

Guideline for Determination of Link Mass of a Robot Arm for Collision Safety

Sang-Duck Lee¹ and Jae-Bok Song²

^{1,2} Department of Mechanical Engineering, Korea University, Seoul, 136-713, Korea
(Tel : +82-2-3290-3363; E-mail: jbsong@korea.ac.kr)

Abstract – In recent years the collision safety between a human and a robot has been increasingly important because of the spread of service robots. In order to design a safe robot arm, the collision safety evaluation must be conducted prior to the construction of the robot arm to compute the necessary design parameters. Previous evaluation methods required the use of the actual robot, which are both time consuming and expensive. In this study we propose a new human-robot collision model and a collision safety evaluation method which does not require the use of the actual robot. A human-robot collision model is developed, and the collision safety of a 3 DOF planar robot arm is evaluated. Then, using the evaluation results, the design of the robot arm is modified to ensure the collision safety. The proposed evaluation method enables the appropriate design parameters for a safe robot arm to be determined in a short period of time at the minimal cost.

Keywords - Collision safety, Effective mass, Manipulability polytope, Manipulator design

1. Introduction

Because service robots work in human environments, safety issues related to physical human-robot interaction have become increasingly important. One of the most reliable solutions to ensure the collision safety is to design an inherently safe robot arm. This design requires the collision analysis and safety evaluation, which help to determine the design parameters of a robot arm. Some researchers analyzed the injury mechanism, and suggested the safety criteria through a series of tests on dummy-robot collisions [1]. The collision safety criteria were proposed in [2] and the collision analysis using an analytic method was conducted. However, the experiment-based methods require the use of the actual robot, and thus they cannot be used in the design phase of a robot. Also, the conventional analysis methods are limited to a 1 DOF robot, whereas most of the service robot arms have multiple DOFs.

In this study, we propose a new, human-robot collision model and a collision safety evaluation method for a multi-DOF robot arm. The collision model is obtained by applying the effective mass and manipulability of the robot arm to the model of human-robot collision. The collision safety of a 3 DOF planar robot arm is evaluated by comparing the safety criterion and the calculated collision force, when the mass and velocity at the end-effector are provided with the configuration of the

robot. Using these evaluation results, the maximum allowable link mass for the safe robot arm can be determined. This determination process can be used as a guideline for the design of the safe robot arm. The proposed collision model and the collision safety evaluation method can be conducted without the use of the actual robot, thus greatly decreasing the development time and cost.

The remainder of this paper is organized as follows. The collision model for the collision safety evaluation is introduced in section 2. Section 3 describes the proposed collision safety evaluation method and its results. Section 4 shows how the proposed method can be used to design a safe robot arm. Finally, our conclusions are drawn in section 5.

2. Human-robot collision model

2.1 Effective mass and manipulability of robot arm

The equation of motion for a typical robot arm is represented by

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau \quad (1)$$

where $M(q)$ and $C(q, \dot{q})$ are the matrices related to the inertia and the Coriolis, q , τ , and $g(q)$ are the joint angle vector, the joint torque vector, and the gravity vector, respectively.

Assume that a collision takes place at the end-effector of a robot. Then, the inertial property of the robot with respect to the collision force can be achieved by using the effective mass. Using the inertia matrix $M(q)$ in Eq. (1), the effective mass can be expressed by

$$m_u^{-1} = u^T [J(q)M(q)^{-1}J^T(q)]u \quad (2)$$

where m_u is the effective mass of the robot arm, u is the direction vector which describes the direction of the force applied to the end-effector and J is the Jacobian matrix [3].

The manipulability is a measure of the manipulation ability in positioning and orienting the end-effector, and the exact maximum velocity of the end-effector can be estimated by using the manipulability polytope [4]. The vertices of the manipulability polytope can be expressed as

$$v_{max} = \tilde{q}_1 \tilde{J}_1 \pm \tilde{q}_2 \tilde{J}_2 \pm \dots \pm \tilde{q}_n \tilde{J}_n \quad (3)$$

where the v_{max} is the vertex of the manipulability polytope, and \tilde{J}_n is the scaled Jacobian matrix. In this study, we assume that the human stands still without any movement. In this case, the collision velocity is equal to the maximum operating velocity of a robot.

2.2 Collision model for safety evaluation

The collision between a human and a robot is a multi-DOF collision, which is complicated and nonlinear in nature. However, the collision can be approximated to take place along a straight line by assuming that a collision happened only for a very short period of time, as shown in Fig. 1. In Fig. 1, m_u is the effective mass of the robot arm at the end-effector, v_c is the collision velocity calculated based on the manipulability polytope of the robot arm, m_h is the mass of the human head (set to 4.4kg), and δ is the penetration depth which is $\delta = x_r - x_h$. The collision force F_c is driven from the cadaver experimental results [5], and the collision force is defined as $F_c = (1000\delta)^{2.5}$

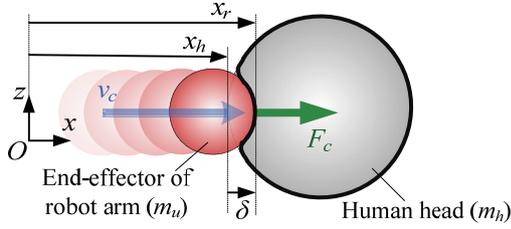


Fig. 1. Simplified collision model.

2.3 Collision force and design parameters

Since the mass and collision velocity of a robot arm are the important design parameters related to collision safety, the collision force need to be expressed in terms of these variables for collision safety evaluation. However, since the collision force used in the collision model is expressed in terms of the penetration depth, the collision force between the robot and the human head is obtained by simulations. The equation of motion for the collision model is solved by the numerical method, and the collision force is calculated under various effective masses and collision velocities. Then, the peak values of the collision force for each effective mass and collision velocity are surface fitted, as shown in Fig. 2.

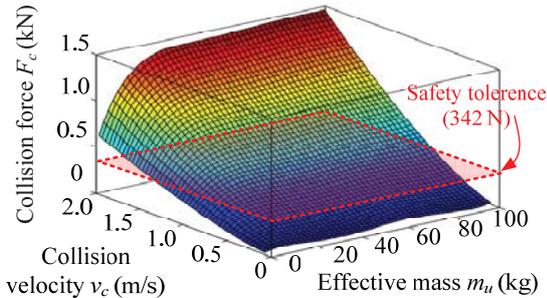


Fig. 2. Collision force as a function of effective mass and collision velocity.

3. Collision safety evaluation of robot arm

An arbitrary 3 DOF planar robot arm is shown in Fig. 3, where m_1, m_2, m_3 are the link masses, I_1, I_2, I_3 are the moment of inertia, l_1, l_2, l_3 are the link lengths, l_{c1}, l_{c2}, l_{c3} are the distances to their centers of mass, q_1, q_2, q_3 are the angular displacements, and $\dot{q}_{1,max}, \dot{q}_{2,max}, \dot{q}_{3,max}$ are the maximum joint velocities. The vector u is the direction vector of the collision force F_c , and in this case, u is given by $u = [\cos\theta \quad \sin\theta]^T$.

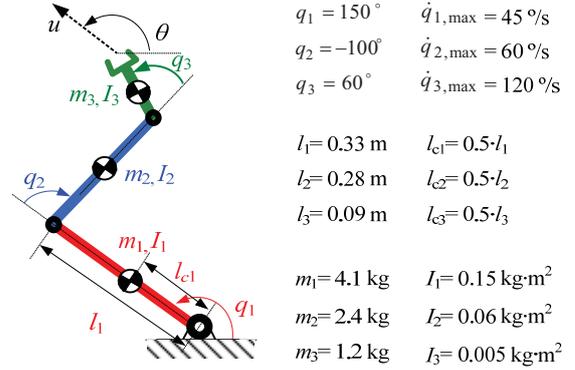


Fig. 3. 3 DOF planar arm for collision safety evaluation

The effective mass and collision velocity of a robot arm for the collision in the direction of u can be calculated from Eq. (2) and Eq. (3). By substituting the calculated effective mass and manipulability into the relation between the collision force, the effective mass and the collision velocity shown in Fig. 2, the collision force related to the direction u can be calculated. The collision force of a 3 DOF planar robot arm in terms of the angle of collision is presented in Fig. 4.

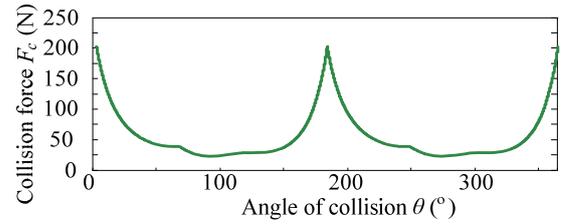


Fig. 4. Collision force of 3 DOF planar arm

In this study, we focused the nasal bone, which is the weakest bone in the head [5, 6]. Hence the fracture force of the nasal bone, which is 342 N [9], is used as the safety criterion.

In Fig. 4, F_c is below the safety criterion (342N) in every collision direction, and thus we can conclude that this robot arm is safe for the given configuration ($q_1 = -150^\circ, q_2 = -100^\circ, q_3 = 60^\circ$). However, the collision force and collision safety depend on the configuration of the robot arm. The robot arm is most dangerous when $q_2 = 0^\circ$ and $q_3 = 0^\circ$ because the collision velocity of end-effector is fastest at this configuration. Thus, if the robot is safe for this worst case, then it is safe for all configurations.

4. Design of a safe robot arm

To ensure the collision safety, one may change the mass, the operating velocity and the link length of a robot. However, the change in link length and operating velocity may not be possible since they directly affect the volume of workspace and the performance, respectively. Therefore, the link mass is considered as the adjustable design parameter to improve the collision safety in this study.

Modifying the material or the structure of the link can reduce the effective mass of a robot arm, but this change may lower the stiffness of the robot. In addition, it may increase the construction cost since more expensive materials or complex structures may be needed, which means that simply lowering the weight as much as possible is not a practical solution. Therefore, a reasonable guideline on how to compute the maximum allowable link mass should be provided to design a safe robot.

Assume that we design a 3 DOF planar robot arm, as shown in Fig. 3. The required payload of the robot is 3 kg, whereas the speed of the end-effector must be 1.1m/s, when fully extended. Figure 5, which corresponds to 1.1 m/s in Fig. 2, shows the collision force as a function of the effective mass. As shown in Fig. 5, at the collision velocity of 1.1 m/s, the effective mass must be less than 3.5 kg to ensure the collision safety. Also, if the robot arm is holding an object of 3 kg, the effective mass on a collision is the sum of the payload and the effective mass. Therefore, in this case, the effective mass of the robot arm must be less than 0.5 kg to satisfy the collision safety with a payload.

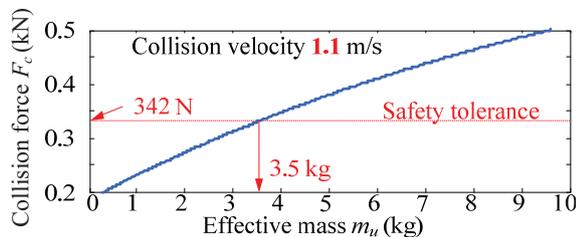


Fig. 5. Collision force with effective mass

Fig. 6 shows the change of effective mass as a function of the change of the link mass m_1 , m_2 and m_3 . m_i' is the changed link mass of link i . As shown in this figure, since the effective mass of the robot arm is the most sensitive to a change of m_3 , changing m_3 is the most effective way to improve the collision safety. As shown in Fig. 6, if the m_3 is reduced to 88 % of the original mass, the effective mass of the robot becomes less than 0.5 kg, and the safety is ensured. Thus, we can conclude that m_3 must be less than 1.05 kg in order to design a safe robot arm.

5. Conclusion

In this study, we propose a new method for evaluating the collision safety of a multi-DOF robot arm. The collision model and safety evaluation method suggested in this study can be easily applied to the design of a safe robot

arm. From this research, the following conclusions are drawn:

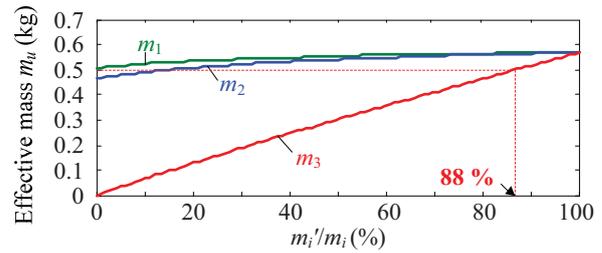


Fig. 6. Allowable link mass for collision safety of 3 DOF planar robot arm

- 1) The proposed method enables the collision safety to be evaluated in the design phase without using the actual robot, thus greatly decreasing the development time and cost.
- 2) The proposed collision safety evaluation method can provide a guideline to determine the link mass of a safe robot. Furthermore, unlike previous methods, this method can be applied to multiple DOFs robots.

Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0001150) and by Human Resources Development Program for Robot Specialists by the Ministry of Knowledge Economy.

References

- [1] S. Haddadin, A. Albu-Schaffer, M. Frommberger, J. Rossmann, G. Hirzinger, "The "DLR crash report": Towards a standard crash-testing protocol for robot sa.ety - Part I: Results," in *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp. 272-279, 2009.
- [2] J. J. Park and J. B. Song, "Collision analysis and evaluation of collision safety for service robots working in human environments," in *Proc. of the IEEE Int. Conf. on Advanced Robotics*, pp. 1-6, 2009.
- [3] O. Khatib, "Inertial Properties in Robotic Manipulation: An Object-level Framework," *The Int. Journal of Robotics Research*, vol. 14, no. 1, pp. 19-36, 1995.
- [4] J. Lee, "A study on the manipulability measure for robot manipulators," in *Proc. of the IEEE Int. Conf. Intelligent Robots and Systems*, vol.3, pp. 1458-1465, 1997.
- [5] G. W. Nyquist, J. M. Cavanaugh, S. J. Goldberg, "Facial impact tolerance and response," *Proc. of the 30th Stapp Car Crash Conference*, SAE Paper No.861896, pp. 733-754, 1986.
- [6] D. C. Schneider and A. M. Nahum, "Impact Studied of Facial Bone and Skull," *Proc. of the 16th Stapp Car Crash Conference*, SAE Paper no. 720965, pp.186, 1972.