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Dynamic task classification and assignment for the management of human-robot collaborative teams in workcells

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Abstract The rise of interest in collaborative robotic cells for assembly or manufacturing has been attested by their inclusion among the principal tools of Industry 4.0. In collaborative cells, robots work side by side with human operators allowing to address a larger production scope characterized by medium production volumes and significant product variability. Despite the advances in research and the availability of suitable industrial robot models, several open problems still exist, due to the necessary consistent changes in the way of working: correct assessment of the economic profitability, definition of a suitable process plan, task assignment to humans and robots, intuitive and fast robot programming. This paper addresses the task assignment problem by proposing a method for the classification of tasks starting from the hierarchical decomposition of production activities. Task classification is employed for workload distribution and detailed activity planning. The method relays on the assumption that tasks should be allocated, exploiting the different skills and assets of humans and robots, regardless of workload balancing. The proposed method was firstly tested on a simplified assembly process executed in laboratory, then it has been applied to the redesign of an actual industrial process.

Keywords Human-robot collaboration · Man-Machine System · Industry 4.0 · Automation · Flexible manufacturing systems

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1 Introduction

Collaboration between humans and robots receives growing proofs of interest [1]. Accordingly to a study published by ABI Research, collaborative robotics is expected to increase roughly tenfold between 2015 and 2020, reaching over US$1 billion from approximately US$95M in 2015 [2].

Human-Robot Collaboration (HRC) brings benefits to industrial applications in terms of speed, efficiency, better quality of the production and better quality of the workplace [3]. Collaborative assembly cells stand half way between the manual and the full automated cell for the execution of complex working tasks [4]. Presently industrial robots are mainly used in full automated cells. Therefore, their employ is convenient only in the context of mass production or when processing large batches [5]. On the contrary, collaborative robots allow to process small volume productions, joining the accuracy and the force of robot with the dexterity and the flexibility of human, as shown in Fig. 1. The choice among manual, automatic or collaborative production is driven by several factors. Among them, product flexibility, number of variants, production volume and batch size play a significant role, even if not exclusive.

Industry 4.0 prompts the re-organization of production systems with flexible collaborative workcells. 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 indicators by improving process flow and are based on the principles of Lean Manufacturing [6]. A robotic workcell is therefore constituted by one or several robots with end effectors, sensors and devices for the feeding and the positioning of the workpiece. Introducing a robot in a former manual workcell, or

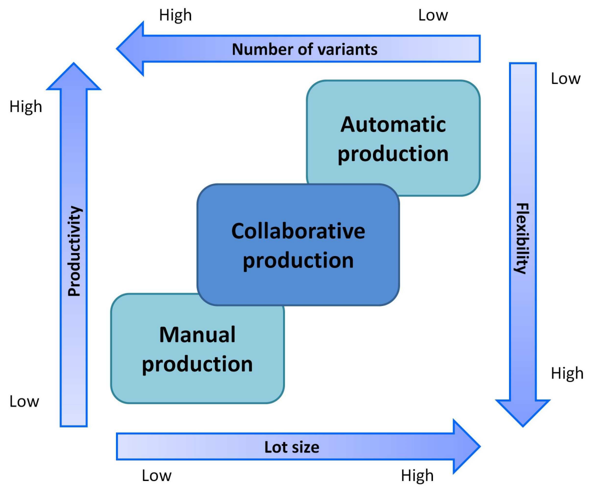


Fig. 1 Key factors in the diffusion of collaborative production

conversely, introducing a human in a completely automated workcell, cannot be done without rethinking not only the components but also the organization of the work [7]. This paper aims at defining a strategy for job assignment to workers and robots, taking into account the characteristics of the job and the peculiar skills of human and robots. The assignment of tasks is based on a classification phase, which makes use of a training set of pre-classified tasks to build a classification model. Such model is then exploited to classify new tasks. Once tasks are classified, a task assignment procedure assigns dynamically the tasks to the available resources, taking also into account the different skills of humans and robots.

The rest of the paper is organized as follows. Section 2 revises the relevant literature available on the topic. Section 3 describes the proposed procedure for task assignment, while Section 4 shows its application to a case study. Finally, Section 5 draws conclusions and outlines future works.

2 State of the art

Collaboration between human and robot is a well established field in robotics since early 1990s. The research started mostly from the design of human-compatible robotic hardware [8] then expanding to human-friendly control modalities [9], social aspects of the interaction [10], natural user interfaces [11], and representation of the complex tasks [12,13]. The Goodrich survey on Human-Robot Interaction [14] summarizes the progress made up to mid-2000s and presents a thorough description of different interaction modes, application domains, and the principal open problems in the field. Industrial robots were seldom considered among the principal application fields.

In the 2000s the search for a better human-robot interaction continued, going from direct brain-computer interface [15], augmented reality [16] to advanced verbal interfaces [17]. The progress in the field of human-compatible robotic hardware is also undeniable [18]. An effort to standardize the robotic devices designed for HRC was undertaken by ISO/TS 15066. Machine learning methods remained the basis of robot knowledge representation, following Nguyen [19]. Notwithstanding numerous field applications to mobile, bio-inspired, medical and service robots, HRC research has seen in the past years relatively scarce industrial applications [3]. In the last years, since the introduction of the concept in Industry 4.0, there has been an explosion in the number of industrial applications exploiting HRC [20].

Several works addressed the evaluation of collaborative robotic cells, especially in automotive industry, providing comparisons between conventional robotic cell and cooperating human-robot cell [21–23]. Optimal task assignment among workers and robots was studied in some use-cases [24], thus major efforts have been devoted to the safety of human-robot collaboration [25, 26].

Considering the production process subdivided in work tasks, it is apparent that some tasks could be performed more proficiently by humans or robots alone, others collaboratively [27]. [28,7] proposed to use a modified version of HTA graphical language, developed for ergonomy studies, to represent in a hierarchical model the tasks to be performed. The human and robot contribution and the choice of collaboration strategy can be represented in their model, but must be decided in advance by the process designer. [29] proposed a decision-making algorithm for task allocation and planning that is based on the evaluation of multiple criteria. The job is divided in several tasks and they are assigned to the human or to the robot following three decision steps: resource suitability, resource availability, minimum operation time. The approach is particularly effective when HRC is operated in conditions of spatial or temporal separation in the workcell between human and robot. This is the most common case of HRC in present days industry.

There is still the need for a general method that allows to classify the suitability of a task to be executed by human, robot or both in one among the several kinds of collaborative work. Furthermore, when more than one solution is possible (task can be executed either by human or by robot), the task assignment could be modified to optimize the completion time of the entire job and to avoid overload of a resource. These are the motivations for present study.

3 Task assignment procedure

Factory planning is an optimization problem with the goal of minimizing production times and costs by respecting several capability and load balancing constraints. A modern approach is oriented to finding local solutions to a number of sub-problems at workcell level, instead of facing the complexity of a full plant optimization. Manual cells have the additional issue of assigning the load on different workers in a balanced way. Very often every worker can execute every task and the assignment is only a matter of workload. HRC workcell needs a completely different strategy for job planning and task assignment. Human and robot have different skills that should be exploited as much as possible. Moreover, there is no need to balance the workload between human and robot.

The strategy for task assignment is schematically represented in Fig. 2. It is composed by four activities, two to be accomplished by the manufacturer, and two executed automatically by the workcell configurator. The first activity is to identify the list of tasks involved in the process. Then, for all the tasks, a set of indicators is defined. The indicators were chosen in order to be described by logical values easy to input in the industrial field.

Based on the indicator values of the tasks, a classifier assigns tasks to the following classes: executable only by a human, executable only by a robot, executable indifferently by human or robot, executable mandatorily by both a human and a robot working together. Eventually, the final assignment is provided by considering task length and precedence constraints.

The procedure is described in details in the remaining of the section.

3.1 Task identification

A collaborative manufacturing process is composed by a set of tasks. To each task is assigned a name, a number, a duration, and the precedence with respect to the other tasks, if any. Table 1 shows an example of four tasks related to a welding process. The first task is the retrieval of tools to execute the operation, the second one a clamp insertion, the third one a welding operation, and the final one the fixing of a support. These tasks have to be executed in sequence.

Table 1 Example of for four tasks of a welding process

Number	Task	Duration [s]	Precedence
1	Tool retrieval	50	
2	Inserting clamp	20	1
3	Welding	100	2
4	Fixing support	80	3

Table 2 Example of indicator values for four tasks

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

3.2 Task indicators

Task indicators are used to describe the features of the task, and thus they are decision factors in the selection of the type of collaboration. Indicators were chosen in order to be described by logical values easy to get from the shop-floor. Task features that should be surely considered are the weight of the assembled part (W), the displacement (Di), accuracy requirements (A) and dexterity requirements (De). Table 2 shows an example of application of the indicators to the four welding tasks of Table 1.

The indicators' values for the first task are 0 except Di, meaning that the weight is not a constraint and there are no particular requirements of dexterity or accuracy. Di is set to 1 because the tools are outside the working area of the robot. The second task is the insertion of a clamp. Due to the weight of the clamp and the fact that the operation requires a high accuracy and dexterity, W, De and A are set to 1.

3.3 Task classification

For collaborative industrial robot systems and the work environment, the ISO Technical Standard 15066 defines the safety requirements. According to that, it is possible to have different kind of collaborative working based on the presence, or less, of temporal and/or spatial separation between human and robot. Main cases of collaboration have been classified as:

1. Safety-rated monitored stop (temporal and spatial separation)
2. Hand-guiding (temporal separation)
3. Speed and separation monitoring (spatial separation)
4. Power and force limiting (workspace sharing)

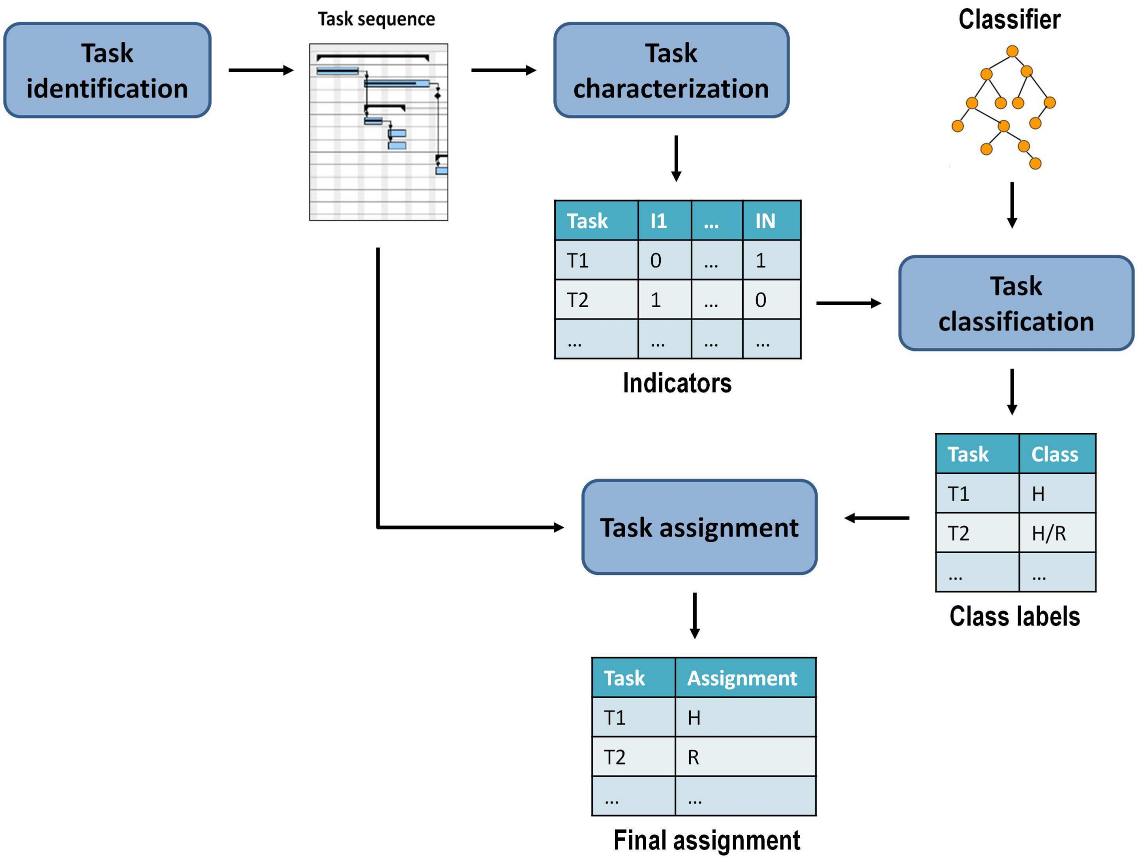


Fig. 2 Procedure of task assignment in a collaborative workcell

The last class represents the most complete and challenging kind of human-robot collaboration. In the industrial field it is far more common to find hand-guiding or speed monitoring. They allow to use standard industrial robots with a minimum refurbishment of the workcell. In this study all the collaborations are considered as equally effective, in function of the purpose the production management is aiming for.

The classes defined by the classifier, on the basis of the indicators, are: executable by human (H), by robot (R), by either of the two (H/R), by the collaborative work of both (H+R).

The classifier is trained by using a training set of previous classified data, like the ones in Table 3. A C4.5 decision tree [30] was used as classifier. The open source Java implementation of the C4.5 algorithm (J48) in the Weka data mining tool was exploited (http://www.cs.waikato.ac.nz/ ml/weka/).

The training set contained 68 tasks: 22 of class H, 28 of class R, 14 of H/R, and 4 of H+R. By setting a K-fold cross validation dividing the data into a training set and a test set with a proportion of 3:1, the accuracy achieved by the model is 88.2%. The total number of correctly classified instances is 60, while the incorrectly classified instances are 8. The resulting classification tree is shown in Fig. 3.

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	1	1	H+R
Welding	0	0	0	1	R
Fixing support	0	0	0	0	H/R

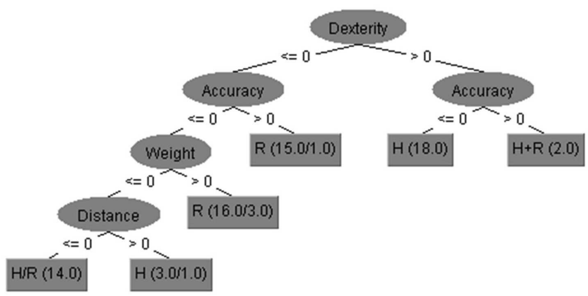


Fig. 3 Classification tree built on the training set

ID	Task	Duration [s]	Precedent	Classification	Assignment
1	Tool retrieval	50		H	H
2	Inserting clamp	20	1	H+R	H+R
3	Welding	100	2	R	R
4	Fixing support	80	3	H/R	R

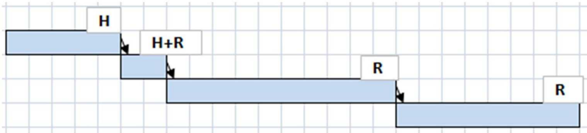


Fig. 4 Final assignment of tasks

3.4 Task assignment

Using the classifier produces a first tentative assignment of tasks to the robot and the operator. By knowing also the task durations and the task precedences, it is possible to define a strategy to assign tasks to operators.

Differently from classical workload balancing problems, here we are not interested in balancing the work between a human and a robot, since it is better to assign to the robot the heaviest workload. We also are not interested in solving an optimization problem, since the times for executing tasks can be variable, thus they can be reassigned dynamically during the process.

We define the following logic for task assignment.

1. Assign to the robot all the tasks classified as R.
2. Assign to the human operator all the task classified as H.
3. Assign to both the human and the robot the task classified as H+R.
4. For task classified with H/R: if the robot is idle, assign the task to the robot, if the robot is already executing another task, assign it to the human.

The final assignment of tasks in our example is reported in Fig. 4. In this case, the choice of assigning the last task to the robot is due to the fact that there is the precedence constraint, thus at time 170, both the human and the robot are free and the task is assigned to the robot. If task 4 could be executed directly after task 2 instead of waiting the end task 3, it would have been assigned to the human, so that the last two tasks will be executed in parallel.

4 Flange assembly use case

We set up a use case in our laboratory to show step by step how to apply the procedure for task assignment. The considered use case is a mechanical assembly process. The components of the assembly, shown in Fig. 5, are the following:

Fig. 5 Components and final assembly of the use case

- a base of dimensions 125 x 93 x 98 mm, with 12 holes of diameter of 10 mm;
- 4 hexagonal head screws M 10 x 30;
- 4 hexagonal nuts M 8;
- 2 perforated flanges.

The assembly process has been divided in tasks. The list of tasks, with the corresponding duration and precedence is reported in Table 4 (first four columns). Task 1 and 2 are preparatory tasks, used to bring all the components inside the working cell and mount the gripper tool on the robot's end effector to allow the picking of objects. Then, task 3 and 4 consist of picking the base and place it on the reference position. After that, the first flange can be mounted and assembled (task 5-15). The flange is picked, positioned near the base, and while hold in this position, the two screws and the two nuts are assembled. There is no precedence between the picking and insertion of the screws (they both can start after task 6), while the insertion of the nuts have to follow the insertion of the nuts. The same tasks are repeated for the assembly of the second flange (task 16-26).

After the definition of tasks, we proceeded with the definition of the indicators values for each task, as reported in Table 4 (from fifth to eighth column). We analysed the weight, distance, dexterity and accuracy required in each task, and we assigned the corresponding 1/0 value.

We then applied the classifier described in Section 3.3, and we obtained the class associated to each task, as reported in Table 4 (last column).

By using the classification results, and the duration and precedences of tasks, we apply the procedure for task assignment.

Table 4 Tasks of the assembly process

Number	Task	Duration [s]	Precedent	W	Di	De	A	Predicted
1	Positioning parts inside workspace	60		0	1	0	0	H
2	Mounting the tool on the robot's end effector	168		0	0	1	0	H
3	Fetch base	20	1, 2	0	0	0	0	H/R
4	Place base on the reference position	20	3	0	0	0	1	R
5	Pick flange 1	6	4	0	0	0	0	H/R
6	Positioning flange 1	4	5	1	0	0	0	R
7	Hold flange 1 in the position	14	6	1	0	0	0	R
8	Pick Screw 1	3	6	0	0	0	0	H/R
9	Insert screw 1	4	8	0	0	1	0	H
10	Pick Screw 2	3	6	0	0	0	0	H/R
11	Insert screw 2	4	10	0	0	1	0	H
12	Pick nut 1	3	9	0	0	0	0	H/R
13	Screw nut 1	40	12	0	0	1	0	H
14	Pick nut 2	3	10	0	0	0	0	H/R
15	Screw nut 2	40	14	0	0	1	0	H
16	Pick flange 2	12	4,7	0	0	0	0	H/R
17	Positioning flange 2	19	16	1	0	0	0	R
18	Hold flange 2 in the position	14	17	1	0	0	0	R
19	Pick Screw 3	3	16	0	0	0	0	H/R
20	Insert screw 3	4	19	0	0	1	0	H
21	Pick Screw 4	3	16	0	0	0	0	H/R
22	Insert screw 4	4	21	0	0	1	0	H
23	Pick nut 3	3	20	0	0	0	0	H/R
24	Screw nut 3	40	23	0	0	1	0	H
25	Pick nut 4	3	22	0	0	0	0	H/R
26	Screw nut 4	40	25	0	0	1	0	H

By applying the task assignment procedure, we obtained the assignment of tasks illustrated in Fig. 6.

The robot used in collaboration with a human worker is the UR3, with 6 joints, a load of 5 kg and a range of 0,5 m. The robot is equipped with a gripper OnRobot for the execution of pick and place operations. The configuration is shown in Fig. 7.

The execution of the collaborative process is shown in Fig. 8. In the image, the robot is holding the second flange (task 18) and the human operator is screwing the nut (task 24).

Fig. 7 Universal robot UR3 with OnRobot gripper

5 Mill assembly use case

The task assignment procedure can be applied also for more complex processes. The second use case considers an assembly process of a 2-stage snowplow mill (shown in Fig.9). The assembly is currently executed in a small factory with small productions that are not suited for traditional full automation. The description of the process was obtained by observing the actual manual work during the assembly of a small number of mills. The process has been recorded on video and all the processing times have been recorded to determine, with the expected high variability of manual processes, mean standard times.

ID	Task	Duration [s]	Precedent	Classification	Assignment
1	Positioning parts	60	-	H	H
2	Mounting tool	168	-	H	H
3	Fetch base	20	1;2	H/R	R
4	Place base	20	3	R	R
5	Pick flange 1	6	4	H/R	R
6	Positioning flange 1	4	5	R	R
7	Hold flange 1	100	6	R	R
8	Pick screw 1	3	6	H/R	H
9	Insert screw 1	4	8	H	H
10	Pick screw 2	3	6	H/R	H
11	Insert screw 2	4	10	H	H
12	Pick nut 1	3	9	H/R	H
13	Screw nut 1	40	12	H	H
14	Pick nut 2	3	10	H/R	H
15	Screw nut 2	40	14	H	H
16	Pick flange 2	12	4;7	H/R	R
17	Positioning flange 2	19	16	R	R
18	Hold flange 2	100	17	R	R
19	Pick screw 3	3	16	H/R	H
20	Insert screw 3	4	19	H	H
21	Pick screw 4	3	16	H/R	H
22	Insert screw 4	4	21	H	H
23	Pick nut 3	3	20	H/R	H
24	Screw nut 3	40	23	H	H
25	Pick nut 4	3	22	H/R	H
26	Screw nut 4	40	25	H	H

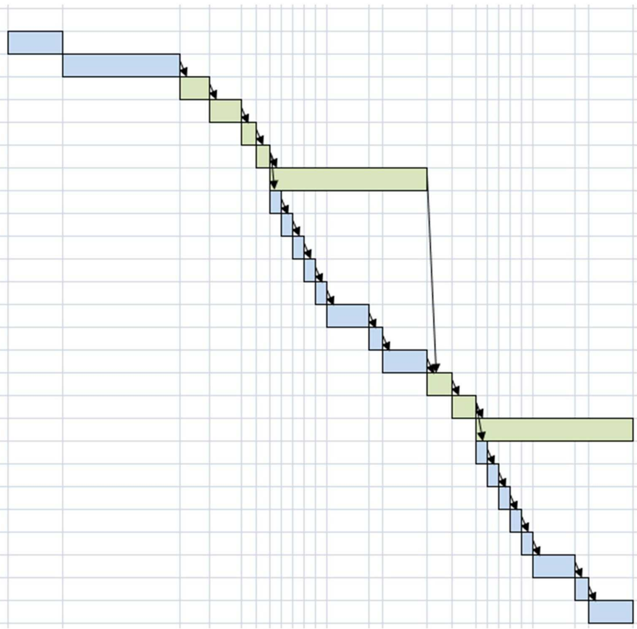


Fig. 6 Assignment of tasks and corresponding Gantt chart (in blue tasks assigned to the human, in green tasks assigned to the robot)

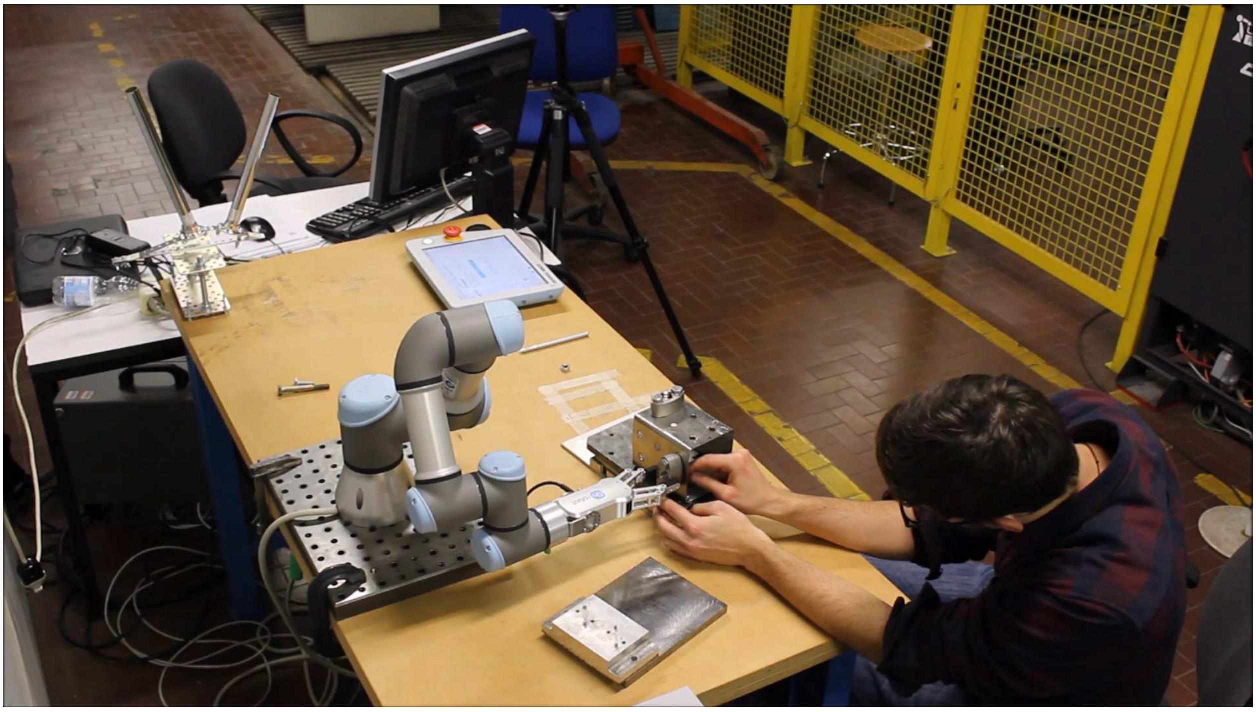


Fig. 8 Execution of the collaborative assembly process

The process cannot be completely automated, due to the small production volumes. At the same time, it is unsafe and unfit for full manual process: many parts are heavy and must be handed with the help of an overhead travelling crane, and the arc welding poses additional safety risks due to the shape of the blades. It is apparent the need for an innovative process where a robot will take the risks of welding and will carry most of the weight of parts and human worker will execute the uncountable series of small tasks that require dexterity and flexibility and that are always present in non-automated processes.

The process is quite complex, it can be decomposed in 11 main phases. They are graphically represented in

Fig. 9 Snowplow mill considered as case study

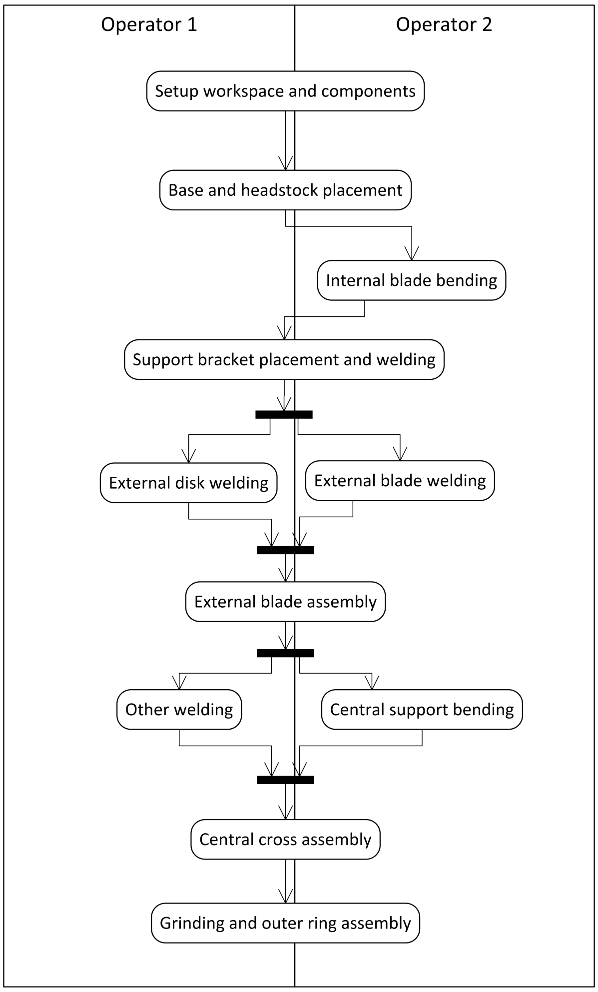


Fig. 10 Activity diagram of the snowplow mill assembly

Fig. 10, as they are currently executed manually by two operators.

The structure is fastened on a slab. The two diagonals are traced to ensure the correct alignment of the radius of the central crossbar, the radius of the inner crossbar and the four-knife brackets. Two reference holes guarantee the placement of the headstock to the slab. There are also other 16 diagonal diagonal holes, needed for fixing the outer disc and the knife mount brackets. The welding in the assembly phase is operated through a GMAW technique with 1.2 mm wire. There is an assembly kit that consists of 4 brackets for fastening the outer disk to the floor and 4 brackets for fixing the knives, 2 lifting rings for the structure repositioning and 2 retaining rings for the crossbar. In the manual process, it is necessary the support of an expensive assembly mask, needless in the robotic process. Assembly is carried out by two operators, both for the need to lift heavy weights and for some complex assembly tasks.

Each phase is further divided into sub-phases, giving origin to a total of 68 different tasks. To each of the identified 68 tasks has been assigned a value for each indicator. We then applied the classifier described in Section 3.3, and we obtained the class associated to each task, as reported in Table 5 (last column).

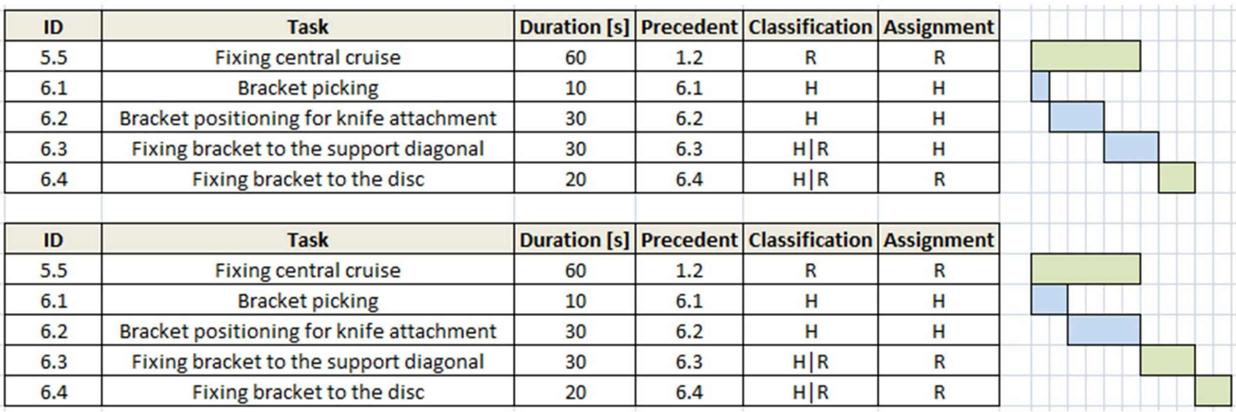
After the classification, we proceed with the final task assignment, taking into consideration also the precedence constraints. The robot is now in charge of nearly all the welding and of assisting the human when the weight to lift is excessive. Human and robots have different and complementary tasks in every process phase.

The assignment has to be done dynamically to cover the delays that can happen during the process. For example, depending on the current availability of the human and the robot, tasks 5.5-6.4 are assigned as reported in the upper part of Fig.11, i.e., the robot executes tasks 5.5, while the human executes the tasks 6.1-6.3. If for some reason the human operator needs more time for executing tasks 6.1 and 6.2, then with the dynamic assignment task 6.3 is automatically reassigned to the robot, since the task is classify as H/R and the robot is idle at that time.

To implement the described human-robot collaboration, a collaborative cell was designed, as represented in Fig.12. Among the available industrial robots, the selection is for a KUKA robot KR 300 R2500 ultra C, compliant with both load and workspace requirements. The holding devices are a tool plan to allow the robot executing the operations, a rotating platform so that the robot can easily reach all the positions required for the operations, and a component storage, where the final components are arranged according to a precise order in such a way that the robot can identify and pick them. Also two laser scanners are inserted, one for verifying the correct positioning of tools and items, and another one to identify the human worker position.

Table 5 Tasks of the mill assembly

Number	Task	Duration [s]	Precedent	W	Di	De	A	Class
1.1	Tool preparation	600	-	0	1	0	0	H
1.2	Tool positioning in the working area	720	1.1	0	1	0	0	H
2.1	Headstock preparation	30	1.2	1	0	1	0	H+R
2.2	Headstock alignment of working plane	30	2.1	1	0	1	0	H+R
2.3	Fastening bolts preparation	20	1.2	0	0	0	0	H/R
2.4	Headstock fixing to the working plane	40	2.2, 2.3	0	0	0	0	H/R
3.1	External disk preparation	30	1.2	1	0	0	0	H+R
3.2	Insertion of internal disk on the headstock	30	3.1	1	0	0	0	H+R
3.3	Fixing disc to the support	30	3.2	0	0	0	0	H/R
3.4	Orienting external disc	50	3.3	0	0	0	1	R
4.1	Internal cruise picking	40	1.2	1	0	0	0	H/R
4.2	Internal cruise insertion on the headstock	30	3.4	1	0	0	0	H+R
4.3	Align the spoke to the support diagonals	10	4.2	0	0	1	0	H
4.4	Alignment verification	60	4.3	0	0	1	0	H
4.5	Fixing internal cruise	60	4.4	0	0	0	1	R
5.1	Central cruise picking	40	1.2	1	0	0	0	H/R
5.2	Central cruise insertion on the headstock	30	5.1	1	0	0	0	H+R
5.3	Align the spoke to the support diagonals	10	5.2	0	0	1	0	H
5.4	Alignment verification	60	5.3	0	0	1	0	H
5.5	Fixing central cruise	60	5.4	0	0	0	1	R
6.1	Bracket picking	10	1.2	0	0	1	0	H
6.2	Bracket positioning for knife attachment	30	6.1	0	0	1	0	H
6.3	Fixing bracket to the support diagonal	30	6.2	0	0	1	0	H
6.4	Fixing bracket to the disc	20	6.3	0	0	0	0	H/R
6.5	Welding bracket to external disc	40	6.4	0	0	0	1	R
...	...	...	...	...	...	...	...	...
17.4	Removing holder	60		1	0	0	0	R



ID	Task	Duration [s]	Precedent	Classification	Assignment
5.5	Fixing central cruise	60	1.2	R	R
6.1	Bracket picking	10	6.1	H	H
6.2	Bracket positioning for knife attachment	30	6.2	H	H
6.3	Fixing bracket to the support diagonal	30	6.3	H|R	H
6.4	Fixing bracket to the disc	20	6.4	H|R	R

ID	Task	Duration [s]	Precedent	Classification	Assignment
5.5	Fixing central cruise	60	1.2	R	R
6.1	Bracket picking	10	6.1	H	H
6.2	Bracket positioning for knife attachment	30	6.2	H	H
6.3	Fixing bracket to the support diagonal	30	6.3	H|R	R
6.4	Fixing bracket to the disc	20	6.4	H|R	R

Fig. 11 Dynamic reassignment of tasks

6 Conclusion

The paper presents a method for task classification and task assignment between humans and robots in industrial production processes. To implement a real collaborative workcell, it is not enough to buy a collaborative robot and meet the safety requirements, but it is also necessary to redesign the workcell and also the methods of organizing the work in the establishment, especially the assignment of tasks.

Our procedure for task assignment (i) exploits the different skills of humans and robots to classify tasks, (ii) tries to load the robot instead of the human where possible, and (iii) allows the dynamic reassignment of tasks in case of unexpected delays in task execution.

Future works will consider the inclusion of more indicators to better represent task characteristics, and the investigation of a communication paradigm to allow an effective collaboration between humans and robots.

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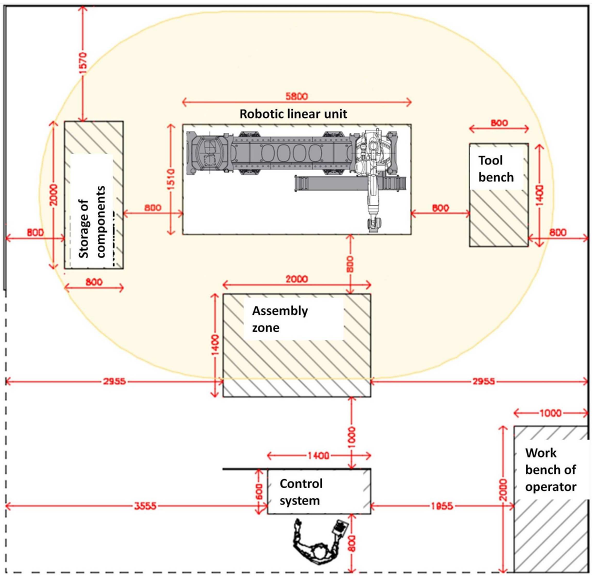

Fig. 12 Layout of the collaborative cell

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