Surgical Robot Control Based on Torque Control Method

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Abstract. Surgical robots are usually controlled by the method of the independent PD or the PD model based on gravity compensation. However, the system is still a open loop control with both of the control models. The two models can not consider the dynamics effectively either. The position error can not be guaranteed. To solve the problem, a torque control model based on dynamic model and adaptive model is proposed. And the position tolerance of PD control based on gravity compensation and that of control based on Torque Control stability theory are compared by Matlab software. The maximal tolerance of the new method is red robot end-effector is 0.15mm.

Introduction

The robotic system is a redundancy, nonlinear dynamic system[1]. The control of the robot is basically talking about the motion and status of the end-effectors. The position control and trajectory tracking are two main categories of the control[2].

The control methods of robotic could be categorized into the kinematic and dynamic methods. The kinematic methods are usually deployed for the motion control. The independent PD control algorithm skips the dynamic model of the robot. The position feedback were compared to the desire value in order to eliminate the error[3]. A more practical method considered the weight of the robot. The gravity compensation could improve the control accuracy.

Both of the algorithms are linear equation based methods which are unable to reflect the nonlinear robotic system[4].

A torque control algorithm based on Dynamic model is proposed. The algorithm calculates the torque of the driving motors instead of position and trajectory. The controller is closed loop with a nonlinear differential equation of the position error.

The Robotic and the Modeling using Sim-Mechanics

The surgical robot in this research is a 6 DOF limb, as fig. 1. the first one is the prismatic joint. The second to the sixth joint sare rotational joints.

The Matlab SimMechanics was used for the robotic modeling. The simulation model shows as fig.2[5].

Dynamic modeling

Newton-Euler method and Lagrange equation are two major method for dynamic calculation of the surgical robot[6]. The Lagrange equation was used in this research, as Eq.1.

L is lagrange function. K is the kinetic energy and P is potential energy of the robot.

$$L = K - P = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{i}\sum_{k=1}^{i} Trace\left(\frac{\partial T_i}{\partial q_i} I_i \frac{\partial T_i^T}{\partial q_k}\right) \quad \text{(Eq. 1)}$$
$$\times \dot{q}_j \dot{q}_k + \frac{1}{2}\sum_{i=1}^{n} I_{ai}\dot{q}_i^2 + \sum_{i=1}^{n} m_i g^T T_i {}^i r_i, n = 1,2,...$$

The T_i is the relative coordination transformational matrix of i*th* joint. I_{ai} is the equivalent moment of inertia. $\dot{q}_j$ is the velocity of the j*th* joint. the dynamic model of the robot shown as Eq. 2 and Eq. 3 [2].

$$T_i = \sum_{j=i}^{n}\sum_{k=1}^{j} Trace\left(\frac{\partial T_j}{\partial q_k} I_j \frac{\partial T_j^T}{\partial q_i}\right)\ddot{q}_k + I_{ai}\ddot{q}_i + \sum_{j=1}^{n}\sum_{k=1}^{j}\sum_{m=1}^{j} Trace\left(\frac{\partial^2 T_i}{\partial q_k \partial q_m} I_j \frac{\partial T_j^T}{\partial q_i}\right)\dot{q}_k \dot{q}_m - \sum_{j=1}^{n} m_j g^T \frac{\partial T_i}{\partial q_i} {}^i r_i \quad \text{(Eq.2)}$$

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \qquad \text{(Eq.3)}$$

q、$\dot{q}$、$\ddot{q}$ are the position, velocity and acceleration of each joint respectively. $H(q)\ddot{q}$ is the inertia force based on generalized acceleration $\ddot{q}$. $C(q,\dot{q})\dot{q}$ is quadric form of generalized velocity. $\dot{q}_i^2$ is the centrifugal force. $\dot{q}_i \dot{q}_j (i \neq j)$ is coriolis force. And $G(q)$ is the gravity force. τ is the driving force of each actuator[7].

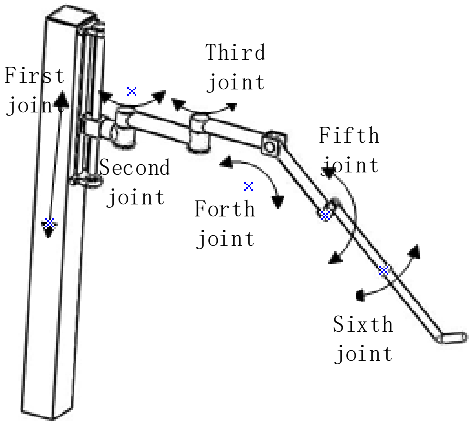

Fig.1 The surgical robot in this research is a 6 DOF limb

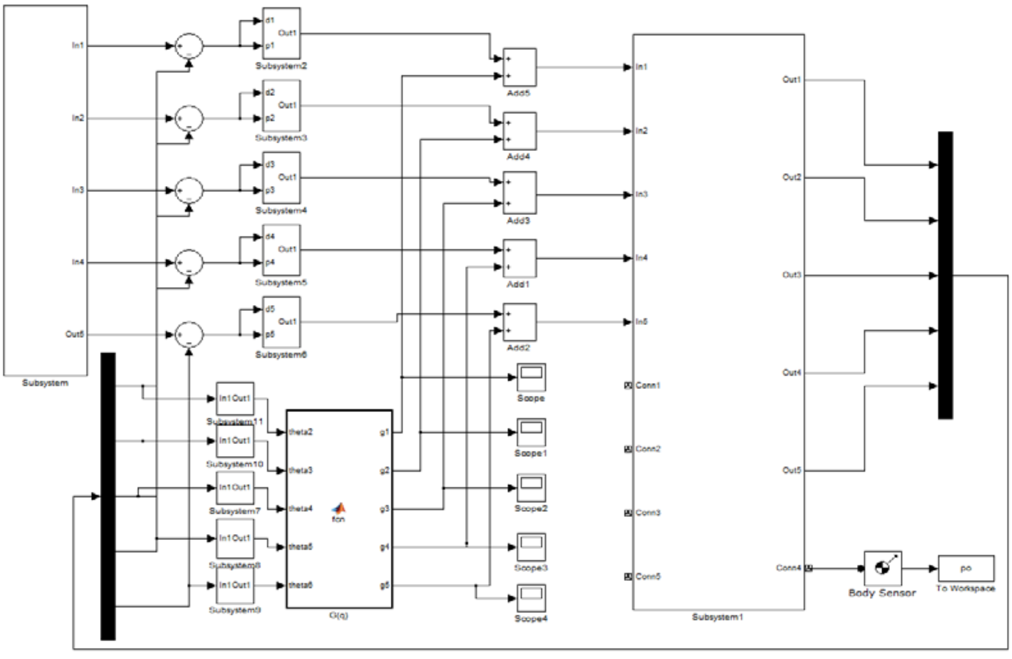

Fig.2 The model of Torque Controller

Control modeling

Robotic is the nonlinear time-variant system. So, the functional analysis was used. The goal of the robot is trajectory tracking, which is a time-variant $q_d(t)$. And the position error: $e = q_d - q$.

$$\dot{q}_r = \dot{q}_d + \Lambda(q_d - q) = \dot{q}_d + \Lambda e \qquad \text{(Eq.4)}$$

Λ is the positive definite matrix. The control law is:

$$\tau = H(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + K_d(\dot{q}_r - \dot{q}) \qquad \text{(Eq.5)}$$

K_d is the positive definite matrix. And the close loop equation will be:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = H(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + K_d(\dot{q}_r - \dot{q}) \qquad \text{(Eq.6)}$$

and

$$H(q)(\ddot{q}_r - \ddot{q}) + C(q,\dot{q})(\dot{q}_r - \dot{q}) + K_d(\dot{q}_r - \dot{q}) = 0 \qquad \text{(Eq.7)}$$

considered:

$$\dot{q}_r - \dot{q} = \dot{e} + \Lambda e, \ddot{q}_r - \ddot{q} = \ddot{e} + \Lambda\dot{e} \qquad \text{(Eq.8)}$$

So:

$$H(q_d - e)\,\ddot{e} + \Lambda\dot{e} + C(q_d - e, \dot{q}_d - \dot{e})\,(\dot{e} + \Lambda e) + K_d\,(\dot{e} + \Lambda e) = 0 \qquad \text{(Eq.9)}$$

The torque control algorithm uses the dynamic model of the robot. And it is a close loop with a nonlinear differential equation for the error e[4].

Simulation and Verification

The trajectory of the surgical robot from A(0,1402.7,878.7) to B(-193.5,1410.8,914.1) was derived by Sim-Mechanics and inverse kinematic method. So the desire trajectory could be gotten,

The PD controller with gravity compensation considered the weight of all limbs and actuators. The close loop control was formed by adding the gravity feedback. The desire trajectory and result were compared in the fig.3.

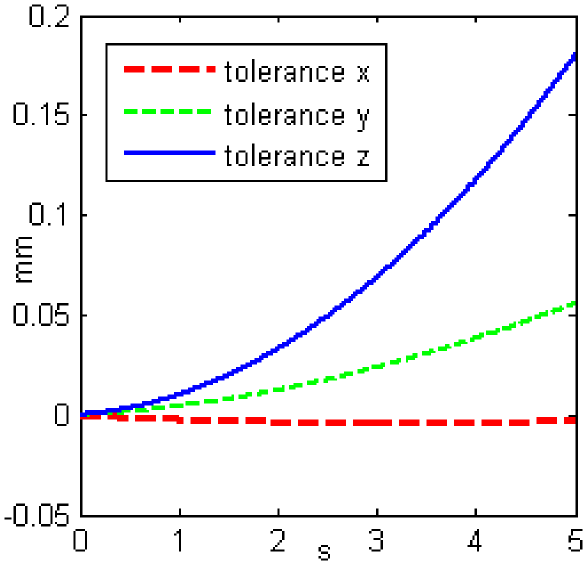

Fig.3 position error of robot based on PD controller with gravity compensation

The PD controller with gravity compensation is fast response and high accuracy. This algorithm achieved its best by using linear modeling to solve the nonlinear system. This research proposed the torque control algorithm. So the dynamic model will be:

$$\tau = H(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + K_d(\dot{q}_r - \dot{q}) \qquad \text{(Eq.10)}$$

and $\dot{q}_r = \dot{q}_d + \Lambda(q_d - q)$ ， Λ =diag[15,0.2,40.1,4,2], K_d =diag[0.1,0.2,0.045,0.06,0.1].

A more straight forward results comparison of the torque controller and PD controller shows as Fig.4. Fig.4 shows the maximum error with torque controller is about 0.15mm, which is a better result than other methods.

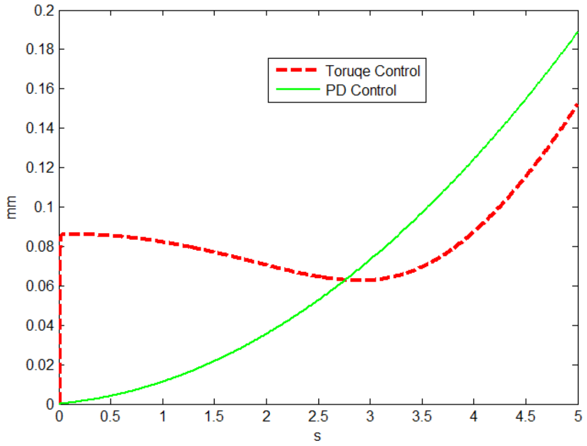

Fig.4 Tolrance Comparison of two control method

The position error shown in Fig.5.

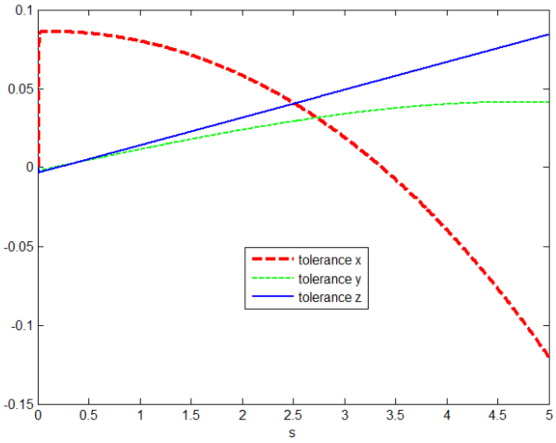

Fig.5 Position error by torque controller

Conclusion

A control algorithm based on Lagrange Equation and troque control were proposed. The dynamic model were considered in the new method. And the controller is closed loop with a nonlinear differential equation of the position error. The simulaition result proved the new algorithm provided a more accuracy in position control and trajectory tracking.

The Matrix Λ and K_d in the control model could be finely tuned to improve the PD controller. And a better control quality could be achieved.

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