Fig. 3 Flowchart of FAST-Lab process

The dual arm robot loads the product basket and materials for the box on the mobile robot. Then, the orchestrator requests the mobile robot to continue its way to the next stage. The mobile robot navigates autonomously through the laboratory and stops beside the collaborative workstation, where the basket can be loaded on the collaborative workspace and the box can be loaded for preparation. At the time, two stationary articulated robotic arms, label and palletize a pre-made box, brought to the collaborative station by a conveyor belt. In the collaborative workstation, human and dual arm cobot assemble the box, then the collaborative robot scan and classify the products using a built-in machine vision application. To conclude, human and robot finalize the packing process by closing the box and dropping it to delivery.

B. *Considerations*

Since the scope of research comprises the collaborative workstation and adjacent processes, the FASTory line process will not influence the experiment. However, the integration of the automated systems interacting with the collaborative workstation relies its operation on Ethernet technologies and Representational State Transfer (RESTful) web services. The prototype implementation will have wired Ethernet network. Nevertheless, wireless links must be available for mobile devices as the MIR or the collaborative interface. This will expose how reliable are the integration technologies running over mixed link technologies. Simply put, the local laboratory environment has strong influence from previous research works on service-oriented architectures presented on [39], [40]. This can provide efficient interoperation methods for this research.

Human handling of process parts can have negative effects on the precision while the robot tries to fit them, due cumulative dynamic error. Since the experiment does not contemplate any image monitoring technology to improve fitting by guiding the manipulator, the operator can correct manually the grasping positions of work pieces taken by the cobot, without triggering any torque alarm. Additionally, to describe better the dynamics in charge of the cobot, the hierarchy of manipulation of its task matches the classification of goal-coordinated, stablished by Smith et al. in [41].

The assembly workstation depends mainly on the collaborative workspace structure. It must facilitate not only simultaneous and coexistent work between the cobot and operator, but multiple tasks as collecting product baskets and box pieces coming through the MIR and side conveyors respectively, or hold the components in a predefined position and keep tools accessible to the operator. Additionally, the grippers installed on the cobot should give it proper grasping characteristics for the tabbed box faces and any other item involved on the process.

Planning the assembly procedure and coding it, should follow independent execution for each arm in the cobot. In addition, the demonstrative purpose of the process will integrate discontinuous workflow for the cobot itself and tasks involving human interaction; this might demand synchronization techniques on the code as synchronization flags or simultaneous bi-arm dynamic execution. Whereas teaching spatial targets for the cobot can follow simple hand-guiding (lead-through) features. To simplify the code on the cobot, trajectories will follow end-to-end paths. Thus, execution of dynamic tests might expose singularities and zones out of reachability, since the displacement relies on the embedded kinematic solver; then, adding via points can be necessary to make effective displacements. Overall, the workstation should allow completing the collaborative and cooperative processes in a safe way, with enough precision to fit all the tabbed faces of the box or allow the operator to correct it manually, without creating any warning or interrupting the automated process running on the cobot. In addition, the interface selected for displaying information from the cobot and capturing commands form the operator is a 12 inches tablet, located in an easy-accessible area of the collaborative workspace. This device will have timed alerts in case of detecting unexpected execution times, buttons and visual alerts.

C. *YuMi*

As shown in Fig. 4, the robot used for experimentation is YuMi, a dual arm cobot produced by ABB. Each arm has 7 Degrees of Freedom (DoF) and includes a smart gripper equipped with one camera and pneumatic suction cups. TABLE I presents general technical specifications of the cobot.

TABLE I. YuMi IRB 14000-0.5/0.5 specifications

Feature	**Value**
Total number of axes per arm	7
Number of arms	2
Protection	IP30
Reach per arm	559 mm
Payload per arm	500 g
Max Tool Center Point (TCP) velocity	1.5m/s
Max TCP acceleration	11 m/s*s
Position repeatability	0.02 mm
Total weight (without stand)	38 kg
Communication Interface	100/10 Base-TX Ethernet

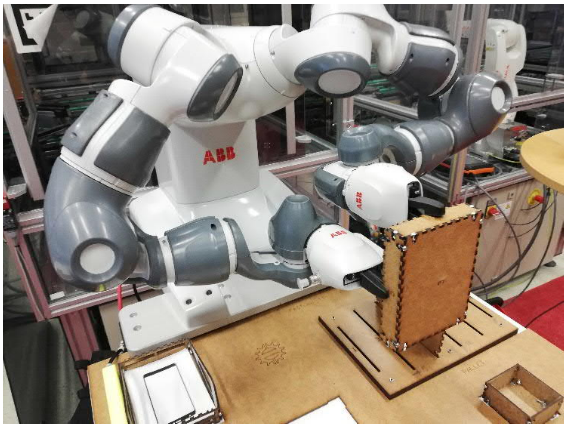

Fig. 4 Cobot holding process parts during collaborative assembly

D. *Collaborative process description*

As aforementioned on section III.A, the collaborative task consists in assembling a product box. The creation of mock-ups for production boxes consists in assisted designs from MakerCase [42], shown in Fig. 5, made of 3mm thick Medium-Density Fiberboard (MDF), processed by a laser cutting machine. Each box face has 6mm width square tabs and slots for fitting, with 0.2mm tolerance. In addition, faces provide fastener slots on every vertex. The assembly process runs over a designated collaborative workspace, which has slots and labels for all the components required. Activities start after fitting a pallet into a slotted location on the workspace, which transports six tabbed faces organized vertically, to build the product box. Then, the operator should indicate readiness to start, by using the tactile interface. Immediately, the cobot should grasp one piece using each arm (labeled as 1 and 2) and fit them in front of the operator, who will tie manually the first fastener using an Allen key, while the robot holds the faces. Fasteners are M3 nut-bolt preassembled pairs with hexagonal socket head. Afterwards, the robot will fit sequentially faces 3 to 5 by picking one piece at the time, using one arm, while the second arm will hold the box partially assembled. Every time the robot fits one face, the operator should tie as many fasteners as indicated on the interface, and confirm completion by tactile commands, available on the interface as well. After joining the initial 5 faces, the robot will place the box on the packing slot, concluding the collaborative process and moving to a cooperative one.

Cooperative process consists on shifted tasks executed individually by the operator or cobot. The cobot performs visual identification and classification of products. To conclude, it grasps and fits the top cover for the box. All the sequence executed for the cobot is completely automatic and based on embedded technologies offered by the built-in controller. The task continues with the operator closing the box by fastening the top cover on four points, and finally removing the box to a delivery container.

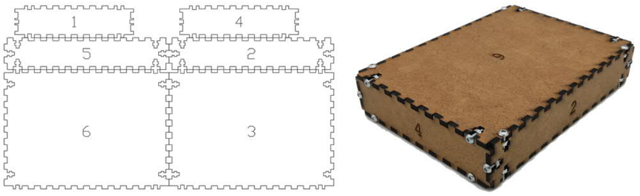

Fig. 5 Mock up template of product box (155x25x110mm)

IV. IMPLEMENTATION

A. *Design of workstation and tools*

Mechanical design of the collaborative workstation follows functional requirements. The standard height from floor level is 82 centimeters. Reachability of all robots involved on the general process influenced the height selection, considering essential the ergonomic recommendations for work surface from section 4.1.6.1. of [43]. This dictates the height of the work surface reachable of the cobot on the collaborative workspace, MIR cargo stands and side conveyors.

Workspace distribution correlates with cobot reachability and convenience to avoid collisions between cobot arms. The design includes a slotted labeled surface to place in predetermined locations all the implements and materials necessary on the process. While, the gripper tool designed locally and 3D printed on engineering grade thermoplastic [44] with carbon fiber reinforcement, consists of two tip-extruded fingers, with rubber padding for enhance frictional contact point area [41].

B. *Code development and teaching*

As explained on III.B, an early version of the code based its command sequence on end-to-end paths. Initially, the program was developed and executed on virtual environment for testing purposes, but as expected, the kinematic solver leaded the cobot through singularities, making the development tasks ineffective and time demanding. Then, it was necessary to redefine the targets by hands-on methods as lead-through and pose sculpt over the manipulators. Validation of dynamic readiness required running the code sequentially for each path, so the developer could define the following target by sculpting its pose from the last target and observing how the kinematic solver leaded the robot to run the pat. Then it was possible to create new displacements doable for the cobot and acceptable for human interaction on the process.

Afterwards, was possible to observe the adverse effects on repeatability caused by involuntary displacements on the cobot's grasping position during teaching, this formed considerable cumulative error and low accuracy on the fitting tasks. Effective target teaching required combined methods, such as remote-controlled jogging (linear and single joint) together with pose sculpt on lead-through mode. Additionally for this application, the fitting tolerance is just 0.4mm (double side 0.2mm), thus, the fitting process required optimization by means of programing simultaneous displacement on opposite directions to approach and contact movements.

Finally, Image acquisition and recognition was developed using the ABB vision module on IRB 14000 gripper, equipped with a Cognex AE3 camera (1.3 Megapixel, 6.2mm f/5 lens). Image recognition relies on Cognex In-Sight software engine (PatMax). Results gave accuracy of 100% on twenty attempts; even the detected similitude of the different mockup product models was always higher than 80%.

C. *Testing*

The collaborative process went through testing on real environment fifty times with two people. Overall, average results in accuracy (95 %) and precision (72 %) are acceptable. However, human intervention has considerable impact on the workpiece handling precision. The average execution time for a skilled operator alone is 255 secs, in contrast with 358 secs, spent by the cobot collaborating to the same skilled operator, increasing roughly 40% the process time.

The built in interoperability method used by the cobot, allowed it to interact with a remote orchestrator by using WebSockets; while other services used RESTful requests (cobot, Interface, MIR). Results of asynchronous service requests were successful, since there was not noticeable delay on execution and mixed connectivity (wireless and wired) gave reliable connectivity. Fig. 6 depicts the structure and methodologies to achieve interoperability.

The information system (orchestrator) for the research pilot relies in a web server developed in Python 3.6 using libraries as sockets and Flask-Socketio, which run on independent threads. The robot (client) connects and generates events with code numbers, handled and processed by the WebSocket instance at the server, which creates a reaction visible in the web interface (HTML) using events generated through Flask-Socketio.

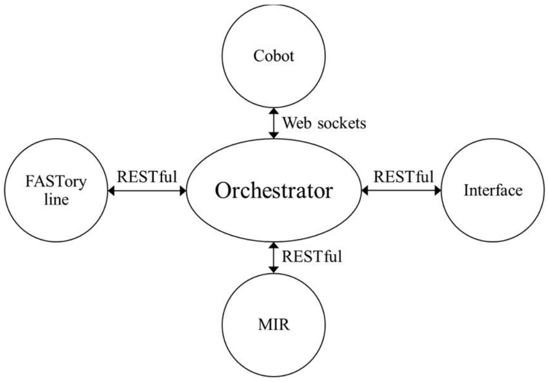

Fig. 6 Structure of interoperability methodologies

D. Cobot implementation assessment

As regards the background and implementation sections of this document, TABLE II presents the results of the assessment performed by the authors about implementing a human - robot collaborative assembly workstation

TABLE II. Assessment of implementing a human-robot collaborative workstation

Advantage	Challenge
Cobots simplify human role in manufacturing	Cobots require high economic investment, compared with labor costs
Standard collaborative features allow safe simultaneous coexistence of robot and human	Compliance with human – robot collaborative standard features based in human safety, reduce robot's agility and force capacity (40% extra time, 500g payload)
State of the art in HRC and HRI gives clear guidelines for better human – robot coexistence (Anthropomorphism, rectilinear paths, etc.)	New technologies should be implemented on cobots to sense and interact with information about human behavior (operator)
Cobots reduce the technological gap between conventional robots and human dexterity skills	In the near future is feasible that humans will need to find and focus in areas of knowledge with superior impact and enhance human-exclusive skills
Collaborative robot standard features facilitate programming by demonstration, lead-through or pose sculpt	Motion controllers in cobots must be ready to solve and execute paths efficiently, being aware of new workspace scenarios where humans are part of the work environment and will be able to modify it anytime
Feasibility of cooperative and collaborative work between humans and robots is demonstrated	Cobots need more development to match capacities of conventional robots, as agility and force, without any impact on human safety
Cobots can include any additional task beside manufacturing to improve the user experience	Commercial cobots require to include interfaces to achive empathy / comfort / esthetic behavior that satisfy and engage human users

V. DISCUSSION

Given the results from the experiment, is can be concluded that a cobot, e.g., the ABB YuMi, can execute a human-robot collaborative assembly process within acceptable precision, accuracy, coexistence and simultaneity parameters without harm a human interacting directly on the process. On the other hand, process times are the major concern, since better working conditions for operators might reduce the work pace. Still, integrating effectively technologies that can benefit humans without compromise productivity features is a challenging goal for contemporary research.

Other factors inherent to partially automated processes, as uncertainty on human intervention times can find solutions by collecting and analyzing process execution data. Besides, this situation excels opportunities for alternative benefits of using cobots, which can be an important source of data about human behavior on future manufacturing.

Initial judgement from local contributors about the simultaneity of tasks as key factor to determine collaboration, was strictly limited to concurrent displacement of the cobot and operator. However, tasks with imperceptible displacements or position holding never ranked as collaborative. Later, in consensus, the authors agreed to accept position holding tasks as an active function, since control systems and drives on the cobot are acting over the manipulators. Then it was possible to formulate the demonstrative process presented in the research pilot.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents the design and implementation of a specific process and workstation to demonstrate human-robot collaboration for assembly part-based products. More precisely, the article illustrates the assembly of a box built by collaborative tasks carried out by a human operator and the ABB YuMi cobot. In turn, the actors of the presented scenario are working at the same time and workspace without the need of physical barriers i.e., fences.

Besides reporting the experiment and the final version of the assembly workstation, this article aims to present and assess a real application with a true collaborative work between the operator and cobot. Many existing works present "collaboration" as a process composed by sequential action (shifted), without any simultaneous and coexistent (parallel) task performed by robots and humans.

In general, such works present the parallel or collaborative work as the summation of holding process parts and manipulation actions performed by robots and humans respectively, which correspond to a former definition of cobots. However, the process presented demonstrates that current denomination of cobots, follows standard features of a robot, focused on fulfill safe operation for humans interacting directly on the processes, breaking the traditional paradigm of reduce risk by limiting exposure (fences and indication).

Further, the authors plan to evaluate the complete integration of this process as part of a larger one, where product variants and orchestration play a more important role among several robotized workstations at different levels and scenarios of automation. Another future works might contemplate the implementation of enhanced machine vision applications for workspace context awareness, product quality assurance, face recognition features for security and ergonomic adaptability purposes, together with behavioral features as integration of social HRI to improve workplace environment and comfort perception of operators.

ACKNOWLEDGMENT

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