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Impedance force control for position controlled robotic manipulators under the constraint of unknown environments

Qiao Bing[1] Lu Rongjian[2]

([1] College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)
([2] College of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing 210037, China)

Abstract: A force control strategy for position controlled robotic manipulators is presented. On-line force feedback data are employed to estimate the local shape of the unknown constraint. The estimated vectors are used to generate the virtual reference trajectory for the target impedance model that is driven by the force error to produce command position. By following the command position trajectory the robotic manipulator can follow the unknown constraint surface while keeping an acceptable force error in a manner depicted by the target impedance model. Computer simulation on a 3-linked planar manipulator and experimental studies on an Adept-3, an SCARA type robotic manipulator, are conducted to verify the force tracking capability of the proposed control strategy.

Key words: robotic manipulators; force/position control; unknown constraint

Force control capability is considered as an important way to expand the applications of robotic manipulator. Two broad approaches for the control of robot executing constrained motion or compliant motion can be classified after reviewing the literature on robot force control: hybrid position/force control and impedance control[1-6].

Hybrid position/force control[7] is based on the intuitive observation that when the robot end-effector comes into contact with the environment, the constraint space can naturally be decomposed into two orthogonal subspaces corresponding to position controlled direction and force controlled direction, respectively. The compliant motion can be obtained by explicitly controlling the end-effector position in position controlled space and the contact force in force controlled space. The hybrid position/force control is a conceptually clear scheme. However, because the implementation strongly depends on the accurate decomposition of constraint space and the correct switching of control law corresponding to this decomposition, the hybrid position/force control strategy requires detailed environmental geometry, which is an impractical requirement in many manipulation tasks.

Impedance control[8] achieves compliant motion through regulating mechanical impedance specified by a target model, which depicts a desired dynamic relationship between end-effector position and contact force. The main objective of the impedance controller is to maintain such a desired dynamic relationship. Impedance control is considered as a unified approach to free motion control and compliant motion control. However, as a consequence of controlling force indirectly, impedance control method shows poor force tracking capability. In fact, lack of force tracking capability has been regarded as the major disadvantage of impedance control over hybrid position/force control[9].

This paper presents a force/position control strategy for position controlled robotic manipulators that combines the advantages of impedance control and hybrid position/force control. On-line force feedback data are employed to estimate the normal and tangent vectors of the contact point. 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 the contact force within an acceptable range in a manner depicted by the target impedance model.

1 Estimation of Unknown Constraint

The normal and tangent vectors of the constraint surface on the contact point can be calculated off-line if precise geometry of the constraint is available. In the cases of unknown constraint environments, we have to resort to the on-line data, such as force feedback, position and velocity of the end-effector, to estimate the local shape of constraints. Some related research efforts in this direction have been made. Merlet[10]

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Biography: Qiao Bing (1967—), male, associate professor, bqiao@nuaa.edu.cn.

proposed using measured force feedback to determine the normal of constraint surface. Blauer, et al.[11] estimated some unknown parameters of the constraint surface using extended Kalman filter. Yoshikawa, et al.[12] and Pelletier, et al.[13] combined the position and force data obtained on-line to estimate the local shape of the constraint surface.

Interaction force is the main form of the contact between the end-effector of manipulator and the constraint environment. If the robot can figure out the normal and tangent of the contact point through sensed force signal, it will demonstrate a tactile characteristic. With this capability, a robotic manipulator will be able to carry out a wider range of tasks. Fig.1 illustrates the motion of end-effector constrained by unknown environment.

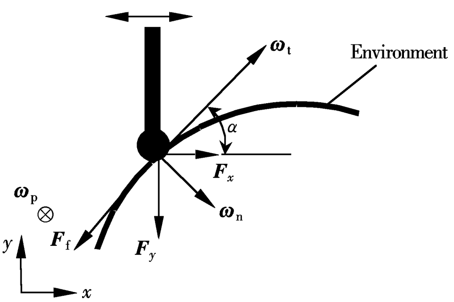

Fig.1 Constrained motion of end-effector

In Fig.1, $\boldsymbol{F}_x$ and $\boldsymbol{F}_y$ denote the force that the end-effector exerted on the environment, which can be measured by a wrist force/torque sensor mounted on the end-effector of manipulator. $\boldsymbol{\omega}_p$ is the unit normal vector of virtual constraint plane, and $\boldsymbol{\omega}_n$, $\boldsymbol{\omega}_t$ are unit normal and tangent vector respectively of environment on the contact point. If the constraint surface is frictionless, the direction of contact force is the normal of the environment, so $\boldsymbol{\omega}_n$ and $\boldsymbol{\omega}_t$ can be obtained by

$$\boldsymbol{\omega}_n = \frac{\boldsymbol{F}_x + \boldsymbol{F}_y}{\| \boldsymbol{F}_x + \boldsymbol{F}_y \|}, \quad \boldsymbol{\omega}_t = \boldsymbol{\omega}_n \times \boldsymbol{\omega}_p \tag{1}$$

in which $\|\cdot\|$ is the Euclidean norm of vectors. However, frictional force usually exists when relative motion occurs between two objects, the problem will become troublesome because friction is difficult to model. If smooth and steady motion is supposed, the frictional force can be reduced to the form $\|\boldsymbol{F}_f\| = \|\boldsymbol{F}_n\| \cdot f$, in which $\boldsymbol{F}_f$ is friction force, $\boldsymbol{F}_n$ is normal force to the constraint surface and f is a frictional coefficient that can be obtained by experiments. According to static mechanical analysis, $\boldsymbol{\omega}_n$, $\boldsymbol{\omega}_t$ can be calculated by

$$\boldsymbol{\omega}_t = [\cos\alpha \quad \sin\alpha \quad 0] \tag{2}$$

$$\boldsymbol{\omega}_n = [\sin\alpha \quad -\cos\alpha \quad 0] \tag{3}$$

$$\tan\alpha = \frac{\| \boldsymbol{F}_x \| - f \| \boldsymbol{F}_x \|}{\| \boldsymbol{F}_y \| + f \| \boldsymbol{F}_x \|} \qquad -\pi \leqslant \alpha \leqslant \pi \tag{4}$$

When the noise of the force sensor is low enough, Eqs. (2) to (4) can satisfactorily estimate the local normal vector and tangent vector of the constraint surface. The estimated normal and tangent vectors will be used for the on-line generation of the virtual reference trajectory for the target impedance model.

2 Impedance Force Control

Impedance control does not attempt to track motion or force trajectory but to regulate a target mechanical impedance model specified in advance. The three most commonly used target impedance models are[7,8]:

$$\boldsymbol{M}_m(\ddot{\boldsymbol{X}} - \ddot{\boldsymbol{X}}_r) + \boldsymbol{D}_m(\dot{\boldsymbol{X}} - \dot{\boldsymbol{X}}_r) + \boldsymbol{K}_m(\boldsymbol{X} - \boldsymbol{X}_r) = \boldsymbol{E}_f \tag{5}$$

$$\boldsymbol{M}_m\ddot{\boldsymbol{X}} + \boldsymbol{D}_m(\dot{\boldsymbol{X}} - \dot{\boldsymbol{X}}_r) + \boldsymbol{K}_m(\boldsymbol{X} - \boldsymbol{X}_r) = \boldsymbol{E}_f \tag{6}$$

$$\boldsymbol{M}_m\ddot{\boldsymbol{X}} + \boldsymbol{D}_m\dot{\boldsymbol{X}} + \boldsymbol{K}_m(\boldsymbol{X} - \boldsymbol{X}_r) = \boldsymbol{E}_f \tag{7}$$

where $\boldsymbol{M}_m$, $\boldsymbol{D}_m$ and $\boldsymbol{K}_m$ are the diagonal mass, damping and stiffness matrices of the target impedance model; $\boldsymbol{X}$ is the position trajectory of end-effector and $\boldsymbol{X}_r$ is the virtual reference trajectory. $\boldsymbol{E}_f = \boldsymbol{F} - \boldsymbol{F}_d$ is the force error, which drives the target impedance model to produce the motion command for robot. $\boldsymbol{F}$ is the sensed contact force and $\boldsymbol{F}_d$ is the desired contact force that is usually a vector with a constant magnitude.

The simple representative model for modeling contact of robot and environment is $\boldsymbol{F} = \boldsymbol{K}_e(\boldsymbol{X} - \boldsymbol{X}_s)$, for $\boldsymbol{X} > \boldsymbol{X}_s$, where $\boldsymbol{K}_e$ is the environmental stiffness matrix, $\boldsymbol{X}$ and $\boldsymbol{X}_s$ stand for the end-effector position and static environment location respectively. If $\boldsymbol{K}_e$ and $\boldsymbol{X}_s$ are precisely known *a priori*, a reference position trajectory $\boldsymbol{X}_r$ can be synthesized as

$$\boldsymbol{X}_r = \boldsymbol{X}_s + \frac{\boldsymbol{F}_d}{\boldsymbol{K}_e} \tag{8}$$

Substituting (8) into, for instance, the target impedance model (7) and considering $\boldsymbol{K}_e$ and $\boldsymbol{X}_s$ as constants yield

$$\boldsymbol{M}_m\ddot{\boldsymbol{X}} + \boldsymbol{D}_m\dot{\boldsymbol{X}} + (\boldsymbol{K}_m + \boldsymbol{K}_e)(\boldsymbol{X} - \boldsymbol{X}_r) = 0 \tag{9}$$

The formula (9) represents a stable second order differential equation. $\boldsymbol{X} \to \boldsymbol{X}_r$ and $\boldsymbol{F} \to \boldsymbol{F}_d$ as $t \to \infty$. That means the end-effector of the robotic manipulator will accurately track the virtual reference position trajectory synthesized by (8) which penetrates into the constraint environment surface with a constant deformation of $\boldsymbol{F}_d/\boldsymbol{K}_e$ to produce the desired contact force $\boldsymbol{F}_d$. However, $\boldsymbol{K}_e$ and $\boldsymbol{X}_s$ are usually unknown or not precisely known when the robot comes into contact with unstructured or unknown constraint environments. It is necessary to generate the reference position trajectory $\boldsymbol{X}_r$ on-line according to the real state of environment/robot contact or the robot will not be able to track the unknown constraint surface with the contact force being well controlled.

3 On-line Generation of Reference Position Trajectory

The drive signal of the target impedance, $\boldsymbol{E}_f(k)$, can be obtained from measured force feedback. The virtual reference position trajectory $\boldsymbol{X}_r(k)$ for the target impedance model must be synthesized in real time based on the actual state of robot/environment contact when robotic manipulator is confronted with an unknown constraint environment. In the practical implementation, the following formulation is used to predict the next reference position for target impedance model,

$$\boldsymbol{X}_r(k+1) = \boldsymbol{X}_r(k) + \left\| \frac{\boldsymbol{F}_d - \boldsymbol{F}(k)}{\boldsymbol{K}_e} \right\| \boldsymbol{\omega}_n(k) + (vT_s)\boldsymbol{\omega}_t(k) \qquad k = 1,2,3,\cdots \tag{10}$$

where k stands for the sampling step; T_s is the sampling time and v denotes the constant tangent velocity. Fig.2 is the block diagram of impedance force control scheme for position controlled manipulators. The area within the dashed rectangle is the position control system of traditional robotic manipulators that usually has a high precision of position servo. The area outside the dashed rectangle constitutes the force control strategy for the traditional position controlled robotic manipulators.

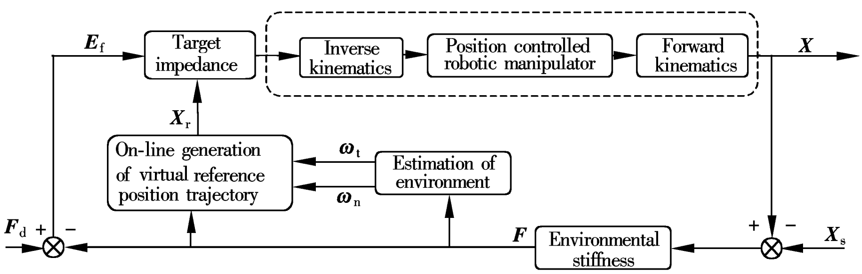

Fig.2 Force control scheme for position controlled robotic manipulator

4 Computer Simulation

Computer simulation has been done to confirm the effectiveness of the proposed controller with a three-linked planar robotic manipulator (see Fig.3).

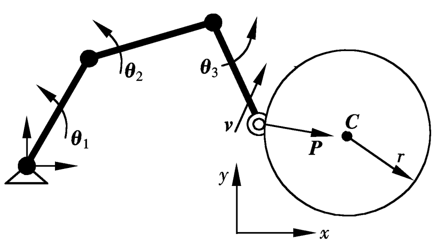

Fig.3 Three-linked planar manipulator

The dynamics model for the robot is as follows:

$$\boldsymbol{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \boldsymbol{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + \boldsymbol{G}(\boldsymbol{\theta}) = \boldsymbol{\Gamma} \tag{11}$$

where $\boldsymbol{M}(\boldsymbol{\theta})$ is the 3×3 symmetric and positive definite joint space inertia matrix; $\boldsymbol{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})$ is the 3×1 vector of Coriolis and centrifugal terms; $\boldsymbol{G}(\boldsymbol{\theta})$ is the 3×1 vector of gravitational terms; $\boldsymbol{\Gamma}$ is the 3×1 vector of torque at joints, and $\boldsymbol{\theta}$ is the 3×1 joint variables. In fact, the detailed dynamic Eq. (11) is not needed for the simulation of the proposed control scheme but for the purpose of mimicking the real behavior of the robotic manipulator. A model-based controller[14] has been designed for the robot so as to make the robot accurately track the commanded position trajectory.

In the simulation the end-effector of the planar robotic manipulator is required to follow the surface of an unknown cylinder while keeping a constant normal force $P = 15$ N exerted on the surface. In order to emulate the sensed force signal, the center of the cylinder is assumed at $\boldsymbol{C}$ and the stiffness of environment is $\boldsymbol{K}_{env} = \mathrm{diag}\,(100,\ 100)$N/mm, where $\mathrm{diag}\,(c_1, c_2)$ stands for a 2×2 diagonal matrix with c_1 and c_2 as the diagonal elements. The sensed force feedback is calculated as

$$\boldsymbol{F}(k) = \begin{cases} \boldsymbol{n} & \|\boldsymbol{X}(k) - \boldsymbol{C}\| \geqslant r \\ \boldsymbol{K}_{env}\left\{[\boldsymbol{X}(k) - \boldsymbol{C}] - r\dfrac{\boldsymbol{X}(k) - \boldsymbol{C}}{\|\boldsymbol{X}(k) - \boldsymbol{C}\|}\right\} + \boldsymbol{n} & \|\boldsymbol{X}(k) - \boldsymbol{C}\| < r \end{cases} \tag{12}$$

where $\boldsymbol{n}$ is a random noise of the force sensor with maximum amplitude of ± 0.25 N and $r = 30$ mm is the radius of the cylinder. The target impedance model used in the simulation is

$$\ddot{\boldsymbol{X}} + \begin{bmatrix} 2\sqrt{15} & 0 \\ 0 & 2\sqrt{15} \end{bmatrix}\dot{\boldsymbol{X}} + \begin{bmatrix} 15 & 0 \\ 0 & 15 \end{bmatrix}(\boldsymbol{X} - \boldsymbol{X}_r) = \boldsymbol{E}_f \tag{13}$$

Since there is no *a priori* knowledge about the constraint environment, the environmental stiffness can only be roughly estimated, say, in the simulation $\boldsymbol{K}_e = \mathrm{diag}(75,\ 75)$N/mm, which together with the sensed force by (13) is fed to (10) to calculate the virtual reference position trajectory for the target impedance model. The local shape of the constraint environment is estimated by (1). The sampling time is 10 ms and the simulation time is 30 s. The results of the simulation are given in Fig.4, which indicates the proposed controller in the paper is able to follow an unknown constraint surface while regulating the contact force acting on the surface within an acceptable range.

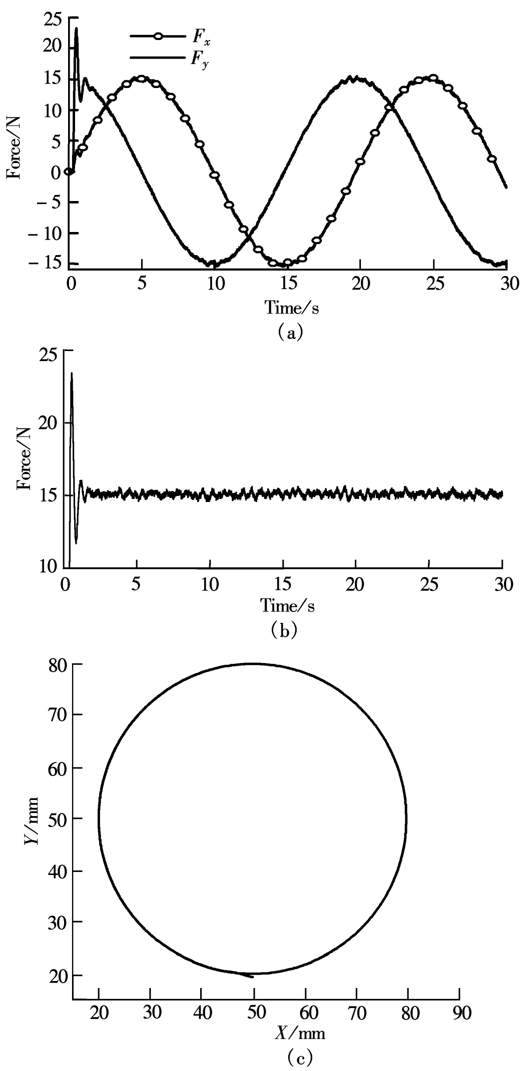

Fig.4 Simulation results for robot tracking unknown cylinder surface. (a) Response of the force components; (b) Normal force acting on the environment; (c) Reference trajectory generated on-line

5 Experimental Studies

The experimental investigation is conducted on an Adept-3, an SCARA type robotic manipulator. A 6-dof wrist force/torque sensor named SAFMS manufactured in Hefei Intelligent Machinery Research Institute of China is mounted on the end-effector. In the experiment, the endpoint of the manipulator will be commanded to follow the surface of a bulb without breaking it. Since the geometric model of the bulb is unavailable, it is an unknown constraint for the robot. During the course of the task, a desired contact force of 10 N should be kept. The target impedance of the task is specified as follows:

$$\ddot{\boldsymbol{X}} + \begin{bmatrix} 2\sqrt{20} & 0 \\ 0 & 2\sqrt{20} \end{bmatrix} \dot{\boldsymbol{X}} + \begin{bmatrix} 20 & 0 \\ 0 & 20 \end{bmatrix} (\boldsymbol{X} - \boldsymbol{X}_{\mathrm{r}}) = \boldsymbol{E}_{\mathrm{f}} \tag{14}$$

Fig.5(a) shows the force error response and Fig. 5(b) illustrates the slope variation of the bulb surface based on the on-line estimation algorithm of Eqs.(2) to (4) with frictional coefficient $f = 0.12$ which is obtained by experiments beforehand. It can be seen from the figures that the proposed controller enables the robot to follow the bulb surface with a desired contact force fluctuated in a small range of ± 0.5 N exerted on the surface despite the lack of *a priori* knowledge regarding the environmental stiffness and geometry. For the inherent full-scale measurement error of the wrist force/torque sensor used in the experiments is ± 0.25 N, the force tracking performance of the proposed control strategy is very satisfactory. Also, the estimated slope curves of unknown constraint surfaces intuitively fit well in the actual situation, which demonstrates that the proposed on-line estimation algorithm is correct and feasible.

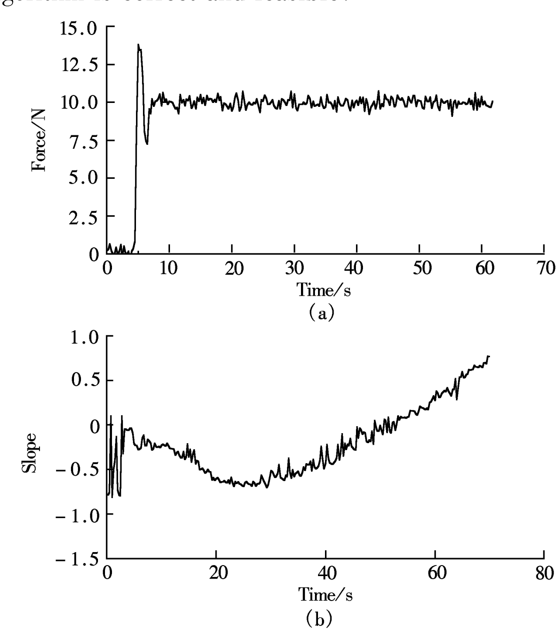

Fig.5 Experimental results. (a) Force response; (b) Estimated slope of bulb

6 Conclusion

An impedance force/position control strategy for position-controlled robotic manipulators has been formulated. As the proposed strategy does not deteriorate but utilizes a high precise position control system of robot manipulators installed in most of today's workshop, the control scheme can be applied to a wide range of manipulator applications.

Computer simulation and experimental study on an Adept-3, an SCARA type robotic manipulator, were conducted to verify the presented control strategy. The results of experiment and simulation show that the strategy performs well in force tracking and estimating unknown constraint surfaces.

The next objective of our research is to estimate the mechanical characteristics of the environment through repetitive learning according to on-line data of force feedback, position and velocity, which will make the control strategy more adaptive and more intelligent.

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受未知环境约束的位控操作机器人臂阻抗力控制

乔 兵[1] 陆荣鑑[2]

([1] 南京航空航天大学民航学院，南京 210016)

([2] 南京林业大学机械电子工程学院，南京 210037)

摘 要 提出了一种面向位控操作机器人臂的阻抗力控制策略.利用在线力反馈数据对未知约束环境的形状进行估计以获得接触点处的环境切矢和法矢,根据该切矢和法矢实时生成目标阻抗模型的虚拟参考运动轨迹,在力误差信号的驱动下由目标阻抗模型产生机器人的指令运动轨迹,通过跟踪该指令运动轨迹机器人臂能够保持和未知约束环境的接触跟踪并将力误差限制在可接受的范围之内,力误差信号的动态行为与目标阻抗模型一致.为了验证控制策略的未知约束环境跟踪能力和力控制能力,以一个三杆平面机器人为例进行了计算机仿真,并在 Adept-3 精密装配机器人上进行了玻璃灯泡表面恒力跟踪的实验研究,仿真和实验结果表明文中提出的策略具有很好的未知表面跟踪和力控制能力.

关键词 操作机器人; 力/位控制; 未知约束

中图分类号 TP24