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An evaluation methodology for the conversion of manual assembly systems into human-robot collaborative workcells

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Abstract

A collaborative robot is an industrial robot, which is able to interact physically and safe with humans in a shared and collaborative hybrid workspace. Collaborative robots are introduced helping operators to perform manual activities in modern manufacturing systems combining human inimitable ability with smart machines strengths. Considering current small and medium enterprises, the introduction of industrial collaborative robots involves the retrofitting process of current production systems, which in many cases is the starting point for collaborative process development. Due to the fact that collaborative assembly will be one of the most challenging and interesting applications for collaborative robotics in the near future, a proper human-robot assembly activity division will be a fundamental part of that retrofitting process. The aim of this work is the development of an evaluation methodology for the conversion from a purely manual assembly workstation into a collaborative one, by considering human and robot activities separation. The proposed model in this paper is based on a technical, qualitative and economic evaluation of the current manufacturing system in order to identify if there is the possibility to successfully re-design the workstation by introducing a collaborative robot in an efficient way. Safety and ergonomics indexes are also considered in order to improve operators work conditions between the current and the desired situation.

Keywords: *Collaborative Robot; Human-Robot Collaboration; Smart Manufacturing; Industry 4.0*

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1. Introduction

The Industry 4.0 concept is commonly used to identify the actual industrial field evolution. In particular, human-robot collaboration (HRC) is a primary cyber-physical technology of the so called “4th Industrial Revolution” [1]. This collaboration is a tangible example of modern human-machine interaction in the context of production and introduces a new concept of industrial robotics by allowing a hybrid combination of manual work and automation. Physical human-robot interaction entails hand-by-hand operations and therefore the sharing of workspace between robots and operators. In particular, HRC combines human abilities like flexibility, creativity and decision-making skills with smart machines strengths like accuracy, repeatability and payload [2]. In order to be competitive and profitable, modern manufacturing companies need further production flexibility and efficiency in terms of lot sizes, variants and time-to-market. These requirements involve an implementation of lean, adaptable and reconfigurable manufacturing systems characterized by a scalable degree of automation. Industrial collaborative robotics is a fundamental technology for achieving these innovative goals [3].

2. Human-robot collaborative assembly

The aim of this work is the development of a multicriteria methodology for the evaluation of the conversion of a manual assembly workstation into a collaborative human-robot workcell. This methodology will be also formalized into a practical tool for supporting small and medium enterprises (SMEs) in self-evaluation for the potential adoption of collaborative systems. In fact, according to [4], part of manufacturing SMEs do not have in-house knowledge and skills about the implementation of collaborative robots even if experts in the field believe that it will be an important technology for the growth of their business. Human-Robot Activity Allocation (HRAA) procedure is a fundamental part of the conversion process. Starting from an existing manual assembly workstation, this procedure allows to separate tasks and activities between the operators and robots by considering the influence of different production indexes concerning technical feasibility, safety and ergonomics, process quality and finally economic aspects. Following, a list of related research works is presented. Heydaryan et al. [5] proposed a hierarchy decision-making method for the human-robot task analysis based on productivity, human fatigue, safety and quality evaluation criteria. Bänziger et al. [6] presented a new method to optimize the task allocation in human-robot teams for a given workplace, using the simulation as fitness function in a genetic algorithm. Michalos et al. [7] developed a multi-criteria CAD-based method that can assign tasks to humans and robots by evaluating different production criteria (ergonomics, quality and productivity). Cencen et al. [8] introduced a human-robot coproduction design methodology to overcome the challenges faced in the SMEs context. Bruno and Antonelli [9] defined a strategy for job assignment by considering the weight of the assembled part, its displacement, the accuracy requirements, and the dexterity requirements. Dannapfel et al. [10] presented a method for the planning of heavy-duty human-robot cooperation in automotive flow. Mateus et al. [11] proposed a methodology to aid the creation of human robot collaborative systems by providing an ontology to support the extraction of relevant requirements. Fechter et al. [12] developed a CAD data input approach to a collaborative workplace design tool-chain considering different strengths of robot and human. Pearce et al. [13] presented an optimization framework for human-robot work allocation by minimizing production makespan and physical strain. Faber et al. [14] proposed an optimal assembly sequence by using an assembly graph as well as generic production rules for assessing the ergonomic conditions. Tsarouchi et al. [15] proposed an automatic workcell layout generation and task planning between human and robot resources by evaluating different production criteria. Zanella et al. [16] defined a multiple Key Parameters methodology for the objective identification of the most suitable HRC technology use. Ranz et al. [17] proposed a multi-stage procedure that allows jobs distribution between human and robot based on capability-oriented job assignment. Tsarouchi et al. [18] developed a HRC framework for the execution of tasks in hybrid assembly cells according to their capabilities. While prior work has underlined the importance of considering different kind of criteria in task allocation, the presented work integrate and extend the main evaluation aspects which are partially considered in the abovementioned researches. A preliminary and specific technical evaluation is introduced as a base part for all further investigations and the specific collaborative robot system features are jointly evaluated by considering the influence of single assembly tasks and components critical issues. The possibility to consider 4 different results as task allocation solutions is also a novelty.

3. The conversion process

During the conversion process, a manual assembly workstation should be analyzed in order to evaluate if it is possible and appropriate to convert the system in a collaborative workcell. A general assembly process is considered as a set of linked activities. Each activity has to be divided into single elementary tasks. Every task should be evaluated using different parameters, which influence the indexes final values. Once all the indexes are evaluated and defined, the HRAA procedure will propose a possible solution trough a dedicated algorithm, which combines the indexes values in a proper way. According to the HRAA results, it should be possible to evaluate if an assembly process is suitable or not for the collaborative conversion. Ideally, the overall evaluation should be done autonomously by medium-skilled SMEs technicians with the help of a dedicated software application. The overall procedure and related algorithm presented in this work will be formalized in the near future by a digital tool for helping SMEs to assess their manual assembly processes. A first prototype is currently in development using MS Excel as a platform. The first step of the methodology is a detailed analysis of current situation, which means to collect product and assembly cycle data. It is recommended to collect all the data through multiple observations of the assembly sequence and work environment, through direct practical tests (learning by doing), through operator interviews, through technical reports and documentation about components and the process. The second step is data elaboration, which means to use the HRAA algorithm for a first human-robot activity allocation. The last step is the final evaluation, which means to evaluate the technical, safety and ergonomic, qualitative and economic feasibility of the conversion process. Main required process inputs are: assembly cycle (sequence, priority), average task time [s/task], average task variability [s], average task labor cost [€/h], components cost [€], value added/not value added activity list, Rapid Upper Limb Assessment (RULA) values, main geometrical and material features of components, risk assessment reports. After a first evaluation, the main expected process output will be a first human-robot activity allocation sequence. This will be a fundamental information for further collaborative workcell re-design and assembly cycle re-definition process. Another important result will be a preliminary technical and economic feasibility study of the collaborative workcell. This will be another crucial information for the decision of future company investments. Finally, the HRAA sequence will help the workcell designer to increase the quality of technical and organizational design solutions for the operator's occupational safety and ergonomics.

3.1 The HRTAA procedure

The HRAA procedure is the core part of the conversion process. It aims to support designers to define if an assembly activity can be performed: exclusively by the operator (H), exclusively by the robot (R), equally by the operator or robot (H or R), by the operator with the help of the robot (H + R). Table 1 shows the allowed indexes values.The final activities allocation is based on the combination of four hierarchical evaluation indexes, which are: 1) Technical Evaluation Index (TEI - evaluation, if an activity can be performed by a robot in an efficient way considering technical limitations); 2) Safety and Ergonomic Evaluation Index (SEEI - evaluation, if an activity can provide physical stress to the operator or if it could be crucial or dangerous for humans and/or the production environment); 3) Qualitative Evaluation Index (QEI - evaluation, if an activity requires process quality improvements in terms of standardization and a reduction of process instability or variability); 4) Economic Evaluation Index (EEI - evaluation, if an activity can provide economic value to the final costumer (reduction of non value adding activities and reduction of cost). The activity index hierarchy is the following (Fig. 1):

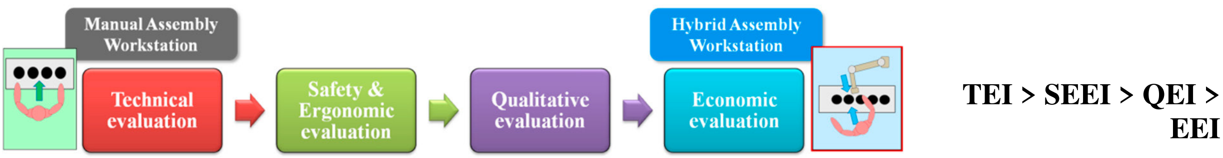

Fig. 1. Activity indexes hierarchy

After a first indispensable technical evaluation, the proposed hierarchy is set to provide more relevance to operators physical wellbeing and occupational safety. This decision comes from the need to improve operators work conditions by designing human-centered and ergonomic cyber-physical systems, which are a fundamental parts of Industry 4.0. The algorithm will then consider the importance of assembly quality through the analysis of process standardization and finally it analyzes the impact on customers value. A detailed explanation of indexes will be provided in Section 4. The algorithm, which combines different HRAA values for each index with the hierarchy is summarized in Table 2 and illustrated in Fig. 2. In this algorithm "FEI" is the Final Evaluation Index giving an indication of the most appropriate activity allocation (H, R, H or R, H+R) by considering the influence and the relationships of all the above mentioned indexes.

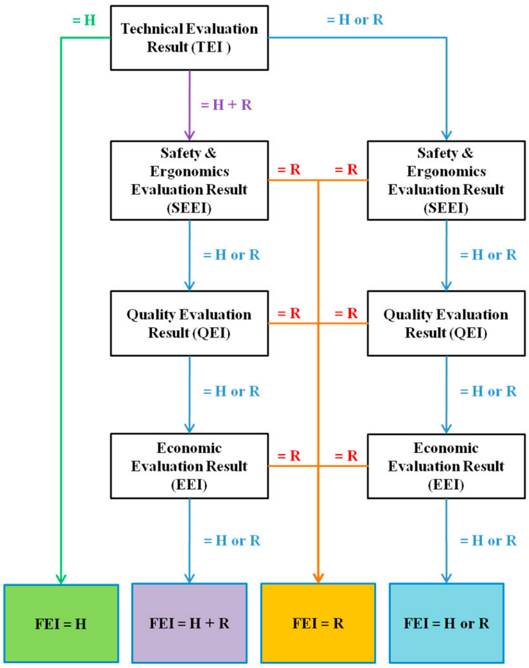

Fig. 2. HRAA algorithm according to indexes hierarchy

Table 1. Allowed indexes values.

Index	H	R	H or R	H+R
TEI	X	/	X	X
SEEI	/	X	X	/
QEI	/	X	X	/
EEI	/	X	X	/
FEI	X	X	X	X

Table 2. Summary of HRAA indexes combination and relative FEI.

Activity TEI	Activity SEEI	Activity QEI	Activity EEI	Activity FEI
H	*irrelevant*	*irrelevant*	*irrelevant*	H
H or R H+R	R	*irrelevant*	*irrelevant*	R
H or R H+R	H or R	R	*irrelevant*	R
H or R H+R	H or R	H or R	R	R
H or R H+R	H or R	H or R	H or R	H or R H + R

4. HRAA indexes

4.1. Technical evaluation index

The first index is represented by the TEI, since it is necessary to firstly evaluate if an activity is efficiently executable by the robot or not due to technical reasons [19] by using a proper amount of production resources in a suitable time. If this is not possible, the TEI and FEI index will be immediately address to "H". In case the activity is executable by the robot, the TEI index will be address to "H or R". In this situation, the algorithm allows other successive indexes to establish the activity FEI. Finally, if the activity is executable by the robot and if there is the need of robot help during the assembly (like a "third hand"), the TEI index will be address to "H+R" (it is a particular application of "H or R" result). In these cases, the FEI value will be set accordingly to successive indexes values (Fig. 2). TEI is obtained by considering different "technical critical issues", which modify the allocation according to their influence on the tasks. Considering a single-arm anthropomorphic industrial collaborative robot (equipped with standard commercial devices), these critical issues can affect the possibility to proper feed, handle and/or assemble a product. The identified critical issues can arise from product or process technical features and could prevent or make more difficult the employment of collaborative robots for assembly or manufacturing tasks. In general, main complexities arise from product geometry, product dimension, product materials features, assembly location and assembly sequence organization [7, 20,21,22]. A list of main technical critical issues are summarized in Table 3. Obviously, the ability to properly pick, handle and assemble a workpiece is strictly related to the gripper typology [23]. Taking into account only small and medium-size workpieces for assembly applications, the considered gripper groups are the following: two-fingers gripper, more than two-fingers gripper, vacuum gripper, magnetic gripper, adaptive (universal) gripper. According to the selected gripper group, each critical issue can affect the TEI in a different way, by addressing the index to “H” or to “H or R”. In particular cases, if there is a critical issue but that situation can be solved by using a low-cost and simple technical solution, the final task allocation will change considering this possibility. Finally, the algorithm combines the single task allocation values in order to have a unique activity TEI. The general rule is, if all task allocations are equal to “H or R”, the activity TEI will be set to “H or R”. On the other hand, if just one task allocation value is equal to “H”, the activity TEI will be set to “H” only. The proposed procedure for single task allocation is summarized in Fig. 3. These guidelines aim to help designers to evaluate if an existing manual activity could really be conducted by a specific collaborative robot system (in terms of robot arm, sensors, equipments and gripper) in an efficient way. Nevertheless, it is suggested to further examine in deep the identified tasks for a more comprehensive analysis.

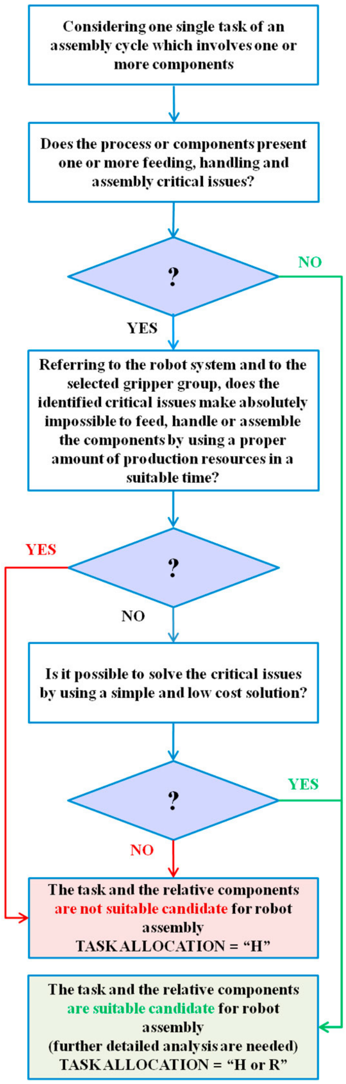

Fig. 3. Procedure for the technical evaluation of manual tasks according to main critical issues

Table 3. Main feeding, handling and assembly critical issues according to Boothroyd and Crowson [20,21,22]

Feeding critical issues
– The component is magnetic or sticky – The component is nest or tangle
Handling critical issues
– The component has none symmetry axis – The component is fragile or delicate – The component is flexible – The component is very small or very big (referring to a human hand) – The component is light so that air resistance would create conveying problems – The component is slippery
Assembly critical issues
– Components do not have a "datum surface" (reference surface) which simplify a precise positioning during the assembly – Components cannot be easily orientate – Components do not include features which allow a self-aligning during the assembly – Components cannot be located before they are released – Components provide resistance to insertion – Components do not provide chamfers or tapers that help to guide and position the parts in the correct position – Components have not a suitable base part on which to build the assembly – Components cannot be assembled in layer fashion from directly above (z-axis assembly) – The assembly is overconstrained – It is difficult to reach the assembly area / the components access for assembly operations is restricted or not easy to reach – The component and/or the assembly sequence requires high physical dexterity – The assembly requires high accuracy and/or demanding insertion tolerances – The assembly needs to reposition the partially completed sub-assembly, other components or fixtures – The assembly requires to reorient the partial assembly or to manipulate previously assembled parts – Components requires to be compress during the assembly – The component and/or the assembly sequence requires two hands for handling – The component and/or the assembly sequence require typical human skills (for example touch perception, haring, ability to interpret situations…)

4.2. Safety and ergonomic evaluation index

The second constraint is SEEI. In this case, if an activity can provide physical stress to the operator or if it could be dangerous for humans and/or production environment, the FEI will be immediately address to “R”, since it is advisable to safeguard the operators from potential risks which can arise during the manufacturing process by using the robot for unhealthy and dangerous activities. The SEEI index is obtained by considering safety and ergonomics criteria, which modify the index according to the combination of their values. A crucial part of that index is the RULA evaluation. Considering the static muscle activity and the force caused on the upper limbs, the RULA method allow a rapid evaluation of the musculoskeletal system through the analysis of postures of the neck, waist and upper limb also taking into account muscle function and the additional burden imposed on the body [24].The method is appropriate for the analysis of upper body activities and it involves body part diagrams integrated with code for joint angles, body postures, load/force, coupling and muscle activity. The output are risk level scores on a given scale to indicate the risk effects [25]. Another important part of the index is characterized by the potential occupational risks for the operators. Dedicated risk assessment documents could be useful for a better comprehension of the situation. Table 4 summarizes the task allocation according to RULA analysis and to the presence of operators and/or production environment risks.

Table 4. Task allocation according to RULA analysis and to the presence of operators and/or production environment risks.

RULA values and relative action levels	Risk Assessment	Task allocation
1;2 The posture is acceptable if it is not maintained or repeated for long periods	The task does not involves occupational risks for the operators and/or for the production environment	H or R
1;2 The posture is acceptable if it is not maintained or repeated for long periods	The task involves occupational risks for the operators and/or for the production environment	R
3;4 Further investigations are needed and changes may be required	*Irrelevant*	R
5;6 Investigations and changes are required soon	*Irrelevant*	R
7+ Investigations and changes are required immediately	*irrelevant*	R

Finally, the algorithm combines the single task allocation values in order to have a unique SEEI. The general rule is, if all the task allocations are equal to “H or R”, the activity SEEI will be set to “H or R”. On the other hand, if just one task allocation value is equal to “R”, the activity SEEI will be set to “R” only.

4.3. Qualitative evaluation index

The third constraint is QEI. In this case, an activity which is characterized by a certain level of process variability, or in other terms, which requires process improvements in terms of standardization, will set the QEI to “R”. In fact, from a manufacturing point of view, it is possible to define variability as an inherent process deviation from a pre-specified requirement, a negative condition which involves more control to achieve the designed process and products quality values [26]. Automation is a useful tool to increase process control and standardization, and as a consequence to improve quality by reducing variability and instability of processes. A value, which can be used to measure and qualify a production systems variability is the Coefficient of Variation (CV), which is defined as the ratio between the standard deviation (σ) and the mean value (Xm) [27]:

$$CV = \frac{\sigma}{Xm}$$

It is possible to have three different process variability categories according to the CV: low process variability ($CV = 0 \div 0.75$), moderate process variability ($CV = 0.75 \div 1.33$) and high process variability ($CV > 1.33$). The QEI is directly influenced by considering the impact of high variability conditions on process quality according to the task value classification. The economic value of the tasks have to be classified into low, medium and high in order to focus the qualitative evaluation only on the tasks which have a certain level of relevance on the overall work. Otherwise, there will be the possibility to change the FEI by considering the quality effect of a task which is quite irrelevant on the overall assembly process from the cost and time point of view. For this reason, all the tasks are firstly evaluated through an ABC (Pareto) analysis based on single task cost (*Tc*), which is calculated by multiplying task time (*Tt*) and task labor cost (*Tlc*):

$$Tc\ \frac{[€]}{[task]} = Tt\ \frac{[s]}{[task]} \times Tlc\ \frac{[€]}{[h/3600]}$$

The ABC classification of tasks values follows a typical 20/80 rule [28]. The activity allocation according to task value classification and CV is summarized in Table 5.

Table 5. CV task classification, ABC task value classification and relative activity allocation.

Coefficient of Variation (CV)	Task cost cumulative %	Task value classification	Task allocation
$0 < CV \leq 1.33$	*irrelevant*	*irrelevant*	H or R
$CV > 1.33$	% cum. ≥ 95%	low	H or R
$CV > 1.33$	95% < % cum.≤ 80%	medium	R
$CV > 1.33$	% cum. < 80%	high	R

Finally, the algorithm combines the single task allocation values in order to have a unique QEI. The general rule is, if all the task allocations are equal to “H or R”, the activity QEI will be set to “H or R”. On the other hand, if just one task allocation value is equal to “R”, the activity QEI will be set to “R” only.

4.4. Economic evaluation index

The fourth and final constraint is EEI. In this case, an activity (and the relative components), which does not provide sufficient economic value to the final costumer will set the EEI to “R”, since it is advisable to address not valuable activities to automation in order to reduce production costs [16]. The EEI is directly influenced by the task Value Added (VA) and Not Value Added (NVA) classification and to product value classification. In industry, a NVA task is a task, which creates production costs by absorbing resources and/or time without adding perceived value (and as a consequence satisfaction) to the final customer. On the opposite, a VA task is a task which generates production cost, but is also able to significantly increase the product value and satisfaction to the final costumer [29]. For a preliminary analysis, it is possible to consider as follows: grasping, handling, moving, positioning are NVA tasks; insertion, fastening, fixing, assembly are VA tasks. As for QEI, the economic value of the components has to be classified into high, medium and low in order to focus the economic evaluation only on those parts, which have a certain level of relevance on the overall process value. Otherwise, there will be the possibility to change the FEI by considering the economic effect of a part, which is quite irrelevant on the overall assembly process from the value point of view. All the products, which are involved in the process are evaluated through an ABC (Pareto) analysis on the basis of product purchase cost. The proposed ABC classification of products values follows a typical 20/80 rule [28]. It is advisable to set the proposed classification value according to the real case data and experience. The activity allocation according to product value classification and VA/NVA classification is summarized in Table 6.

Table 6. VA/NVA task classification, ABC products value classification and relative activity allocation.

VA/NVA task classification	Product value classification	Task allocation
VA	low (% cum. $\geq$ 95%)	R
VA	Medium (95% < % cum. $\leq$ 80%)	H or R
VA	High (% cum. < 80%)	H or R
NVA	*Irrelevant*	R

If a task involves more products or assembled components (which involves a combination of different values products), it is necessary to use the highest classification value for the definition of the task allocation.

Finally, the algorithm combines the single task allocation values in order to have a unique EEI. The general rule is, if all the task allocation are equal to “H or R”, the activity QEI will be set to “H or R”. On the other hand, if just one task allocation value is equal to “R”, the activity EEI will be set to “R” only.

5. Conclusions and outlook

This paper deals with the development of a multicriteria methodology for the evaluation of the conversion of a manual assembly workstation into collaborative human-robot workcell. The mehod is based on a HRAA algorithm based on different hierarchical activity indexes (TEI, SEEI, QEI, EEI), which is able to define if an activity can be performed efficiently by the operator (H), by the robot (R), by the operator with the help of the robot (H + R) or by both (H or R). A crucial part of activity allocation is the technical evaluation, which indicates if an activity can be performed in an efficient way by a robot considering possible technical limitations. One of the main result of the proposed method is to provide a tool to obtain a quick indication of activity allocation. This information is important for a collaborative workcell re-design and assembly cycle re-definition. In particular, the proposed methodology enables SMEs to carry out a preliminary feasibility analysis of collaborative processes including technical aspects, but also, occupational safety and ergonomics, process quality and economic aspects. In the future this methodology will be used as a basis to develop a digital tool for supporting SMEs technicians to self evaluate the potential of collaborative systems in assembly processes. Such a software application will help SMEs to proper use industrial collaborative robots and as a result, to improve assembly performances, operators work conditions and production quality. Further, this research leads also to another conclusion, showing a lack in research regarding the design of products for collaborative manufacturing and assembly processes. In fact, certain products, which are designed for manual assembly, do not present suitable features for a robotic or automated handling and assembly. Considering that the industrial collaborative robot market is continuously growing [30], it is reasonably possible to suppose that collaborative assembly will be an interesting challenge in the near future. For these reasons, it will be useful to develop new product design methodologies, which consider requirements for human-robot interaction during assembly tasks. Therefore, a new research field for product design could be to enrich commonly known Design For X (DFX) techniques by adding new “Design For Collaborative Assembly” (DFCA) methods.

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