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Abstract: The human-robot collaboration (HRC) in industrial assembly cells leads to great benefits by combining the flexibility of human worker with the accuracy and strength of robot. On the other hand, collaborative works between such different operators can generate risks and faults unknown in current industrial processes, either manual or automatic. To fully exploit the new collaborative paradigm, it is therefore essential to identify these risks before the collaborative robots are introduced in industry and start working together with humans. In the present study the authors analyze a benchmark set of general assembly tasks performed by HRC in a laboratory environment. The analyses are executed with the use of an adapted Process Failure Mode and Effects Analysis (PFMEA) to identify potential mistakes which can be made by human operator and robot. The outcomes are employed to define proper mistake proofing methods to be applied in the HRC assembly work cell.

Keywords: Lean manufacturing, Mistake proofing, Classification, Human-Robot Collaboration, HRC-PFMEA, Poka-Yoke.

1. INTRODUCTION

Both, industry and academics look at the collaborative robots (cobots) with a consideration that confines with the enthusiasm. Human-robot collaboration (HRC) is one of the enabling technologies in the framework of Industry 4.0. A number of European states adopted supporting policies in order to make affordable, or even profitable, the upgrade of existing machine tools and robots with new collaborative models compliant with industry 4.0 guidelines (Almada-Lobo, 2016). Before the introduction of cobots, industrial robots were employed only in full automated cells. 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." Production is evolving towards small batches, or even individual customized products. Collaborative work cells exploiting the dexterity of humans and the efficiency of robots are a possible solution.

Industrial cobots have been developed by all the main robot manufacturers and are compliant with updated safety standards (ISO/TS 10218 and ISO/TS 15066). Studies have exposed that precision, accuracy and repeatability of HRC assembly satisfies the standard industrial requirements (Antonelli and Astanin, 2016). The organization of work and the task assignment between humans and robots is another problem that have been widely discussed (Bruno and Antonelli, 2018). The objections to the introduction of cobots in factories are not only technical but more psychological: human workers are not confident with their robotic partner in the team. Building the confidence in the robot team mate is widely studied by psychologists (Hinds, 2004).

There is another, more subtle risk in the HRC introduction in industrial production: the insurgence of defects caused by mistakes in the communication between human and robot. Defects elimination is at the basis of modern production strategies (Six Sigma). In manual assembly, the human worker is responsible for most of nonconformities, far more than design errors, malfunctions of the machines or tools. In automatic assembly nonconformities are generated because of program errors or because of wrong handling or joining. HRC risks to superpose the defects of manual assembly over the defects of automatic assembly. Additionally, there are specific defects due to communication errors.

In order to maximize the benefits of HRC it is therefore necessary to contrast defect insurgence by developing proofing methods that neutralize the most common failure modes in the process. Adopting lean manufacturing approach, the possible failure modes are analyzed, and their gravity is assessed using modified PFMEA. PFMEA was previously successfully used in other contexts in risk assessment of production system (see e. g. Burduk, 2012) but in this application the method had to be modified. The most important failure risks are then prevented by applying proper Poka-Yoke (P-Y) techniques.

The study stresses the importance of considering the possibility of unexpected mistakes during HRC assembly and of providing the necessary countermeasures. Otherwise HRC won't succeed after the initial interest in novelty. The study presents modified PFMEA and the corresponding P-Y actions to implement.

Section 2 provides short description of the proposed PFMEA adjusted to human-robot collaboration. Section 3 reviews P-Y solutions. Section 4 describes case study and section 5 the

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results of the analysis performed with the support of modified PFMEA. Finally, the last section presents conclusions.

2. MISTAKES IDENTIFICATION

Most problems concerning human-robot collaboration are analyzed from safety point of view. Different methods are applied to identify hazardous situations and analyze the risk of safety problems (Etherton, 2007). In (Suwoong and Yamada, 2012) FMEA is applied to a collaborative robot analyzing the safety issues. In the work (Guiochet, 2016) HAZOP (Hazard and operability study) coupled with UML (Unified Modeling Language) notation is applied. In (Bensaci et al., 2017) FMEA was applied in risk analysis on one robot and FTA (Fault Tree Analysis) method was chosen to analyze the multi-robot communication risks.

The objectives of mentioned works can be adapted to the present case, namely:

- The potential mistakes should be identified at the stage of a collaborative work cell organization.
- Both, human and robot can make mistakes.
- Interaction between human and robot introduces additional sources of mistakes
- Analysis method of potential mistake consequences should be developed and adjusted to HRC.
- Preventive actions for the most serious mistakes should be suggested and possibly implemented.

The risk analysis techniques can be classified into two categories using bottom-up or top-down strategies (Guiochet *et al*., 2017):

- *Bottom-up*: a mistake effect is estimated in terms of cause consequence, severity and probability, e.g. FMECA (Failure Modes Effects and Criticality Analysis), HAZOP. These methods lead to propose possible corrective actions for the critical processes.
- *Top-down*: determination of mistakes and their combination leading to an undesirable effect. FTA (Fault Tree Analysis) is applied to represent the combinations of events leading to the effect in a form of a logical three.

Common methods for robotic systems risk analyses are FTA and FMEA (Gopinath and Johansen, 2016). There is consensus among authors that both of them are not immediately applicable because the information of the risks cannot be estimated at this stage. Additionally, in the presented case study FTA could not be taken into consideration since the method starts from defining the specific defective state of the system and then analyzes faults in individual elements of the system. The goal of this work was to find the potential problems which might appear in the specified steps of the HRC process. Therefore, in this paper the authors started from decomposition of the process and then they were looking for potential mistakes. Thus, present study used the modified standard PFMEA, under the name of HRC-PFMEA, overcoming the problem of difficulties in risk estimation and making the method applicable for development of new collaborative workcell. The analysis is presented in **Fig. 1** and is prevalently, although non-exclusively, oriented at assembly process design. The outcome of the analysis is a developed and validated process which consists of steps assigned to robot, human or which should be performed in collaboration by human and robot working together. For each step of the assembly process, failure modes are identified, separating human from robot potential mistakes. **Table 1** presents a list of potential mistakes (errors) in HRC. The authors propose to assess the consequences taking into consideration safety, quality, time and process performance. On the base of this, severity level criteria can be assessed (**Table 2**).

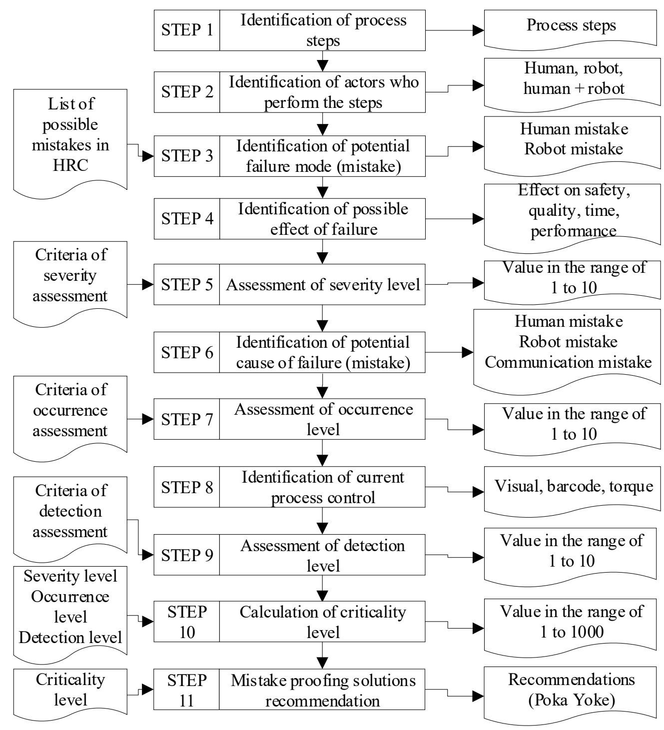

Fig.1. Steps of HRC-PFMEA analysis.

Table 1. Possible mistakes in HRC

Possible mistakes made by a robot	Possible mistakes made by a human
Handling the wrong part	Handling the wrong part
Failed positioning	Dropping a part
Wrong positioning	Wrong positioning
Wrong mount	Part damaging
Incomplete removal	Forgetting to place a part

Then possible causes of mistakes should be identified. A human can make a mistake, a robot can make a mistake or communication mistakes can happen. Occurrence level should be assessed with the use of the assessment criteria presented in the **Table 3**. The lower occurrence level is for robot mistakes, because it is a validated process a mistake can occur only because of technical problems. More often an operator mistake can happen. It derives from not following the procedures. Even more often a communication mistake occurs because it depends on procedures and time in which certain activities should be undertaken.

In the next step a control process should be identified. The process should detect mistakes to prevent problems. Assuming that detection made by robot is more reliable the criteria for detection have been ordered accordingly. Eventually, criticality of process steps should be calculated and then mistake proofing solutions should be recommended especially for the steps with the highest criticality level. For low risk level organizational solutions can be implemented. For medium risk level organizational or technical solutions can be applied. For high risk level, technical solutions are recommended (**Table 5**). These criteria ranking are obviously different from the standard ones, but the advantage of being dedicated to HRC justify the use of non-standard criteria.

Table 2. Criteria of severity

<table>
<tr><th>Safety</th><th>Quality</th><th>Time</th><th>Performance</th><th>Severity</th></tr>
<tr><td rowspan="4">Not affect safety</td><td>Not affect quality</td><td>Not affect time</td><td>Not affect performance</td><td>1</td></tr>
<tr><td rowspan="2">Internal rejection to be corrected</td><td rowspan="2">Time loss below tact time</td><td>Micro downtime</td><td>2</td></tr>
<tr><td>Small disturbances</td><td>3</td></tr>
<tr><td rowspan="2">Internal rejection to be repaired</td><td rowspan="5">Exceeded tact time</td><td rowspan="6">Process stop until a problem is solved</td><td>4</td></tr>
<tr><td rowspan="4">Human stressed</td><td>5</td></tr>
<tr><td rowspan="2">External rejection to be corrected</td><td>6</td></tr>
<tr><td>7</td></tr>
<tr><td rowspan="2">External rejection to be repaired</td><td>8</td></tr>
<tr><td rowspan="2">Human injury</td><td rowspan="2">Caused delivery delay</td><td>9</td></tr>
<tr><td>Scrap</td><td>Operation not performed</td><td>10</td></tr>
</table>

Table 3. Criteria of occurrence

Cause of mistake	Occurrence level
Robot mistake	1-3
Operator mistake	4-6
Communication mistake	7-10

Table 4. Criteria of detection

Detection means	Detection level
Detection achievable only by a robot (visual, barcode, torque etc.)	1-5
Detection made by a human with the use of appropriate devices	6-7
Detection made visually by a human	8-10

Table 5. Risk levels and recommended preventive actions

Risk level	Preventive actions
Low (1-45)	Organizational solutions
Medium (46-294)	Organizational solutions or technical devices
High (295-1000)	Technical devices

3. MISTAKES PREVENTION

The rationale behind P-Y methods (Shingo, 1986) is that it is preferable to put the worker in a working environment that facilitates the implementation of the correct operations and prevents the execution of the wrong operations (Stewart & Grout, 2001). The result is effective in terms of error reduction and hence costs reduction which is good for companies (Tkaczyk & Jagła, 2001; Yoo *et al.*, 2012).

Despite its widespread use in modern production, P-Y has not yet a rigorous formal definition that states application boundaries. Therefore, nearly every device utilized in production is called P-Y. In the literature Poka Yoke is defined equivalently as a solution which prevents mistakes, allows to discover and correct the mistakes already occurred, prevents not the mistakes but their outcomes (Plonka, 1997; Tsou & Chen, 2008; Lopes and Foster, 2013; Saurin *et al.*, 2012).

Different definitions probably descend from the fact that there are different kinds of Poka Yoke solutions as well as different applications of the same solution.

It can be assumed that P-Y be a solution developed to reduce the number of mistakes, or to eliminate the mistakes entirely. Adopting the classification of Stadnicka and Antonelli (2016) different P-Y solutions are presented in **Table 6**.

Table 6. Classification of P-Y solutions

Function	Task	Goal
Technical devices		
Preventive	Exclusion of mistakes	Mistake preventing
Corrective	Stop the process in case of mistake	Preventing the forward flow of non-conforming products
Informative and preventive	Information concerning mistake probability	Preventing mistakes
Warning	Information on mistake	Disclosing a place for improvement
Organizational solutions		
Informative	Information to avoid mistakes	Preventing mistakes
Corrective	Information on what to do in case of mistake	Preventing reoccurrence of mistakes

The presented classification facilitates selection of solutions for HRC process improvement.

4. DESCRIPTION OF THE CASE STUDY

The case study is not a standard industrial assembly. Unfortunately, HRC has recent applications and most of the industrial implementations are falsely collaborative, having the human operator and the robot working in separate zones of the workspace. The difference with the past is only the absence of safety fences.

It was decided to implement a benchmark assembly process that could exploit different degrees of collaboration as expected by a state of the art HRC workcell.

Collaborative modes in industry are classified based on the safety levels of interaction: safety-rated monitored stop, hand guiding, speed and separation monitoring, power and force limiting (following ISO-TS 15066). The maximum collaboration level is obtained when robot and human share the same workspace at the same time and contacts between human and robot are allowed but limited in the amount of force and power exchanged.

Apart from safety considerations, HRC workcells should have the characteristics identified by Wang (2017):

- intuitive and multimodal programming environment: the human worker doesn't need an in-depth knowledge of the work cell;
- 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;
- context/situation dependency: the system should be capable of interleaving autonomous human with robot decisions based on inputs from on-site sensors and monitors.

The assembly case study, mounting multiple flanges on a common base, is shown in **Fig. 2.** The figures represent the assembled and the exploded view of the assembling CAD model of components. To determine the relationships between assembly parts, CAD models of the components have been developed, using Solidworks software. The case study consists of four principal components: base(B), square flange(S), flange(F1) and flange(F2). An assembly diagram has been created for the product and every assembly task has been assigned either to the human or to the robot. Some complex assembly tasks must be executed by both operators, human and robot, simultaneously and collaboratively. The case study implements intuitive robot programming. Indeed, the assembly sequence is not programmed manually by a robot programmer but is generated automatically once the operator communicates the task sequence to the robot. The program is obtained as a composition of several elementary sub-programs, predefined. Every subprogram executes a simple operation and their combination allows to complete the full task. Therefore, the robot is commanded through task-based programming. The assembly has been executed a number of times in laboratory, using Universal Robots UR-3 collaborative robot with OnRobot RG2 haptic gripper. The joining operation is executed collaboratively: the robot keeps the flange in position and the human screws the bolts.

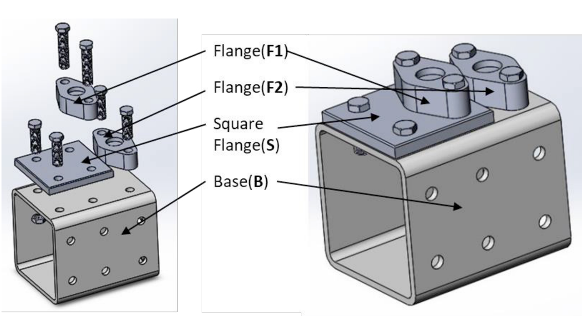

Fig. 2. HRC assembly case study.

In **Fig. 3** a picture is taken in a moment of actual collaborative work. The human-robot interface is a communication system, using a combination of touch-screen commands, gestures detected by a Leap Motion device, and button-sequence menus. In **Fig. 4**, the logic of functioning of the human-robot interface is described through the list of tasks executed by the different operators.

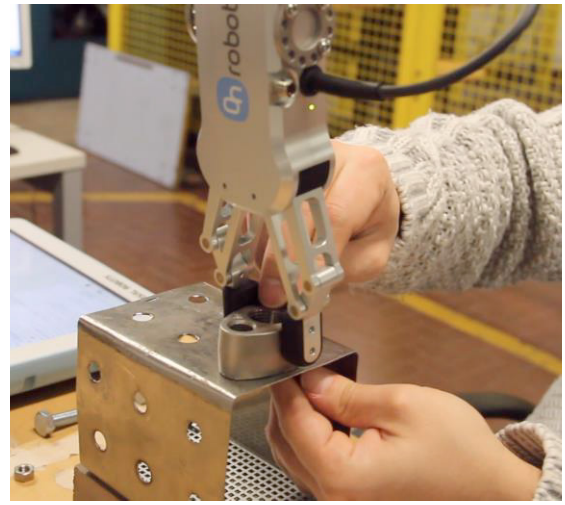

Fig. 3. Collaborative joining of the flange. Human and robot share the same workspace at the same time.

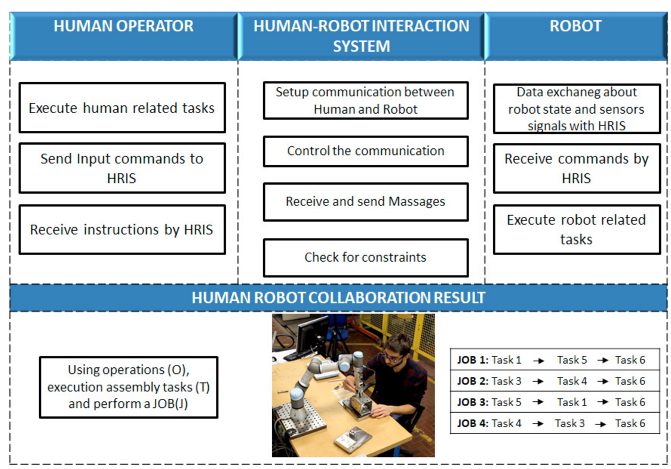

Fig. 4. Task sequence for the human, the robot and list of the interactions between human and robot.

5. ANALYSIS OF THE CASE STUDY

The case study was analyzed with the HRC-PFMEA method. The results of the analysis are presented in **Table 7**. In the table we can see that achieved criticality level varies from 9 to 300. Therefore, there are process steps which are critical, and for them Poka Yoke solutions should be proposed. While, in other steps the criticality level is low and organizational solutions are enough or even no recommendations are needed. In the example of **Fig. 5** a mistake is highlighted: incorrect positioning of the flange due to wrong program sequence imparted to the robot. However apparent, it can only cause internal reject to be corrected and the mistake could be easily detected by an associated vision system, therefore the criticality level will be low (9). In this case no further corrective actions are recommended.For high risk they are recommended such solutions as parts standardization or a device implementation to prevent mistakes. This is the case of wrong screws inserting fixtures (see **Table 7**).

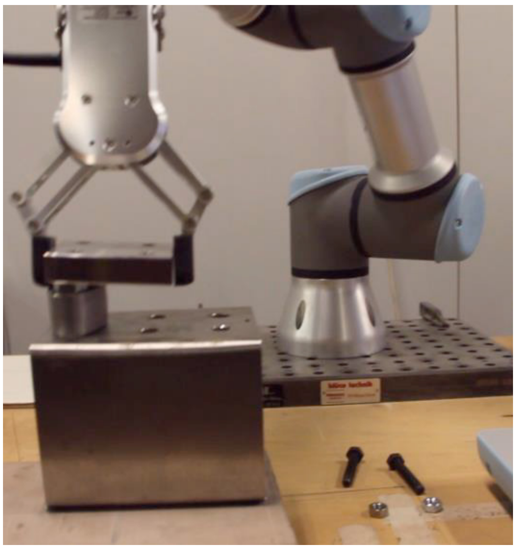

Fig. 5. Example of incorrect positioning of the flange due to a wrong order imparted to the robot.

This is a collaborative operation that, probably would have been easily solved in a human-only environment and lead to difficult situations as the human cannot reprogram the robot on the spot to accommodate different fixtures, therefore the most viable solution is the standardization of the parts, avoiding to have different screws in every process.

6. CONCLUSIONS

The paper presents a novel HRC-PFMEA method to be used on the stage of work cell organization for HRC. The limitations of FMEA were overcome by setting such criteria for severity, occurrence and detection which don't require historical data to perform the analyses. **Table 3**, **4** and **5**, introduced for the purpose, supports the PFMEA design. Therefore, the proposed method worked adequately in the presented case study. The assembly process was performed several times to assess whether the potential mistakes identification and analysis was completed properly. The study proposes adequate corresponding P-Y actions to be implemented.

In a future work proposed method will be applied to an actual collaborative industrial assembly to assess its limitations.

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Table 7. Process FMEA for the HRC of multiple flange assembly

Process Phase	Ref.	Actors	Potential Failure mode	Potential Effect of Failure	Severity	Potential Cause of Failure	Occurrence	Current Process Controls	Detection	Criticality	Recommended Actions
Fetch from conveyor belt	10	H	Fall Damage	Internal reject	5	OM	4	VH	8	**160**	Poka Yoke device to prevent falling
Position on assembly jig	20	H	Wrong positioning	Robot cannot find the target	4	OM	4	VH	8	**128**	Redesign jig to prevent wrong positioning
Take plate	30	R	Wrong part	Operation can't be performed	10	OM	6	Barcode read by R	1	**60**	Standardize parts
Remove from packaging	40	R	Incomplete removal	Small disturbances	3	RM	3	VR	1	9	
Position plate	50	R	Failed positioning	Process stop	5	RM	3	VR	1	15	Use centring rods and holes
		R	Wrong positioning	Internal reject to be corrected	3	RM	1	VR	3	9	
Insert fixtures	60	C	Screw fall	Micro downtime	2	CM	8	VH	8	**128**	Redesign work cell
		C	Wrong screws	Internal rejection	5	OM	6	VH	10	**300**	Standardize parts
Join fixtures	70	H	Stripped screw	Internal rejection	5	OM	6	Torque control-led by H	6	**180**	Use torque wrench
Take flange	80	R	Wrong part	Operation can't be performed	10	OM	6	Barcode read by R	1	**60**	Standardize parts
Remove from packaging	90	R	Incomplete removal	Small disturbances	3	RM	3	VR	1	9	
Position flange	100	R	Failed positioning	Process stop	5	RM	3	VR	1	15	Use centring rods and holes
		R	Wrong positioning	Internal reject to be corrected	3	RM	1	VR	3	9	
Insert fixtures	110	C	Screw fall	Micro downtime	2	CM	8	VH	8	**128**	Redesign work cell
		C	Wrong screws	Internal rejection	5	OM	6	VH	10	**300**	Standardize parts
Join fixtures	120	H	Stripped screw	Internal rejection	5	OM	6	Torque control-led by H	6	**180**	Use torque wrench
Take actuators	130	R	Wrong part	Operation can't be performed	10	RM	3	Barcode read by R	1	**30**	Standardize parts
Mount actuator	140	R	Wrong mount	Internal reject to be corrected	3	RM	3	Torque control-led by R	3	27	Use centring rods and holes
Stick direction label	150	R	Failed part marking	Internal reject to be repaired	3	RM	3	VR	1	9	

VR – Visual control made by robot, VH – Visual control made by human, H – human, R – robot, C – collaboration, OM – Operator mistake, RM – robot mistake, CM – communication mistake