Improving Collision Detection Algorithm using Switching Notch Filter

Chang-Nho Cho[1], Joon-Hong Kim[1], Jae-Bok Song[1]

[1] *School of Mechanical Eng., Korea Univ., Seoul, Korea*

Abstract

Service robots often physically interact with humans, and thus, the safety of human must be guaranteed during human-robot cooperative tasks. One of the most likely causes of human injury in these tasks is the collision of a human and a robot, and the most promising solution to such a problem is to use collision detection algorithm. Most of the collision detection algorithms employ joint torque sensors to detect collisions. However, often, the sensor signal is not usable due to the noise from harmonic drives, which is also known as torque ripple. Torque ripple is caused by the structural characteristics of harmonic drives, and the amount of noise increases if a torque sensor is directly installed on a harmonic drive. In this paper, we propose a torque ripple filter which can effectively minimize torque ripple. The relationship between torque ripple and joint velocities was analyzed, and based on this relationship, the switching notch filter was designed. The proposed method does not require any additional circuitry, and its filtering performance and fast response time were verified through simulations. Also, simulation results show the improvements in collision detection by adopting the switching notch filter.

Keywords: Collision detection; Switch notch filter; Torque ripple; Torque sensor

1. Introduction

The use of service robots is expected to be more frequent in the near future and the interest in the safety issues regarding the physical contacts between robots and humans have increased significantly. During a physical interaction between a robot and a human, a collision may occur, which can harm the human. Several strategies have been proposed to cope with this problem, such as using skin sensors [1], installing a mechanism to absorb the impact [2], and using dual actuators to control the stiffness [3]. However, the first solution may increase the cost of robots, whereas the second solution is rather a passive solution, and its performance is limited. The third approach requires the use of two actuators, which would increase the complexity in control, as well as the price of robots. Thus, collision detection algorithms using only joint torque sensors are proposed. Furthermore, in order to avoid the use of the acceleration information, which is hard to obtain, an algorithm based on generalized momentum was proposed [4]. This allows a robot to detect a collision with the minimum computational load.

Collision detection algorithm requires joint torque sensors to monitor joint torques. However, often, the sensor signal is not usable due to the noise from harmonic drives. Harmonic drives offer high gear ratio, high precision, and light weight, and thus they are widely used in robots as speed reducers. However, due to their unique structural characteristics, harmonic drives tend to add noise to the torque sensor signal, which is also known as torque ripple. Furthermore, the amount of torque ripple increases significantly if a torque sensor is directly mounted on a harmonic drive. Torque ripple decreases the sensitivity of collision detection, thus preventing robots from detecting relatively small collisions. Several methods have been proposed in order to remove torque ripple from torque sensor signal. Multiple strain gauges were used on a torque sensor in order to compensate torque ripple [5], but the positioning accuracy was crucial, which was hard to achieve. Another solution using the Kalman filter [6] was proposed, but this induces a time delay, which is not desired.

In this paper, based on the relationship between the speed of a harmonic drive and the frequency of torque ripple, we propose a switching notch filter, which can effectively remove torque ripple from sensor signals. The switching notch filter only removes the major frequency components of torque ripple, which minimizes computational loads. Also, the proposed solution does not require any additional circuitry or mechanical structures, and can be easily used on any robots with joint torque sensors. Through simulations, the performance of the proposed filter and how it can improve collision detection was verified.

The remainder of this paper is organized as follows. In section 2, the collision detection algorithm and the characteristics of torque ripple will be examined. Section 3 describes the proposed switching notch filter, and the simulation results are presented in section 4. The final conclusions will be given in section 5.

2. Collision detection and torque ripple

2.1 Torque ripple

There have been many researches done on the characteristics of torque ripple [5-6]. Torque ripple is the noise from harmonic drives due to the harmonic drive's mechanical structure. It adds a sinusoidal noise to the torque sensor signal when the harmonic drive is moving at a speed.

It was found from the previous researches that there are two major frequencies present in the torque ripple, which are directly related to the joint velocity. The relationship between the joint velocity and the two frequencies of the torque ripple were found as:

$$f_1(\dot{q}) = \frac{K_g \dot{q}}{360}, \quad f_2(\dot{q}) = 2\frac{K_g \dot{q}}{360} \tag{1}$$

where f_1 and f_2 are the two major frequencies (Hz) whereas K_g is the gear ratio of a harmonic drive, $\dot{q}$ is the joint velocity(°/s) and 360 is to convert units. As the joint velocity increases, the ripple frequencies increases, which makes filtering difficult.

2.2 Collision detection

When a collision occurs, an external torque will be applied to a robot's joints. Thus, a collision can be detected by monitoring the joint torques. The equation of motion of an n-DOF manipulator can be expressed as follows.

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau - \tau_e \tag{2}$$

Where $M(q)$ is the inertia matrix, $C(q,\dot{q})$ is the Coriolis matrix, $g(q)$ is the gravity vector, τ is the actuator torque and τ_e is the external torque. Using this equation, the external torque can be computed given that the robot's positions, joint velocities, torques and accelerations are known. However, usually, the acceleration is hard to measure using optical encoders. Thus, a disturbance observer based on generalized momentum p was used instead.

$$p = M(q)\dot{q} \tag{3}$$

By following the calculation presented in the previous research [4], the residual, which estimates the external torque, can be found:

$$r(t) = K[\int_0^t (\alpha(q,\dot{q}) + \tau - r)\,dt - p] \tag{4}$$

where r is the residual, K is the cutoff frequency of the filter and α is the sum of nonlinear terms. The overall system with collision detection is shown below:

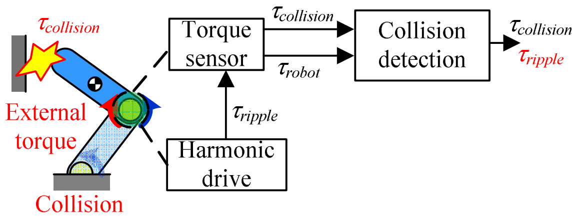

Fig. 1. The problem of torque ripple.

The residual observer described in Eq. (4) extracts the collision torque from torque sensor signal in the form of the residual. Then, by comparing the computed residual to the threshold, collisions can be detected. However, torque ripple from harmonic drive adds noise to the residual, thus the threshold must be increased to avoid possible malfunctions. This would prevent the robot from detecting small collisions.

Note that taking the Laplace transform of the residual observer shows that it has a form of a low–pass filter.

$$\frac{r(s)}{\tau_e(s)} = \frac{K}{s+K} \tag{5}$$

A low–pass filter is embedded in the residual observer, which would be able to remove torque ripple from the sensor signal. However, since torque ripple has two major frequency components which are functions of the joint velocity, the effect of the low–pass filter is limited.

3. Switching Notch Filter

A notch filter is a band-reject filter that rejects a particular frequency. In this study, a twin-tee notch filter was used. Its transfer function is given below:

$$H(s) = \frac{s^2 + \frac{1}{R^2C^2}}{s^2 + \frac{4}{RC}s + \frac{1}{R^2C^2}} \tag{6}$$

where R and C are the resistance and capacitance of the filter circuit. The cutoff frequency is $2\pi RC$. Torque ripple has two major frequencies, and thus by using two notch filters, torque ripple can be successfully removed. In order to eliminate torque ripple, the cutoff frequency must change along with the joint velocity. However, changing the cutoff frequency in real-time may lead to an unstable system. Thus, we propose the switching notch filter, which consists of multiple notch filters with different cutoff frequencies.

The block diagram of the switching notch filter is shown in Fig. 2. The supervisor monitors the joint velocity, from which it calculates the frequencies of torque ripple. Then, the supervisor chooses the most appropriate set of notch filters among the filter candidates. Whenever necessary, the switching signal will be sent to switch the filter.

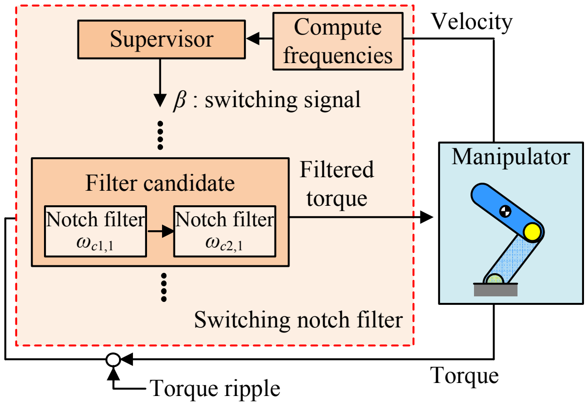

Fig. 2. Block diagram of the switching notch filter.

The relationship between the cutoff frequency and the joint velocity is shown in table 1. In order to effectively compensate torque ripple, the notch frequencies increase along with the joint velocity.

Table 1. The cutoff frequency and joint velocity.

Filter No.	Joint velocity (°/s)	Cutoff frequency 1 (Hz)	Cutoff frequency 2 (Hz)
1	18 ~ 36	7.5	15
2	36 ~ 54	12.5	25
3	54 ~ 72	17.5	35
4	72 ~ 90	22.5	45
5	90 ~ 108	27.5	55
6	108 ~ 126	32.5	65

Figure 3 shows the overall system employing the switching notch filter. The switching notch filter is used before collision detection to remove torque ripple from the torque sensor data. Thus, the residual with the minimum noise level can be obtained and the sensitivity of collision detection can be greatly improved.

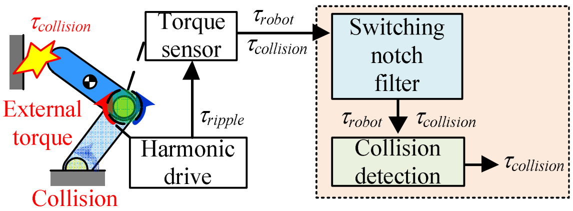

Fig. 3. The overall system with the switching notch filter.

4. Simulation

In order to verify the performance of the proposed filter, a planar 1-DOF robot was simulated using Simulink. Torque ripple can be simulated as a sinusoidal signal with two frequencies.

$$\tau_{ripple} = A_1 \sin(2\pi f_1 t) + A_2 \sin(2\pi f_2 t) \quad (7)$$

where A_1 and A_2 are the amplitudes and f_1 and f_2 are the frequencies of torque ripple.

The joint torque of the robot was measured while the robot was moving in a sinusoidal trajectory, and a collision torque using a spring-mass model was added at a particular time. The simulated torque ripple was also added to the calculated joint torque. Then, the torque with torque ripple was filtered by the proposed switching notch filter, and the collision detection algorithm was employed. The shown below is the overview of the simulation.

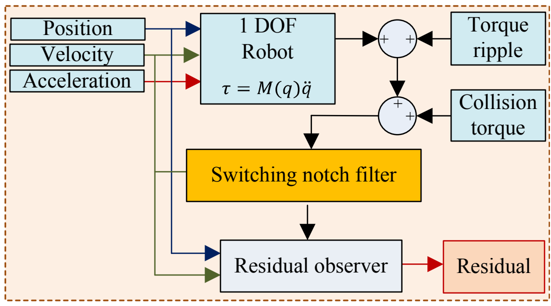

Fig.4. Simulation overview.

First, in order to show the performance of the switching notch filter, the normal torque without ripple, the torque with ripple and the filtered torque were compared.

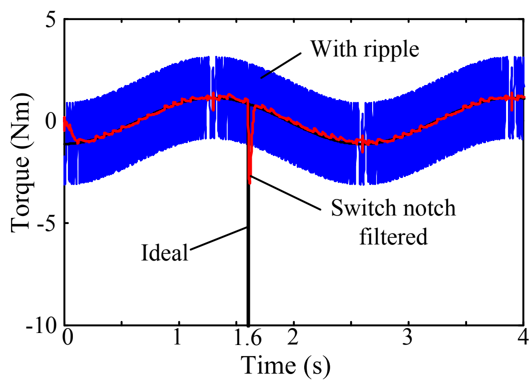

Fig. 5. Comparison between original, rippled, and filtered torques.

Figure 5 shows that the most of torque ripple was successfully removed using the proposed filter. The collision occurred at t = 1.6 s, which is also clearly shown.

The improvement in collision detection is also investigated. Two residuals were computed. The first was when only the low–pass filter was used, but the cutoff frequency was set low, K = 100 rad/s, to eliminate as much noise as possible. The second residual used the switching notch filter with the high cutoff frequency for the low–pass filter, so that the noise reduction from the low–pass filter was kept at the minimum.

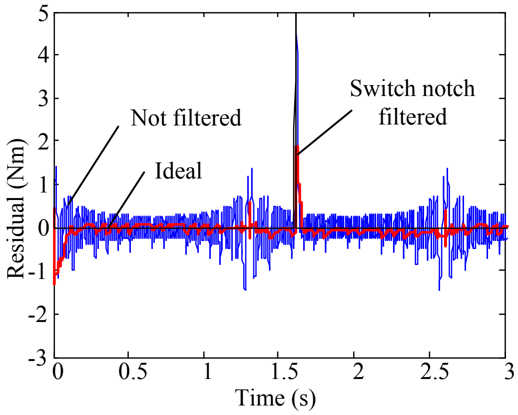

Fig. 6. The computed residuals with and without the switching notch filter.

The result shows that the switching notch filter shows much better noise suppression performance against torque ripple. The low–pass filtered residual has noise of 1.5 Nm, whereas the noise of the switch notch filtered residual is 0.8 Nm. Thus, the threshold of the residual observer can be set much lower, allowing small collisions to be detected. This will ultimately lead to a safer robot.

Lastly, the time delay of the proposed filter was analyzed by measuring the time delay between the time of the collision and the time it took the residual to reach the threshold. It was noted that there was a 6 to 8 ms of delay, which would delay the robot's reaction to the detected collision. However, the use of extra safety measures, such as a soft cover, would be sufficient to cope with this problem.

5. Conclusions

The collision detection is essential to ensure human safety during a human-robot interaction, and joint torque sensors are usually employed to detect collisions. However, the use of harmonic drives may add noise to the torque sensor signal, which is also known as torque ripple. This noise significantly decreases the sensitivity of collision detection, and we proposed the switching notch filter to effectively remove the noise from the torque sensor signal. The simulation results verify that the switching notch filer can effectively removes torque ripple, allowing much smaller collisions to be detected. The proposed filter requires minimal computation, and without any additional mechanisms or circuitries, the performance of collision detection can be greatly improved.

Acknowledgment

This work was supported by the Development of Manipulation Technology for Human-Robot Cooperation and by the Center for Autonomous Intelligent Manipulation under Human Resources Development Program for Robot Specialists (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] Hamid, D. T. and Belanger P. R., 1998, "Torque Ripple and Misalignment Torque Compensation for the Built-In Torque Sensor of Harmonic Drive Systems," *IEEE trans. on instrumentation and measurement,* Vol. 47, No. 1, pp. 309~315.

[3] J. J. Park, H. S. Kim, and J. B. 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.

[4] B. S. Kim, J. J. Park, J. B. 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.

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

[6] Ivan, G., Tamotsu, N. and Masashi, H., 2001, "Ripple Compensation for Torque Sensors Built into Harmonic Drives," *IEEE Trans. on instrumentation and measurement,* Vol. 50, No. 1, pp. 117~122.

[7] Hamid, D. T. and Belanger P. R., 1998, "Torque Ripple and Misalignment Torque Compensation for the Built-In Torque Sensor of Harmonic Drive Systems," *IEEE trans. on instrumentation and measurement,* Vol. 47, No. 1, pp. 309~315.