The study of design and operation of collaborative machines - risk assessment and communication

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ABSTRACT

Based on coexistence machines that can work in a coexisting space operators and machines, collaborative machines are advancing that is able to work operators and machines together for the same subject. The collaborative machine adjusts their behaviour and speed to achieve collaborative work between the operator by monitoring his action. Therefore, the collaborative machine shall have operator-machine collaborative work program (application) which recognize operator's work and adjusts its motion. And the related safety functions shall be included in the application, too. Furthermore, the operator shall also have training to become proficient in working with the machine. The collaborative work depends on changes in materials and work procedures, the skills and physical condition of the operator, the maintenance of the machine, and the workplace environment. During an operation period, the collaborative machine including the collaborative work program with safety related functions shall be maintained. Thus, the safety of collaborative machines includes not only safety machine design but also requirements for the operator, machines, and management. In addition, the information necessary for risk assessment shall be exchanged between the parties involved. This paper analyses the characteristics and structure of collaborative machines, and describes the lifecycle of collaborative machines and risk assessment and communication among related parties in the lifecycle.

1 INTRODUCTION

New technologies are creating new uses for machines, such as autonomous driving and collaborative robots (Cobots). Collaborative machines, in which an operator and a machine share the same goal and work together, allow the machine to regulate its procedures and speeds to adjust the operator's work, and the operator can interrupt or intervene in the machine while working. It is said that a new relationship between humans and machines can be established by machines being close to humans and humans support the machines [1].

Safety measures for these applications have become an urgent issue, and collaborative safety, Safety 2.0, has been proposed [2]. Safety of machines is based on the concept of risk analysis and risk reduction. We estimate the risk of hazards lurking in machines based on the severity of the harm and its probability of occurrence, and take risk reduction measures until the risk is below a tolerable risk.

The major reason why safety for new applications have not been resolved is that the relationships between humans and machines are diverse, making it impossible to completely address risks during design [3]. For example, when a collaborative machine adjusts its working speed for the operator in collaborative work, the speed depends on the skill of him. Furthermore, the management of operator's skill depends on the company's occupational safety and health management (OSHM) maturity level. Therefore, it is necessary for each party to conduct risk assessment many times during the lifecycle of the machine. For example, component shipment, system integration, commissioning and start to use, and when changing usage or configuration of the machine. This differs from conventional style, where risk assessment was performed only when the shipping the machine and starting to use it. Additionally, the information necessary for each risk assessment shall be obtained from his activities or other parties. The exchange of information regarding risks between related parties is called "risk communication"[4].

In this paper, we first discuss the characteristics and the structure of collaborative machines. Based on these, we discuss the lifecycle and stakeholders of collaborative machines, and describe risk assessment and risk communication between the stakeholders.

2 CHARACTERISTICS OF COLLABORATIVE MACHINES

First, we classify machines from the perspective of the relationship between the operator and the machine, that is, whether they are independent or cooperative. The classification is shown in Table 1.
[Autonomous] A machine performs its functions assuming that there is no operator. This corresponds to the automatic mode of many machines.
[Isolated] A machine and an operator isolated by distance or guards. If he approaches or opens the guard, the machine should stop. If there is no operator or the guard is functioning, the machine can be autonomous mode. Existing many machines are isolated types with automatic modes.
[Coexistence] An operator and a machine can work in the same space (coexistence space). The machine has a mechanical structure and behaviour that does not harm the operator even if it collides with it. Furthermore, if a hazardous event (cf. contacting) occurs in the coexistence space, the machine takes a safety measure such as pausing [5].
[Collaborative] An operator and a machine can work together toward a shared goal. Collaborative work involves contact (material handling) and parallel operation between the operator and the machine in the coexistence space, so the relationship is closer than the coexistent machines. Specifications of the collaborative work differs for each application, so the control program of the collaborative machine (collaborative work program) is an individual application.[6]
A collaborative machine is a coexistent machine with a collaborative work program added. "Collaborative machine" which are generally used, are classified as a coexistent machine in this paper. There are very few collaborative machines which have collaborative task programs.
A collaborative machine is characterized by having a collaborative task program for the operator and the machine, and by understanding the tasks of the operator. Similarly, the operator is required to know the task of the machine. For a team to work together efficiently, it is important that the team members know each other's tasks and capabilities and are adequately trained. The collaborative machine estimates the operator's tasks and capabilities and tries to perform the optimal work procedure and work speed. If the operator is in poor health or is an inexperienced beginner, the collaborative machine will not force him to work at an appropriate speed. In this way, safety and efficiency in collaborative work can be achieved. A collaborative machine system is characterized by the fact that it places demands not only on the collaborative machine, but also on the operator.

Table 1. *Types of the machines*

type	relationship operator/machine	use case
autonomous	no operator	automatic operation
isolated	an operator isolated from a machine	set enough distance or proper guard
coexistence	working in same place	low power, material handling
collaborative	working for same object	Cobots

3 STRUCTURES OF COLLABORATIVE MACHINES

The evolution of IT has popularized functional safety using CPU and software. Commercially available safety controllers and PLCs have reduced the effort of design and constructing functional safety systems. Safety engineers can focus on safety applications. Figure 1 shows the schematic of a machine including functional safety. Functional safety and safety applications are added to the control system.
A collaborative machine has a collaborative work program for the operator and machine and adjusts the machine's behaviour and speed according to the operator's ability. Therefore, general control and safety control are not separated, and both are realized as a collaborative work (application) program. In the past, the safety principle was to separate general control and safety control so that it did not affect safety control. However, functional safety is being applied to intrinsic safety, which controls the basic operation of a machine to keep it safe. For example, autonomous-driving and communication-based train control system. If general control and safety control are not separated, the whole shall be designed as safety related system. Thus, the entire collaborative work program of collaborative machines is positioned as a safety application in Figure 1.
This also applies to new technologies such as AI. When the collaborative machine determines safety behaviour and speeds that are tailored to the operator based on the machine learning, this is considered a safety application using AI. In this case, safety of AI must be guaranteed by referring to AI safety standards [7]. Currently, many countries are regulating AI, and various organizations are developing AI standards [8]. It is necessary to keep a close eye on these trends.

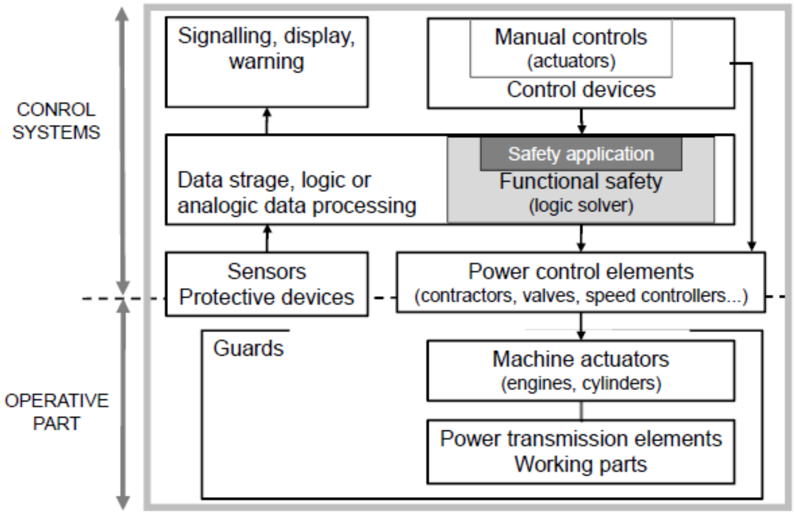

Figure 1. *Schematic representation of a machine (based ISO 12100 Figure A.1)*

4 LIFECYCLE OF COLLABORATIVE MACHINES

The collaborative machine has some stakeholders in its lifecycle, and each of them shall execute risk assessment and risk reduction at the appropriate time. Here, we would describe the stakeholders and lifecycle of collaborative machines.

4.1 Stakeholders

The stakeholders involved in collaborative machines are listed below.

[Provider] There is a provider of the machine components to construct the machine system. Components include sensors, logic processors, drives, contactors, and even commercially available software. Components can be broken down into detail parts, but we will not discuss the supply chain here. Components include safety related compliant with safety standards and non-safety related.

[Integrator] A system integrator builds collaborative machine systems by combining safety components. An integrator designs, assembles, evaluates, and delivers collaborative machine systems based on the application requirements from the machine user. Advanced and complex machines such as robots require multiple programs and parameter settings within the system. These are also the integrator's roles. In emergent collaborative machine systems, the integrator's design and construction are extensive.

[User] The system built by the integrator is handed over to the user for operation. The user is also the owner of the system. The user participates in the longest stage of the lifecycle, from installation, operation, maintenance, modification, and disposal. Here, the user is the owner and manager of the machine, not the operator who work with the machine. The user is responsible for not only the machine system, but also the occupational safety and health management (OSHM) of the workers including the operator.

[Operator] He collaborates with the machine, is defined independently of the user. Because although the operator is a part of the user (company), he has specific requirements such as the risk of harm during work and training for collaborative work.

In this paper, these stakeholders are identified: provider, integrator, user, and operator. In addition to these, there are other stakeholders such as component or system conformity assessors, government officials, and control panel manufacturers, but we focus on these four stakeholders that play major roles in the lifecycle.

4.2 Lifecycle

Consider the life cycle of a collaborative machine.

[System requirement] First, it is the user who wants to introduce or acquire a collaborative machine system. The user analyzes the requirements for the desired collaborative machine application and places an order with an integrator.

[System realization] The integrator designs, assembles, evaluates, and delivers the collaborative machine system to the user based on the presented requirements from the user. For convenience, this series of processes is called the "realization". The build system is installed to the user, and after witness inspection and handover, the user starts operating it.

[Training] The operator has training on the collaborative machine system and the work procedures. Training is either conducted using a manual and training equipment before installing the system or conducted during a trial run using the installed system.
[Operation] After that, the user and operator start operating the collaborative machine system. The operator checks the work procedure and sets or checks the parameters of the collaborative machine system in every day. Sometimes, he processes prescribed cleaning, jig replacement, or irregular events (breakdowns or adjustments with other processes).
[Management/Maintenance] The user manages workers including the operators. Since operators are on a shift system, operators who can use the collaborative machine system shall be secured and trained. In addition, their skills, abilities, and physical condition shall also be managed. These are the items of OSHM. The maintenance of the machine system and the improvement of the work environment are also the responsibility of the user.
[Modification] The integrator conducts the modification of the machine system based on the user's requirements. In this case, the operator will be re-trained, as necessary.
[Disposal] When the collaborative machine system is no longer needed, it will be disposed of following the prescribed procedure. In some cases, the integrator will cooperate in the disposal.
[Component development] Component development is not synchronized with other lifecycle stages, but is developed independently. Some integrators are also providers that provide the components to be adopted.
Figure. 2 shows the lifecycle of collaborative machine systems for each stakeholder. In the table, the management stage of the user and the operation stage of the operator may be more than 10 years. During the operation, there will be changes in personnel, the content of the collaborative work, and the parts and deliverables (recipe) used for the work. Sometimes, the division of roles between the integrator and the user will vary depending on the field, region, company customs and contracts, and will not necessarily be the same as in the figure.

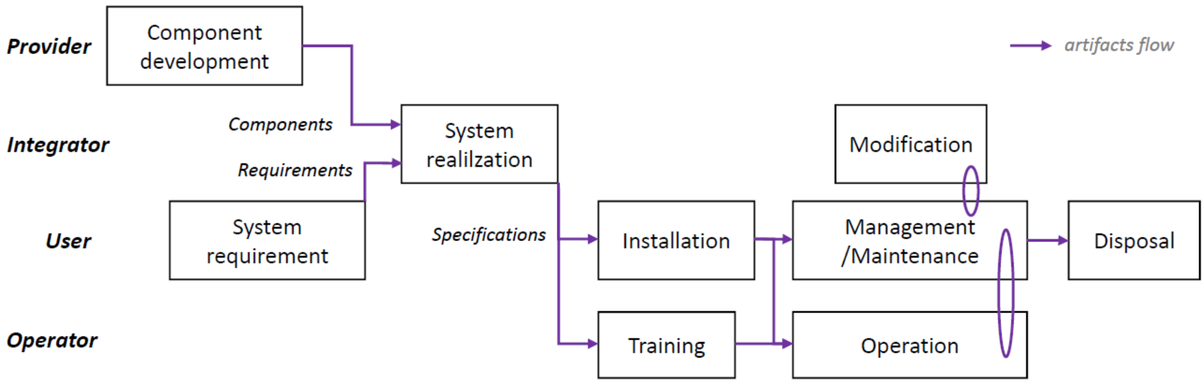

Figure 2. *Lifecycle of collaborative machines and stakeholders*

4.3 Risk assessment and risk communication

Based on Figure 2, we would identify the time to perform risk assessment.
[Provider] First, the provider must perform risk assessment to ensure safety when shipping the component. Information for using the component safely is provided in manuals, etc.
[User] The user performs hazard analysis and risk analysis (HARA) for the expected collaborative work between operators and machines, and incorporates safety-related requirements into the system requirements. However, the user only performs risk analysis and does not consider risk reduction measures.
[Integrator] The integrator realizes the collaborative machine system based on the user requirements. In the process, he performs risk assessment and implements appropriate risk reduction measures for the system. Here, the integrator obtains information about the collaborative work between the operator and the machine from the user, such as the operator's role, work area, work speed, and task interval, etc. The user also needs machine specifications to consider operator-related information, so cooperation between the user and the integrator is necessary. As a result of the integrator's realization, an installation manual, a maintenance manual, and an operation manual including safety-related information for the collaborative machine system are released. The operation manual becomes the input for training.
[Integrator and User] In general, the integrator's final risk assessment is performed at the time of shipment from the factory. However, it may be performed in a witness test after installation on user's workplace, or it may be performed jointly by them.
[User] It is desirable to perform risk assessments many times during the operation and management the machine system. In particular, it is required to review the risk assessment when materials/recipes, work procedures, the machine configurations, or the work environment are changed. In addition, it is often the case that the evaluation

of the risk assessment at installation is different when the machine is operated. It is important to perform a re-assessment based on the actual results of operation. The operator should also participate in this risk assessment.
[Integrator and User] The user requests a system modification, and the integrator modifies (realizes) it. As same as the initial realization, a risk assessment is performed on the changes to confirm safety. After the modification, the user also performs a re-assessment conformed with OSHM.
[Operator] The operator does not perform risk assessments, but if there is something unusual in daily operation, he reports it to the user and takes appropriate measures.
Figure 3 shows the flow with the above risk communication added to Table 2. In the figure, the bold line represents risk assessment, and the arrows represent artifacts or inputs.

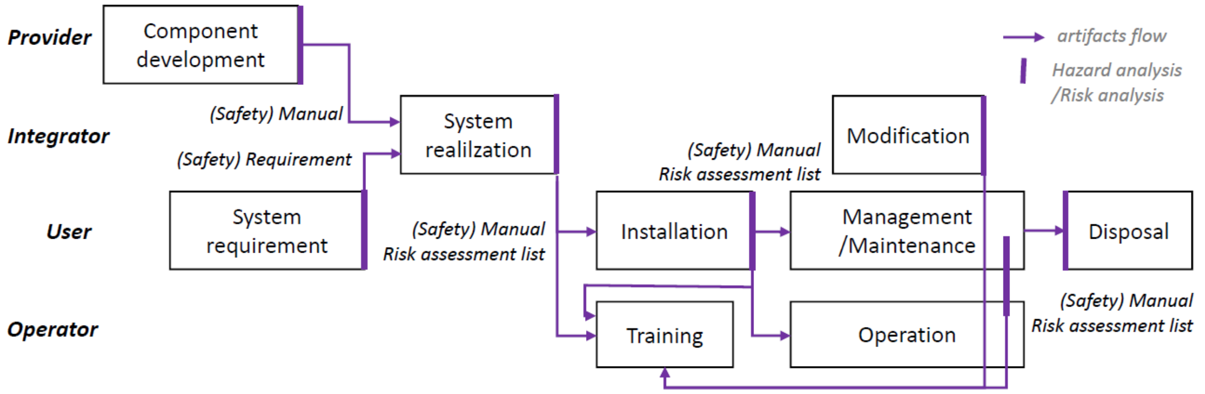

Figure 3. *Risk assessment and communication in lifecycle of collaborative machines*

5 REQUIREMENTS FOR RISK ASSESSMENT

The collaborative machine limits common safety functions for collaborative work, which reduces safety margins. In another hand, to compensate for the saved safety margins, it regulates its safe behaviours and speeds for the operator by monitoring him. The specifications of collaborative work have a significant impact on safety. Therefore, before risk assessment of collaborative machines, the content of the collaborative work, the distance between the operator and the machine, the work speed, and the necessary skills must be clarified.
The following lists requirements that should be considered for risk communication in Figure 3. This is not a complete list.

- The user, integrator, and operator shall describe the specifications of the collaborative work. The user can put together the requirements, and the integrator can put together the specifications.
- The specifications of the collaborative work shall include the operator's work procedure and speed, and the corresponding machine's work behaviour.
- The collaborative machine shall have the function of monitoring the operator's actions and adjusting the machine's behaviours and speeds so that the collaborative work shall be achieved.
- HARA shall be performed on the specifications of the collaborative work, and the safety requirements and specifications of the collaborative work shall be described.
- The Integrator should design risk reduction measures to enable collaborative work to be achieved. However, if the operator may be harm, the collaborative work shall not be continued.
- The user and integrator shall perform HARA for collaborative machine systems with safety measures and confirm that the residual risk is tolerable.
- During the user's operational stage, if there are changes to materials or work procedures, improvements to equipment or the environment, or new operator, a risk assessment shall be carried out again and risk reduction measures shall be added if necessary.
- The operators shall take training for collaborative work.
- The user shall manage the abilities and physical condition of operators and maintain and manage the machines.

6 CONCLUSIONS

We have considered the characteristics and lifecycle of collaborative machines, as well as their risk assessment and communication. The collaborative machines are designed for collaborative work between operators and machines, and in exchange restricting common safety functions, the collaborative machine monitors the operator and regulates its behaviours and speeds to guarantee safety. Therefore, a lot of information and specifications about collaborative work shall be gathered before risk assessment. In addition, the specifications for collaborative work and the parameters in risk assessment are reviewed according to its operation results, and re-assessment.
The collaborative machine needs the establishment of a new safety concept beyond legacy one, so we discuss in long time. We would like to collect use case applications and proceed with analysis and discussion [9].

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