Force Control for Positional-Controlled Robotic Manipulators Based on Vision/Torque

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ABSTRACT: This paper presents a hybrid force position control strategy for position-controlled robotic manipulator based on the vision. Vision data are employed to estimate the local shape of constraint. The relationship between actual force and measure force is analyzed and derived. The estimated vectors are used to generate the virtual reference trajectory for the target impedance model, which is driven by the force error to produce a command position to the manipulator. By following the commanded position trajectory the robotic manipulator can follow unknown constraint surface while keeping an acceptable force error in a manner depicted by the target impedance model. Two fuzzy parameters are thus developed to tune the reference trajectory in order to adapt the reference trajectory generated for the changeable unknown stiffness in environment. The tracking speed reach 15 mm/s with a small field of view (26.4mm × 26.4mm), Experiment is conducted to verify its force tracking capability.

KEYWORDS: Vision-guided; Hybrid force/position control; Impedance control; Unknown environment.

INTRODUCTION

Many manipulation tasks, such as assembly, polishing, machining operation, require the end-effector of the manipulator to establish and maintain contact with the objects to be handled. Most industrial robots with high positioning accuracy are being used at present, but they generally do not have force control capability, which greatly limits the application field of robotics. Therefore, force control is worth to be studied for position-controlled robotic manipulator [1].

At present, the main force control methods are the impedance control [2] and hybrid position/force control [3], from the aspect of improving the adaptability of the robot to the environment and the ability to reflect the rapid, in recent years many researchers explore the vision formation as the feedback control source involved in the feedback control system [4], but these studies have not considered that the constrained environment shape information and stiffness are unknown at the same time, aiming at this problem, use the visual/torque information to implement force control research for the position control robot. In fact, use force sensor to measure the actual force, there are two cases: when the force sensor center is far distance from the end of contact point, the force sensor measurement does not truly reflect the force information [5], through measuring torque calculate end actual contact force; when the terminal point of contact is very near distance from force sensor center, terminal actual contact force can be directly through the force information [6].

Force control for positional-controlled robotic manipulators based on vision/torque is proposed, the scheme doesn't need precise robot model and detailed geometry information of environmental constraints, use visual image and the torque information to estimate the local geometry of the environmental constraints, calculate the position control direction and the force control direction, generate the online motion planning, use robotic high precision servo position control to achieve contact force tracking of the unknown constraint surface.

Online Estimation of Unknown Constraint Based on Torque

The main form of the robot contact with the environment is the contact force, if force information can be used to estimate constraints of unknown environment, online get the position control and force control direction, can realize the robot compliant control. Contact force in edge tracking is shown in Figure 1. \( F^t, F^n \) is respectively at the contact point of the tangential contact force and the normal contact force, the end of tool radius is \( r \), the angle between \( F^n \) and \( Y_3 \) axes reverse is \( \theta \). The control task is: with a constant velocity \( V \) along the tangential direction of the workpiece surface, the given positive pressure is applied in normal direction.
In general, the end of tool after installation and force sensor is parallel, the offset displacement which the end of tool in force sensor coordinate system \( S \) is \((\Delta X, \Delta Y, \Delta Z)\), assuming only the plane motion as shown in the diagram, there are relations:

\[
\begin{align*}
\tau_x &= \{ F_n \cdot \cos \theta + F_t \cdot \sin \theta \} \cdot \Delta Z \tag{1} \\
\tau_y &= \{ F_n \cdot \sin \theta - F_t \cdot \cos \theta \} \cdot \Delta Z \tag{2} \\
\tau_z &= \{ F_n \cdot \sin \theta - F_t \cdot \cos \theta \} \cdot [\Delta Y + r \cdot \cos \theta] + \{ F_n \cdot \cos \theta + F_t \cdot \sin \theta \} \cdot [\Delta X + r \cdot \sin \theta] \tag{3}
\end{align*}
\]

In the equations (Equation 1, Equation 2, Equation 3), \( \tau_x \), \( \tau_y \), \( \tau_z \) are torque information, three torque components contain the normal contact force \( F_n \), tangential contact force \( F_t \) and angle \( \theta \). \( F_n \), \( F_t \) and \( \theta \) can be solved, the unit tangent vector \( \hat{k}_t \) and the unit normal vector \( \hat{k}_n \) of the contact point can be determined, \( \hat{k}_t \) and \( \hat{k}_n \) For are used to online plan motion sequence of impedance control.

\[
\begin{align*}
k_t &= \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \end{bmatrix},
k_n &= \begin{bmatrix} \sin(\theta) & -\cos(\theta) & 0 \end{bmatrix}.
\end{align*}
\]

In reference [7], \( \hat{k}_t \) and \( \hat{k}_n \) have been obtained, but need to know the friction coefficient between the terminal and the environment, consider the friction makes the system analysis becomes more complex and difficult to model, the ability adapting to environment uncertainty will reduce.

**Online Estimation of Unknown Constraint Based on Image Information**

The environmental tangential direction and normal direction can be calculated by image feature extraction, high speed tracking relies on real time of image feature extraction, the most concise method must be used to ensure that the extraction process can complete within robot servo cycle (2 ms).

Environmental edge tracked in image is a black ribbon pixel set, the smallest black line width in the image coordinate. In order to obtain environment trajectory characteristics near the camera center, establish the child window \( W \) around the center coordinates \((x_0, y_0)\), the window length is \( d \), along the sub window boundary clockwise search, \( n \) is the number of the continuous black pixels recorded, if \( n > W_{\text{min}} \), recognized as trajectory coordinates, calculate the continuous black pixel center to get the intersection point coordinate \((x_1, y_1)\) between the trajectory and the window, repeat the above process can get another intersection point coordinate \((x_2, y_2)\), if \( d << 1/K \) (\( K \) is trajectory curvature), the intersection point of trajectory and the window is only two, the trajectory tangent angle can be calculated:
\[ \alpha_i = \arctan(2(y_2 - y_1, x_2 - x_1)) \] (4)

If the intersection of the trajectory with the window more than two, thus with the last tangential vector minimum angle tangent vector is the tangential direction. At this point you can estimate the unit tangent vector and the unit normal vector of the environment.

\[ \omega_t = [\cos(\alpha_i) \sin(\alpha_i)], \omega_n = [\sin(\alpha_i) - \cos(\alpha_i)] \] (5)

The calculated \( \omega_t, \omega_n \) is used to online plan robot impedance control reference trajectory.

The Reference Trajectory Fuzzy Adjustment

Impedance control is through the adjustment the target impedance model set by the user, the robot terminal reach compliant motion. The target impedance models commonly used such as Eq.6 are shown.

\[ M_m(\ddot{X} - \ddot{X}_r) + D_m(\dot{X} - \dot{X}_r) + K_m(X - X_r) = E_f \] (6)

In the formula, the specific parameters meaning can be seen in literature [7]. When the robot contact the unknown environment, must use online estimation method, generate impedance model motion sequences. Because of the vision itself specific weaknesses and force sensor high requirements on flexibility, and if the robot end contact with soft materials, the environment can be deformed, \( \omega_t, \omega_n \) if used Eq.5 alone, will affect the accuracy of the reference trajectory. In this paper, combined with the torque information and image feature, deduce a simple effective and available fuzzy regulating reference trajectory algorithm, fuzzy regulation reference trajectory:

\[ X_r(k) = X(k - 1) + \frac{F_d - F(k)}{k_e} \omega_n(k) + (VT)\omega_t(k) + \gamma(k) \times \Delta X_r(k), \quad k = 1, 2, 3, \ldots \] (7)

Where, \( \Delta X_r(k) \) is the variation range of the reference trajectory adjustment amount, it determines the range deformation environment in constrained motion, assume \( e_{pn} \) is the position error is the normal direction, then

\[ \Delta X_r(k) = \frac{F_d(k - 1)e_{pn}(k - 1)}{F_n(k - 1)} - \frac{F_d(k - 2)e_{pn}(k - 2)}{F_n(k - 2)} \] (8)

Fuzzy regulation is divided into two parts, respectively is \( \alpha_i(k) \) and \( \gamma(k) \). Fuzzy regulation formula for \( \alpha_i \) in unit tangent vector \( \omega_i = [\cos(\alpha_i) \sin(\alpha_i)] \) is

\[ \alpha_i(k) = \alpha_i(k - 1) + [1 - \beta(k)] \cdot [\theta(k - 1) - \alpha_i(k - 1)], \quad k > 1 \] (9)

Where, \( \theta(k - 1) \) is the equations (Equation 1, Equation 2, and Equation 3) calculated direction angle, the size of the parameter \( \beta(k) \in [0, 1] \) is adjusted by fuzzy reasoning. The adjustment principle of the \( \beta(k) \): when the direction angle error \( [\theta(k - 1) - \alpha_i(k - 1)] \) is small, \( \beta(k) \) tends to 1, on the other hand, \( \beta(k) \) tends to 0.

\( \gamma(k) \in [0, 1] \) is a scaling factor, \( \gamma(k) \) is adjusted by fuzzy scaling machine.

Experimental Study

To verify the hybrid force position control strategy for position-controlled robotic manipulator based on vision, experimental research is conducted on the unknown workpiece edge tracking by the Adept-3 robot, the robot control parameters see the literature [8], SAFMS-11 six dimension wrist force/torque sensor developed by Chinese Academy of Sciences Hefei Intelligent Machinery Research Institute is used. A CCD camera is installed at the end of the robot arm,
used to collect trajectory data and draw the tangent angle and normal angle. Figure 2 and Figure 3 is the experiment result, from the workpiece edge tracking and force tracking curve can be seen, the hybrid control strategy is proposed in this paper can basically meet the control requirements.

CONCLUSION
In this paper, the machine vision is used to real-time adjust the reference trajectory model in the impedance control, improves the global force control performance. But the control algorithm proposed in this paper is only for two-dimensional workpiece edge, the next phase of work is hybrid control for unknown environment in three-dimensional space.

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