

Potential Runaway Motion Volume in Task Space for Estimating The Probability of Occurrence of A Human-Robot Collision

Yoji Yamada¹ Shunya Takeda² Tomoya Nishiyama³ Shogo Okamoto¹

Abstract—The paper deals with a critical safety issue on a human-robot coexistence system which is highly expected to be introduced in such fields of manufacturing as cell production lines. We discuss a method for quantitatively estimating the probability of occurrence of a collision between a human and a fixed-type robot when it falls into a runaway state. We apply the concept of dynamic manipulability ellipsoid to compute the potential runaway space of a robot. Then, we conduct a psychological experiment in which each subject avoids abrupt approaching motion of the end effector of the robot and determine the collision simulation parameters. Further, we show an estimation procedure of protective separation distance taking into account the avoidance action on the participants' side. The study contributes to obtaining the protective separation distance required for a robot to be separated from a worker. We finally confirm that the experimental results validate the separation distance to converge.

I. INTRODUCTION

In the field of manufacturing, the robot safety accomplished development from an isolation technology symbolized by safety fences to collaborative operation technology allowing the coexistence of industrial robots with workers following a revision of ISO 10218-1 [1]. From a global regulation trend, on the other hand, it has come to be possible these days to determine the operating conditions of a robot in the collaborative operation mode within the range of an acceptable risk based upon the result of risk assessment. By the systematic review of the standard harmonized in 2010 with the machine directive, a manufacturer is allowed to reasonably determine the speed of the robot in the collaborative operation mode under a certain level of technical requirements for a safety-related system based on a result of the risk assessment.

The aim of the collaborative operation of a robot which can coexist with a worker is to narrow the distance between both, and thereby further saving of the work space as well as the work time to enhance the productivity while ensuring his/her safety. Based upon the change of regulation trend, researchers have discussed the optimality of collision avoidance between a human worker and a robot

in the collaborative environment of manufacturing under the following regulation: It is known that there exist international safety standards in which the and safety requirements quantitatively state the minimum protective separation distance (PSD, hereafter) [2] and further the safety distance taking the relative motion vectors of both a robot and a human approaching to it as shown in the appendix of [3]. The speed and separation monitoring formula specified in the above standard is intensively discussed at a practical research level in [4]. Further, applications are already reported both in practice [5] and in simulation [6] where the speed and separation monitoring techniques are assumed to be installed. Among researchers, the primary interest of enhancing the productivity while securing human safety is to discuss pre-collision avoidance control or motion planning with constraints in the research frame work of safety human robot interaction which was categorized by [7]. It is seen that some researchers try combining the safety preservation problem with collision avoidance ones Their technical interests have been shifted, given a start and a terminal points in the partially dynamical environments with obstacles, from creating a complete roadmap to dynamically avoiding obstacles in real time: The former includes the introduction of a dangerzone [8] for a generic obstacle avoidance objective, which is extended to the safety problem with a proposal of Danger Field [9] for solving the collision avoidance problem faster. On the other hand, the latter is started by a proposal of introducing potential fields [10] which is historically categorized as a problem of reactive motion planning. A magnetic action of electric current serves as an obstacle field definition called a circulatory field [12] which regulates a point mass robot motion. Later, the circuitry field is applied to the collision avoidance control of a manipulator[13]. The elastic strips [11] are constructed by candidate paths in which local potential field are applied again modifies the trajectory. Modelling of obstacles is one of the main technical clues to real-time collision avoidance control of a robot, which directly affects to narrow the distance between the robot and surrounding obstacles. Representation of obstacles using circulatory fields is considered to be most effective from the viewpoint of modelling the obstacles because the method can geometrically reflect their profiles with high fidelity. Human psychological aspect is also promising to reduce ineffectual space between a human and a robot. An approach to making use of psychological reactions for path planning is demonstrated in [14] which discusses how to assess the risk level to improve the safety of the human robot interaction and proposes the control algorithm for

*The work was supported in part by KAKENHI Grant Number 2124604, MEXT, Japan.

¹Yoji Yamada and ³Shogo Okamoto are with Department of Mechanical Systems Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya City 464-8603, Japan yoji.yamada@mae.nagoya-u.ac.jp, okamoto-shogo@mech.nagoya-u.ac.jp

²Shunya Takeda is with Bridgestone Co., Ltd., 1-1, Kyobashi 3-chome, Chuo-ku, Tokyo 104-8340, Japan

³Tomoya Nishiyama is with Mitsubishi Electric Co., Ltd., 1, Hishimachi, Inazawa CVity, Aichi Prefecture 492-8682, Japan

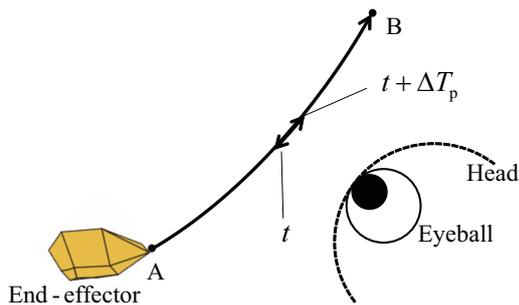


Fig. 1. How close a human can approach to a manipulator operated along a pretaught trajectory A-B?

minimizing the estimated risk. A simulation technique called extrapolation simulation is developed in [15] which shows that the avoidable motion range varies depending on a robot's approach speed and its initial distance from a human subject based on a psychological experiment in which the end effector of a robot suddenly approaches to human eyes and studied human avoidance motion characteristics against the approach [16]. However, there has been no report on how much of volume on the manipulator side we shall probabilistically estimate in 3D space at an instant. The PSD criteria can apply only to the situations where a robot is normally run and start shutting off only by decreasing the speed from the break-down point. In other words, any fault originating eg. in a sensor fault which may cause the erratic sensor output [17] at the joint control level is not taken into account even though it possibly leads to an instant runaway state. This aspect is also indispensable to consider from the view point of probabilistically worst case scenario. To stress the difference of the effect in the event of a fault specifically in one of the joint torque controller parts, we discuss the typical case where an industrial manipulator is operated along a pre-taught trajectory from A to B as shown in **Fig. 1**. The problem is how close a human can approach to the manipulator. In the study, we develop a method for securing a marginal volume called Potential RunAway Motion volume in task space (PRAM-t) by which a human body part in the vicinity is distant enough from the end tip of the manipulator under such technical requirements for collaborative operation of the manipulator that a single fault detection capability be equipped with the manipulator [1]. We conduct a psychological experiment in which each participant avoids abrupt approaching motion of the end effector of the robot supposing the robot goes to a runaway state to determine the collision simulation parameters. Further, we show an estimation procedure of protective separation distance taking into account the avoidance action on the participants' side.

II. POTENTIAL RUNAWAY MOTION VOLUME IN TASK SPACE

A. Derivation of probability of occurrence of a collision in the manipulator's fault mode

The trajectory in Fig.1 is supposed to be taught to a robot in advance for normal operation and the trajectory A-B is repeated in an operation cycle of T_p . A risk assessment reveals first of all a potential consequence of a collision between the robot end effector and the human head which, including eyes, is considered to be one of the most hazardous parts on human body and more likely to cause irreversible injury. From a viewpoint of risk assessment to quantify, the next demand should be to compute the probability of occurrence of such a hazardous collision. There has never been any study conducted on the derivation of this probability.

First, the probability that the human enters the workspace and by mistake coming close in the vicinity of the robot's predetermined trajectory can be estimated statistically under his/her routine task where the human enters the workspace periodically. Let this probability be defined as $P_H(t)$. Human error analysis is well established to compute $P_H(t)$ eg. [5].

Then, the probability that the robot fails and runs off the trajectory in the interval $[\tilde{t}, \tilde{t} + T_p)$ of its lifetime \tilde{t} is computed [18] by introducing the failure rate of the safety-related robot control system as $\lambda(\tilde{t})T_p$ since $(\lambda(\tilde{t}) \ll 1)$ and therewith

$$\frac{F(\tilde{t} + T_p) - F(\tilde{t})}{R(\tilde{t})} = 1 - e^{-\lambda(\tilde{t})T_p} \quad (1)$$

$$\approx \lambda(\tilde{t})T_p \quad (2)$$

where $R(\tilde{t})$ and $F(\tilde{t})$ are the reliability and the unreliability at time \tilde{t} respectively.

$$R(\tilde{t}) = e^{-\lambda(\tilde{t})\tilde{t}}$$

$$F(\tilde{t}) = 1 - R(\tilde{t})$$

The failure rate is time-dependent in general, but is considered to be constant in the normal life, which leads formula (2) to λT_p .

Further at this moment, the probability that the system goes into a fault mode and the end-effector tip runs into the human head is defined as $P_{C|R}(t)$. Such an event that a human enters the operational space of the robot, and the event that the robot comes into a fault and runs away to collide with the human head are statistically independent of each other. Therefore, the probability of occurrence of a collision between the robot end-effector tip and the human head under the supposed situation where he/she comes in the vicinity of the robot trajectory and the robot runs off it is computed by

$$P_C(t) = P_H(t) \times \lambda \cdot \Delta T_p \times P_{C|R}(t) \quad (3)$$

Fig.1 also shows the time interval ΔT_p for which the probability of the robot going into a fault mode is computed. We will revisit this formula (3) later in Section IV for

discussing the null probability of occurrence of the collision event.

B. Runaway motion due to a single fault

When a robot goes to a fault state at time t , it is considered that the robot end-effector tip traces along other path different from the original one which has been taken in the normal operation. We can assume that an industrial robot for the manufacturing environment is required to have a single fault tolerance i.e. a single fault shall be detected at or before the next demand upon the safety function of making a protective stop during the collaborative operation, which is a safety requirement stated in ISO 10218-1 [1]. The self diagnosis function of the safety-related control system can command a protective stop on the robot by detecting any foreseeable single fault in the system to lead it to the safe stop state after a certain period of time, i.e. reaction time. Once the robot comes in a runaway state, it is uncertain how much of angular speed the motor at each joint can exert and therefore, the transient positioning of the robot end-effector tip before the robot is led to a stop state becomes also uncertain and is considered to construct an uncertain volume after the robot end-effector tip goes out of the trajectory predetermined for the normal operation of the robot. We derive the formula representing the volume PRAM-t. **Fig. 2** illustrates an ellipsoid volume PRAM-t to be estimated along the trajectory.

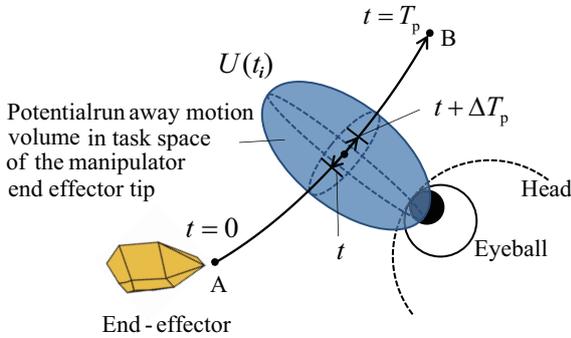


Fig. 2. Illustration of an ellipsoid volume PRAM-t to be estimated along the trajectory

C. Parametric definitions of robot motion characteristics

Fig. 4 shows the speed pattern of the robot end-effector tip at the time when a protective stop is commanded to observe the maximum change of the speed deceleration.¹

First, the reaction time which is defined as $t_R^{(r)}$ in **Fig. 4** can be estimated through either technical specification or practical experimentation. A safety PLC is assumed to be installed as the controller of the robot, and $t_R^{(r)}$ is assumed to be 70 ms in the study. Taking the rated speed of HIRO into consideration, the maximum speed $v_{Rmax}^{(b)}$ is set to be

¹We set the robot to output the same highest possible speed percentage for each pattern. While the initial acceleration was similar to each other, the maximum speed inevitably decreased as the travel distance decreased.

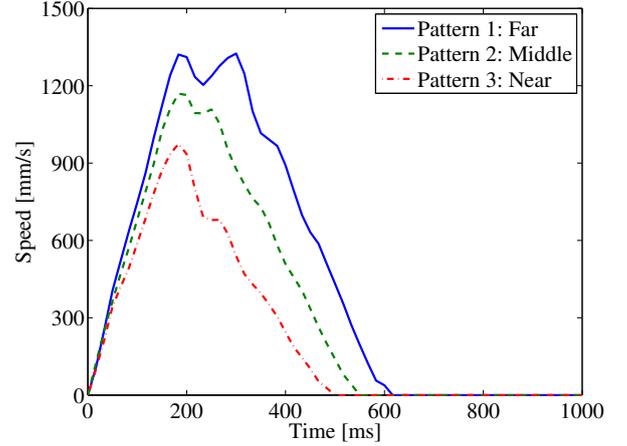


Fig. 3. Speed patterns of the robot end effector during the experiment

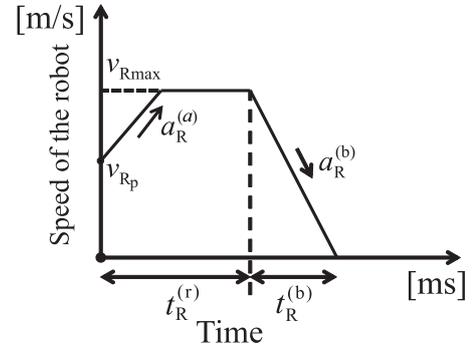


Fig. 4. Definitions of the robot motion characteristics for computing PRAM-t

2000 mm/s. The absolute value of the maximum acceleration (deceleration) represented by either $a_R^{(a)}$ or $a_R^{(b)}$ defined in **Fig. 4** is set to be 9000 mm/s².

Each of the arm links is modeled by a cylinder with 60 mm diameter, and the mass is approximately 5.0 kg. Substituting the above parameter values into formula (9) in subsection II-D and the formula (13) below which, with the parametric definitions in **Fig. 3**, allows us to compute the runaway distance d_p in the direction toward the human head.

$$d_p = t_R^{(r)} \times v_{Rmax} - \frac{(v_{Rmax} - v_{Rp})^2}{2a_R^{(a)}} + \frac{v_{Rmax}^2}{a_R^{(b)}} \quad (4)$$

where v_{Rp} represents the speed at $t_R^{(r)}$. On the other hand, the human head is modeled by a sphere with 200 millimeter diameter as shown in **Fig. 5**. Note that the human eyeball is also defined in the figure: Even though the probability of occurrence of collision with a human eye is small, the harm caused by the collision is irreversible i.e. the severity is comparatively so high that we always take a stab of the eye into consideration.

D. Computation of potential runaway motion volume in task space

The first-order kinematic relationship between the joint velocity vector $q \equiv (q_1, \dots, q_N)^T \in \mathbb{R}^N$ and end effector

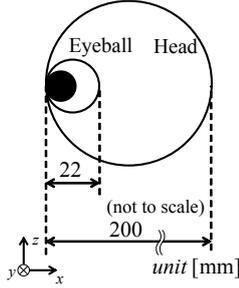


Fig. 5. Position relationship between an eyeball included in the head

velocity vector $v \in \mathbb{R}^3$ is expressed by

$$v(q) = J(q)\dot{q} \quad (5)$$

where J is the Jacobian matrix.

The dynamic manipulability ellipsoid is a set of acceleration vector which is realized by the set of joint torque vector of a robot. Originally, the space volume satisfies $\|\tilde{\tau}\| \leq 1$. However, in the context of our proposal,

$$\tilde{\tau}(q) = (\tau_1(q), \dots, \tau_N(q))^T \quad (6)$$

where the i -th joint torque component, $\tilde{\tau}_i$, is normalized by the rated value of the actuator installed at the corresponding joint.

$$\tilde{\tau}_i(q) = \frac{\tau_i(q)}{\tau_{i\max}} \quad (7)$$

Let the inertia matrix of the robot be $M(q) \in \mathbb{R}^{N \times N}$, we can compute the acceleration of the robot end-effector.

$$\dot{v}(q) = J(q)\tilde{M}^{-1}(q)\tilde{\tau}(q) \quad (8)$$

where

$$\tilde{M}(q) = TM(q) \quad (9)$$

$$T = \text{diag}\left(\frac{1}{\tilde{\tau}_{1\max}}, \dots, \frac{1}{\tilde{\tau}_{N\max}}\right) \quad (10)$$

By use of the above acceleration $\dot{v}(q)$, we can compute PRAM-t which will be shown later in section IV.

Furthermore, Nishiyama et al. monitored avoidance motion in the experimental situation where a worker erroneously intruded the work space of the robot at the wrong time, and again, the robot end-effector tip approached the worker's eyes. They reported that avoidance reaction time also changed depending on the approach speed of the end effector when the approaching robot was provided with different acceleration patterns.

III. PSYCHOLOGICAL EXPERIMENTS PRACTICALLY DETERMINING THE PARAMETERS FOR COLLISION SIMULATION

We conducted a psychological experiment which was approved by the ethical committee in Nagoya University. As is shown later, the experiment was conducted under a

considerably critical condition in terms of the closeness of the range between each of the participants and the robot end-effector tip.

When the participant sits slouchingly, the initial distance between the participant's eyes and the robot's end-effector tip is shorter. Hence, the results of the previous psychological experiments, which was reported in [16], suggest that the harm-avoidance action characteristics are contingent on the initial distance between the human's eyes and the end-effector tip. To investigate this dependence, psychological experiment was conducted with three different initial positions of the end-effector. The experimental setup and conditions are similar to those in the psychological experiment.

1) *Participants*: The nine participants in this experiment were five males and four females aged ranging from 18 to 28. Part of them participated also in the previous psychological experiment. Each of the participant was asked to perform a task of inserting bearings and retainers using a pair of tweezers in a container to assemble cross roller bearings. The robot end effectors made of urethane form were mounted on the two arms of the humanoid at the end effector, which were supposed to be caught by the peripheral visual field of the participant.

2) *Experimental Setup*: Each participant was exposed to the working area of the robot and performed task of psychological experiment.

3) *Experimental Conditions*: In this experiment, statistically random foreperiods were determined by taking the sum of 10 s and an exponentially distributed random value with a mean of 15 s. Foreperiods longer than 60 s were excluded.

Fig. 6 shows a schematic diagram of the locations and distances for this experiment. The bearing rings were located at the position indicated by the bold cross. Three patterns were chosen for the initial positions of the end effector. The initial distance between the participant's eyes and an end-effector tip was approximately 470, 370, and 270 mm for patterns 1, 2, and 3, respectively. Each participant was asked to confirm that the end-effector tips were in his or her peripheral view when the tips were located at a viewing angle of approximately 30° for all patterns with the task position in the center of the visual field. In a trial, the end-effector tip arrived at a point approximately 50 mm forward of the participant's initial eye position at the end of the robot motion.

4) *Experimental Procedure*: Each participant performed 60 trials, and the end-effector speed pattern and the approaching end-effector, either left or right, were both chosen at random for each trial. HIRO, which is a product made in Co., Ltd. Kawada Industries, was used as the robot in the experiment. This is an upper-body humanoid robot each of the right and left arms having five joints ($N = 5$).

IV. ESTIMATION OF PROTECTIVE SEPARATION DISTANCE

Fig. 7 shows a sample of PRAM-t and a time change of the human head's movement induced as an avoidance action. The figure views the movements of both the space and the

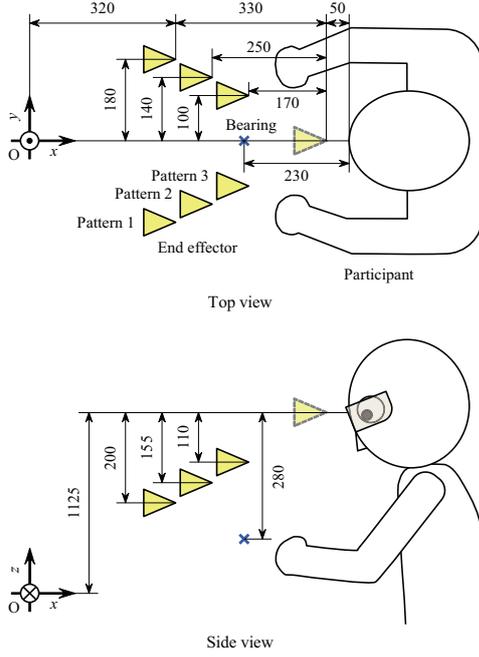


Fig. 6. Schematic diagram of the interactive human-robot locations during the psychological experiment (unit: mm).

TABLE I
RESULTS OF THE SEPARATION DISTANCES

	Participant A [mm]	Participant B [mm]	Participant C [mm]
Average(Right)	558.9	553.3	568.9
Average(Left)	545.5	538.5	551.6
Average(Total)	551.8	546.4	558.8
Maximum(Total)	580	586	597

human head in the O - xy coordinate plane defined in Fig. 6. They capture shortly before and after the PRAM-t and the human head collides with each other, when $P_{C|R}(t)$ turns to be $P_{C|R}(t) \neq 0$. We can compute the collision probability $P_{C|R}(t)$ expressed by the following formula.

$$P_{C|R}(t) = \frac{W_k(t)}{U(t)} \quad (11)$$

where $W_h(t)$ is the volume of a part of the human head that overlaps with that of the PRAM-t on the robot side which is represented by $U(t)$. $U(t)$ is computed from the ellipsoid of PRAM-t derived from the formula (12) using singular value decomposition.

$$J(q)\tilde{M}^{-1}(q) = U_d \Sigma_d V_d^T \quad (12)$$

and the ellipsoid is characterized by the lengths of σ_{d1} , σ_{d2} , and σ_{d3} in the directions of the principal axes u_{d1} , u_{d2} , and u_{d3} .

The PRAM-t gradually approaches the human head as the robot travels, and the PRAM-t of the robot and the human head become overlapped with each other at $t = 300$, when $P_{C|R}(t) \neq 0$.

To determine the minimal protective separation distance Δ_{pq} defined in formula (14), a small quantity of Δ is shifted

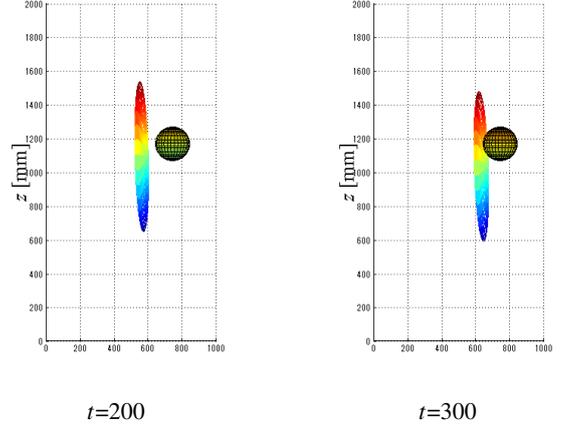


Fig. 7. PRAM-t of the robot and a human head

in x direction to check whether $P_{C|R}(t) \neq 0$. It is assumed that the variation of human avoidance reaction time against a manipulator's attack is small unless the change of the distance between them is too large.

This process is algorithmically repeated until $W_h(t) = 0$. The overall process is shown by the flowchart in Fig. 8. The result of Δ_{pq} is added to the initial distance of 220mm in the x -axis direction.

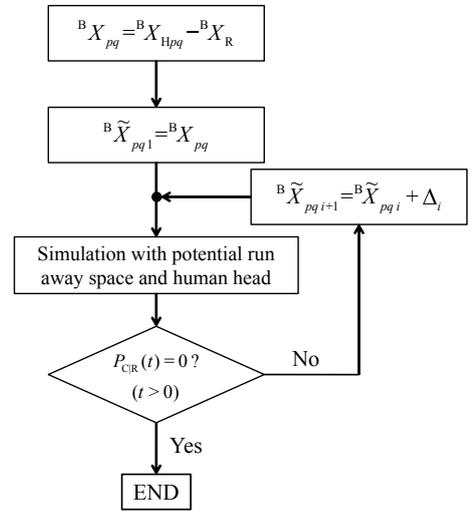


Fig. 8. Calculation process for obtaining separation distance

$${}^B X_{pq} \equiv {}^B X_{Hpq} - {}^B X_R \quad (13)$$

$${}^B \tilde{X}_{pq} = {}^B X_{pq} + \Delta_{pq} + X_S \quad (14)$$

where X_S is a safety factor to be taken into account if necessary. We show in Table I the resultant separation distance computed by (13) and (14).

V. DISCUSSIONS

As was introduced in section I, it was statistically shown in [16] the reaction time on the participant side depends on the

initial distance between the robot end-effector and the human eyes. If the resultant Δ_{pq} obtained by following the process described in the previous section IV becomes so large that the avoidance action of the participants are different in terms of the distance, the initial separation distance may need to be changed: While we conducted experiments at the initial distance of either 220mm, 300mm, or 380mm, we focus on the closest positional relationship between the robot and the participant in the paper.

Accepting that the number of the participants is small, it is observed that the results do not provide a large variation in ${}^B X_{pq}$ i.e. the data are not considered to be dependent on the initial distance from the Table I. We can also observe that the variation in the data obtained for the three participants is considerably small.

As was described in Table I, an avoidance action of the participant was observed in the transient states before and after the collision. The amount of his/her moving backward, without the simulated Δ_{pq} , was small enough to be counted as several centimeter at most. This means that it is indispensable to allow any avoidance action taken by a participant during such a psychological experiment from an ethical view point, but we can say that the separation distance obtained through the experiment was considerably optimized that we do not count the avoidance actions as a part of psychological effect in expectation of making the separation distance further shorter.

VI. CONCLUSIONS

In the study, we built a method for estimating the probability of occurrence of a collision between a human and a fixed-type manipulator when it falls into a fault to generate a runaway motion. We applied the concept of dynamic manipulability ellipsoid to compute the potential runaway motion volume of a robot in task space under the assumption that the safety-related control system is capable of detecting a single fault to command a protective stop. Then, we computed the minimum separation distance in such a manner as the probability of occurrence of a collision between a robot and a human goes to null who is in the vicinity of the robot's pre-taught trajectory even taking into account his/her avoidance actions. For the three participants, the minimum separation distance under the robot operation conditions of 9000 mm/s^2 was obtained approximately as 550 mm. By use of the mathematical expression of dynamic manipulability, the study specifies the amount of a runaway motion volume in the worst case which was not clearly quantified in the conventional studies even though the same regulatory statement " v_r is the directed speed in the direction of an operator " is defined in the formula of the protective separation distance.

It is necessary to collect more statistically abundant data of experiments verifying how slow the robot speed in the runaway state should be so that human reflective avoidance motion surely contributes to narrowing the protective separation distance.

ACKNOWLEDGMENT

This work was supported in part by MEXT KAKENHI Grant Number 21246041.

REFERENCES

- [1] ISO 10218-1, Robots for individual requirements – Safety requirements, 2008.
- [2] ISO/TS 15066, Robots and robotic devices – Collaborative robots, 2016.
- [3] ISO 13482, Robots and robotic devices – Safety requirements for personal care robots, 2014.
- [4] J. A. Marvel, R. Norcross, Implementing speed and separation monitoring in collaborative robot workcells, *Robotics and Computer Integrated Manufacturing*, Vol.44, pp.144–155, 2017.
- [5] A. R. Sanderud, M. Niituma und T. Thomessen, A Likelihood Analysis for a Risk Analysis for Safe Human Robot Collaboration, IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA), Luxembourg, pp.1–6, 2015.
- [6] G. Belingardi, S. Heydaryan, P. Chiabert, Application of speed and separation monitoring method in humanrobot collaboration: industrial case study, *Proc. of XVII International Scientific Conference on Industrial Systems*, Novi Sad, pp. 96–101, 2017.
- [7] T. F. P. A. Lasota, A Survey of Methods for Safe Human-Robot Interaction, *Foundations and Trends in Robotics*, Bd. 5, Nr. 4, pp. 261–349, 2014.
- [8] L. E. Kavradi, M. N. Kolountzakis, J. C. Latombe, Probabilistic roadmaps for path planning in high-dimensional configuration spaces, *IEEE Trans. on Robotics and Automation*, Vol.14, No.1, pp.166–171, 1998.
- [9] B. Lacevic, P. Rocco, Kinetostatic Danger Field - a Novel Safety Assessment for Human-Robot Interaction, *Proc. of 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Taipei, pp.2169–2174, 2010.
- [10] O. Khatib, Real-time obstacle avoidance for manipulators and mobile robots, *Proc. of 1985 IEEE International Conference on Robotics and Automation*, St. Louis, vol. 2, pp. 500–505, 1985.
- [11] O. Brock, O. Khatib, Elastic Strips: A Framework for Motion Generation in Human Environments, *The International Journal of Robotics Research*, Vol. 21, No. 12, pp. 1031–1052, 2002.
- [12] L. Singh, H. Stephanou, and J. Wen, Real-time robot motion control with circulatory fields, *IEEE International Conference on Robotics and Automation*, Minneapolis, Vol.4, pp. 2737–2742, 1996.
- [13] S. Haddadin, H. Urbanek, S. Parusel, D. Burschka, A. Albu-Schffer, G. Hirzinger, Dynamic Motion Planning for Robots in Partially Unknown Environments. *Proc. of 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Taipei, pp. 3109–3116 2010.
- [14] D. Kulic, E. Croft, Pre-collision safety strategies for human–robot interaction, *Autonomous Robots*, Vol. 22, No. 2, 149–164, 2007.
- [15] K. SUNADA, Y. YAMADA, T. HATTORI, S. OKAMOTO and S. HARA, Extrapolation Simulation for Estimating Human Avoidability in Human-Robot Coexistence Systems, *Proc. of IEEE International Symposium on Robot and Human Interactive Communication*, Paris, pp. 785–790, 2012.
- [16] T. HATTORI, Y. YAMADA, S. MORI, S. OKAMOTO, and S. HARA, Psychological Experiments on Avoidance Action Characteristics for Estimating Avoidability of Harm to Eyes from Robots, *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 5400–5405, 2012.
- [17] M. L. Visinsky, J. R. Cavallaro, I. D. Walker, Robotic fault detection and fault tolerance: A survey, *Reliability Engineering and System Safety*, Vol. 46, pp.139–158, 1994.
- [18] H. Kumamoto, E. J. Henley, *Probabilistic Risk Assessment and Management for Engineers and Scientists*, IEEE Press, p. 268, 1996.
- [19] T. NISHIYAMA, Y. YAMADA, S. OKAMOTO, S. HARA, S. TAKEDA, Human Avoidance Action Characteristics against Approaching Motions of a Robot End Effector at Close Range Triggered by Human Errors, *Proc. of TOKAI ENGINEERING COMPLEX 2015(TEC15)*, pp. 153–156, 2016 (in Japanese).