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Current-Based Direct Teaching for Industrial Manipulator

Jiaolong Du
School of Mechanical Engineering
Shanghai Jiao Tong University
Minhang, Shanghai, China
jiaolongdu@foxmail.com

Jianjun Yuan
Shanghai Robotics Institute
School of Mechatronic Engineering and Automation
Shanghai University
Baoshan, Shanghai, China
terabit@shu.edu.cn

Zhedong Han and Yingjie Qian
School of Mechanical Engineering
Shanghai Jiao Tong University
Minhang, Shanghai, China
hzdsjtu@gmail.com and qyjluck@aliyun.com

***Abstract* - In this paper, a novel human direct teaching method of industrial manipulator with large mass and friction based on internal current sensors installed in joints is proposed. Dynamic model for an industrial robot is analyzed in detail, where the gravity torque and friction torque are the main items that need to be considered. Friction torque is influenced by joint speed and temperature. A method to identify joint friction parameters rapidly is proposed, and experiments are carried out to acquire friction characteristics under different temperatures. Then, the implementation method and improvement measures of direct human teaching are introduced in consideration of robot gravity torque and friction torque of joints. Finally, validation tests are conducted to verify the feasibility of the direct teaching method. Experiment result shows that the method based on internal current sensors is capable of realizing direct teaching flexibly and easily.**

Index Terms - Manipulator control, Direct Teaching, Current Sensors.

I. INTRODUCTION

Nowadays, industrial manipulators have been widely used in automated production line. In practical use, collaborative ability, such as direct human teaching, is demanded. Much studies have focused on collaborative robots, but few of them pay attention to traditional industrial manipulators. There are two main ways to realize direct human teaching. The first one bases on position loop, which uses impedance control proposed by Hogan [1]. The principle of impedance control is to establish a mass-spring-damping model in Cartesian space or joint space, making robots compliant to realize direct teaching. The second one bases on torque loop, which uses Force-Free control. The principle of Force-Free control is to compensate dynamic torque and friction torque for realizing direct teaching, as shown in Fig.1 [2].

In industry, a mature solution to realize direct teaching bases on position loop is using force/torque sensors [3]. For example, joint torque sensors are used to obtain external torques of each joint, then the total external torque can be calculated. However, this solution suffers from additional costs and decrease of position accuracy caused by the reduction of joints' stiffness.

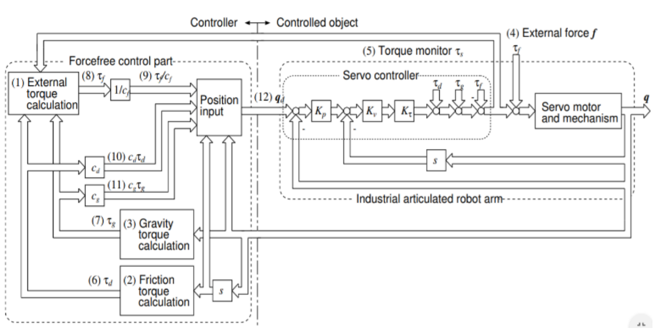

Figure 1. Block Diagram of Force-Free Control [2]

Direct teaching strategies based on position loop without force/torque sensors have been proposed in [4, 5, 6, 7] since 1990s. They used kinds of observers without considering friction effects. Some other researchers [8] transfer force to target position based on joint current to realize direct teaching. They compensated the gravity torque in current loop and obtained joint external torque by dynamic model. Then they converted the torque to desired position.

Traditionally, position control is the most common control scheme of industrial robots. Because position control suits to assignments which need fast speed and high position accuracy. However, force-free control based on position loop will be restricted by the position loop cycle due to its narrow bandwidth. It is not suitable for industrial robots with huge frictional force. Therefore, direct teaching without force/torque sensors based on torque loop has been developed. Some groups indicate that joint torques can be estimated by double encoders [9, 10]. In these methods, the force of friction was ignored, which led to big errors. Another manner of measuring joint torque relies on internal current sensors in joints. Wang [11] implemented direct teaching by using current sensors. You [12] realized direct teaching by compensating torques in the current loop. However, they only accomplish direct teaching in simple collaborative robots or planar linkage whose friction are much smaller than industrial manipulators.

This paper proposed the force-free control method to realize direct human teaching for common industrial manipulators based on joint current sensors. In this method, rapid recognition of friction parameters has important significance. Therefore, a new scheme to identify friction characteristics was proposed in the meantime. The robot used in this paper is an ordinary manipulator from S company. Without loss of generality, we believe this method can be widely applied to other industrial robots.

The rest of this paper is organized as follows. Section II analyzes the dynamic model of the robot. Besides, methods of dynamic modeling and friction parameters identification are discussed in detail. Section III introduces the method to realize and optimize direct human teaching. In Section IV, validation

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experiments are executed, and the experiment results are discussed. Finally, Section V concludes the paper.

II. Dynamic Model

The robot used in this research is a common industrial robot (see Fig.2) from S company with six rotational joints, a maximum end payload of 6 kilograms and a working radius of 1400 millimeters. It has been widely used in industrial manufacture and automatic production, such as welding, bending, heaping and assembling. There is no force/torque sensor and temperature sensors in joints or end effector. Each joint is mainly composed of motor, reducer, encoder, and linkage. Some specifications of this robot are shown in Table I. All of them are common in industrial manipulators.

A. *Robot Dynamic Model*

In the joint space coordinates, the dynamic model of robots can be described by [13]:

$$\tau_m = \tau_f + \tau_e + \tau_d \tag{1}$$

where τ_m is driving torque provided by motor, τ_e is external torque, τ_f is joint friction torque, τ_d is dynamic torque for the robot, and [13]:

$$\tau_d = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \tag{2}$$

where $\ddot{q}$, $\dot{q}$, q are joint acceleration, velocity, and position, respectively, $M(q)\ddot{q}$ is robot inertia torque, $V(q,\dot{q})\dot{q}$ is coupling torque caused by Coriolis force and centripetal force, $G(q)$ is gravity torque.

Figure 2. The robot used in this paper

TABLE I
ROBOT SPECIFICATIONS

Joint No.	Joint motion range	Joint maximum speed
J1	$\pm 165^\circ$	180° /s
J2	$-90^\circ \sim +155^\circ$	180° /s
J3	$-200^\circ \sim +70^\circ$	200° /s
J4	$\pm 170^\circ$	450° /s
J5	$\pm 120^\circ$	320° /s
J6	$\pm 360^\circ$	450° /s

B. *Driving Torque Control*

Drive torque τ_m is determined by:

$$\tau_m = K_t \cdot I \tag{3}$$

where K_t is torque coefficient of motor, I is joint current. K_t is a constant for each specified motor, and it can be calibrated by experiment method proposed in the reference [11] in advance. The torque coefficients of joints in this type of robot are shown in Table II.

C. *Dynamic Torque Derivation*

Dynamic torque τ_d can be calculated by Inertia parameters and dynamic modeling. Inertia parameters of joints are obtained from CAD data which are provided by S company, including mass, central gravity vector, and inertia tensor of each joint. Moreover, this research uses Recursive Newton-Euler Algorithm [14] to model and calculate dynamic torque.

At first, modified D-H coordinate system for the robot is built as Fig.3. D-H specifications are listed in Table III.

Then D-H conversion matrices relating the ith frame with respect to (i-1)th frame are determined by:

TABLE II
TORQUE CONSTANTS OF JOINTS

Joint No.	J1	J2	J3	J4	J5	J6
Torque constant (Nm/A)	76	76	56	20	22	15

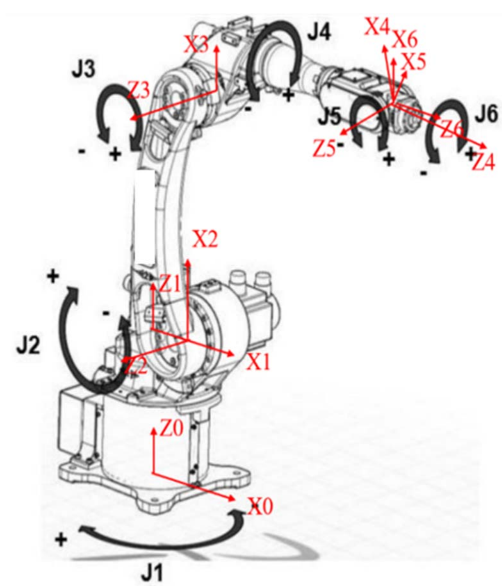


Figure 3. D-H coordinate system of the robot

TABLE III
D-H SPECIFICATIONS OF THE ROBOT

Joint No.	$\alpha_{i-1}(^\circ)$	$a_{i-1}(m)$	$d_i(m)$	$\theta_i(^\circ)$
J1	0	0	0.415	$-pos_1$
J2	90	0.18	0	$90-pos_2$
J3	0	0.59	0	$-pos_3$
J4	90	0.125	0.625	$-pos_4$
J5	-90	0	0	$-pos_5$
J6	90	0	0	$-pos_6$

$$
{}^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -d_i \sin\alpha_{i-1} \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i \cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)
$$

rotation matrix relating the ith frame with respect to (i-1)th frame are determined by:

$$
{}^{i-1}R_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} \end{bmatrix} \quad (5)
$$

translation vector relating the ith frame with respect to (i-1)th frame is determined by:

$$
{}^{i-1}P_i = \begin{bmatrix} a_{i-1} \\ -d_i \sin\alpha_{i-1} \\ d_i \cos\alpha_{i-1} \end{bmatrix} \quad (6)
$$

Finally, velocity and acceleration of joints are derived by forward recursion ($i: 0 \rightarrow 5$):

$$
\begin{cases} {}^{i+1}\omega_{i+1} = {}^{i+1}R_i {}^{i}\omega_i + \dot{\theta}_{i+1} {}^{i+1}Z_{i+1} \\ {}^{i+1}\dot{\omega}_{i+1} = {}^{i+1}R_i {}^{i}\dot{\omega}_i + {}^{i+1}R_i {}^{i}\omega_i \times \dot{\theta}_{i+1} {}^{i+1}Z_{i+1} + \ddot{\theta}_{i+1} {}^{i+1}Z_{i+1} \\ {}^{i+1}\dot{v}_{i+1} = {}^{i+1}R_i ({}^{i}\omega_i \times {}^{i}P_{i+1} + {}^{i}\omega_i \times ({}^{i}\omega_i \times {}^{i}P_{i+1}) + {}^{i}\dot{v}_i) \\ {}^{i+1}\dot{v}_{C_{i+1}} = {}^{i+1}\omega_{i+1} \times \left({}^{i+1}\omega_{i+1} + {}^{i+1}P_{C_{i+1}}\right) + {}^{i+1}\dot{\omega}_{i+1} \times {}^{i+1}P_{C_{i+1}} \\ \quad + {}^{i+1}\dot{v}_{i+1} \\ {}^{i+1}F_{i+1} = m_{i+1} {}^{i+1}\dot{v}_{C_{i+1}} \\ {}^{i+1}N_{i+1} = {}^{C_{i+1}}I_{i+1} {}^{i+1}\dot{\omega}_{i+1} + {}^{i+1}\omega_{i+1} \times {}^{C_{i+1}}I_{i+1} {}^{i+1}\omega_{i+1} \end{cases} \quad (7)
$$

where ${}^{i}\omega_i$ is angular velocity of joint i in the ith frame, ${}^{i+1}R_i$ is rotation matrices of i-th frame relative to $(i+1)$th frame, $\dot{\theta}_i$ is angular velocity of joint i， ${}^{i}Z_i$ is axial direction vector of joint i, ${}^{i}\dot{\omega}_i$ is angular acceleration of joint i in the ith frame, $\ddot{\theta}_i$ is angular acceleration of joint i, ${}^{i}\dot{v}_i$ is linear acceleration of origin of linkage i in the ith frame, ${}^{i}P_{i+1}$ is translation vector of $(i+1)$th frame relative to ith frame, ${}^{i}\dot{v}_{C_i}$ is linear acceleration of the center of gravity of linkage i in the ith frame, ${}^{i}F_i$ is force applied to linkage i, m_i is the weight of linkage i, ${}^{i}N_i$ is torque applied to linkage i, ${}^{C_i}I_i$ is inertia tensor of linkage i. $\dot{\theta}_i$ and $\ddot{\theta}_i$ can be obtained by the robot control system. Dynamic torque τ_d is derived by backward recursion ($i: 6 \rightarrow 1$):

$$
\begin{cases} {}^{i}f_i = {}^{i}R_{i+1} {}^{i+1}f_{i+1} + {}^{i}F_i \\ {}^{i}n_i = {}^{i}N_i + {}^{i}R_{i+1} {}^{i+1}n_{i+1} + {}^{i}P_{C_i} \times {}^{i}F_i + {}^{i}P_{i+1} \times {}^{i}R_{i+1} {}^{i+1}f_{i+1} \\ \tau_i = {}^{i}n_i^T {}^{i}Z_i \end{cases} \quad (8)
$$

where ${}^{i}f_i$ is force applied to linkage i by linkage $i-1$, ${}^{i}n_i$ is torque applied to linkage i by linkage $i-1$, τ_i is dynamic torque of joint $i-1$.

D. Friction Torque Derivation

This research uses a new method to realize quick friction parameters recognition. During five joints motioning along specified trajectories, data including position, velocity, acceleration, and current of each joint are being collected. Then we can identify friction parameters rapidly by data fitting. In advance research, we have found that the main factors affecting joint friction for this type of robot are speed and temperature. The speed-dependent friction model used in this research is:

$$
T_f = f_c + f_v * v + f_b * v^2 + f_t * v^3 \quad (9)
$$

where T_f is friction torque expressed in current permillage, f_c is coefficient of Coulomb friction, f_v is coefficient of viscous friction, f_b is the second-order coefficient, f_t is the third-order coefficient, v is joint speed.

Joints 1, 4, 6 of this robot are yaw joints. Frictional parameters of them can be identified under the condition of no load. The experiment conditions: joints 2, 3, 5 remain stationary, joints 1, 4, 6 stay vertical and motion with specific velocity at the same time. For example, designed position and velocity curves for joint 6 have been shown in Fig.4. Under such conditions, driving torque provided by motor is equal to frictional torque.

Joints 2, 3, 5 are pitch joints. Therefore, Frictional parameters of them cannot be measured without load. However, frictional torque can be calculated by the difference of actual current and ideal current. Ideal current is computed by Recursive Newton-Euler Algorithm. The experiment conditions: joints 1, 4, 6 remain stationary, joints 2, 3, 5 motion with specific velocity.

Besides, before starting each experiment, make the robot run with load at least 20 minutes to stabilize joints temperature. Results of frictional parameters are shown in Table IV. Comparison of actual experiment result and joint friction model is shown in Fig.5.

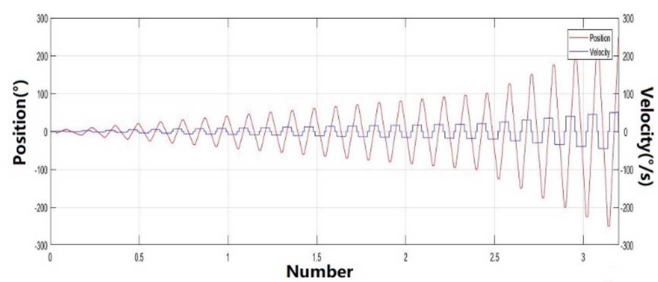
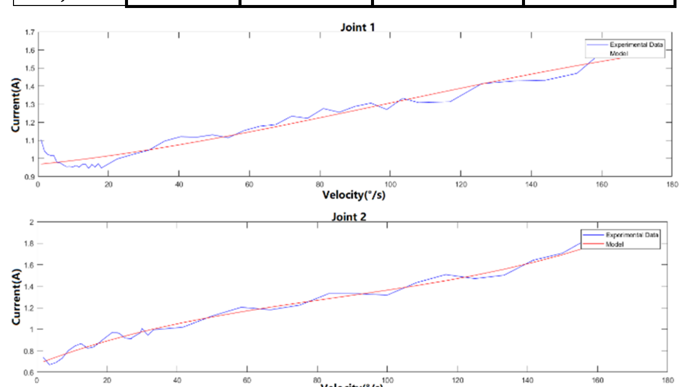


Figure 4. Designed velocity and position of experiment for Joint 6

TABLE IV
FRICTION PARAMETERS OF JOINTS

Joint No.	f_c	f_v	f_b	f_t
J1	0.8210	1.966e-3	7.438e-6	-1.824e-8
J2	0.8733	8.08e-4	2.33e-5	9.477e-8
J3	0.5092	3.910 e-3	1.2064e-6	-4.337e-8
J4	0.1109	6.51e-4	-1.397e-6	2.13e-9
J5	0.1333	2.280e-3	-8.39e-6	1.461e-8
J6	0.0991	1.46e-4	2.112e-7	-5.47e-10



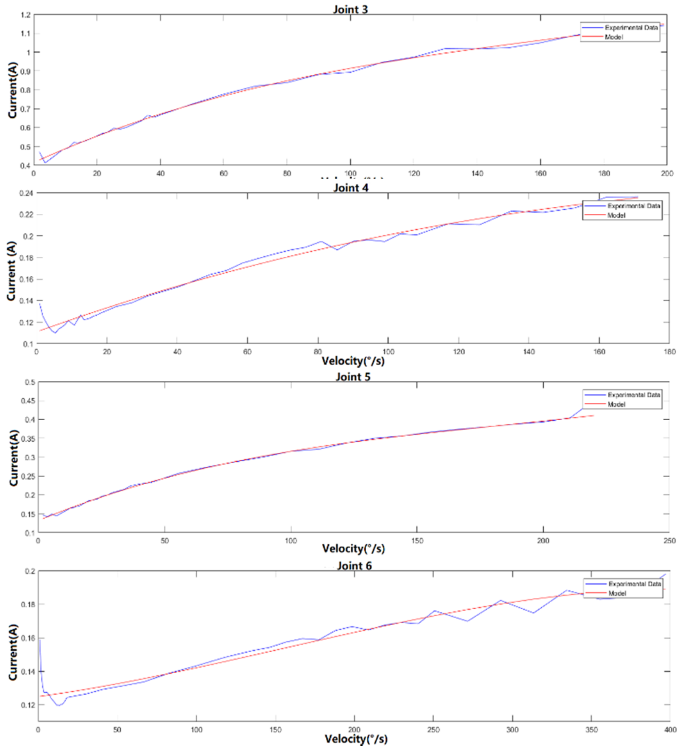


Figure 5. Actual experiment result and joint friction model

Joint temperature affects viscous friction by changing lubricating oil parameters. However, there is no temperature sensor in joints, so we use external temperature sensors to measure joint temperature. Moreover, discrete measure scheme has been adopted. By table look-up, choose different friction model to satisfy variable work temperature. For example, Fig.6 shows different friction models for joint 4 under variable temperature. We can see that friction almost stay unchanged around $0°/s$, which indicates that temperature does not influence Coulomb friction.

III. REALIZATION OF HUMAN DIRECT TEACHING

Direct teaching is usually carried out under low speed and acceleration. Therefore, inertia torque and coupling torque are quite small. According to equation (1) and (2), when the driving torque is equal to the sum of gravity torque and friction torque:

$$\tau_{mt} = G(q) + \tau_f \tag{10}$$

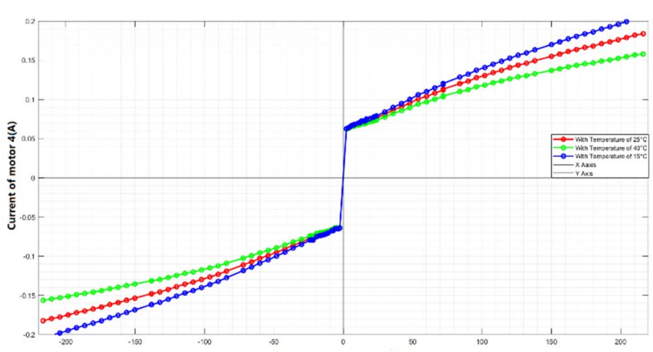


Figure 6. Friction of joint 4 under different speed and temperature

direct teaching operator could easily actuate robot by overcoming small inertia torque and coupling torque:

$$-\tau_e = M(q)\ddot{q} + V(q,\dot{q})\dot{q} \tag{11}$$

A. Compensation of Gravity Torque

Traditional industrial robots usually have high mass, so accurately compensating gravity is vital. Excessive gravity compensation causes difficulty when dragging in gravity direction and unknown crash for the opposite direction, on the contrary, inadequate gravity compensation makes joints possible to fall spontaneously. Therefore, gravity torque compensation must be accurate. The ideal state is that joints are weightlessness.

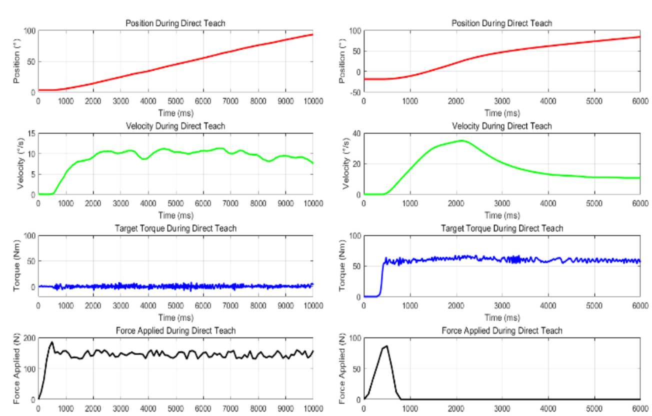
Gravity torque is also derived by Recursive Newton-Euler Algorithm.

B. Compensation of Dynamic Friction

Traditional industrial robots usually have non-negligible friction. If we do not compensate friction torque, a huge force is needed to actuate the robot, which is not acceptable in human teaching. Reversely, if we compensate friction entirely, joints will keep moving after dragging because of inertia. This phenomenon is called joint flap, which may lead to an unknown crash. Therefore, we need to avoid joint flap. Fig.7 (a) and Fig.7 (b) show applied force, joint position, and velocity performance under no friction compensation and completely friction compensation, respectively. As a result, a compensation coefficient $k(0 < k < 1)$ is brought in, which means the compensation of friction is not complete. We have compared direct teaching performances under various k. Fig.8 shows teaching performances under two different k among them. Finally, $k = 0.9$ is chosen on account of smaller driving force and no flap.

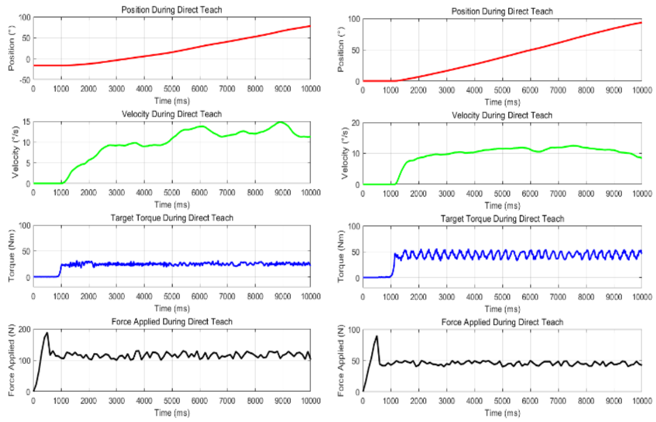
C. Compensation of Static Friction

Static friction appears just before joint starting motion, the value of which changes with external force. When we try to drag joints, if we ignore static friction, external force rises from zero to maximum static friction to overcome it, which is not easy. Besides, even when a joint is stationary, velocity gathered by control system bounces around zero instead of remaining at



(a) Without friction compensation (b) Entire friction compensation

Figure 7. Direct teaching performances



(a) $k = 0.5$ (b) $k = 0.9$

Figure 8. Direct teaching performances

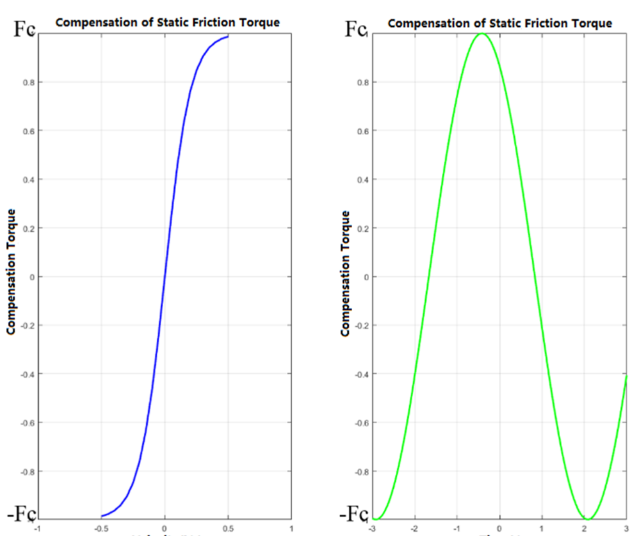
zero. Therefore, drive torques will bounce with it. this may cause vibration of joints. In this research, two compensate methods are used:

- Sigmoid function interpolation method, as shown in Fig.9 (a), which connecting Coulomb friction between positive and negative velocity around zero:

$$f_s(\dot{q}) = \left(\frac{2}{1+e^{-b|\dot{q}|}} - 1\right) * f_c \quad (8)$$

  where $f_s(\dot{q})$ is actual compensate value of static friction, b is sigmoid parameter. This method suits for joint 2, 3, 5, which do not have obvious Stribeck Effect.

- Trigonometric function method, as shown in Fig.9 (b), which changes symbol with time. The amplitude of it is equal to Coulomb friction, and the period is very short. In friction parameters identification, we found joint 1, 4, 6 are influenced by Stribect effect distinctly, which is bad for teaching flexibility. Therefore, we use this method to overcome static friction for joint 1, 4, 6. When the joint is pushed and the direction of driving torque is the same as pushing force, the joint will be actuated easily.



(b) (c)

(a) Sigmoid function (b) Trigonometric function

Figure 9. Compensation method of static friction

D. *Restriction of Joint Position*

This force-free control method based on current has a problem that joint may move out of the allowable range in teaching progress. Therefore, it is important to set software limitation to make sure joints are motion in allowed ranges. In this research, we restrict joints position by decreasing compensation of friction before joints reach extreme position. Huge friction will slow down joints. Moreover, when joint approaching to limiting position, motor provides a reversed torque equal to Coulomb friction, as shown in Fig.10, which allows the operator could drag joint back flexibly.

E. *Restriction of Joint Velocity*

This force-free control method has another problem that external torque is unknown. Oversize external torque leads to high velocity, which may cause unnecessary damage. Therefore, it is also necessary to set software limitation to limit joint speed. When joint velocity approaches speed threshold, compensation of viscous friction is decreased to zero to slow down joints.

IV. VALIDATION TEST OF THE DIRECT TEACHING METHOD

After accomplishing compensation for gravity torque, friction torque and optimization of static friction, joint position, speed, we conduct direct teaching tests to each verify this method.

A. *Validation Tests for Single Joint*

Experiment conditions: under torque control mode, all the joints were locked except the testing joint. A dynamometer was used to push a specified point and measure the minimum dragging force that can drive the joint. After converting dragging forces to torques, minimum dragging torques for each joint are shown in Table V. Minimum dragging torques are much smaller than Coulomb friction, which validated the friction compensation ability of this model

B. *Validation Test for the Whole Robot*

In this experiment, the operator could drag the robot end to an appointed position smoothly and easily. For joint 4, 5, 6, the operator could actuate them by one hand. For large joint 1, 2, 3, the operator could drag robot end by two hands. Some experiment photos are shown in Fig.11.

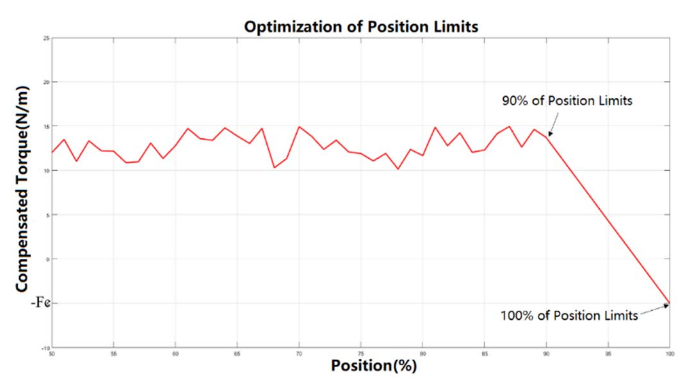


Figure 10. Optimization of position limits

TABLE V
DIRECT TEACHING FORCE OF JOINTS

Joint No.	J1	J2	J3	J4	J5	J6
Coulomb friction torque (Nm)	61	117	41	2.4	4.2	1.0
Minimum dragging force (N)	30	50	30	20	20	16
Minimum dragging torque (Nm)	27	35	19	1.4	2	0.36

V. CONCLUSION

This research proposed a flexible direct human teaching method based on joint current sensors aims at traditional industrial robots with large mass and friction. In this research, a common manipulator was token as an example, so we have reasons to believe that this method can be widely applied to other industrial robots.

The key points of this method are complete compensation of gravity torque and incomplete compensation of friction torque. Then the operator can actuate robot easily by overcoming small inertia torque and coupling torque. Therefore, dynamic modeling of the robot is important. Gravity torque can be acquired by Recursive Newton-Euler Algorithm. In this algorithm, D-H coordinate system is established, inertia parameters of joints which is necessary can be obtained from CAD data. Friction torque can be calculated by using driving torque to minus dynamic torque, as described in this paper. A novel method to rapidly identify parameters of friction is proposed. Besides, the friction model takes account of joint speed and temperature.

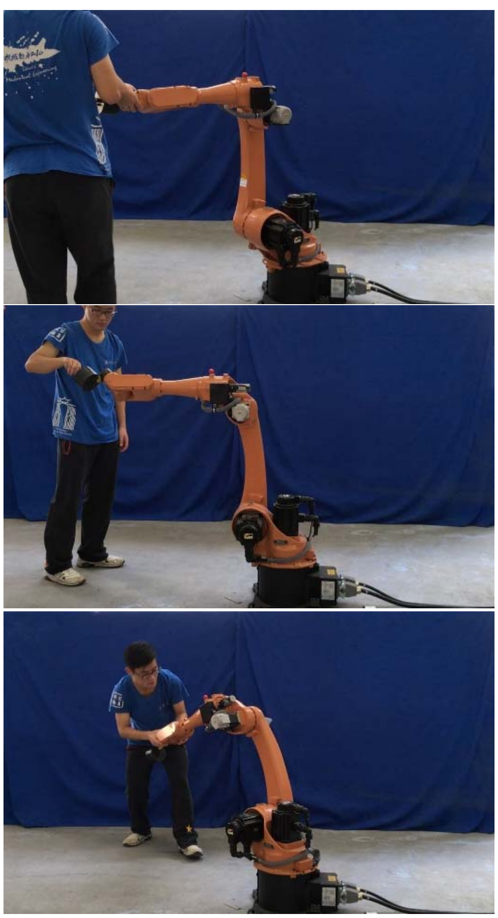


Figure 11. Direct Teaching experiments for the Robot

After compensating gravity torque and friction torque, we optimize the method by handling static friction, which make direct teaching more smoothly. The realization method is using sigmoid function related to speed and trigonometric function related to time to overcome static friction. Sigmoid function suits for friction model without Stribeck effect. On the contrary, trigonometric function is propitious to friction model with obvious Stribeck effect. Then we handle some possible security problems, including using software restrictions to limit joint position and speed. Otherwise, unknown damage or crash may occur during teaching.

Finally, validation direct teaching tests are conducted to each single joint and entire robot. Experiment result shows that this teaching method could realize flexible direct teaching for traditional industrial robots.

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