Proceedings of the 2002 IEEE
International Conference on Robotics & Automation
Washington, DC • May 2002

Safety-optimizing Method of Human-care Robot Design and Control

Makoto NOKATA Koji IKUTA Hideki ISHII

Department of Micro System Engineering, School of Engineering, Nagoya University

Furo-cho, Chikusa-ku, Nagoya-shi, Aichi, 464-8603 JAPAN

Abstract

We propose a safety-optimizing method for safety strategies of human-care robots using our danger evaluation method. First, various safety evaluation methods are discussed, and an optimizing method of safety design is proposed. Second, we make a comparative study of two general safety control methods, and then a method of optimizing robot control is proposed. 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 .

1 Introduction

Many types of human-care robots have been developed in the world. These robots work around humans, so safety is a top priority. But conventional safety strategies are applicable not to human-care robots but to industrial ones, and so repeated trials and errors must be used. Efficient methods are required for designing safe human-care robots.

We have already proposed a new type of safety evaluation method and defined several evaluation indexes such as a danger index, improvement rate, and total evaluation index [1] [2]. Discussions of general safety strategies have proven the viability of our safety evaluation method.

In this paper, we propose a general method of optimizing the safety design and control strategies for human-care robots. We solve a suitable combination of safety design methods and study optimization of safely controlling a multi-link manipulator.

2 Discussion of various safe evaluation methods

Technology for nursing a human by a human-care robot is inconsistent with safeguarding people against robots. For example, a high-power actuator is necessary for holding people, but it can produce a fatal impact force. If a safe distance is kept, the robot can't care for the person. Therefore it is important to evaluate safety strategies and harmonize care with safety by robot design and control.

International safety standards have defined safety as "freedom from unacceptable risk of harm, " and thus estimate only the risk of harm [3] [4]. This estimation method lacks a quantitative basis because it relies on the use of insufficiently provable data. It is hard to accurately describe differences among safety methods.

Other safety evaluation methods have been studied, such as calculating consumed kinetic energy by braking [5], decreased impact force by compliance control [6] and dynamics of robot motion. These methods can analyze only specific safety strategies in detail, and cannot investigate other ones nor safety strategies.

In this paper, we do not calculate the risk of safety separately but evaluate and optimize the methods comprehensively.

The concept of the danger evaluation method that we have already proposed [1] [2] is described below.

First, we select a suitable physical parameter as an evaluation measure, which can express the degree of danger factor. In the case of mechanical injury at a collision accident, the shock depends on impact force, and the scar depends on impact stress. In our study, we considered the impact force as an evaluation measure . Next, we define the critical impact force F_c as the minimal impact force that causes injury to a human upon collision with a body part. We define the danger index α as the producible impact force F of a robot against F_c in eq.(1).

$$\alpha = \frac{F}{F_c} \quad (\alpha \geq 0) \tag{1}$$

α is dimensionless quantity, so it is possible to express the safety of various design and control methods on the same scale.

The total danger index of the whole robot α_{all} is expressed by the multiplication shown in eq.(2), where n is the total number of safety methods and i is the number of safety strategies. So this equation enables us to totally evaluate plural safety methods.

$$\alpha_{all} = \prod_{i=1}^{n} \alpha_i \tag{2}$$

Defining the impact force and the danger index before improvement as F_0 and α_0 respectively, the improvement rate η can be calculated by the ratio of the two.

$$\eta = \frac{\alpha_0}{\alpha} = \frac{F_0}{F_c}\frac{F_c}{F} = \frac{F_0}{F} \qquad \eta_{all} = \prod_{i=1}^{n} \frac{\alpha_0}{\alpha_i} \tag{3}$$

In eq.(3) F_c is canceled, so we can simply compare the safety strategies before and after.

Therefore, our danger evaluation method enables us to estimate the danger of each safety method quantitatively.

3 Proposal of design optimization and practical examples

This section proposes a design optimization using our danger evaluation method, which used to be done empirically in general.

3.1 Formulating the optimization method

First, we calculate the cost performance of safety methods. When a safety method $i(1, 2, \ldots, n)$ costs Δy_i and increases the improvement rate $\Delta\eta_i$, then the improvement rate for cost ϕ_i is expressed as eq.(4).

$$\phi_i = \frac{\Delta\eta_i}{\Delta y_i} \tag{4}$$

Improvement rate η_i of safety method i is expressed as eq.(5), which is incresed improvement rate (invested cost y_i times ϕ_i) plus 1 (initial). 1 (initial) means a improvement rate before improving.

$$\eta_i = 1 + y_i\phi_i \tag{5}$$

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, which are decreasing weight, modifying shape and protective surfacing. The improvement rate per unit cost of each method is derived by our danger evaluation method.

The safety method of decreasing weight by replacing the stainless steel of a robot arm (100x80x300[mm], $\rho_{sus} = 7.87[g/cm^3]$) by duralumin ($\rho_{dur} = 2.80[g/cm^3]$) is as follows. Danger index can be expressed as eq.(6) [1], and improvement rate is derived by eq.(7),

$$\alpha = \frac{ma}{F_c} \tag{6}$$

$$\eta = \frac{\alpha_0}{\alpha} = \frac{\rho_{sus} V a}{F_c} \frac{F_c}{\rho_{dur} V a} = \frac{7.87}{2.80} = 2.81 \tag{7}$$

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

The cost is \$364, which consists of material expense of \$64 plus wages of \$300. The increase in improvement rate is the value giving by eq.(7) minus the initial value of one. As a result, the improvement rate per cost is expressed as eq.(8).

$$\phi_{weight} = \frac{2.81 - 1}{364} = 0.005 \tag{8}$$

By modifying the shape by planing off the four corners ($R5$), we 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 $\phi_{surface} = 0.0154(\Delta\eta_{surface} = 2.16, \Delta y_{surface} = \$140)$.

Table 1 shows the improvement rates per cost. Practical examples of optimizing the cost distribution can be solved by using these values.

3.2 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.(9))and total cost $Y = const$ (eq.(10).

$$T_\eta = (1 + y_1^*\phi_1) \cdot (1 + y_2^*\phi_2) \cdots (1 + y_n^*\phi_n) : max \tag{9}$$

$$y_1^* + y_2^* + \cdots + y_n^* = Y : const \tag{10}$$

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 Table 1 for eq.(9) and $Y = \$500$ for eq.(10). The result is shown in Table 2, 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.

Table 1 The ratio of increasing safety per the cost

design method	$\Delta\eta$	y[dollars]†	ϕ
weight (Fe → Duralumin)	1.81	364.00	0.005
shape (chamfering)	0.67	200.00	0.0034
surface (rubber)	2.16	140.00	0.0154

† a piece of arm (100x80x300)

Table 2 The optimized cost of each safety strategy (Maximizing safety under fixed cost)

design method	cost[dollars]	executing rate[%]
weight	227.05	62
shape	132.95	66
surface	140.00	100
	total improvement rate	**9.76**

Table 3 The optimized cost of each safety strategy (Minimizing total cost under fixed safety)

design method	cost[dollars]	executing rate[%]
weight	272.40	74
shape	179.00	89
surface	140.00	100
	total cost	**591.40[dollars]**

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 combination in Table 1 is the best optimized cost distribution.

3.3 Minimizing total cost under fixed safety

This section describes how to minimize the total cost under fixed safety. Minimum total cost can be obtained by $Y \Rightarrow min$ (eq.(11)), $T_\eta = const(eq.(12))$.

$$Y = \sum_{i=1}^{n} y_i^* : min \tag{11}$$

$$T_\eta = \prod_{i=1}^{n} (1 + y_i^*\phi_i) : const \tag{12}$$

Table 3 shows the calculation result, where the improvement rate is 12. Total cost \$591.40 can realize an improvement rate of 12 by \$272.40 for decreasing weight (executing rate: 74%), \$179.00 for modifying shape (89%) and \$140.00 for protective surfacing (100%). A combination of decreasing weight and protective surfacing costs \$700.00, whereas another combination of modifying shape and protective surfacing costs \$963.52

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

4 Development of algorithm for optimizing control

This chapter describes optimization and formulation for safety path planning of a multi-link manipulator.

4.1 Study of optimization method and formulation of safety path planning

Generally speaking, there are the following methods of optimizing robot motion using danger evaluation.

1. Minimizing the greatest danger index
2. Minimizing the total amount of danger index

Method 1 optimizes the whole robot motion so that the greatest danger index is minimized (eq.(13)), for example smoothing the whole danger indexes, dividing them equally and so on.

$$\alpha_{max}(t) \rightarrow min \quad 0 < t < T \tag{13}$$

Method 2 optimizes the whole robot motion so that the total amount of danger index is minimized (eq.(14)).

$$\int \alpha(t)dt \rightarrow min \quad 0 < t < T \tag{14}$$

Method 1 can keep the greatest danger index low, but may increase total danger. Method 2 is the exact opposite of method 1, and safer, providing for the most dangerous situation or keeping the whole danger uniform. This problem often divides researchers in opinion.

The authors have already studied an optimization method called "sequential search " , which calculates the danger index sequentially and determines only the next motion each time [7]. Fig.1 shows the concept of the method. We use the approach motion of a multi-link manipulator to describe the method. Danger-minimized tip movement $\triangle p$ toward goal point P_{goal} is calculated each time. Specifically, the area of $\triangle p$ is limited so that the tip reaches P_{goal} finally (fan-shaped area shown in Fig.1), $\triangle p_i$ below the target danger index is selected, and danger-minimized tip path $P(t)$ can be obtained by connecting all $\triangle p_i$.

$$\begin{gathered} P(t) = P_0 + \sum_{i=1}^{t} \triangle p_i \\ (P(0) = P_0, P(T) = P_{goal}, \\ \alpha(P(i), \triangle P_i) < \alpha_{max}) \end{gathered} \tag{15}$$

The obtained results are shown in Fig.2. The right figure shows the time-space danger chart, in which all danger indexes are plotted on time and space axes [2]. The circle indicates $\alpha^* = F^*/F_c = 1$. When the danger index crosses over the line, it means that the robot will always injure the human. The results suggest that a safety tip path has been obtained, for which danger indexes are below 1. But the path requires a big revision at the end of approaching, and so travel time is increased because the tip goes a long way round to reduce the danger indexes. This method calculates only the next step, so it is impossible to predict the whole motion.

This section studies a) minimizing the greatest danger index, and b) minimizing the total amount of danger index for optimizing overall motion.

We quantitatively analyze optimization of the approaching path. Danger indexes are calculated by assuming that a human does not move. Fig.3 shows the model used for analysis. The tip of the manipulator is regarded as a material point. The human is stationed at the origin of the coordinate axes. The position of the tip is (x,y), velocity of the tip is v, and the relative velocity and distance between the human and tip are v_h, l. Control parameters for optimization are v, l.

The authors have already derived equations of danger indexes [2]. But in order to analyze these two methods quantitatively, this section uses the approximate equation eq.(16), in which the danger index is proportional to relative velocity v_h and inversely proportional to distance l.

$$\alpha = \frac{F}{F_c} = \frac{mav_h dt/l}{Fc} = k\frac{v_h}{l} \quad (\alpha \geq 0) \tag{16}$$

Eq.(16) can be explained by using the geometry of Fig.3.

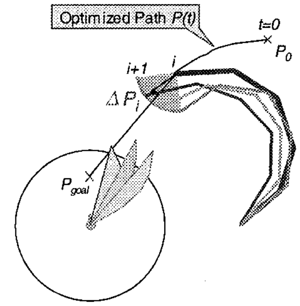

Fig.1 Sequential path calculation for approaching

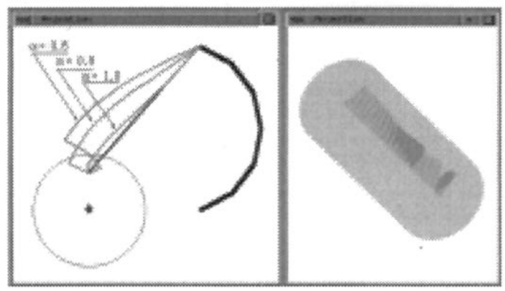

Fig.2 Safety approach with sequential path calculation

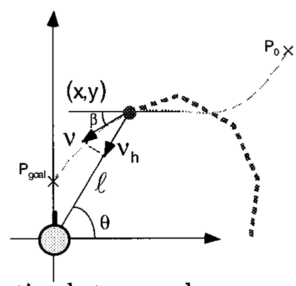

Fig.3 Location between a human and a moving body

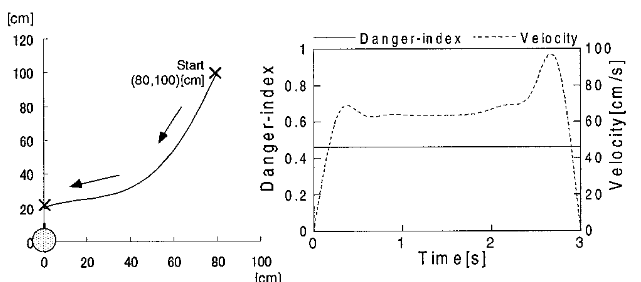

Fig.4 Approaching path under decreasing maximum danger index condition

$$\alpha = k\frac{v\cos(\theta - \beta)}{l} = k\frac{x + yy'}{x^2 + y^2} \tag{17}$$

We investigate these two optimization methods by use of eq.(17).

4.2 Minimizing the greatest danger index

This section examines the optimization method, "Minimizing the greatest danger index. " Overall danger indexes are averaged for suppressing instantaneous increase of danger.

First, danger index eq.(17) is defined as a constant.

$$\frac{x+yy'}{x^2+y^2} = A \quad : const \tag{18}$$

x^2+y^2 in eq.(18) is replaced with u, then both sides are differentiated by x, tha is $2x+2yy' = u'$. Eq.(18) is explained by use of the differentiated equation.

$$\frac{u'}{2u} = A \quad \rightarrow \frac{1}{2A}\frac{du}{u} = dx \tag{19}$$

Variables in eq.(19) are separated, then the equation of tip path can be obtained by integrating the both sides.

$$x^2+y^2 = e^{2A(x+C)} \tag{20}$$

Next we consider the example of optimizing the tip motion of a manipulator. The tip approaches 20[cm] in front of a human from the point (80,100)[cm], and the travel time is 3[s]. Eq.(20) calculates the tip path that can arrive at (0,20)[cm] and A is minimum.

The obtained path, danger indexes and velocity of tip are shown in Fig.4. The danger index when the tip approaches the goal directly is 1.11, but the obtained one is only 0.462. Thus, the danger is halved by optimizing the tip path. However, the tip velocity is increased just before the goal ($t = 2.7[s]$) in order to keep danger index constant.

4.3 Minimizing the total amount of danger index

This section calculates the tip path for which the total amount of danger index is minimum. The aim is to reduce overall danger. The solution is obtained by calculus of variations. For minimizing the total amount of danger index (eq.(21)), it is necessary to satisfy the Euler-Lagrange, eq.(22)

$$\int \alpha dt = k \int \frac{x+yy'}{x^2+y^2} dx \rightarrow min \tag{21}$$

$$\frac{\partial \alpha}{\partial y} - \frac{d}{dt}\left(\frac{\partial \alpha}{\partial y'}\right) = 0 \rightarrow \frac{ky'(x^2-y^2)}{(x^2+y^2)^2} = 0 \tag{22}$$

The equation of the tip path obtained from eq.(22) is as follows:

$$y = x, \quad y = -x, \quad \frac{dy}{dx} = 0 \tag{23}$$

A human is stationed at the origin of the coordinate axes, so eq.(23) is the most dangerous path because the tip approaches the human directly, namely it is the maximum solution. It seems that there is no minimum solution in eq.(23) because many non-danger solutions exist, which have no relative velocity between the human and tip and which do not reach the goal.

To derive a minimum solution, it is necessary to consider some boundary conditions and equations, but this makes it complicated and difficult to derive an equation of path.

The authors propose a new solution method as shown in Fig.5, which subdivides the working area, sets up passing points at each time and calculates the safety-optimized approach path. The curvatures of arcs are adjusted so as to leave a space between each point.

In order to derive the solution, we choose discrete dynamic programming because the danger index is related not with the course but with only the position and the vector of movement. We considered the total danger indexes as an objective functional, time interval for dividing path as time step for the calculation.

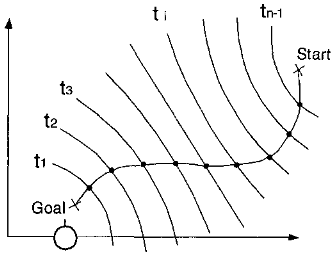

Fig.5 Subdividing motion area for minimizing the sum of danger index

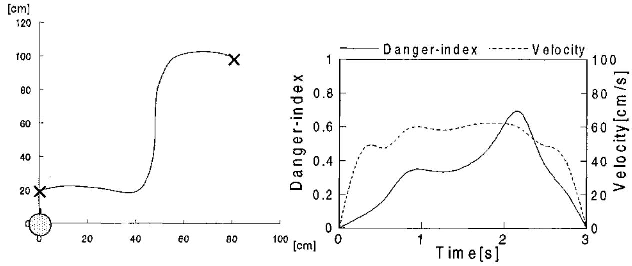

Fig.6 Approaching path optimized by minimizing the sum of danger index

The merits of this calculation are (1) the solution can be absolutely obtained, (2) the travel time and area can be easily changed, and (3), the equation for calculating danger index can be easily replaced.

For example, by using the above method, we calculate the optimum path when the tip comes close to (0,20)[cm] from (80,100)[cm]. The results are shown in Fig.6. The average danger index is 0.352, which is less than the result in Fig. 4, but the maximum is 0.690.

The characteristics of the two methods of optimizing path are as follows:

Method 1: Minimizing the greatest danger index

- Optimum path that minimizes the greatest danger index
- local maximum velocity

Method 2: Minimizing the total amount of danger index

- Optimum path that minimizes the total amount of danger index
- Local maximum danger index

5 A new method of calculate a safe approach motion

This chapter proposes a new method for calculating a safe approach motion with reference to the results of the above section. The new method minimizes the total amount of danger index (method 2) considering the allowable danger index. This method chooses a safe path for which all danger indexes are below the allowable danger index. The aim is to prevent the danger index from increasing.

Fig.7 shows a tip path calculated by the new method. The tip of the manipulator approaches from (80,100)[cm] to (0,20)[cm], the allowable danger index is 0.6, and the travel time is 3[s]. As a result, safe tip path, for which maximum danger index is 0.592, is obtained.

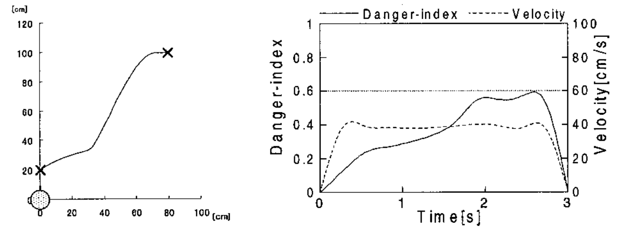

Fig.7 Optimized result of minimizing the sum of danger index considered allowable danger index

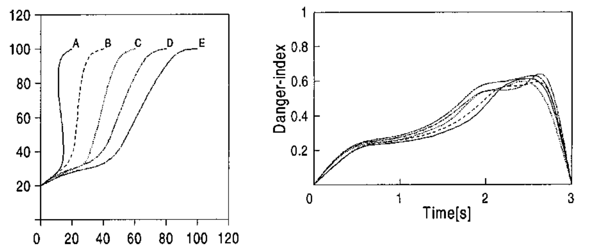

Fig.8 Optimized approaching path started from several points

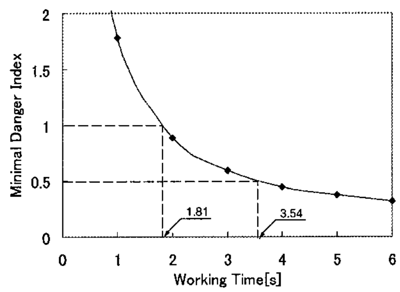

Fig.9 Relationship between travel time and minimal danger index calculated by optimum algorithm

This method enables us to derive the optimized tip path from any point to the same goal. For example, we calculated several tip paths from points A, B, C, D and E shown in Fig.8 to (0,20)[cm], for the same travel time of 3[s]. The calculation starts from the allowable danger index is 0.5, and the index value is increased until a solution is obtained. The result is shown in Fig.8. Each maximum danger index (allowable danger index) is A: 0.610(0.62), B: 0.576(0.60), C: 0.596(0.60), D: 0.592(0.60) and E: 0.621(0.63). As a result, we can obtain the optimized tip path from any point to goal and the allowable danger index.

This method can solve the relationship between travel time and minimum allowable danger index. The obtained relationship is shown in Fig.9. This graph shows that the path of allowable danger index of 1, which means the robot will always injure the human, requires 1.81[s] for work, so it is impossible to shorten the travel time. A path of allowable danger index 0.5 can cut the travel time to the limit 3.54[s].

Therefore, this method enables us to calculate not only safe motion but also a suitable travel time for the robot approaching close to the human.

6 Application to a multi-link manipulator

We optimize the whole motion of a multi-link manipulator by using the new method, that is, minimizing the total

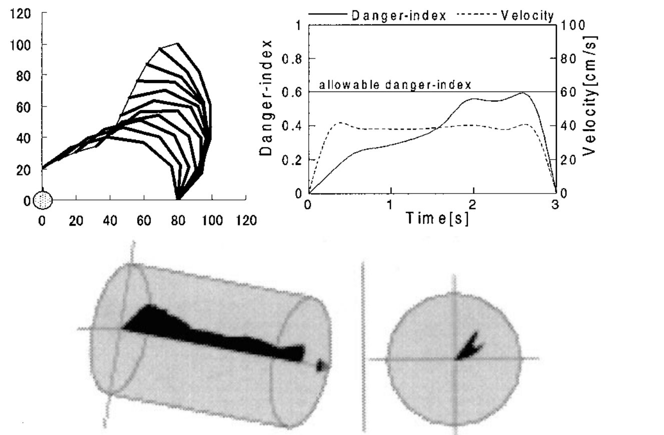

Fig.10 Optimized approaching motion of a multi-link manipulator, a human stays at (0,0)[cm]

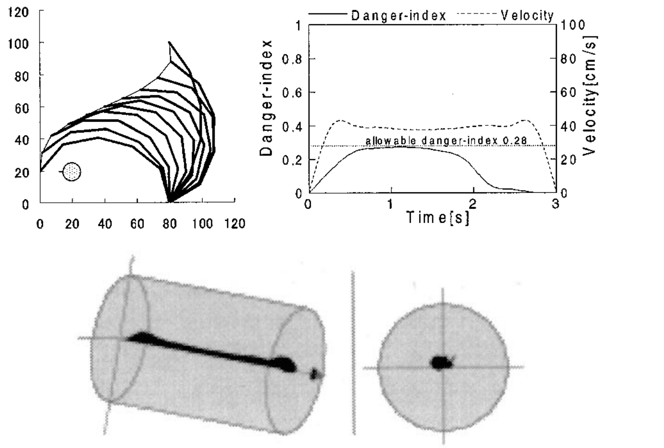

Fig.11 Optimized approaching motion of a multi-link manipulator, a human stays at (20,20)[cm]

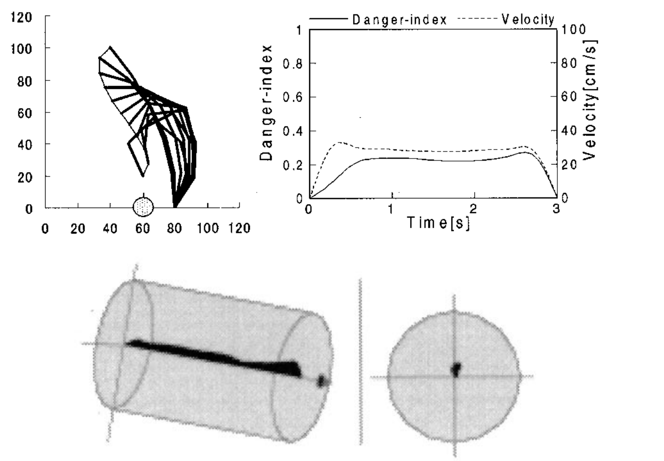

Fig.12 Optimized approaching motion of a multi-link manipulator, a human stays at (60,0)[cm]

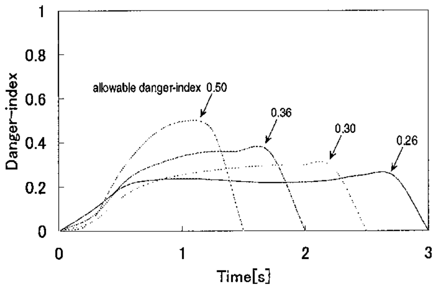

Fig.13 Relationship between travel time and danger index calculated by minimizing the sum of danger index considered allowable danger index

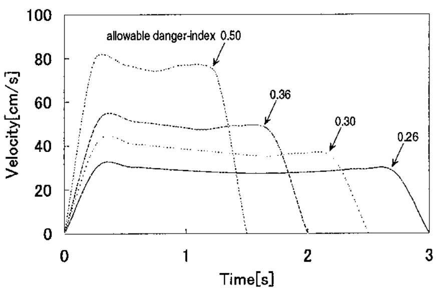

Fig.14 Relationship between travel time and approaching velocity of a multi-link manipulator

amount of danger index considering the allowable danger index. The tip approaches 20[cm] in front of the human from point (80,100)[cm], and the travel time is 3[s]. The danger of the approaching motion is evaluated by eq.(16), so we can obtain the optimized posture which is proportional to relative velocity and inversely proportional to distance. Each posture of a multi-link manipulator is given so that the danger index is minimum.

Fig.10 shows the obtained approaching motion and velocity of the tip when a human is stationed at (0,0)[cm]. The maximum danger index is 0.592, and the allowable danger index is 0.6. The approaching postures are as follows: first, the manipulator turns on the nearest joint from the base, and then keeps a distance between the human and itself by changing the turning joint as it approaches the human. For reference, Fig.10 shows the time-space danger chart that indicates the danger of the manipulator. The maximum danger index is 0.581, and all danger indexes are below the allowable one, so a safe obtain safe-optimized approaching motion is achieved.

Next, we calculate the safe motion when a human is stationed at (20,20)[cm]. The result is shown in Fig.11. The maximum danger index is 0.273, and the allowable danger index is 0.28. Comparing it with Fig.10, it achieves safety tip path and posture that avoid the human.

Fig.12 shows the calculation result of safe motion when a human is stationed at (60,0)[cm]. First, the tip joint moves, and then the whole part approaches the human by stooping. The maximum danger index is 0.251, and the allowable danger index is 0.26. We can obtain a safe approaching motion in which the relative velocity is small and the posture is kept away from the human.

Finally, we examine calculation examples for reducing the travel time. Allowable danger indexes of a motion in Fig.12 are changed from 0.26 to 0.50. The relationship between travel time and danger index is shown in Fig.13, and the relationship between travel time and danger index is shown in Fig.14. If the travel time is half (1.5[s]) , the tip velocity is speeded up, and the approaching motion can done at the allowable danger index 0.5. High-speed, high-safety motion can thus be realized.

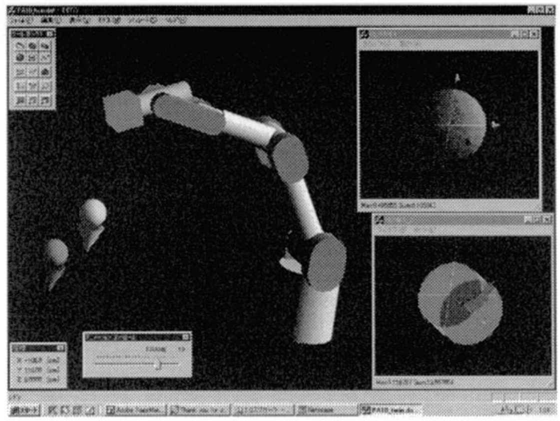

Fig.15 Special robot simulator for danger evaluation

Therefore, safety-optimized motion for any relationship between a human and a robot is achieved.

To make good use of the safety-optimizing method, we are now installing of it in our special robot simulator for danger evaluation (Fig.15) [2]. 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.

7 Conclusion

In this paper, 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. We made a comparative study of two general safety control methods, minimizing the greatest danger index and minimizing the total amount of danger index. We then 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 allowable danger index.

This method allows us to assess the contribution of each safety strategy to the overall safety performance of human-care robots.

References

[1] K.Ikuta et al : "General Evaluation Method of Safety for Human-Care Robots, " Proc. of ICRA'99 , pp.2065-2072, 1999.

[2] K.Ikuta, M.Nokata and H.Ishii: "General Danger-Evaluation Method of Human-Care Robot Control and Development of Special Simulator, " Proc. of ICRA'01 , pp.3181-3188, 2001.

[3] "Guidelines for the inclusion of safety aspects in standards, " ISO/IEC GUIDE 51, 1990.

[4] prEN1050.

[5] N.Sugimoto, H.Muratsubaki, "Safety Condition and Control for Cooperative work manipulator -Ensuring of Safety velocity by Inching-, " Proc. of 13th Annual Conference of the Robotics Society of Japan, pp.727-728, 1995 (in Japanese).

[6] K.Yokoi, "Control Methods for Human Friendly Robots, " Proc. of 74th Annual Conference of the Japan Society of Mechanical Engineers,pp.224-225, 1997.

[7] M.Nokata, K.Ikuta and H.Ishii, "Study of Safety Strategy in the Coexistent Space of Human and Robot No.10 Development of optimizing algorithm for safety control of human-care robot, " Proc. of 18th Annual Conference of the Robotics Society of Japan, pp.283-284, 2000 (in Japanese).