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Sensor module design and forward and inverse kinematics analysis of 6-DOF sorting transferring robot

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Abstract: To meet the demand of high strength express sorting, it is significant to design a robot with multiple degrees of freedom that can sort and transfer. This paper uses infrared sensor, color sensor and pressure sensor to receive external information, combine the plan of motion path in advance and the feedback information from the sensors, then write relevant program. In accordance with these, we can design a 6-DOF robot that can realize multi-angle seizing. In order to obtain characteristics of forward and inverse kinematics, this paper describes the coordinate directions and pose estimation by the D-H parameter method and closed solution. On the basis of the solution of forward and inverse kinematics, geometric parameters of links and link parameters are optimized in terms of application requirements. In this way, this robot can identify route, sort and transfer.

1 Introduction

Robot is a typical digital intelligent equipment which has been widely applied in industrial area, such as welding robot, cutting robot, handling robot and spraying robot. Industrial robot has become a support of advanced manufacturing technology. The 6-DOF robot, which is flexible and has a wide working space, is one of the most common robots[1]. There has been an in-depth scientific research on robots' sensors and kinematic analysis now. Peter.I.Corke[2] introduced the D-H parameter method and developed Robotics toolbox which can be used to analyse forward and inverse kinematics of the robot arm，but it is only a simple kinematics simulation. Mao Li[3] has used robot structural, homogeneous transformation and the cubic polynomial interpolation method to design each composition unit of the robot, but internal planning is not combined with the external environment of feedback. WANG Qi-jun[4] combined the Line and Circular Interpolation algorithm with the camera vision positioning to get the spatial motion path of the robot, which was based on solving the problem of matrix forwardly and reversely, but the calculation of visual servo control and design is too complicated.

Establishing a 6-DOF robot's three-dimensional model and analysing, solving the problem of forward and inverse kinematics can realize the function of sorting and transferring, which is based on the combination of sensing technology and external environment. Research is based on era development needs which combines sensing technology with robot technology, and expands application range of robots. Therefore the robot has a certain application value.

2 Sensor module design

K60 as the core element, Voltage Regulator Module LM2596S and Motor Module L298N are made up of electric circuit. Every sensor scans the external environment to acquire information all the time. The acquired information is compared with optimizing test data. We choose the better information to accomplish the planning path and sort and transfer things.For Sorting and transferring, infrared sensor, color sensor and pressure sensor are used to acquire environmental information. Combined with the planning path, it guide the robot to move, sort and transfer, just as shown in figure 1.

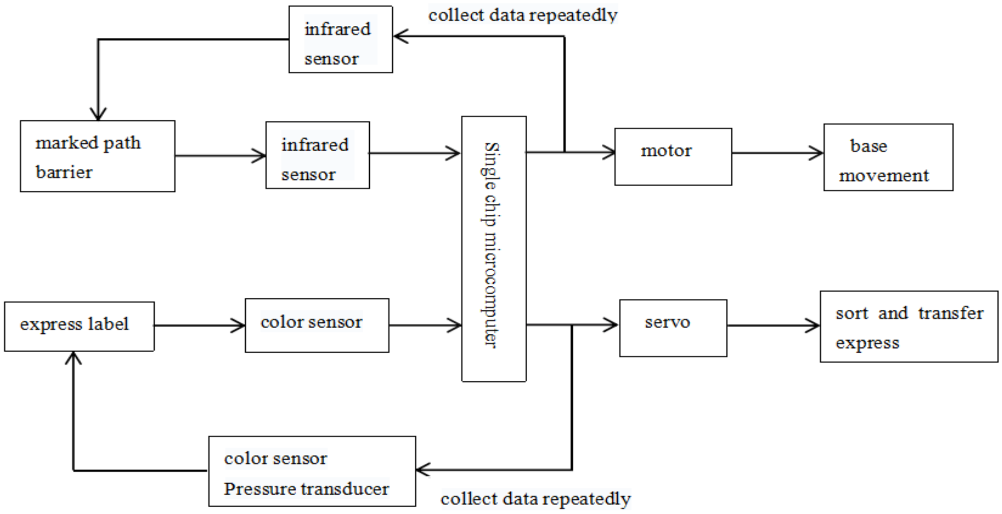

Figure 1: The control flow chart of robot

2.1 Infrared sensor

The movement of the robot base is based on sensing planning path in advance and judging obstacles .It does not need to get accurate value of distance .So the infrared sensor is used to control robot moving. The infrared sensor has reliability and anti-jamming ability. It processes data simply and quickly, so it is suit to small robots. Ahead of the robot base to the left (right), the location of the 45° two infrared sensors are installed. They can track path and avoid obstacles. Figure 2 shows program.

```
if(P0==0x03)   //(00000011)
{
P1=0X05         //(00000101) go forward
}
if(P0==0x01)    //（00000001）
{
P1=0X07         //（00000111）turn right
}
if(P0==0x02) //（00000010）
{
P1=0X0D       //（00001101）turn left
}
if(P2==0x00) //（00000000）
{
P1=0X0F      //（00001111）stop
}
```

Figure 2: Infrared sensor program

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2.2 Color sensor

Sorting express is achieved by identifying express labels belong to different areas. Compared with CCD and CMOS, the color sensor TCS230 does not need to AD converter. Because express in different areas correspond with different colorful labels, we can acquire value of RGB from three channels. Comparing grey value with different colorful labels to judge express is a effective way. For studying distinguishing degrees and accuracy of the color sensor, we collect RGB values by experiments, just as shown in table 1.

Table 1: Data collection chart of color sensor

Color	Theoretical value of RGB	Experimental value of RGB	Comparison of similarity
Black	0，0，0	16，22，11	similarity
White	255，255，255	242，250，251	similarity
Blue	0，0，255	11，15，253	similarity
Green	0，255，0	13，254，20	similarity
Red	255，0，0	248，13，18	similarity

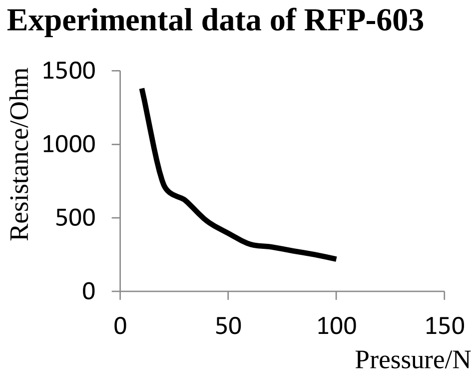
Results show: color sensor is sensitive to outside light, and values of similar colors are difficult to distinguish. So in fact, we need to place sensors in the space with low light interference and use the shield for it to filter stray light.

2.3 Pressure sensor

When robot clamps express, its force conditions and clamping results are unpredictable. So it needs feedback signal to judge whether it clamps the express correctly. Pressure sensor FSR402 is installed on manipulator to detect pressure. The pressure sensor is light-weight with small size and high precision. Pressure of taking place in FSR film area is changed into resistance variation to acquire the information of pressure. For acquiring results of pressure's perception, control variate method is proper. The pressure on the pressure sensor is changed to acquire testing data, just as shown in table 2. Results shows: the larger the pressure is, the lower the resistance is. Its precision is higher, but pressure range is from 0N to100N. When pressure is too large, it will affect the precision.

3 The solution to robot’s forward and inverse kinematics

Table 2: Data collection chart of pressure sensor



3.1 Descriptions of robot’s poses and D-H parameter method

This kind of sorting transferring robot has 6 degrees-of-freedom. The end effector which can flexibly pick up target by opening, closing, stretching and retracting itself, is a mechanical grabber. Mechanical structure is designed and built model by using the three-dimensional software, just as shown in figure 3. The integral structure's deformation of Robot under stress is complicated because of the material of links, inertia and etc. Therefore it should be calculated as rigid body, and we can neglect dynamic deformation. Robot is made up of revolute joints and supporting connecting rods. Every part is described by pose. We use D-H parameter method which is amended by Craig to get transformation matrixes between reference coordinate systems and rigid body coordinate systems. Equivalent coordinate systems are shown in figure 4. Reference coordinate system {0} is fixed on the base,and coordinate system {i} is fixed on the link {i}. The D-H parameter of links is shown in chart 3. Transformation matrix between adjacent coordinate systems is as below:

$$ {}^{i-1}_{i}T = \begin{bmatrix} \cos\Theta_i & -\sin\Theta_i & 0 & a_{i-1} \\ \sin\Theta_i\cos\alpha_{i-1} & \cos\Theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1}d_i \\ \sin\Theta_i\sin\alpha_{i-1} & \cos\Theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

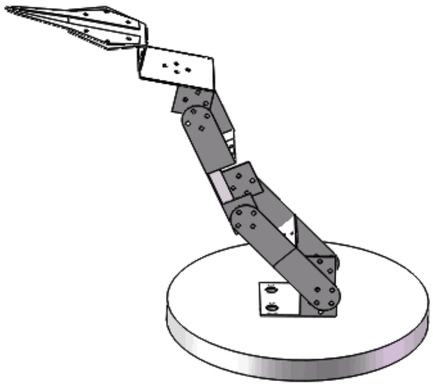


Figure 3: 3D modeling of robot

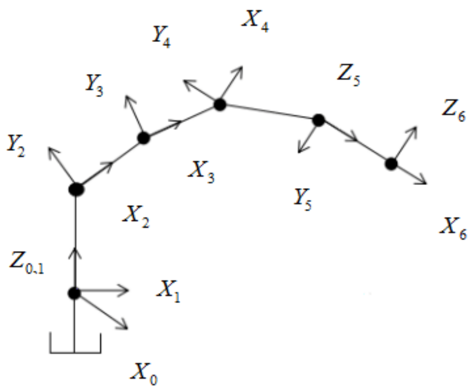


Figure 4: Chart of robot coordinate system

Corresponding parameters: a_{i-1} is the distance that is measured from z_{i-1}-axis to z_i-axis along x_{i-1}-axis; α_{i-1} is the angle that is measured from z_{i-1}-axis to z_i-axis by spinning around x_{i-1}-axis; d_i is the distance that is measured from x_{i-1}-axis to x_i-axis along z_i-axis; Θ_i is the angle that is measured from x_{i-1}-axis

Table 3: Chart of the D-H parameter of links

i	a_{i-1}	∂_{i-1}	d_i	θ_i
1	0	0°	0	θ_1
2	0	90°	0	θ_2
3	d_2	0°	0	$-\theta_3$
4	d_3	0°	0	θ_4
5	l_m	90°	l_n	$\theta_5(90^\circ)$
6	0	90°	0	$\theta_6(90^\circ)$

to x_i-axis by spinning around z_i-axis. All certain parameters are put into formula above, and every transformation matrix can be listed below in order.

$$
{}^0_1T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad
{}^1_2T = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^2_3T = \begin{bmatrix} c_3 & s_3 & 0 & d_2 \\ -s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad
{}^3_4T = \begin{bmatrix} c_4 & -s_4 & 0 & d_3 \\ s_4 & c_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^4_5T = \begin{bmatrix} c_5 & -s_5 & 0 & l_m \\ 0 & 0 & -1 & -l_n \\ s_5 & c_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad
{}^5_6T = \begin{bmatrix} c_6 & -s_6 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

3.2 The solution to robot's forward kinematics

The solution to robot's forward kinematics is a homogeneous transformation matrix which is based on reference coordinate system. The process is as follow: build axis on every link; describe poses between coordinate systems by means of homogeneous transformation; use product form recurrence algorithm to get a homogeneous transformation between reference coordinate system and end effector. What in the every brace shows a column of matrix ${}^0_6T$.

$$
{}^0_6T = {}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_4T\,{}^4_5T\,{}^5_6T
$$

$$
{}^0_6T = \begin{bmatrix} a & b & c & d \end{bmatrix}
$$

$$a=\begin{Bmatrix} c_1c_2c_3c_4c_5c_6+c_1s_2s_3c_4c_5c_6+c_1c_2s_3s_4c_5c_6-c_1s_2c_3s_4c_5c_6+ \\ s_1s_5c_6+c_1c_2c_3s_4s_6+c_1s_2s_3s_4c_6-c_1c_2s_3c_4s_6+c_1s_2c_3c_4s_6, \\ \\ s_1c_2c_3c_4c_5c_6+s_1s_2s_3c_4c_5c_6+s_1c_2s_3s_4c_5c_6-s_1s_2c_3s_4c_5c_6 \\ -c_1s_5c_6+s_1c_2c_3s_4s_6+s_1s_2s_3s_4s_6-s_1c_2s_3c_4s_6+s_1s_2c_3c_4s_6, \\ \\ s_2c_3c_4c_5c_6-c_2s_3c_4c_5c_6+s_2s_3s_4c_5c_6+c_2c_3s_4c_5c_6 \\ +s_2c_3s_4s_6-c_2s_3s_4s_6-s_2s_3c_4s_6-c_2c_3c_4s_6, \\ \\ 0 \end{Bmatrix}, \quad b=\begin{Bmatrix} c_1s_2c_3s_4c_5s_6-c_1c_2c_3c_4c_5s_6-c_1s_2s_3c_4c_5s_6-c_1c_2s_3s_4c_5s_6 \\ -s_1s_5s_6+c_1c_2c_3s_4c_6+c_1s_2s_3s_4c_6-c_1c_2s_3c_4c_6+c_1s_2c_3c_4c_6, \\ \\ s_1s_2c_3s_4c_5s_6-s_1c_2c_3c_4c_5s_6-s_1s_2s_3c_4c_5s_6-s_1c_2s_3s_4c_5s_6 \\ +c_1s_5s_6+s_1c_2c_3s_4c_6+s_1s_2s_3s_4c_6-s_1c_2s_3c_4c_6+s_1s_2c_3c_4c_6, \\ \\ c_2s_3c_4c_5s_6-s_2c_3c_4c_5s_6-s_2s_3s_4c_5s_6-c_2c_3s_4c_5s_6 \\ +s_2c_3s_4c_6-c_2s_3s_4c_6-s_2s_3c_4c_6-c_2c_3c_4c_6, \\ \\ 0 \end{Bmatrix},$$

$$c=\begin{Bmatrix} c_1c_2c_3c_4s_5-c_1s_2c_3s_4s_5+c_1s_2s_3c_4s_5+c_1c_2s_3s_4s_5-s_1c_5, \\ s_1c_2c_3c_4s_5-s_1s_2c_3s_4s_5+s_1s_2s_3c_4s_5+s_1c_2s_3s_4s_5+c_1c_5, \\ s_2c_3c_4s_5-c_2s_3c_4s_5+s_2s_3s_4s_5+c_2c_3s_4s_5, \\ 0 \end{Bmatrix}, \quad d=\begin{Bmatrix} c_1c_2c_3c_4l_m+c_1s_2s_3c_4l_m+c_1c_2s_3s_4l_m-c_1s_2c_3s_4l_m+c_1c_2c_3s_4l_n+ \\ c_1s_2s_3s_4l_n-c_1c_2s_3c_4l_n+c_1s_2c_3c_4l_n+c_1c_2c_3d_3+c_1s_2s_3d_3+c_1c_2d_2, \\ \\ s_1c_2c_3c_4l_m+s_1s_2s_3c_4l_m+s_1c_2s_3s_4l_m-s_1s_2c_3s_4l_m+s_1c_2c_3s_4l_n+ \\ s_1s_2s_3s_4l_n-s_1c_2s_3c_4l_n+s_1s_2c_3c_4l_n+s_1c_2c_3d_3+s_1s_2s_3d_3+s_1c_2d_2, \\ \\ s_2c_3c_4l_m-c_2s_3c_4l_m+s_2s_3s_4l_m+c_2c_3s_4l_m-c_2s_3s_4l_n+ \\ s_2c_3s_4l_n-s_2s_3c_4l_n-c_2c_3c_4l_n+s_2c_3d_3-c_2s_3d_3+s_2d_2, \\ \\ 1 \end{Bmatrix}$$

In the formulas,
$c_1=\cos\Theta_1$, $s_1=\sin\Theta_1$, and so on.

The question of get solution to robot's forward kinematics is to put known variable parameters into final transformation matrix.

In experiments, we choose values of Θ_1、Θ_2、Θ_3、Θ_4、Θ_5、Θ_6 arbitrarily, then use Solidworks and entity model to check results, and it is consistent with the calculation.

3.3 The solution to robot's inverse kinematics

The solution to robot's inverse kinematics is to get values of joint variables when the expected pose of end effector which is based on the reference coordinate system is known. The question of existence of solution and multiple solutions should be considered, and algebraic method is widely used [5].The motion equation of robot is as below:

$$ {}^0_6T=\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$={}^0_1T(\Theta_1){}^1_2T(\Theta_2){}^2_3T(\Theta_3){}^3_4T(\Theta_4){}^4_5T(\Theta_5){}^5_6T(\Theta_6) \quad (2)$$

When equation is being solved, the pose of end effector ($\vec{n},\vec{o},\vec{a},\vec{p}$) is certain and we need to get values of Θ_1、Θ_2……、Θ_6.

(1) The value of Θ_1

Inverse transformation

${}^{0}_{1}T^{-1}(\Theta_1){}^{0}_{6}T = {}^{1}_{2}T(\Theta_2){}^{2}_{3}T(\Theta_3){}^{3}_{4}T(\Theta 4){}^{4}_{5}T(\Theta_5){}^{5}_{6}T(\Theta_6)(3)$, that's $\begin{bmatrix} c_1 & s_1 & 0 & 0 \\ -s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^{1}_{6}T$

Variables (2,4) on both sides of equation are equal, so we use trigonometric substitution in $p_x = \rho\cos\phi, p_y = \rho\sin_\phi$, thus get the value of $\Theta_1 : \Theta_1 = \arctan 2(p_y, p_x)$

(2) The value of Θ_5, Θ_6

Variables on both sides of equation are equal and we use trigonometric substitution to solve it. That is

$$c_1 n_y - s_1 n_x = -s_5 c_6;$$

$$c_1 o_y - s_1 o_x = s_5 s_6; ,$$

$$c_1 a_y - s_1 a_x = c_5$$

And get the expression of

$\Theta_5 : \Theta_5 = \arccos(c_1 a_y - s_1 a_x)$ .When Θ_5 is not equal to 0°or180° ,we put the value of it into formulas, thus get the value of Θ_6,

$$\Theta_6 = \arcsin\left(\frac{c_1 o_y - s_1 o_x}{s_5}\right)$$

$$= \arccos\left(\frac{c_1 n_y - s_1 n_x}{-s_5}\right) .$$

Because of restrictions on links' angles,

$\Theta_5 \neq 0^\circ$or180° , thus we can get the value of Θ_5, Θ_6 .

(3).The value of Θ_2

Inverse transformation:

${}^{0}_{3}T^{-1}(\Theta_1, \Theta_2, \Theta_3){}^{0}_{6}T = {}^{3}_{4}T(\Theta_4){}^{4}_{5}T(\Theta_5){}^{5}_{6}T(\Theta_6)(4)$,

that's ${}^{3}_{6}T = \begin{bmatrix} c_1c_2c_3 + c_1s_2s_3 & s_1c_2c_3 + s_1s_2s_3 & s_2c_3 - c_2s_3 & 0 \\ c_1c_2s_3 - c_1s_2c_3 & s_1c_2s_3 - s_1s_2c_3 & s_2s_3 + c_2c_3 & 0 \\ s_1 & -c_1 & 0 & 0 \\ c_1c_2d_2 & s_1c_2d_2 & s_2d_2 & 1 \end{bmatrix}$

$\cdot\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Variables (4,4) on both sides of equation are equal, and

$$(c_1 p_x + s_1 p_y)\cdot c_2 d_2 + s_2 d_2 p_z + 1 = 1$$

$s_2 p_z = -(c_1 p_x + s_1 p_y)\cdot c_2$, thus get the value of Θ_2 .

$$\Theta_2 = \arctan 2(-(c_1 p_x + s_1 p_y), p_z)$$

(4).The value of Θ_3

Inverse transformation:

${}^{0}_{4}T^{-1}(\Theta_1, \Theta_2, \Theta_3, \Theta_4){}^{0}_{6}T = {}^{4}_{5}T(\Theta_5){}^{5}_{6}T(\Theta_6)(5)$, that is

$$ {}_4^0T^{-1}(\Theta_1,\ \Theta_2,\ \Theta_3,\ \Theta_4)=[m \quad n \quad p \quad q] $$

$$ m=\begin{Bmatrix} c_1c_2c_3c_4+c_1s_2s_3c_4+c_1c_2s_3s_4-c_1s_2c_3s_4 \\ -c_1c_2c_3s_4-c_1s_2s_3s_4+c_1c_2s_3c_4-c_1s_2c_3c_4 \\ s_1 \\ c_1c_2c_3d_3+c_1s_2s_3d_3+c_1c_2d_2 \end{Bmatrix}, \qquad n=\begin{Bmatrix} s_1c_2c_3c_4+s_1s_2s_3c_4+s_1c_2s_3s_4-s_1s_2c_3s_4 \\ -s_1c_2c_3s_4-s_1s_2s_3s_4+s_1c_2s_3c_4-s_1s_2c_3c_4 \\ -c_1 \\ s_1c_2c_3d_3+s_1s_2s_3d_3+s_1c_2d_2 \end{Bmatrix}, $$

$$ p=\begin{Bmatrix} s_2c_3c_4-c_2s_3c_4+s_2s_3s_4+c_2c_3s_4 \\ -s_2c_3s_4+c_2s_3s_4+s_2s_3c_4+c_2c_3c_4 \\ 0 \\ s_2c_3d_3-c_2s_3d_3+s_2d_2 \end{Bmatrix}, q=\begin{Bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{Bmatrix}. $$

Variables (4,1) on both sides of equation are equal,

$$ \begin{aligned} & s_3(c_1s_2d_3n_x+s_1s_2d_3n_y-c_2d_3n_z) \\ & +c_3(c_1c_2d_3n_x+s_1c_2d_3n_y+s_2d_3n_z) \\ & =-(s_2d_2n_z+s_1c_2d_2n_y+c_1c_2d_2n_x) \end{aligned}. $$

Meanwhile, formula: $s_3^2+c_3^2=1$ and the angle of restriction on Θ_3 is known, so we synthesize equations above, thus get the value of Θ_3.

(5)The value of Θ_4

Inverse transformation:

$$ {}_2^0T^{-1}(\Theta_1,\ \Theta_2){}_6^0T={}_3^2T(\Theta_3){}_4^3T(\Theta_4){}_5^4T(\Theta_5){}_6^5T(\Theta_6) \text{(6) that's } \begin{bmatrix} c_1c_2 & s_1c_2 & s_2 & 0 \\ -c_1s_2 & -s_1s_2 & c_2 & 0 \\ s_1 & -c_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}={}_6^2T $$

variables (1,3) on both sides of equation are equal, $c_3c_4s_5+s_3s_4s_5=c_1c_2a_x+s_1c_2a_y+s_2a_z$,

When the right side of equation is not equal to 0, $\frac{c_3s_5}{c_1c_2a_x+s_1c_2a_y+s_2a_z}c_4+\frac{s_3s_5}{c_1c_2a_x+s_1c_2a_y+s_2a_z}s_4=1$

Meanwhile, formula: $s_4^2+c_4^2=1$ and the angle of restriction on Θ_4 is known, so we synthesize equations above, thus get the value of Θ_4.

When calculating variables, there are many kinds of reverse solutions. Because of the limitation between mechanical structures, articulated variables cannot reach 360-degree movement rage. Therefore, results which are against with facts should be neglected. There are multiple possibilities of variables, such as Θ_1、Θ_2、Θ_3, etc. In practice, according to rules of weighted shortest path [6], we can get optimal solutions. To meet need of robot working, we may give preference to rules of longer path if there is barrier in the environment.

4 Conclusions

(1)Basing on the sensing module, combining three kinds of sensors with the mechanical structure through hardware and software, we can do research on all kinds of sensor performance respectively.

(2)After establishing a 6-DOF sorting and transferring robot's three-dimensional model, We can analyse motion to solve the problem of forward and inverse kinematics. At last, we can have a preliminary validation of reasonable requirements of the robot's whole movement.

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