

Stability of Parallel Control

STEFANO CHIAVERINI AND BRUNO SICILIANO

Dipartimento di Informatica e Sistemistica
Università degli Studi di Napoli Federico II
Via Claudio 21, 80125 Napoli, Italy
E-mail: chiaverini@disna.dis.unina.it
E-mail: siciliano@vaxna1.na.infn.it

Abstract

The parallel control approach provides an effective framework to design force/position controllers for manipulators interacting with the environment. Control actions are operated in a full-dimensional space without use of selection matrices. Conflicting situations are handled by ensuring dominance of the force control action over the position control action. The approach is surveyed in this work and its key features are pointed out. With reference to elastic contact with a planar surface, both an inverse dynamics control law and a linear control law with gravity compensation are presented, and a study of the resulting equilibrium is accomplished. Stability issues are analyzed for the above controllers. Adaptation with respect to gravity parameters is introduced to ensure regulation of force and position around the same equilibrium as in the perfect compensation case.

1. Introduction

In order to make a robot manipulator capable of interacting with the environment, the forces arising from the contact must be properly considered. When the end-effector of a position-controlled robot manipulator comes into contact with the environment, the experienced forces are treated as disturbances by the controller leading to instability phenomena. It is then opportune to design robot control strategies that can handle the interaction effects.

One can distinguish between techniques that assign a dynamic relationship between force and position variables without explicitly using force sensor feedback information, e.g. impedance control [1,2], and techniques that provide the robot with force sensor capabilities and suitably embed the force measurements into the control scheme, e.g. force feedback control [3,4].

The most widely adopted approach to force/position control of robot manipulators is the hybrid control [5-8]. Distinct force and position control loops are designed and selection matrices are introduced to suitably switch from one loop to the other along each task direction. Therefore, this technique well matches the framework of natural vs. artificial constraints [9]. One intrinsic drawback of the approach is that the selection mechanism is based on the available model of the task; thus lack of knowledge about the environment may cause improper operation of the system. Stability of hybrid control was addressed in [10]. The problem of force/position control with force sensory feedback was also treated in [11] for the general case of constrained motion tasks.

In the framework of force/position control techniques, a new control strategy was proposed, namely the *parallel control* [12], which combines the simplicity and robustness of the impedance and external force feedback schemes with the ability of controlling both position and force typical of the hybrid control schemes. The goal is achieved by using two controllers acting in parallel and managing conflicting situations by means of a priority strategy, i.e. the force control loop is designed to prevail over the position control loop. This feature makes the scheme suitable to manage contacts with an unstructured environment and unplanned collisions, which are known to represent a drawback for hybrid controllers. Extensive description of the parallel approach and performance analysis of a control scheme with full dynamic compensation in the case of contact with an elastically compliant frictionless surface can be found in [13,14].

In the case of a force/position regulation problem, a parallel control scheme was recently proposed which is based on simple position *PD* action + gravity compensation + desired force feedforward + force *PI* action [15].

At the equilibrium, for given force and position set points, the force error is driven to zero at the expense of a position error. Both local asymptotic and exponential stability of the system have been proved [16,17]. If the assumption of perfect gravity compensation is relaxed, the closed-loop system converges to a different equilibrium; a suitable parameter adaptation law can be designed so as to recover the original equilibrium [18].

This work is aimed at surveying the key features and stability properties of parallel control laws for a manipulator in contact with an elastically compliant planar surface.

2. Parallel control

The fundamental issue to consider when designing force/position control strategies is that it is not possible to simultaneously impose on the environment arbitrarily assigned position and force values along each task space direction. As a consequence, the task requirement must be compatible with the contact geometry. This demands for correct modeling of the interaction task as well as for accurate task planning. Nevertheless, during task execution, deviations from the planned task are usually experienced so that the planned requirements may no longer be compatible with the actual task. Therefore, the control of the interaction must be able to handle also requirements that are inconsistent with the task.

The hybrid control approach [5] allows force/position control capabilities but it strongly relies on detailed geometric modeling of the contact. However, sensor information about the real task is subordinated to a selective action which is instead performed on the basis of the planned task.

The impedance control approach [2] allows to specify a suitable rule-based dynamic behavior between the end-effector and the environment. However, it is not possible to control both position and force variables.

In the external force feedback approach [4], an outer force control loop is closed around an inner position control loop. However, it is not easy to achieve position control of the unconstrained motion components of the task.

The goal of the parallel control approach [14] is to combine the simplicity and robustness of the impedance control and the external force feedback control with the capability of controlling both force and position of the hybrid control. This is realized by designing two control loops—one in position and one in force—acting in parallel along each task space direction. Conflicts between position and force actions are handled through a rule-based priority strategy.

A physical analysis of the interaction leads to recognize that dominance of the force control loop over the position control loop should be achieved

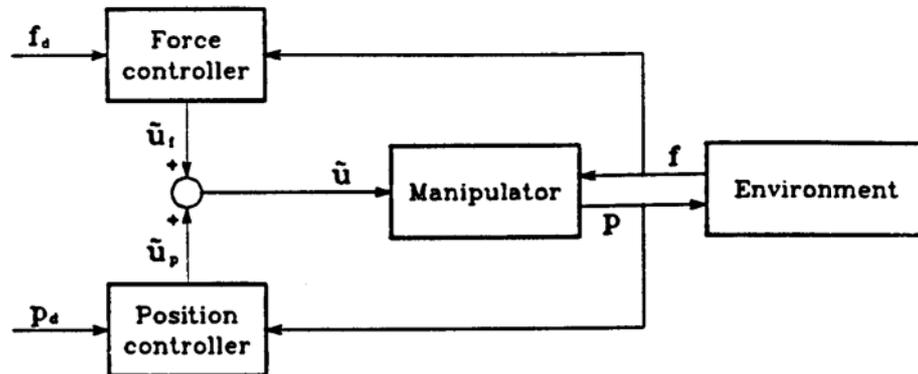


Figure 1 — Block scheme of parallel control

so as to accommodate unplanned contact forces in any situation. The most natural way to implement the sought dominance is to use a PI force control loop working in parallel to a PD position loop. In this respect, the scheme can be regarded as an extension of an impedance control scheme (with added direct force control capabilities) and an external force feedback scheme (with improved position control capabilities). At the same time, force and position controlled directions are not established a priori in the parallel control, as instead in the hybrid control; full sensor measurements can thus be exploited without any task-based filtering action.

The task planning results in force or position references along suitable task space directions, as in the hybrid control case. A perfect planning obviously makes the task successful, but contact is safely handled by the parallel control even in the case of planning errors. Recovery from unexpected impacts is made possible thanks to the force dominance rule.

A conceptual block scheme of the parallel control is presented in Fig. 1, where f denotes the contact force, p the end-effector position, u the end-effector driving force —obtained by adding a force component u_f to a position component u_p — and f_d , p_d are respectively desired force and position. In the following, the attention is focused on three-dimensional vectors, i.e. translational motion and force components.

The dynamic model of the manipulator in a singularity-free region of the workspace can be written in the well-known form

$$B(p)\ddot{p} + C(p, \dot{p})\dot{p} + g(p) = u - f, \quad (1)$$

where B is the symmetric and positive definite inertia matrix, $C\dot{p}$ is the

vector of Coriolis and centrifugal forces, and g is the vector of gravitational forces; all quantities are expressed in a common reference frame.

According to an inverse dynamics concept with contact force sensor measurements, the vector of driving forces can be synthesized as

$$\mathbf{u} = \frac{1}{m_d} \hat{\mathbf{B}}(\mathbf{p}) \tilde{\mathbf{u}} + \hat{\mathbf{C}}(\mathbf{p}, \dot{\mathbf{p}}) \dot{\mathbf{p}} + \hat{\mathbf{g}}(\mathbf{p}) + \hat{\mathbf{f}}, \quad (2)$$

where the hat denotes the available estimates of the dynamic terms, m_d is a desired mass and $\tilde{\mathbf{u}}$ is a new force input. Substituting control (2) into model (1), under the assumption of perfect compensation, gives

$$m_d \ddot{\mathbf{p}} = \tilde{\mathbf{u}} \quad (3)$$

that is a linear decoupled purely inertial system.

In the framework of the parallel control approach, the new force input is designed as [12]

$$\tilde{\mathbf{u}} = \tilde{\mathbf{u}}_p + \tilde{\mathbf{u}}_f \quad (4)$$

$$\tilde{\mathbf{u}}_p = m_d \ddot{\mathbf{p}}_d + k_D \dot{\mathbf{e}}_p + k_P \mathbf{e}_p \quad (5)$$

$$\tilde{\mathbf{u}}_f = k_F \mathbf{e}_f + k_I \int_0^t \mathbf{e}_f d\tau \quad (6)$$

with $\mathbf{e}_p = \mathbf{p}_d - \mathbf{p}$ and $\mathbf{e}_f = \mathbf{f}_d - \mathbf{f}$. Substitution of (4-6) in (3) yields

$$m_d \ddot{\mathbf{e}}_p + k_D \dot{\mathbf{e}}_p + k_P \mathbf{e}_p + k_F \mathbf{e}_f + k_I \int_0^t \mathbf{e}_f d\tau = \mathbf{0} \quad (7)$$

which reveals how \mathbf{e}_f is allowed to prevail over \mathbf{e}_p at steady-state. Note that if $\mathbf{f}_d = \mathbf{f}$ during task execution then $\mathbf{u}_f = \mathbf{0}$ and the usual resolved acceleration behavior is recovered.

The parallel control scheme based on (2,4,5,6) requires complete knowledge of manipulator dynamic model. If a force/position regulation task is of interest, i.e. \mathbf{p}_d and \mathbf{f}_d are constant set points, a computationally lighter control law can be chosen as [15]

$$\mathbf{u} = -k_D \dot{\mathbf{p}} + k_P \mathbf{e}_p + \hat{\mathbf{g}}(\mathbf{p}) + \mathbf{f}_d + k_F \mathbf{e}_f + k_I \int_0^t \mathbf{e}_f d\tau \quad (8)$$

which corresponds to position *PD* action + gravity compensation + desired force feedforward + force *PI* action. Note that the use of gravity compensation is inherited from ordinary *PD* position control to avoid steady-state position errors.

3. Study of equilibrium

In order to analyze the performance of the above parallel control laws, a study of interaction with the environment must be accomplished.

Accurate modeling of the contact between the manipulator and the environment is usually difficult to obtain in analytic form, due to complexity of the physical phenomena involved during the interaction. It is then reasonable to resort to a simple but significant model, relying on the robustness of the control system in order to absorb the effects of inaccurate modeling. Following these guidelines, the case of an environment constituted by a rigid, frictionless and elastically compliant plane is analyzed. The choice of a planar surface is motivated by noticing that it is locally a good approximation to surfaces of regular curvature. The rigidity of the contact plane allows to neglect the effects of local deformation at the contact. The total elasticity, due to end-effector force sensor and environment, is accounted through the compliance of the plane. Friction effects are neglected within the operational range of interest.

With the above assumptions, the model of the contact force considered takes on the simple form

$$\mathbf{f} = \mathbf{K}(\mathbf{p} - \mathbf{p}_0), \quad (9)$$

where \mathbf{p} is the position of the contact point, \mathbf{p}_0 is a point of the plane at rest, and \mathbf{K} is the constant symmetric stiffness matrix that establishes a linear mapping between $(\mathbf{p} - \mathbf{p}_0)$ and \mathbf{f} ; note that Equation (9) holds only when the manipulator is in contact with the environment and all quantities are expressed in the common reference frame. Further, observe that:

- The contact force is orthogonal to the plane for any vector $(\mathbf{p} - \mathbf{p}_0)$; then, a base of $\mathcal{R}(\mathbf{K}) - \mathcal{R}(\mathbf{K})$ denotes the range space of matrix \mathbf{K} — is the unit vector \mathbf{n} orthogonal to the plane, and $\text{rank}(\mathbf{K}) = 1 < 3$.
- All vectors $(\mathbf{p} - \mathbf{p}_0)$ lying on the plane do not contribute to the contact force; then, a base of $\mathcal{N}(\mathbf{K}) - \mathcal{N}(\mathbf{K})$ denotes the null space of matrix \mathbf{K} — is a pair of linearly independent unit vectors $(\mathbf{t}_1, \mathbf{t}_2)$ tangential to the plane.
- In force of the symmetry of \mathbf{K} , $\mathcal{R}(\mathbf{K}) \equiv \mathcal{R}(\mathbf{K}^T)$, and a convenient choice for $(\mathbf{t}_1, \mathbf{t}_2)$ is such that the columns of the matrix

$$\mathbf{R} = (\mathbf{t}_1 \quad \mathbf{t}_2 \quad \mathbf{n}) \quad (10)$$

form a set of orthonormal vectors constituting a base of \mathbb{R}^3 .

According to the above remarks, the matrix \mathbf{K} can be decomposed as

$$\mathbf{K} = \mathbf{R} \text{diag} \{0, 0, k\} \mathbf{R}^T = k \mathbf{n} \mathbf{n}^T, \quad (11)$$

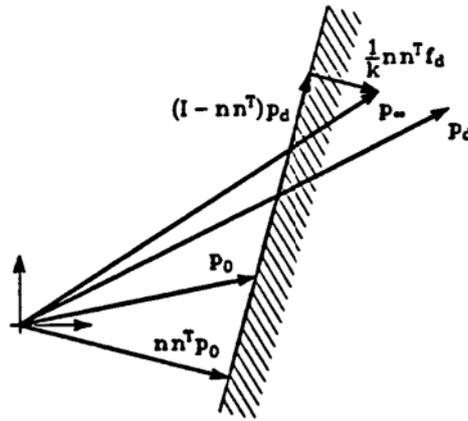


Figure 2 — Construction of the equilibrium in a two-dimensional case

where R is the rotation matrix from the contact frame to the reference frame, and $k > 0$ is the stiffness coefficient.

The elastic contact model (9,11) suggests that a null force error can be obtained only if $f_d \in \mathcal{R}(K)$. If no information about the geometry of the environment is available, i.e. n is unknown, the null vector can be assigned to f_d that is anyhow in the range space of any matrix K . Analogously, it can be recognized that null position errors can be obtained only on the contact plane (t_1, t_2) , while the component of p along n has to accommodate the force requirement specified by f_d ; thus, p_d can be freely reached only in $\mathcal{N}(K)$, i.e. along the unconstrained directions of the task space.

As demonstrated in [14] for the perfect gravity compensation case ($\hat{g} = g$) and in the assumption that $f_d \in \mathcal{R}(K)$, the equilibrium $\{p_\infty, f_\infty\}$ for the system (1) under the control (2,4,5,6) is

$$p_\infty = \frac{1}{k} n n^T (f_d + k p_0) + (I - n n^T) p_d \quad (12)$$

$$f_\infty = f_d; \quad (13)$$

this is consistent with the above considerations about specification of position and force set points. An example of construction of the equilibrium point in a two-dimensional case is illustrated in Fig. 2. It is not difficult to show that the same equilibrium is reached also under the control law (8).

If the desired force set point f_d is not aligned with n , an equilibrium trajectory rather than an equilibrium point is obtained. In fact, the equilibrium $\{p_\infty, f_\infty\}$ for the system (1) under the control (2,4,5,6) is [14]

$$p_\infty(t) = \bar{p} + \bar{v}t \quad (14)$$

$$f_\infty = n n^T f_d, \quad (15)$$

where

$$\bar{p} = \frac{1}{k} nn^T (f_d + k p_0) + (I - nn^T) p_d \quad (16)$$

$$\bar{v} = \frac{k_I}{k_P} (I - nn^T) f_d, \quad (17)$$

showing a drift motion due to both misalignment of f_d with n and presence of the integral action ($k_I \neq 0$); note that in practical designs it is $k_P \gg k_I$ which attenuates the magnitude of the drift. A more complex analysis is needed to compute the equilibrium trajectory for the system (1) under the control (8).

As a final remark, in the case of a curved surface, a linear contact force model as in (9) can still be written but K becomes a function of p_0 which is in turn a function of p [19]. The problem becomes far more involved and deserves further investigation case by case.

4. Stability analysis

In this section it is assumed that the desired force is aligned with the normal to the contact plane and the contact is not lost after the impact.

The stability analysis of the system (1) under the inverse dynamics parallel control (2,4,5,6) with the environment (9-11) can be developed according to classical linear systems theory. In detail, plugging (9) in (7) gives

$$\begin{aligned} m_d \ddot{p} + k_D \dot{p} + (k_P I + k_F k n n^T) p + k_I k n n^T \int_0^t p d\tau \\ = m_d \ddot{p}_d + k_D \dot{p}_d + k_P p_d + k_F (f_d + k n n^T p_0) + k_I \int_0^t (f_d + k n n^T p_0) d\tau \end{aligned} \quad (18)$$

which represents a third-order linear system, whose stability can be analyzed by referring to the unforced system

$$m_d \ddot{p} + k_D \dot{p} + (k_P I + k_F k n n^T) p + k_I k n n^T \int_0^t p d\tau = 0. \quad (19)$$

According to (10), projection of the position vector on the contact frame yields

$$R^T p = \begin{pmatrix} p_1 \\ p_2 \\ p_n \end{pmatrix} \quad (20)$$

which leads to the system of three scalar decoupled equations

$$\begin{aligned}
 m_d \ddot{p}_1 + k_D \dot{p}_1 + k_P p_1 &= 0 \\
 m_d \ddot{p}_2 + k_D \dot{p}_2 + k_P p_2 &= 0 \\
 m_d \ddot{p}_n + k_D \dot{p}_n + (k_P + k_F k) p_n + k_I k \int_0^t p_n d\tau &= 0;
 \end{aligned} \tag{21}$$

a stable behavior is then ensured by a proper choice of the feedback gains k_P, k_D, k_F, k_I for the third equation. The following remarks are in order [14]:

- Stability is obtained independently of the actual normal direction to the plane; this essential feature of the parallel approach allows to design the controller based on the contact stiffness coefficient while the actual contact geometry is taken into account only at the planning level.
- The decoupled dynamics of the system (19) derives from structural properties of the parallel control scheme by virtue of the contact force measurement; this is different from the hybrid approach where a decoupled dynamics is imposed by the control law on the basis of the environment model.

The study of stability for the force/position regulation case requires methods from nonlinear systems theory. To this purpose, an energy-based argument inspired by the kind of Lyapunov functions used for stability of *PID* position control [20] can be pursued. It should be emphasized that the Lyapunov method is used only as a means to prove stability of the closed-loop system, and not to derive the control law in a constructive manner; the control law, in fact, has been postulated above on the basis of physical considerations related to the parallel approach in a problem of interaction with an elastically compliant surface.

The key point is to find a state description for the system which is suitably augmented to take into account the interaction force in respect of the constraints imposed by the contact. Such a description should lead to a Lyapunov function composed by a potential energy term related to the deviation from the equilibrium contact position, a kinetic energy term related to the system rate of motion, as well as a term related to the energy stored along the normal direction to the plane due to the integral force action. This is accomplished by considering the (7×1) state vector [16]

$$z = \begin{pmatrix} \dot{p} \\ e \\ s \end{pmatrix}, \tag{22}$$

where

$$e = p_\infty - p = e_p + \frac{1}{k_P} d \tag{23}$$

$$s = \frac{1}{k} n^T \left(\int_0^t e_f d\tau - \frac{1}{k_I} d \right), \quad (24)$$

with

$$d = \frac{k_P}{k} n n^T (f_d + k(p_0 - p_d)) \quad (25)$$

being a constant vector taking into account the effects of the environment contact force and the desired force set point. It is important to remark that $z = 0$ corresponds to the equilibrium (12,13), as can be easily verified. Also, note that

$$n^T e = \frac{1}{k} n^T e_f \quad (26)$$

$$\dot{e} = -\dot{p} \quad (27)$$

$$\dot{s} = n^T e. \quad (28)$$

The augmented system described by (1,27,28) under the control (8) can be written in the standard compact homogeneous form:

$$\dot{z} = Fz, \quad (29)$$

where

$$F = \begin{pmatrix} -B^{-1}(C + k_D I) & B^{-1}(k_P I + k'_F k n n^T) & k_I k B^{-1} n \\ -I & 0 & 0 \\ 0^T & n^T & 0 \end{pmatrix} \quad (30)$$

with $k'_F = 1 + k_F$. Note that some handy reductions —using the structural properties of K in (11) and the definition of s in (24)— have been performed to derive (30).

On the basis of the above augmented state space description, suitable Lyapunov function candidates can be constructed to derive local stability results around the origin of the state space in (22). The key feature of such functions is the introduction of off-diagonal terms and positive constants which are remarkably not used by the control law. These constants serve as additional degrees of freedom to satisfy conditions on the feedback gains guaranteeing stability of the system (29,30). Two major results have been recently obtained [17] and are stated below.

- *Local asymptotic stability* can be demonstrated by choosing the following Lyapunov function:

$$V = \frac{1}{2} z^T P z, \quad (31)$$

where

$$P = \begin{pmatrix} B & -\rho B & 0 \\ -\rho B & (k_P + \rho k_D)I + k'_F k n n^T & k_I k n \\ 0^T & k_I k n^T & \rho k_I k \end{pmatrix} \quad (32)$$

with $\rho > 0$.

- *Local exponential stability* can be demonstrated by choosing the following Lyapunov function:

$$W = \frac{1}{2} z^T Q z, \quad (33)$$

where

$$Q = \begin{pmatrix} B & -\beta B & -\gamma B n \\ -\beta B & (k_P + \beta k_D)I + k'_F k n n^T & (k_I k + \gamma k_D) n \\ -\gamma n^T B & (k_I k + \gamma k_D) n^T & \beta k_I k + \gamma(k_P + k'_F k) \end{pmatrix}, \quad (34)$$

with $\beta, \gamma > 0$.

Technical details about the stability proofs have been omitted for brevity and can be found in [17]. It is worth reporting here that k_P is not involved by the conditions on the feedback gains that guarantee local asymptotic stability, and then is available to meet further design requirements during the unconstrained phase of the task. On the other hand, local exponential stability is more demanding and in fact leads to more complex conditions on the feedback gains involving also k_P .

It is important to point out that local asymptotic stability holds also in the case of imperfect gravity compensation. It can be shown that a different equilibrium $\{\hat{p}_\infty, f_\infty\}$ is reached for the system (1) under the control (8) with $\hat{g} \neq g$ [21], i.e.

$$\hat{p}_\infty = \frac{1}{k} n n^T (f_d + k p_0) + (I - n n^T) \left(p_d - \frac{1}{k_P} (g(\hat{p}_\infty) - \hat{g}(\hat{p}_\infty)) \right) \quad (35)$$

$$f_\infty = f_d. \quad (36)$$

In this case, the force set point is still attained while a different end-effector equilibrium position is reached compared to the case of perfect gravity compensation. More specifically, a comparison between (12) and (35) reveals that the components of p along the constrained task direction n coincide, while the imperfect gravity compensation affects the components of p along the unconstrained task directions t_1, t_2 .

In order to counteract imperfect estimation of the gravity term, the control law (8) can be made adaptive with respect to a suitable vector of manipulator and load constant parameters θ in g , i.e.

$$g(p) = G(p)\theta. \quad (37)$$

In view of this, the control law can be rewritten as [18]

$$u = -k_D \dot{p} + k_P e_p + G(p) \hat{\theta} + f_d + k_F e_f + k_I \int_0^t e_f d\tau, \quad (38)$$

where $\hat{\theta}$ is the vector of estimated parameters. With this choice, the equations of the closed-loop system become

$$\dot{z} = Fz + \mu \quad (39)$$

with z as in (22), F as in (30), and

$$\mu = \begin{pmatrix} -B^{-1}G(x)\tilde{\theta} \\ 0 \\ 0 \end{pmatrix} \quad (40)$$

where $\tilde{\theta} = \theta - \hat{\theta}$ is the parameter error vector.

In addition to the control law (38), the parameter estimate vector is determined according to the update law

$$\dot{\hat{\theta}} = -\frac{1}{\nu} G^T(p) \left(\dot{p} - \beta \left(e_p + \frac{k_I}{k_P} \int_0^t e_f d\tau \right) \right) \quad (41)$$

with $\nu > 0$.

Local asymptotic stability around the original equilibrium (12,13) can be proved [18]. It is worth mentioning here that the proof is based on the Lyapunov function candidate

$$W'(z, \tilde{\theta}) = \frac{1}{2} z^T Q z + \frac{1}{2} \nu \tilde{\theta}^T \tilde{\theta}, \quad (42)$$

in which remarkably Q is the same as in (34). Differently from the local exponential stability case, γ is not available to satisfy conditions on the feedback gains but it is keenly chosen to render the adaptation law a function of physically measurable quantities already used in the control law (38), i.e. position, velocity and force measurements [18]. Finally, observe that the parameter error vector is not guaranteed to converge to zero and a residual error may exist at steady-state, depending on the structure of the regressor G ; this is like in classical adaptive motion control theory.

5. Conclusions

The key features and stability properties of the parallel control approach have been surveyed in this work. The effectiveness of the approach resides

in the capability of controlling the interaction while the task geometry is accounted at the planning level. Two parallel control laws have been illustrated: one with full dynamics compensation meant for tracking tasks, the other with just gravity compensation meant for regulation tasks. Remarkably, the two controllers exhibit the same steady-state performance. Stability issues have been analyzed for both schemes, in the linear and nonlinear settings respectively. When the assumption of perfect gravity compensation is relaxed, the system preserves the stability property converging to a different equilibrium though. Recovering of the original equilibrium can be ensured by resorting to an adaptive law on the parameter estimates in the gravity term.

Acknowledgments

The research work reported in this paper was supported by *Consiglio Nazionale delle Ricerche* under contract 92.01064.PF67.

References

- [1] N. Hogan, "Impedance control: An approach to manipulation, Parts I-III," *ASME J. of Dynamic Systems, Measurement, and Control*, vol. 107, pp. 1-24, 1985.
- [2] H. Kazerooni, P.K. Houpt, and T.B. Sheridan, "Robust compliant motion for manipulators," *IEEE J. of Robotics and Automation*, vol. 2, pp. 83-105, 1986.
- [3] D.E. Whitney, "Force feedback control of manipulators fine motion," *ASME J. of Dynamic Systems, Measurement, and Control*, vol. 99, pp. 91-97, 1977.
- [4] J. De Schutter and H. Van Brussel, "Compliant robot motion, Parts I-II," *Int. J. of Robotics Research*, vol. 7, no. 4, pp. 3-33, 1988.
- [5] M.H. Raibert and J.J. Craig, "Hybrid position/force control of manipulators," *ASME J. of Dynamic Systems, Measurement, and Control*, vol. 103, pp. 126-133, 1981.
- [6] O. Khatib, "A unified approach for motion and force control of robot manipulators," *IEEE J. of Robotics and Automation*, vol. 3, pp. 43-53, 1987.
- [7] T. Yoshikawa, "Dynamic hybrid position/force control of robot manipulators—Description of hand constraints and calculation of joint driving force," *IEEE J. of Robotics and Automation*, vol. 3, pp. 386-392, 1987.
- [8] A. De Luca, C. Manes, and F. Nicolò, "A task space decoupling approach to hybrid control of manipulators," *Proc. 2nd IFAC Symp. on Robot Control*, Karlsruhe, D, pp. 157-162, 1988.

- [9] M.T. Mason, "Compliance and force control for computer controlled manipulators," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. 11, pp. 418-432, 1981.
- [10] J.T. Wen and S. Murphy, "Stability analysis of position and force control for robot arms," *IEEE Trans. on Automatic Control*, vol. 36, pp. 365-371, 1991.
- [11] J.K. Mills and A.A. Goldenberg, "Force and position control of manipulators during constrained motion tasks," *IEEE Trans. on Robotics and Automation*, vol. 5, pp. 30-46, 1989.
- [12] S. Chiaverini and L. Sciavicco, "Force/position control of manipulators in task space with dominance in force," *Proc. 2nd IFAC Symp. on Robot Control*, Karlsruhe, D, pp. 137-143, 1988.
- [13] S. Chiaverini, *Controllo in forza di manipolatori* (in Italian), Tesi di Dottorato di Ricerca, Dipartimento di Informatica e Sistemistica, Università degli Studi di Napoli Federico II, Napoli, I, 1990.
- [14] S. Chiaverini and L. Sciavicco, "The parallel approach to force/position control of robotic manipulators," *IEEE Trans. on Robotics and Automation*, to appear, 1993.
- [15] S. Chiaverini and B. Siciliano, "On the stability of a force/position control scheme for robot manipulators," *Proc. 3rd IFAC Symp. on Robot Control*, Vienna, A, pp. 183-188, 1991.
- [16] S. Chiaverini, B. Siciliano, and L. Villani, "A stable force/position controller for robot manipulators," *Proc. 31st IEEE Conf. on Decision and Control*, Tucson, AZ, pp. 1869-1874, 1992.
- [17] S. Chiaverini, B. Siciliano, and L. Villani, "Force/position regulation of compliant robot manipulators," *IEEE Trans. on Automatic Control*, vol. 39, 1994.
- [18] B. Siciliano and L. Villani, "Force/position regulation of robot manipulators with gravity parameter adaptation," *Prepr. 12th IFAC World Congress*, Sydney, AUS, July 1993.
- [19] S. Chiaverini and L. Sciavicco, "Edge-following strategies using the parallel control formulation," *Proc. 1st IEEE Conf. on Control Applications*, Dayton, OH, pp. 31-36, 1992.
- [20] S. Arimoto and F. Miyazaki, "Stability and robustness of PID feedback control for robot manipulators of sensory capability," in *Robotics Research: 1st Int. Symp.*, M. Brady and R.P. Paul (Eds.), MIT Press, Boston, MA, pp. 783-799, 1984.
- [21] B. Siciliano and L. Villani, "An adaptive force/position regulator for robot manipulators," *Prepr. 2nd Workshop on Adaptive Control: Applications to Nonlinear Systems and Robotics*, Cancun, MEX, Dec. 1992.