Human–Robot Collaboration in Industry: Threats and Opportunities

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Human-Robot Collaboration in Industry: threats and opportunities

Dario Antonelli, Giulia Bruno

Department of Management and Production Engineering, Politecnico di Torino, Torino, Italy

Mobile: +393316923928 – E-mail: dario.antonelli@polito.it; giulia.bruno@polito.it

Abstract

The steep rise of interest in Collaborative Robots applied to industrial tasks is a fallout of the emergence of Industry 4.0 in most industrialized countries. Workcells with both human workers and robots employed together extend the field of use of robotics to medium and small series productions. In a collaborative workplace, robots and humans can exploit to the best their mutual skills and strengths. With the goal of supporting Collaborative Robotics, the paper points out several issues that may arise by introducing robots in manual production. Paper's statement is that success of collaborative workcells in manufacturing relies on dedicated and accurate design activities and should not be approached by a mere addition of a robot to the existing workplace.

Keywords: Human Robot Collaboration, Communication, Man-Machine System, Industry 4.0, Automation, Ontology, Assembly, Robot Programming, Flexibility.

1. Introduction

The interest and even the enthusiasm that worldwide industrial operators and academic researchers show toward human-robot collaboration (HRC) in the framework of industry 4.0 is undoubtable and surely positive. In several European countries, there have been introduced supporting policies that made affordable the transformation of existing equipment with new collaborative models that are compliant with industry 4.0 guidelines (Almada-Lobo, 2016).

Principal robot manufacturers already produce collaborative robot models, expressly designed to allow human workers to share workspaces with robots. For the introduction of collaborative robots in industry, the starting point was the ISO Technical Standard 15066, published in 2016, that specifies the safety requirements to be followed by collaborative industrial robots. ISO TS 15066 completed the revised safety standards for industrial robots ISO 10218-1 and ISO 10218-2, published in 2011 (Rosenstrauch, 2017). Since 2016, collaborative robotic was made possible in industry with all the necessary security guarantees.

From the viewpoint of robot manufacturers, collaborative robots became a new market opportunity for their products, extending the existing one. Until then, industrial robots were only used in fully automated work environments. The high fixed costs of an automatic plant and the need for a complete standardization of the process limited the use of robots to factories where mass production was carried out. Following Hägele (2016): “Today’s industrial robots are mainly the result of the requirements of capital-intensive large-volume manufacturing, mainly defined by the automotive, electronics, and electrical goods industries.” Presently industrial production is evolving towards smaller batches and customized products. They need a degree of flexibility that it is not obtainable in a full automated workstation. The collaborative human-robot workcell is a solution to this issue.
The technical challenges for robot manufacturers are described by De Santis (2008) with the term *dependability*. Dependability is the sum of different, partly correlated attributes:

- Safety: avoid damaging users and working environment.
- Availability: service readiness.
- Reliability: continuity during the time of available service.
- Integrity: absence of incorrect changes to the system.
- Maintainability: ability to overcome equipment outages.

These challenges have been addressed by robot manufacturers and it is possible to assert that the current generation of collaborative robots guarantees dependability to a degree sufficient for many industrial applications by conforming to safety standards ISO/TS 10218.

From the viewpoint of industrial robots’ users, there is an appealing prospect: being able to execute processes for small volume productions, joining the accuracy and the force of robot with the dexterity and the flexibility of human. The most frequent objections are not technical but related with social and psychological factors: the fear that robots could steal jobs to humans and the lack of confidence when working in team with a non-human partner. Therefore, the human-robot collaboration is collecting agreements but also some concerns regarding psychological stress induced in the human team. Although these issues have been widely investigated either by economists or by psychologists (see Hinds, 2004), they are not discussed in present paper. It is reasonable to expect that the massive spread of collaborative robots in every production activity will significantly reduce the fears that many workers have of them, due to lack of familiarity with the new machines.

The real dimensions of the problems and the issues raised by HRC extend wider than the ethical and economic problems and involve different engineering fields. It is important to remark that the industrial robot is only one of the many components in a modern production system. The basic working unit in a modern factory, before and after industry 4.0, is the workcell. “A workcell is an arrangement of resources in a manufacturing environment to improve the quality, speed and cost of the process. Workcells are designed to improve these by improving process flow and are based on the principles of Lean Manufacturing" (Womack, 1991). Robotic workcells are therefore composed by robots, their end-effectors, associated sensors, workpiece feeding and positioning devices. It is an expensive industrial system, whose design poses several problems that involve expertise in manufacturing, production planning and logistic. In order to convert a manual workcell in a collaborative one it is necessary to review and redesign all its components and even its organization.

It is helpful to describe with the diagram of Table 1, on different abstraction levels, the problems that are met during the design of a collaborative human-robot workcell.

Table 1. Aspects in Human-Robot Collaborative workcell

Workcell Design	Process Planning	Robot Programming	Process Execution
Model the collaborative workstation	Work Breakdown Structure	Task learning	Collaborative interaction H-R
Model the manufacturing / assembly process	Task assignment	Trajectory generation	Program Execution
Model the tools	Task Scheduling	VR / AR feedback	Collision Detection

Therefore, the design of a collaborative workcell should consider different abstraction levels and the different types of tasks that constitute the industrial production process. Firstly, the cell must be designed by considering the different requirements of humans and robots, reflected in classic layout through the differences between manual and automatic working cells. To execute a collaborative process, it is necessary to define a complete and comprehensive model of the whole workcell, considering the robots, the rotating table if any, the part to be produced, the tools to be used, the human workers to put beside the robots and the kind of skills provided by different agents. The concepts behind such workcell cannot be borrowed either from manual production or from automatic production. The layout is different, the tools are different, the skills of human workers should be complementary with the skills of the robot. In other words, to design a collaborative cell, experience on full automated factories is of little help.

A second abstraction level refers to the process planning. In the manual processes, often all workers are able to execute every operation and the tasks are assigned in a way to have balanced workloads. Differently from manual or automatic processes, in HRC it is crucial to explicit which tasks must be performed collaboratively and which separately by humans and by robots. Additionally, collaboration is a general concept that can have many different applications: sharing workspace at different times, working simultaneously on different areas of the workspace, robot assistant, hand guiding (ISO-TS 15066). The correct preparation of activities should start from the definition of the tasks, sub-tasks, and sequences. Then the tasks should be assigned to the human, to the robot or to both jointly. Task sequence should be scheduled and capacity planning on parallel tasks should be performed in order to avoid overload of operators.

The third level in the collaborative process design is the interactive programming of the robot. Standard robot programming, trajectory-oriented using the teach pendant or the offline robot simulation, is a time-consuming process that requires to be executed a specialized robot programmer. New programming approaches were introduced to exploit the collaborative skills of the robots: training by demonstration, manual guidance, voice or gesture task-oriented commands. These new programming techniques have been tested in research environments but their maturity level is far from acceptable to permit their diffusion in the factory.

Eventually, during the task execution, a number of activities are performed and need to be properly prepared. They are enabled by the collaborative interaction that pass through a human-machine interface. To the present state of technology, the interface and the terms used to interact with robots cannot be expressed in natural language. They must be application based and defined using a Domain Specific Language. Another activity is the execution of the program and the error recovery plan. When working with humans, it is not possible to avoid many small deviations from the programmed and expected behavior. As an example, the human can end his task before or after the allotted time, can change the assembly order, and many other small variations that require to the robot the capacity of reprogramming. In the automatic production, if there is an even small non-conformity, robots stop and control personnel intervenes to reset the standard work conditions. Working with humans this would lead to continuous halts. Therefore, a wider range of flexibility is required during program execution on the side of the robot. The safety management and the collision detection is another activity that raises some concerns. The new ISO 15066 standard put different prescriptions depending on the collaboration type.

Based on the scheme of Table 1 the study is structured as follows. Section 2 describes the state of the art on human-robot collaboration by comparing HRC with corresponding automatic and manual production. Section 3 introduces operational procedures applicable to both manual and automatic workstations. The basic concepts of the assembly process are represented by an ontology. This ontology is related to a second one describing the relations between the elements of a robotic cell. The two ontologies are coupled and instantiated, allowing to redesign the robotic workcell with HRC. Section 4 describes the problem of collaborative task assignment. Section 5 stresses the importance of feedback in the communication between human and robot. Section 6 discusses the importance of flexibility to assure the success of a collaborative operation by applying continuous adaptations to the working program during task execution.

2. Collaborative workcell as a third way between fully automatic and fully manual

Despite the only recent industrial application, HRC is subject of research since 30 years. At the beginning, the research starts by designing human-compatible robotic hardware (Kazeroomi, 1990) then by expanding to control modalities that were human-friendly (Luh, Hu, 1998). Further research topics in HRC were social characteristics of the human-robot interaction (Breazeal, 1998), the development of natural user interfaces (Kang, 1995), the definition and description of collaborative tasks (Yang, 1997 and Klingspor, 1997). Goodrich' survey (Goodrich, 2007) reviews the progresses in HRC up to 2000s and offers a comprehensive description of possible interactions with robots, how they could be exploited, the main difficulties to overcome. Nevertheless industrial robots are neglected as every kind of interaction in automatic workstation was completely absent.

The evolution of the research considered not only physical interaction but also cognitive interaction. Communication system between human and robot ranges from brain-computer interface (Bell, 2008), to augmented reality (Mavrikios, 2013) or advanced speech recognition (Mavridis, 2015). The progress is pushed by the advances in Machine Learning (ML) and in the dedicated robotic hardware (Kim, 2013). Robotic devices HRC oriented are tentatively classified in ISO/TS 15066. ML is now the core of knowledge representation in robotics (Nguyen, 2011). Despite various applications in the field of autonomous, bio-inspired, health or service robots, industrial exploitation of HRC were limited to the elimination of safety fences (Helms, 2002). After Industry 4.0, there has been an increase in the number of research projects focused on industrial applications (Almada-Lobo, 2016).

The characteristics that distinguish a HRC workcell have been classified by Wang (2017) as:

- *"intuitive and multimodal programming environment:* the human worker doesn't need an in-depth knowledge of the workcell",
- *"zero-programming:* workers communicate with robots via gestures, voice commands, manual guidance and other forms of natural inputs without the need of coding",
- *"immersive collaboration:* with the help of different devices, e.g. screens, goggles, wearable displays", the robot can communicate receive collaborate with the worker, and
- *"context/situation dependency:* the system should be capable of interleaving autonomous human with robot decisions based on inputs from on-site sensors and monitors".

It is worth noting the focus on programming time and straightforwardness. A big issue in having human and robot working together in the factory layout stands in the longer learning time of the robot compared with the human. To understand which are the perspectives and which the threats in HRC, it is useful to compare conventional automated processes and manual ones. In automatic processes, programming time is roughly related to the number of significant way points along the work trajectory. Applying this concept, it is possible to assert that programming time depend on the complexity and the length of the trajectories executed in the task. Another way to see it is that tasks requiring dexterous movements require longer programming time. On the contrary, humans, having better dexterity, don't need longer time to execute dexterous tasks.

For the sake of discussion it is worth classifying collaborative work in three classes: fully automated, with only robots assigned to all tasks, fully manual, without robots and with only human workers, collaborative, where humans and robots divide up tasks. The three scenarios are described in terms of process time by Fig. 1.

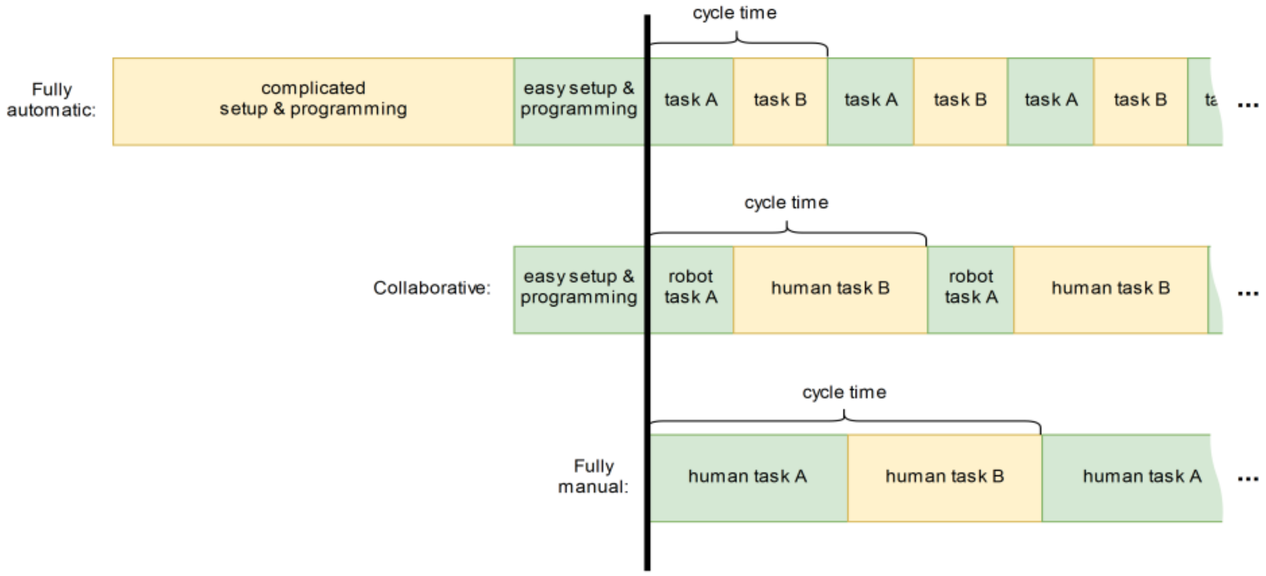

Figure 1. Cycle time in the three considered scenarios: fully automated, collaborative and fully manual.

It is apparent that, according to the proposed example, robots require shorter cycle time with respect to humans both in the execution of simple or dexterous tasks. Also, humans require the same time to execute dexterous or simple tasks, even if way longer than robots. Conversely, automatic production adds long programming time to the cycle time. How much this affects total process time is a function of the number of repeated tasks. In the collaborative scenario, robot task is executed faster than human task. The programming time is short as the dexterous tasks have been assigned to humans. Summing up the considerations: in large batches full automated scenario should be preferred as the time spent in robot programming is a fraction of execution time; in very small batches the manual scenario is advantageous as no time is spent in robot programming. There is an exploitation area between large and small batches where HRC could bring benefits in terms of less programming time and less execution time. The strengths of both human and robot are combined.

The choice of the preferred work organization is therefore dependent on production volumes, programming time and cycle time. In the considered example, two welding tasks are executed by human or robot. The first welding is along a line, while the second follows an Archimedean spiral, that is a complex trajectory. Fig. 2 shows the total execution times as a function of the number of consecutive welding executed. There are three curves, for the automatic, manual and collaborative process. In the collaborative case, robot executes the linear welding and human executes the spiral welding. The experiment has been executed in laboratory and welding was only simulated (welding gun was turned off).

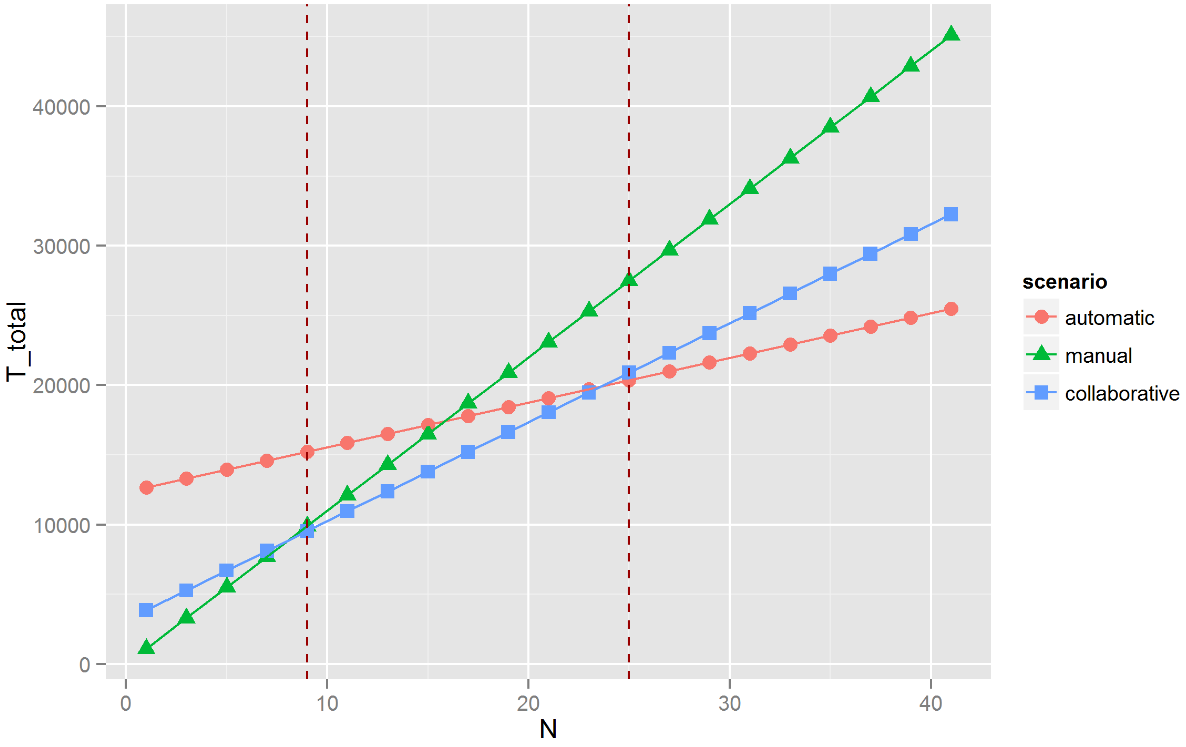

Figure 2. Comparison of the total times in the three scenarios showing the range of the batch size in which the collaborative scenario is the most efficient. K = 10.

Obviously, if programming time of easy task is shorter or if the difference in time between human and robot task is smaller, the area where HRC is competitive can increase. Robot programming for easy tasks can be shortened by preprogramming some repetitive operations, as an example palletizing several parts could be programmed on actual robots by just giving the pallet dimensions, the position where to place the first part on the pallet and the number of parts in the rows and in the columns. Another way to reduce programming time is to program the robot through manual guidance or even to employ programming by demonstration techniques (Argall, 2009).

3. Modelling a collaborative workcell

The design of a HRC system starts from a shared knowledge of both workcell components and working activities. The harmonization of terminology related to collaborative robotics is a relevant task to exchange information among the researchers in the field and to define a standard that can be shared by users and producers (Haidegger, et al. 2013). To this aim, ontologies were defined, to provide a knowledge base for human-robot collaborative systems.

An ontology is a formal structure used to describe relevant concepts and relations between them in a given domain (Guarino, 1998). Ontologies are used in a variety of different context, to explicit the knowledge of interest in each specific domain.

In the robotic context, the Ontologies for Robotics and Automation Working Group (ORA WG) define a core ontology for robotics and automation (CORA), which provides the concepts common to industrial robots (Prestes, et al., 2013). CORA is an extension of SUMO, Suggested Upper Merged Ontology. SUMO is an open-source upper ontology, used in several domains (Niles, & Pease, 2001). CORA focuses on defining robots, along with any related object. CORAX is an ontology that stand in the middle between CORA and SUMO., CORAX represents concepts and relations of common subdomains that are too general to be included in CORA (Fiorini, et al., 2015).

Fig. 3 (left) shows the main concepts of CORA related to SUMO and CORAX. Entity is the more inclusive category, given as a separate partition of physical and abstract entities. Physical entities are those extending in space or time, abstract entities are those that do not allow a description in terms of spatial or temporal dimensions. Descending from Entity there are further specializations: Physics consist of Object and Process, Abstract consist of Quantity, Attribute, SetOrClass, Relation and Proposition. Presently SUMO has more than 500 entities. The CORAX ontology defines concepts that are too general to be present in CORA, essential for modeling, but not explicitly or completely representable in SUMO. Examples of entities included in CORAX ontology are: physical environment, interaction, artificial system, processing device, robot movement, human robot communication, machine - machine communication. CORA focuses on defining a robot, along with specifying other related entities. CORA ontology is made of the following concepts: Robot part, Robot interface, Robot group, Robotic system (further divided into Single Robotic System and Collective Robotic System), Robotic environment.

In order to adapt the ontology to HRC systems, Antonelli and Bruno (2017) add collaborative concept to CORA ontology, generating a new extended ontology called Collaborative CORA (CCORA). Fig. 3 (right) shows the main concepts of CCORA with reference to SUMO and CORA. CCORA introduces the definition of collaborative robotic system as an entity made of robots, human operators, dedicated devices. HRC requires two specific families of devices for observing the work area and for pointing to relevant points in the work area. Furthermore CCORA defines collaborative robotic environment as an environment in which operate only collaborative robots. Collaborative robotic environment admits three specializations: spatial collaboration environment, temporal collaboration environment, and speed and force limited collaboration environment. The requirements in terms of devices depend on the environment specialization. When human and robot share the workspace but working in different time instants, the spatial collaboration environment, there is the need for a monitoring device that detect the presence and the movement of human. For this application, laser scanner is fit. Laser scanner gives a 2-dimensional map of distance from the robot of every moving point. The information is sufficient to avoid human presence when the robot is moving.

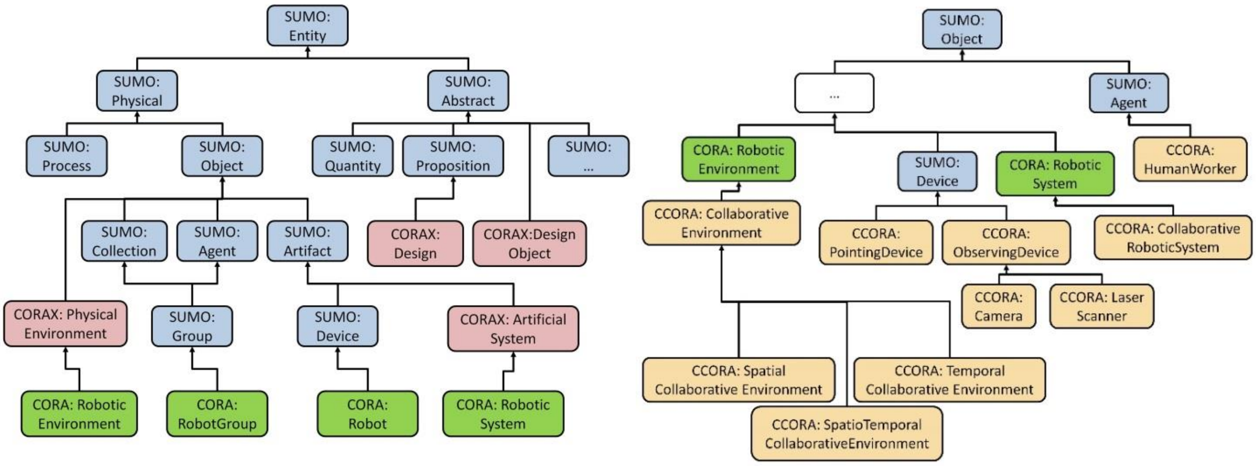

Figure 3. Left: CORA concepts related to SUMO and corax, Right: CCORA concepts related to CORA and SUMO.

Regarding the working operations, Antonelli and Bruno (2017) defined the MPRO ontology covering the knowledge associated with manufacturing operations. Figure 4 shows the components of the MPRO ontology associated to the SUMO ontology.

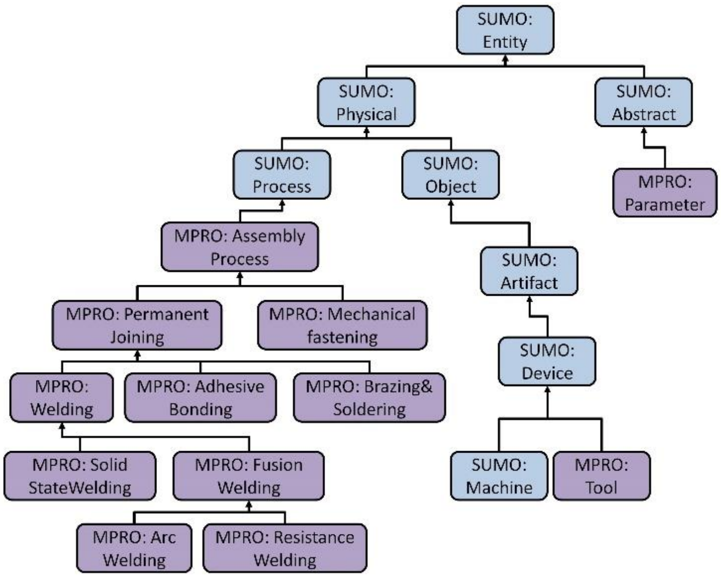

Figure 4. Merging MPRO and SUMO ontologies.

MPRO ontology has the main classes: Machine, Tool, Manufacturing process and Process Parameter (Bruno, 2015). Tool is the component that is used during process or directly working on the workpiece. As an example, Welding tool is applied by different welding processes comprising Welding mold, Solid state tool, and Fusion welding tool. Fusion welding tool is primarily referred to the Electrodes, which can be Consumables or Non-consumables. Among the Consumables electrodes there are Coated electrodes, Electrogas welding electrodes, Flux cored electrodes, Wire electrodes, and GMAW guns.

Conversely, Manufacturing process generates two sub-classes: Process operation and Assembly operation. Assembly operation generates two sub-classes: Permanent joining process and Temporary joining process. Permanent joining process can be subdivided in Welding, Brazing, Soldering or Adhesive bonding. Welding process is the parent class of Fusion welding and Solid state welding. Fusion welding is parent to Arc Welding, Resistance Welding, Oxyfuel gas welding, and others.

Process Parameter class contains the parameters of manufacturing processes that need to be explicitly set up, such as cutting speed of the drill process, welding temperature, cooling water pressure.

Having at disposal these ontologies, it is possible to populate them by instantiating different production processes and different workcell components. The ontologies put the basis to define the design requirements of HRC work environment.

4. Task definition, assignment and scheduling

Production planning is commonly written as an optimization problem with, as objective function, the minimization of time and costs of production and, as constraints functions, the capacity of workstations and the balancing of workload. The common approach at production control try to decompose the full factory optimization problem in a set of subproblems, i.e. the optimization of individual workcells by finding local optimal solutions. If the different cells are sufficiently uncorrelated, the superposition of local optimal solutions approximate well the global optimum. When the production is completely or partly manual, an additional management problem is the workload balancing among the workers, provided that labor is flexible so that every worker can execute every task. This is hardly the case in a collaborative work cell with robots and humans.

As man and robot have different skills that should be exploited as much as possible. HRC requires a different strategy for the work assignment by exploiting individual task execution skills and without any balance of workload between humans and robots. Fig. 5 presents a skill exploiting strategy that assign tasks to humans and robots based on task indicators. The sequence of tasks involved in the process is the initial step of the procedure. The next step is the evaluation of selected collaborative indicators for every task. Indicators make reference to the skills owned by human or robot, like dexterity, accuracy and so on. Indicators don’t require the exact evaluation of a performance index but can be expressed by using categorial values, or even logical values.

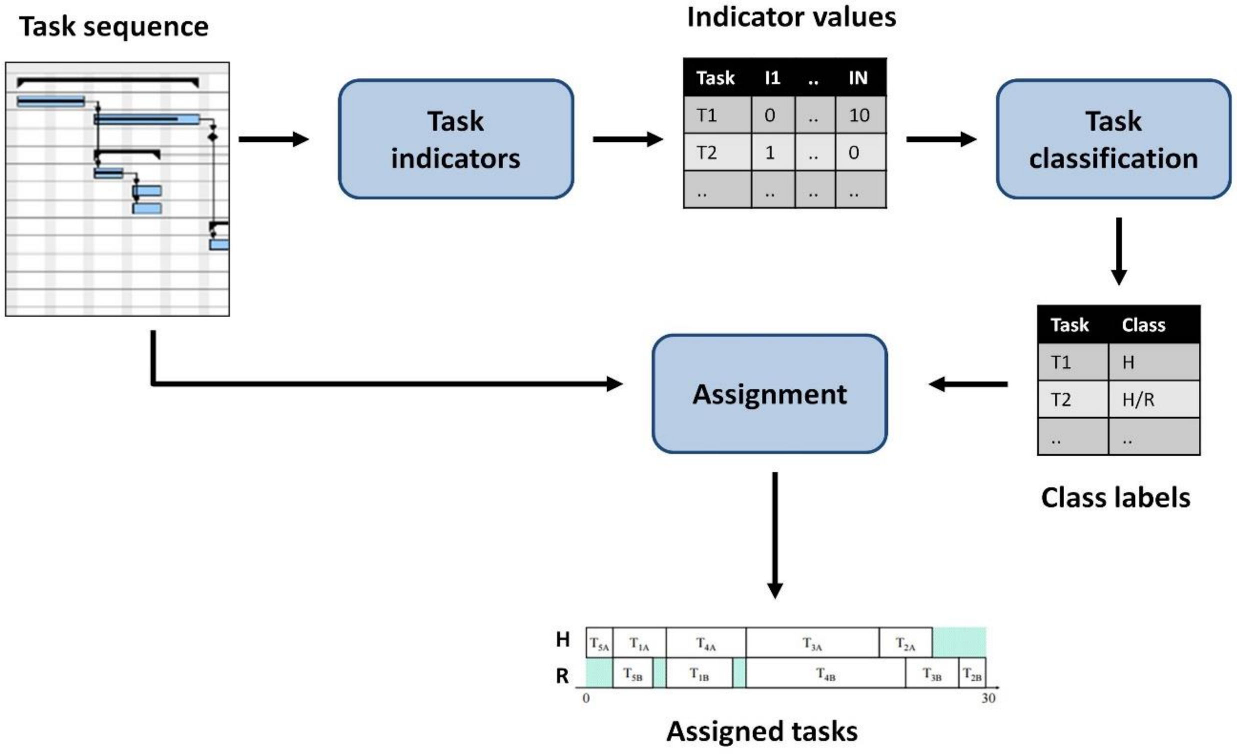

Figure 5. Procedure for task assignment to human and robot.

The purpose is not the assessment of tasks on the base of how much they are fit for robot or human. They are just used to feed a classifier that assign the tasks to human, robot or to their collaborative work. There is also an important class made by the tasks that can be executed at will by human or by robot. The final step is the task assignment to the first idle worker respecting the constraints put by the classifier. More details follow in the next section.

4.1 Task indicators

The assignment of task to human, robot or the type of collaboration involved is a decision process. The decision process is supported by indicators that refer to the collaborative features of the task. that will be used as decision factor in the selection of the type of collaboration. Having in mind the assets of human and robot, some features are surely to be considered: the payload of the job (W), the length of displacement inside the work area (Di), accuracy required to perform the task (A), the necessity of executing dexterous moves or trajectories (De). Table 2 shows an example of application of the indicators to common tasks. The logical value of indicators in the example is 1 if the feature is present, e.g. accuracy is required, 0 otherwise.

Table 2. Example of indicator values for four tasks

Task	W	Di	De	A
Tool retrieval	0	1	0	0
Inserting clamp	1	0	0	1
Welding	0	0	0	1
Fixing support	0	0	0	0

4.2 Task classification and assignment

ISO/TS15066 defines the safety requirements for collaborative industrial robot systems and for the environment in which it operates. Accordingly, there different types of collaboration. The logic behind the definition of them is the presence, of temporal and/or spatial separation between human and robot. Main cases of collaboration have been classified by ISO/TS 15066 as: "Safety-rated monitored stop (temporal and spatial separation), hand-guiding (temporal separation), speed and separation monitoring (spatial separation), power and force limiting (workspace sharing)".

While sharing the workspace is a compelling collaborative goal, in most industries it is more widespread the speed and separation monitoring, or just the hand guiding. Collaborative robots are not exploited to their best but just as an easy way to get rid of protective barriers. The reason is that full collaboration between human and robot would require a complete rethinking of the productive / assembly tasks and perhaps a redesign of the task itself.

In present example, the classes that have been defined are: to be executed only by human (H), to be exclusively performed by the robot (R), to be executed indifferently by either the human and the robot (H/R), to be the result of HRC (H+R).

The supervised classifier was trained with the help of prior classified data, assigned by a team of experts. Continuing the example of Table 2, the aforementioned tasks are classified as in Table 3. Supervised classification of logical data can be achieved by several Machine Learning (ML) algorithms. In this study, C4.5 decision tree was used as classifier (Quinlan, 2014), applying its open source Java implementation that can be accessed in the Weka data mining tool (http://www.cs.waikato.ac.nz/ml/weka/).

Table 3. Example of classified data used as training set

Task	W	Di	De	A	Class
Tool retrieval	0	1	0	0	H
Inserting clamp	1	0	0	1	H+R
Welding	0	0	0	1	R
Fixing support	0	0	0	0	H/R

The strategy of task assignment must be integrated by consideration about the task duration, precedence constraints, other than just the classification. The most significant difference between the task assignment in HRC and conventional task assignment is that in HRC it is not necessary to balance the amount of workload of every operator. As a matter of fact, robot can and should work more and longer than its human teammate. In essence the robot should take charge of risky, repetitive, tiresome tasks, unless the human dexterity is required. The only tasks were a strategy is required is when the task can be executed at will by humans or robots (H/R). The amount of such tasks is depending on the kind of process considered: in the assembly a large number of parts can be handled indifferently by robots or humans, while the joining requires often ingenuity or, at least, dexterity.

5. Programming collaborative robots in the workcell

Despite having witnessed strong growth in sales of robots to small or medium-sized companies over the last few years, there isn’t a corresponding increase in the actual use of robot in the production. The limiting factor continues to be the complexity and lengthiness of robot programming.

Pan (2012) describes all the common used programming methods, either by online programming, or by offline programming, possibly with the help of Virtual Reality (VR). Both methods have known consistent evolution in last years. Online programming now can be performed without any knowledge on robots, through sensors assisted programming. Force sensors allow manual guidance of the arm of the robot: the pose is obtained by simply push and drag the robot with a hand. Vision sensors allow a Training by Demonstration approach (TbD): the programmer executes the task in front of the camera and a governing system extracts a general policy for the robot trajectory. Manual guidance is already applied in some commercial robots: all Universal Robots, Kuka LBR, ABB YuMi. Vision assisted TbD is still confined in research laboratories: movement policy generalization from demonstrations requires the recourse to advanced machine learning techniques.

Billard (2008) complains that a large effort in TbD has been dedicated to studying ‘how to imitate’ and ‘what to imitate’, while less effort was directed to study ‘who to imitate’ and ‘when to imitate’. In other words, an inadequate consideration is paid to the type and amount of experience the teacher should have and to the time instant chosen for the demonstration. In actual industrial processes, the importance of solving these last two issues becomes apparent. The robot should be trained to execute a welding task by observing a human welder with no experience on robot programming. The demonstration phase should waste a minimum amount of time, and can be executed only when the parts to be welded are already fixed to the work table.

Following Argall et al. (2009), industrial programming through TbD can be classified as derivation of a policy by a mapping function approach that apply regression on a dataset built by the external observation of the demonstration through remote sensors.

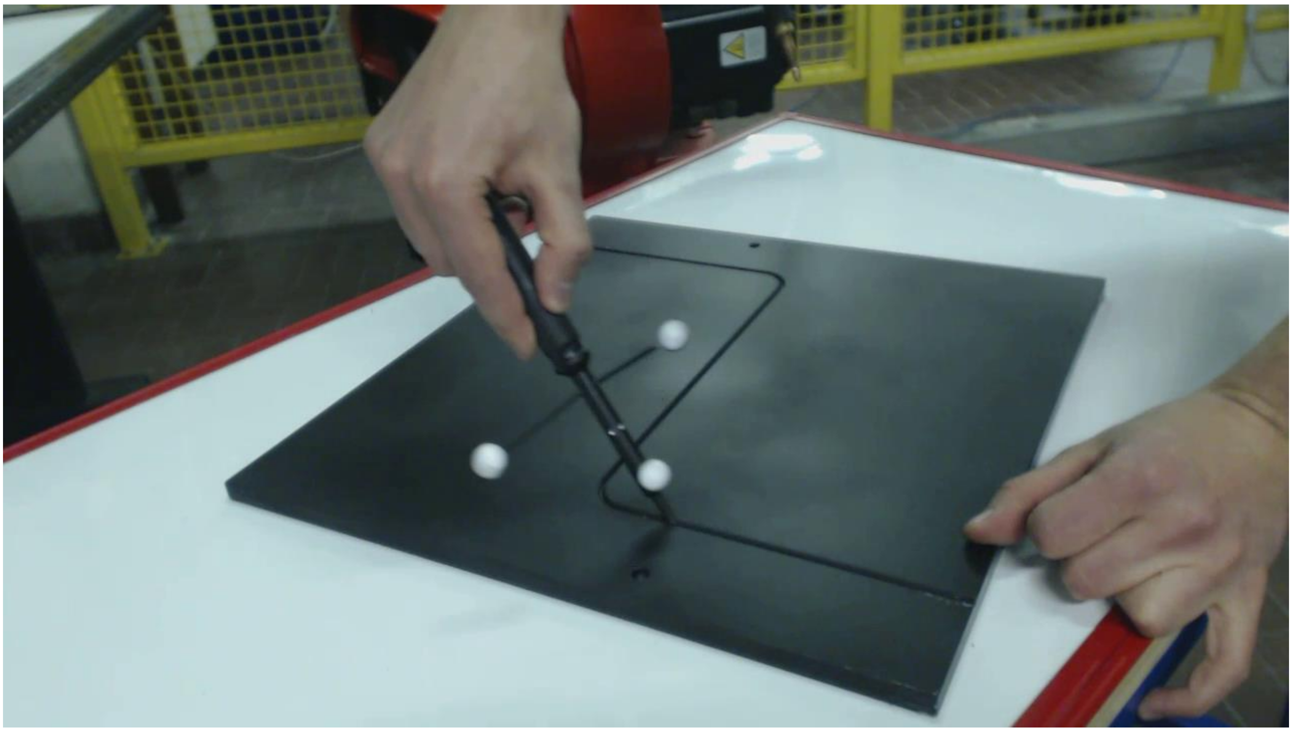

Figure 6. Robot training with Training by Demonstration.

Consider the example of training the robot to execute welding, presented in Antonelli (2013). The operator moves a light tool (named pointer) along a given trajectory (Figure 6) to teach the robot the welding path. Some cameras observe the action and collect the poses of the pointer in an ordered list. From the list, robot trajectory is derived. Derivation of the path from the measured points is not trivial. Multiple overlapping segments are merged. Their points are properly reordered to obtain a single directed curve. Capability of the system to build a path from multiple overlapping segments is critical for industrial applications. There are many circumstances when indicating a path using just one continuous gesture is impossible or undesirable. Optical acquisition produces noisy data points, outliers that must be eliminated (Fig. 7). The teacher's hand is not stable and subjected to waviness. The learning system should convert a fuzzy set of points in a welding trajectory to be performed with robot's accuracy. The trajectory curve require a further smoothing and the elimination of excessive numbers of waypoints. The resulting smooth trajectory is shown in Fig. 8.

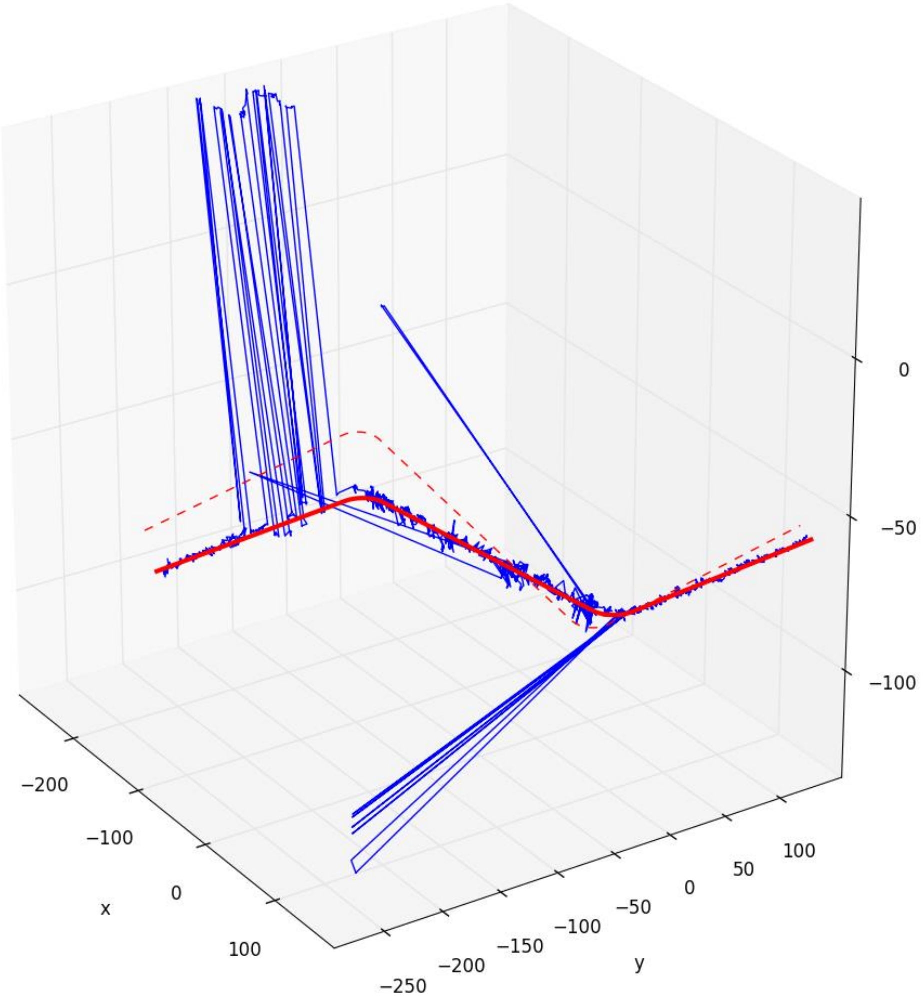

Figure 7. Noisy data acquired before outliers removal.

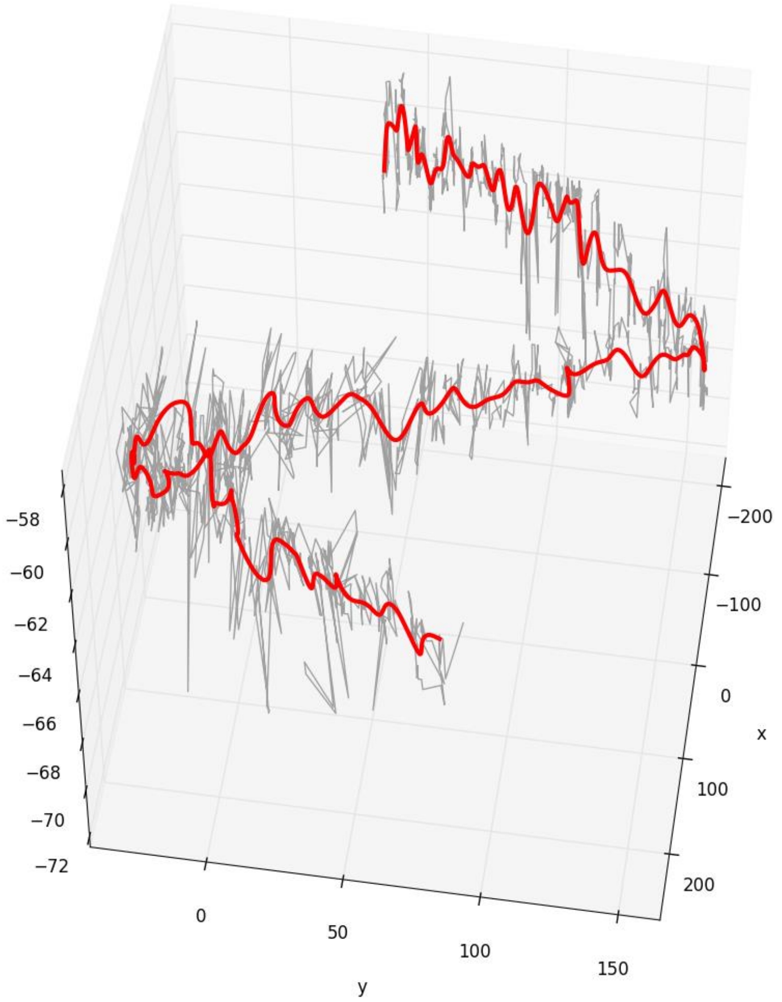

Figure 8. Resulting smoothed trajectory.

It is apparent that the trajectory is not yet optimal. The only way to obtain a feasible trajectory is to add in the system the knowledge of how the welding task should be executed. Welding is expected to produce linear weld on flat surfaces. The curve of Figure 8 must be converted in a polyline by adopting an algorithm that reduce the number of intersected points, namely Douglas Peucker, obtaining the red curve in Fig. 7.

6. Exploiting collaboration

As far as this section, no definition has been given for the term ‘collaboration’. Collaboration has been applied to a wide range of human robot interactions inside the factory. Presently, in most industrial applications it is used in place of sharing the same workspace. In Table 4, commonly accepted classification of human robot interactions are described.

Table 4. Types of collaboration according to ISO/TS 15066

Time / Workspace	Spatial separation	Spatial coincidence
Temporal separation	Standard full automated robotic workcell	Speed and separation monitoring

Temporal coincidence	Safety rated monitored stop	Power and force limiting

The maximum degree of collaboration involves the sharing of both time and workspace. Even so the interactions between human and robot are often limited to a few operations. It should be noted that the collaboration is not peer to peer, but it is more a coordination. Collaboration means working with the others for the success of an activity. Coordination is a kind of work optimization searching the best division of activities to be performed by humans and machines. Following Malone (1994): "Coordination is managing dependencies between activities". Coordination infers the necessity of a coordinator and, therefore, a form of hierarchy. Instead, collaboration is the process of various individuals working together on a voluntary basis without the need for a manager or a work program. Collaboration infers the respect of a set of good behavior rules, as the ones proposed by Talukdar (1999) in the case of collaborative software agents.

In the use of robot as an assistant for the human worker, i.e. by carrying the greatest part of the workload, the task is apparently coordinated by the human and the robot is employed as a useful assistant (Helms, 2002). It is not given for granted that the future of HRC does not reserve new collaborative paradigms. With the evolution of the cognitive capabilities of the robots, it will be evident the usefulness to entrust the robot with most of the coordination tasks. Robot knows the finished product perfectly thanks to the access to CAD models. Robot access and combine the signals of a large number of sensors, always having accurate and real-time information about the current state of the work and detect possible nonconformities. For these reasons, robot could take the leading role in several assembly operations, by indicating to the human operator the exact position and sequence of tasks to perform. Human workers would be therefore lightening the task of keeping long and complex sequences of operations in memory. It would also lessen the need for expensive positioning devices and fixtures.

This way of collaborating with the robot means that the robot could be programmed offline: robot simulation software assists in generating the trajectories and in choosing the process parameters from the 3D-CAD model of the product. During production, the robot will have the burden of training the human operator to execute his/her part of the task, possibly with the help of Augmented Reality.

Regardless of who is in control, the success of collaboration relies on a prompt and reliable communication between the collaborative agents. Communication is reliable only if it is not one way. In human communication, even when only one is speaking, the other gives involuntary feedback of positive understanding by facial expression and eyes movement. Replicating the human-like feedback is complex and unnecessary, the robot could show what it has understood and what will be its next actions using virtual or augmented reality simulations. The importance of communicating the intentions of the robot to the human is not neglected in modern research and even in some industrial applications (Mavrikios, 2013). Thus, the lack of empathy by man and machine, make it quite hard to correctly understand the exact intentions of the robot. This means that misunderstanding between human and robot will be frequent. It will be necessary to adopt mistake proof procedures and devices and to make it straightaway the correction of wrong actions.

7. Conclusions

The paper discusses the topic of collaboration between man and robot in industrial production processes. The main thesis presented in the article is that it is not enough to build a collaborative robot and meet the safety requirements. It is also necessary to redesign the workcell and also the methods of organizing the work in the establishment: the planning of operations and assignment of tasks.

As for the implementation phase of collaborative work, the need for advanced and smarter robot programming methods is discussed. The paper also highlights two fundamental aspects that should always be kept in mind when introducing a HRC-based production system: the need to receive and give steadily feedback messages to ensure correct communication, the importance of providing a system to correct misunderstandings during communication between man and robot.

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