# Collision Detection Algorithm to Distinguish between Intended Contact and Unexpected Collision

Joon-Hong Kim
Korea University
known@korea.ac.kr

Young-Loul Kim
Korea University
kimloul@korea.ac.kr

Jae-Bok Song
Korea University
jbsong@korea.ac.kr

***Abstract*** − When a robot directly interacts with a human, human safety becomes the most important issue. Thus, several safety strategies have been proposed so far, including collision detection algorithms using joint torque sensors. Most conventional collision detection algorithms are based on the measurement of the external torque which is caused by a collision. Once a manipulator detects the external torque acting on it, it makes proper responses to minimize the effect of this torque. However, this type of scheme causes the manipulator to make unnecessary responses even against human's intentional contacts with the manipulator. In this paper, we propose a novel collision detection algorithm based on the rate of change of external torque. Because unexpected collision usually leads to a rapid increase of the external joint torque, the manipulator can distinguish between intended contact and unexpected collision through the analysis of a torque sensor signal. A series of simulations and experiments show that the proposed scheme works well for various situations.

***Keywords*** − Collision detection algorithm, Collision observer, Safe manipulator.

## 1. Introduction

As robot manipulators are widely used in industrial and service applications, safety issues related to physical contact between humans and robots have become increasingly important. To realize a safe manipulator, several types of safety strategies have been proposed such as covering the manipulator with skin sensors [1], having mechanical components to absorb the collision force [2], and using dual actuators to control the position and stiffness simultaneously [3]. However, these strategies have some limitations; the first solution tends to increase the cost of a robot, whereas the less sensibility in detecting collision force is an issue for the second solution, and using two actuators as proposed in the third solution will increase the size of a robot. For these reasons, some safety strategies which observe the joint torque have been proposed. A disturbance observer was to detect the collision, but the measurement of acceleration which introduces noise in practice was needed because of their inverse dynamics calculation [4][5]. A nonlinear observer, which could find the external torque without measuring the acceleration, was proposed, but it required a large computational load [6]. An observer proposed in [7] was based on the generalized momentum which led to the same results with [6] but required less computational load. These conventional schemes have detected the external torque caused by a physical contact with the environment including human bodies, and then generated proper responses against it. Therefore, it is difficult to apply these schemes to the cases when intended contacts with the environment frequently occur (e.g., teaching and playback, force control) because the manipulator should not respond to this external torque.

In this paper, we propose a novel collision detection method which can distinguish between intended contact and unexpected collision through the analysis of the rate of change of external torque. The intended (and thus safe) contact tends to cause a slow rate of change in the magnitude of external torque, while the unexpected (and thus dangerous) collision makes a rapid change. The proposed observer uses the generalized momentum to extract the external joint torque excluding the components caused by the dynamics of the manipulator without measuring acceleration. Note that this algorithm does not need any extra sensors to measure the acceleration, and can be applied to any type of the manipulators.

The remainder of this paper is organized as follows: In Section 2, the observer to realize safe manipulation is introduced. The conducted simulations are presented in Section 3, followed by the experimental configurations and results in Section 4. Finally, Section 5 presents our conclusions.

## 2. Design of Collision Observer

In this section, we propose a collision observer which can extract only rapidly changing components of the external torque. The equation of motion of a general manipulator is given by

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

where $M(q)$ is the inertia matrix, $C(q,\dot{q})$ is the matrix related to the Coriolis effect, $g(q)$ is the gravity vector, $\tau$ is the actuator torque vector, and $\tau_{ext}$ is the external torque vector. Because the joint acceleration vector $\ddot{q}$ is difficult to measure with an optical encoder, the following generalized momentum $p$ is required to design the observer.

$$p=M(q)\dot{q} \tag{2}$$

Because $N(q,\dot{q}) = \dot{M}(q) - 2C(q,\dot{q})$ is skew-symmetric [8], $\dot{M}(q)$ is given by

$$\dot{M}(q) = C^T(q,\dot{q}) + C(q,\dot{q}) \tag{3}$$

and with its skew-symmetric property, the derivative of the generalized momentum $\dot{p}$ is given by

$$\dot{p} = \alpha(q,\dot{q}) + \tau - \tau_{ext} \tag{4}$$

where $\alpha(q,\dot{q}) = C^T(q,\dot{q})\dot{q} - g(q)$ is a nonlinear term of the equation. The collision observer $r$ can be designed as (5), which consists of a low-pass filter to attenuate high-frequency noise and a high-pass filter to extract the high-frequency components of the external torque.

$$\frac{r_i(s)}{\tau_{ext,i}(s)} = \frac{K_N s}{s^2 + (K_N + K_S)s + K_N \cdot K_S} \tag{5}$$

where $K_N$ is the gain for noise reduction, and $K_S$ is the gain for the sensitivity adjustment of the observer $r$. Therefore, the observer is given by

$$r = \int [b_1(\alpha(q,\dot{q}) + \tau) - a_1 r - a_2 \int r\, dt]\, dt - b_1 M(q)\dot{q} \tag{6}$$

where $a_1 = K_N + K_S$, $a_2 = K_N \cdot K_S$, and $b_1 = K_N$. This observer only detects rapidly changing components of the external torque except for the actuator torque. The block diagram of the proposed observer is shown in Fig. 1. If the observer $r$ is larger than the collision detection threshold $r_{th}$, the manipulator can judge that unexpected collision occurs.

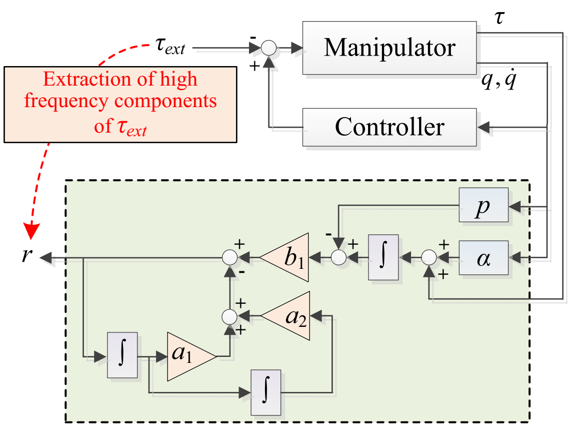



Fig. 1. Block diagram of the collision observer.

## 3. Simulations

In order to verify the proposed observer, various simulations were conducted on a two-link planar manipulator model moving along the gravitational direction using the Matlab/SimMechanics. Physical parameters of the manipulator are shown in Fig. 2 and the gains for the observer are chosen as $K_N = 60$ and $K_S = 30$.

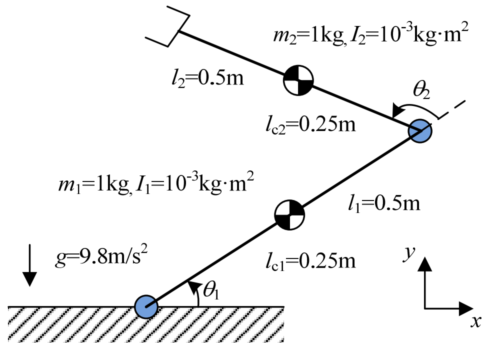
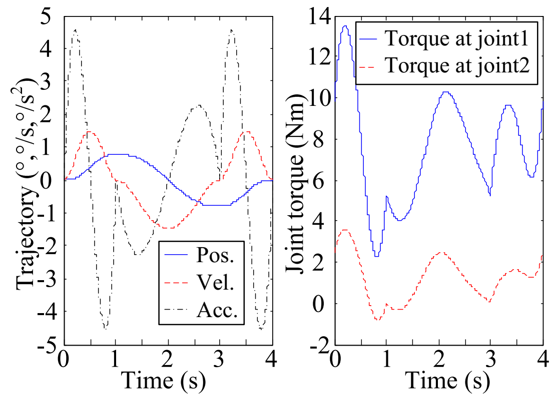



Fig. 2. Two-link manipulator model for the simulation.

Each joint moves from -45° to 45° on the 6th polynomial trajectory shown in Fig. 3(a), and the joint torques of the simulation results are shown in Fig. 3(b).

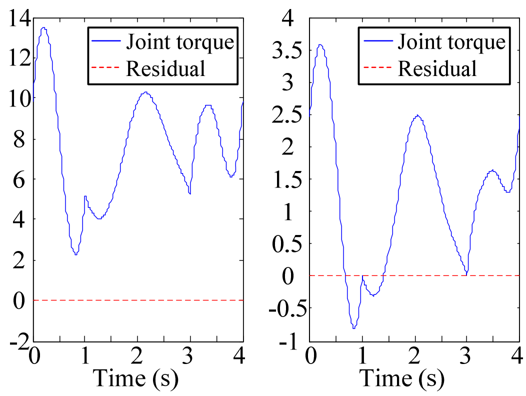



(a) Joint trajectory (b) Joint torque

Fig. 3. Simulation results

### 3.1 Without external torque

Figure 4 shows the joint torque and residual when the manipulator is moving without any external torque. Although the joint torque is affected by the motion of the manipulator, $r$ remains zero because no external torque is applied.

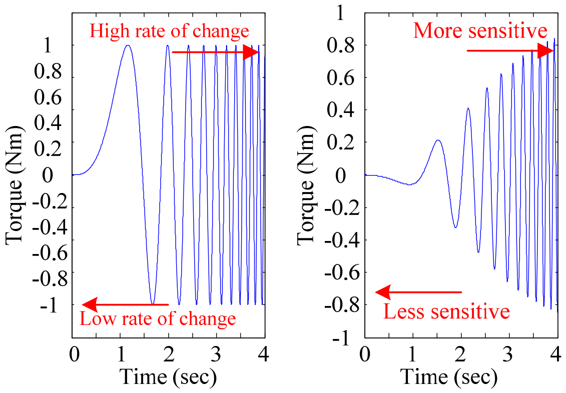



(a) Joint 1 (b) Joint 2

Fig. 4. Simulation results with no external torque.

### 3.2 External torque: Sinusoidal

When a sinusoidal external joint torque is applied at each joint, the residual is affected by the rate of change in the magnitude of the external joint torque as shown in Fig. 5. As the rate of change increases, $r$ becomes more sensitive to the external torque. This simulation shows the proposed observer can detect only rapidly changing components of external joint torque. It is important to detect only rapidly changing components of the external joint torque because unexpected collision tends to cause rapid changes, while intended contacts does not.

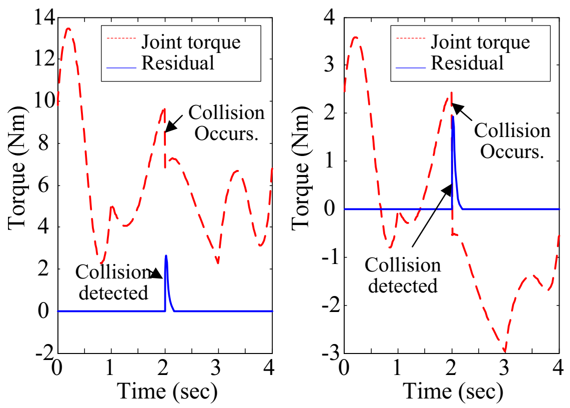



(a) External joint torque (b) Observer $r$

Fig. 5. Simulation results when sinusoidal external torque is applied.

### 3.3 External torque: Impulsive

Figure 6 shows the residual $r$ when an impulsive external torque is applied to each joint. The unexpected collision can be regarded as an impulse as will be experimented and discussed in Section 4.2. The observer responds to this impulsive torque very well, so the manipulator can detect the dangerous collision.




(a) Joint 1 (b) Joint 2

Fig. 6. Simulation results when impulse external torque is applied at each joint

## 4. Experiments

In this section, the configurations of the experimental results will be presented. All physical properties of the manipulator are taken from the CAD model.

### 4.1 Configuration of experimental setup

A one link manipulator equipped with the BLDC motor and joint torque sensor was used for the experiments as shown in Fig. 2. This manipulator is controlled by 3.0GHz dual-core PC with real-time operating system and the sampling time is 1ms.

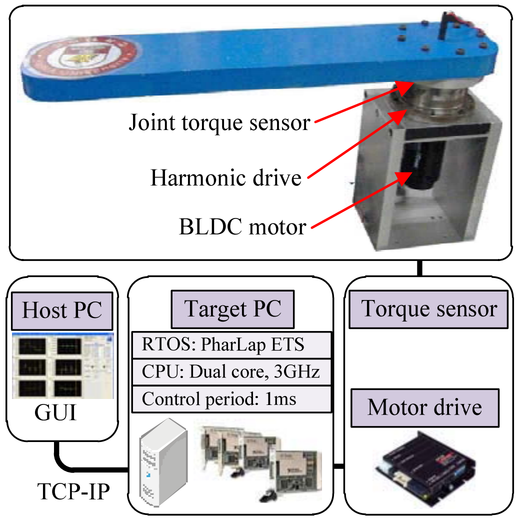
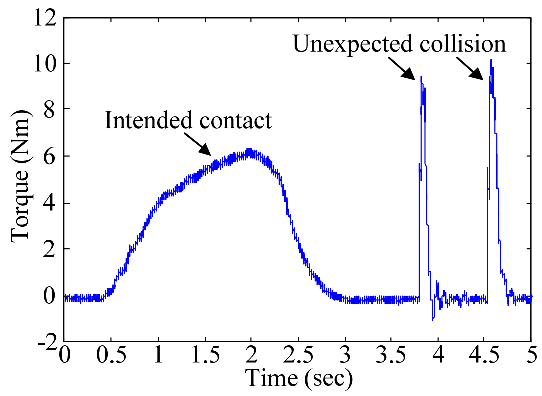



Fig. 6. Configuration of experimental set.

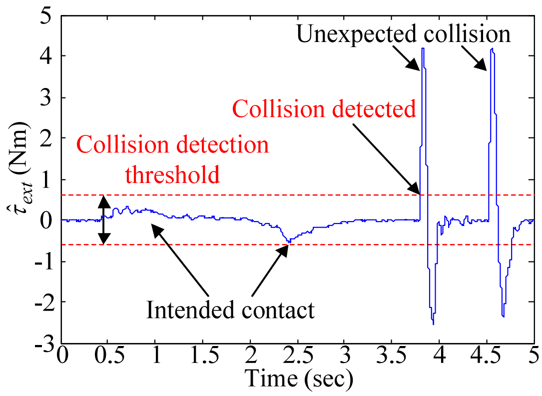
### 4.2 Experimental results

The experiment was conducted when the manipulator was under position control. The gains were chosen as $K_N$= 60 and $K_S$=30. The threshold value $r_{th}$ was set to 0.7 Nm for reliable detection without any failure.

Figure 7(a) shows the joint torque sensor signal due to the physical contact between a human and a robot. The first contact torque was generated by the intended contact force which causes neither any pain nor harm to a human. However, the second and third torques showed very rapidly changing signals, which indicate that these are unexpected and dangerous collisions. For the intended contact torque, $r$ remained smaller than $r_{th}$ because the rate of change of the external torque was low. In this case, the manipulator did not detect the collision and could continue its own tasks. However, when an unexpected collision torque was applied to the manipulator, $r$ started to increase rapidly. When $r$ was larger than $r_{th}$, the manipulator could detect the dangerous collision. After the collision was detected, the manipulator could stop urgently or react against the collision torque until safety was ensured.




(a) Measured joint torque from sensor.




(b) Observer $r$

Fig. 7. Experimental results on safe contact and dangerous collision between human and robot.

## 5. Conclusion

In this paper, we proposed a novel collision detection algorithm to guarantee the collision safety between humans and robots. This algorithm can not only detect the collision, but also judge that the contact is unexpected collision or intended contact by analyzing the rate of change of the external torque. Also, it can be applied to various types of manipulators without having to install any additional sensors other than joint torque sensors and optical encoders. The simulations and experimental results show that the proposed observer can reliably distinguish the dangerous collisions from the intended collisions. If the manipulator quickly reacts against the detected collision signal, the safety of human can be guaranteed while human co-works with the manipulator.

## Acknowledgements

This work was supported by the Center for Autonomous Intelligent Manipulation under Human Resources Development Program for Robot Specialists and by the Development of Manipulation Technology for Human-Robot Cooperation (Ministry of Knowledge Economy).

## References

[1] V. Lumelsky and E. Cheung, “Real-time collision avoidance in teleoperated whole-sensitive robot arm manipulator,” IEEE Trans. on Systems, Man, and Cybernetics, vol. 23, no. 1, pp. 194–203, 1993.

[2] Jung-Jun Park, Hwi-Su Kim, and Jae-Bok Song, “Safe Robot Arm with Safe Joint Mechanism using Nonlinear Spring System for Collision Safety,” Proc. of the IEEE International Conference on Robotics and Automation, pp. 3371-3376, 2009.

[3] Byeong-Sang Kim, Jung-Jun Park, Jae-Bok Song, “Double Actuator Unit with Planetary Gear Train for a Safe Manipulator”, Proc. of IEEE Int. Conf. on Robotics and Automation, pp. 1146-1151, 2007.

[4] S. Takakura, T. Murakami, and K. Ohnishi, “An approach to collision detection and recovery motion in industrial robot,” Proc. of 15th Annual Conf. of IEEE Industrial Electronics Society, pp. 421–426, 1989.

[5] Y. Yamada, Y. Hirasawa, S. Huang, Y. Umetani, and K. Suita, “Human-Robot Contact in the Safeguarding Space,” IEEE/ASME Trans. on Mechatronics, Vol. 2, No. 4, pp. 230-236, 1997.

[6] W. E. Dixon, I. D. Walker, D. W. Dawson, and J. P. Hartranft, “Fault detection for robot manipulators with parametric uncertainty: A prediction-error-based approach,” IEEE Trans. on Robotics and Automation, vol. 16, no. 6, pp. 689~699, 2000.

[7] A. De Luca and R. Mattone, “Actuator Fault Detection and Isolation using Generalized momenta,” IEEE Int. Conf. on Robotics & Automation, pp. 634~639, 2003.

[8] L. Sciavicco and B. Siciliano, Modelling and Control of Robot Manipulators, Springer, 2000