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Force Perception of Industrial Robot Based on Multi-parameter Coupled Model

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***Abstract*— The precision force sensing information of industrial robots to the environment is important for high-precision and flexible assembly operations. This paper proposed a calibration and calculation method to the contact force with the data from a six-dimensional force/torque sensor, which is installed between the end of the robot and the end-effector. In the proposed method, a multi-parameter coupled model was considered including the gravity of the end-effector, the zero-point of the sensor and the installation angle of six-dimensional force/torque sensor. The contact force/torque could be precisely obtained using this model, and the influence of the gravity and zero drift of sensor can be compensated. Experiments were performed with KUKA iiwa. The results show that the force/torque information was more precise with the coupled model.**

***Index Terms*— Force perception, Coupled Model, Industry Robot**

I. Introduction

Nowadays, industry robots mostly use visual and force sensors to perceive the environment[1]. The visual information is generally the shapes and colors, while most force information reflects the contact flexibility. However, some information is lost during visual occlusion, and it will not be very effective to describe the current contact state of end tool. To guarantee the flexibility of the robot work, it is necessary to perceive the end force accurately[2]. Therefore, in order to provide real-time feedback of the robot operation process, it is necessary to use a force sensor to sense the terminal contact force. Thus, the movement of the robot can be corrected to ensure the flexibility of operation. It is the basis of flexible control[3], [4] and safe operation to accurate perception of the tool force at the end of the robot.

Nowadays, the industrial robot uses a six-dimensional force/torque sensor to detect contact force(see Fig.1), which is installed between the wrist and the end[5], [6]. However, the obtained data is not a pure contact force between the robot and the environment, which cannot be directly used as a feedback signal for force control. There are many factors that affect the accuracy of perception, such as mechanical installation errors, sensor system errors and other information fusion without force.

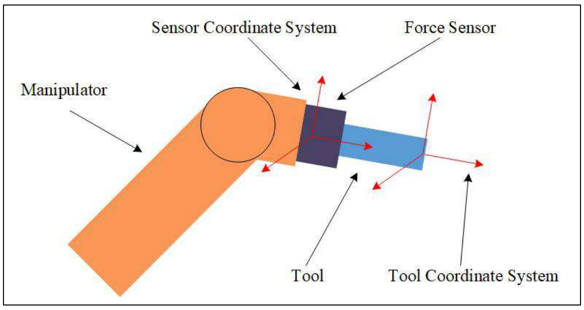

Fig. 1
THE FORCE SENSOR OF INDUSTRIAL ROBOT

In addition, the robot end force can be calculated by the joint torque. Each joint of the robot is equipped with a torque sensor on the output side between gear unit. The contact force between the end of the robot and the environment is the force of the last axis, which is determined by the measuring moment of each joint. Currently, only a few robots have joint torque sensors, the cost of which is relatively expensive, such as KUKA iiwa[7], ROKAE Mate and Franka Panda. The difference between the calculated force and the actual contact force includes the error of the torque of each joint which is a cumulative error that has a serious impact on the accuracy of the results.

Therefore, a multi-parameter coupled model of end force perception is proposed to improve the accuracy of industrial processing operations. Some researchers have done lots of work. The reading of the six-dimensional force transducer

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is not zero in the no-load condition, which is named as the sensors system error. The way and angle of installation between the load and the sensor will affect the size of the error. Zero drift value must be measured under load installation condition. Junjian Lin and Mingjun Cai [8], [9] compensates zero drift by counteracting a measured component by gravity, which using adjusting specific posture of the robot. The effect of gravity can be eliminated by integrating the sensor data of the corresponding posture [10], [11].

It is generally assumed that the Z-axis of the base coordinate system of the robot is the same as the direction of gravity. The installation angle of the sensor is calibrated by changing the pose of the robot[12], [13], [14]. Wenbo Liu[15] eliminated the influence of load gravity on the measurement of sensor torque. The least square method [16] is used to obtain the installation angle of the robot, the weight of the load and the coordinates of the center of gravity [17], [18]. The error of perceived external force is calculated, but the installation angle of the sensor is not considered.

For industrial robot force signal measurement, a multi-parameter coupled model was build to compensate six-axis force/torque sensor sampling data in this paper. The contributions of this paper are as follows.

- The proposed model considers a variety of factors, including a deflection angle between the sensor coordinate system and the robot seventh-axis coordinate system, the gravity of end effector, the center of gravity of the end effector and the zero point of sensor, which improve the measurement accuracy of the contact force.
- The application process of the six-dimensional force/torque sensor calibration is simplified, the proposed model only needs six sets of data to complete the calibration.
- The proposed method was verified using a KUKA iiwa robot with 7-DOF, and the force perception error is calculated to obtain the pure contact force which is simulated by load installed on the end effector.

This paper is organized as follows. Section II introduces Problem Description. Section III contains Parametric Coupling Model. Experiments were performed to verify the proposed model and experimental results are discussed in Section IV. Finally, Section V concludes the main work and discusses the further development direction.

II. Problem Description

Under the static condition, the obtained data of the six-dimensional force sensor mainly includes the following factors. In addition to the external contact force on the load, the zero drift of the sensor is important, which is not zero in the empty load. Zero point measurement must be carried out under the condition of load installation, the installation angle and the degree of tightening will affect the accuracy. The influence of load gravity on sensor data varies with the motion of the robot. It is impossible to accurately extract the contact force, if only the gravity parameters of the end-effector are identified. To eliminate the influence of load gravity, it is necessary to carry out in real time according to the current robot posture. The inertial force of the robot motion is not considered for the moment. The problem to be solved is to identify the parameters that affect the detection accuracy of terminal contact force.

III. Parametric Coupling Model

A. Coordinate System Establishment

The robot involved in this paper is the iiwa manipulator with 7-DOF. For the convenience of describing the relationship between the six-dimensional force/torque, the position of the robot and the end gravity, we establish the coordinate system as shown in Fig.2, including the robot base coordinate system, the robot seventh-axis coordinate system, and the 6-dimensional force/torque sensor coordinate system. The 6-dimensional force/torque sensor coordinate system is a space rectangular coordinate system with three axes of X, Y and Z, the origin of which is at the centre of gravity of the sensor.

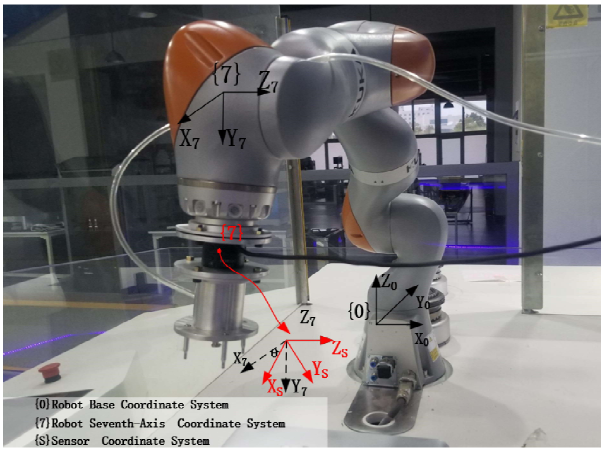

Fig. 2

Robot coordinate system

In addition, ${}^{7}_{S}R$ is the representation of the six-dimensional force sensor coordinate system relative to the seventh-axis coordinate system of the robot. The installation of the six-dimensional force sensor on the end flange of the arm ensures the parallel connection between the sensor mounting surface and the flange mounting surface of the robot arm. The six-dimensional force/torque sensor coordinate system is obtained by rotating seventh axis coordinate system of the robot according to the right-hand screw rule by θ degree to ensure the parallel of the Z axis between the two coordinate systems and ${}^{S}_{7}R$ can be represented by θ. ${}^{0}_{7}R$ is the representation of the seventh-axis coordinate system of the robot relative to the base coordinate, and its value can be read from the robot control system.

B. Multi-parameter Coupled Model

By establishing the relationship between the force measured by the sensor and the position of the robot end, we can get a multi-parameter coupled contact force identification model. Then by recombing parameter, the parameters that need to be identified are reorganized into unknown vectors.

1) The Relationship between Six-dimensional Force and Torque: Set the zero values of three vertical force components as F_{x0}, F_{y0} and F_{z0}, and the zero values of three vertical torque components as T_{x0}, T_{y0} and T_{z0}, the three force components directly measured by the six-dimensional force/torque sensor as F_x, F_y and F_z, the three force components directly measured by the six-dimensional force/torque sensor as T_x, T_y and T_z.

When the end effector is not in contact with the environment, the six-dimensional force/torque sensor only senses the gravity of the end effector and its own gravity. In the six-dimensional force sensor coordinate system, the effect of gravity is shown in the Fig.3. The gravity is represented by G. The coordinate of the center of gravity in the six-dimensional force/torque sensor coordinate system is set as p_x, p_y and p_z. The force component of gravity G in the X, Y, and Z directions is G_x, G_y and G_z, and the torque component is T_{gx}, T_{gy} and T_{gz}.

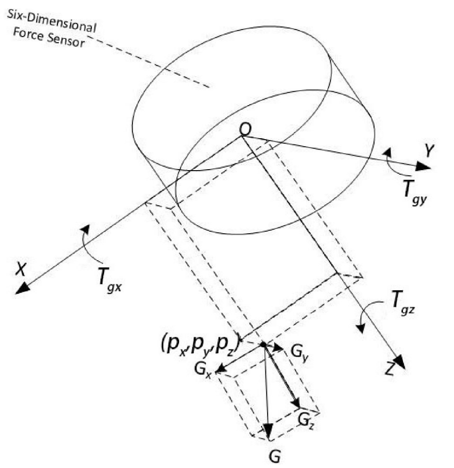

Fig. 3
THE GRAVITY IN COORDINATE OF FORCE/TORQUE SENSOR

According to the relationship between force and torque, it is easy to get(refer to Fig.3):

$$\begin{cases} T_{gx} = G_z \times p_y - G_y \times p_z \\ T_{gy} = G_x \times p_z - G_z \times p_x \\ T_{gz} = G_y \times p_x - G_x \times p_y \end{cases} \tag{1}$$

And the force and torque measured by the sensor is composed of gravity and zero values of the sensor, so the relationship is described as:

$$\begin{cases} F_x = G_x + F_{x0} \\ F_y = G_y + F_{y0} \\ F_z = G_x + F_{z0} \\ T_x = T_{gx} + T_{x0} \\ T_y = T_{gy} + T_{y0} \\ T_z = T_{gz} + T_{z0} \end{cases} \tag{2}$$

Substituting Equation.2 into Equation.1, we have:

$$\begin{cases} M_x = F_z \times p_y - F_y \times p_z + T_{x0} + F_{y0} \times p_z - F_{z0} \times p_y \\ M_y = F_x \times p_z - F_z \times p_x + T_{y0} + F_{z0} \times p_x - F_{x0} \times p_z \\ M_x = F_y \times p_x - F_x \times p_y + T_{z0} + F_{x0} \times p_y - F_{y0} \times p_x \end{cases} \tag{3}$$

Here, F_{x0}, F_{y0}, F_{z0}, T_{x0}, T_{y0}, T_{z0}, p_x, p_y and p_z are constant, we set:

$$\begin{cases} l_1 = T_{x0} + F_{y0} \times p_z - F_{z0} \times p_y \\ l_2 = T_{y0} + F_{z0} \times p_x - F_{x0} \times p_z \\ l_3 = T_{z0} + F_{x0} \times p_y - F_{y0} \times p_x \end{cases} \tag{4}$$

Substituting Equation.4 into Equation.3, turn into the form of matrix as Equation.5.

$$\begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} = \begin{bmatrix} 0 & F_z & -F_y & 1 & 0 & 0 \\ -F_z & 0 & F_x & 0 & 1 & 0 \\ F_y & -F_x & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} p_x \\ p_y \\ p_z \\ l_1 \\ l_2 \\ l_3 \end{bmatrix} \tag{5}$$

In this way, we can reorganize Equations.5 into the following form:

$$T = FL \tag{6}$$

Here, L is an unknown parameter vector that needs to be identified, T is an output vector which is the torque value vector, F is an input matrix which is the force value vector. If $A^T A$ is an invertible matrix, we can get:

$$L = (F^T F)^{-1} F^T T \tag{7}$$

By collecting multiple sets of data and using the least squares method, p_x, p_y, p_z, l_1, l_2 and l_3 can be obtained.

2) The Relationship between the Force Measured and Gravity: Set the end position of the robot as

$$^{0}_{7}R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \tag{8}$$

For general industrial robots, the values of elements in matrix $^{0}_{7}R$ can be obtained directly by the robot control system. ${}^7_sR$ can be represented by θ in the following matrix.

$$
{}^7_sR = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{9}
$$

We set G as the value of the gravity of the end effector and the six-dimensional force/torque sensor. The direction vector of gravity in the base coordinate system is

$$
\mathbf{g_0} = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \tag{10}
$$

Here, -1 indicates that the direction of gravity is opposite to the z-axis direction of the base coordinate system.

Through the coordinate transformation, the direction vector of gravity in the sensor coordinate system can be obtained as following.

$$
\begin{aligned}
\mathbf{g_s} &= {}^0_sR \cdot \mathbf{g_0} \\
&= {}^s_0R^T \cdot \mathbf{g_0} \\
&= [{}^0_7R\,{}^7_sR]^T \mathbf{g_0}
\end{aligned} \tag{11}
$$

Substituting Equation.9-10 into Equation.11, we can obtain $\mathbf{g_s}$:

$$
\mathbf{g_s} = \begin{bmatrix} -R_{31}\cos\theta - R_{32}\sin\theta \\ -R_{32}\cos\theta + R_{31}\sin\theta \\ -R_{33} \end{bmatrix} \tag{12}
$$

From Equation.2, we have

$$
\begin{aligned}
\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} &= \begin{bmatrix} G_x \\ G_y \\ G_z \end{bmatrix} + \begin{bmatrix} F_{x0} \\ F_{y0} \\ F_{z0} \end{bmatrix} \\
&= G \begin{bmatrix} -R_{31}\cos\theta - R_{32}\sin\theta \\ -R_{32}\cos\theta + R_{31}\sin\theta \\ -R_{33} \end{bmatrix} + \begin{bmatrix} F_{x0} \\ F_{y0} \\ F_{z0} \end{bmatrix} \\
&= \begin{bmatrix} -R_{31} & -R_{32} & 0 & 1 & 0 & 0 \\ -R_{32} & R_{31} & 0 & 0 & 1 & 0 \\ 0 & 0 & R_{33} & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} G\cdot\cos\theta \\ G\cdot\sin\theta \\ G \\ F_{x0} \\ F_{y0} \\ F_{z0} \end{bmatrix}
\end{aligned} \tag{13}
$$

In this way, we can reorganize the Equations.13 into the following form.

$$
F_M = RG \tag{14}
$$

Here, G is an unknown parameter vector that needs to be identified, F_M is an output vector which is the force value vector measured by the sensor, R is an input matrix which is composed of some elements of the end position matrix. If R^TR is an invertible matrix, we can get:

$$
G = (R^TR)^{-1}R^TF_M \tag{15}
$$

By collecting multiple sets of data and using the least squares method, θ, G, F_{x0}, F_{y0} and F_{z0} can be obtained.

3) The other parameters: From Equation.5, we can obtain T_{x0}, T_{y0} and T_{z0}.

$$
\begin{cases} T_{x0} = l_1 - F_{y0} \times p_z + F_{z0} \times p_y \\ T_{y0} = l_2 - F_{z0} \times p_x + F_{x0} \times p_z \\ T_{z0} = l_3 - F_{z0} \times p_y + F_{y0} \times p_x \end{cases} \tag{16}
$$

All the model parameters have been obtained.

C. Environmental Contact Force Calculation

When the end effector of the robot is in contact with the external environment, the force and torque measured by the six-dimensional force sensor is compensated by the part caused by the zero drift and the part caused by the gravity which can be calculated by the current position, so the contact force can be obtained.

From Equation.13, we can obtain the force component of the gravity in the X, Y, and Z axis directions of the six-dimensional force sensor/torque coordinate system.

$$
\begin{bmatrix} G_x \\ G_y \\ G_z \end{bmatrix} = G \cdot \begin{bmatrix} -R_{31}\cos\theta - R_{32}\sin\theta \\ -R_{32}\cos\theta + R_{31}\sin\theta \\ -R_{33} \end{bmatrix} \tag{17}
$$

And from Equation.1, we can obtain the torque component of the gravity in the X, Y and Z axis directions of the six-dimensional force sensor/torque coordinate system T_{gx}, T_{gy} and T_{gz}.

The component of the contact force and torque in the X, Y and Z axis directions of the six-dimensional force/torque sensor coordinate system are:

$$
\begin{cases} F_{sx} = F_x - F_{x0} - G_x \\ F_{sy} = F_y - F_{y0} - G_y \\ F_{sz} = F_z - F_{z0} - G_z \\ T_{sx} = T_x - T_{x0} - T_{gx} \\ T_{sy} = T_y - T_{y0} - T_{gy} \\ T_{sz} = T_z - T_{z0} - T_{gz} \end{cases} \tag{18}
$$

IV. EXPERIMENTS

A. Experiment Setup

In this paper, experiments are performed in the platform (see Fig.4) which uses the KUKA iiwa 7R800 robot (TableI), and the M8125 six-dimensional force/torque sensor (TableII) which is installed at the seventh-axis end of the robot. Each joint of the KUKA robot is equipped with a position sensor and a torque sensor, so the robot can be operated with position and impedance control. The M8125 sensor has reliable and stable performance, and supports the online setting of parameters on the network. Users can directly set the parameters of the sensor by logging in the webpage of the sensor through the network cable through the personal computer. The sensor includes an Ethernet interface. In order to ensure the accuracy of the data collected by the sensor, we use a low-pass filter to process the data.

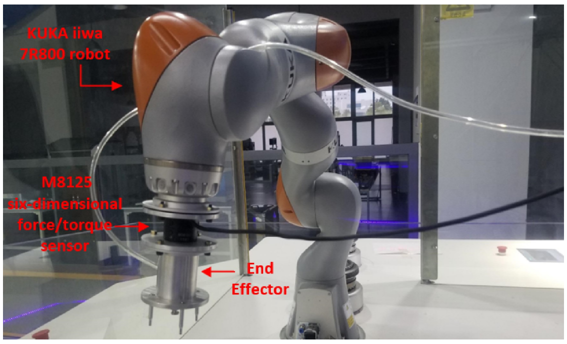

Fig. 4
END FORCE PERCEPTION EXPERIMENT PLATFORM

TABLE I
ROBOT PERFORMANCE PARAMETERS

Attributes	load	axis	radius	accuracy
Values	7kg	7	800mm	0.1mm

TABLE II
TECHNOLOGY PARAMETERS OF M8125

Attributes	F_x	F_y	F_Z	T_x	T_y	T_z
CAPACITY(N/Nm)	70	70	70	3.0	1	1
Output(mV/V)	0.9	0.9	0.6	0.9	0.9	0.9
BRIDGE RES(Ω)	350	350	700	350	350	700

B. Experiment Results

To identify the required parameters of the coupled model, adjust the robot to different 6 positions (see fig.5) and collect the arm end position(listed in tableIII) and sensor data(listed in tableIV).

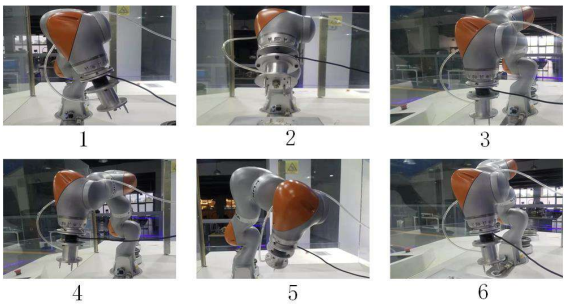

Fig. 5
SIX POSTURE OF ROBOT

TABLE III
POSITION PARAMETERS OF ROBOT

No.	x	y	z	α	β	γ
1	-630.55	0.56	359.45	44.29	-0.09	179.21
2	-617.60	-124.86	371.01	55.73	7.86	172.57
3	-650.49	-102.96	419.47	45.52	19.56	167.11
4	-650.75	81.99	431.99	36.65	0.16	-171.65
5	-694.01	86.99	444.66	40.72	14.30	-156.48
6	-695.02	127.99	367.67	39.38	8.51	-160.23

TABLE IV
DATA FROM THE SENSOR

No.	F_x	F_y	F_z	T_x	T_y	T_z
1	4.231	-6.582	58.432	2.236	0.972	0.012
2	4.287	-7.448	57.085	2.255	0.963	0.014
3	4.676	-8.412	55.250	2.274	0.964	0.015
4	4.774	-6.153	58.598	2.218	0.999	0.011
5	6.394	-6.139	56.942	2.204	1.054	0.018
6	5.902	-6.001	57.640	2.206	1.037	0.017

Using the the least squares method, we can compute the results of the the coordinate of the center of gravity, the installation inclination degree, the weight of the end-effector and the zero drift values in the proposed model listed as tableV.

TABLE V
RESULTS OF GRAVITY CENTER

p_x	p_y	p_z	l_1	l_2	l_3	θ
-0.006	0.006	0.032	1.661	0.496	-0.002	33.918
G	F_{x0}	F_{y0}	F_{z0}	T_{x0}	T_{y0}	T_{z0}
1.980	3.769	-6.903	57.657	2.228	0.963	-0.002

In the above six position, the force and torque values calculated by the proposed model are shown in table VI and the error of the estimated outputs are shown in table VII. The maximum force error occurs in the Z-axis direction, which is $1.177N$, mainly caused by random errors.

To compare with the method of compensating only gravity, the results of contact force when the end-effector is not in contact are shown in table VIII. The maximum force error is $57.097N$, we can easily find that the errors calculated by the proposed method are much smaller and the weights of the load calculated are much more accurate.

To validate the proposed model, a load was installed on the end effector of the robot to simulate the contact force with the

TABLE VI
THE CONTACT FORCE/TORQUE VALUES CALCULATED

No.	F_x	F_y	F_z	T_x	T_y	T_z
1	0.155	0.434	-1.177	0.054	0.032	0.003
2	0.105	0.638	-0.560	0.065	0.157	0.001
3	0.154	0.359	-1.005	0.087	0.235	0.002
4	0.155	0.437	-1.107	0.055	0.073	0.004
5	0.134	0.584	-0.980	0.056	0.121	0.002
6	0.151	0.383	-1.201	0.081	0.243	0.005

TABLE VII
THE ERROR OF THE ESTIMATED OUTPUTS

Error	F_x	F_y	F_z	T_x	T_y	T_z
Average Error	0.142	0.472	1.005	0.066	0.144	0.003
Maximum Error	0.155	0.638	1.177	0.087	0.243	0.005

TABLE VIII
THE ERROR OF THE OUTPUTS COMPENSATING ONLY GRAVITY

Error	F_x	F_y	F_z	T_x	T_y	T_z
Average Error	3.911	6.431	56.652	2.294	1.107	0.001
Maximum Error	3.924	6.544	57.097	2.301	1.206	0.003

external environment. The gravity of the load was considered as a verification condition. Use four weight value loads for verification test(100g, 200g, 500g and 1000g). We compare results calculated with the actual gravity as shown in table IX. The minimum error value is only 2.89%, which proves the proposed force perception model has good estimation accuracy and efficiency.

TABLE IX
RESULT OF VERIFICATION TEST

No.	$G_{measure}$	$G_{actucal}$	Error
1	94.3g	100g	5.70%
2	191.5g	200g	4.25%
3	480.8g	500g	3.84%
4	971.1g	1000g	2.89%

V. CONCLUSIONS

The factors were analyzed that affect the measurement accuracy of human sensors in industrial machines, including zero drift, end-tool gravity and installation inclination. By establishing a parameter coupled model, the relationship between the measured values of sensors and these factors is obtained. The parametric coupled model can be used to compensate the data collected by the six-dimensional force sensor and improve the sampling accuracy of the end-effector and the environmental contact force. The proposed model has two advantages: First, it can overall identify all the parameters, the application process of the contact force perception is simplified; Second, compared with the method of compensating only gravity, the measurement accuracy of contact force is improved.

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