Trajectory tracking control method of robotic intra-oral treatment

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Abstract. At present, people suffer from a high rate of cross-infection of oral diseases, and it is an urgent clinical need to explore effective methods to promote high-security and high-quality imaging. This paper proposes a collaborative robot control strategy that assists in oral diagnosis and treatment. This method can track the dynamic movement of the patient's upper and lower jaw during treatment. According to the small space of the oral cavity and the change of the tooth position, dynamic trajectory tracking with adaptive control is performed on the robotic arm. This control strategy is of great significance for accurate oral diagnosis and treatment and reducing cross-infection between doctors and patients.

1. Introduction

Due to the high incidence of oral diseases and the explosive spread of the novel coronavirus (COVID-19), the number of patients has increased sharply, which is a huge clinical challenge [1]. Reducing cross-infection between doctors and patients and exploring high-safety and high-quality oral diagnosis and treatment methods are urgent clinical needs. Therefore, robot-assisted oral imaging medical treatment has become a trend.

In the field of dental medical robots, my country is still in its infancy, and only a few medical and research institutions are experimenting with the development of dental assistant robots [2]. Since entering the 21st century, based on the development and application of robotics technology, medical surgical robotics technology can be roughly divided into the following directions: medical surgical robotics based on industrial robot platforms [3], dedicated medical surgical robotics [4, 5], small modular medical surgical robot technology [6, 7], and telesurgery medical robot technology [8]. However, there is no dental medical robot technology dedicated to the research of assisted imaging. In order to promote the rapid development of the oral imaging medical process to be more efficient, accurate and low-cost [9, 10], Akhoondali [11] proposed an automatic segmentation method based on region growth. Keyhaninejad et al. [12] and Hosntalab [13] proposed a level set model based on 3D regions to extract teeth. Keustermans [14] and Hiew et al. [15] proposed an interactive method of segmenting three-dimensional teeth using graph cut algorithm. Barone et al. [16] proposed a new frame iteration method to simulate the three-dimensional shape information of a single tooth in CT images. The method is to outline the two-dimensional outline of the target tooth from a set of projection images, and use the outline to model the B-spline representation of the three-dimensional tooth shape, and finally obtain the...
segmentation result of the tooth. G.C. Burdea et al. [17] proposed a robot-assisted treatment system with a position sensor arm. The system uses X-rays to generate teeth images to diagnose tooth erosion activities and bone loss. The Renaissance manufactured by Israel's Mazor Robotics company uses the intraoperative C-arm X-ray machine to obtain two-dimensional images and pre-operative three-dimensional graphics for real-time registration for positioning, which greatly improves the accuracy [18]. However, in view of the current spread of the coronavirus, no oral assistant diagnosis and treatment robot has been developed to reduce the cross infection of the novel coronavirus. Therefore, this paper proposes a trajectory tracking method for an oral assisted diagnosis and treatment robot. For the photosensitive plate holding robot, according to the small space of the oral cavity and the change of the tooth position, a dynamic trajectory tracking method with adaptive control is proposed, which reconstructs and matches the oral model to control the robot to perform auxiliary diagnosis and treatment operations.

2. Design of intra-oral assistant robot system
Oral diagnosis and treatment imaging assistance robots are designed to reduce virus cross-infection caused by doctor-patient contact, and cross-combining robotics and oral medical expert knowledge systems. The realization process of avoiding virus cross-infection mainly includes oral lesion spatial positioning and tube automatic tracking. And the doctor interacts with the robot. As shown in Figure 1, the overall control scheme of the image-assisted robot is proposed on the basis of oral diagnosis and treatment, which realizes the stable interaction between the robot and the oral space with the goal of stability and reduction of cross-infection.

3. Trajectory tracking control of photosensitive plate clamping robot
As shown in Figure 1, the photosensitive plate clamping robot system mainly includes a UR5 mechanical arm, a force sensor and the end photosensitive plate clamping. The main body of the photosensitive plate clamping robot system is the UR5 robotic arm, and the three-dimensional sensor is installed at the end of the arm. The end effector includes a fixing device and a photosensitive plate fixed on the sensor. The camera is placed as far as possible to monitor the entire working space of the robot arm.
3.1. Trajectory tracking control
In order to achieve the transition from oral lesions to robot end gripping, it is necessary to pre-treat the inside of the patient's mouth before treatment. First, a CT scan is performed on the patient's oral cavity to reconstruct the patient's 3D oral model and obtain the lesion site. Second, calibrate the end grip of the robot, and convert the angle of the lesion from the oral coordinate system to the end grip coordinate system. Then, perform hand-eye calibration. After that, the posture of the marker is estimated and converted from the camera coordinate system to the basic coordinate system of the robot arm. Finally, when the posture detected by the camera of the marker changes, the robotic arm clamped at the end will track the trajectory of the teeth in the patient's mouth. After the manipulator moves to the specified position, if the patient does not move within the specified time, the force control mode will be turned on to make the end clamp as close as possible to the lesion area. Figure 2 shows the trajectory tracking control process of the robotic dental diagnosis and treatment system.

3.2. Robot hand eye calibration
In order for the camera and the robot to work together, hand-eye calibration must be performed. The robot hand-eye calibration system is shown in Figure 3.

The calibration plate is an image composed of black and white, and the projection of the corner points in the pixel coordinate system is as follows:
Where $u$ and $v$ are the coordinate values of the corner points in the pixel coordinate system. $f / dx$, $f / dy$, $u_0$, $v_0$ are the inherent parameters of the camera, and $[R\{T]$ is the Euler transformation matrix.

The calibration board is installed at the end of the robot arm, and the calibration board is attached instead of the photosensitive plate at the end of the robot arm. It can be reliably detected by the camera and displayed in the image. Project the position of the corner point of the calibration plate in the robot coordinate system to the pixel coordinate system to obtain as

\[
P_{\text{cam}} = [R\{T] \cdot [R\{T] \cdot p_{\text{board}}
\]

Where $p_{\text{board}}$ is a corner point in the coordinate system of the calibration board, $T_{\text{board}}^{\text{tool}}$ is the conversion matrix from the end of the robotic arm to the calibration board, $T_{\text{board}}^{\text{base}}$ is the transformation from the robotic arm to its end, $l_{\text{cam}}$ is the camera projection matrix and $p_{\text{cam}}$ is the position of the point in the camera image. Finally, the mathematical model of the robotic arm coordinate system and the camera coordinate system can be expressed as

\[
\begin{bmatrix}
    z \\
    y \\
    z \\
    1
\end{bmatrix} = 
\begin{bmatrix}
    M_1 & M_2 \\
    0 & 1 \\
    0 & 0 \\
    1 & 1
\end{bmatrix}
\begin{bmatrix}
    U \\
    V \\
    W \\
    1
\end{bmatrix}
\]

Where $x$, $y$ and $z$ are the coordinate values of the target in the basic coordinate system of the robot arm. $U$, $V$ and $W$ are the coordinates of the target point in the camera coordinate system. $M_i$ and $M_2$ are expressed as follows:

\[
M_1 = 
\begin{bmatrix}
    R_{11} & R_{12} & R_{13} \\
    R_{21} & R_{22} & R_{23} \\
    R_{31} & R_{32} & R_{33}
\end{bmatrix}
\]

\[
M_2 = 
\begin{bmatrix}
    R_{11}T_x + R_{12}T_y + R_{13}T_z \\
    R_{21}T_x + R_{22}T_y + R_{23}T_z \\
    R_{31}T_x + R_{32}T_y + R_{33}T_z
\end{bmatrix}
\]

The two unknown matrices $T_{\text{board}}^{\text{tool}}$ and $T_{\text{base}}^{\text{cam}}$ use internal point optimization method to find the parameter that minimizes the point projection error. Since there are many unknown parameters, it is easy to make the optimization fall into the local optimal solution. Therefore, the flag is used for initial calibration, and the calibration value is used as the initial value of the above optimization process.

Then the position of the mark center point is projected into the camera coordinate system, and the posture of the camera can be obtained as

\[
\text{Pose}_{\text{maker}} = T_{\text{base}}^{\text{cam}} \cdot T_{\text{tool}}^{\text{maker}} \cdot P_{\text{center}}
\]

Where $P_{\text{center}}$ is the center posture of the marking plate in the marking coordinate system. $T_{\text{tool}}^{\text{maker}}$ is the conversion from the end of the robot arm to the mark, and the coordinate system of the mark is parallel to the coordinate system of the end of the manipulator. At the same time, the position of the center point of the mark refers to the end coordinate system of the arm that can be obtained through kinematic analysis, so the parameter of $T_{\text{tool}}^{\text{maker}}$ is known. $\text{Pose}_{\text{maker}}$ is the posture of the marker in the camera.
coordinate system. Just collect $\text{Pose}_{\text{marker}}$ and $T_{\text{tool}}^\text{base}$ in a specific state to obtain the initial value of hand-eye calibration according to Eq. (6).

Therefore, before the trajectory tracking, the movement model of the end photosensitive plate clamping can be obtained as

$$T_{p-p}^\text{maker} = (T_{\text{base}}^\text{tool} T_{\text{tool}}^\text{marker})^{-1} \text{Pose}_{\text{marker}}$$

(7)

Among them, $T_{p-p}^\text{maker}$ is the conversion relationship between the marking plate and the end photosensitive plate.

3.3. Adaptive tracking control

In order to improve safety and make the photosensitive plate as close as possible to the dental lesion in the mouth. Therefore, the force/position control is performed on the robot, and the end presses the photosensitive plate to make the patient's tooth surface contact the photosensitive plate.

As shown in Figure 4, create a coordinate system scene. Where $\{W\}$ is the world coordinate system, $\{R\}$ is the manipulator coordinate system attached to the robot base, and $\{S\}$ is the sensor coordinate system and the coincident Z axis parallel to the tool center point (TCP) coordinate system of the manipulator. At the same time, the Z direction of $\{S\}$ is perpendicular to the TMS coil plane.

According to the D-H parameters of the universal robot, the conversion matrix from the sensor coordinate system to the basic frame can be obtained by the following methods:

$$^sR = ^sR \cdots ^iR \times ^iR = 
\begin{bmatrix}
n_x & o_x & a_x \\
n_y & o_y & a_y \\
n_z & o_z & a_z \\
\end{bmatrix}, \quad i = 1, 2, \ldots, 6$$

(8)

Where $^iR$ is the rotation matrix of $\{S\}$ relative to the TCP coordinates. $^{i-1}R$ is the rotation matrix of the i-th joint coordinate system relative to the (i-1)th joint coordinate. $^sR$ is the rotation matrix of $\{S\}$ relative to $\{R\}$.

In order to achieve active control and approach the lesion in the patient's mouth, we applied a force of 1 N to the patient's teeth in a direction perpendicular to the plane of the photosensitive plate. Figure 5 is a structural diagram of an active control system. It can be seen that the output of the adaptive PD controller is the posture correction of the robot arm, $q$ is the angle of the robot arm joint, $F_i$ is the sensor measurement value, and $F_i$ is the expected force acting on the patient's mouth.
Define the coordinate system \( \{T\} \) in the plane of the photosensitive plate, as shown in Figure 4, the Z direction is perpendicular to the plane of the photosensitive plate. \( \{T\} \) is parallel to the sensor coordinate system. After the robot arm moves to the specified position, if the patient does not move within the specified time, the force control mode will be turned on to make the photosensitive plate as close as possible to the lesion tooth area. If the head is moving, the tracking robot arm and the photosensitive plate are always relative to the front side of the tooth position of the lesion, and there is no interaction force between the robot arm and the tooth position in the mouth. At the same time, after reaching the designated area, the arm only moves in the Z direction of \( \{T\} \), and the posture of the photosensitive plate will not change in the active control mode.

Due to the use of traditional PD controllers, system instability will occur [19]: when the input value is small, the angle of motion of the arm is too small, and the amount of time is too long. If the input value is large, the adjustment amount of the arm is too large to swing back and forth. Therefore, an adaptive PD controller is used to determine the motion angle of the manipulator. The measured value after gravity compensation and the expected force value acting in the mouth are used as the input of the adaptive PD controller, which is used to determine the correction of the robot posture. The logarithmic function is used as the identification function of the adaptive controller as

\[
\begin{align*}
    k_p &= k_p + \Delta k_p \cdot \log_n(1 + |E|) \\
    k_d &= k_d + \Delta k_d \cdot \log_m(1 + |EC|)
\end{align*}
\]

(9)

Where \( n>1 \) and \( m>1 \), \( \log_n(1 + |E|) > 0 \) and \( \log_m(1 + |EC|) > 0 \), \( n \) and \( m \) can be obtained through experiments.

The output of the adaptive PD controller is the position calibration value in \( \{S\} \), converted to \( \{R\} \) coordinate system as

\[
\delta X_R = \frac{1}{\delta R} \delta X
\]

(10)

4. Conclusion
This paper proposes a collaborative robot control strategy that assists in oral diagnosis and treatment. According to the small space of the oral cavity and the change of the tooth position, a dynamic trajectory tracking method with adaptive control was proposed. This control strategy is of great significance for accurate oral diagnosis and treatment and reducing cross-infection between doctors and patients.

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