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Risk Evaluation of Human-Care Robots

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1. Introduction

Human-care robots must be realized to nurse aged and disabled persons. These robots will need to work around elderly people and give them touches; therefore conventional safety strategies for industrial robots can not be applied to human-care robots. It is now necessary to make a new study of safety in the space where a human and a machine will exist together.

In this chapter, I carry out a Case Study of assessing several human-care robots according to ISO/TR 12100-1:1992 and ISO 14121:1999. Next, I propose a risk evaluation method of human-care robots and define evaluation measures which describe the degree of safety. Next, I apply my method to evaluate several safety design and control strategies, and then I prove the viability of my risk evaluation method. These proposed methods enable us to optimally distribute cost among several safety strategies, and to derive suitable approaching motion of a multi-link manipulator to a human. The validity and effectiveness of these methods are demonstrated by numerical analysis. As a result, the design and control to increase safety are successfully obtained.

2. Case Study on Safety of Human-care Robots

In general, the risk assessment and the risk reduction of machinery are carried out according to ISO/TR 12100-1 “Safety of machinery-Basic concepts, general principle for design” and ISO 14121:1999 “Safety of machinery-principles of risk assessment”. I have carried out Case Study of assessing several human-care robots according to ISO/TR 12100-1:1992 and ISO 14121:1999. The aim of this case study is to clarify the key points of risk assessment and risk reduction for these robots. The following human-care robots are carried out case study of the risk assessment by use of block chart shown in Fig. 1 which is modified by ISO14971, that is “Medical devices: Application of risk management to medical devices”.

Human-care robots

- ☐ Continuous passive motion device (CMP)
- ☐ Meal assistance robot
- ☐ Mobile ceiling lift
- ☐ Bed transfer
- ☐ Pet robot / Mental care robot.

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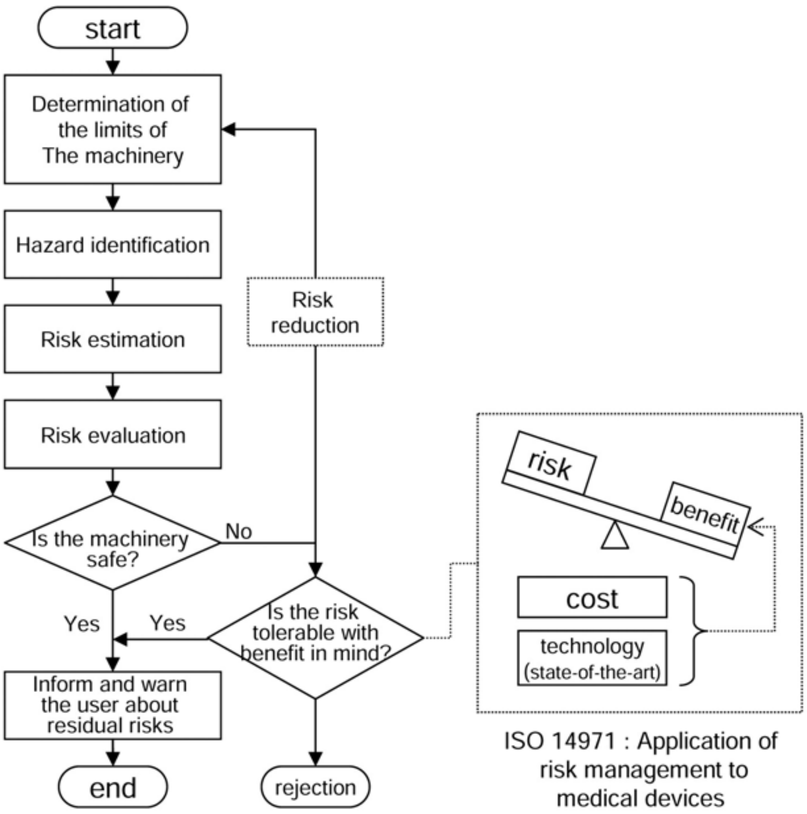


Fig. 1. The iterative process to achieve safety modified by ISO 14971.

Risk related to the considered hazard can be calculated by the following equation:

$$R = Q * F * C * N \tag{1}$$

R : risk related to the considered hazard
Q : probability of occurrence of harm
F : frequency and duration of exposure
C : severity of possible harm that can result from considered hazard
N : number of exposed people

Equation 1 has been used for estimating the risk of marketed human-care robots. However, this approach showed a lot of significant disadvantages. Some of them are briefly commented below:

(a) "R: risk related to the considered hazard " is influenced by the difference in a user and the body situation of cased person.

In case of in-home care, a caretaker or a cared person has to operate a human-care robot by himself / herself. Most of caretakers or cared persons are not familiar with their operation, the number of "Q: probability of occurrence of harm" becomes large caused by their incorrect operation or misuse. Even though correct operation and movement, robots can injure the patient whose joint is stiff or whose bone is breakable such as osteoporosis, the Q number is so high.

As a result, risk of human-care robots is influenced by the difference in a user and the body situation of cased person. This is far different from a risk of machinery which can be estimated on the assumption that user is a specialist of operation and a person with a normal healthy body.

(b) The difference in the state of robot's work space greatly influences "R: risk related to the considered hazard ".

Stretcher and lifter have residual risk of the user's fall. The damage is dependent on a fall place. For example, the damage of falling to bed is low, but to rigid floor is high. Manipulator also gives user a risk of collision accident, the probability of accident is dependent on room space or user's position. As mentioned above, the difference in the state of robot's work space must be considered in estimating a risk of human-care robots.

(c) There is little judgment material for determining "Q: probability of occurrence of harm" and "C: severity of possible harm".

Compared with machinery, there are few statistics data about the accident report of human-care apparatus. The accident occurrence number of cases including a slight injury is unknown, so it is extremely difficult to determine "Q: probability of occurrence of harm". In addition, there is no method to calculate "C: severity of possible harm". In the present circumstances, these values are estimated experimentally or subjectively by the risk assessor.

(d) The risk cannot be expressed correctly by the multiplication of a risk element like Eq.1.

On the assumption that risk factors in Eq.1 have been independent mutually, risk level is calculated by multiplied each of them. However, there is a certain correlation between "F: frequency and duration of exposure" and "Q: probability of occurrence of harm" of human-care robots. No harm will come from only using Eq.1.

3. Proposal of Risk Assessment Guideline for Human-care Robots

This section proposes safety strategy for human-care robots according to results of case study mentioned above. Proposed guideline of risk assessment and risk reduction is shown in Fig. 2.

Fig.2 has similar structure to those, shown in Fig. 1. As a difference, the new structure is additionally improved:

- ☐ Determine limits: user, the extent of handicap, the condition of health, the ability of operation and so on
- ☐ The 3rd person who can do objective judgment with technical knowledge evaluates the contents of the carried-out risk assessment.

Judgments whether apparatus is introduced or not by carer, cared person and manager in consideration of benefit.

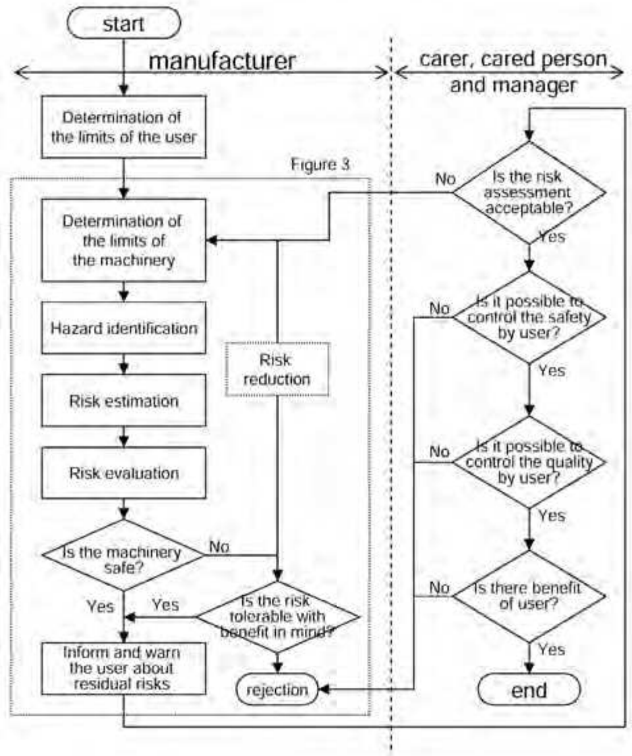


Fig. 2. Proposed guideline of safety strategy for human-care robots

4. Proposing Evaluation Measures of Risk

It is necessary to define ''evaluation measures'' for devising the general safety strategies of human-care robots. Evaluation measures enable us to compare the effect of each safety strategy on the same scale and to optimize the design and control of human-care robots.

In the field of information science, Dr. Shannon has defined information as the degree of entropy, he has there by advanced information theory remarkably. In the robotics field, Dr. Uchiyama and Dr. Yoshikawa defined the measure of manipulability, which has enabled us to compare the manipulation performance of various kinds of robot uniformly.

The former definition doesn't express enough about the quality of the information; the latter doesn't express various kinds of control performance completely. But I cannot deny their contribution to science and engineering. If I overcome some different opinions and define the risk evaluation measures of human-care robots, I will able to achieve similar effects.

First, I examined in detail the occurrence process of collision accidents. According to ISO 12100, some formulas for estimating the risk of machinery are proposed. A typical equation for risk related to the considered hazard is shown as Eq.1.

Many researchers have analyzed the ''Q: probability of occurrence of harm'' caused by human error, manipulation and so on. Their main topic is how to reduce the probability of accident and how to estimate it. The relation between the design and control of human-care robots and the dangerousness of injury has been paid little attention.

In the event of careless collision between robots and humans, the degree of ''C: severity of possible harm that can result from considered hazard'' can be expressed as Eq.2 by using only main factors such as design and control.

$$C = f\ (design) \cdot g\ (control) \tag{2}$$

In this research, I have been taking a stand on studying ''what design or control can minimize human injury'' at the occurrence of an accident. Put another way, the aim is to make quantitative evaluation of the effectiveness of safety design or control measures, and to minimize its dangerousness on condition that the Q: probability of occurrence is 1.

What should the evaluation measures be?

A human-care robot works around humans who move irregularly. I consider an appropriate safety strategy while adapting the classified design/control safety strategy mentioned previously. A safety design strategy is a means for reducing the injury to a human after an irregular collision. A safety control strategy is a means for minimizing the injury before a human-robot collision. It is important to estimate not the occurrence rate but the injury due to collision.

No matter what the cause of collision accident may be, the shock of mechanical injury depends on impact force, and the scar depends on impact stress. Namely I consider impact force and stress as evaluation measures.

5. Risk Evaluation Method Using Evaluation Measures

In this section, I propose a general quantitative method of evaluation using evaluation measures.

First, I define critical impact force F_c as minimal impact force that causes injury to human. Next, I define the danger-index α as the producible impact force *F* of robot against F_c in Eq.3.

$$\alpha = \frac{F}{F_c} \qquad (\alpha \geq 0) \tag{3}$$

Strictly speaking, the value of force F_c varies according to age, sex and body part. But I use one representative value for realizing the generality of risk evaluation. In exceptional cases such as eyes, where F_c is very low, these body parts are treated as a singular point. Another evaluation is needed for such points.

Next, I consider the overall danger-index provided by some safety strategies. I express the characteristic of safety strategies for minimizing the impact force by using a block chart, which is popular in the control field. For example, producible impact force is input, a safety strategy is a factor, its danger-index is transfer function, and injury to a human is output. The index is dependent on the transfer function. In this system, several factors are connected with each other in series. The characteristic of whole system can be expressed as the multiplication of each transfer function.

The total danger-index of whole robot α_{all} is expressed by the multiplication shown in Eq.4. This equation enables us to quantify the effect of safety strategies on the same scale:

$$\alpha_{all} = \prod_{i=1}^{n} \alpha_i \tag{4}$$

where ''n'' is the total number of safety strategies and ''i'' is the number of safe strategies.

As an example, I consider the case of reducing impact force by a perfect shock absorption material. Even if a robot collides with a human, the impact force to the human is qualitatively 0 because it is isolated by the material. The danger-index α_i about the shock absorption material is expressed as 0 by using the proposed risk evaluation method. The total danger-index multiplied by each index results in 0, so it is obvious to agree the usual.

Too many safety strategies reduce the ability of robot work or operation. This problem can be solved by devising a safety strategy on condition that required working ability is satisfied, or calculating the optimum solution between Eq.4 and efficiency of robot working. This is an advantage produced by a quantitative evaluation of dangerousness.

Defining impact force and the danger-index before improvement as F_0 and α_0 respectively, the improvement rate η can be calculated by Eq.5.

$$\eta = \frac{\alpha_0}{\alpha} = \frac{F_0}{F_c}\frac{F_c}{F} = \frac{F_0}{F} \tag{5}$$

F_c is cancelled in Eq.5, I can simply compare before and after safety strategies.

The algorithms of my risk evaluation method are the following:

1. Investigating the factor of damage to a human as evaluation measures.
2. Calculating the impact force F of each safety strategy.
3. Calculating the danger-index α from Eq.3.
4. Executing the risk evaluation by using the total danger-index.
5. Discussing the safety strategy from the result.

This method enables to evaluate the effect of each or all safety strategies.

6. Deriving Danger-Indexes of Safety Strategy

In this section, examples of safety design and control strategies will be given to show the practical derivation of a danger-index.

6.1 Safety design strategy

At first, I propose a linear approximate model of each safety strategy and solve it individually. The aim of approximation is in order to extract only the effect of a safety factor and remove the effects of other factor, as much as possible.

Usually, I make models and equations which satisfy all effects of boundary conditions at the same time. This method requires the reconsideration of them when the conditions are changed. If more phenomena are considered, it makes the equation complicated and increases unknown variables.

For evaluating and comparing safety strategies, it is necessary not only to consider all phenomena strictly but also to quantify the safety with the aim of wide use. As a result, I work out the danger-index of the safety strategy by using a linear approximate model individually.

This research supposes a collision accident between human and robot, and each safety strategy for reducing the damage from the collision is discussed. For example of a safety design measure, the reducing a robot weight in order to minimize the impact force is shown as follows. Impact force F is derived as Eq. 6 by Newton's equation of motion. This impact force *F* of robot against the critical one yields the danger-index α , Eq. 7.

$$F = ma \tag{6}$$

$$\alpha = \frac{ma}{F_c} \tag{7}$$

As an example, a danger-index is shown when robot material is changed from steel (density: 7.86 x 10^3[kg/m^3]) to aluminium (density: 2.69 x 10^3[kg/m^3]). When the robot moves at 1[m/s^2], the danger-index α is 0.34. Or if replaced with a plastic (density: 1.40 x 10^3[kg/m^3]), the index α is 0.18. In short, if the weight is reduced by half, α is half, too.

Similarly, it is possible to derive danger-indexes of several design strategies, such as absorbing impact force by soft cover, safety joint compliance, minimizing impact stress caused by shape, reducing surface friction and so on. The equations of these danger-indexes have been shown in References.

6.2 Safety Control Strategy

Danger-index equations of safety control strategy are derived in this research. If dynamical analysis or consideration of extra parameters is needed, the safety is evaluated by using some assumptions. For example of safety control strategy, ''Effect of keeping distance'' is shown as follows.

Sufficient distance between a human and a robot produces enough time to reduce impact force by braking, actions to avert collision, and so on. When the approaching speed of a robot (mass: m) is reduced at acceleration a from distance l. Time until collision Δt is obtained by Eq. 8, when v>0 and a>0.

$$l = v\Delta t - \frac{a\Delta t^2}{2} \quad \Delta t = \frac{v}{a} - \sqrt{\left(\frac{v}{a}\right)^2 - \frac{2l}{a}} \tag{8}$$

The collision speed becomes $v - a\Delta t$, and impact force F and danger-index α are expressed as in Eqs. 9 and 10. I assume that the impact force does not become a negative value.

$$F = m\frac{(v - a\Delta t) - v'}{dt} \tag{9}$$

$$\alpha = \frac{F}{F_c} = m\frac{(v - a\Delta t) - v'}{dt} \tag{10}$$

Here, I examine nursing motion by a multi-joint manipulator. First, ''normalization technique of impact force'' is introduced in order to pick up the effect of distance. In Eqs. 8 – 10, acceleration a has no influence on the effect of distance and differs between every robot. Velocity after collision v' cannot be specifically determined before the collision. These parameters are determined by the assumption that impact force is 1 [N] (normalized impact force). Therefore, unknown parameters in these equations, obtained from this technique, should be a=1[m/s^2], v'=0 [m/s], Δt =1.0 [s]. That is a normalization technique

I consider a concrete example of a robot with mass 10 [kg] approaching a human from a distance of 0.5 [m] at a velocity of 2[m/s]. The time until collision Δt, calculated from Eq. 8, is 0.27 [s]. Impact force F_0, obtained from Eq. 9, is 64.65 [N]. The critical impact force F_c is 490 [N] that is 10[%] of the force which the human head can withstand without injury. A safety factor of 10 on F_c is introduced on my own terms. Strictly speaking, F_c changes according to age, sex and body part. But I use 490 [N] as one representative value for realizing the generality of risk evaluation. If another value of F_c is needed, the safety is evaluated by replacing just the equation of impact force F in Eq.3. Of course, exceptional cases exist, such as eye, where F_c is very low, these are treated as a singular point, and therefore another evaluation is needed for such points. The danger-index α_0 calculated from Eq. 10 is 0.13. When the robot is set up at 1.0 [m] apart from human, *dt*, *F* and α are 0.59[s], 24.15[N] and 0.049, respectively. The improvement rate η is 3.01. The result revealed quantitatively that the danger was decreased almost to 30[%].

Similarly, it is possible to derive danger-indexes of several control strategies, such as approaching safety velocity and safety posture so on. The equations of these danger-indexes have been shown in references.

7. Proposal of Design Optimization and Practical Examples

This section proposes a design and control optimization using my risk evaluation method.

7.1 Formulating the Design Optimization Method

First, I calculate the cost performance of safety methods. When the cost of safety method i (1,2,---,n) is Δy_i and the increased improvement rate is $\Delta \eta_i$, then the improvement rate for cost $\Delta \phi_i$ is expressed as Eq. 11.

$$\phi = \frac{\Delta \eta_i}{\Delta y_i} \tag{11}$$

Improvement rate η_i of safety method *i* is expressed as Eq. 12, which is increased improvement rate (invested cost $y_i \times \phi_i$) plus 1 (initial). 1 (initial) means an improvement rate before improving.

$$\eta_i = 1 + y_i \phi_i \tag{12}$$

Practical examples of optimizing the cost distribution are maximizing safety under fixed cost and minimizing total cost under fixed safety. These examples use three safety methods: decreasing weight, modifying shape and protective surfacing. The improvement rate per unit cost of each method is derived by my risk evaluation method.

The safety method, which is decreasing weight by replacing the stainless steel of a robot arm (100 x 80 x 300 [mm], $\rho_{\text{sus}} = 7.87$ [g/cm^3]) by duralumin ($\rho_{\text{dur}} = 2.80$ [g/cm^3]) is as follows. Danger-index can be expressed as Eq. 7, and improvement rate is derived by Eq. 13,

$$\eta = \frac{\alpha}{\alpha_0} = \frac{\rho_{sus} Va}{F_c} \frac{F_c}{\rho_{dur} Va} = \frac{7.87}{2.80} = 2.81 \tag{13}$$

where V is volume of material, a is acceleration at a collision.

The costs will come to \$364, which consists of material expense of \$64 plus wages of \$300. The increase in the improvement rate is the value derived by Eq. 13 minus 1 (1 is value of the improvement rate before the improvement). As a result, the improvement rate per cost is expressed as Eq.14.

$$\phi_{weight} = \frac{2.81 - 1}{364} = 0.005 \tag{14}$$

By modifying the shape by planning off the four corners (*R5*), I obtain $\phi_{shape} = 0.0034$ ($\Delta\eta_{shape} = 0.67, \Delta y_{shape} = \$200$). A protective surfacing of soft material (thickness: 10[mm], E = 5.0[Mpa], 4 sides) gives $\phi_{shrface} = 0.0154$ ($\Delta\eta_{surface} = 2.16, \Delta y_{surface} = \$140$).

7.2 Maximizing Safety Under Fixed Cost

This section solves maximizing safety under fixed cost. The optimized cost distribution is obtained by satisfying total improvement rate $T_\eta \Rightarrow \max$ (Eq.15) and total cost Y=const (Eq. 16).

$$T_\eta = \left(1 + y_1{}^* \phi_1{}^*\right) \cdot \left(1 + y_2{}^* \phi_2{}^*\right) \cdots \left(1 + y_n{}^* \phi_n{}^*\right) : \max \tag{15}$$

$$y_1^* + y_2^* + \cdots + y_n^* = Y : const \tag{16}$$

If the total cost of improving one robot arm is $500, each cost can be obtained by substituting the improvement rate per unit cost shown in above section for Eq.5 and Y=$500 for Eq.16. The safety can be improved 9.76 times by distributing $500 among decreasing weight $227.05, modifying shape $132.95 and protective surfacing $140.00, specifically, replacing 62% iron with duralumin, chamfering 66% of corners and covering 100% of surface with rubber. As a result, it is possible to quantitatively determine the enforcement percentages of the safety method.

Another combination, such as decreasing weight $360.00 (98%) and protective surfacing $140.00 (100%) can increase safety 8.85 times, or decreasing weight $300.00 (83%) and modifying shape $140.00 (100%) can increase safety 3.91 times. These results clarify that the above combination is the best-optimized cost distribution.

As a result, this method enables us to quantitatively optimize safety design methods while considering cost and makes it easy to execute them efficiently.

7.3 A New Method of Calculate a Safe Approach Motion

This section proposes a new method for calculating a safe approach motion. The new method minimizes the total amount of danger index (Eq.17) considering the tolerant danger index.

$$\int \alpha(t) dt \to \min \quad 0 < t < T \tag{17}$$

This method chooses a safe path for which all danger indexes are below the tolerant danger index. The aim is to avoid the rise of the danger index.

I optimize the whole motion of a multi-link manipulator by using the new method, which is to minimize the total amount of danger index considering the tolerant danger index.

Fig. 3 shows the calculation result of safe motion when a human is stationed at 60[cm]. First, the tip joint moves, and then the whole part approach the human by stooping. The graph in Fig. 4 shows the danger index and the velocity of the optimized motion (Fig. 3). The maximum danger index is 0.251, and the tolerant danger index is 0.26. I can obtain a safe approaching motion in which the relative velocity is small and the posture is kept away from the human.

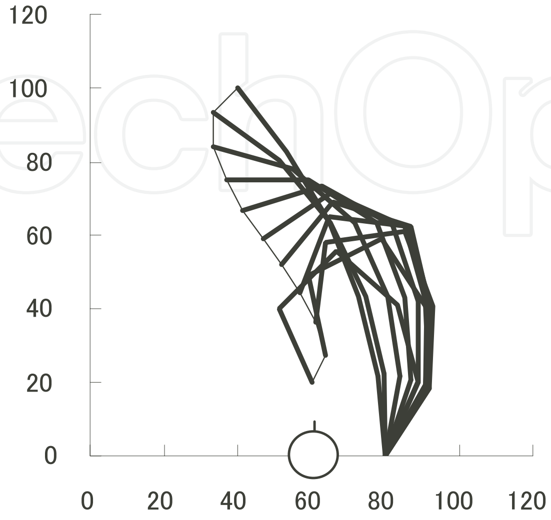


Fig. 3. Optimized approaching motion of multi-links manipulator; a human stays at 60[cm]. First, the tip joint moves, and then the whole part approach the human by stooping.

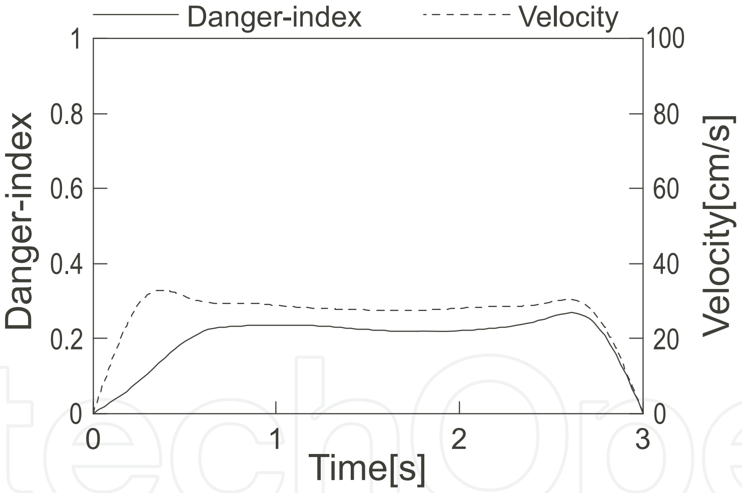
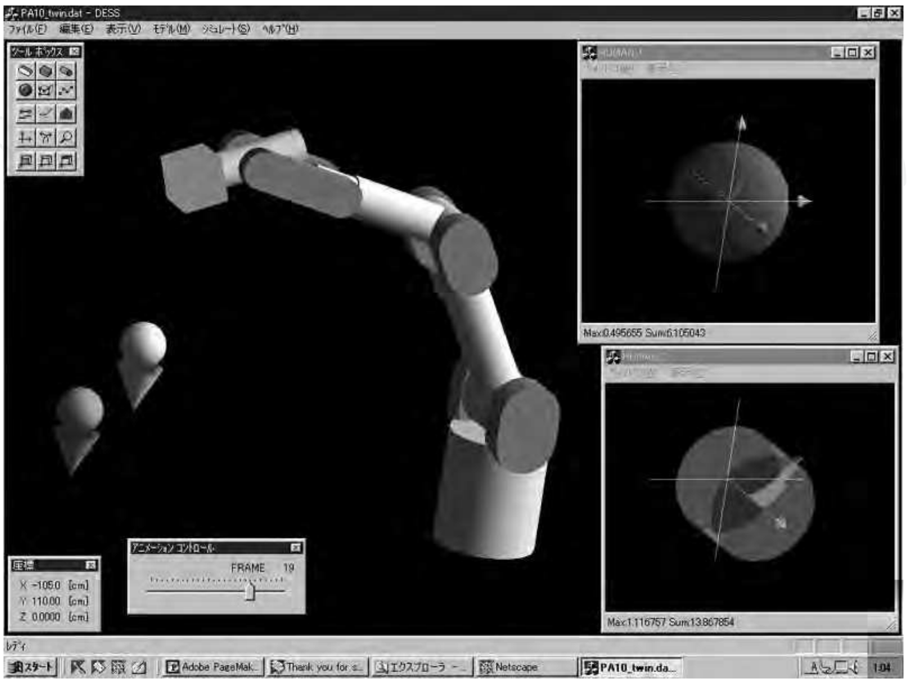


Fig. 4. Danger index and the velocity of the optimized motion shown in Figure 11.1. The maximum danger index is 0.251, the relative velocity is small.

Therefore, safety-optimized motion for any relationship between a human and a robot is achieved. To make good use of the safety-optimizing method, I ame now integrating the method into my special robot simulator for risk evaluation (Fig. 5). The robot simulator evaluates the designs and controls of various robots three-dimensionally, so this installation enables us not only to optimize practical robots but also to obtain various safety-optimized human-care motion.



X -105.0 [cm]
Y 110.00 [cm]
Z 0.0000 [cm]

Fig. 5. Special robot simulator for risk evaluation.

8. Conclusion

This chapter presented the study of a safety strategy for human-care robots. Case study of assessing several human-care robots was carried out according to ISO/TR 12100-1:1992 and ISO 14121:1999. The problems of assessing these robots were discussed, a safety strategy for human-care robots has been proposed. Determine limits of special factors, judgments by certification system, benefit of robots for user have been added to the strategy.

I undertook a new study of safety in the coexistent space of human and machine in order to realize a human-care robot for the nursing of the aged or disabled. First, the human injury from robot and machine was investigated thoroughly, and I found that it was important to treat safety strategies in the light of mechanical injury. I grouped them as safety design and control strategy according to the difference in their contents. In order to take every safety strategy into consideration, impact force and stress were chosen as evaluation measures for quantifying risk. I proposed risk evaluation method and defined danger-index, improvement rate, and total evaluation index. Discussions of some general safety strategies proved the viability of my risk evaluation method.

Safety-optimizing method for human-care robot design and control was studied theoretically. A method of optimizing the safety design was proposed, and practical examples of optimizing the cost distribution were solved. I proposed a method of optimizing robot control and optimized the whole motion of a multi-link manipulator by minimizing the total amount of danger index while considering the tolerant danger index.

I will contribute my risk evaluation method to the overall safety performance of human-care robots.

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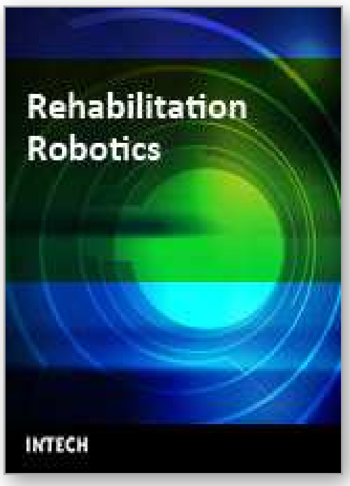

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