Force and Position Tracking: Parallel Control With Stiffness Adaptation

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Force and position control strategies are aimed at handling the interaction of a robot manipulator with the environment. Among them, the parallel force/position control approach offers good performance in the face of uncertainty on the geometry of the contact surface. This article presents a new parallel control scheme which ensures tracking of end-effector position along the unconstrained directions and tracking of contact force along the constrained direction, in spite of uncertainty on the contact stiffness. The controller is of inverse dynamics type with a force feedforward action. Adaptation to the unknown stiffness coefficient is achieved by resorting to a suitable estimate update law driven by the force error. Experimental results on an industrial robot with open control architecture are reported.

Introduction

In order to handle the interaction of a robot manipulator with the environment, suitable control strategies should be sought which employ not only the end-effector position but also the contact force. If the geometry of the contact surface is known, the hybrid control approach [1] can be adopted where position and force are controlled along complementary task directions which are a priori selected. This technique has been extended to the case of a generic constraint surface of regular curvature [2, 3]. On the other hand, if uncertainty occurs on the contact geometry, successful interaction can be entrusted to schemes which require no pre-selection of task directions. Impedance control defines a desired dynamic relationship between the end-effector displacement and the contact force [4]. Inner/outer control achieves regulation of a desired contact force thanks to the closure of an outer force feedback loop around the inner position feedback loop [5]. Parallel control combines the inherent robustness of the former with the force control capability of the latter; a force feedback loop is devised in parallel to a position feedback loop, while the control structure guarantees dominance of the force action over the position action along the constrained task directions [6].

Several parallel control schemes have been proposed in the literature, among which are an inverse dynamics controller [7], a force/position regulator [8], and a passivity-based controller [9]. Adaptive schemes have also been developed [10, 11], where uncertainty on the robot manipulator parameters was counteracted. For a recent survey, the reader is referred to [12]; experimental results with various controllers of this kind can be found in [13].

The common feature of all the above parallel control schemes is the possibility of regulating the contact force to a desired value without using explicit information on the constrained and unconstrained task directions. The key limitation preventing force tracking is the typical uncertainty on the contact stiffness.

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It is worth mentioning that the problem of designing interaction controllers with stiffness adaptation has been treated in previous works, e.g. [14-18], by adopting different approaches, both for impedance and force control.

The contribution of this work is to present a new parallel control scheme which yields tracking of the contact force along the constrained task direction together with tracking of the end-effector position along the unconstrained task directions. This is achieved by designing a model-based controller of inverse dynamics type with a suitable force feedforward action. Then, adaptation to unknown stiffness is provided by an estimate update law which is driven by a properly filtered version of the force error [19].

The scheme is experimentally tested on the available laboratory setup consisting of an industrial robot manipulator with open control architecture and force/torque sensor. Results are reported with different values of contact stiffness.

Inverse Dynamics Parallel Force/Position Control

For the purpose of this work, a three-joint rigid robot manipulator is considered performing a three-degree-of-freedom task. Its joint space dynamic model can be written in the well-known form

\[ B(q) \ddot{q} + C(q, \dot{q})q + d(q, \dot{q}) + g(q) = u - J^T(q)f, \]

where \( q \) is the (3 x 1) vector of joint variables, \( B \) is the (3 x 3) symmetric inertia matrix, \( C \dot{q} \) is the (3 x 1) vector of Coriolis and centrifugal torques, \( d \) is the (3 x 1) vector of friction torques, \( g \) is the (3 x 1) vector of gravitational torques, \( u \) is the (3 x 1) vector of driving torques, \( f \) is the (3 x 1) vector of contact forces exerted by the end effector on the environment, and \( J \) is the (3 x 3) Jacobian relating joint velocities \( \dot{q} \) to the (3 x 1) vector of end-effector velocities \( \dot{p} \), i.e.,

\[ \dot{p} = J(q)\dot{q}, \]

which is assumed to be nonsingular.
where the hats denote the available estimates of the dynamic terms $B, C, d, g,$ and $f$ is the measured contact force. On the assumption of perfect dynamic compensation and exact force cancellation, substituting control (5) into model (1) and taking the time derivative of (2) gives a linear decoupled system expressing a resolved end-effector acceleration. By conveniently adopting a description in terms of the input-output transfer function, system (1) and (5) can be expressed as

$$s^2p = a$$

where $s$ is the Laplace variable. Notice that the same symbol is used for both Laplace-domain variables and time-domain variables to simplify notation.

Let $p_d$ and $f_d$ denote the desired values of position and force, respectively. Accordingly, let $\hat{p} = p_d - p$ and $\hat{f} = f_d - f$ denote the position and force errors. By following the parallel control approach, the new control input $a$ is designed as the sum of a position control action and a force control action; namely, as [7]

$$a = a_p + a_f$$

where the force control action shall dominate the position control action along the constrained task direction.

The classical design is to take $a_p$ as a PD action on the position error plus velocity and desired acceleration feedforward, and $a_f$ as a PI action on the force error plus desired force feedforward [6]. In this way, however, the control parameters for the force loop cannot be chosen independently of the control parameters for the position loop, and stability of a third-order linear system has to be guaranteed [7].

A modified design consists of taking the force control action in such a way as to cancel the dynamics imposed by the position control action and replace it with a new second-order dynamics; still, a pole at the origin has to be assigned in order to obtain null force error at steady state. This has the advantage of making the force control loop design independent of the position control loop design [21].

Therefore, the two control actions in (7) are taken as:

$$a_p = s^2 p_d + (k_p s + k_v) \hat{p}$$

$$a_f = \frac{\vartheta \lambda_1 (s^2 + k_p s + k_v)}{s (s + \lambda_2)} \hat{f}$$

where $k_p, k_v > 0$ are suitable control parameters to impose the desired dynamics on position, $\lambda_1, \lambda_2 > 0$ are suitable control parameters to impose the desired dynamics on force, and the role of $\vartheta$ will be clear afterwards.

Following the guidelines in [7], it is convenient to analyze the behavior of system (6)-(9) by projecting its dynamics in terms of contact plane components and the component along $n$. It can be recognized that, if $f_d$ is along $n$, system (6)-(9) ensures tracking of the position reference trajectory along the contact plane components. On the other hand, the presence of the integral action on the force error guarantees that $f$ tends to $f_d$ at steady state—when $f_d, p_d,$ and $p_0$ are constant along $n$—with a dynamics depending on the stiffness coefficient $k$, for any given $\lambda_1$ and $\lambda_2$.

A block scheme describing the dynamics of system (6)-(9) with the environment model (3) is shown in Fig. 1.

If $k$ were exactly known, it would be possible to choose $\vartheta = k^{-1}$ and the dynamics of the force loop depends on $\lambda_1$ and $\lambda_2$ only. In such a case, by adding a feedforward action, the performance during the transient could be improved and force tracking capabilities could be obtained. The resulting block scheme is shown in Fig. 2, where the original dependence on the position control loop parameters in Fig. 1 has been eliminated.

As can be recognized in this scheme, the force control loop dynamics act upon the input signal

$$f = \vartheta \varphi$$

where

$$\varphi = f + \frac{s (s + \lambda_2)}{\lambda_1} f_d.$$
In view of (4) with \( \theta = k^{-1} \), the closed-loop system is described by

\[
(s^2 + \lambda_s s + \lambda_c) \ddot{f} = s(s + \lambda_s) k M \ddot{y} \quad (p_0 - p_d)
\]  

where the equality \( M \ddot{r} = \ddot{f} \) has been used. At this point, the quantity \( p_0 \) is typically a constant. Thus, if \( p_d \) has a constant component along \( n \), it follows that the force error \( \ddot{f} \) tends to zero with a dynamics shaped by \( \lambda_s \) and \( \lambda_c \). Further, in [22] it is shown that the components of the position error \( \ddot{p} \) on the contact plane also tend to zero. Otherwise, if \( p_d \) has a non-constant component along \( n \), then a drift occurs during the transient which can be anyhow recovered at steady state when the imposed end-effector motion is over.

**Stiffness Adaptation**

In most practical cases, the value of the stiffness coefficient is not exactly known *a priori*. However, it is possible to replace the parameter \( \theta = k^{-1} \) with a time-varying estimate \( \hat{\theta} \). An adaptive update law can be found for \( \hat{\theta} \) to ensure tracking of the force reference trajectory. As a consequence, an action of the kind (10) becomes nonlinear, and the following analysis shall be carried out back in the time domain.

Inspired by the technique in [15], the input signal \( f_c \) can be modified into

\[
f_c = \phi \ddot{y} + \ddot{\phi} \ddot{\phi}
\]  

where \( \ddot{\phi} \) is the output of a first-order filtering action upon \( \phi \), i.e.,

\[
\ddot{\phi} + \lambda_s \ddot{\phi} = \phi
\]  

with \( \lambda_s > 0 \), while the estimate \( \hat{\theta} \) is updated as

\[
\dot{\hat{\theta}} = \gamma \ddot{\phi} \ddot{\phi}
\]  

with \( \gamma > 0 \) and an initial condition \( \hat{\theta} = \hat{\theta}_0 \).

In [22] it is shown that force tracking is achieved and \( \ddot{\phi} \) remains bounded provided that \( \lambda_s, \lambda_{s2}, \lambda_2 \) are chosen such that the transfer function

\[
\frac{s + \lambda_s}{s^2 + \lambda_s s + \lambda_c}
\]  

is strictly positive real. In particular, sufficient conditions are \( \lambda_s > 0, \lambda_{s2} > 0, \lambda_2 > \lambda_2 \).

The resulting block scheme is illustrated in Fig. 3, with some abuse of notation caused by mixing time-domain with Laplace-domain quantities.

**Experiments**

The setup in the PRISMA Lab consists of an industrial robot Comau SMART-3 S. The robot manipulator has a six-revolute-joint anthropomorphic geometry with nonnull shoulder and elbow offsets and non-spherical wrist; only the inner three joints are considered while the outer three joints are mechanically braked. The joints are actuated by brushless motors via gear trains; shaft absolute resolvers provide motor position measurements. The robot is controlled by an open version of the C3G 9000 control unit, which has a VME-based architecture with a bus-to-bus communication link to a PC Pentium 133. This is in charge of computing the control algorithm and passing the references to the current servos through the communication link at 1
ms sampling interval. Joint velocities are reconstructed through numerical differentiation of joint position readings.

A six-axis force/torque sensor ATI FT30-100 with force range of ±130 N and torque range of ±10 Nm is mounted at the manipulator’s wrist. The sensor is connected to the PC by a parallel interface board which allows readings of six components of generalized force at 1 ms. An end effector has been built as a stick with a sphere at the tip, both made of steel.

A picture illustrating the robot with the wrist force sensor and the built end effector is given in Fig. 4. The environment is constituted by a cardboard box whose stiffness is approximately of $10^4$ N/m.

The parameters of the manipulator dynamic model (1) have been identified [23] in order to achieve accurate compensation of dynamic terms, where only viscous friction has been included. Notice that other effects, e.g., joint backlash, elasticity, and static friction, as well as contact friction, are present in the system but have not been taken into account.

As a first case study, a task in the $yz$-plane is assigned. An end-effector displacement of 0.25 m along $y$ is commanded. The trajectory along the path is generated according to a fifth-order interpolating polynomial with null initial and final velocities and accelerations, and a duration of 12 s after an initial lapse of 2 s. The surface of the cardboard box is nearly flat and is placed horizontally, i.e., in the $xy$-plane, and the end effector is initially in contact with the surface. After the same lapse of 2 s, the desired force along $z$ is taken to 40 N according to a fifth-order polynomial with null initial and final first and second time derivatives, and a duration of 1 s. The constant value is kept for 0.5 s, and then the desired force is taken back to zero in 1 s with the same polynomial as above, making a tooth-shaped profile. Then, the tooth is replicated three times with a 0.5 s lapse between each pair of teeth.

The above task is first executed using the control scheme illustrated in Fig. 2. The control parameters in (8) have been set to $k_p = 2500, k_d = 90$. Also, the control parameters in (9) have been set to $\lambda_1 = 180, \lambda_2 = 30$ so as to achieve a satisfactory behavior with a design value of 15000 N/m for the stiffness coefficient $k$. These values have been properly tuned by performing extensive MATLAB and SIMULINK simulations before running the experiments on the real system.

The experimental results are presented in Fig. 5 in terms of the time histories of the desired (dashed) and actual (solid) contact forces, and of the end-effector position errors. It can be recognized that a time delay is experienced on the tracking of the reference force trajectory along $z$, whereas the appreciable deviation from zero of the component along $y$ is mainly due to contact friction. On the other hand, a position error occurs along $z$ which is due to the imposed force trajectory, whereas an error is accumulated along $y$ as a consequence of the integral action complying to the contact friction force. Notice also that a steady-state error along $z$ occurs when the reference force goes to zero, because the surface is not perfectly horizontal.

The above task has been repeated using the control scheme in Fig. 3. The values of $k_p, k_d, \lambda_1, \lambda_2$ are the same as before, while the design parameters in (14) and (15) have been chosen as $\lambda_1 = 60, \gamma = 0.0001$. The initial estimate $\hat{\theta}$ has been set so as $1/\hat{\theta}_0 = 15000$, according to the above design value.

The experimental results are presented in Fig. 6 in terms of the time histories of the desired (dashed) and actual (solid) contact forces, of the end-effector position errors, and of the stiffness estimate. It can be recognized how the adaptation mechanism is capable of ensuring good contact force tracking along $z$. This is obtained at the expense of a larger end-effector position error along $y$ since the force control action with stiffness adaptation operates on all the task directions. Notice also that the stiffness estimate does not converge to the real value because of unmodeled disturbances, e.g., contact friction.

Another case study is carried out to investigate the performance of the parallel control scheme with stiffness adaptation when contact occurs with a surface of unknown location. Again, a task in the $yz$-plane is assigned. This time, however, a displacement of 0.12 m along $z$ is commanded besides the above end-effector displacement of 0.25 m along $y$. The trajectory along the path is generated according to a fifth-order interpolating polynomial with null initial and final velocities and accelerations, and a duration of 6 s after an initial lapse of 2 s. The cardboard box is placed horizontally in such a way as to obstruct the desired end-effector motion, but the actual contact location is unknown. Initially, the end effector is not in contact with the surface, and a null set point is assigned to the contact force. When the end effector comes in contact with the surface, i.e., when a nonnegligible

![Fig. 7. Experimental results with the scheme of Fig. 2 in the second case study.](image-url)
force. The experimental results are presented in Figs. 7 and 8 in terms of the time history of the desired (dashed) and actual (solid) contact forces, the desired (dashed) and actual (solid) end-effector path, and the time history of the stiffness estimate (only for the scheme of Fig. 3). It can be recognized (Fig. 7) that a large peak occurs on the contact force along $z$ due to the nonnull velocity at the impact; such peak is considerably reduced (Fig. 8) with the scheme of Fig. 3. The positive effects of the stiffness adaptation mechanism can be observed also by the enhanced force tracking with respect to the scheme of Fig. 2. Concerning the position tracking performance, this is very good before the contact, whereas after the contact the end-effector position has to comply with the surface in respect of the imposed reference force.

Conclusions

A parallel force/position control for a robot manipulator in contact with a compliant plane has been presented in this work. The novelty here, compared to the class of previous schemes of inverse dynamics type, is the introduction of an adaptation mechanism on the stiffness coefficient which allows force tracking along the constrained task direction. The scheme has been implemented in a number of experiments on an industrial robot with open control architecture. Robustness to uncertainty on the contact geometry as well as on the stiffness coefficient has been successfully tested.

Future investigation in the framework of parallel force/position control will be devoted to generalizing the whole approach to six-degree-of-freedom tasks, i.e., by including end-effector orientation as well as contact moments, along the lines of a recent work on spatial impedance control [24].

References


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