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Risk Management Simulator for Low-powered Human-collaborative Industrial Robots

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Abstract— **It is believed that from this point forward, there will be a need for industrial robots that work alongside and cooperatively with humans. However, the current development of existing robotics technology is inadequate to ensure the safety of such new industrial robots. Our research proposes a safety-planning technology called Coexistence Hazard Avoidance Technology, designed for use with a low-powered human-collaborative industrial robot. We load this technology into a risk-management simulator and verify that by using it, a dynamic planning method for the safe operation of robots can be reasonably undertaken in terms of both theory and calculation.**

I. INTRODUCTION

In the near future, robots will be able to operate very closely alongside humans and their applications will expand broadly. One of the problems in realizing such robots is the maintenance of safety. As a result, the development of risk-management technology to maintain safety between humans and cooperative robots is considered to be very important.

The world's advanced industrialized nations are suffering from low birthrates and aging populations. Japan, in particular, has the highest rate of aging in the world, and it continues to climb. It is believed that the trend will lead to the problem of insufficient labor in the future. Broadening roles of robots should provide an effective means of compensating for the dwindling workforce. However, such future industrial robots, which will be different from today's robots, must be equipped with safety features that enable them to work cooperatively with humans in general industrial workspaces.

Conventional industrial robots work in areas separated from humans by a fence. That is because they designed to increase productivity by eliminating humans from the production process. In accordance with this use objective, the target of safety standards was to eliminate humans from the robots' work area. The international standard, ISO10218:2006, “Robots for industrial environments – Safety requirements” [1] references ISO12100:2003, “Safety of machinery – Basic concepts, general principles for design” [2]; however, these require safeguards, for instance, fixed guards for moving parts. Japan's Industrial Safety and Health Law requires the same type of safeguards for robots as a general rule.

The new concept of *service robots*, which emphasizes personal-service applications contrasting to industrial robots, is attempting to change robot’s roles significantly. Service robots are robots that are anticipated will spread to all households in the future and provide support for the daily lives of humans, examples being doing housework and caring for the elderly. As such robots will be used in human living spaces without safety barriers, they come with safety issues involving what is called Physical Human Robot Interaction (pHRI). As a result of this, in the field of pHRI research, study into new safety technologies that will enable service robots to coexist with humans is in progress. The trends in these technologies are also having an impact on industrial robots. Many industrial robot manufacturers have announced new industrial robot research results that enable robots to operate next to humans without being enclosed within a physical fence. In ISO10218:2006, the latest robot safety standards, the Technical Committee of the International Standards Organization has added standardized usage that allow workers to come into contact with industrial robots while operating under special conditions.

We have undertaken the development of the SP-02 industrial robot that is driven by low-powered motors legally permissible to labor alongside humans, to work cooperatively with other humans. Japan’s legislation permits to operate industrial robots outside of fences only if the robots are driven by low-power motors not exceeding 80 W in rated power. In this condition anticipated severity of injuries will be rather small and therefore risk of this type of robot will be reasonably mitigated by concentrating to reduce probability of occurrence of hazardous situations. Simulation-based planning should be a good choice in predicting and controlling the chances. In this paper, we propose

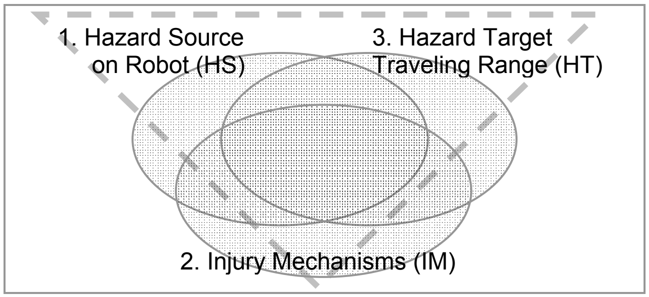

Fig. 1. three components of Robot Hazard Triangle: modification of *Hazard Triangle Model* originally proposed by Ericson.

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Coexistence Hazard Avoidance Technology (CHAT), a simulation-based hazard detection algorithm, as well as demonstrate specific abilities of CHAT using actual data.

II. RELATED WORK

Safety technologies for industrial robots are summarized in past literature. Ward and Went give an overview of the safety standards, safety regulations and safety technology for industrial robots [3]. Kochan has put together an overview of the new robotics technology shown at Automatica 2006, the international industrial robot exhibition [4]. While introducing exhibited robots, the author concluded that a recent trend was to develop robots that are safe and able to work together with humans without being enclosed within a fence.

As for the safe-pHRI researches of service robots, in the European Union an industrial-academic consortium initiated two research projects. The first was Physical Human-Robot Interaction in Anthropic Domains (PHRIDOM), which had the objective of creating a overall map of safe-pHRI research issues and which conducted expert debates for around one year from 2005 under the sponsorship of EURON [5]. This was succeeded by physical Human-Robot Interaction: dependability and Safety (PHRIENDS), which has been conducting actual research activities for three years from 2006 under the sponsorship of the EU Research Framework Programme [6]. Currently, many experimental results and technological proposals are published on this project's Web site.

Pervez and Ryu have written a survey of the literature concerning safe pHRI, comparing 35 research activities, including PHRIENDS described above, and have classified the research focuses as indicated below [7].

1. Interaction safety assessment
2. Interaction safety through design
   a. Design of lightweight manipulators
   b. Design of passive compliant systems
   c. Design of safe actuators
   d. Design of passive robotic systems
3. Interaction safety through planning and control
   a. Interaction safety through planning
   b. Interaction safety through control.

Our research falls under 3a, interaction safety through planning. An example of advanced research in this class is planning research using Kulic's danger index [8]. Kulic proposed the danger index, which includes the functions of two variables—human-robot distance, and robot inertia—and incorporated these in the evaluation function of the robot motion planner. The main feature of the Kulic planning is the generalization of the potential field to allow automating of safety planning in ill-structure environments, such as living spaces. The distinguishing feature of our technology against the work is the generalization of the safety zoning in well-structured environments such as those of a factory.

III. COEXISTENCE HAZARD-AVOIDANCE TECHNOLOGY

The risk management simulator that we are developing is based on CHAT, which combines two technological concepts on three-dimensional robot simulation. They are the Robotic Hazard Triangle (RHT) and Safety Policy Logic (SPL).

A. Robotic Hazard Triangle

We are proposing a hazard modeling RHT for the pHRI of low-powered human-collaborative industrial robots.

Under MIL-STD-882D [9], a hazard is defined as "Any real or potential condition that can cause injury, illness, or death to personnel; damage to or loss of a system, equipment or property; or damage to the environment." A variety of modeling has been proposed for hazards in correlation to the problem area. However, Ericson has proposed a hazard structuring in which three components, such as those below, called the hazard triangle, are the required conditions [10].

1. Hazardous Elements: This is the basic hazardous resource creating the impetus for the hazard, such as a hazardous energy source such as explosives being used in the system.
2. Initiating Mechanism: This is the trigger or initiator event(s) causing the hazard to occur. The IM causes actualization or transformation of the hazard from a dormant state to an active mishap state.
3. Target and Threat: This is the person or thing that is vulnerable to injury and/or damage, and it describes the severity of the mishap event. This is the mishap outcome and the expected consequential damage and loss.

Ericson says that if one or more of the components of these hazards can be invalidated, it is no longer a hazard.

The RHT that we are proposing comprises the following three components for expressing the mechanical hazards peculiar to the pHRI of low-powered human-collaborative industrial robots. If these come about simultaneously at one point in a space, we can theorize that there is a hazard (Fig. 1).

1. Hazard Source on Robot (HS): a mechanical source of danger on the robot, such as a hard edge, a sharp point, or a hinged part in which fingers could be caught easily.
2. Injury Mechanisms (IM): mechanisms in which the hazards of Number 1 operate, such as operation using a lot of energy, operation in which a sharp edge faces outward; and in which, at its narrowest, a hinged part closes to less than a safe gap.
3. Hazard Target Potential Range (HT): An area in which a human body part can easily be injured if the hazard source in Number 1 manifests the mechanisms of Number 2.

The RHT is specialized for the expression of the mechanical hazards possessed by robots in the structured environment. Each component is correlated to robot components, kinematics and human body areas, making it easy for mechanical engineers to specify them concretely. Furthermore, because it is possible to identify the potential interferences of the robot components and parts of the human body in three-dimensional (3D) space and the kinematics of a certain instance in time can be identified with the robot control program, the modeling of the hazard is convenient in predicting and avoiding the hazard in a 3D simulation. For example, under certain conditions, the corner of a robot parts would not cause fatal injury if it were to collide with a human limb, but would cause fatal injury if it were to collide with the human torso. However, if a sufficiently low-speed control mode is utilized, that would cease to be a hazard. In the case of each hazardous situation, a sharp point or hinge, by consolidating them in this manner and describing them with RHT, the hazard can be predicted using the 3D robot simulator, in trial runs of the robot control program in virtual 3D space.

TABLE I
HAZARDS OF SP-02
IN ROBOT HAZARD TRIANGLE REPRESENTATION

Hazard Component	Description
(1) Hazard causing sharp force injuries	
HS	End-effectors and workpieces
IjM	Sharp point exposed, faces human and moves rapidly
HT	Range in which all parts of the operator's body moves. Risk to head is particularly serious
(2) Hazard of midair impact	
HS	Both robot arms
IjM	Moves rapidly toward human
HT	Human head and torso
(3) Hazard of pinching human body	
HS	All 7 robot joints and both end-effectors
IjM	When a human touches the robot, it assumes a position that exceeds the safe movement range and bends a joint
HT	Range in which the operator's hand moves
(4) Hazard of crushing human against wall or objects	
HS	All movable robot parts
IjM	While a human is between the robot and surrounding objects, the gap narrows to below a certain distance
HT	A range in which an operator's body moves within the certain distance from fixed surrounding objects. The distances for hands and the torso should be different

TABLE II
CLASSIFICATION OF HAZARD SOURCE OF ROBOT

ID	Title	Description
SP	Sharp Point	End-effectors and workpieces
IP	Impactor	Both robot arms
PP	Pinching Point	All robot joints and both end-effectors
CR	Crusher	All movable robot parts

TABLE III
CLASSIFICATION OF HAZARD TARGET POTENTIAL RANGE

ID	Title	Description
HZ	Head Region Zone	Area where neck and head of a standing operator are located
TZ	Trunk Region Zone	Area where torso of a standing operator is located
LZ	Limb Region Zone	Area where arms of a standing operator are located
BZ	Fixed Body Zone	Overlapping space of an area where head and torso of a standing operator are located, and an area with less than the safe distance (cf. ISO13854) around fixed objects
FZ	Fixed Finger Zone	Overlapping space of an area where fingers of a standing operator can reach, and an area with less than the safe distance (cf. ISO13854) around fixed objects

B. Safety Policy Logic

Human-collaborative robots should be equipped with additional functions that regulate performance, speed or other attributes of robot control for safety. We have proposed safety policy logic (SPL), a safety maintain algorithm of giving the norm of operating these safety functions (SF), as follows.

```
If (D(H, S) =1)
  { Robot_Motion_Enabled = TRUE; }
else
  { Robot_Motion_Enabled = FALSE; }
```

The function D(H, S) is formulated as follows.

$$D(H,S) \equiv \wedge_{h_i \in H}[\vee_{s_j \in S}\{d_{s_j}(h_i)\}] \qquad (1)$$

$$d_{s_j}(h_i) = \delta; \quad \delta \in \{0,1\}\,. \qquad (2)$$

Here:

$H \subseteq \{h_i\}$: Subset of pairs of HS and HT (h_i), the pairs of HS and HT interfering in the same space at a specific time ,among all of the hazards described by RHT.

$S \subseteq \{s_i\}$: Subset of SFs (s_i), the SFs currently activated in the robot.

$D(H,S)$: Boolean function, to determine robot's operability for given H and S. $d_{s_j}(h_i)$ is a function that sets a 1 if the spatial interference h_i of a certain combination of HS and HT is permitted in a certain condition in which a certain SF s_i activated. Otherwise it sets a 0. In general, $d_{s_j}(h_i)$ is provided by a truth table type database such as Table V. In this research, this is called the SPL database. However, each SF s_i should be set to negate one or more IM. To make this expression generalized, S should include s_0, the robot's inherent safety feature at pristine state before regulating the control.

To give a straightforward explanation, SPL is the algorithm that theoretically formulates the timing of giving suitable friendly motion corresponding to positional relationship between the robot parts and the human body parts. As the variables of this formulation correlate to the three components of RHT, the SPL can be used in the RHT

Fig. 2. SP-02, Upper-Body Humanoid Industrial Robot

TABLE IV
DESIGN OF SP-02 SAFETY FUNCTION

ID	Title	Description
SR	Speed Regulation	Control function that restricts speed so there is no blunt trauma if the robot should collide with an operator.
DR	End-Effector Direction Regulation	Control function that makes the end-effector face inward
ED	End-Effector Deactivation	Control function that stows the end-effector, making it ineffective
PPR	Pincer Posture Regulation	Control function that keeps the gap between robot elements from reaching an unsafe distance for all movable parts
ASS	Alarm and Slow-Speed Operation	Control function that sounds an alarm for the operator while operating at very slow speed

TABLE V
SPL DATABASE FOR SP-02

Applied SF: No				
	SR	*IP*	*PP*	*CR*
HZ	0	0	0	0
TZ	0	0	0	1
LZ	0	1	0	1
BZ	0	0	0	0
FZ	0	1	0	0

Applied SF: *SR*				
	SP	*IP*	*PP*	*CR*
HZ	0	0	0	0
TZ	0	1	0	1
LZ	0	1	0	1
BZ	0	1	0	1
FZ	0	1	0	0

Applied SF: *DR*				
	SP	*IP*	*PP*	*CR*
HZ	0	0	0	0
TZ	0	0	0	1
LZ	1	1	0	1
BZ	0	0	0	0
FZ	1	1	0	0

Applied SF: *ED*				
	SP	*IP*	*PP*	*CR*
HZ	0	0	0	0
TZ	1	0	0	1
LZ	1	1	0	1
BZ	1	0	0	0
FZ	1	1	0	0

Applied SF: *PPR*				
	SP	*IP*	*PP*	*CR*
HZ	0	0	0	0
TZ	0	0	1	1
LZ	0	1	1	1
BZ	0	0	1	0
FZ	0	1	1	0

Applied SF: *ASS*				
	SP	*IP*	*PP*	*CR*
HZ	1	1	1	1
TZ	1	1	1	1
LZ	1	1	1	1
BZ	1	1	1	1
FZ	1	1	1	1

Fig. 3. Assembly Task in Human-Robot Collaborative Workstation

framework. Thus, using the RHT model, hazard analysis, SF designing and dynamic SF planning can be uniformly conducted. CHAT is the methodology of this series of hazard treatments related to pHRI.

Concrete demonstration of how this process can be carried out will be described in the next sections.

IV. MATERIALS AND METHOD

In the case of the SP-02 industrial robot, we will conduct a hazard analysis, model these hazards using the RHT, design SFs, and build an SPL database. Next, we will add a risk-management simulator that makes it possible to visualize RHT on Delmia Envision, the 3D robot simulator.

A. Target Industrial Robot: SP-02

SP-02 has the upper-body humanoid form shown in Fig. 2. To enable it to easily replace a human operator, its physical characteristics (size, weight, speed, output, and ambidexterity) have been designed to be similar to those of a human. As for its axial configuration, it has two 6-DOF robot arms, a 2-DOF camera mount in the head, and a 1-DOF pivot axis waist. As shown in Fig. 3, currently we have introduced a prototype in a cellular production system and are conducting verification tests. The current research is one of the development projects that are taking place in parallel for this robot development.

B. Performing Hazard Analysis

We spent about three months conducting an analysis of the SP-02 robot. The hazard analysis took place in accordance with formal analysis procedures called the preliminary hazard analysis (PHA), allowing us to identify 125 hazards. Among these, it was determined that 29 hazards were related to pHRI. We discovered that we could divide these basically into the four categories shown in Table I [11].

C. Constructing SPL Database

We analyzed the RHT of the four categories of hazards summarized in Table I. HS and HT, which are the building blocks, were each extracted as shown in Tables II and III, respectively. The SFs for controlling IMs were set as

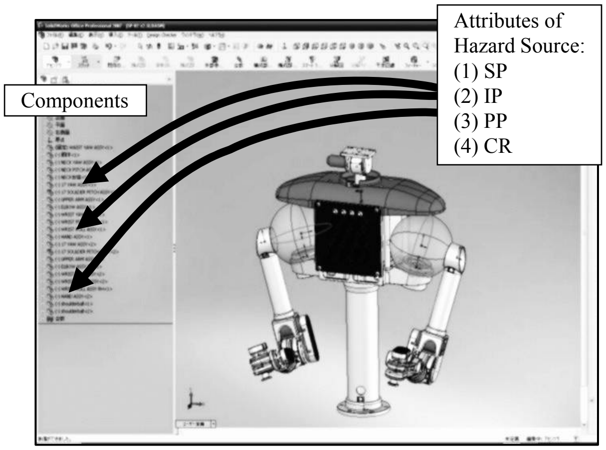

Fig. 4. Assignment of Hazard Source (HS) Attributes in CAD Data

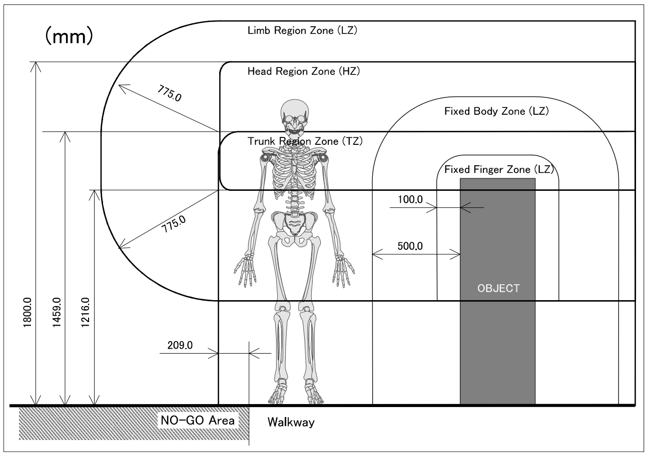

Fig. 5. Dimensions of Hazard Target Potential Range (HT)

Fig. 6. Screenshot of Risk Management Simulator

indicated in Table IV. The SPL database, which was indexed to these, is shown in Table V. In each respective state of SF application, the SPL database expresses in binary form a judgment of whether or not the ST and HT interference risks can be accepted. By applying the SFs, some IMs will be deterred and some RHTs will become incomplete, allowing risks to be acceptable. In this case, the reference values in the SPL database will become 1 (acceptable), and the value will be substitute by $d_{s_j}(h_i)$ in Eq. (2). If there are no other hazards, the value of Robot Motion Enabled becomes True in SPL.

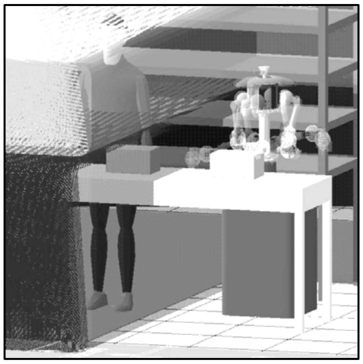

Fig. 7. Checking Intersection between Hazard Source of Robot (HS) and Hazard Target Potential Range (HT)

D. *Implementing Hazard Management Simulator*

As shown in Fig. 4, the HSs shown in Table II are expressed concretely as the robot component attributes in CAD data. As shown in Fig. 5, the HTs in Table III are expressed concretely by the envelope determined by the measurements that have the operator-accessible area as a criterion. The measurements come from the maximum and minimum values (5 percentile and 95 percentile) of Japanese body measurements and the International Standard, ‘Minimum gaps to avoid crushing of parts of the human body’ (ISO 13854:1996).

Fig. 6 shows the risk-management simulator that is under development. This was implemented by modifying Delmia Envision, a general-purpose robot simulator. Delmia Envision has high-level customizability and a powerful interference detection algorithm. The modifications automatically generate the HT envelopes and enable detection of interference with HSs. If the robot operation program is simulated as shown in Fig. 7, the HS and HT interferences, for which risk cannot be accepted, can be detected dynamically.

V. RESULTS AND DISCUSSION

We used the risk-management simulator to conduct a simulation of a situation in which the robot SP-02 is used in a cellular production system. The risk-management simulator was successful in identifying the correct timing for applying the SFs for each separating distance respectively, as shown in Fig. 8.

The scenario we envisioned for the simulation was the elimination of the sensor light curtain that isolates the robot in the actual cellular production system, as shown in Fig. 3, and securing the safety of the operator by only dividing the floor surface into entry-permitted and entry-prohibited zones. The robot control program was one for an actual machine that we

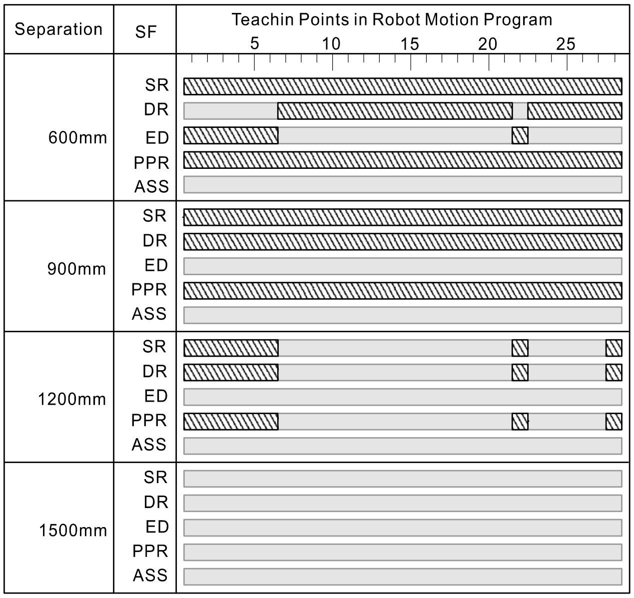

Fig. 8. Identified Safety Functions (SF) required in a given robot motion program. Note that "Separation" designates the horizontal length between the center of robot pedestal and the end of a workers' safety area. That of 600 mm is identical to the actual workstation.

downloaded to the simulator. The distance from the sensor light curtain to the center of the robot pedestal was 600 mm. Based on the simulation we discovered that if we remove the sensor light curtain under these conditions and maintained safety using the SFs only, nearly all the SFs had to be applied for all time periods the robot control program was in operation. The simulated results shown in Fig. 8 indicate that when a robot is separated from humans, the required number of SFs and the time periods in which they are applied decrease. The robot can exert the utmost capacity with no SF applied when they are separated 1500 mm or more.

As the robot control program used in the simulation did not originally take into account the safety gap between a fixed object and the robot, in the simulation we did not evaluate one of the hazards in Table 1 Number (4), "hazard of crushing human against wall or objects."

In the current risk-management simulator simulation, we clarified that the RHT modeling and SPL logic have made it possible to carry out comprehensive operation of SFs that prevents hazardous robot conditions, depending on the layout of the factory. This is reasonable to say that low-powered human-collaborative industrial robots are achievable with CHAT, in condition that the robots are employed at a structured environment where work tasks are strictly predetermined.

VI. CONCLUSION

We have developed a risk management simulator. It is a demonstration of Coexistence Hazard-Avoidance Technology (CHAT) that incorporates two technological concepts, Robotic Hazard Triangle (RHT) and Safety Policy Logic (SPL), on a 3D robot simulator. Based on our simulations, we were able to clarify that CHAT is able to comprehensively manage the safety functions (SF) of robots. This indicates that the safe-pHRI problems on low-powered human-collaborative industrial robots can be resolved decisively.

As we move forward, we would like to take advantage of the high level expressive capability of the RHT to dynamically alter the hazard target traveling range (HT) using a human detection sensor, for instance, a safety mat or a vision system. We also would like to expand the risk-management simulator so that it is capable of assessing supplemental safety measures such as a tabletop partition, which cab finely tune the HT definition in a workstation.

APPENDIX: LIST OF ACRONYMS

pHRI	physical human robot interaction
CHAT	coexistence hazard avoidance technology
RHT	robotic hazard triangle (cf. Fig. 1, Table I)
HS	hazard source on robot (cf. Table II, Fig. 4)
IM	injury mechanisms
HT	hazard target potential range (cf. Table III, Fig. 5)
SPL	safety policy logic (cf. eq. (1), (2), TABLE V)
SF	safety function (cf. Table IV)
PHA	preliminary hazard analysis

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