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A COMPARATIVE ANALYSIS FOR THE EVALUATION OF PRODUCTIVITY IN HUMAN-ROBOT COLLABORATION

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Abstract
Background: Industrial Revolution 4.0 is on the verge to deploy collaborative robots, or cobots, in industrial assembly tasks. These innovative machines have the potential to increase efficiency and productivity in assembly workstation. **Objective**: The object of this study is an observational analysis of productivity of a manual assembly task in which participants perform activities in a standard and collaborative scenario with the robot. **Method**: The paper proposes an experimental design of an assembly task in a laboratory environment in which participants accomplish the task working with and without the robot. Furthermore, the study highlights the equipment involved for the design of the workstation. Observational methods like questionnaire and a checklist are adopted for the purpose of the study to evaluate the efficiency of the task in both scenarios and the level of satisfaction of the operator after performing the activity with the robot. **Results**: A higher level of operator' satisfaction and productivity, in terms of components assembled correctly, is shown from the analysis in the collaborative activity with the robot. **Conclusion**: The results highlight promising benefit in terms of ergonomics and productivity with application of cobots in workcell. **Application**: The Mitsubishi cobot MELFA ASSISTA is deployed for the collaborative task.

Keywords: Collaborative Robots; Human-Robot Collaboration; I4.0; Experimental Design; Productivity

Introduction

Industrial Revolution 4.0, or I4.0, is the ongoing evolution of modern production systems, which are focusing on mass customization, overcoming the conventional manufacturing systems. This era sets the creation of an interconnected world between humans and machines to products and customers. For this reason, the relationship between humans and technologies has become fundamental (Thoben et al., 2017).

One of the most innovative technologies that has paved the way to an interconnected relationship with the human is the collaborative robot, or cobot. These machines overcome the limitations of conventional industrial robots, working in fenceless environments with the operator thanks to safety assurance mechanisms and intuitive interaction technologies (Faccio et al., 2019; Zhang et al., 2021).

Collaborative robotics, thus co-botics, aims to improve production performances and operators' work conditions by matching typical machine strengths, such as repeatability, accuracy, power, and payload with human skills, such as flexibility, intelligence, problem-solving abilities, adaptability, and decision-making (Gualtieri et al., 2020; Grushko et al., 2021).

The application of cobots opens the door to the Human-Robot Collaboration field or HRC. HRC is an innovative strategic field of robotic application. A HRC activity consists of an application of an advanced grade of interaction between the robot and the operator. The goal is to achieve a safe and ergonomic environment where humans co-work simoultanously alongside robots in those critical, non-ergonomic, and repetitive tasks. However, the design of a HRC activity is the result of a rigorous ergonomic and safety analysis regarding its efficiency and effectiveness in manual assembly scenarios (Gervasi et al., 2021; Lorenzini et al., 2023). With the peculiarity of robots to execute precise and repetitive tasks on manufacturing shop floors, it is possible to combine their accuracy and strenght with the cognitive ability and flexibility of humans in critical manufacturing tasks (Wang et al., 2019).

Hence, HRC aims at designing a challenging work environment where the human and the robot can work in proximity. The outcome is to enhance the overall productivity and quality of the process (Jain et al., 2022). Enhancement of productivity in the field of manufacturing production is of very great importance to an organization's ability to compete and make profits over time. This is also due to the multi-functionality of a HRC workcell in which it is possible to enable a multimodal control for the collaboration (Schmidtler et al., 2015).

Numerous advantages may be brought in a manufacturing process. (Kopp et al., 2020). The HRC research studies has indicated the design of future robotic workplaces. These are modular places where the assembly of components is set according to ergonomic and safety principles (Savkovic et al., 2022).

Furthermore, in HRC systems, operator safety is the most important criterion (Carvalho et al., 2022). One of the biggest challenges in the development of collaborative systems is to ensure operators' psychophysical well-being in terms of Occupational Health and Safety (OHS) while preserving high the task performance (Brun & Wioland, 2020; Robla-Gomez et al., 2017). In order to ensure maximum operator safety, various safety-related requirements are imposed on the collaborative workstation according to standards. (Gualtieri et al., 2020)

Despite the increasing interest of researchers in HRC, the overall effects of this close interaction on worker's performance have not been deepened in detail. To achieve an optimal level of collaboration, it is necessary to take into account the psycho-physical state of the human involved in operations with the robot (Munoz, 2017; Colim et al., 2020). In fact, the introduction of new technologies in the workplace has an impact on the people involved. Emotions and cognitive processes can influence the success of the collaboration and, consequently, the performance of the task (Villani et al., 2022)

This paper shows the beneficial effects, in terms of ergonomic aspects and productivity, of the deployment of a cobot in a assembly task performed in a modular industrial assermbly workstation after a rigorous analysis of the design of its implementation in the workplace environment. The results, shown through questionnaires and a checklist, set the basis for further ergonomic assessment and evaluation of workload in industrial collaborative scenarios.

Material and Methods

The set-up of the HRC assessment took place in the modular industrial assembly workstation designed at the laboratory of the Faculty of Engineering, University of Kragujevac, Serbia (FINK) (Caiazzo et al., 2022). The tests were conducted in an isolated environment at room temperature constantly regulated. The equipment involved in the tests are:

- A PC touch-screen allowing the operator to be guided during the task activity;
- A video-camera for the record and track of the sequential assembly activities;
- The cobot, a MELFA ASSISTA from Mitsubishi Electric, used for carrying the pieces in the assembly area.

The task consisted of prototypal industrial components to be assembled by candidates, designed at FINK for educational purposes for University students, performing the task. Indeed, the prototypes present no sharp edges, light weight and are composed of plastic material. An explanation of the previous task is represented in the paper of Savkovic et al. (2022).

The experiments were conducted in two different scenarios, shown in Fig. 1: standard and collaborative work. In the standard work scenario, the task was accomplished by the participants without any interference in the workplace. This scenario is relevant as a baseline for the comparative analysis: starting from this initial scenario, in this paper, authors set the assembly task into a collaborative scenario.

The role of the robot is to pick and place the component in the assembly where the participant performed the task. The cobotic workcell is moveable and allows the robot to act in fenceless environments. In this regard, the cobot was placed side-by-side the participant. This solution allowed the participants to grasp the pieces carried by the robot in the same area where they had grabbed them in the standard work scenario. In this way, the piles of pieces are removed and the bulk ratio on the workstation is reduced. The robot implementation is the only component altering the design phase. The goal of the study is to analyze the impact of the robot implementation in the assembly task. The robot pace is set in collaborative mode: according to the regulations, the speed of the cobot when interacting with an operator in the workcell must be below 250 mm/s. The robot station was positioned at a distance of 1000 mm from the operator in order to let the operator perceive the machine not as a hazard during its movements (Arai et al., 2011).

The candidates are students from FINK of serbian mother-tongue, male gender, right-handed, with no previous experience in robotic applications. The number of participants selected, from an open application form, is 10. The participants signed a consensus agreement for the treatment of personal data. The number of components to be sequentially assembled is 150. The candidates assembled the piece according to the illustration presented on the PC touch-screen.

A checklist is used to define the pieces that were correclty assembled during the task. This observational method provides a qualitative analysis of the productivity and efficiency of the task between the standard and collaborative scenario. Moreover, candidates underwent a questionnaire at the end of the sessions regarding the collaborative activity alongside the robot.

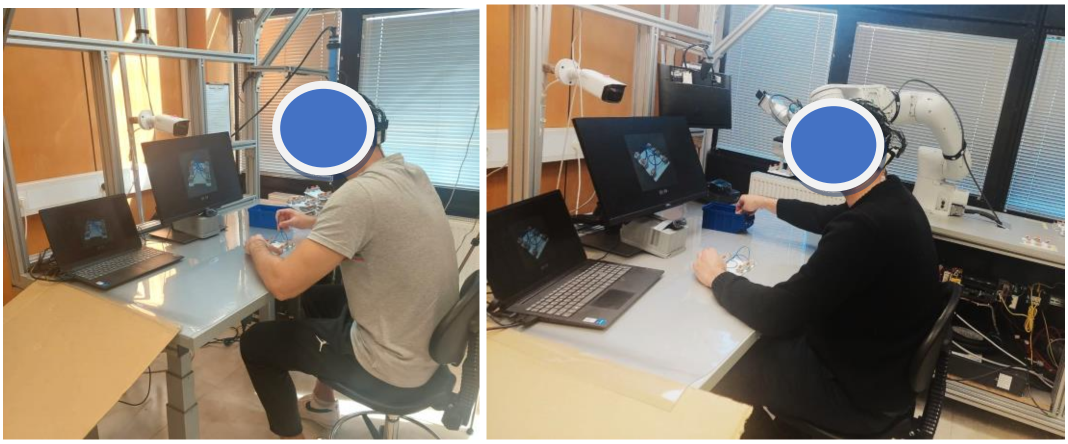

Figure 1. *Representation of the two scenarios: the standard scenario, on the left, in which the operator performs the standard assembly task; the collaborative scenario, on the right, in which the operator performs the task with the cobot.*

Results and Discussion

The level of productivity, as the number of pieces correctly assembled by the participants, in the standard and collaborative scenario is presented in the Table 1 below:

Table 1. *Variation of pieces completed correctly in the standard and collaborative scenario.*

No. Subject	N. pieces in the Standard scenario (S)	N. pieces in the Collaborative scenario (C)	Variation of Productivity (C-S)	$\%_{150}$
Subject 1	86	95	+9	+6%
Subject 2	76	83	+7	+4.67%
Subject 3	120	126	+6	+4%
Subject 4	98	108	+10	+6.67%
Subject 5	104	112	+8	+5.33%
Subject 6	80	92	+12	8%
Subject 7	103	107	+4	2.67%
Subject 8	60	69	+9	6%
Subject 9	97	105	+8	5.33%
Subject 10	90	101	+11	7.33%

As shown in the table, the number of pieces correctly completed by the subjects in the collaborative scenario is higher than in the standard scenario.

Before conducting an analysis of the displayed samples, it is necessary to statistically examine whether the results obtained in the Collaborative scenario (sample 2) are better compared to the Standard scenario (sample 1). Since this study involved 10 participants, this can be considered a small sample. Therefore, A Student's t-test will be used to conduct the examination. In this case, a one-tailed test will be used.

The problem can be posed in the following way:

- Step 1: The hypothesis being tested is whether the mean value in sample 2 is greater than the mean value in sample 1. The hypotheses are:

$$H_0: \mu_1 = \mu_2; H_1: \mu_1 < \mu_2;$$

- Step 2: The testing is conducted at a risk level $\alpha = 5\%$. This value is commonly used in statistical hypothesis testing. It represents the acceptable level of risk that the researcher/expert is willing to take in making a decision about the hypothesis.
- Step 3: The value of the test statistic for the considered samples is $t_0 = 4.08$.
- Step 4: Table value for $T_{0.05, 18} = 1.734$.
- Step 5: Since the value of $t_0 > T_{0.05, 18}$ the null hypothesis (H_0) is rejected. This means that there is sufficient evidence to claim that the work performance of the participant is better in sample 2 than in sample 1.

The mean values in the samples are 91.4 and 99.8, indicating that performance has improved in sample 2, which has been statistically proven. However, since the improvement varies from participant to participant, we need to examine how significant that improvement is.

The correlation coefficient between the participants' performance in sample 1 and the Variation of Productivity is $r = 0.45$. This means that there is some correlation between them, but it is not strong. This means that the Variation of Productivity does not depend too much on the initial performance of the participants. In other words, it does not necessarily mean that a participant with good performance in sample 1 will have a high value of Variation of Productivity, i.e. improve their performance. The same is true in reverse.

By calculating the confidence interval, we can determine the range in which the expected number of pieces correctly completed can vary, both for sample 1 and sample 2. Let us reconsider the 5% risk level. In that case, the confidence interval for both samples can be expressed as follows:

- Sample 1: $79.62 \leq \mu_1 \leq 103.18$, or 91.4 ± 11.78;
- Sample 2: $89.74 \leq \mu_1 \leq 109.86$, or 99.8 ± 10.06;

From the given information, it can be concluded that there is a 95% chance that the means of samples, under the same conditions in some future studies, will be within the displayed intervals.

Finally, it can be concluded that the number of pieces in the Collaborative scenario is statistically significantly higher compared to the number of pieces in the Standard scenario. Additionally, it has been established that the Variation of Productivity is not dependent on the results that the participants had in the Standard scenario. Also, it was concluded that the performance of activities in better conditions (collaborative scenario) does not affect all respondents equally. Respondents generally performed better in the second scenario, but having over 100 does not mean that it improved the score more than the subject who had about 90.

Regarding the questionnaire undergone at the end of the collaborative sessions, a summary of the asnwers of the participant were:

- How was the experience with and without the robot ?
  - *Working with a robot was time-saving. I was more engaged in the collaborative task rather than working alone.*
- How was the robot motion flucency in the interaction ?
  - *The robot interacted with natural fluency and responsiveness, executing commands quickly and accurately for a more interactive experience. This enabled it to create a more natural feel and pace for the interaction*
- How safe and comfortable was the participant during the interaction ?
  - *It was safe but and I was free from distractions. The session was conducted in a respectful manner*

• Was better the desk without the pieces placed next to you ?

○ *Without the pieces next to my desk, I had more space to think and focus on my work*

The Table and the answers from the participants showed a benefit in terms of satisfaction and productivity working with the cobot. The presence of the robot allowed the candidates to be more engaged and satisfied during the task and the results are shown in terms of pieces completed. Furthermore, the design of the collaborative scenario allowed to reduce the bulk presented in the workstation: as the pieces are not set next to the participant, but carried by the robot, the subject felt more freedom during the dexterous activity.

The initial results are promising for the evaluation of the efficiency and effectiveness of the HRC in the assembly task. However, the choice of the HRC to be implemented in the assembly task depends on the task to perform. This is a crucial aspect to take into account during the design phase of the HRC. Different key performance indicators are involved in the design of a HRC. The success of the deployment of the cobot depends on the different aspects that the company aims to achieve (Caiazzo et al., 2022b).

Regarding the assessment of the grade of satisfaction of the HRC activity, this observational method might be subject of bias. In this regard, further analysis of the collaborative scenario involving direct observational methods would be exploited in the coming studies. Authors point out that a comparative neuroergonomic analysis would provide further indicators. Among the direct parameters affecting the physiological state of the operator during a task, the mental workload is the most promising (Naismith & Cavalcanti, 2015; Brunzini et al., 2021). In this regard, advanced neuroergonomic studies would be carried out in the next phase of these experiments through electroencephalogram (EEG) devices (Savkovic et al., 2022b).

Conclusions

The research presented in this paper showed an observational analysis conducted in a modular assembly experimental workstation in which HRC tasks are performed by participants. The analysis, shown in terms of productivity and questionnaire at the end of the sessions to evaluate the level of satisfaction of the participants, set the promises of further studies in the HRC applications. In this regard, a neuroergonomic analysis through sophisticated devices such as EEG would allow a better representation of the cognitive workload index affecting the operator while working with the robot. The necessity of continuous improvement of an enterprise is a subsequence of permanent and dynamic changes in its surrounding as well as inside it. Continuous improvement of processes is defined as a purposeful action, assuming systematic and continuous development of selected process parameters (time, cost, quality), in the interconnection of these parameters and improved processes. The goal of this paper is to point out how the HRC application, after a careful design phase, might affect the task performance not only in terms of productivity, but also in terms of ergonomics and satisfaction of the human agent. Further studies would allow to assess metrics regarding the operator’s performance from a neuroergonomic point of view (Caiazzo et al., 2022c).

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