Natural Gesture Control of a Delta Robot Using Leap Motion

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Abstract. Human-Robot Interaction (HRI) is a research hotspot in recent years, most robots used for HRI are serial robots. This paper deals with the natural gesture control of a Delta parallel robot, using the touchless optical sensor Leap motion controller. The kinematics of the Delta robot is firstly described, its inverse kinematic solutions are obtained, and its workspace is plotted. The Leap motion controller is introduced and the key functions used in this research are described, eight gestures are defined. The experimental rigs are established, experiments are successfully carried out and results are discussed. Results show that it is a natural way for users to control the Delta robot with an acceptable accuracy and efficiency, by using the Leap motion controller, even though they have never operated a robot before. This research extends the interaction way between human and robots.

1. Introduction

Human-Robot Interaction is a research hotspot in recent years [1], in which nature interaction is one of the key issues [2]. Leap motion controller is a touchless sensors and is widely used and studied by many researchers since it was firstly developed [3]. Compared with other sensors, such as Kinect or haptic glove, it has the advantage of high accuracy, touchless, small volume, and importantly, very cheap. Guna [4] analyzed the precision and reliability of the leap motion sensor and its suitability for static and dynamic tracking. Xu [5] studied the natural gesture control of a rotor-craft using the Leap motion controller. Ruffaldi [6] and Gunawardane [7] applied the Leap motion controller on the adaptive robotic arm manipulator. In the papers of Artal-Sevil [8] and Vani [9], the Arduino smart car is controlled by the leap motion. In order to enhance the touchless interaction, Nguyen combines a haptic glove with the Leap motion [10], which indicates that this way is feasible when some specific conditions are met, but still with some bottlenecks.

The robots used for HRI are mostly serial robots. Compared with the serial mechanism [11], the parallel mechanism has the advantage of high stiffness, high speed and high accuracy [12, 13]. One representative is the Delta robot, which was firstly developed by Clavel [14] and now is successfully used for factory application and laboratory research [15], its moving platform has 3 translational DOFs. The research area of Delta robots includes the kinematics [16, 17], dynamics, optimal design, control strategy and so on. Codourey [18] proposed a simplified dynamic model of the Delta robot for real time computed-torque control. Liu [19] presented a new design method considering a desired workspace and swing range of spherical joints of a Delta robot. Zhao [20] presented a method for parameter tuning of the fixed gain motion controller of Delta robot based on servo identification.

Footnotes:

[1] Human-Robot Interaction is a research hotspot in recent years.
[2] One of the key issues.
[3] Leap motion controller was developed.
[4] The precision and reliability of the leap motion sensor were analyzed.
[5] The natural gesture control was studied.
[6] The adaptive robotic arm manipulator was applied.
[7] The Arduino smart car was controlled.
[8] A haptic glove was combined with the Leap motion.

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these researches about Delta robot, HRI is not taken into consideration, this concern will be studied in this research.

This research deals with the natural gesture control of a Delta robot using the Leap motion controller, which combines the advantages of both devices. The contributions of this research are that, firstly, a touchless control method is applied to the Delta parallel robot. Secondly, eight natural hand gestures are defined to interact with the robot. Thirdly, experiments are successfully carried out, which verified the effectiveness of the proposed method. This research is a fundamental research for the further study of the HRI of the Delta robot.

This paper is organized as follows, Section 1 gives a brief research background of this topic; Section 2 describes the modelling of the Delta robot, the detailed process of the kinematics is presented, and the workspace of the moving platform is plotted; Section 3 introduces the Leap motion controller, the key functions used in this research are clarified and eight hand gestures are defined; In Section 4, the experimental rigs are introduced, experiments are carried out and the results are discussed; Conclusions are made and future developments are prospected in Section 5.

2. Modelling the Delta robot
The Delta parallel robot is shown in Fig. 1. The robot includes the fixed platform, the moving platform, the active links, and the passive links. The fixed platform and active links are connected by revolute joints $A_1A_2A_3$, the active links and passive links are connected by spherical joints $B_1B_2B_3$, while the passive links and moving platform are connected by spherical joints $C_1C_2C_3$. The global coordinate system O-XYZ is that, the origin point O is the center of triangle $A_1A_2A_3$, the axis OX is parallel with $A_2A_3$, the axis OY is perpendicular with OX, while axis OZ is perpendicular with plane $A_1A_2A_3$, fitting the right-hand law. The end point P is the center of triangle $C_1C_2C_3$, the moving platform has 3 translational DOFs. In experiment, a gripper actuated by steering gear is attached to the moving platform.

![Figure 1. Delta robot.](image)

2.1 Constraint equation

![Figure 2. Geometry of a single train.](image)
To simplify the modeling process, one of the 3 chains is analyzed, as is shown in Fig. 2. The radius of the circle $A_1A_2A_3$ is referred as $R$, the radius of the circle $C_1C_2C_3$ is referred as $r$, the length of active link is referred as $l_1$, and the length of passive link is referred as $l_2$. The fixed loop of the bold line in Fig. 2 can be replaced by the dash line, so the vector equation of end point $P$ is

$$
\overrightarrow{OP} = \overrightarrow{OA} + \overrightarrow{AB} + \overrightarrow{EP}
$$

where $i=1\sim3$. $\overrightarrow{OP}=(x, y, z)^T$; $x$, $y$, $z$ is the global coordinate of end point $P$; $\overrightarrow{OA}=(e, 0, 0)^T$; $e=R-r$; $\overrightarrow{AB}=T \cdot (l, \cos \theta, 0, l, \sin \theta)^T$; $T$ is the rotation matrix

$$
T = \begin{bmatrix}
\cos \beta_i & -\sin \beta_i & 0 \\
\sin \beta_i & \cos \beta_i & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

in which $\theta_i$ is the input angle of each active link, while $\beta_i$ is the assemble angle of each chain.

Thus the Equation (1) can be transformed into

$$
\begin{bmatrix}
x - (e + l_1 \cos \theta) \cos \beta_i \\
y - (e + l_1 \cos \theta) \sin \beta_i \\
z - l_2 \sin \theta
\end{bmatrix}
$$

(3)

As the length of passive link is constant, so the equation above is

$$
\begin{bmatrix}
x - (e + l_1 \cos \theta) \cos \beta_i \\
y - (e + l_1 \cos \theta) \sin \beta_i \\
+ (z - l_2 \sin \theta)^2 = l_2^2
\end{bmatrix}
$$

(4)

in which $i=1\sim3$. These three equations are the kinematic constraint equations.

2.2 Inverse kinematics

The inverse kinematics is that given the position of end point, to know the inputs. As for the parallel mechanism, the inverse kinematic is simple. The constraint Equation (4) can be transformed into

$$
A_i \cos \theta_i + B_i \sin \theta_i = C_i
$$

(5)

in which

$$
\begin{cases}
A_i = 2l_1 (e - x \cos \beta_i - y \sin \beta_i) \\
B_i = -2l_2 z \\
C_i = l_2^2 - (l_1^2 + x^2 + y^2 + z^2 + e^2) + 2e(x \cos \beta_i + y \sin \beta_i)
\end{cases}
$$

(6)

Applying the half-angle formulation, Equation (5) is changed into

$$
(C_i + A_i) \tan^2 \left( \frac{\theta_i}{2} \right) - 2B_i \tan \left( \frac{\theta_i}{2} \right) + (C_i - A_i) = 0
$$

(7)

Thus the solution of the above equation is

$$
\theta_i = 2 \tan^{-1} \left( \frac{B_i \pm \sqrt{A_i^2 + B_i^2 - C_i^2}}{C_i + A_i} \right)
$$

(8)
It can be seen that there are 2 solutions for each chain, so there are totally 8 solutions for the robot. In real application, the angle of the active link which is outer side is accepted.

2.3 Workspace
The dimensions of the established Delta robot are that $R=86$, $l_1=140$, $l_2=320$, $r=30\text{mm}$. The workspace of the end point can be calculated point by point using the Matlab software, they are plotted in Fig. 3. It can be seen that although the dimensions of the robot are small, the workspace is pretty large, which indicates that the structure of the Delta robot is properly designed. A cuboid space with dimension 400*400*150mm can be found in the workspace. Considering the assembly limitation and rotational range of spherical joints, the real workspace is a little smaller than the ideal one.

![Figure 3. Work space of the Delta robot: (a) XOZ plane, (b) YOZ plane.](image)

3. Leap motion controller
The appearance and coordinate system of Leap motion controller is shown in Fig. 4. The Leap motion controller used in this research is the second generation, it uses optical sensors and infrared light, which recognizes and tracks hands and fingers. The device operates in an intimate proximity with high precision and tracking frame rate and reports discrete positions and motion. Its workspace is an inverted pyramid, with a field of view of about 150 degrees, and the working height is 25~600mm, the resolution is up to 1mm [3].

![Figure 4. Leap motion controller.](image)

The first key function used in this research is "hand.palmPosition()", part of the C++ code is

```cpp
Frame frame = controller.frame();
HandList hands = frame.hands();
Leap::Vector handCenter = hand.palmPosition();
```

The code returns a vector `handCenter` representing the palm position in Leap motion coordinate system. In the application of this research, the workspace of the delta robot is limited to be [-80, 80, -80, 80, -380, -260], while the working space of the Leap motion controller is chosen to be [-100, 100, 100, 250, -100, 100], so there should be a mapping matrix between the two coordinates, which can be expressed as
\[
\begin{align*}
    x_o &= 0.8x_l \\
    y_o &= -0.8z_l \\
    z_o &= 0.8y_l - 460
\end{align*}
\] (9)

in which \((x, y, z)_D\) is the coordinate of moving platform in Delta coordinate system, while \((x, y, z)_L\) is the coordinate of hand palm in the Leap motion coordinate system. There is a scaling ratio 0.8 between the two coordinates.

The second function used is “hand.sphereRadius()”, which captures the opening status of the palm. It is used to control the steering gear, to decide the opening and closing of gripper, which is fixed at the end of the moving platform. Part of the code is

\[
\text{float sphereRadius} = \text{hand.sphereRadius}();
\]

There should be thresholds of the \text{sphereRadius} to determine the rotate angel of steering gear, when the \text{sphereRadius} is smaller than the lower threshold, the gripper is closed, while when the \text{sphereRadius} is larger than the upper threshold, the gripper is opened.

Using the above information, eight gestures are defined to control the robot, as listed in Table 1. The mapping between the hand gesture and platform movement is very straightforward, which means that it is an easy way for users to interact with the robot.

Table 1. Gesture define and robot response.

| Hand Gesture | Robot Response |
|--------------|----------------|
| Palm up      | Moving platform up |
| Palm down    | Moving platform down |
| Palm left    | Moving platform left |
| Palm right   | Moving platform right |
| Palm forward | Moving platform forward |
| Palm backward| Moving platform backward |
| Palm open    | Gripper open |
| Palm close   | Gripper close |

4. Experiment

4.1 Experimental systems

The experimental rig established in this research is shown in Fig. 1(a), the block diagram is shown in Fig. 5. The system includes the Arthur IPC-610 (CPU-i5, ROM-4G, RAM-128G), the Googol motion controller (GTS-400-PG-PCI), the DELTA servo driver and motor (ASD-B2-0421-B, ECMA-C20604RS), the planetary reducer (PLF060-L1-10-S2-P2), the Delta parallel mechanism, the gripper and the connecting lines. The rated power of servo motor is 400W, the rated torque is 1.27Nm, and the rated speed is 3000r/min. The ratio of the reducer is 10:1, the electronic gear ratio is set carefully to make sure that, 1000 pulses will lead to the active link rotate one degree, which means that the resolution of the input angle is 0.001degree/pulse. The motion controller communicates with IPC through PCI bus line, while the leap motion connects with IPC through USB. The steering gear of gripper is controlled through PWM signal.
The program is written in visual studio 2010 environment, using the C++ language. The working procedure is as follows, the Leap motion catches the position of the palm, and then it is transformed into the coordinate of the moving platform of Delta robot through Equation (9). The inverse kinematic is carried out, then the input angles are obtained through equation (8). The IPC gives order to Googol motion controller, the motion controller gives order to servo drivers, and the servo drivers give order to servo motors, thus the moving platform moves as expected. The motion mode of the servo is in P2P mode. On the other hand, when the Leap motion detects the opening status of the palm, the PWM signal is produced by the motion controller and sent to the steering gear, thus the opening or closing of the gripper is realized. The whole process keeps going on in real time until the program is stopped.

4.2 Experimental results
Eight gestures are tested in the experiments, the results are shown in Fig. 6, it can be seen that the robot is successfully controlled by the natural gesture using Leap motion.

(a)      (b)     (c)     (d)     (e)     (f)

Figure 6. Experimental results: (a) Palm up & opened, (b) Palm down & closed, (c) Palm left & opened, (d) Palm right & closed, (e) Palm forward & opened, (f) Palm backward & closed.
To estimate the accuracy and efficiency of the control method, a picking and placing task is carried out. From point A, an object is picked up, then move through point B, C and D, on each point picking and placing actions are executed, then back to point A and the object is placed. This procedure is carried out by 10 different peoples, the average placing error and time spent are recorded and listed in Table 2.

Table 2. Accuracy and Efficiency of the Experiment.

| Point         | Action       | Success rate | Error [mm] | Time [s] |
|---------------|--------------|--------------|------------|----------|
| A(50,50,-300) | Pick         | 10/10        | -          | 2.2      |
| B(-50,50,-300)| Pick & place | 10/10        | 1.3        | 4.2      |
| C(-50,-50,-300)| Pick & place| 10/10        | 1.4        | 4.3      |
| D(50,-50,-300)| Pick & place | 10/10        | 1.3        | 4.2      |
| A(50,50,-300) | Place        | 10/10        | 1.3        | 2.1      |

It can be seen from the results that the successful rate is one hundred percent, the average position error is around 1.3mm, and the average time for each picking and placing is about 4.2s. The results show that the users can control the robot successfully with acceptable accuracy and efficiency, even though they have never operated a robot before.

5. Conclusion
This paper deals with the natural gesture control of a Delta robot using the Leap motion controller, which combines the advantages of both devices. The kinematics of the Delta robot is analyzed and experiments are successfully carried out. This research shows the feasibility of touchless natural gesture control of the robot, which allows the user to operate the robot naturally, without knowing the complex principles of the system. This is a fundamental research for HRI, there are still some aspects can be improved, such as the delay of the moving platform with respect to human hands, and the accuracy of the system. Moreover, the robot should have more intelligence to predicate the behavior of the human. These topics are to be considered in the further.

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