

Compliance Control for a Robot with Elastic Joints

L. Zollo (1), B. Siciliano (2), A. De Luca (3), E. Guglielmelli (1), P. Dario (1)

(1) *Scuola Superiore Sant'Anna*
ARTS Lab – c/o Polo Sant'Anna Valdera
Viale Rinaldo Piaggio 34, 56025 Pontedera (Pisa), Italy
Email: {l.zollo, e.guglielmelli, p.dario}@arts.sssup.it

(2) *PRISMA Lab*
Dipartimento di Informatica e Sistemistica
Università degli Studi di Napoli Federico II
Via Claudio 21, 80125 Napoli, Italy
Email: siciliano@unina.it

(3) *Dipartimento di Informatica e Sistemistica*
Università degli Studi di Roma “La Sapienza”
Via Eudossiana 18
00184 Roma, Italy
Email: deluca@dis.uniroma1.it

Abstract

This work focuses on the consideration that the elasticity in the robot joints is one cause for the vibrational and chattering phenomena emerging in the interaction between a robot and the environment. Hence, a compliance control scheme in the Cartesian space is proposed as a possible solution to reduce these effects.

The results reported in the paper demonstrate that a PD action plus an appropriate relation between the rotor and the link position variables can stabilize a robot arm with flexible joints as well as control its level of compliance.

Asymptotic stability of the control strategy is ensured and an application to a particular class of flexible robots, i.e. cable-actuated robots, is proposed, since their intrinsic mechanical compliance can be successfully utilized in applications of biomedical robotics and assistive robotics.

The compliance control scheme in the Cartesian space is implemented and experimentally tested on an 8-degree-of-freedom robot manipulator actuated through pulleys and steel cables.

1 Introduction

The presence of vibrational phenomena during the motion of robot manipulators with elastic joints is a limiting factor in situations of contact and interaction with the working environment and becomes particularly dangerous in applications of biomedical robotics or else assistive robotics, which require a very close human-robot interaction. In such a

context, the need for a human-like behavior and a high level of safety and reliability is often faced with mechanical solutions. On one hand, an intrinsic compliance in the structure, lightness, and even an anthropomorphic aspect has to be provided. On the other, it is required to compensate for the intrinsic mechanical elasticity while controlling the interaction force.

One approach to the mechanical design of lightweight and low inertia manipulators is the distributed elastically coupled macro mini parallel actuation [1], which aims at ensuring high performance in position tracking tasks as well as in interaction tasks, through a stiff transmission system and low inertia actuators for the micro system.

Flexible transmission systems realized through pulleys and steel cables can be regarded as another approach to the design of safe robots. They represent a feasible mechanical solution in biomedical and assistive robotics since they can ensure human-like dimensions of the artifact, lightness and anthropomorphic mass distribution, but present the limitation of low performance in tracking tasks in view of the joint flexibility. To this regard, using control strategies based on the compensation of the elastic effects can suitably improve manipulator performance. Yet, the use for flexible robot manipulators of interaction control schemes conceived for rigid robots can determine undesirable effects of chattering during contact [2].

The control problem of robots interacting with the working environment is widely treated in robot

control theory. They ranged from the concept of active compliance to the concept of making the robot's end-effector to behave as a mechanical impedance (see e.g. [3] for a survey), up to the hybrid position/force control approach, useful for interaction with a completely structured environment [4].

The basic assumption of all the cited approaches is a robot manipulator with rigid joints. In [5] and [6] it is demonstrated that control algorithms derived for completely rigid robots notably degrade the system performance when applied to robots showing a certain degree of elasticity in the actuation system or in the link structure. The robot is yet stabilized by the closed loop but, during tracking tasks, lightly damped vibrational phenomena are observed.

In view of the dynamic effects of elastic joints [7], classical techniques used for rigid robots, input-output decoupling, feedback linearization or else inversion control, are to be revisited. Hence, one has to resort to a nonlinear static state feedback, if a reduced model of the robot can be used [8], whereas a nonlinear dynamic state feedback is needed in the case of a complete dynamic model [9].

Whenever regulation is desired, a simple PD control plus gravity compensation in joint space can be adopted, as proposed in [10]. Instead, when trajectory tracking is desired, an approximate singular perturbation model of elastic joint manipulator dynamics can be used [11]. This allows compensating for joint flexibility by introducing a corrective torque input.

The problem of controlling robot manipulators with elastic joints in situations of interaction with the working environment is not widely dealt within the literature.

The PD control proposed in [10] can be regarded as a feasible interaction control since it provides a sort of compliance at joints if the feedback gains are properly adjusted. On the other hand, the singularly perturbed model can be suitably exploited to achieve force control either in a hybrid position/force control or impedance control framework [12], or when a constraint on the environment is present [13].

Nevertheless, it should be stressed that all the interaction control schemes for robots with elastic joints proposed in the literature are validated by means of simulation tests on 2- or 3-degree-of-

freedom (d.o.f.) manipulators.

This paper extends the approach in [10] by proposing a proportional-derivative control in the Cartesian space plus gravity compensation.

The controller is analogous to a compliance control in the Cartesian space for rigid robots but a new position variable, named the gravity-biased motor position, is introduced. This means that the position and velocity information, available from the position sensors on the rotors, suffices to achieve an easy regulation of compliance in the Cartesian space.

Further, the proposed compliance control in the Cartesian space is applied to an 8-d.o.f. cable-driven robot manipulator, and experimental results are finally provided.

2 Robot dynamic model

Robot manipulators with n moving rigid links driven by electrical motors through n joints/transmissions subject to small elastic deformations are considered.

Under the assumptions in [8], the dynamic model of a robot with elastic joints can be expressed as

$$\begin{aligned} M(q)\ddot{q} + S(q, \dot{q})\dot{q} + g(q) + K(q - \theta) &= 0 \\ I\ddot{\theta} + K(\theta - q) &= u \end{aligned} \quad (1)$$

where $q \in \mathfrak{R}^n$ is the vector of link positions and $\theta \in \mathfrak{R}^n$ is the vector of (reflected) motor positions. It is assumed that only the motor variables θ and $\dot{\theta}$ are measurable, or at least obtained by accurate numerical differentiation.

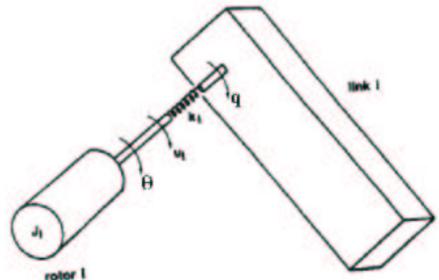


Figure 1: Elastic joint

In (1) $M(q)$ is the $(n \times n)$ robot link inertia matrix, I is a constant diagonal matrix including the rotor inertia and the gear ratios, $S(q, \dot{q})\dot{q}$ is the vector of centrifugal and Coriolis torques, $K \in \mathfrak{R}^{n \times n}$ is the diagonal matrix of joint stiffness coefficients, and $g(q) = \left(\frac{\partial U_g(q)}{\partial q}\right)^T$ where $U_g(q)$ is the potential energy due to gravity.

The robot dynamic model (1) presents three important properties which are useful in the derivation of the control law.

- P1.** The inertia matrix $M(q)$ is symmetric and positive definite for all q .
- P2.** If a representation in Christoffel symbols is chosen for the elements of $S(q, \dot{q})$, the matrix $\dot{M} - 2S$ is skew-symmetric.
- P3.** A positive constant α exists such that $\left\| \frac{\partial g(q)}{\partial q} \right\| \leq \alpha$.

3 Compliance control in the Cartesian space

Inspired the approach in [10] on the PD control for robots with elastic joints, a compliance control scheme in the Cartesian space is developed in order to regulate robot compliance directly in the operational space. To this regard, let $x \in \mathfrak{R}^m$ be the task vector (i.e. the Cartesian end-effector pose), with $m \leq n$, and $x_d \in \mathfrak{R}^m$ the constant desired value. The direct and differential kinematics are, respectively,

$$x = x(q), \quad \dot{x} = J(q)\dot{q} \quad (2)$$

and depend on the link position variables only. If $m = n$, a finite number of inverse kinematics solutions $q_d \in \mathfrak{R}^n$ is associated with x_d , i.e., such that $x(q_d) = x_d$. In general, singular configurations are to be avoided, i.e., $\det J(q_d) \neq 0$. Hence, the vector q_d has to be selected in the same class of inverse kinematics solutions as the initial configuration q_0 . If $m < n$, ∞^{n-m} inverse kinematics solutions q_d exist and some of them can be singular ($\text{rank } J(q_d) < m$). Also in this case, a nonsingular inverse kinematic solution has to be selected as q_d .

The control law provides the torque vector u of the robot dynamic model (1) as a combination of a proportional term, acting on the Cartesian error, a motor damping (derivative) term, and a constant compensation of gravity at the desired q_d :

$$u = J^T(\tilde{\theta})K_P(x_d - x(\tilde{\theta})) - K_D\dot{\theta} + g(q_d). \quad (3)$$

The matrix $J(q)$ is the robot Jacobian matrix, K_P and K_D denote $(n \times n)$ positive definite matrices of proportional and derivative gains, and

$$\tilde{\theta} = \theta - K^{-1}g(q_d). \quad (4)$$

The variable $\tilde{\theta} \in \mathfrak{R}^n$ is a ‘gravity-biased’ modification of the measured motor position θ .

It is worth noting that the kinematic terms $x(\tilde{\theta})$ (direct kinematics) and $J^T(\tilde{\theta})$ (Jacobian transpose) are evaluated as a function of $\tilde{\theta}$ (instead of the correct argument q); the rationale is that, as shown afterwards, these expressions shall provide the correct values at steady state, even without a direct measure of q . As a matter of fact, the control law (3) can be implemented using only motor variables.

4 Closed-loop equilibria

The equilibrium configurations of the closed-loop system (1)–(3) are computed by setting $\dot{q} = \dot{\theta} = 0$ and $\ddot{q} = \ddot{\theta} = 0$. This yields

$$g(q) + K(q - \theta) = 0 \quad (5)$$

$$K(\theta - q) = J^T(\tilde{\theta})K_P(x_d - x(\tilde{\theta})) + g(q_d). \quad (6)$$

From (5) it follows that, at any equilibrium, $\theta = q + K^{-1}g(q)$. Then, adding (5) to (6) leads to

$$J^T(q + K^{-1}(g(q) - g(q_d)))K_P x_d - K_P x(q + K^{-1}(g(q) - g(q_d))) + g(q_d) - g(q) = 0. \quad (7)$$

Indeed

$$q = q_d \quad \text{and thus} \quad \theta = q_d + K^{-1}g(q_d) := \theta_d \quad (8)$$

is a closed-loop equilibrium configuration. Moreover, in correspondence to this equilibrium, $\tilde{\theta}_d := \theta_d - K^{-1}g(q_d) = q_d$ and consequently $x(\tilde{\theta}_d) = x_d$.

In the hypothesis of $m = n$, i.e. the robot is not kinematically redundant for the considered task, the uniqueness of such equilibrium is now shown. Adding to both (5) and (6) the term $K(\theta_d - q_d) - g(q_d) = 0$ leads to

$$K(q - q_d) - K(\theta - \theta_d) + g(q) - g(q_d) = 0 \quad (9)$$

$$-K(q - q_d) + K(\theta - \theta_d) + J^T(\tilde{\theta})K_P(x(\tilde{\theta}) - x_d) = 0 \quad (10)$$

where the sign of the last equation has been changed. The following expansion holds true (locally around $\theta = \theta_d$)

$$\begin{aligned} x(\tilde{\theta}) - x_d &= x(q_d + (\theta - \theta_d)) - x_d = x(q_d) \\ &\quad + J(q_d)(\theta - \theta_d) + o(\|\theta - \theta_d\|^2) - x_d \\ &= J(\tilde{\theta} + (\theta_d - \theta))(\theta - \theta_d) + o(\|\theta - \theta_d\|^2) \\ &= J(\tilde{\theta})(\theta - \theta_d) + o_1(\|\theta - \theta_d\|^2). \end{aligned} \quad (11)$$

Therefore, Eqs. (9) and (10) can be rearranged as

$$\begin{aligned} \begin{bmatrix} K & -K \\ -K & K + J^T(\tilde{\theta})K_P J(\tilde{\theta}) \end{bmatrix} \begin{bmatrix} q - q_d \\ \theta - \theta_d \end{bmatrix} \\ = \begin{bmatrix} g(q_d) - g(q) \\ o_1(\|\theta - \theta_d\|^2) \end{bmatrix}. \end{aligned} \quad (12)$$

Assuming to be close enough to θ_d , the vanishing second-order terms can be neglected. In addition, away from kinematic singularities, the smallest (real) eigenvalue $\lambda_{\min}(\bar{K})$ of the symmetric matrix

$$\bar{K} = \begin{bmatrix} K & -K \\ -K & K + J^T(\tilde{\theta})K_P J(\tilde{\theta}) \end{bmatrix} \quad (13)$$

can be always bounded away from zero. In fact, in the above assumptions, a sufficiently large (diagonal) K_P can be always selected such that

$$\lambda_{\min}(\bar{K}) > \alpha. \quad (14)$$

As a consequence, using the inequality

$$\|g(q_1) - g(q_2)\| \leq \alpha \|q_1 - q_2\| \quad (15)$$

for any $q_1, q_2 \in \mathbb{R}^n$, which follows from property **P3**, leads to

$$\begin{aligned} & \left\| \begin{bmatrix} K & -K \\ -K & K + J^T(\tilde{\theta})K_P J(\tilde{\theta}) \end{bmatrix} \begin{bmatrix} q - q_d \\ \theta - \theta_d \end{bmatrix} \right\| \\ & \geq \lambda_{\min}(\bar{K}) \left\| \begin{bmatrix} q - q_d \\ \theta - \theta_d \end{bmatrix} \right\| \geq \lambda_{\min}(\bar{K}) \|q - q_d\| \\ & > \alpha \|q - q_d\| \geq \|g(q_d) - g(q)\| \end{aligned} \quad (16)$$

and thus equality (12), neglecting $o_1(\|\theta - \theta_d\|^2)$, holds only for $(q, \theta) = (q_d, \theta_d)$.

Summarizing, locally around $(q, \theta) = (q_d, \theta_d)$ and away from kinematic singularities in a non-redundant robot, (q_d, θ_d) is a unique isolated equilibrium configuration of the closed-loop system (1)–(3).

5 Proof of asymptotic stability

The stability of the proposed control law is proved by using the direct Lyapunov method and then invoking La Salle's theorem.

Consider the function

$$\begin{aligned} V' &= V'(q, \theta, \dot{q}, \dot{\theta}) = \frac{1}{2} \dot{q}^T M(q) \dot{q} + \frac{1}{2} \dot{\theta}^T I \dot{\theta} \\ &+ \frac{1}{2} (q - \theta + K^{-1}g(q_d))^T K (q - \theta + K^{-1}g(q_d)) \\ &+ \frac{1}{2} (x_d - x(\tilde{\theta}))^T K_P (x_d - x(\tilde{\theta})) \\ &+ U_g(q) - q^T g(q_d). \end{aligned} \quad (17)$$

The function derived from (17) as $V = V'(q, \theta, \dot{q}, \dot{\theta}) - V'(q_d, \theta_d, 0, 0)$ is zero in the chosen equilibrium state, $q = q_d$, $\theta = \theta_d$, $\dot{q} = \dot{\theta} = 0$, and positive for any other state in an open neighborhood of this equilibrium, provided that condition (14) holds (as in [10]). Therefore, V is a candidate Lyapunov function.

Along the trajectories of the closed-loop system (1)–(3), the time derivative of V becomes

$$\dot{V} = \dot{q}^T M(q) \ddot{q} + \frac{1}{2} \dot{q}^T \dot{M}(q) \dot{q} + \dot{\theta}^T I \ddot{\theta} + (\dot{q} - \dot{\theta})^T \times$$

$$\begin{aligned} & K (q - \theta + K^{-1}g(q_d)) - \dot{\theta}^T J^T(\tilde{\theta}) K_P (x_d - x(\tilde{\theta})) \\ & + \dot{q}^T \left(\frac{\partial U_g(q)}{\partial q} \right)^T - \dot{q}^T g(q_d) = \dot{q}^T (-S(q, \dot{q}) \dot{q} - g(q)) \\ & + \dot{q}^T \left(-K(q - \theta) + \frac{1}{2} \dot{M}(q) \dot{q} + K(q - \theta) + g(q_d) \right) \\ & + \dot{q}^T (g(q) - g(q_d)) + \dot{\theta}^T (u - K(\theta - q) - K(q - \theta)) \\ & + \dot{\theta}^T (-g(q_d) - J^T(\tilde{\theta}) K_P (x_d - x(\tilde{\theta}))) \\ & = \dot{\theta}^T (J^T(\tilde{\theta}) K_P (x_d - x(\tilde{\theta})) - K_D \dot{\theta} + g(q_d) - g(q_d)) \\ & + \dot{\theta}^T (-J^T(\tilde{\theta}) K_P (x_d - x(\tilde{\theta}))) = -\dot{\theta}^T K_D \dot{\theta} \leq 0 \end{aligned} \quad (18)$$

where the skew-symmetry of matrix $\dot{M} - 2S$ and the identity $\dot{\tilde{\theta}} = \dot{\theta}$ have been used.

Since $\dot{V} = 0$ iff $\dot{\theta} = 0$, at the equilibrium the closed-loop equations give

$$\begin{aligned} M(q) \ddot{q} + S(q, \dot{q}) \dot{q} + g(q) + Kq &= K\theta = \text{const} \quad (19) \\ Kq &= K\theta - J^T(\theta - K^{-1}g(q_d)) K_P \times \\ & (x_d - x(\theta - K^{-1}g(q_d))) - g(q_d) = \text{const}. \end{aligned} \quad (20)$$

From (20), it follows that $\dot{q} = \ddot{q} = 0$, which in turn simplifies (19) to

$$g(q) + K(q - \theta) = 0. \quad (21)$$

It has been already shown in Sect. 4 that the system of (20)–(21) has a unique solution, locally around a nonsingular (q_d, θ_d) , provided that condition (14) holds true. Therefore, $q = q_d$, $\theta = \theta_d$, $\dot{q} = \dot{\theta} = 0$ is the largest invariant subset contained in the set of states such that $\dot{V} = 0$ (locally around the equilibrium configuration). By La Salle's Theorem, local asymptotic stability of the desired (nonsingular) set point can be concluded.

6 A modified control law

The control law (3) uses a *constant* gravity compensation at the desired closed-equilibrium. A better transient behavior can be expected if a form of gravity compensation is performed at any configuration during motion. However, note that the gravity vector in (1) depends on the link variables q , which are not directly measurable. This is similar to the dependence on q of the direct and differential kinematics of the arm (see (2)) and therefore one can attempt, by analogy, using the 'gravity-biased' variable $\tilde{\theta}$, defined in (4), in place of q also for the *on-line* gravity compensation, i.e.,

$$u = J^T(\tilde{\theta}) K_P (x_d - x(\tilde{\theta})) - K_D \dot{\theta} + g(\tilde{\theta}). \quad (22)$$

It can be shown that the control law (22) provides local asymptotic stability of the closed-loop equilibrium configuration (8), under similar assumptions as in (14). The analysis, however, is more involved and requires in particular a different Lyapunov function candidate.

7 Experimental results

In order to test the validity of the proposed compliance control scheme in the Cartesian space, the implementation of (22) has been carried out on an 8-d.o.f. cable-actuated robot, named the Dexter arm [14], designed for applications of rehabilitation robotics.

In the particular case of a cable-actuated robot manipulator, such as the Dexter arm, the actuators are not directly connected to the links since, after the gear reduction, a mechanical transmission system realized by pulleys and steel cables is present. This causes a mechanical coupling among the joints (Fig. 2).

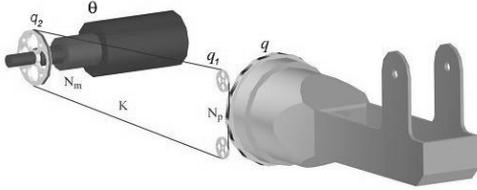


Figure 2: A cable-actuated joint

The position variables are 16, decomposed in 8 rotor position values measured by incremental encoders, and 8 link position values.

The experimental trials are aimed at demonstrating the stability of the system in reaching the desired reference position x_d as well as at showing the capability of the controller to modulate the level of force in the interaction. To this purpose, a desired trajectory $x_d(t)$ has been planned from an initial position until the desired reference position x_d . The assumption is made that at the initial time instant the robot has a zero position error. The data shown in the following correspond to two different sets of proportional gains $K_P = \text{diag}\{240, 220, 240, 5, 5, 5\}$ and $K_P = \text{diag}\{100, 100, 100, 2, 2, 2\}$ and to the derivative gains $K_D = \text{diag}\{20, 20, 12, 10, 4.5, 5, 0.4, 0.4\}$.

Fig. 3 shows the time evolution of the position error and orientation error when the higher values K_P are chosen. The robotic system is asymptotically stable and shows a lower level of fluctuation

and vibration with respect to the case of a compliance controller with the same gains for the equivalent rigid robot [14], that is the case of joints assumed completely rigid, with $\theta = q$ (Fig. 4). Further, convergence to zero is ensured in the elastic case while the system is stabilized around a value different from zero in the rigid case.

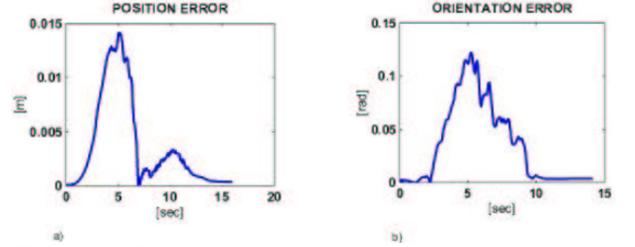


Figure 3: Position error and orientation error when $K_P = \text{diag}\{240, 220, 240, 5, 5, 5\}$

On the other hand, choosing the lower values for K_P increases the level of compliance, at the expenses of a larger position and orientation error (Figs. 5). A comparison between the two choices has been carried out by means of an impact against an obstacle equipped with a load cell. It is illustrated in Fig. 6, revealing a reduction of the values of interaction forces with the lower feedback gains. In any case, the asymptotic stability is always achieved even if with a different convergence rate.

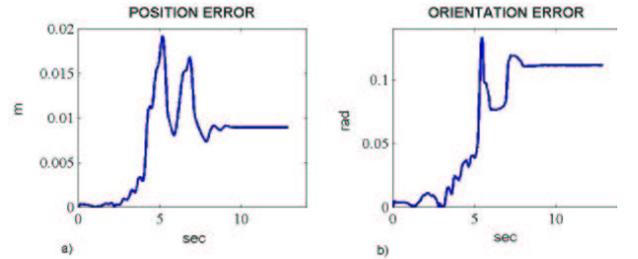


Figure 4: Position error and orientation error in the rigid case

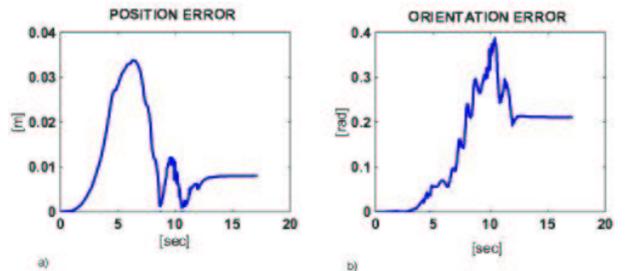


Figure 5: Position error and orientation error when $K_P = \text{diag}\{100, 100, 100, 2, 2, 2\}$

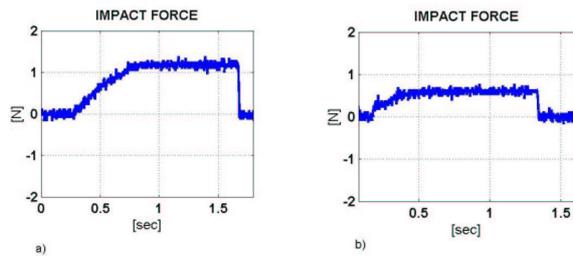


Figure 6: Interaction force in case of high K_P (left) or low K_P (right)

8 Conclusions

In order to reduce the vibrational phenomena or chattering effects in contact situations between a robot manipulator and the environment, the elasticity in the joint actuation system cannot be neglected in the design of control strategies.

To this purpose, interaction control schemes typically utilized for rigid robots can be still applied if suitable corrective terms are introduced.

This paper has demonstrated that a compliance control scheme in the Cartesian space for rigid robots can stabilize also a robot with elastic joints, by using only the sensor information on the rotor positions. A control law with constant gravity compensation has been proved. Then, a modified version with on-line gravity compensation has been proposed and successfully implemented on an 8-d.o.f. cable-actuated robot manipulator. The experimental trials have confirmed asymptotic stability of the system and the capability to act on the robot interaction force by varying its compliance.

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