Study on Application of a Human-Robot Collaborative System Using Hand-Guiding in a Production Line

FUJII Masakazu : Manager, Control & Communication Technology Deparment, Products Development Center, Corporate Research & Development
MURAKAMI Hiroki : Deputy General Manager, Products Development Center, Corporate Research & Development
SONEHARA Mitsuharu : Manager, Robot Technology Department, Products Development Center, Corporate Research & Development

Power assist devices and automated facilities are applied to the transportation and assembly of heavy or large parts in production lines to improve efficiency, keep workers safe and reduce the number of workers. However, power assist devices cannot reduce the number of workers. Moreover, automated facilities have to be equipped with advanced sensing devices and controls for positioning purposes and judging when a task is complete, and then such facilities may hamper utilization or make the return on investment too small. In this paper, to resolve such problems, we studied the application of a human-industrial robot cooperative system to a production line. Safety, operability and the assistance of human skills were studied as they relate to hand-guiding, in which a human operates an industrial robot directly and they work collaboratively.

1. Introduction

In the manufacturing industry, the reduction in labor population due to the declining birthrate and growing population of elderly people is hampering the handing down of the techniques of skilled workers. This is in turn reducing production quality and weakening corporate competitiveness due to increasing difficulties in acquiring qualified workers, even when a favorable market allows increasing production volumes.

To make up for the labor shortage and the lack of skills, automated production has been implemented in companies producing products on a large scale. However, in contrast to increasing automation in welding and materials handling, assembly work has not been much automated. It is difficult to automatically perform assembly work that require skilled labor and confirm the completion of work or the presence or absence of defects. Also, automation requires advanced control and sensing technologies. Thus, one of the reasons for sluggish advancement in automation of assembly work is that these factors frequently trigger brief shutdowns (suspension of device operation not by malfunction but by minor events), thereby reducing operation rates and generating no significant effects in return on investment for automation of production.

To solve these issues, we proposed a human-robot collaborative operation system called hand-guiding.[(1), (2)] In the hand-guiding system, an industrial robot takes charge of simple and repetitive automatic operations such as holding a workpiece, conveying it to an assembly area, where assembly and installation are executed using an industrial robot controlled by an operator via a control device located close to the end-effector of the robot. Hand-guiding can decrease the number of brief shutdowns and save the operator such bothersome works in automation as detailed positioning and confirmation of the completion of works and the presence or absence of defects. In addition, the industrial robot can be used as a power assist device to reduce the physical burden for the operator when handling large or long components by supporting heavy weight and maintaining the position of a component. There are devices developed for actively performing power assist and work support.[(3), (4)] However, these devices are not industrial robots for automatic operation and require permanent control by operators in the same way as power assist devices do. One advantage of establishing the human-robot collaborative operation system using the industrial robot is the availability, for some works, of automatic operation without an operator.

Safety and operability are important factors in the human-robot collaborative operation system. For safety, the international standards for safety requirements for industrial robots stipulate the prerequisites for human-robot collaborative operation, including the specific requirements for hand-guiding. Compliance with international standards is also required by Japanese laws and regulations related to safety. In response, based on our risk assessment, we have proposed systems for securing safety, incorporating ① separation of workspaces for operators and industrial robots, ② release of an interlock so an operator can access the control device of an industrial robot during the collaborative operation.[(1), (2)] The operability is the performance of the system necessary for enabling the operator to control the industrial robot at his discretion and complete operations. We also proposed the following two methods for improving operability of a human-robot collaborative operation system. The one is letting the operator to change the patterns of robot command speeds in accordance with types of input devices and actuating variables.[5] This is aimed at enabling the operator to realize operations just as he intends. The other method is allowing the operator to select motion axes and to switch robot's rotational centers. This is aimed at enabling the unskilled operator to easily accomplish tasks requiring skills.[6], [7]

The following sections explain the outcomes of our study on the subjects to be discussed and designed when applying the human-robot collaborative operation system to production lines for assembling works involving large or long components.

2. Standards, national safety laws and regulations and collaborative operation configuration

2.1 Standards for human-robot collaborative operations

The international standards stipulating safety requirements for industrial robots are ISO 10218-1: 2011[8] and ISO 10218-2: 2011.[9] The former is for an individual robot and the latter for robot systems and integration. To harmonize Japanese Industrial Standards (JIS) with international ones, JIS B 8433-1: 2015[10] was revised and JIS B 8433-2: 2015[11] was published in March 2015. The prerequisites for human-robot collaborative operation are stipulated in these standards. **Table 1** shows an outline of prerequisites for collaborative operation in these standards. Of course, measures to reduce risks to an allowable level must be implemented by conducting risk assessment.

2.2 Safety laws and regulations for the human-robot collaborative operation

Conventionally, the safety requirements for industrial robots in Japan were stipulated in Section 4, Clause 150 of the Ordinance on Industrial Safety and Health based on Clause 20 of the Industrial Safety and Health Act. In the ordinance, industrial robots were defined by rated output of motors (80 W or more) and the degrees of freedom of motion. The ordinance also required the provision of necessary means, such as fences or enclosures to prevent possible risk of accidental contact between humans and industrial robots. However, the ordinance lacked clear correspondence with international standards in terms of requirements for human-robot collaborative operation.

In 2013, the interpretation of the ordinance was reviewed to clarify the correspondence between international standards and national safety laws and regulations. National safety laws and regulations currently require safety measures for both robots and robot systems as stipulated in international standards.

Table 1 Collaborative operation requirement according to the standard

Collaboration configuration	Requirements (Summary)
General	To provide visual indication of collaborative operation. To satisfy any one of the requirements below.
Safety-rated monitoring stop	Requirements for robot behavior (suspension and resumption of automatic operation) when a human exists in a collaborative workspace.
Hand-guiding	Requirements for the arrangement and functions of a control device required for hand-guiding equipment; operation speeds and posture of a robot; and the indication of a collaborative workspace.
Speed and separation monitoring	Requirements for the speeds of a robot and a distance between a human and the robot.
Power and force limiting	Requirements for limiting power and force by inherent design or control.

(Note) The collaborative workspace means a workspace allowing a human to simultaneously work with a robot inside a safety protection space of a robot work cell.

2.3 Collaborative operation configurations

Table 2 shows collaborative operation configuration defined by international standards. The safety-rated monitoring stopping and speed and separation monitoring are configurations for operating robots for keeping themselves from colliding with operators. Power and force limiting is a configuration of limiting robot power and force so as accidental collisions pose only allowable risk to operators. These collaboration configurations allow operators and robots to share a workspace without physically dividing it. In other words, these configurations make human-robot coexistent tasks practicable.

In contrast, hand-guiding is a configuration for letting an operator control an industrial robot through a control device located close to the end-effector of the industrial robot. Hand-guiding represents collaborative operations, where operators are to guide by hand the industrial robots to handle workpieces held by them. Such ways of performing tasks can be called, human-robot cooperative tasks.

Human-robot coexistent task is not significantly different from that of the conventional industrial robot system, except for the need for an electronic detection device (such as a light curtain or mat to detect the presence of humans) which performs a similar function to a fence. In human-robot coexistent work, industrial robots and operators each perform separately their own tasks. Conversely, in human-robot cooperative task, industrial robots and operators collaboratively perform one task. For example, when performing a certain task to convey and assemble large or long components and adjust their positions without changing postures, the operator may use the industrial robot as a power assist device and allow it to perform only translational motions, restricting rotational motions. Likewise, when performing a task to adjust postures, the operator may select appropriate rotational

Table 2 Method of collaborative operation

Collaboration configuration	Operation method
Safety-rated monitoring stop	Operation of a robot is suspended when an operator exists in a collaborative workspace.
Hand-guiding	The position and speed of an end effector are instructed through an input device situated close to the end effector while an operator activates the enabling device situated close to an end effector.
Speed and separation monitoring	A robot operates while the robot and an operator keep a predetermined separation distance. The operation of the robot is suspended when they cannot keep the separation distance.
Power and force limiting	The power and force of a robot are controlled or inherently limited until the risk of an operator is reduced to an allowable level.

centers and to allow the robot to perform only rotational motions. The human-robot collaborative operation system provides the operator, no matter whether skilled or unskilled, with the skills needed to perform tasks such as assembly, allowing him to easily execute work requiring skills.

In the human-robot collaborative operation system it is necessary to select an appropriate collaboration configuration most suitable for the task be achieved, taking into consideration the characteristics of the configurations. An appropriate collaboration configuration must be selected after paying due consideration to the safety and operability, described below, to obtain benefits from it in the form of higher efficiency, operation rate, reliability or lower costs than those obtained from manual operation or conventional automated systems using industrial robots.

3. Design of the human-robot collaborative operation system

The following three items must be considered when designing a human-robot collaborative operation system:

(1) Collaboration configuration
(2) Safety
(3) Operability

These items are explained in detail hereafter assuming application to a production line to convey and assemble large workpieces.

3.1 Collaboration configuration

This paper focuses on hand-guiding design. As described in **Section 2.3**, hand-guiding allows operators to handle large or long components, which cannot be handled manually, by making robots perform collaborative operations as power assist devices. Also, hand-guiding allows the industrial robots to perform automatic operations on their own, while the operators are able to execute other tasks. That is, while hand-guiding allows operators to handle workpieces held by a robot just as general power assist devices do, it can also let the robot conduct other automatic operations by itself, thus contributing to laborsaving. We consider this feature as the advantage obtained from applying human-robot collaborative operation systems to production lines that handle large or long components. In the case of the coexistent tasks where operators and industrial robots each perform their respective tasks, however, they could not perform tasks that can be accomplished only through their cooperation. Thus, hand-guiding was selected as the collaboration configuration for this paper.

Figure 1 shows the concept of the hand-guiding system.[(1), (2)] The characteristic composition elements which distinguish the hand-guiding system from general systems using only industrial robots are a collaborative workspace, where robots and operators collaboratively execute tasks; an automatic operation workspace, where robots automatically execute tasks without operator entry; a boundary to separate the two spaces using physical or presence detection; and a hand-guiding equipment for operators to control the hand-guiding system.

The following sections explain these composition elements in detail, from the viewpoint of safety and operability.

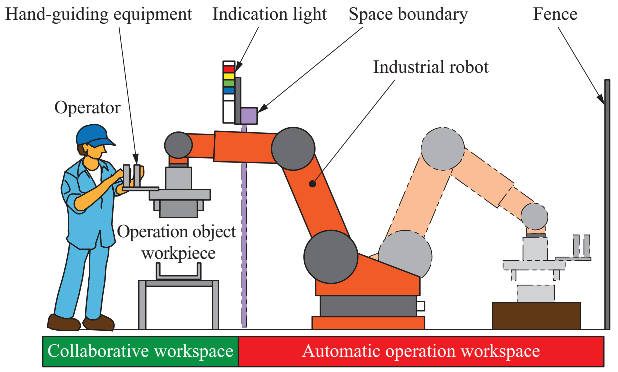


Fig. 1 Concept of a hand-guiding system

3.2 Safety

Based on JIS B 8433-1: 2015 and JIS B 8433-2: 2015, the hand-guiding system must satisfy the following safety requirements:

(1) Implementation of risk assessment
(2) Provision of visual indication of collaborative operation when in progress
(3) Arrangement of a hand-guiding equipment (including an emergency stop and enabling device which conform to JIS B 8433-1: 2015) located close to the end-effector
(4) Availability of clear visual confirmation by the operator of the entire collaborative workspace
(5) Provision of robots, protection and presence detection devices, and safety-rated monitoring speed function which conforms to JIS B 8433-1: 2015 and JIS B 8433-2: 2015

As required in (1) above, risk assessment was implemented and, based on the assessment results, the concept was formulated as shown in **Fig. 1**, and an experimental system designed as shown in **Fig. 2**.[(1), (2)]

Conforming to requirement (2), an indication light is situated at a position visible to an operator as shown in **Fig. 1**.

Also, conforming to requirement (3), the hand-guiding equipment comprising the 3-position enabling switch, emergency stop switch and the input device for position and speed commands is located close to the end-effector as shown in **Fig. 3**.

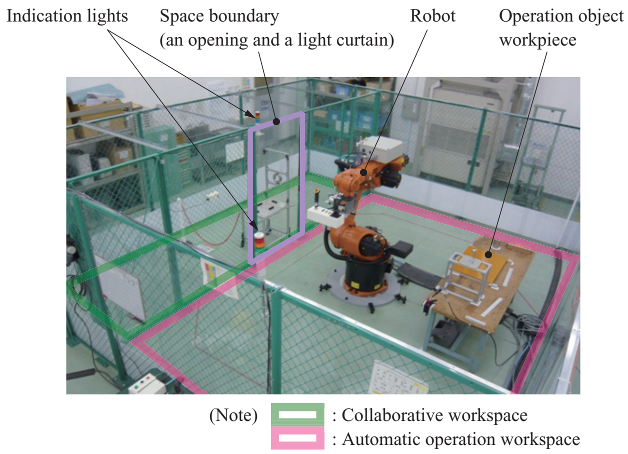


Fig. 2 View of experimental system

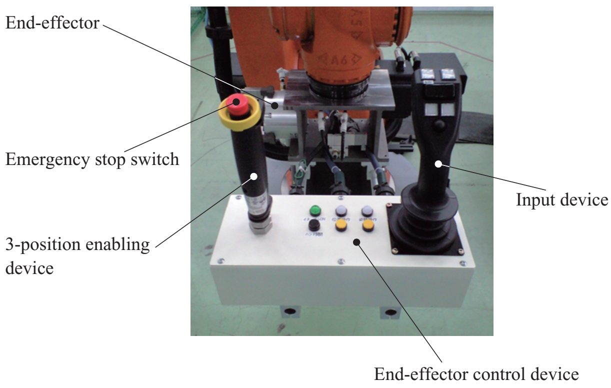


Fig. 3 Hand-guiding equipment

Against the possible risk that an operator using only one hand may get the other free hand stuck in the robot or workpiece, the enabling device and the input device are arranged for respective operation using either hand, with sufficient distance between to prevent the operator from operating both using one hand. The input device is a joystick type, as shown in **Fig. 3**, where an inclination angle of the joystick becomes a sensor value input for the robot. Or, the other input device is a force sensor that inputs applied force to a stick used in place of the joystick, as explained in a later section.

To meet the requirement of (4), a fence was used to clearly mark the border between the collaborative workspace and the automatic operation workspace as shown in **Fig. 2**. The fence was also used to prevent persons other than operators from entering the spaces.

A partition and a working table were installed to prevent operators from entering the automatic operation workspace. A safety sensor (a light curtain) was also installed to stop the industrial robot when any part of an operator's body enters the automatic operation workspace through an opening or the industrial robot enters the collaborative workspace during non-collaborative-operation mode. Also, coexistent operations as explained in **Section 3.1** can be combined with the collaborative operations. For example, it is possible not to physically separate the collaborative workspace from the automatic operation workspace. When this is the case, after clearly demarcating the spaces by colors painted on the floor, etc., hand-guiding can be performed within the collaborative workspace during collaborative operation mode, provided that industrial robot operations are suspended if the distance between operator and industrial robot be smaller than the pre-determined acceptable distance when he enters the collaborative workspace while the industrial robot performs its automatic operations.

The industrial robot, a control device and other detection devices are designed to satisfy the requirement of (5).

Also, operation speeds, industrial robot movements during collaborative operation mode, switching control between automatic operation and collaborative operation and arranging respective compositional elements have been determined, based on risk assessment results. The measures explained in this paper are not sufficient to reduce all risks to allowable levels and cannot be applied as appropriate to all systems. It should be noted that suitable measures need to be studied by appropriately implementing risk assessment of the specific system structures and usage of the actual system to be designed.

3.3 Operability

The operability of the collaborative operation system in human-robot coexistent tasks includes such subjects as the switching between automatic and collaborative operation and return performance of the industrial robot after it is suspended due to collisions with the operator or some large impacts. Also, the operability of hand-guiding includes how to send commands on positions and speeds to the industrial robot. With well-designed methods, operations can be completed speedily with a high success rate. The ideal operability is to control the industrial robot to the operator's satisfaction, as if he were holding workpieces with his own hands. The important points to consider for achieving such ideal operability are:

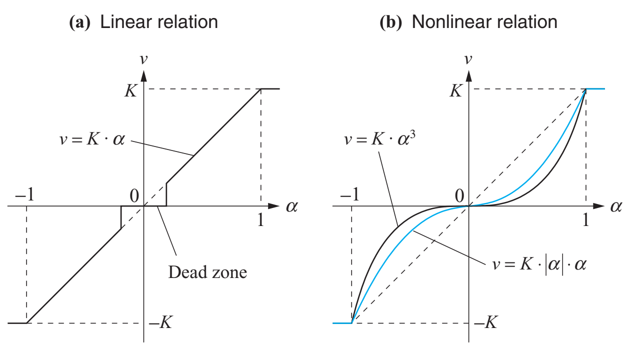
(1) Types of relations between actuating variables of input devices and robot velocity command values
(2) Types of input devices

Also, the following items are skill support mechanisms for allowing difficult tasks requiring skill to be easily executed by supporting unskilled operators by human-robot collaborative operation systems:

(3) Limits on degree of freedom of operation and TCP (Tool Center Point) selection
(4) Conversion of task coordinate systems

3.3.1 Relationships between actuating variables of input devices and robot velocity command values

Preferably, robots move fast with broad manipulation when conveying workpieces in a direction away from the operator, moving slowly and finely when performing assembly tasks, etc. Thus, it is important what kind of robot velocity command value is calculated from the actuating variable of the input device. **Figure 4** illustrates two types of relationships between actuating variables of input devices and robot velocity command values: one is for calculating the velocity of command values in proportion to actuating variables (**Fig. 4-(a)**); the other is for calculating the velocity of command values in proportion to the square or cube of actuating variables



(Note) K : gain
α : actuating variable (the maximum speed of K between −1 and 1)
v : velocity command value

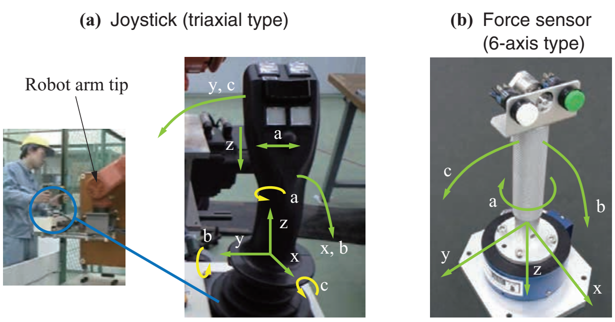
Fig. 4 The relationship between input device and robot velocity command

(**Fig. 4-(b)**). As shown in **Fig. 4-(a)**, the linear relation contains a dead zone to prevent a minute velocity command value from being calculated when the actuating variable is near zero. The experiment on these calculation methods revealed that velocity command values in relation to the square of actuating variables produce the shortest time to execute operations.[5] However, such effective relations may change depending on the relative lengths of duration of fine and broad manipulation in hand-guiding operations.

3.3.2 Types of input devices (Fig. 5)

There are two types of input devices: the joystick types which output inclination angles and the force sensor types which output force and moment of force, acting on the joystick. Input devices using force sensors are considered to give the operator the feeling of natural control as, in general, people apply forces to objects when holding and conveying them.

After some experiments on the two types of input devices, operations using force sensors capable of 6-axis input produced the shortest operation time.[5] By contrast, in operations to adjust posture by rotational motion, the force sensor caused more frequent retrying than a joystick. As mentioned above, force sensors allow operations to be performed intuitively, but it remains difficult to apply moment of force only in a specific direction through a lever control. This, we think, is because, with the force sensors, the posture of robot arm will unintentionally change to another direction.



(Note) a : Rotational direction around z axis
b : Rotational direction around y axis
c : Rotational direction around x axis

Fig. 5 Input device

3.3.3 Limitation on degree of freedom of operation and selection of TCP

It was discovered that force sensors may cause rotational movement in unintended directions. In this respect, the hand-guiding can limit degree of freedom of operation by intentionally preventing the robot from moving in undesired directions.

Also, hand-guiding can perform operations more in accord with the intentions of operators by changing the TCP, which is to be set as the center of rotational motion, according to the type of operation.

Moreover, hand-guiding can help with tasks requiring skills by changing the degree of freedom of movement and switching rotational centers according to the content (phases) of operation. Hand-guiding used in this way is also called operation guidance.

Figure 6 shows an example of an operation to assemble a panel, in which an object workpiece has holes at four corners. The limitation on degree of freedom of operation and TCP selection for respective operation phases are decided for this assembling operation. The example of operation guidance for panel assembly is shown in **Table 3**. In phase 1, only translational motion is allowed to move the panel. In phase 2, 2-axial rotational motion is allowed to align the panel parallel to the object onto which the panel is fitted. In phase 4 of aligning all the positions of four holes, TCP is shifted to any one of the holes that the operator can easily see, with the degree of freedom limited to uniaxial rotation. By an assembly performance experiment, it was confirmed that the time required to assemble the panel can be shortened

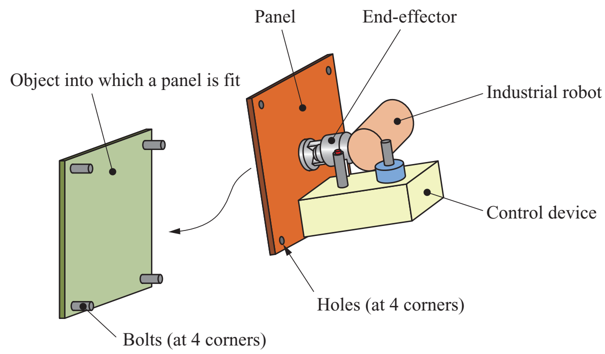
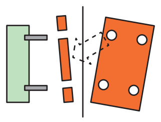
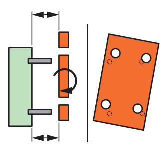
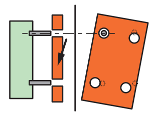
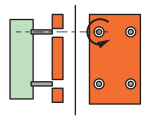
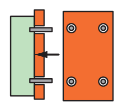


Fig. 6 Example of panel assembly

Table 3 Example of operation guidance for panel assembly

Phase	1	2	3	4	5
Operation	To convey a panel to a place close to an axis.	To align the panel parallel to the object into which the panel is fit.	To align a hole on the panel with the axis.	To rotate the panel around the axis to align the positions of other holes with corresponding axes.	To fit the panel.
Explanatory diagram					
Necessary degree of freedom	Tri-axial translation	Biaxial rotation	Biaxial translation	Uniaxial rotation	Uniaxial translation

(Note) The operation is executed from Phase 1 to Phase 5 in series.

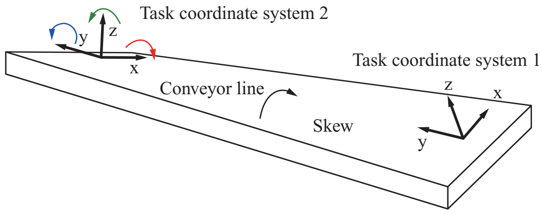


Fig. 7　Skew of conveyor line

by using operation guidance.(6) It is a difficult task to adjust a large panel with six degree of positional and postural freedom by confirming the positional relations between the four corner holes and their corresponding bolts. However, combination of hand-guiding with limits on degree of freedom of operation and TCP selection can easily realize such a difficult task in a manner that supplements an operator's skill deficiency.

3.3.4 Conversion of task coordinate systems

A task coordinate system may be changed if a position at which to place the operation object workpiece or to perform the assembling operation differs from operation to operation. For example, there are cases of operations conducted on conveyer lines installed flat and straight (ideally) on a drawing but in fact are installed askew because of imperfect flatness of the ground on which they are placed. **Figure 7** shows an example of skewed conveyer line.

In such cases, operations may be performed by switching between the task coordinate systems preset for different operational positions. Thus, the operator can perform translation operations using hand-guiding without regard to skews on a production line as adjustments of robot moving direction or posture can be automatically performed. After the experiment on the effect of task coordinate system conversion, we confirmed that operation hours were shortened by eliminating time required for adjusting posture during hand-guiding.(7) With general power assist devices, operators need to acquire skills to perform tasks by consciously and intentionally adjusting device postures according to the skew on a production line. By contrast, hand-guiding allows operators without skills to perform tasks using industrial robots and switching task coordinate systems. Therefore, in this sense too, hand-guiding would serve as a compensating measure for an operator's skill deficiency.

4. Conclusion

In order to apply the human-robot collaborative operation system to a production line, this paper studied methods to improve safety and operability of the system called hand-guiding. To improve safety of human-robot collaborative operation systems their design needs to be done according to the results of risk assessment and in compliance with international standards. To improve operability, this paper introduced types of input devices and techniques such as limiting degree of freedom of operation and switching TCPs and task coordinate systems. Human-robot collaborative operation systems, by combining these techniques, allow operators to exert control at their own discretion, and easily perform tasks requiring skill by supplying them with needed skills. As human-robot collaborative operation systems allow a wide range of people, including women and the elderly, perform tasks requiring skills, these systems would contribute to productivity increases of a society as a whole.

Although national laws and regulations are revised, few human-robot collaborative operation systems have been introduced. We will continue our efforts to apply the human-robot collaborative operation systems to production systems within and outside our company and to further improve safety and operability as a promising kind of systems for enhancing the value of production lines.

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