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Investigating the Influence of a Cobot's Average Tool Center Point Speed on Human Work Behavior in a Cooperative Human-Robot Collaboration Assembly Station

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Abstract

Industry 5.0, an extension of the Industry 4.0 paradigm, points out the need for human-centered solutions in cyber-physical manufacturing technologies, including context-aware cobots that can self-adapt to human needs. Whereas humans are flexible and able to work autonomously, cobots rely on static controls equipping them with motion precision and repeatability to support their human counterparts. However, changing circumstances require the cobot to adapt autonomously to changes, including human working behavior, which depends on the psychological perception of cobots. Understanding the influence bears the potential to improve autonomous decision-making for self-adaptation regarding the cobot's TCP speed. This paper investigates quantitatively and qualitatively the influence of a cobot's motion speed on the Task Time and Human-Active Time in a cooperative assembly station. Concludingly, the TCP speed was found to challenge the operator and change the perception of teamwork.

Keywords: HRC; Individualized HRC; TCP speed

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1. Introduction

Since Colgate et al. [1] presented the first cobot, the field of Human-Robot Collaboration (HRC) evolved. Not only do safety controls and actuators allow for concurrent close collaboration in the same workspace, but also intelligent sensors enhance cobots. Connecting robotic systems with sensors to collect environmental data and enabling the processing, returning, and using of this data in the physical world creates cyber-physical systems (CPSs), which are considered a fundamental technology of the Industry 4.0 paradigm. CPSs envision autonomously adapting to changing environmental conditions and system needs. Such technological advancement allows for the next step toward individualized, flexible human-centered manufacturing solutions. The European Commission sees the next stage of industrial development in expanding Industry 4.0 to include human-centric approaches in which intelligent systems do not replace humans but rather integrate, promote and empower them.

Within such a paradigmatic shift towards Industry 5.0 [2], individualized human-machine interaction, which also concerns HRC [3], plays a central role. Machines to be able to adapt autonomously to individual human needs require various capabilities, including situation and context awareness as well as decision-making [4]. Cobots must be able to analyze and understand the recorded data to make the right decision for adaptations. However, without underlying modeled knowledge about the context of human work behavior, a meaningful human-centered adaptation of the cobot's behavior is impossible.

Weiss et al. [5] have accordingly identified the need for research on the psychologically related aspects of HRC. Knowledge and insights into the modeling of HRC scenarios

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and tasks regarding the influence of cobots on human work behavior are not yet comprehensively investigated. Possible factors that influence human work behavior are noise, size, trajectory, and speed of the automated counterpart in an assembly station [6].

However, a deeper understanding of the singular factors is paramount to further research. In the context of self-adaptive systems, the tool center point speed (TCP) speed as an easy-adaptable feature is of significant interest. Accordingly, the present work investigates the influence of speed and its impact on process performance indicators and human perception of the cobot.

The remainder of this paper is organized as follows: Section two provides the related work on HRC. Section three describes the experimental setup and measurements. Section four presents the results and reflects on the findings, and section five elaborates on the experiment and future work.

2. Related Work

The HRC covers a widespread range of scenarios, influential factors, and perspectives. Section two accordingly provides a delimitation for the scope of the present investigation.

2.1. Human-Robot Collaboration

The ISO/ TS 15066 defines HRC as a "state in which a purposely designed robot system and an operator work within a collaborative workspace" [7]. Moreover, the norm defines the workspace in an HRC as the "space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation" [7]. Hence, the definition allows for summarizing different levels of working together as HRC.

2.2. Distinguishing Cooperation and Collaboration in HRC

Di Marino et al. [3] classify collaborative human-robot interactions based on temporal and spatial dimensions. *Workspace Sharing* includes interactions involving robots and humans sharing the workspace but performing tasks sequentially. *Time and Workspace Sharing* comprises interactions in which humans and robots work in the same workspace at the same time.

Bauer et al. [8] use a similar classification and consider the task to be performed, including the workpiece. The *sequential* scenario in the shared workspace category is also present here. However, simultaneously working in the workspace is subdivided into *cooperative* and *collaborative* scenarios. *Cooperative* includes interactions in which team members perform tasks independently of each other, working together in a parallel fashion toward a process goal. *Collaborative*, in comparison, describes interactions in which the team members perform interdependent tasks and, for example, jointly manipulate the same workpiece.

2.3. Evaluating HRC and Human Work Behavior

For collaborative scenarios, the Human Idle Time (H-Idle), the Robot Idle Time (R-Idle), and the Task Time (TT) are used to evaluate HRC systems. Thereby, the H-idle describes the time the operator does not contribute to completing the task, for example, due to waiting times for the other team member. Similarly, the R-idle is the counterpart to the H-idle concerning the cobot. The causes for the idle times are versatile in both indicators. Under the assumption of turn-taking models, the dependence on the process design becomes apparent, which Hoffmann has already determined. [9, 10] Although the relationship between the metrics and the fluency perception of workers is not yet exhaustively investigated [9], the metrics provide information about the processual flow of the collaborative scenario. In cooperative teamwork, the cobot is shown to meet programmed times due to its intrinsic capabilities of speed, repetition accuracy, and persistence. Thus, the explanatory power of the metrics depends on the measurement and process design, as Hoffman [9] points out. The direct examination of idle times can only be used to a limited extent in cooperation scenarios. However, the presented metrics describe the work behavior in a temporal context.

2.4. Factors Influencing the Perception of HRC

The perception of cooperating with the cobot appears to depend on various factors. Arai et al. [10] investigated that industrial robot movement speed induces stress and strain on humans in HRC scenarios. Their experiment showed that the speed perception changes depending on the robot's proximity and the movement direction. However, the influence on process indicators and individual perception was not considered. Dragan et al. [11] found that the TT changes depending on the robot's trajectory. Thereby the human team member showed hesitation and delayed beginning the task when the cobot moved disturbingly. In contrast, the participants did not hesitate when the robot moved in a legible [12] manner. Their experiment showed that humans infer the goals of their team members and orient their actions regarding the mutual goals. Koppenborg et al. [13] showed that the predictability of the robot goals not only depends on the trajectory but also on the movement speed. In comparison, high speeds hinder correct goal inference. However, human thoughts and conscious perception were not investigated with an explorative approach.

2.5. Additional Indicator Consideration

After considering the various influencing parameters in collaborative turn-taking scenarios, the assumption is made that the disturbance variables increase the TT and influence the time during which humans are actively working on the task. However, investigating the influence of the different robot disturbances on humans and the associated execution times requires an indicator tied to the human process performance. Similarly to the H-Idle, the Human Active Time (H-Active) is considered here. The H-Active represents the time when the human is actively working on the task and corresponds to the activity time [14].

2.6. Hypotheses

1. The cooperative interaction with the cobot influences human working behavior depending on the TCP speed.
2. The influence of cooperative interaction can be determined using process time indicators depending on the TCP speed.
3. The influence of cobot speed is perceptible to humans and evokes distinct reactions depending on the TCP speed.

3. Methodology

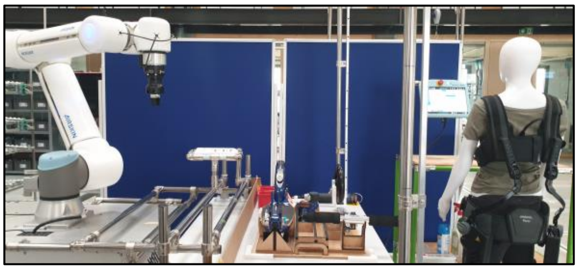
Investigating the influence of a cobot's TCP- motion speed on human working behavior in a cooperative scenario used a completely randomized experimental design. Besides the quantitative analysis of the process performance, the human-centric approach requires a qualitative understanding of humans' individual perceptions of the task.

The experiment was designed assuming that the TCP speed influences the human. Thereby a slow speed and waiting for the cobot is assumed to be disturbing for the human. Likewise, excessive movement speed is expected to have a negative impact on the human team member.

3.1. Experimental Design & Setup

In a cooperative setup, the operator and cobot worked together. **Error! Reference source not found.** (a) shows the l ateral view of the workspace setup and (b) the top view, respectively. The assembly station consists of a workbench that fixes the cobot coordinate system with the workbench coordinate system. The station has a screwplate on the cobot side and a switching automation light grid on the operator side of the station. The light grid detects the operator's presence in the shared operating space. The cobot is a *Universal Robots UR10e*, augmented with a *Blue Danube Robotics Airskin* that increases safety and thus allows for higher cobot movement speeds. The workpiece carrier holds the scooter parts and has a fixed position on the workbench using fixation brackets. The red boxes store bulk material such as screws, nuts, washers, and sleeves.

a)



b)

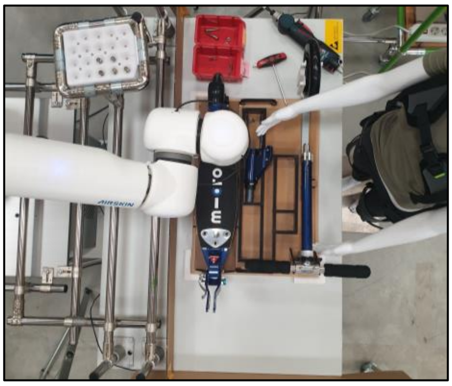


Fig. 1. HRC-Assembly Station (a) lateral view (b) top view.

All participants obtained the same work instructions. First, the subjects were required to assemble parts of the city scooter without the cobot five times. The subjects activated the CPS using the cobot teach pendant to begin the assembly process. After initiating the task, the subjects entered the workspace and began the assembly. Eventually, the participants left the collaborative workspace and feedbacked the task state.

Subsequently, the participants were randomly assigned into three groups (G1, G2, G3). Each group had to execute the same tasks as before; however, the cobot also participated in the workspace. The cobot picked up the screws from the screw plate and placed them in the holes on the footboard.

The cobot programming interface logged events using the light grid and programmable variables and transferred them to a server. Activating the CPS started the monitoring and represented the first event of a sequence. The TCP speed of the cobot was set using the speed factor via the Polyscope software of the UR10e, whereby the pick and place program was programmed at 100% (G3) speed. The other speed settings are 33% (G1) and 66% (G2).

3.2. Quantitative Data Collection

The CPS uses a monitoring program to report events written into a NoSql cloud database (Mongo DB Atlas). An event comprises a timestamp and particular status messages. The TCP speed is also recorded for each event besides the UserID and the assembly process iteration. Table 1: ExampleTable 1 shows an excerpt from a generated event.

The *Cobot Running State = True* indicates the time during which the cobot actively contributes to completing the task. The *Light Curtain State = False* indicates when the light curtain is occupied, representing the human's activity during the completion of the task. After each process run, information is retrieved from the raw data. TT, H-Idle, R-Idle, C-Act, Cobot Active Time and H-Act may be obtained from the events. For the investigation in this work, TT and H-Act are used as process indicators.

Table 1. Example Eventlog.

Time Stamp	Cobot Running State	Light Curtain State
1647334230.8835	True	False
1647334233.8212	True	True

3.3. Qualitative Data Collection

After the experiment, the participants first took part in a short interview, after which they completed a questionnaire. The short interview consisted of explorative questions intended to reveal the subject's thoughts and perceptions regarding the cooperative task. Furthermore, the experiment footage was analyzed for subject comments. The qualitative data analysis is based on a grounded theory approach that thematically codes the participants' statements [15].

4. Results and Discussion

The evaluation of the cooperative scenario using H-Idle, R-Idle, and C-Act describes the process, although the variables determined are strongly dependent on the process design. Thus, depending on the design, indicators may provide only limited information about the influence of cooperation. Due to the cooperative nature of the process, a stable Cobot Active Time emerges for each group, as shown in Table 3. Furthermore, Table 3 shows the measured average TCP speeds across all process runs of each group. The acceleration of the cobot was not measured.

Table 3. Cobot setup for the respective group.

Groups	Cobot Active Time [sec]		TCP-Speed Angular [deg/ sec]	TCP-Speed Cartesian [mm/ sec]
	$\bar{x}$	sd	$\bar{x}$	$\bar{x}$
G1 33%	60.07	0.90	36.96	179.23
G2 66%	31.48	0.12	70.32	344.10
G3 100%	21.69	0.29	103.89	511.02

Table 2. Outliers based on IQR*1.5.

without Cobot			with Cobot		
Task Time	H-Act	H-idle	Task Time	H-Act	H-idle
81.49	72.76	8.36	81.02	74.19	8.89
65.34	78.16	9.69	91.63	87.10	6.26
75.43	63.37	7.35	103.38	97.13	
94.15	67.08	7.25			
99.77	90.56				
	94.46				

Of 19 participants, one participant was eliminated due to insufficient data caused by a server breakdown. Out of G1, one subject was assigned to group two due to a software mistake. Hence G1 consists of 5, G2 of 7, and G3 of 6 participants. Only one of the participants had worked with a cobot before.

4.1. Task Time

When looking at the TT in Figure 1Figure 2 (a), the dependence of the measured times on the limiting factor of process design becomes apparent. In G1, the cobot determines the TT at a low speed. The group's variance within the TT is explained by the participant's feedback time after the cobot has finished its task. The range of the TT is comparatively small in this case. The measured TTs of all groups without cobot seem to be constant. Likewise, the TTs of groups 2 and 3 do not seem to differ. Furthermore, the TT range is larger when the human is the determining factor, i.e., when the human completes his tasks after the cobot.

4.2. Human Idle Time

Figure 2 (b) underlines the design dependency. The H-idle describes the timespan the subject needs between the feedback of the process status and activation or deactivation of the light curtain. According to the boxplot, G1 in cooperation with the cobot, shows a significant deviation from the other recorded H-Idle, a deviation caused by the experiment-related programmed cobot speed. Here, the human finishes its task before the cobot completes its task. Participants took longer to report during the experiments when they had a long waiting time for the cobot.

4.3. Human Active Time

The H-Active describes the accumulated times during which the participant actively contributes to the fulfillment of the task. The time was measured by accumulating the light barrier occupancy. Figure 2 (c) shows that H-Active tended to be lower for all groups when working with a cobot than without a cobot.

4.4. Test Statistics

Reviewing the outliers and comparing their occurrence with the recorded experiments showed that the outliers were due to

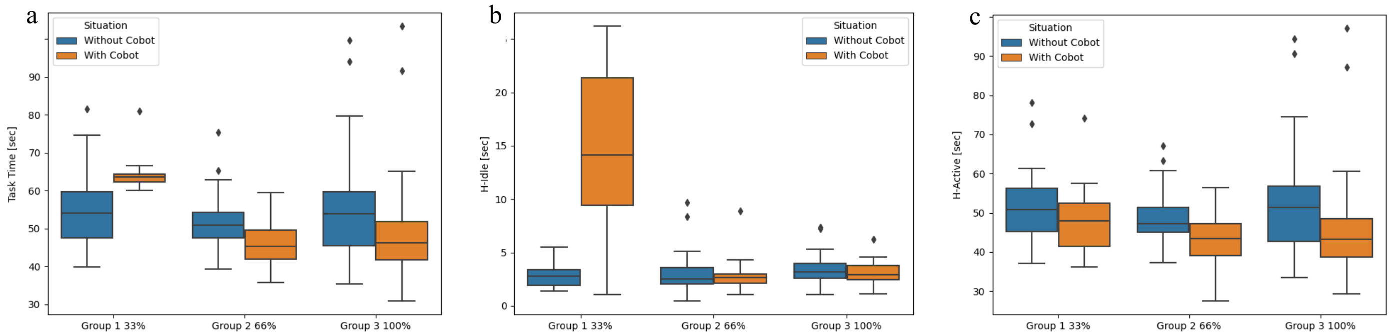


Fig. 2. Boxplots (a) Task Time, (b) H-Idle, (C) H-Active.

the participant's errors, e.g., dropping screws or delays in threading the axle. The outliers in Table 2 were deleted from the data, even though the errors were real possible events. The video analysis indicated that cooperation was not a decisive factor in the occurrence of these outliers.

The independent t-test is used to check whether a significant difference occurs between working with and without a cobot. Subsequently, a one-way ANOVA is used to test whether there is a significant difference between the speed levels. For the tests, the significance level is fixed at $\alpha = 0.05$.

4.5. Using a Cobot vs. Not using a Cobot

Table 5 displays the test results of the independent t-test [16] to compare cobot use and no cobot use. The TT is significantly smaller for all groups using a cobot. For H-Idle, only G1 shows a significant test result. As in the descriptive analysis, the significantly higher H-Idle with a cobot could be attributed to the slower speed setting. The influence of the cobot speed on human work behavior is not detectable. In G2 and G3, the use of the cobot significantly causes a decrease in H-Active. G1 is not significantly affected.

Table 5. t-test Table Situations with/ without cobot.

Indicator	Groups	G1 33%	G2 66%	G3 100%
Task Time	t-Stat	5.580	-3.208	-2.171
	p-Value	0.000	0.002	0.034
H-Idle	t-Stat	8.771	-0.575	-0.644
	p-Value	0.000	0.567	0.522
H-Active	t-Stat	-1.637	-3.102	-2.150
	p-Value	0.109	0.003	0.036

4.6. Testing different TCP Speeds

The summary of the F-statistic ANOVA [16] in Table 6 shows a significant difference in the mean values for the TT and H-Idle. Looking at the boxplots for TT and H-Idle, the difference was expected, and a closer look at the individual indicators using the Tukey-Kramer procedure for unequal sample sizes [17] shows that G2 and G3 differ significantly from G1 concerning TT and H-Idle. The t-test confirmed that in the cobot trials, the process design explains the difference. Therefore, the difference in both indicators is not flawlessly traceable to the influence of the TCP speed on human work behavior. For H-Active, the null hypothesis cannot be rejected at a significance level of $\alpha = 0.05$. The null hypothesis is rejected at a significance level of $\alpha = 0.1$. Examination of the Tukey-Kramer HSD listed in Table 6 shows a significant difference between G1 and G3 and no significant difference between G2 and G3.

Table 6. F-Stat Summary.

	F-Stat	p-Value
Task Time	68.5909	0.0000
H-Idle	79.5497	0.0000
H-Active	3.2520	0.0848

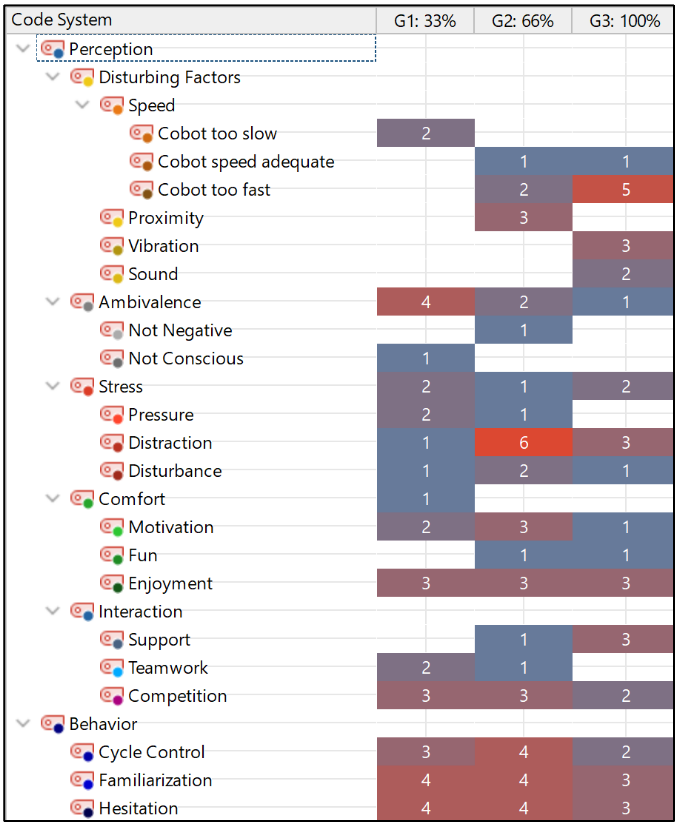
Table 4. Excerpt Tukey HSD.

Group1	Group2	Statistics	p-value
Task Time			
G2 66%	G3 100%	0.582	0.900
H-Idle			
G2 66%	G3 100%	0.053	0.900
H-Active			
G1 33%	G2 66%	3.955	0.107
G1 33%	G3 100%	4.526	0.056
G2 66%	G3 100%	0.570	0.900

4.7. Qualitative analysis

The data basis results from the interviews and questionnaires of the 18 participants. One participant from G2 could not be included due to missing data. Thus there are five transcripts for G1, six for G2, and six for G3.

Two main categories emerged during the analysis and coding. Whereas the first considers the subjects' perceptions, and the second collects the behavior described by the participants. The numbering does not imply a hierarchical relation. Figure 5 shows the occurring codes assigned to the respective groups. The perception category includes disturbance, ambivalence, self-perceived sensations, and interaction. In addition, the subjects named behaviors. The code system intents to allow for intuitive reading comprehension; for example, participants perceived the disturbing factors of speed, proximity, vibration, and sound.



Code System	G1: 33%	G2: 66%	G3: 100%
Perception			
Disturbing Factors			
Speed			
Cobot too slow	2		
Cobot speed adequate		1	1
Cobot too fast		2	5
Proximity		3	
Vibration			3
Sound			2
Ambivalence	4	2	1
Not Negative		1	
Not Conscious	1		
Stress	2	1	2
Pressure	2	1	
Distraction	1	6	3
Disturbance	1	2	1
Comfort	1		
Motivation	2	3	1
Fun		1	1
Enjoyment	3	3	3
Interaction			
Support		1	3
Teamwork	2	1	
Competition	3	3	2
Behavior			
Cycle Control	3	4	2
Familiarization	4	4	3
Hesitation	4	4	3

Fig. 3. Code Occurence Matrix.

When perceiving speed, the subject distinguished slow, adequate, and fast.

The behaviors of habituation and hesitation always occur together. Participants found that the cobot initially disturbs or attracts attention, but users habituate quickly after 1 to 3 trials and no longer perceive the cobot afterward. In general, the distracting perception increases at high speeds. The distraction is strongest in G2. Regarding the interaction category, users in G3 perceived the cobot as support, whereby they also reported that the cobot seemed independent. G1 and G2 perceived the interaction as teamwork, and two participants in G2 stated that they would rather have had a human team member.

4.8. Discussion

The t-test confirms that the trials using the cobot have a lower average TT and H-Active. Even though the association between high speed and process indicators was not confirmed at a significance level of $\alpha = 0.05$, the presented investigation covers only one possible experimental setup. The workstation configuration causes the participant to be only peripherally aware of the cobot while performing the task, caused by the operator's head position and line of sight. Especially for H-Active and H-Idle, a changed layout that puts the cobot more into the visual focus of the operator is likely to reveal a stronger association. Moreover, the determination of H-idle and H-active using light curtain measurement is an exclusive presence control. This method cannot determine flinching, pausing, evasive movements, or eye contact with the cobot.

The subjects reported that they perceived the cobot as a pace-setter against which they measured their working speed. G1 beat the cobot without effort; G2 had to hurry and put effort into beating the cobot, whereas group 3 could not finish before the cobot. Noticeably, subjects in G1 and G2 perceived the cobot as a competitor or a team member. The subjects in G3 seemed to perceive the cobot as an independent working device to which they no longer paid attention after a short time. The high speed in G3 can therefore lead to a decoupling of the team members. In G1, the cobot was no longer perceived due to the too low speed and the fast familiarization. However, when beating the cobot was in reach, the subjects in G2 tried harder to do so and paid more attention to the cobot resulting in a higher distractive perception.

During the study, different personalities were found to lead to different perceptions of the cobot. For instance, competitive people in G2 and G3 were more likely to try to beat the cobot and experienced stress in doing so.

5. Conclusion

The present work has investigated the influence of varying TCP motion speeds on the human working style in a cooperative assembly station. Moreover, the subjective perception of the experiment participants was investigated. The speed of the cobot was shown to influence the type of perception. The simultaneous completion of the task causes more consciously perceived disturbance factors than when the cobot is decoupled in perception.

Stress is more likely to be perceived when the cobot is perceived as part of the team, arousing human ambition to beat the cobot, even if the tasks are not comparable.

For further research, a long-term study is recommended to see whether the function of a pace-setter appears stable even after an extended time. The study should include a mapping of the HRC perception to human personality.

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