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Research on Collision Detection and Collision Reaction of Collaborative Robots

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Background

With the development of manufacturing from automation to intelligence, the application of collaborative robots is more and more extensive. It has potential possibilities of a collision between human and the environment due to misoperation or machine failure of robots. Therefore, in recent years, the importance of collision safety and contact force estimation has become increasingly prominent.

(a) Security fence (b) Cooperative operation (c) Safety of collisions

In this paper, we construct different second-order observers and compare their detection performance with GMO in terms of detection delay, sensitivity and accuracy. Moreover, we design a collision reaction strategy in position control mode. By mapping the output of the observer to the increment of joint velocity, the evacuation point is calculated and sent to the controller, realizing the safe evacuation of the robots. Our contributions are:

- According to the frequency distribution of error, collision signal and measurement noise, we put forward the improvement strategy of GMO.
- We propose a collision reaction strategy in position control mode.

Preliminaries

The generalized momentum $\boldsymbol{p}$ is defined: $\boldsymbol{p} = \boldsymbol{M}\dot{\boldsymbol{q}}$, where $\boldsymbol{M}$ is the symmetric and positive-definite inertia matrix, and $\dot{\boldsymbol{q}}$ is the joint velocity vector. The relation between the generalized momentum $\boldsymbol{p}$ and the external joint torque $\boldsymbol{\tau}_{ext}$ can be expressed as:

$$\begin{cases} \dot{\boldsymbol{p}} = \boldsymbol{\tau}_m + \boldsymbol{\tau}_{ext} - \boldsymbol{\tau}_f + \boldsymbol{C}^T\dot{\boldsymbol{q}} - \boldsymbol{G} = \boldsymbol{\tau}_m + \boldsymbol{\tau}_{ext} - \boldsymbol{\tau}_f + \boldsymbol{\beta}(\boldsymbol{q},\dot{\boldsymbol{q}}) \\ \boldsymbol{\beta}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{C}^T\dot{\boldsymbol{q}} - \boldsymbol{G} \end{cases} \quad (1)$$

where $\boldsymbol{q}$ is the joint position vector, $\boldsymbol{C}$ is the matrix of centrifugal force and Coriolis force $\boldsymbol{G}$ is the gravity vector, $\boldsymbol{\tau}_f$ is the friction torque vector, and $\boldsymbol{\tau}_m$ is the active motor torque vector. $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{G}$ can be obtained by dynamic identification experiments.

Set the $\boldsymbol{r}_1$ as the external joint torque monitoring value. Considering the output signal of the first-order inertia system changes with the step signal inputting, the system model can be expressed as:

$$\boldsymbol{r}_1 = \frac{\boldsymbol{K}_1}{\boldsymbol{K}_1 + s}\boldsymbol{\tau}_{ext} \Rightarrow \dot{\boldsymbol{r}}_1 = \boldsymbol{K}_1(\boldsymbol{\tau}_{ext} - \boldsymbol{r}_1) \quad (2)$$

where $\boldsymbol{K}_1$ is the coefficient matrix, and $\boldsymbol{r}_1$ is the GMO output vector.

Second-order Damped System (Damp)

Replacing the GMO transfer function with the Second-order Damped System:

$$\frac{\boldsymbol{r}_D}{\boldsymbol{\tau}_{ext}} = \frac{\boldsymbol{K}_1}{s^2 + \boldsymbol{K}_1\boldsymbol{K}_2 s + \boldsymbol{K}_1} \quad (3)$$

Second-order Damped System with PD regulation (PD)

The PD regulator can be connected in series after the Second-order Damped System:

$$\frac{\boldsymbol{r}_P}{\boldsymbol{\tau}_{ext}} = \frac{\boldsymbol{K}_1(\boldsymbol{K}_3 s + 1)}{s^2 + \boldsymbol{K}_1\boldsymbol{K}_2 s + \boldsymbol{K}_1} \quad (4)$$

Band-pass Filter (BPF)

To obtain a band-pass filter by connecting a high-pass filter in series on the basis of GMO:

$$\frac{\boldsymbol{r}_B}{\boldsymbol{\tau}_{ext}} = \frac{\boldsymbol{K}_1 s}{s^2 + (\boldsymbol{K}_1 + \boldsymbol{K}_2)s + \boldsymbol{K}_1\boldsymbol{K}_2} \quad (5)$$

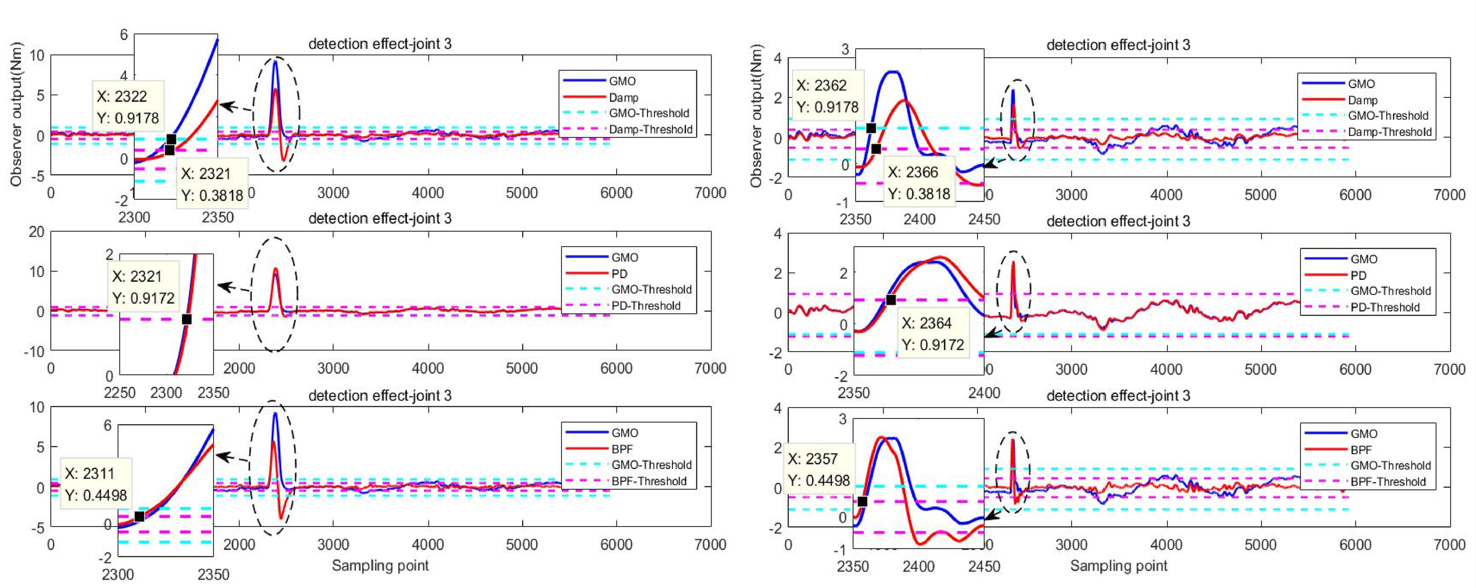
Abstract

The first-order model-based generalized momentum observer (GMO) is a low pass filter with high-frequency attenuation characteristics and detection delay. Therefore, it can not detect short impacts (extremely short time intervals) sensitively. According to the frequency distribution of modeling errors, collision signal, and measurement noise, we design three different second-order model-based GMOs, which improve the performance of collision detection effectively. Specifically, these GMOs include a second-order damped system (abbreviated as Damp), a second-order damped system with PD regulation (abbreviated as PD), and a band-pass filter (abbreviated as BPF). Typically, the collision reaction function can be realized by switching to the torque control mode with gravity compensation. However, the robot can not continue to move along its original trajectories after switching from position to torque control, and can not continue to perform subsequent tasks. To address this problem, we design a collision reaction strategy in position control mode by mapping the output of the observer to the increment of joint velocity, realizing a safe collision reaction.

Experiment Result

We performed several tests on collision detection with a collaborative robot HSR-Co605, which is developed by the HSR company, and validated the designed robot reaction strategy.

The soft collisions and hard collisions are applied to 3-rd link of the tested robot respectively, and the monitoring signals of the joint 3 are shown in Fig.1.



(a) Soft collisions for joint 3 (b) Hard collisions for joint 3

Fig.1 Performance comparison between second-order observers and GMO

The results in Fig.1 are summarized in the Table.

	Link 3 applied soft collisions (joint 3)			Link 3 applied hard collisions (joint 3)		
	Upper threshold (NM)	Inspected sampling point	Maximum amplitude (NM)	Upper threshold (NM)	Inspected sampling point	Maximum amplitude (NM)
GMO	6.000	2610	12.82	0.9178	2362	2.382
Damp	1.814	2602	8.437	0.3818	2366	1.638
PD	6.016	2609	15.17	0.9172	2364	2.578
BPF	2.037	2589	8.341	0.4498	2357	2.414

After the collision, the reaction strategy in position control mode is adopted. According to the expectation, the robot will evacuate along the direction of external force and stop after evacuating to appropriate distance. The whole process from collision detection to reaction is shown in Fig.2.

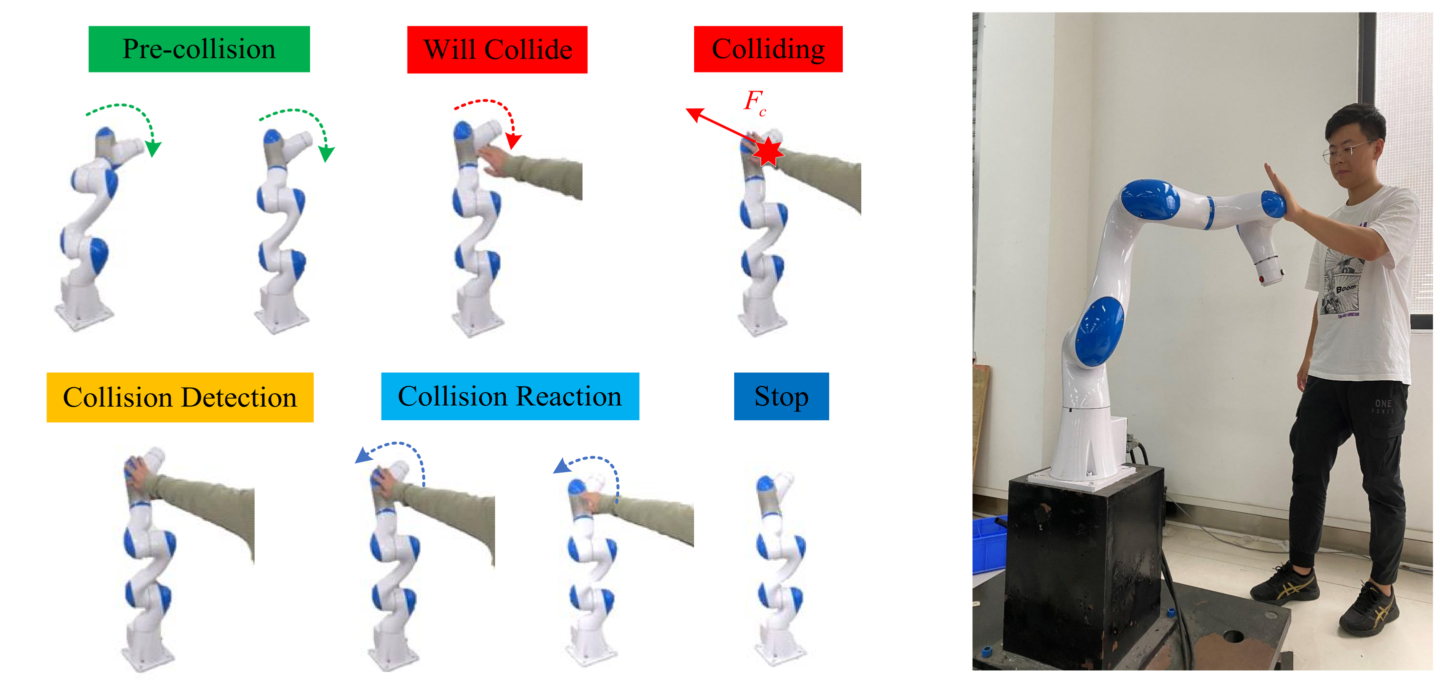


Fig.2 Collision detection and reaction of collaborative robot

Conclusions

In this paper, according to the frequency distribution of error, collision signal and measurement noise, three kinds of second-order observers are designed on the basis of GMO. The experimental results show that three second-order observers have higher detection sensitivity than GMO.

Moreover, a collision reaction strategy in position control mode is designed, which can make the robot safely evacuate from the collision point along the direction of external force without switching the control mode.

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