Collaborative Safety to Improve Safety and Productivity Simultaneously at Manufacturing Site - Theory and Effect -

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ABSTRACT

Recently, coexistence/collaborative applications such as collaborative robot system and autonomous mobile robots (AMRs) has been introduced increasingly at manufacturing sites. However, the introduction of such applications based on the rules of current machinery safety often leads to higher costs due to the installation of high integrity level of safety devices and lower productivity due to frequent stoppages, so it is difficult for users to take the benefits of coexistence/collaboration at the maximum. Therefore, we focused on "Collaborative Safety," in which humans and machines share and utilize information and cooperate with each other, and considered how to apply it to the manufacturing site. Under the concept of collaborative safety, human characteristic can contribute to safety, so that we consider the contribution of human characteristics to safety in risk estimation and quantify it based on behaviour analysis. As a result, we have developed a risk assessment method that takes into account the human characteristics, which newly added the rate of unsafe behaviour depending on whether information is provided or not. Next, the results of the study of the new risk assessment method were compiled into the collaborative safety guideline, which was first applied to applications where humans and machines coexist /collaborate within the Toyota Group. We confirmed that it not only improved safety and productivity, but also contributed to enhancing the well-being of the related workers.

1 INTRODUCTION

At manufacturing sites, there are many needs for equipment that can be changed flexibly to accommodate variable-type and variable-volume production, and for robots and other machines to work in place of humans to compensate for labour shortages due to a shrinking workforce. In recent years, there has been a rapid increase in the use of collaborative robots and AMRs, which is not said to require the installation of safety fences or guards, as applications where humans and machines can coexist/collaborate.

However, the actual condition is such coexistence/collaborative applications are not used effectively in many workplaces. Conventionally, machinery safety based on ISO 12100 has been applied to ensure safe design of machines, but since machine safety is based on the principle of isolation and stop, it is not suitable for environments where humans and machines coexist/collaborate. Therefore, applying machinery safety to coexistence/collaborative applications often lead to higher costs due to the installation of high integrity level of safety devices and lower productivity due to frequent stoppages, so the benefits of coexistence/collaboration is hard to be taken at the maximum by users.

Under these situations, a new concept of safety, "Collaborative Safety," in which humans, machines, and the environment share and utilize information to ensure not only safety but also productivity, has been proposed [1]. Tripartite system describing the concept of collaborative safety is shown in Figure 1 [2]. Also, as shown in Figure 2, collaborative safety is expected to achieve positive domain by improving well-being. We believe that the above issues can be solved by applying this concept to coexistence/collaborative applications. However, the rules for the introduction of collaborative safety at manufacturing sites, including methods of risk assessment and risk reduction, have not yet been established.

Therefore, we have studied the rules for applying collaborative safety to manufacturing sites and compiled them into guideline for demonstration in Toyota Group. In this paper, we report on this guideline, especially our approach to establishing a risk assessment method for collaborative safety, as well as examples of actual demonstrations at manufacturing sites.

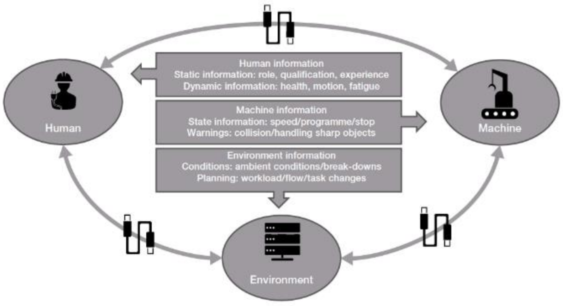

***Figure 1**. Tripartite system for safety in the future*

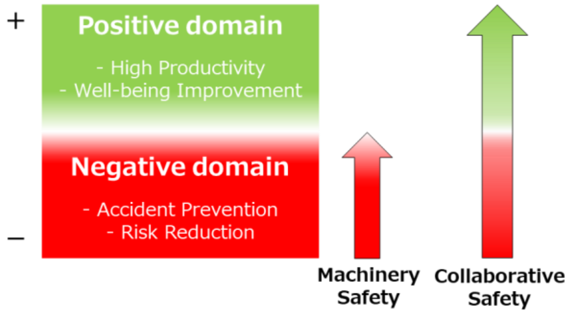

***Figure 2**. Effect of Collaborative Safety*

2 APPLICATION OF COLLABORATIVE SAFETY TO MANUFACTURING SITE

2.1 Way of thinking about contribution of human to safety

In order to apply collaborative safety to the manufacturing sites, it is necessary to shift the conventional way of thinking about the contribution of human to safety in machinery safety. Each concept of safety is compared in Table 1. In the concept of machinery safety, a worst-case probability is assumed for occurrence of a hazardous event based on the premise that "people always make mistakes", so there is a way of thinking that safety is ensured only by machine [3]. Because of this, although human characteristic contributes to safety in coexistence/collaborative work in fact, the contribution of it to safety is not allowed by taking the safety side extremely, i.e., it is regarded that the uncertainty of human behaviour cannot be reduced. On the other hand, under the concept of collaborative safety, human can contribute to safety, i.e., human can take safety actions autonomously by providing appropriate information to support human characteristic. Considering from this position, uncertainty of human behaviour can be reduced and the entire system including human is made to ensure safety, then we believe this is just the realization of collaborative safety.

We have taken two approaches in reaching this way of thinking of recognizing the contribution of human to safety. The details are described in the next section.

***Table 1**. Comparison of Machinery Safety vs. Collaborative Safety.*

Item	Machinery Safety	Collaborative Safety
Methods to ensure safety	Safety is ensured only by machine.	Human and machine share information with each other and ensure safety with both.
Basic way of thinking	Contribution of human to safety is not allowed because people always make mistakes.	Contribution of human to safety can be increased by providing appropriate information and proper education/ management that supports human characteristics.

2.2 Adoption of the trend of considering human characteristics in risk estimation

The first approach is the adoption of the trend to consider human characteristics in risk estimation. In risk estimation for the determination of required performance level (hereinafter referred to as PLr) of a safety function performed by the safety-related parts of control systems (hereinafter referred to as SRP/CS), a method to include human characteristics has been proposed in the latest/upcoming international standards on machinery safety such as ISO10218-2 under development. Specifically, human skills and awareness of the hazard are added to "possibility of avoidance" and inappropriate human behaviour should be considered in the newly added "probability of occurrence of the hazardous event." This indicates that there is also a trend in the conventional machinery safety to change from the assumption that "human do not contribute to safety because people always make mistakes" to the assumption that "human contribute to safety because human error can be reduced under certain conditions with human characteristic." However, no quantitative indicators of the extent to how human contribute to safety is mentioned in the standard.

2.3 Quantification of the contribution of human characteristics to safety

Therefore, we decided to take another approach of quantifying the contribution of human characteristics to safety based on behaviour analysis. In behaviour analysis, human behaviour can be classified into three categories shown in Figure 3: 1) unconditioned behaviour, 2) conditioned behaviour, and 3) learning behaviour. Conditioned behaviour and learning behaviour are well-known for the experiment of Pavlov's dogs and that of Skinner's reinforcement schedule, respectively. We considered we could promote autonomous safety behaviours by making good use of these human characteristics. Typical examples of conditioned stimuli in actual workplaces are green/red visual information. In our previous experiment, which is reported in another paper, we confirmed that compared to work without visual information, work with real-time green/red visual information reduces the probability of human errors, such as touching a machine when it is dangerous, i.e., the rate of unsafe behaviour to 1/10 or less. This indicates that workers changed their behaviour because of the widespread meaning of green as safe and red as dangerous. From this result, the contribution of human characteristics to safety by providing information was quantified, which is reflected in the risk estimation described below.

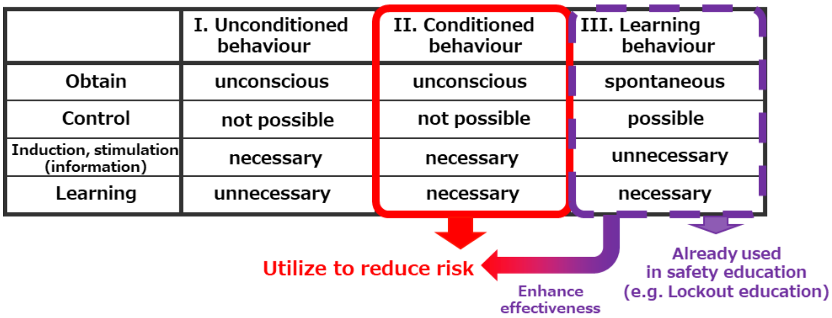

***Figure 3**. Human behaviour to be utilized for risk reduction*

3 METHODOLOGY OF RISK ASSESSMENT AND RISK REDUCTION FOR COLLABORATIVE SAFETY

3.1 Overview of risk reduction process for collaborative safety

Next, we examined how to proceed with risk assessment and risk reduction for collaborative safety. Figure 4 shows the overview of risk reduction process, partially modified from ISO12100. As with conventional machinery safety, the process remains the same: risk assessment, risk reduction measures implemented by the designer (including an iterative process for design of SRP/CS), and risk reduction measures implemented by the user. In risk assessment, the safety goals to be achieved and the premise that the safety goals are achieved by reducing the severity or the probability of occurrence of harm on the machine side, i.e., even if human makes mistakes, no harm will occur by ensuring safety on the machine side, must not be changed.

On the other hand, in collaborative safety, it is assumed that information is provided to encourage people to change their behaviour. This means that providing information should be regarded as one of the risk reduction measures, which can lead to optimize the dependability of SRP/CS that decelerates/stops the machine. As a result, the number of options for risk reduction measures increases and those measures can be applied flexibly according to the risk. This chapter details the risk reduction measures implemented by the designer in collaborative safety, which is different from that in conventional machinery safety, especially focusing on the three-step method of risk reduction and the design of SRP/CS.

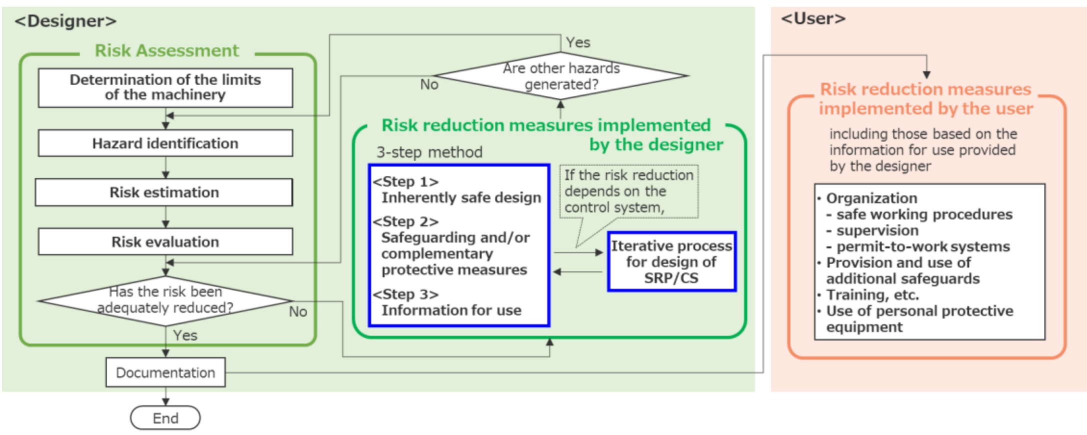

***Figure 4**. Overview of risk reduction process*

3.2 3-step method of risk reduction for collaborative safety

Figure 5 shows the three-step method of risk reduction for collaborative safety. While based on the conventional three-step method for machinery safety, we have established two routes of risk reduction measures based on machinery safety and/or collaborative safety after step 1, so that the optimal measures can be selected according to the assumed hazardous event. Step 2 of the newly added risk reduction measures for collaborative safety (hereinafter referred to as collaborative safety measures) consists of two control systems: a machine control system that decelerates, evacuates, or stops the machine depending on the distance between human and hazard, and an information transmission system that acts on human characteristics as notification/caution/warning information. This is because we believe that in order to maximize support for human characteristics by providing information, it is most effective to conduct providing information to human and controlling the machine in steps by dividing the zone according to the distance between human and hazard as shown in Figure 6. This enhances human characteristics such as conditioned behaviour and learning behaviour, and it is expected to promote autonomous safety behaviour and to reduce unsafe behaviour. Step 3 of collaborative safety measures was also set as a step to present operational rules and human/management requirements to the users and to get their agreement. Since the collaborative safety assumes risk reduction measures with the support of human characteristics, designer and users should collaborate and communicate risks more closely than before.

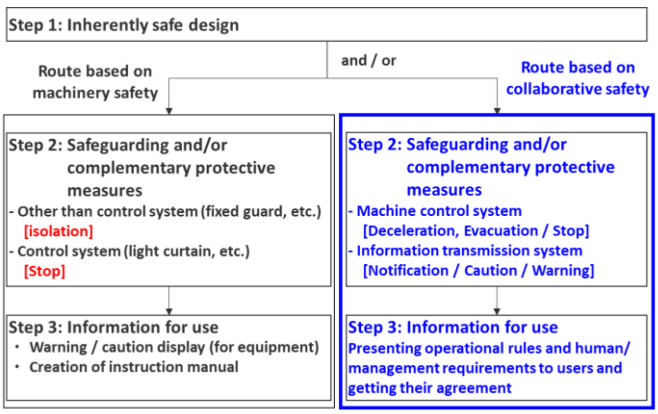

Figure 5. *3-step method of risk reduction*

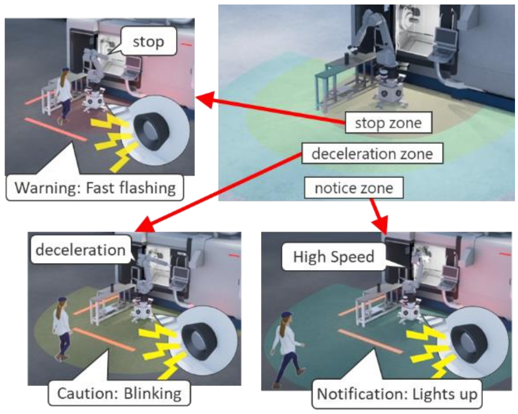

Figure 6. *Example of control depending on the distance between human and hazard*

3.3 Design of SRP/CS for collaborative safety

As mentioned in the previous section, collaborative safety measures are premised on the use of control systems, so it is important to correctly determine PLr. In this study, we considered that PLr of SRP/CS can be optimized by taking human characteristics into account in risk estimation under the concept of collaborative safety, which acknowledge the contribution of human to safety. In this chapter, we describe how to reflect human characteristics in risk estimation and the parameters to be considered.

According to ISO 12100, the risk consists of the severity of harm (S) and the probability of occurrence of that harm. Also, the probability of occurrence of that harm is a function of the exposure of persons to the hazard (F), the occurrence of a hazardous event (O), and the possibility of avoiding or limiting harm (P) [4]. The parameter O is estimated by considering reliability and other statistical data, accident history, history of damage to health, and comparison of risks. However, in ISO 13849-1, the human element has been excluded from the parameters, assuming a 100% probability of occurrence of a hazardous event as a worst-case scenario, because it is difficult to calculate the probability of human error.

Therefore, we have invented a method to incorporate "occurrence of a hazardous event by human (O_H)" into risk estimation as a new parameter alternative to the parameter O based on the idea that human contributes to safety in collaborative safety. Note that the parameter O_H means the probability of human error, that is, unsafe behaviour rate. In this method, human characteristics can be utilized in risk estimation by changing this parameter depending on whether information is provided or not, based on the effect of reducing the unsafe behaviour rate by providing information, which is quantified as 1/10 in section 2.2.

Next, the concept of occurrence of a hazardous event by human (O_H) is described. There are two types of unsafe behaviour assumed by this parameter: 1) wrong entry into a hazard zone, and 2) wrong contact with hazard while in a hazard zone. Furthermore, we consider that the probability of occurrence of this unsafe behaviour depends on what kind of hazardous event is assumed. Specifically, if third person or nearby workers, who do not need to enter the hazard zone, are provided with information on distance from hazards or evacuation at the appropriate timing, the possibility of unintended entry into a hazard zone can be expected to be reduced to a minimum. On the other hand, for workers who are supposed to always work near the machine and perform complex tasks, such as troubleshooters and maintenance workers, no matter how much information is provided, their behaviour cannot be expected to be changed because there is work to be done there, which means that the information cannot promote evacuation but just can be an alert. Altogether, the effect of providing information in reducing unsafe behaviour varies depending on the target person and the work style. We have developed a method to incorporate the parameter O_H into risk estimation by assigning three ranges (high, medium, and low) as the rate of unsafe behaviour depending on whether an information provision system is used or not. According to this method, the parameter O_H can be considered as medium or low in the case that an information transmission system is utilized for specific type of work, resulting in PLr of SRP/CS can be optimized. Parameters considered in risk estimation to determine PLr is shown in Table2. The details of this method will be reported in the future.

***Table 2**. Parameters considered in risk estimation to determine PLr of SRP/CS*

Parameter	Range
Severity of harm (S)	Three levels: Fatal, Serious, and Minor
Exposure of persons to the hazard (F)	Two levels: High and Low
Occurrence of a hazardous event by human (O_H)	Three levels: High, Medium, and Low as the rate of unsafe behaviour which varies depending on availability of information transmission system
Possibility of avoiding or limiting harm (P)	Three levels: Scarcely possible, Possible under specific conditions, and Possible

4 INITIATIVES WITHIN TOYOTA GROUP

4.1 Establishment of Collaborative Safety Guideline

The rules and requirements of technology, human, and management for introduction of collaborative safety at manufacturing sites, mainly based on what has been described so far, have been compiled and issued as "Collaborative Safety Guideline" for the purpose of demonstration. We believe this is the world's first practical guideline at manufacturing sites specifying methodology of risk assessment and risk reduction for collaborative safety. We will improve it through demonstrations within Toyota Group from now on.

4.2 Case Study: Effect of behaviour change by introduction of collaborative safety measures on collaborative robot

This section presents a case study in which collaborative safety measures were introduced based on the above guidelines and the effect of behaviour change was verified. As shown in Figure 7 and 8, for a collaborative robot operating around the walkway, the line lighting device as information transmission system was installed to provide workers with information about the situation of accessing the robot. When workers access the robot side from the walkway, the red line lighting (here after referred to as lighting) becomes turned on to prevent their unnecessary access to the robot. The zones were defined from the robot side as no walk zone, walkway, and outside of walkway, representing the hazard zone near the robot, correct route to walk, and the zone where walking is less efficient due to excessive distance from the robot, respectively. The number of times workers accessed each zone was visually measured by video recording for a certain period, when before the introduction of this measure, after one week of that, and after one month of that, respectively. The measured data were used to calculate safety, represented by inverse of the percentage of entering no walk zone, and productivity, represented by percentage of entering walkway. The workers were interviewed after the demonstration. Regarding the collaborative robot used in this study, the contact force was measured and confirmed not to cause harm.

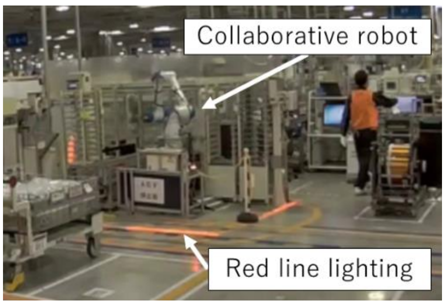

***Figure 7**. Demonstration site*

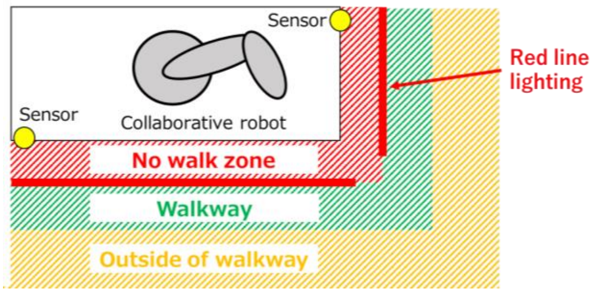

***Figure 8**. Layout and zone definition*

Figure 9 shows a comparison of safety and productivity before and after the introduction of the measure. This graph is plotted by converting the result of after one week to 1. For safety, the value improved dramatically after the introduction compared to before. This indicates that workers no longer access the robot side due to the installation of the lighting. On the other hand, the value of productivity slightly decreased after one week, but improved after one month compared to before the introduction. This may be because the workers were not yet accustomed to the lighting and avoided accessing the robot to the extreme, resulting in a temporary decrease in productivity after one week, while the workers adapted to the lighting and began to pass through the more efficient zone for walk, that is walkway, autonomously after one month. In addition, interviews with workers revealed the positive effect that the lighting makes workers be alerted and feel ANSHIN*.

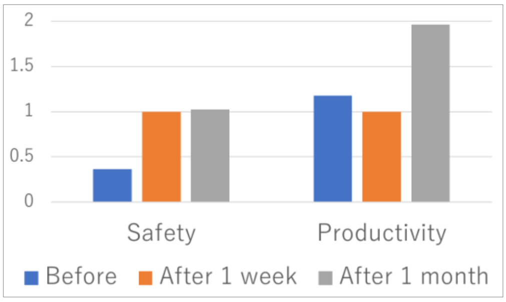

Figure 9. *Comparison of safety and productivity in each period*

From this case study, it was confirmed that the information transmission system in collaborative safety has the effect of changing human behaviour and giving them ANSHIN feelings. Further case studies should be implemented to confirm that the collaborative safety measures would contribute to improving safety, productivity, and the well-being of workers.

* ANSHIN: a sense of trust and assurance without any fear or stress (a Japanese word)

5 CONCLUSIONS

In order to make good use of coexistence/collaborative applications at manufacturing sites, we focused on collaborative safety and incorporated the new way of thinking about recognizing contribution of human characteristic to safety into conventional machinery safety, resulting in creating the rules for introduction of collaborative safety. In the demonstration based on the rules, it was confirmed that collaborative safety measures not only improved safety and productivity, but also contributed to enhancing ANSHIN feelings. We will verify the validity of the rules and their effectiveness in improving the well-being of workers through further demonstrations from now on.

We believe it is necessary to establish clear rules or standards to introduce collaborative safety at more manufacturing sites. Currently, we are discussing with Japanese companies who have similar issues what the rules or standards for introducing collaborative safety should be based on the guidelines we have created. Our activity will be expected to contribute to international standardization of collaborative safety in the future.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

1. Mukaidono M., Takaoka H., Ogihara H., Ariyama M., Fujita T., *Japan's Approach for the Realization of the Future Safety Concept by Implementing Collaborative Safety Technologies*, 9th International Conference on Safety of Industrial Automated Systems (SIAS), France, 2018, pp. 77-87
2. IEC White Paper "Safety in the Future", 2020, https://webstore.iec.ch/publication/67876
3. ISO 13849-1:2023, Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design
4. ISO 12100:2010, Safety of machinery - General principles for design - Risk assessment and risk reduction