Robotics 2

Iterative Learning for Gravity Compensation

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Control goal

- regulation of arbitrary equilibrium configurations in the presence of gravity
  - without explicit knowledge of robot dynamic coefficients (nor of the structure of the gravity term)
  - without the need of "high" position gain
  - without complex conditions on the control gains
- based on an iterative control scheme that uses
  1. PD control on joint position error + constant feedforward term
  2. iterative update of the feedforward term at successive steady-state conditions
- derive sufficient conditions for the global convergence of the iterative scheme with zero final error

Preliminaries

- robot dynamic model

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) = u$$

- available bound on the gradient of the gravity term

$$\left\| \frac{\partial g(q)}{\partial q} \right\| \leq \alpha$$

- regulation attempted with a joint-based PD law (without gravity cancellation nor compensation)

$$u = K_P(q_d - q) - K_D\dot{q} \qquad K_P > 0, K_D > 0$$

- at steady state, there is a non-zero error left

$$q = \bar{q}, \dot{q} = 0 \qquad g(\bar{q}) = K_P(q_d - \bar{q}) \qquad \bar{e} = q_d - \bar{q} \neq 0$$

Iterative control scheme

- control law at the i-th iteration (for $i = 1, 2, \ldots$)

$$u = \gamma K_P(q_d - q) - K_D\dot{q} + u_{i-1} \qquad \gamma > 0$$

with a constant compensation term u_{i-1} (feedforward)

  - $K_P > 0, K_D > 0$ are chosen diagonal for simplicity
  - q_0 is the initial robot configuration
  - $u_0 = 0$ is the 'easiest' initialization of the feedforward term
  - at the steady state of the i-th iteration ($q = q_i, \dot{q} = 0$), one has

$$g(q_i) = \gamma K_P(q_d - q_i) + u_{i-1}$$

- update law of the compensation term (for next iteration)

$$u_i = \gamma K_P(q_d - q_i) + u_{i-1} \qquad [= g(q_i)]$$

$\leftarrow$ for implementation $\rightarrow$ [for analysis]

Convergence analysis

Theorem

(a) $\lambda_{\min}(K_P) > \alpha$

(b) $\gamma \geq 2$

guarantee that the sequence $\{q_0, q_1, q_2, \dots\}$ converges to q_d (and $\dot{q} = 0$) from any initial value q_0 (and $\dot{q}_0$), i.e., globally

- condition (a) is sufficient for the global asymptotic stability of the desired equilibrium state when using

$$u = K_P(q_d - q) - K_D\dot{q} + g(q_d)$$

  with a known gravity term and diagonal gain matrices

- the additional sufficient condition (b) guarantees the convergence of the iterative scheme, yielding

$$\lim_{i \to \infty} u_i = g(q_d)$$

Proof

- let $e_i = q_d - q_i$ be the error at the end of the i-th iteration; based on the update law, it is $u_i = g(q_i)$ and thus

$$\|u_i - u_{i-1}\| = \|g(q_i) - g(q_{i-1})\| \leq \alpha\|q_i - q_{i-1}\|$$
$$\leq \alpha(\|e_i\| + \|e_{i-1}\|)$$

adding and subtracting q_d

- on the other hand, from the update law it is

$$\|u_i - u_{i-1}\| = \gamma\|K_P e_i\|$$

- combining the two above relations under (a), we have

$$\gamma\alpha\|e_i\| < \gamma\lambda_{\min}(K_P)\|e_i\| \leq \gamma\|K_P e_i\| \leq \alpha(\|e_i\| + \|e_{i-1}\|)$$

or $$\|e_i\| < \frac{1}{\gamma}(\|e_i\| + \|e_{i-1}\|)$$

Proof (cont)

- condition (b) guarantees that the error sequence $\{e_0, e_1, e_2, \ldots\}$

$$\|e_i\| < \frac{\frac{1}{\gamma}}{1-\frac{1}{\gamma}}\|e_{i-1}\| = \frac{1}{\gamma-1}\|e_{i-1}\|$$

  is a contraction mapping, so that

$$\lim_{i\to\infty}\|e_i\| = 0$$

  with asymptotic convergence from any initial state ◁

⇒ the robot progressively approaches the desired configuration through successive steady-state conditions

- K_P and K_D affect each transient phase
- coefficient γ drives the convergence rate of intermediate steady states to the final one

Remarks

- combining (a) and (b), the sufficient condition only requires the doubling of the proportional gain w.r.t. the known gravity case

$$\widehat{K}_P = \gamma K_P \quad \Rightarrow \quad \boxed{\lambda_{\min}\left(\widehat{K}_P\right) > 2\alpha}$$

- for a diagonal $\widehat{K}_P$, this condition implies a (positive) lower bound on the single diagonal elements of the matrix
- again, it is only a sufficient condition
  - the scheme may converge even if this condition is violated ...
- the scheme can be interpreted as using an integral term
  - updated only in correspondence of a discrete sequence of time instants
  - with a guaranteed global convergence (and implicit stability)

Numerical results

- 3R robot with uniform links, moving in the vertical plane

  $l_1 = l_2 = l_3 = 0.5$ [m]

  $m_1 = 30, m_2 = 20, m_3 = 10$ [kg] ➡ $\alpha \cong 400$

- with saturations of the actuating torques

  $U_{1,\max} = 800, U_{2,\max} = 400, U_{3,\max} = 200$ [Nm]

- three cases, from the downward position $q_0 = (0,0,0)$

I: $q_d = (\pi/2, 0, 0)$

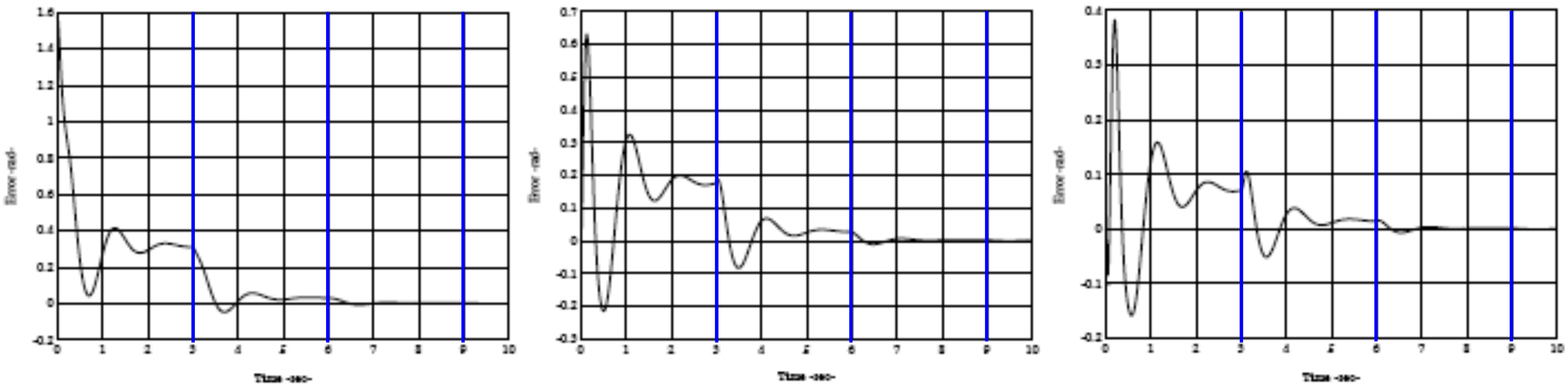
II: $q_d = (3\pi/4, 0, 0)$

(cases I and II) $\hat{K}_P = \mathrm{diag}\{1000, 600, 280\}$, $K_D = \mathrm{diag}\{200, 100, 20\}$

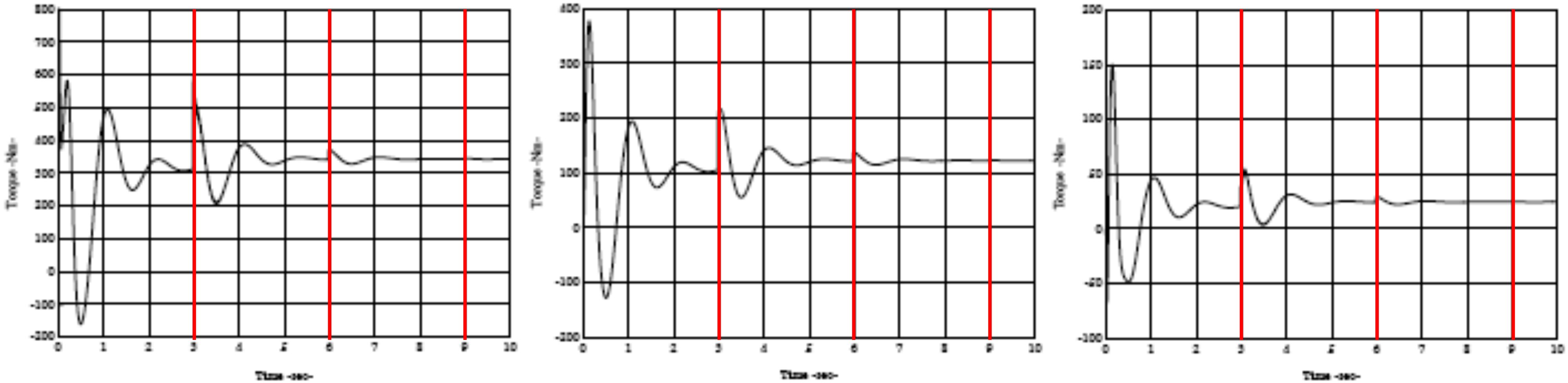
III: $q_d = (3\pi/4, 0, 0)$

$\hat{K}_P = \mathrm{diag}\{500, 500, 500\}$, $K_D =$ as before

Case I: $q_d = (\pi/2, 0, 0)$

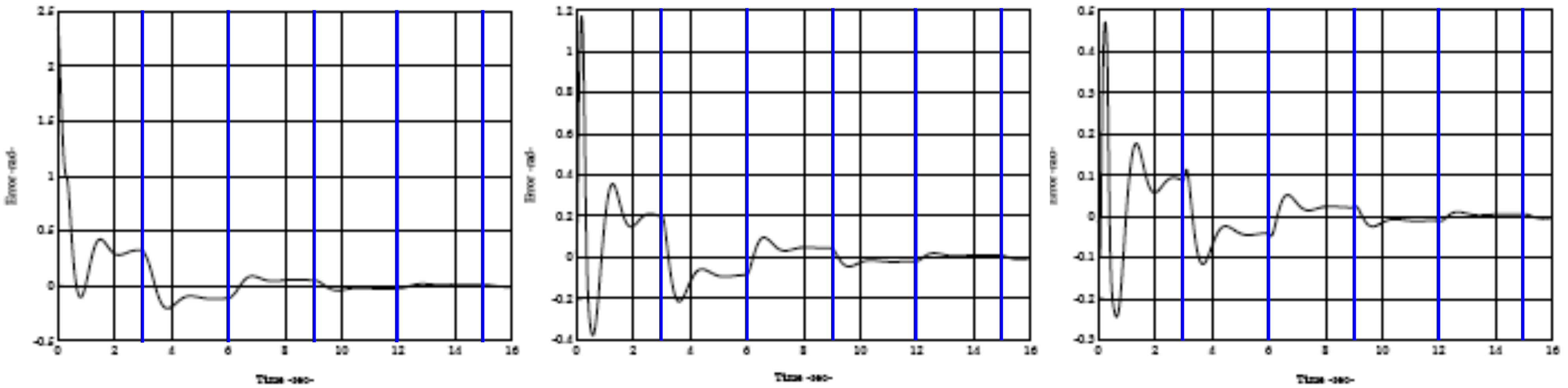


joint position errors (zero after 3 updates)

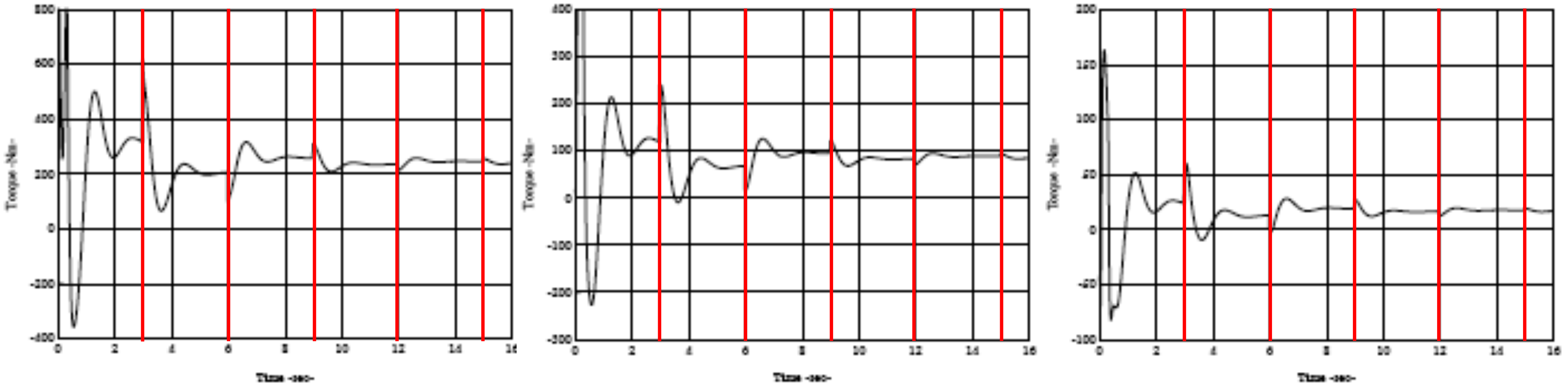


control torques

Case II: $q_d = (3\pi/4, 0, 0)$

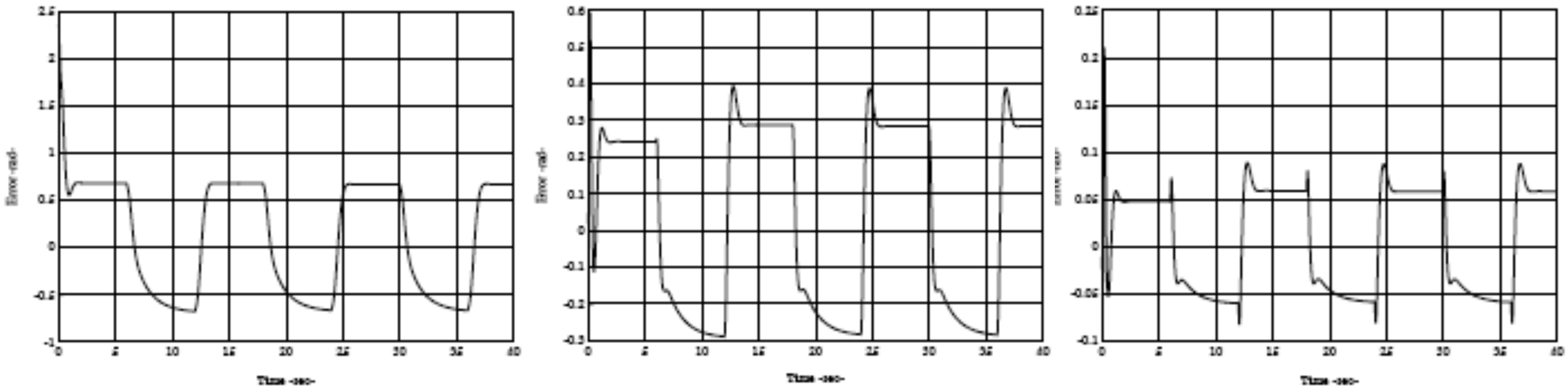


joint position errors (zero after 5 updates)

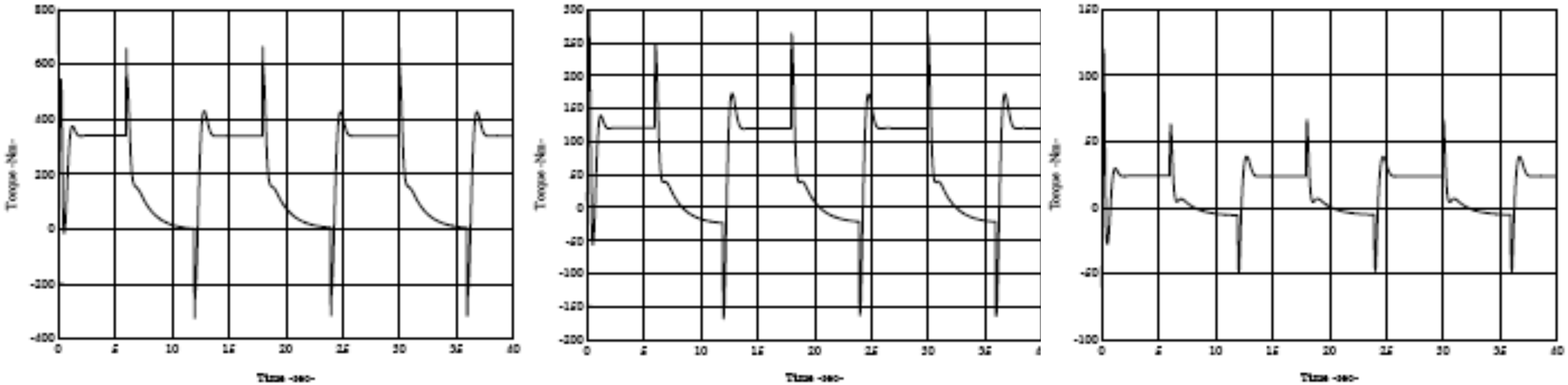


control torques

Case III: $q_d = (3\pi/4, 0, 0)$, reduced gains



joint position errors (limit cycles, no convergence!)



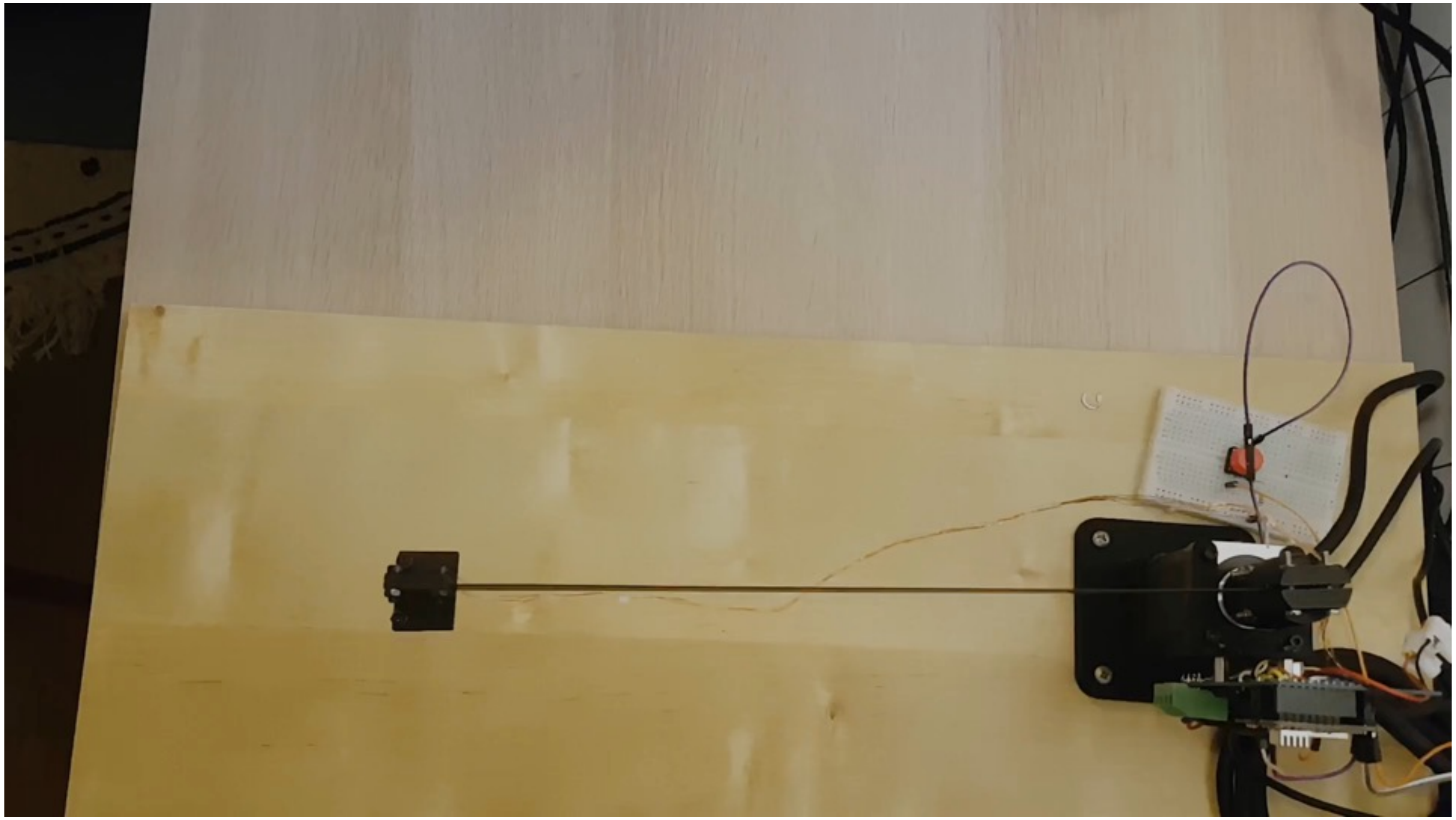
control torques

Final comments

- only few iterations are needed for obtaining convergence, learning the correct gravity compensation at the desired q_d
- sufficiency of the condition on the P gain
  - even if violated, convergence can still be obtained (first two cases); otherwise, a limit motion cycle takes place between two equilibrium configurations that are both incorrect (as in the third case)
  - this shows 'how far' is sufficiency from necessity
- analysis can be refined to get lower bounds on the K_{Pi} (diagonal case) that are smaller, but still sufficient for convergence
  - intuitively, lower values for K_{Pi} should still work for distal joints
- in practice, update of the feedforward term occurs when the robot is close enough to a steady state (joint velocities and position variations are below suitable thresholds)

Control experiments with flexible robots
without gravity

even for just a single but flexible link in the absence of gravity, a rest-to-rest maneuver without residual oscillations is difficult to be performed by a pure PD joint control action



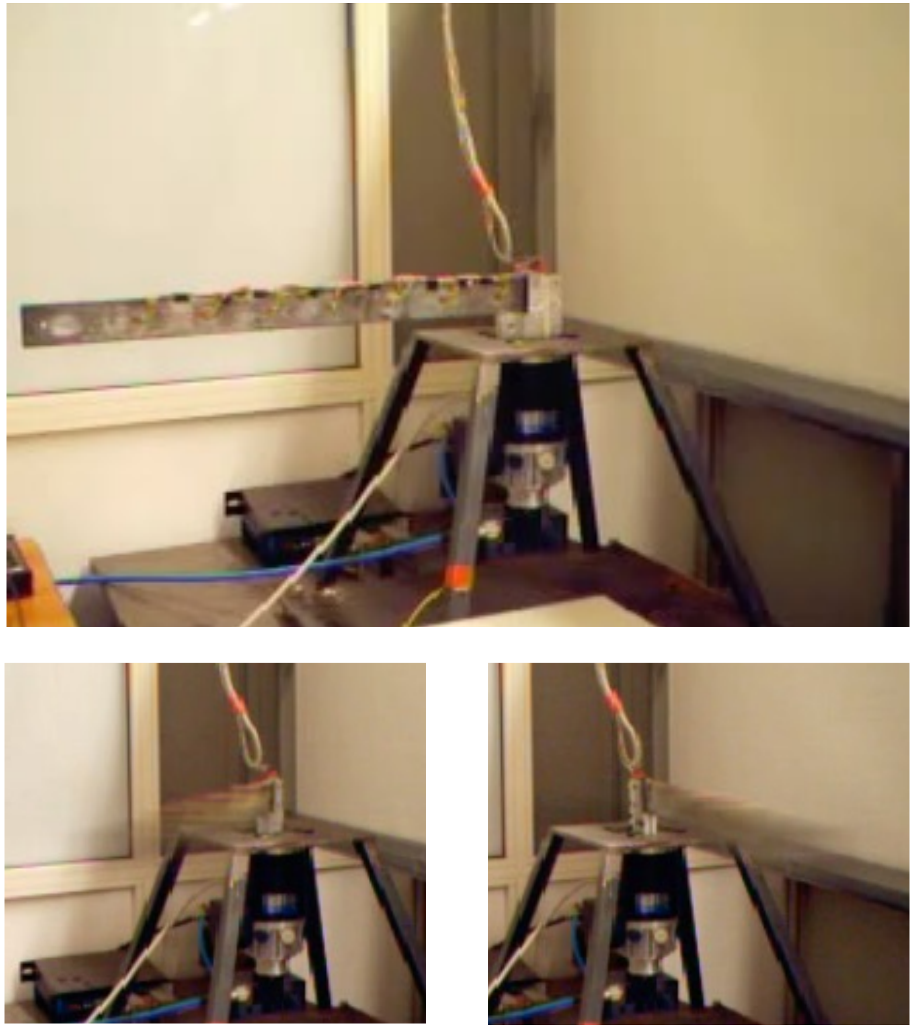
video

ICRA 2023

S. Drost. P. Pustina. F. Angelini, A. De Luca, G. Smit, C. Della Santina,
"Experimental validation of functional iterative learning control on a one-link flexible arm"

Control experiments with flexible robots
without gravity

video



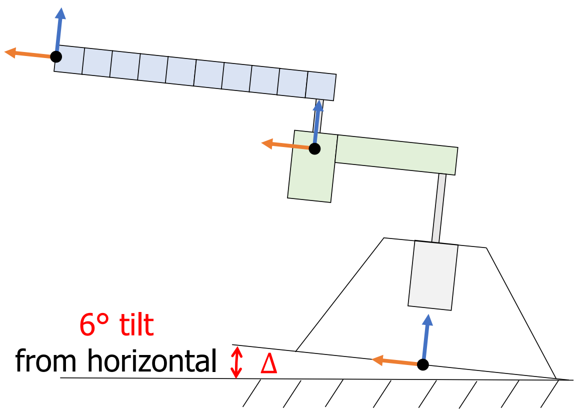
rest-to-rest maneuver in given motion time for a single flexible link (PD + feedforward)

video

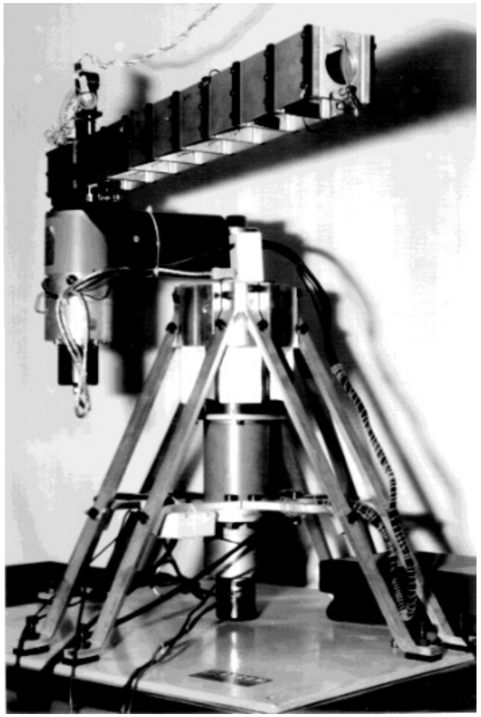
end-effector trajectory tracking for FlexArm —a planar 2R robot with flexible forearm

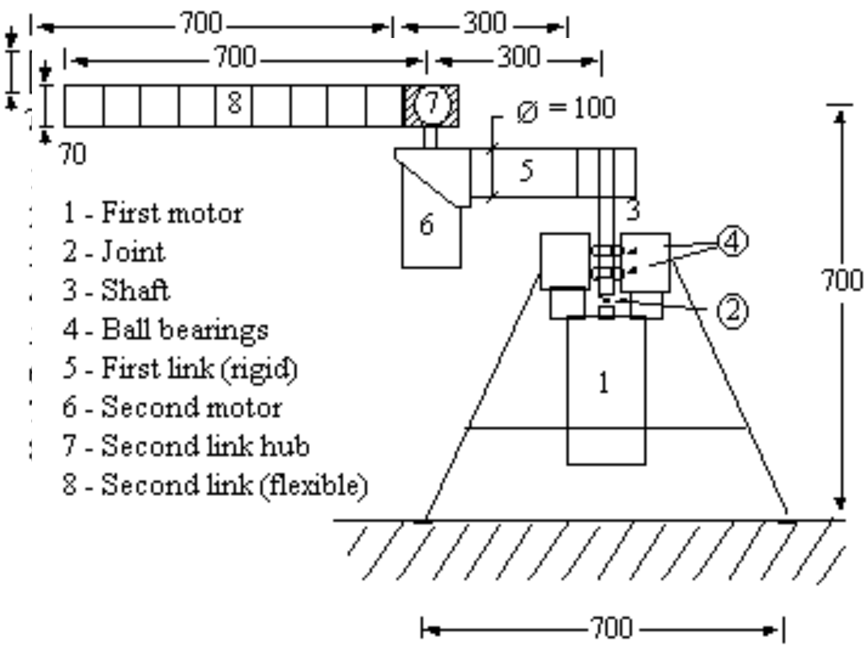
Extension to flexible robots

- the same iterative learning control approach has been extended to position regulation in robots with flexible joints and/or links under gravity
  - at the motor/joint level
  - at the Cartesian level (end-effector tip position, beyond flexibility), using a double iterative scheme
- experimentally validated on the two-link FlexArm @ DIS (now DIAG!)

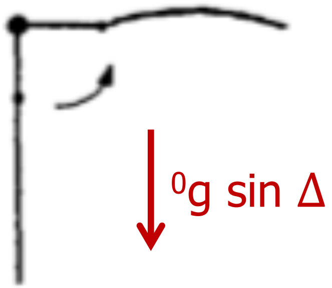


with supporting base
tilted by $\Delta \approx 6°$
(inclusion of gravity)

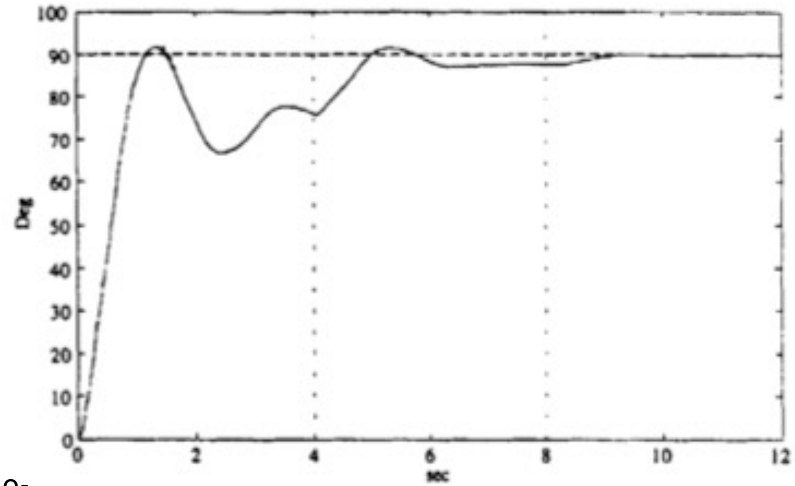




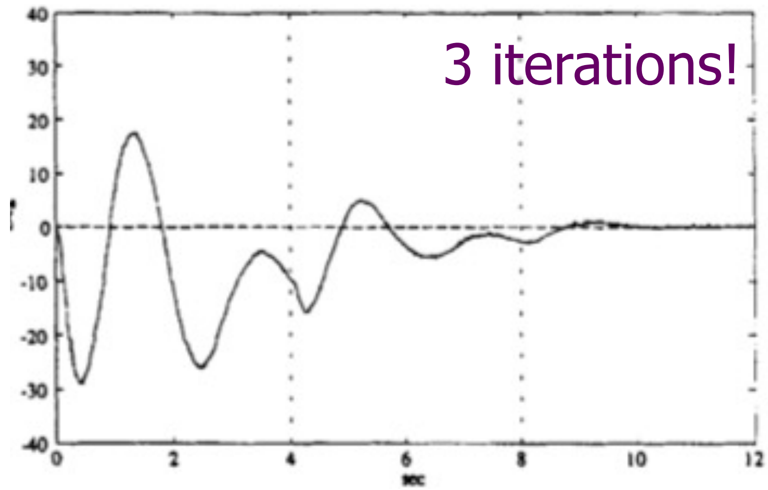
Experimental results for tip regulation



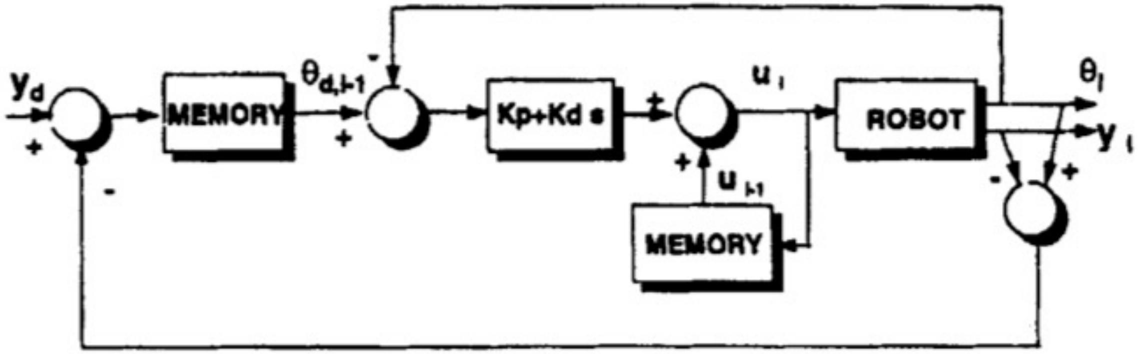
motion task:
$(0^\circ,0^\circ) \Rightarrow (90^\circ,0^\circ)$



first link position

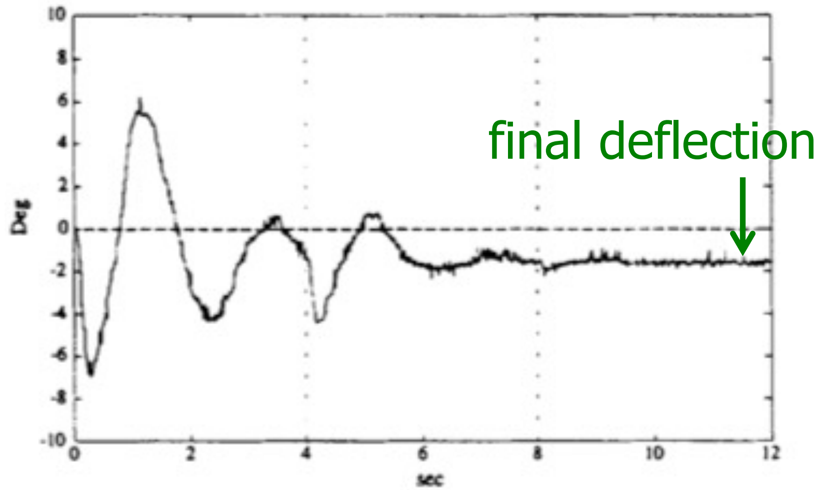


tip angle w.r.t. first link



double iterative scheme

De Luca, Panzieri: Int J Adapt Cont & Sign Proc, 1996
(factor $\gamma \rightarrow 1/\beta$ in the original paper)



second link deflection