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Force control of the KUKA LBR Med without external force sensor

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INTRODUCTION

In recent years, robots embedding joint torque sensors and impedance control have been industrialized and commercialized, aiming to deploy safe human-robot collaboration applications. Among them, the Kuka LBR Med benefits from all the certifications to ease its integration in medical applications. The embedded torque sensors open the opportunity to implement force control [1], a feature that is missing in most existing surgical robots. Yet, it is crucial for safety in a context where uncertainties and disturbances, such as tissue deformations or physiological movements, challenge robot stability at contact.

Impedance control preserves the robot's stability in the presence of uncertainties when the robot contacts its environment [2]. However, within this framework, explicitly controlling interaction forces applied by a robot to its environment is impossible when the environment position and stiffness are unknown. In this framework, force-regulation or tracking can be achieved using inner-outer loop control schemes [3], [4].

Installing a force/torque sensor on an end-effector to implement explicit force control brings two drawbacks: i) non-collocated modes that challenge stability [5]; ii) from the perspective of a translation to clinical application, adding costly and fragile equipment to a medical system is of high cost and risk.

In this paper, we experimentally investigate the possibility of finely controlling the forces applied by the robot to the environment based on KUKA's built-in joint impedance controller. We first use an external force/torque sensor to provide the feedback signal, leading to poor performance due to non-collocated dynamics. We then introduce a pseudo-force feedback approach using joint position sensors that significantly improves force response rapidity and robustness.

MATERIALS AND METHODS

We consider a robot equipped with an inner joint impedance controller. The dynamic relationship between the external joint torque vector τ_e and the joint position vector \mathbf{q} of an impedance-controlled robotic arm is:

$$M_d \ddot{\mathbf{q}} = K_d(\mathbf{q}_r - \mathbf{q}) + B_d(\dot{\mathbf{q}}_r - \dot{\mathbf{q}}) - \tau_e, \quad (1)$$

where M_d , B_d , K_d , and \mathbf{q}_r represent the desired mass, damping, stiffness matrices, and the reference joint position vector. Typically, diagonal constant matrices are used for K_d , B_d , and M_d , leading to independent linear dynamic equations.

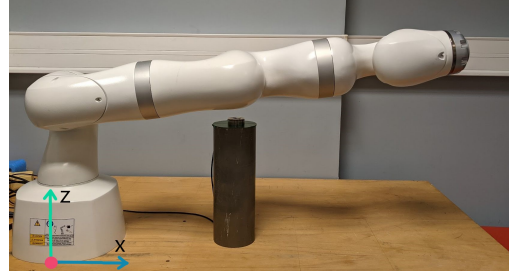


Fig. 1: Setup used for the 1-DoF experiment.

In a first step, we study a one-joint problem and use plain lowercase letters to symbolize scalars:

$$m_d \ddot{q} = k_d(q_r - q) + b_d(\dot{q}_r - \dot{q}) - \tau_e. \quad (2)$$

Regulating the torque to its desired value τ_d requires adjusting q_r in real-time by means of an outer torque loop. Two different outer loops are considered. The first one uses classical explicit torque regulation ([3], Fig. 2a):

$$\dot{q}_r = \lambda(\tau_d - \tau_e), \quad (3)$$

where λ is a proportional gain and τ_e is the measured at the end-effector level using the installed force sensor. The second one exploits a pseudo-torque signal $\tilde{\tau}_e = k_d(q_r - q)$ as the feedback signal (Fig. 2b):

$$\dot{q}_r = \lambda[\tau_d - k_d(q_r - q)]. \quad (4)$$

Note that according to Eq. (2), the pseudo-torque signal corresponds to the real external torque at the equilibrium, *i.e.*: if $\ddot{q} = \dot{q} = \dot{q}_r = 0$, then $\tilde{\tau}_e = \tau_e = k_d(q_r - q)$.

In a second step, we expand the 1-DoF case to a multi-DoF problem for force regulation. The control law is then:

$$\dot{\mathbf{q}}_r = J^\dagger \Lambda [F_d - (J^\dagger)^T K_d(\mathbf{q}_r - \mathbf{q})], \quad (5)$$

where F_d is the desired force/torque (wrench) vector; J^\dagger denotes the *Moore-Penrose* inverse of the Jacobian matrix J ; And, Λ is a diagonal matrix whose elements denote the proportional gains $\Lambda = \text{diag}(\lambda_1, \dots, \lambda_6)$. Gain λ_i is set to zero for directions where the force is not controlled, leaving it free for conventional trajectory control, similar to hybrid position/force control.

Experiments, 1-DoF and 7-DoF, were conducted using the KUKA LBR 7 Med robotic arm running its built-in joint impedance controller. For the 1-DoF experiment, the second joint of the KUKA arm (Fig. 1) was controlled. The other joints were servoed to their initial position. An ATI Mini40 force and torque (F/T) sensor was placed at the interface between the robot and the environment to

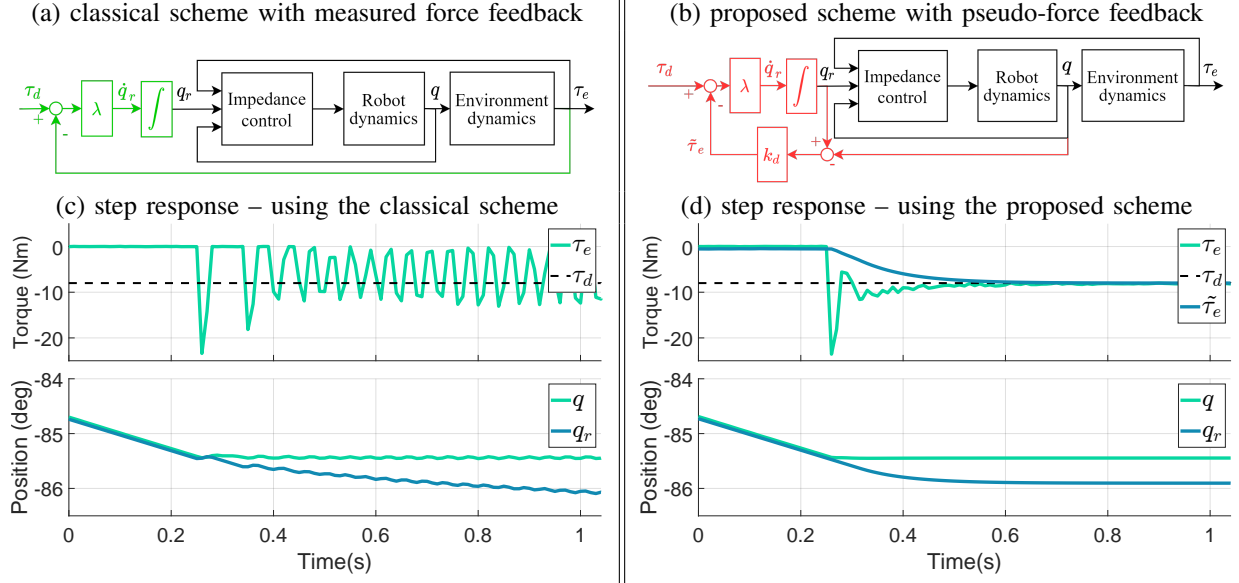


Fig. 2: The 1-DoF experiment – control schemes and results. Comparison between the control schemes.

provide τ_e by projection about the robot's second joint axis. In practice, for safety, a velocity saturation \dot{q}_{\max} was added to Eq. (3). This had the experimental effect of inducing limit cycles when stability conditions were not met [6]. The desired torque was set to $\tau_d = -8.0$ Nm. Tuning the controller consisted of experimentally selecting $\lambda = 0.01$ rad/s/Nm and $\dot{q}_{\max} = 0.05$ rad/s to ensure stability in various experimental conditions with the pseudo-force feedback. The same tuning was kept for a fair comparison with the external sensor force feedback.

For the 7-DoF experiment, all joints of the KUKA arm were controlled using the pseudo-force feedback control scheme. The F/T sensor was placed at the interface between the robot and the environment only for evaluation. Similar to the 1-DoF experiment, an operational space velocity saturation $\dot{x}_{\max} = 0.02$ m/s was added. The desired force was -20.0 N along the vertical axis to contact a hard horizontal plane (see Fig. 1). The gains λ_i were all set to zero but for $\lambda_3 = 0.03$ m/s/N, corresponding to the vertical force component.

RESULTS AND DISCUSSION

Figure 2 shows the results obtained during the 1-DoF experiment, when the robot started in the free-space and contacted the environment, using the external (left) or pseudo (right) joint torque signal. Although the gains are identical, the external sensory approach leads to instability (Fig. 2c), whereas the pseudo-torque feedback method leads to a stable and precise response and, compared to literature with this robot arm, relatively fast (Fig. 2d). The servoed signal $\tilde{\tau}_e$ smoothly converged towards the desired value within approximately 200 ms. Meanwhile, the real torque τ_e experienced a peak at the impact that was not fed back through the outer loop, thus not destabilizing the system. Observed robustness arises from the fact that the feedback signal $\tilde{\tau}_e$ excludes the high-frequency components. Yet, it does not involve any low-pass filtering,

that would add poles within the closed-loop bandwidth and induce stability issues.

Figure 3 shows the results of the 7-DoF experiment. Similar to the 1-DoF experiment, we observed a stable behavior. The servoed signal (pseudo-force, blue) was smooth and converged toward the desired force value rapidly. The observed slope, before reaching the desired value, corresponds to the speed saturation that was set.

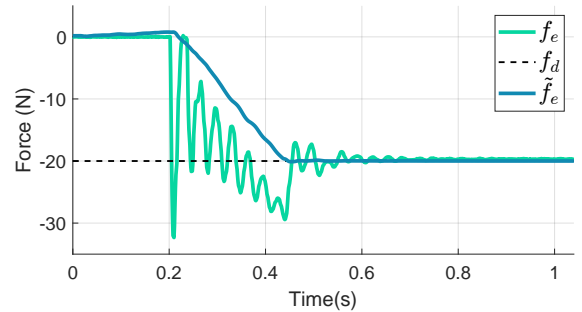


Fig. 3: The 7-DoF experiment – results.

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