Paper:

Sensorless Collision Detection for a 6-DOF Robot Manipulator

Lin Cheng*, **Jiayu Liu***, **Juyi Li*,**** **and Jianzhong Tang***

*Robotics Innovation Center, Aerospace science and industry intelligence robot CO.,LTD
E-mail: jyliu_bit@hotmail.com
**College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics
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Abstract–Safety is a very important consideration for collaborative robot, which stands for robot working with humans. This paper proposed an improved generalized momentum observer to detect collision of AR10, a 6-DOF cooperative robot. In the experiment, the friction force is identified by employing the LuGre friction model. With friction force and gravity calculated out, collisions are detected by the modified generalized momentum observer, which can distinguish collisions from normal moves in the case that dynamic model error is large. False collisions are avoided from the difference between the target velocity and the actual velocity. The final results of experiments are significative.

Keywords: Cooperative robot, Collision detection, Modified momentum observer

1. Introduction

Human-Robot collaboration is the essential characteristic of intelligent robots. Traditional industrial robots have improved work efficiency of human society significantly. However, industrial robots have obviously disadvantages in large size and complicated instructions. Meanwhile, the collaborative robots have the advantages in human-robot collaborative control, intelligent perception and soft operation. Thus, the collaborative robots can be used wildly in medical cares, small workpiece assembly, electronic information, family services and other fields.

In the process of Human-Robot collaboration, to ensure the safety of human, the collision detection technology is especially important. Maurtua [1] proposed that when the robot collides to an object, the actual torque of the corresponding joint will exceed the threshold value, so that the robot is colliding. However, this method cannot fully achieve the protection of human safety. Lu S. [2] added a force/torque sensor on a 2-DOF manipulator and developed a neural network approach and a model based method to obtain the the external collision position and collision force of the manipulator. However, the force sensor was expensive and could only identify the collision at the end of manipulator. A built-in torque sensor for harmonic-drive systems was introduced in [3]. It shown that the intelligent built-in torque sensor is a viable and economical way to measure the harmonic-drive transmitted torque. Sensorless torsion control of elastic-joint robots is proposed in [4], with the geared drives subject to hysteresis and friction nonlinearities. The method was validated in a classical two-degrees-of-freedom robot. Zhang [5] put forward a method for estimating joint torque based on harmonic drive transmission. In the presented joint torque estimation method, motor-side and link-side position measurements along with a proposed harmonic drive compliance model, are used to realize stiff and sensitive joint torque estimation.

In this paper, our collision detection method is based on the generalized momentum method. A method based on the use of generalized momenta for detecting and isolating actuator faults in robot manipulators was presented in [6] firstly. Haddadin [7] extend and evaluate experimentally the momentum observer for real-time collision detection on the basis of [6]. Haddadin summarized and evaluated the calculation amount and required measurement amount of various collision detection and identification methods, and established the collision identification and isolation based on generalized momentum observer for collision detection, and tested on DLR robot. The proposed algorithm used only proprioceptive sensors and completed a collision detection using current.

Motivated by [6]–[7], this paper estimate the joint torque by modifying the momentum observer to overcome the error caused by inaccurate dynamic model. The collision detection algorithm proposed in this paper is appropriate for engineering. The dynamic model of the robot manipulator in this paper is established based on the parameters given by SolidWorks model. The main contributions of this paper are as follows:(1) considering the stribeck and hysteresis effect of friction, LuGre model is used to identify joint friction quickly; (2) the change rate of momentum observer value are utilized to detect the collision, which modifies the momentum observer to a second order filter; (3) the motion stage of the robot manipulator is judged by the difference between the target joint velocity and the actual velocity to avoid false detection of collision.

The remaining paper is organized as follows. The mathematical model of the robot is presented in Section 2. In Section 3, a modified momentum observer to collision detection is presented. In Section 4, a LuGre friction model is used to identify the joint friction. Finally, the proposed algorithm is verified in a 6-DOF robot control system in Section 5.

2. Robot Dynamic Model

The robot manipulator studied in this paper is depicted in Fig. 1. Let $\boldsymbol{q}$ denotes its joint configuration, $\boldsymbol{\tau}_m$ denotes the vector of actuation torques, exerted by the robot motors. A robot consisting of an open kinematic chain of N rigid links connected through N rigid joints collides with the environment. The dynamic model takes the form

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})+\boldsymbol{\tau}_{\mathrm{F}}=\boldsymbol{\tau}_{\mathrm{m}}+\boldsymbol{\tau}_{\mathrm{ext}} \quad . \quad (1)$$

where $\boldsymbol{M}(\boldsymbol{q}) \in \mathbb{R}^{N\times N}$ denotes the symmetric inertia matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) \in \mathbb{R}^{N\times N}$ denotes the centrifugal and Coriolis matrix,and $\boldsymbol{g}(\boldsymbol{q}) \in \mathbb{R}^{N}$ is the gravity vector. $\boldsymbol{\tau}_{\mathrm{F}}$ is the dissipative torque which includes friction force. $\boldsymbol{\tau}_{\mathrm{ext}} = \boldsymbol{J}_c^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{F}_{\mathrm{ext}}$, where $\boldsymbol{J}_c$ is the Jacobian at collision, $\boldsymbol{F}_{\mathrm{ext}}$ is the Cartesian collision wrench is defined by

$$\boldsymbol{F}_{\mathrm{ext}} = \begin{bmatrix} \boldsymbol{f}_{\mathrm{ext}} \\ \boldsymbol{m}_{\mathrm{ext}} \end{bmatrix}.$$

This paper will identify the external joint torque $\boldsymbol{\tau}_{\mathrm{ext}}$ based on the robot dynamic model and momentum observer.

3. Momentum Observer

3.1. Basic

A basic character of the robot dynamics is that $\dot{\boldsymbol{M}}(\boldsymbol{q}) - 2\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is a skew symmetric matrix and satisfies

$$\dot{\boldsymbol{M}}(\boldsymbol{q}) = \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{C}^{\mathrm{T}}(\boldsymbol{q},\dot{\boldsymbol{q}}). \quad (2)$$

In order to avoid the calculation of the inertia matrix and the acceleration estimate, we use the generalized momentum observer method to estimate the external force disturbance of the robot manipulator. The generalized momentum is defined as

$$\boldsymbol{p} = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}}. \quad (3)$$

Differentiating (3)with respect to time, we obtain

$$\dot{\boldsymbol{p}} = \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}^{\mathrm{T}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} \quad (4)$$

Substitute (1)into (4), we obtain

$$\dot{\boldsymbol{p}} = \boldsymbol{\tau}_{\mathrm{m}} + \boldsymbol{\tau}_{\mathrm{ext}} - \boldsymbol{\tau}_{\mathrm{F}} + \boldsymbol{C}^{\mathrm{T}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) \quad (5)$$

The momentum observer is designed as

$$\begin{aligned} \dot{\hat{\boldsymbol{q}}} &= \boldsymbol{\tau}_{\mathrm{m}} - \boldsymbol{\tau}_{\mathrm{F}} - \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{C}^{\mathrm{T}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}\boldsymbol{C}^{\mathrm{T}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} \\ \dot{\boldsymbol{r}} &= \boldsymbol{K}_{\mathrm{o}}\left(\dot{\boldsymbol{p}} - \dot{\hat{\boldsymbol{q}}}\right), \end{aligned} \quad . \quad (6)$$

where $\boldsymbol{K}_{\mathrm{o}} = \mathrm{diag}\{k_i\} > 0$ is the diagonal gain matrix of the observer. Letting $\boldsymbol{\alpha}(\boldsymbol{q},\dot{\boldsymbol{q}}) = -\boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{C}^{\mathrm{T}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ and integrating the output $\boldsymbol{r}$, we have the following equation

$$\begin{aligned} \boldsymbol{r} &= \boldsymbol{K}_{\mathrm{o}}\left(\boldsymbol{p}(t) - \int_0^t \dot{\hat{\boldsymbol{p}}}(s)\,ds - \boldsymbol{p}(0)\right) \\ &= \boldsymbol{K}_{\mathrm{o}}\left(\boldsymbol{p}(t) - \int_0^t (\boldsymbol{\tau}_{\mathrm{m}} - \boldsymbol{\tau}_{\mathrm{F}} - \boldsymbol{\alpha}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{r})ds - \boldsymbol{p}(0)\right), \end{aligned} \quad (7)$$

where $\boldsymbol{r}$ is the estimate of $\boldsymbol{\tau}_{\mathrm{ext}}$. Under reasonable assumption that the estimation of $\boldsymbol{g}(\boldsymbol{q})$, $\boldsymbol{C}^{\mathrm{T}}(\boldsymbol{q},\dot{\boldsymbol{q}})$ and $\boldsymbol{\tau}_{\mathrm{F}}$ is error-free, the relationship between the joint collision torque $\boldsymbol{\tau}_{\mathrm{ext}}$ and $\boldsymbol{r}$ is derived as

$$\dot{\boldsymbol{r}} = \boldsymbol{K}_{\mathrm{o}}(\boldsymbol{\tau}_{\mathrm{ext}} - \boldsymbol{r}) \quad (8)$$

Taking the Laplace transform of (8), we obtained that

$$\boldsymbol{r}(s) = \frac{\boldsymbol{K}_{\mathrm{o}}}{\boldsymbol{K}_{\mathrm{o}} + s}\boldsymbol{\tau}_{\mathrm{ext}}(s), \quad (9)$$

which is a first-order low pass filter substantially.

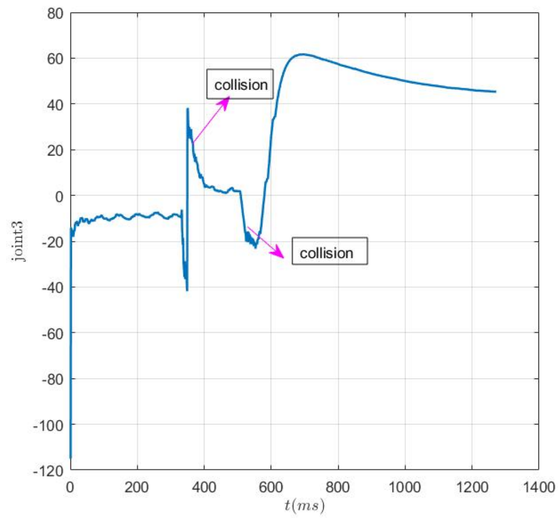

Fig. 1. Momentum residual $\boldsymbol{r}$ of joint3.

3.2. Modified

Let's take joint 3 as an example to verify the effectiveness of the momentum observer. If the fixed threshold value is used to determine whether the collision is caused directly, the results will be shown in Fig. 1. It shows that owing to the inaccuracy of robot dynamic model and the high deceleration ratio of the joint, the residual $\boldsymbol{r}$ is a bit of large. And when there is no collision, the residual is not zero. Therefore, we utilize the change rate of $\boldsymbol{r}$ to detect the collision, i.e. the momentum observer is a second order filter. The results are shown in Fig. 2: The above two figures reveal that the change rate of momentum residual $\boldsymbol{r}$ can identify collision can more accurately and quickly.

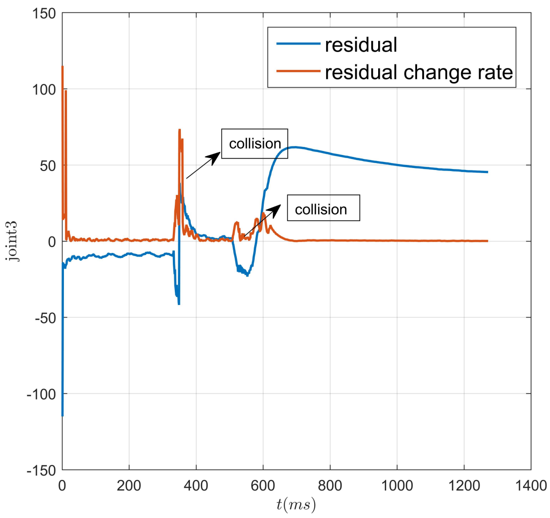

Fig. 2. Change rate of momentum residual $\boldsymbol{r}$ of joint3.

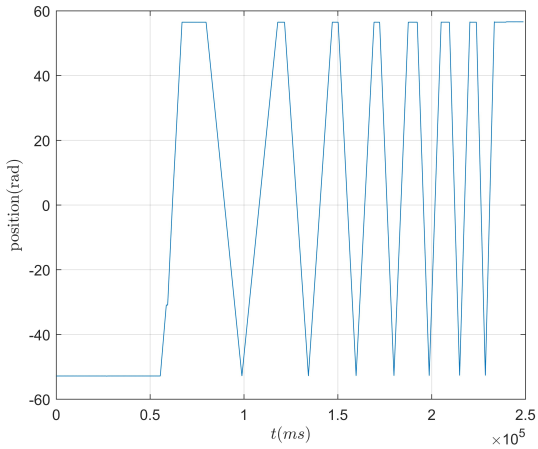

Fig. 3. Joint2 position.

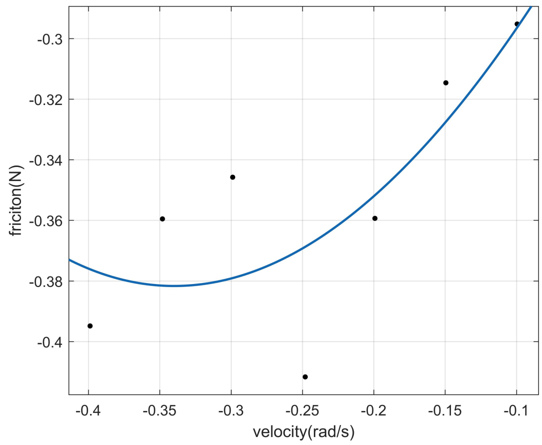

Fig. 4. Joint2 friction identification.

4. Fast Friction Identification

Real-time friction compensation is an important basis for collision detection. The joint friction is considered to be a function of joint velocity, and its accurate modeling is complicated. Considering the robot joint generally consists of motor, harmonic reducer and output link, it is not appropriate to characterize the friction force by simple viscous damping. This section will introduce a fast friction identification method. We employ the LuGre friction model which includes stribeck effect, hysteresis, and spring characteristics. The expression of LuGre friction model is derived as

$$\tau_{\mathrm{F}} = a + b \cdot e^{-c*\dot{q}} + d \cdot \dot{q}, \quad (10)$$

where a, b, c are the parameter to be estimated, $\dot{q}$ is the joint velocity. We take the frictional identification of joint2 and joint5 as examples, where one deceleration is larger and the other deceleration is smaller. Considering (2), we let the joint rotate back and forth at different speeds uniformly, and extract the motor torque data, which are shown in Fig. 3. In view of the following equation

$$\begin{aligned} \boldsymbol{g}(+\boldsymbol{q}) + \boldsymbol{\tau}_{\mathrm{F}}(+\dot{\boldsymbol{q}}) &= \boldsymbol{\tau}_{\mathrm{m}}^{+}, \\ \boldsymbol{g}(-\boldsymbol{q}) + \boldsymbol{\tau}_{\mathrm{F}}(-\dot{\boldsymbol{q}}) &= \boldsymbol{\tau}_{\mathrm{m}}^{-}. \end{aligned} \quad (11)$$

At the same speed and the same joint position, the torque difference yields twice the friction force, i.e.

$$\boldsymbol{\tau}_{\mathrm{F}}(+\dot{\boldsymbol{q}}) = \frac{1}{2}\left[\boldsymbol{\tau}_{\mathrm{m}}^{+} - \boldsymbol{\tau}_{\mathrm{m}}^{-}\right]$$

Fig. 4–Fig. 5 reveal the relationship between joint friction and joint velocity based on the LuGre friction model.

Noted from Fig. 4, friction decreases at the beginning and then increases with joint velocity, whereas the friction increase linearly in Fig. 5. This is due to joint 2 has a higher torque and higher gear ratio than other joints'.

5. Experimental Evaluation

5.1. Experiment Platform

In this section, the independent research and development of robot system is shown in Fig. 6. This system consists of cooperative robot, controller, electric control cabinet and so on. The self weight of the cooperative robot is 33kg and the maximum load is 10kg. The joint includes harmonic reducer, servo driver and motor. The controller and servo driver communicate in real time through EtherCAT, and the communication cycle is 1ms. The teach pendant is demonstrated in Fig. 7. The current, velocity and position of the joint can be read through the servo driver. The D-H parameters of the robot are shown in the Table 1.

5.2. Robot collision detection experiment

In order to verify the effectiveness of the algorithm in this paper, we impact from various positions of the robot. The end of the manipulator runs a randomly generated

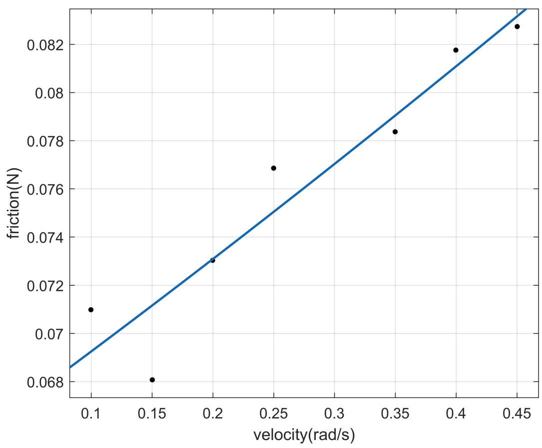

Fig. 5. Joint5 friction identification.

Fig. 6. The cooperative robot–AR10.

trajectory at the speed of 0.4m/s. The collision detection results of human and robot are shown in Fig. 8. We can observe that collision1 and collision2 occur at the end of the robot manipulator, whereas collision3 occurs behind joint4.

5.3. Avoid False Detection

Avoiding false collision is the difficulty of collision detection. In the experiments in the literature, the manipulator moves at a constant velocity. However, in reality, the robot will have a variety of movements such as start, stop, accelerate and decelerate, change the direction of motion and so on. Therefore, how to avoid accidental collision becomes very important. In our experiments, it is found that the observer value will change greatly when the robot starts or stops. Therefore, we need to identify this stage and do not carry out collision detection at this stage. We employ the difference between the target velocity and the actual velocity to judge the motion of the manipulator. Fig. 9 reveals that this difference will be giant when the manipulator starts or stops or changes the direction of motion.

Table 1. System parameters and coefficients

i	a_i	α_i	d	θ
1	0	$\pi/2$	d_1	$\theta_1+\pi/2$
2	a_2	0	0	$\theta_2-\pi/2$
3	a_3	π	0	0
4	0	$-\pi/2$	d_4	$\theta_4-\pi/2$
5	0	$\pi/2$	d_5	0
6	0	0	d_6	0

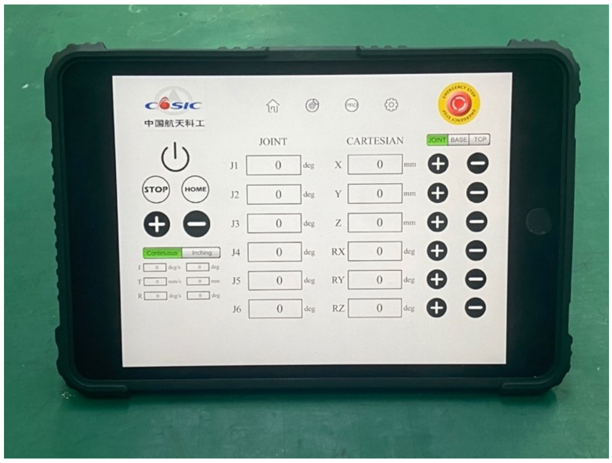

Fig. 7. The teach pendant .

6. Conclusions

A modified momentum observer is utilized to the joint torque detection. The algorithm can overcome the dynamic model inaccuracy. It is tested and verified on a 6-DOF robot manipulator. A difference between the joint target velocity and joint actual velocity is employed to avoid false detection. Further work will include the safety reaction strategies after collision for the rigid body arms and then extend momentum observer to the elastic joint robot.

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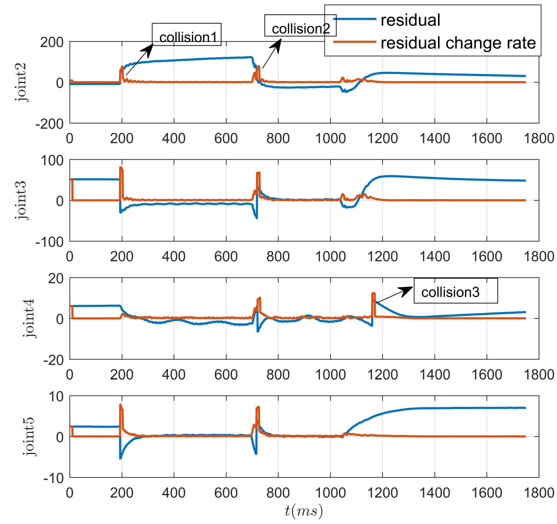

Fig. 8. The observation results of joint2–joint5.

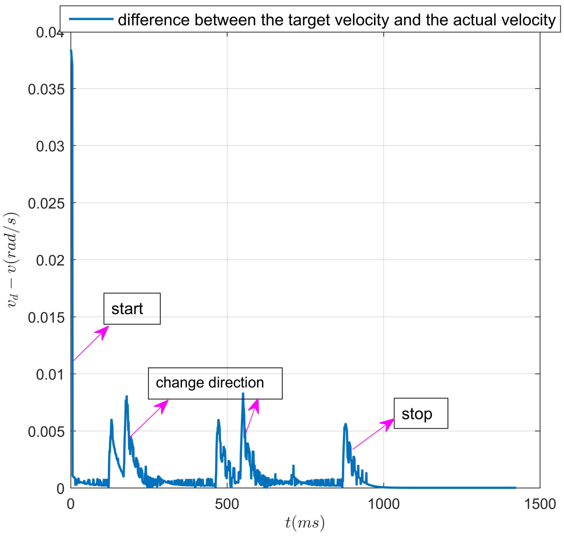

Fig. 9. The difference between target velocity and actual velocity under different motion conditions.

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