Examination of unsafe behaviour and conditions causing human errors during human-machine interaction in a collaborative production system

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ABSTRACT

Conventionally, in the field of machine safety, there are three main methods for reducing risks of machinery: 1) Inherently safe design: eliminating the hazardous source (the dangerous part of the machine) or reducing risk the risk associated with hazards; 2) Stop: stopping the machine when an individual enters the dangerous area of the machine; allow individuals to enter the hazardous area of the machine by shutting it down; 3) Isolation: providing guards or enclosure beyond hazardous area so that people cannot reach the area. However, the current introduction of new technologies, such as collaborative robots or autonomous mobile robots, into the marketplace and manufacturing sites has created difficulties in applying these methods, especially stop and isolate. In response to this situation, an urgent need is to establish a system safety approach that can be adapted. Technological innovations suggest that machines can be made safer by developing new safety functions rather than stopping and isolating them. There is also an emerging trend to utilize human factors in risk assessment/risk evaluation rather than relying solely on conventional safeguards. This movement is beginning to be explored in various fields of safety management systems. In industrial workplaces, many collaborative tasks are performed by machines and humans, and there are increasing opportunities for humans and robots to get closer together. On the other hand, many aspects still depend on human attention, such as the worker adjusting their movements to match the robot's, and there are concerns about the stress and burden on workers. In the future, a system safety approach that is a systematic and reliable management system that is not affected by stress and burden on workers will be essential. However, at present, there is not enough information available to determine the specific conditions that lead to unsafe behavior and human error when working with a collaborative production system. This paper presents the results of simulated a workplace where collaborative robots and workers worked together, tried collaborative work under various conditions, and identified conditions that induced unsafe behavior and human errors. For example, various conditions were combined, such as the appearance rate of defective products, the operating speed of collaborative robots, the procedure from E-stop to restart, manual work, and more. Then, the appearance rate of unsafe behavior or errors, stress, and workload were measured and analyzed as evaluation indicators.

1. INTRODUCTION

The manufacturing industry is experiencing a shortage of human resources due to the decreasing working population. To meet consumer needs, high-mix, low-volume production is needed. One solution is to construct a flexible and collaborative production system that balances the productivity of humans and machines.

In machine safety, risk reduction measures for human access to hazardous areas of machinery can be divided into two main categories: (1) Shutdown: temporary shutdown of the machine when a person enters, or shutdown of the machine by eliminating the machine's power (power-shutdown). (2) Isolation: placing an enclosure or other guard outside the hazardous area to prevent people from entering the hazardous area. These were effective measures for systems in which the workspaces of man and machine were separated. However, machines designed to have close or overlapping workspaces between humans and machines have been introduced to industrial sites in recent years. When aiming for both safety and productivity for these machines, there are cases where conventional risk reduction measures become difficult to apply. There is an urgent need to establish a "system safety approach" as a risk reduction method to use in these situations. This approach not only improves the safety of machines but also innovates safety technology to create an environment where people can achieve higher productivity by considering their behavioral characteristics.

In today's industrial settings, various levels of human-machine collaborative works are executed according to the characteristics of the production system. All production systems implement protective devices to reduce the risk of unintended human proximity or contact with the machine. Therefore, workers adjust their work actions relative to the machine's operation, for example, so that the machine's productivity will not be reduced by a worker's unintentional activation of the protective device. Such actions not only lead to stress and burden on the operator but also to defeating the protective device, which may lead to a decrease in the safety of the equipment. In the future, it will be essential to integrate a systematic and reliable system safety approach focusing on people in machinery safety. However, there is insufficient information to determine the specific conditions that lead to dangerous human behavior or human error when working in collaborative production systems.

This study utilizes a collaborative robot and a worker, part of a collaborative production system, to test collaborative work under various conditions. Verification is conducted to identify the conditions that induce unstable behavior and human error. We examine the robot's and the worker's behavior under these conditions by manipulating the experimental conditions based on the robot's assembly failure rate and work experience as preliminary results. Some of the results are reported in this paper.

2. MATERIALS and METHODS

Experimental timing and site: From March to April 2024, experiments were conducted in a collaborative work environment using a testing machine that consists of a production line for control devices at OMRON Corporation. A robot's and a worker's workspace on the testing machine are adjacent, and a partition separates each workspace. Parts trays (Figure. 1-a), fed to the robot's assembly work area to assemble parts, are placed on shuttles arranged in a double row on the left and right. The partition is shaped so only the parts tray can pass through to the robot's work area (Figure. 1-b). The products are discharged via the parts tray if the parts are assembled successfully. If the assembled products do not meet the required conditions, a tray is placed for defective products (Figure1-c). The operator removes defective products by stopping the machine and opening the door. On the left, there is a touch panel (Figure1-d) for overall control of the machine and an operation interface (Figure1-e) for controlling the robot's operation below the door through which defective products are removed.

Experimental workers: One novice worker (subject A) from outside the company who participated in the collaborative production system and two employees (subjects B and C) from the company's development and business planning departments were used as experimental workers. Subjects B and C have worked for more than 20 years and have basic knowledge of the machines used in the production line.

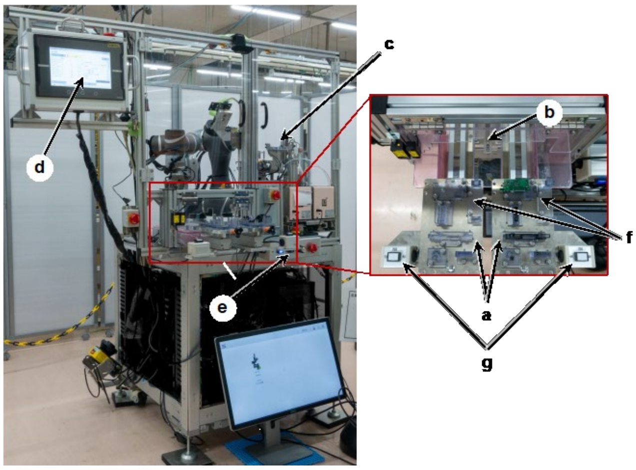

Figure 1. Testing machine, operator interface and parts trays

Work in the collaborative production system: The work procedure is as follows. The operator places the six parts required for assembly on a tray dedicated placeholder on the parts tray (Figure1-f). The tray has holders to ensure each part is correctly positioned and oriented. The operator pushes the button (Figure1-g) after placing the parts in the parts tray and inserts the parts into the robot side. As soon as the part is pulled into the robot, the operator places the part in the other part tray. The robot removes the part from the tray within the robot workspace, assembles the part, and performs a final inspection. Products assembled and passed the inspection are placed in the finished part holder of the parts tray. If the inspection result is not acceptable, the product is placed in the defective product discharge tray. When a product is placed in this tray, the operator performs the following procedure to remove the product. Operate the operation interface at hand to stop the robot. Open the door to access the defective product tray, remove the faulty product, and close the door. The robot must return to automatic mode to restart the production system. There are two steps to return to automatic mode, depending on the robot's stopped condition (position): (1) Press and hold the blue pushbutton on the operation interface at hand and press the restart button on the touch panel. (2) If the robot has stopped at a position where it cannot automatically return to the automatic mode, the worker should call a robot operator to perform the return operation because it is impossible to return to the automatic mode only by the operation interface at hand.

Experimental conditions: The duration of the experimental work was set to 40-60 minutes, and the defects production ratios were divided into 0, 25, 50, and 75%. The robot worked continuously for 10-15 minutes each.

Instruction: The experiment was started by explaining to the operator: "You are now going to assemble the product using this device. You are now going to assemble the product using this equipment. You are going to set six parts on this parts tray. When you have finished, please operate this shuttle to feed the parts to the robot. The robot will combine the parts into a single product. If the parts are combined correctly, they are placed in the parts tray and discharged. If the parts are not combined correctly, they are discharged to this tray as defective products. The ejected product must be removed and collected. To remove the product, follow the steps below. Press the emergency stop button. Open this cover, take the returned product, and place it in this box. Close the cover. Press the reset button of the device to recover from the emergency stop. Press the reset button to put the robot into automatic mode. The robot will return to its origin and change to automatic mode. The work can then be resumed. The total working time is 40 minutes (60 minutes for subject A). Please make as many products as possible during that time. The final points will differ depending on the number of products made. Do your best to get as many points as possible. We will now begin the experiment".

Evaluation benchmarks: The number of parts supplied to the robot, the time required to place parts on the parts tray, the number and rate of occurrence of anxious behavior and mistakes, and the vitals (body temperature, blood pressure, pulse rate, and blood oxygen saturation concentration) before and after work were measured and analyzed. In this presentation, we measured the performance from pressing the button to completing the tasks (Table 1), help calls (Table 2), error rates (Table 3) and efficiency of individuals (not shown) so on in completing their assigned tasks.

3. RESULTS

Table 1 shows the number of press button (shown as Pressed) and insert parts to the robot tasks (Send), which means completing the task and returned task (Returned). Also, the number of the valid, which is calculated as (Sent – Returned), is shown in the table 1 (Valid). Then Valid rate was revealed with (Valid/Sent). As a result, the Valid rates of the subjects A, B and C were 96.3%, 26.7% and 70.0%, respectively. In addition, we analyze Pressed, Sent and Returned counts divided into Right and Left. Subjects A and C did not show any lateralization in the three kinds of counts, but Return of subject B showed it as 4 in Returned Left and 7 in Returned Right.

Table 1. Performance from pressing the button to completing the tasks.

Button Count											
Subjects	Pressed	Sent	Returned	Valid	Valid/Sent %	Pressed Left	Pressed Right	Sent Left	Sent Right	Returned Left	Returned Right
A	33	27	1	**26**	**96.3%**	18	15	15	12	1	0
B	17	15	11	**4**	**26.7%**	7	9	7	8	4	7
C	25	20	6	**14**	**70.0%**	13	10	10	8	2	2

Subject A called staff if she recognized the robot needed to return to the origin position in the middle of the task stopping the work. The number of calls (Help calls) was 3 times in whole experiment conditions (Table 2). Similarly, Help calls of the subjects B and C were seven times each. Table 3 showed the Error rates of each subject. Table 3 shows the number of errors and error rate, i.e., the number of errors divided by the number of sents for each subject. Subject A made 4 errors and the error rate was 14.8%; subject B made 13 errors and the error rate was 86.7%; and subject C made 9 errors and the error rate was 45.0%.

Table 2. The number of Help calls.

Staff's help	
A	3
B	7
C	7

Table 3. The number of Error (Count) and Error rate.

Errors		
Person	Count	error % (error/sent)
A	4	14.8%
B	13	86.7%
C	9	45.0%

Figure 2. shows the result of the Assembly time of subject A, who showed the best performance in the present experiment. It is shown that Subject A's assembly time appears to be shortened as the number of trials (n) increases, making it clear that he is becoming accustomed to the work and is now able to complete the task in a shorter time. We plan to conduct analyses on subjects B and C in the future.

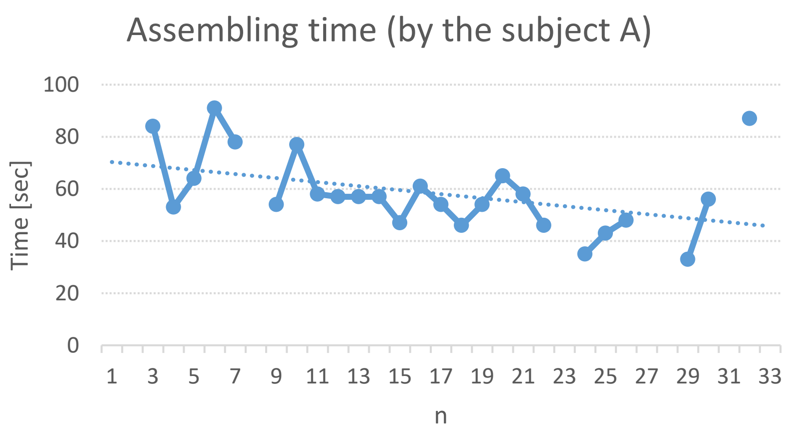

Figure 2. Assembling tiem of the subject A.

Figure 3 shows the results of the waiting time for subject A. There was almost no difference in the assembly time for subject A between experimental condition 1 (robot defect production ratios: 0%) and experimental condition 2 (robot defect production ratios: 25%), and it was significantly less than 200ms. This short waiting time indicates that the robot did not produce any defective products in this situation. However, at the end of experimental condition 2, the waiting time was more than 200ms. This indicates the occurrence of defective products, and similarly, one defective product occurred in each of experimental conditions 3 (robot defect production ratio: 50%) and 4 (robot defect production ratio: 75%). In that case, the number of tasks was reduced. It was suggested that subject A performed the most tasks in condition 2. In the future, a similar analysis will be conducted for subjects B and C.

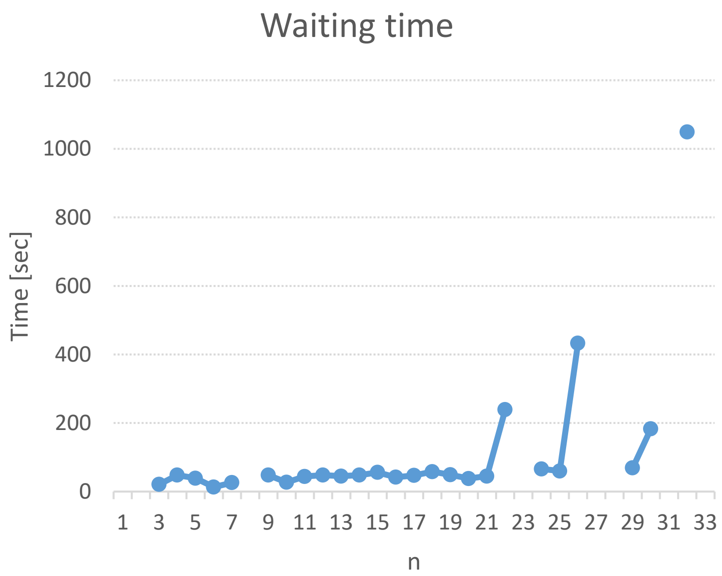

Figure 3. Waiting time of the subject A.

4. DISCUSSION

This preliminary experiment provided valuable insights into the dynamics of human-robot collaboration and highlighted areas for potential improvement. As context outside of the data, one of the subjects, A, was a beginner, while the other workers already had experience in similar activities. Additionally, subject A, unlike the workers, would call the staff when encountering a problem, while the others would try to fix things on their own from the beginning until the staff came to help. In the first result, the subject A showed the best efficiency in completing the task. Unlike the other workers, she made no obvious mistakes when assembling the board. The testing footage shows that none of her samples were incorrectly placed on the part holders, and the robot failed only four times, less than the others. Also, she needed the least help from the staff.

Additionally, subject A completed most of the tasks according to Table 1. It is important to note that subject A was a beginner, while the other workers already had knowledge of this type of machinery and task. The second subject, B, had better average and standard deviation results. However, it is worth noting that he made many experimental errors. The third person had good average results, but their standard deviations were very high. Overall, A had better and more consistent results than the others.

5. CONCLUSION

The goal of this experiment was to achieve and analyze safe collaboration between human and machines. As observed with three individuals showing completely different behaviors and results, with one of them being the best with good and consistent results, it can be concluded that not everyone is ready to work well with robots. People need to be comprehensively trained to reduce human error as much as possible.

It is important to consider that the machine error rate increases over time for various reasons, so failures can also happen. However, it is possible to have a low error rate with the same machine by changing the person (operator). Therefore, initially, the robot does not appear to be the primary cause of the high error rate observed in other individuals.

The prior experience of the individuals could be an interesting factor to analyze. Why did a beginner have better results than people with more experience or knowledge in dealing with the machine? Additionally, why did these workers try to fix problems themselves instead of immediately seeking assistance, even though they were told to do so if any problem occurred? This questions still need more investigation and analysis.

To create a safe collaborative work environment, both parts need to be ready to work together. As we focus on human behavior, it's important to highlight the significance of good preparation or training for people when working with machines. This training could focus on relevant factors such as understanding the robot's operation, working methods to avoid errors, safety and accident prevention, problem-solving (starting with calling the staff and not touching the robot without permission), and communication for teamwork.

In conclusion, the partial findings from this experiment underscore the importance of comprehensive training and readiness for good collaboration between humans and machines. Understanding individual behaviors, addressing training gaps, and implementing clear protocols for all workers involved is essential.