Movement Characteristics Analysis and Dynamic Simulation of Collaborative Measuring Robot

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Abstract. Human-machine collaboration is becoming increasingly more necessary, and so collaborative robot applications are also in high demand. We selected a UR10 robot as our research subject for this study. First, we applied D-H coordinate transformation of the robot to establish a link system, and we then used inverse transformation to solve the robot's inverse kinematics and find all the joints. Use Lagrange method to analysis UR robot dynamics; use ADAMS multibody dynamics simulation software to dynamic simulation; verifying the correctness of the derived kinetic models.

1. Introduction

Since human-machine collaborations are currently in high demand, collaborative robot applications are being used with increasing frequency. UR robots have a force feedback function, meaning that when they collide, they automatically stop working. Therefore, in most applications a collaboration robot model does not require a security fence[1].

We selected a UR10 robot as our research subject for this study. First, we applied D-H coordinate transformation of the robot to establish a link system, and we then used inverse transformation to solve the robot's inverse kinematics and find all the joints. Using Lagrange method to analysis UR robot dynamics; using ADAMS multibody dynamics simulation software to dynamic simulation; verifying the correctness of the derived kinetic models.

2. Kinematics Solution

The traditional process to solve kinematics involves studying movement relationships, but does not consider the interaction force between each link[2]. To solve a forward kinematics problem we must solve the position and orientation of the end-effector in the base coordinate system, which is in turn based on the joint angle and dimensions of the known links. Once this has been done, the essential components are in place and it is possible to solve kinematic equations. With inverse kinematics, we strike each joint's angles when the end-effector reaches a location based on its known position and orientation the in base coordinate system.

2.1. Establishing the connecting coordinate system

UR10 is a series robot with six revolute joints. In this study, we used the D-H coordinate transformation method to solve the position and orientation relationship between each link of the robot.The steps are as follows[3]:

(1) Establish the coordinate system $x_0y_0z_0$ and confirm initial position and orientation;

(2) Establish a second joint coordinate system based on the DH coordinate principle;

IOP Conf. Series: Materials Science and Engineering **187** (2017) 012043 doi:10.1088/1757-899X/187/1/012043

(3) Establish a robot tool coordinate system $x_6 y_6 z_6$.

Fig. 1 below illustrates the DH coordinate system of a UR10 robot.

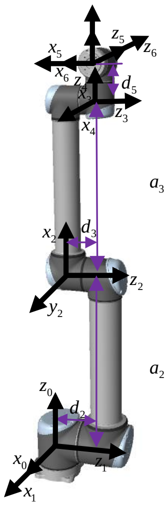

Figure 1. DH coordinate system of UR10

2.2. Forward kinematics solution

DH parameters can be determined based on the conversion relationship between adjacent joints and the links' coordinate system. All the joints of UR10 are revolute joints. This means that only the joint angle θ is variable, while joints with a twist angle α, link length a, and link distance d are constant. Table 1 shows the DH parameters for a UR10.

Table 1 DH parameters of UR10 robot

joint	α/(°)	a/(mm)	d/(mm)	θ/(°)	range(°)
1	-90 °	0	0	θ_1	-360~360
2	0 °	a_2	d_2	θ_2	-360~360
3	0 °	a_3	d_3	θ_3	-360~360
4	90 °	0	0	θ_4	-360~360
5	90 °	0	d_5	θ_5	-360~360
6	0 °	0	0	θ_6	-360~360

The transformation matrix between the robot's adjacent joint coordinates are shown in Formula (1) .

$$
\begin{aligned}
{}^{i-1}T_i &= Rot(z,\theta_i)\times Trans(0,0,d_i)\times Trans(a_i,0,0)\times Rot(x,\alpha_i) \\
&= \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{aligned} \tag{1}
$$

In order to obtain the transformation matrix between the adjacent coordinate system, we must enter the DH parameters of Table 1 into Formula (1). Subsequently, we multiply the resulting transformation matrix, which provides positive solutions as shown in Formula (2). ($c_i = \cos\theta_i, s_i = \sin\theta_i, c_{ijk} = \cos(\theta_i+\theta_j+\theta_k), s_{ijk} = \sin(\theta_i+\theta_j+\theta_k)\ i = 1\cdots 6, j = 1\cdots 6, k = 1\cdots 6$)。

$$
{}^0T_6 = {}^0T_1\,{}^1T_2\,{}^2T_3\,{}^3T_4\,{}^4T_5\,{}^5T_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}
$$

In which

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$$n_x = c_1 s_{234} s_6 - c_6 \left(s_1 s_5 - c_1 c_5 c_{234} \right); n_y = s_1 s_{234} s_6 + c_6 \left(c_1 s_5 + s_1 c_5 c_{234} \right) \; n_z = s_{234} s_6 - c_5 c_6 s_{234}; o_x = c_1 s_{234} c_6 + s_6 \left(s_1 s_5 - c_1 c_5 c_{234} \right)$$

$$o_y = s_1 s_{234} c_6 - s_6 \left(c_1 s_5 + s_1 c_5 c_{234} \right); o_z = c_5 s_{234} s_6 - c_6 c_{234} \; a_x = c_1 c_{234} s_5 + s_1 c_5; a_y = s_1 c_{234} s_5 - c_1 c_5; a_z = -s_5 s_{234}$$

$$p_x = d_5 c_1 s_{234} + c_1 a_3 c_{23} + c_1 a_3 c_{23} - s_1 d_2 - s_1 d_3 \; p_y = d_5 s_1 s_{234} + c_2 a_2 s_1 + s_1 a_3 c_{23} + c_1 d_3 + c_1 d_2 \; p_z = d_5 c_{234} - s_2 a_2 - s_3 s_{23}$$

2.3. Formatting author affiliations The inverse kinematics solution

According to the configuration characteristics of UR10, the second, third, and fourth joint axes are parallel. This meets the condition that three adjacent joint axes are parallel or intersecting at one point. Therefore, inverse kinematics for the UR robot exist.

1) Solve θ_1

Put ${}^0T_6 = {}^0T_1 {}^1T_2 {}^2T_3 {}^3T_4 {}^4T_5 {}^5T_6$ left and right side multiplied by $\left({}^0T_1\right)^{-1}$, then

$$\left({}^0T_1\right)^{-1} {}^0T_6 = \begin{bmatrix} c_1 n_x + s_1 n_y & c_1 o_x + s_1 o_y & c_1 a_x + s_1 a_y & c_1 p_x + s_1 p_y \\ -n_z & -o_z & -a_z & -p_z \\ -s_1 n_x + c_1 n_y & -s_1 o_x + c_1 o_y & -s_1 a_x + c_1 a_y & -s_1 p_x + c_1 p_y \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$\text{make: } {}^1T_2 {}^2T_3 {}^3T_4 {}^4T_5 {}^5T_6 = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \tag{4}$$

Take the third row and transpose into：

$$\left[A_{31} \quad A_{32} \quad A_{33} \quad A_{34} \right] = \left[s_5 c_6 \quad -s_5 s_6 \quad -c_5 \quad d_2 + d_3 \right] \tag{5}$$

The third row and the fourth column of Formula (3) and Formula (4) correspond with:

$$-s_1 p_x + c_1 p_y = d_2 + d_3 \tag{6}$$

Perform the following triangle substitution for Formula (6)

$$\begin{cases} p_x = r\cos\varphi \\ p_y = r\sin\varphi \end{cases} \quad r = \sqrt{p_x^2 + p_y^2} \quad \varphi = \arctan\left(\frac{p_y}{p_x}\right) \text{So} \quad \theta_1 = \arctan\left(\frac{p_y}{p_x}\right) - \arctan\frac{\left(d_2 + d_3\right)^2}{\pm\sqrt{r^2 - \left(d_2 + d_3\right)^2}}.$$

2) Solve θ_5 The third row and third column of Formula (3) and Formula (4) correspond with:

$$-c_5 = c_1 a_y - s_1 a_x \tag{7}$$

So

$$\theta_5 = \arccos(s_1 a_x - c_1 a_y)$$

3) Solve θ_6 The third row and the first column of Formula (3) and Formula (4) correspond with:

$$c_6 s_5 = c_1 n_y - s_1 n_x \tag{8}$$

So $\theta_6 = \arccos(\dfrac{c_1 n_y - s_1 n_x}{s_5})$ Where $s_{234} = \dfrac{-a_z}{s_5}$ $c_{234} = \dfrac{c_1 a_x + s_1 a_y}{s_5}$

4) Solve θ_2 Put ${}^0T_6 = {}^0T_1 {}^1T_2 {}^2T_3 {}^3T_4 {}^4T_5 {}^5T_6$ left and right side multiplied by the $\left({}^0T_1 {}^1T_2\right)^{-1}$,then

$${}^2T_3 {}^3T_4 {}^4T_5 {}^5T_6 = \begin{bmatrix} c_{34} c_5 c_6 + s_{34} s_6 & s_{34} c_6 - c_{34} c_5 s_6 & c_{34} s_5 & c_3 a_3 + d_5 s_{34} \\ s_{34} c_5 c_6 - c_{34} s_6 & -c_{34} c_6 - s_{34} c_5 s_6 & s_{34} s_5 & s_3 a_3 - d_5 c_{34} \\ s_5 c_6 & s_5 s_6 & -c_5 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

make:

$$\left({}^0T_1 {}^1T_2\right)^{-1} {}^0T_6 = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \end{bmatrix} \tag{10}$$

The second column, third column and fourth elements (respectively):

$$\begin{bmatrix} B_{12} \\ B_{22} \\ B_{32} \\ B_{42} \end{bmatrix} = \begin{bmatrix} c_1 c_2 o_x + s_1 c_2 o_y - s_2 o_z \\ -c_1 s_2 o_x - s_1 s_2 o_y - c_2 o_z \\ c_1 o_y - o_x s_1 \\ 0 \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} B_{13} \\ B_{23} \\ B_{33} \\ B_{43} \end{bmatrix} = \begin{bmatrix} c_1 c_2 a_x + s_1 c_2 a_y - s_2 a_z \\ -c_1 s_2 a_x - s_1 s_2 a_y - c_2 a_z \\ c_1 a_y - s_1 a_x \\ 0 \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} B_{14} \\ B_{24} \\ B_{34} \\ B_{44} \end{bmatrix} = \begin{bmatrix} c_1 c_2 p_x + s_1 c_2 p_y - s_2 p_z - a_2 \\ -c_1 s_2 p_x - s_1 s_2 p_y - c_2 p_z \\ p_y c_1 - p_x s_1 - d_2 \\ 1 \end{bmatrix} \tag{13}$$

The first row and second column of Formula (9) and Formula (10) correspond with:

$$c_1 c_2 o_x + s_1 c_2 o_y - s_2 o_z = s_{34} c_6 - c_{34} c_5 s_6 \tag{14}$$

So
$$\theta_2 = \arctan \frac{c_1 o_x + s_1 o_y + c_5 c_6 \dfrac{c_1 a_x + s_1 a_y}{s_5} + c_6 \dfrac{a_z}{s_5}}{o_z - c_6 \dfrac{c_1 a_x + s_1 a_y}{s_5} + c_5 c_6 \dfrac{a_z}{s_5}}$$

5) Solve θ_3 The second row and third column, and the second row and fourth column of Formula (9) and Formula (10) correspond with:

$$c_{34} s_5 = -c_1 s_2 a_x - s_1 s_2 a_y - c_2 a_z \tag{15}$$

$$s_3 a_3 - d_5 c_{34} = -c_1 s_2 p_x - s_1 s_2 p_y - c_2 p_z \tag{16}$$

So
$$\theta_3 = \arcsin\left(\frac{-c_1 s_2 p_x - s_1 s_2 p_y - c_2 p_z + d_5 \dfrac{c_1 c_2 a_z + s_1 c_2 a_y - s_2 a_z}{s_5}}{a_3} \right)$$

6) Solve θ_4 Based the above，joints θ_{234} θ_2 θ_3 are known，so $\theta_4 = \theta_{234} - \theta_2 - \theta_3$

$$\theta_4 = \arcsin\left(\frac{-a_z}{s_5}\right) - \arctan \frac{c_1 o_x + s_1 o_y + c_5 c_6 \dfrac{c_1 a_x + s_1 a_y}{s_5} + c_6 \dfrac{a_z}{s_5}}{o_z - c_6 \dfrac{c_1 a_x + s_1 a_y}{s_5} + c_5 c_6 \dfrac{a_z}{s_5}} - \arcsin\left(\frac{-c_1 s_2 p_x - s_1 s_2 p_y - c_2 p_z + d_5 \dfrac{c_1 c_2 a_z + s_1 c_2 a_y - s_2 a_z}{s_5}}{a_3} \right)$$

3. Dynamics Equation of Measuring Robot

There is many methods to study robot dynamics, mainly Newton-Euler method (Newton-Euler)[4], Lagrangian (Lan-grange) method[5], Gauss (Gauss) law[6], Kane (Kane) method and Robertson-Weiden Fort (Robson-Wittenburg) method[7]. In this paper, creating dynamic equations of the robot used Lagrange way.Lagrange equation is:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i \left(i = 1, 2 \ldots 6 \right) \tag{17}$$

Type, q_i， $\dot{q}_i$ is the generalized coordinates and generalized velocity; Q_i is the generalized force for the generalized coordinates.Seting the translational velocity vector is v_{ci}， the angular velocity vector is ω_i, for the quality is m_i, relative to the center of mass of inertia tensor is I_i in the base coordinate system，the kinetic energy of i th joints is：

$$T_i = \frac{1}{2} m_i v_{ci}{}^T v_{ci} + \frac{1}{2} \omega_i{}^T I_i w_i \tag{18}$$

Among them, the first item is the kinetic energy of the object in the translational motion, the second is the kinetic energy of the object rotating around the center of mass. The i th joint velocity in basic coordinate system and the joints and before each joint can be expressed as the relationship between the speed

$$\begin{bmatrix} v_{ci} \\ w_i \end{bmatrix} = \begin{bmatrix} J_{L1}^{(i)} & \cdots & J_{Li}^{(i)} \\ J_{A1}^{(i)} & \cdots & J_{Ai}^{(i)} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \vdots \\ \dot{q}_i \end{bmatrix} = \begin{bmatrix} J_L^{(i)} \dot{q}_i \\ J_A^{(i)} \dot{q}_i \end{bmatrix}$$

Because joints for the rotational joint, so the total kinetic energy for the robot is：

$$T = \sum_{i=1}^{n} T_i = \frac{1}{2}\sum_{i=1}^{n} \dot{q}^T M \dot{q} = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} M_{ij}\dot{q}_i\dot{q}_j \tag{19}$$

M_{ij} is the n square matrix of M element

$$M = \sum_{i=1}^{n}\left(m_i J_L^{(i)T} J_L^{(i)} + J_A^{(i)T} I_i J_A^{(i)} \right) \tag{20}$$

The robot's potential energy $U = \sum_{i=1}^{n} m_i g^T O_{P_{ci}}$ Among them, g is acceleration of gravity vector on the basis of coordinates system, $O_{P_{ci}}$ is the vector of origin of coordinates to the center of mass of the vector on the basis of the origin of coordinates. Generalized force is： $Q = \tau + J^T F$

Among them, τ and F respectively joint force vector and the force vector of end of actuator contact with the external environment.Put the robot's kinetic energy, potential energy and generalized force generation into the Lagrange equation, available the robot dynamics equation.

$$\sum_{j=1}^{n} M_{ij}\ddot{q}_j + \sum_{j=1}^{n}\sum_{k=1}^{n}\left(\frac{\partial M_{ij}}{\partial q_k} - \frac{1}{2}\frac{\partial M_{ij}}{\partial q_i} \right)\dot{q}_j\dot{q}_k + \sum_{j=1}^{n} m_i g^T J_{Li}^{(j)} = Q_i \tag{21}$$

As can be seen by the above formula is derived to calculate the theoretical advantage of solving the dynamic equations of the robot more complex, so the general multi-body dynamics simulation method to accomplish each robot joint force or torque solving.

4. Dynamics Simulation of Measuring Robot

We us ADAMS to simulate the dynamics of the measuring robot, the simulation time is set to 5s, step number is set to 500. add drivers in each of the joints as follow setting.
1)The first joint rotation control function
STEP(time,0,0,0.5,72d)+STEP(time,0.5,0,5.5,0)+STEP(time,5.5,0,6,-72d),
2)The second joint rotation control function
STEP(time,0,0,1,40d)+STEP(time,1,0,9,0)+STEP(time,9,0,10,-40d)
3)The third joint rotation control function
STEP(time,0,0,1,40d)+STEP(time,1,0,9,0)+STEP(time,9,0,10,-40d)
4)The forth joint rotation control function
STEP(time,0,0,1,50d)+STEP(time,1,0,7,0)+STEP(time,7,0,8,-50d)
5)The fifth joint rotation control function
STEP(time,0,0,1,60d)+STEP(time,1,0,6,0)+STEP(time,6,0,7,-60d)
6)The sixth joint rotation control function
STEP(time,0,0,1,80d)+STEP(time,1,0,5,0)+STEP(time,5,0,6,-80d)

4.1. Angular Velocity of each joint

Each joint angular velocity curve shown in figure 2, which play a very important role in the dynamics of the robot's overall design, therefore needs to measure each joint angular velocity changes during the simulation.

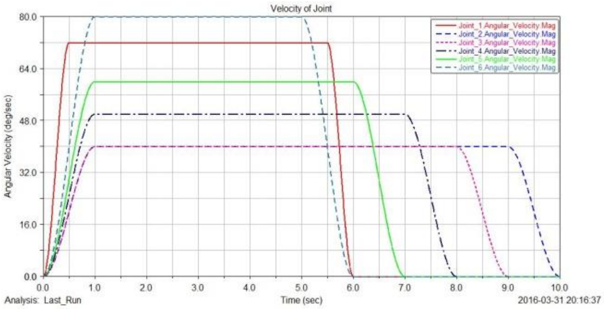

Figure 2 angular velocity curve of each joint robot

As we can see from the joint angular velocity graph, during the period of the robot dynamics simulation, the angular velocity of each joint in line with the changes of setted, uniformly accelerated start - uniform run - even retarding the working conditions, and in the acceleration phase and deceleration phase transition is relatively stable, there is no mutation phenomenon, each robot joint operation is in accordance with the actual situation, will not affect the overall performance of the robot.

4.2. Force and Moment of each joint
The force and moment of each joint in the robot dynamics simulation are an important parameter. By measuring the torque of each joint suffered,can verify whether the drive motor selected can meet the requirements, but also can verify whether the reduction ratio and torque harmonic reducer chosed can meet the design requirements, so dynamics simulation has play a very important role in the design of the robot ,joint forces and torques suffered is hown in fig 3 each joint of UR10 robot can withstand the torque value is shown in table 2.

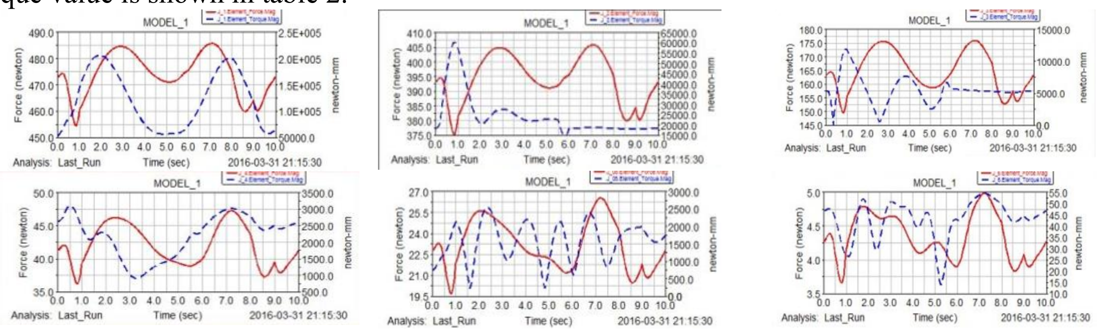

Figure 3 the station of stress and torque of each joint

Table 2 withstand torque value of UR robot

Joint	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6
torque	330Nm	330Nm	150Nm	56Nm	56Nm	56Nm

We can see from figure 3, the force of each joint and moment of force during robot movement are withstand the torque range of UR10 robot can suffer as shown in table 2 withstand the torque range, meets the needs of the movement. moment of force.

5. Conclusions
In this study, we selected a UR10 robot as our research subject. We first used D-H coordinate transformation of the robot to establish a link system. Then, we used inverse transformation to solve inverse kinematics for the robot and locate all the joints. Use Lagrange method to analysis the UR robot dynamics, use ADAMS multibody dynamics simulation software to realize dynamic simulation.

The results show that the measuring robot UR10 has a good static balance of performance, stability and dynamic response of the motion.

6. References

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