



Robotics 1

Kinematic control

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Robot motion control

- need to “actually” realize a desired robot motion task ...
 - **regulation** of pose/configuration (constant reference)
 - **trajectory** following/**tracking** (time-varying reference)
- ... despite the presence of
 - external disturbances and/or unmodeled dynamic effects
 - initial errors (or arising later due to disturbances) w.r.t. desired task
 - discrete-time implementation, uncertain robot parameters, ...
- we use a **general** control scheme based on
 - **feedback** (from robot state measures, to impose **asymptotic stability**)
 - **feedforward** (nominal commands generated in the planning phase)
- the **error** driving the feedback part of the control law can be defined either in **Cartesian** or in **joint** space
 - control action **always** occurs at the joint level (where actuators drive the robot), but performance has to be evaluated at the task level



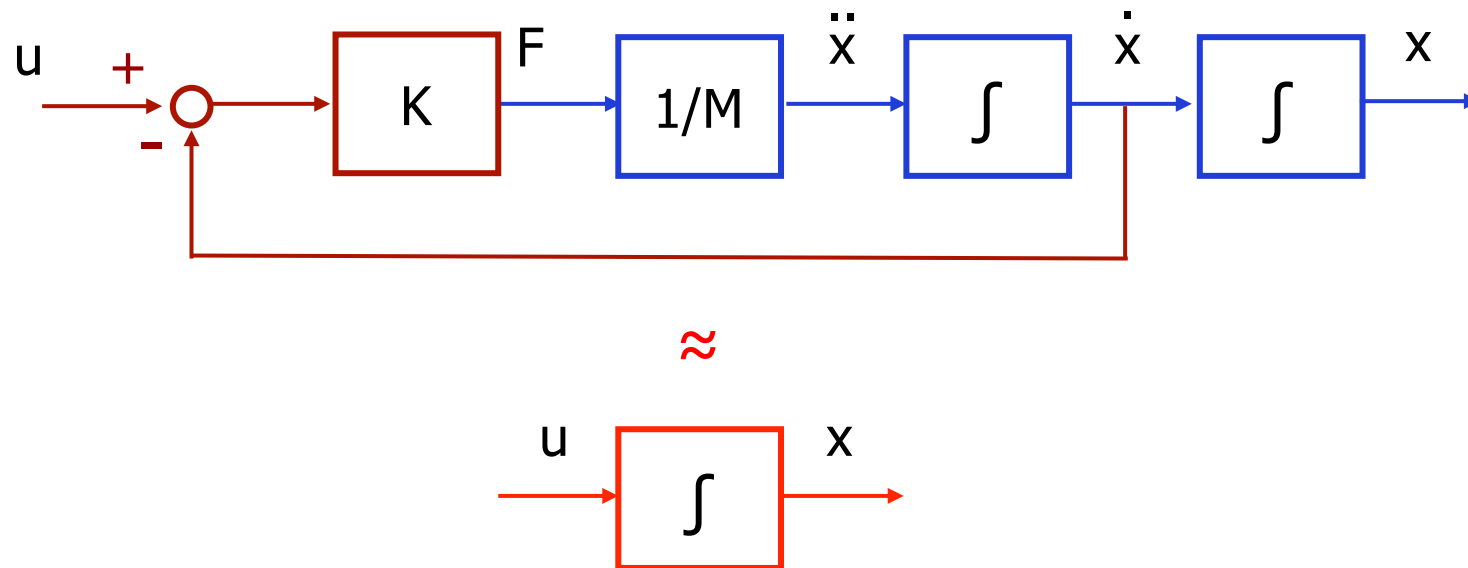
Kinematic control of robots

- a robot is an electro-mechanical system driven by actuating **torques** produced by the motors
- it is possible, however, to consider a **kinematic command** (most often, a **velocity**) as control input to the system...
- ...thanks to the presence of **low-level feedback control** at the robot joints that allow imposing commanded reference velocities (at least, in the “ideal case”)
- these feedback loops are present in industrial robots within a **“closed” control architecture**, where users can only specify reference commands of the kinematic type
- in this way, **performance** can be very satisfactory, provided the desired motion is **not too fast** and/or **does not require large accelerations**



An introductory example

- a mass M in linear motion: $M \ddot{x} = F$
- low-level feedback: $F = K(u - \dot{x})$, with u = reference velocity
- equivalent scheme for $K \rightarrow \infty$: $\dot{x} \approx u$
- in practice, valid in a limited frequency “bandwidth” $\omega \leq K/M$

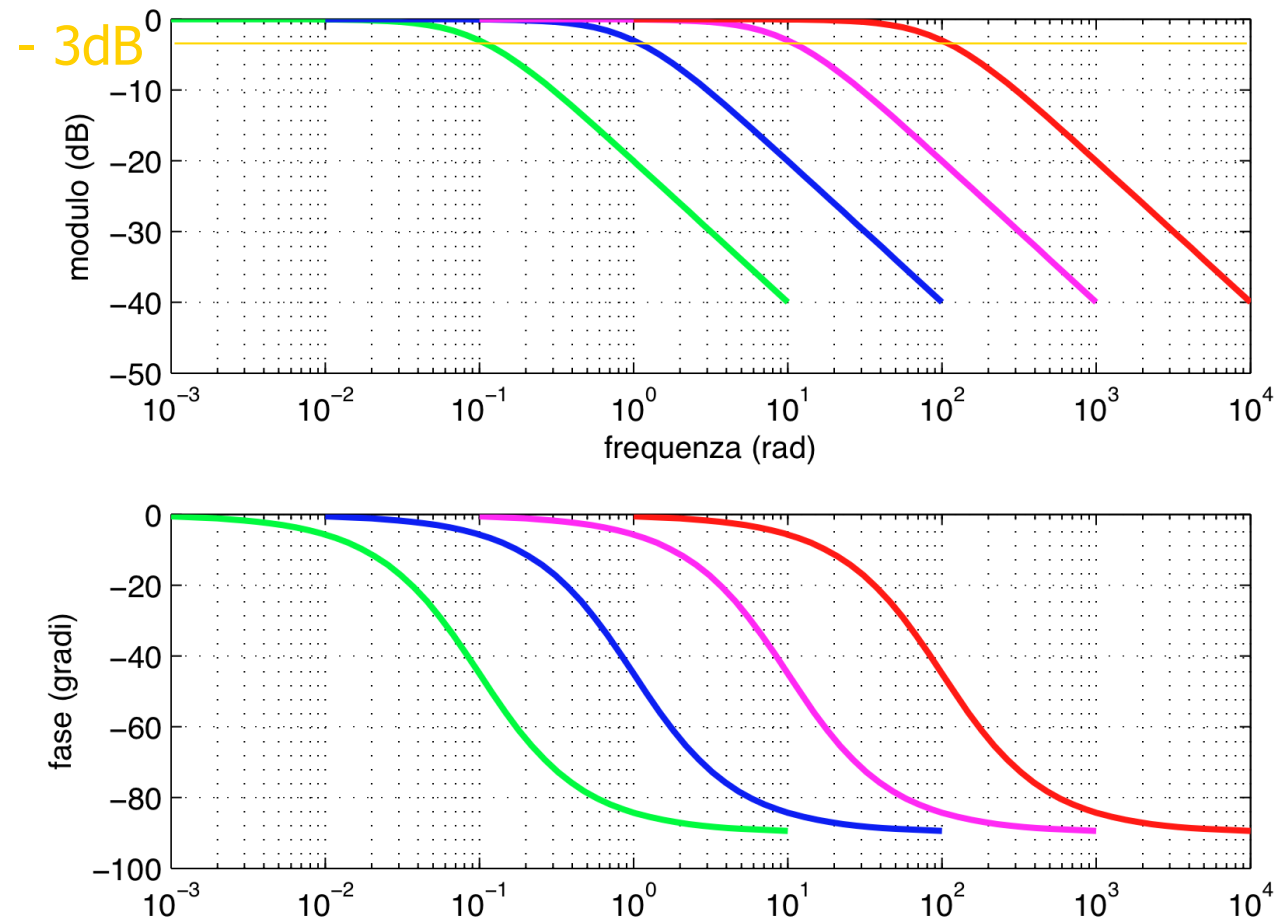




Frequency response of the closed-loop system

- Bode diagrams of $sx(s)/u(s)$ for $K/M = 0.1, 1, 10, 100$

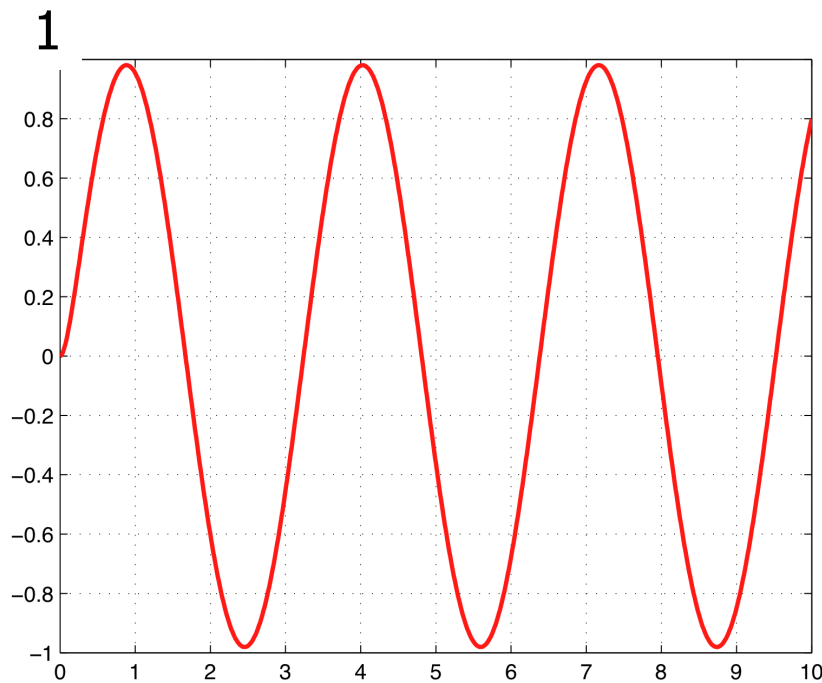
actual
velocity
 \dot{x}
commanded
reference
velocity
 u



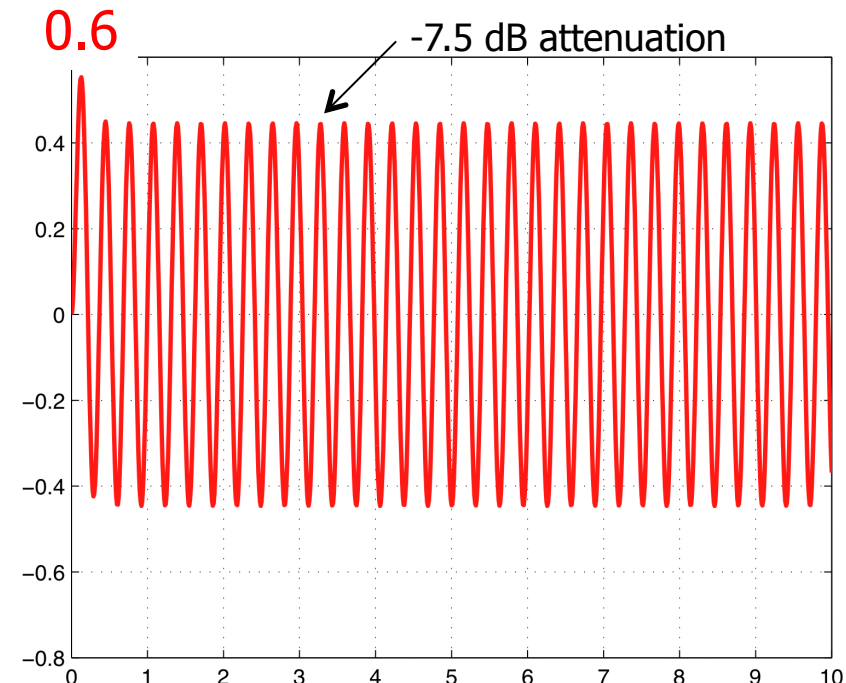


Time response

- setting $K/M = 10$ (bandwidth), we show two possible time responses to unit sinusoidal velocity reference commands at different ω



$\omega = 2$ rad/s



$\omega = 20$ rad/s

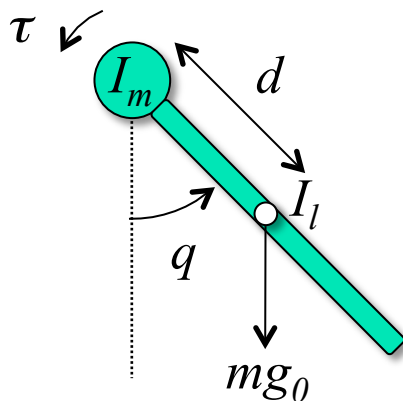
actually realized velocities



A more detailed example

including nonlinear dynamics

- single link (a thin rod) of mass m , center of mass at d from joint axis, inertia M (motor + link) at the joint, rotating in a vertical plane (the gravity torque at the joint is configuration dependent)



dynamic model

$$\underbrace{(I_m + I_l + md^2)}_M \ddot{q} + mg_0 d \sin q = \tau$$

$$g_0 = 9.81 [m/s^2]$$

$$m = 10 [kg]$$

$$d = \frac{\ell}{2} = 0.2 [m]$$

$$I_l = \frac{1}{12} m \ell^2 = 0.1333 [kg \cdot m^2]$$

$$I_m = 0.5333 [kg \cdot m^2] (= I_l + md^2)$$

$$\Rightarrow M = 1.0667 [kg \cdot m^2]$$

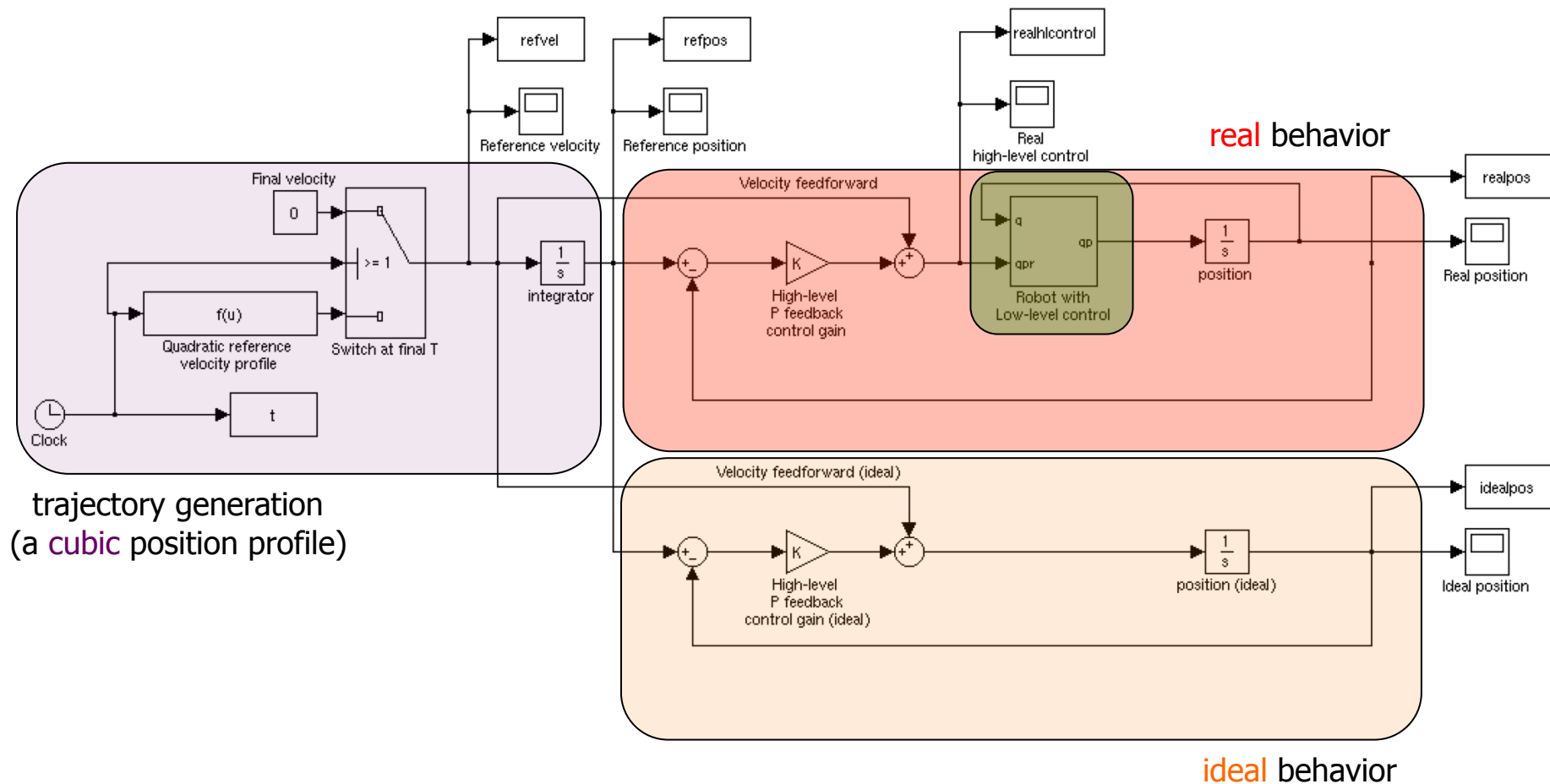
- fast **low-level feedback** control loop based on a PI action on the velocity error + an approximate acceleration feedforward
- **kinematic control** loop based on a P feedback action on the position error + feedforward of the velocity reference
- evaluation of tracking **performance** for rest-to-rest motion tasks with "increasing dynamics" = higher accelerations



A more detailed example

differences between the ideal and real case

- Simulink scheme

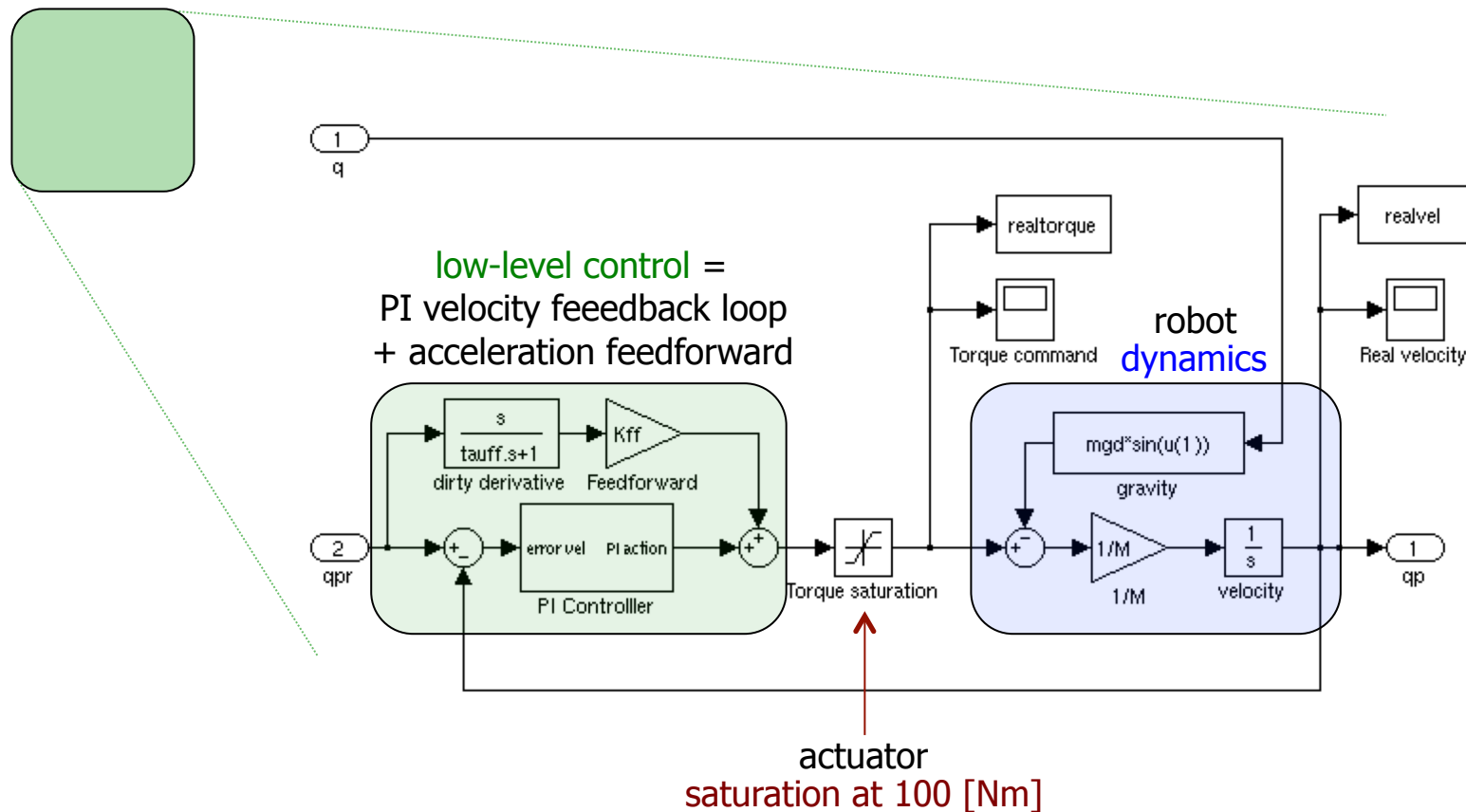




A more detailed example

robot with low-level control

- Simulink scheme

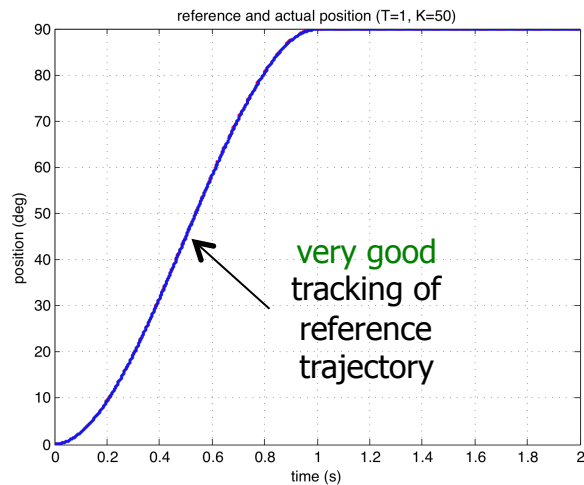




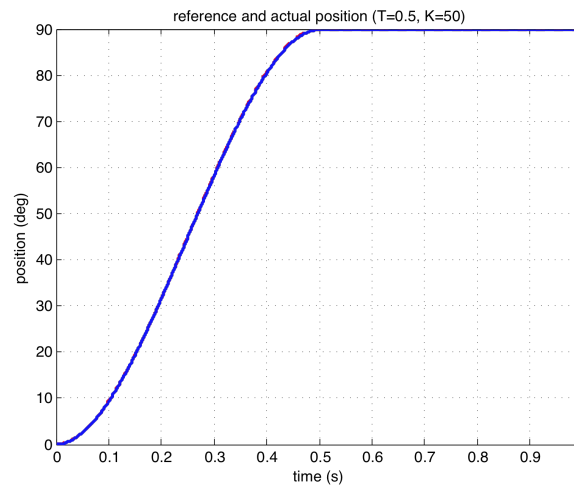
Simulation results

rest-to-rest motion from downward to horizontal position

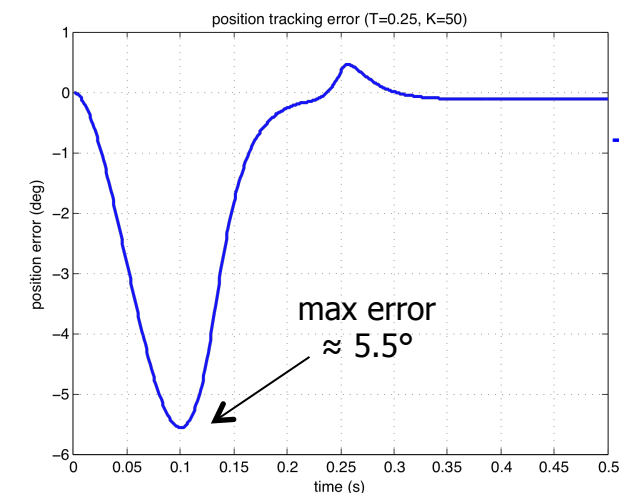
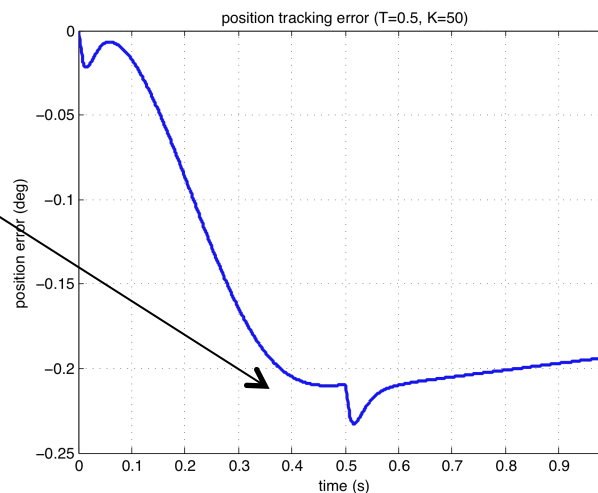
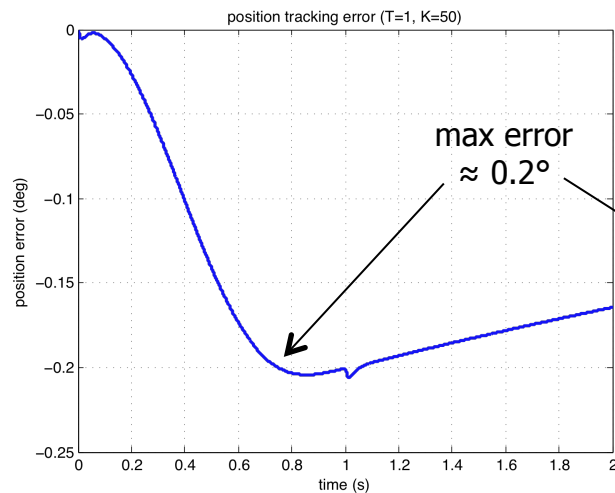
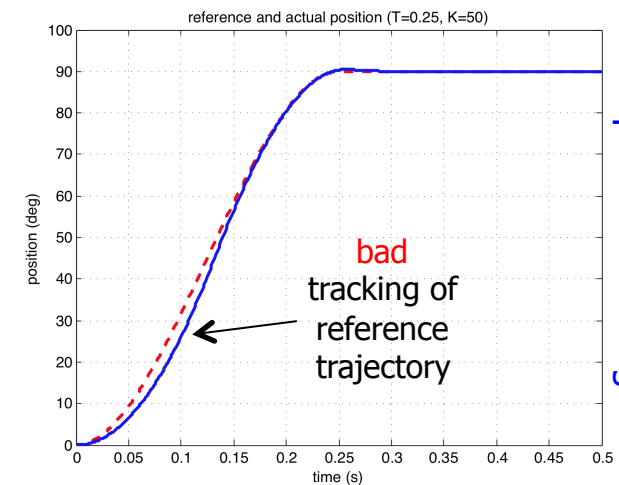
■ in $T = 1$ s



■ in $T = 0.5$ s



■ in $T = 0.25$ s



position tracking

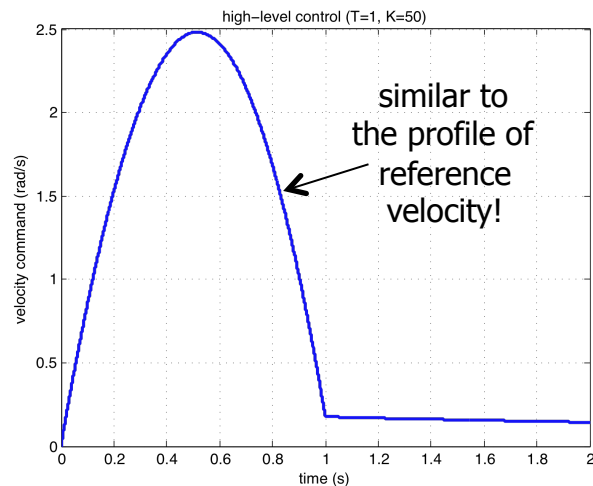
position error



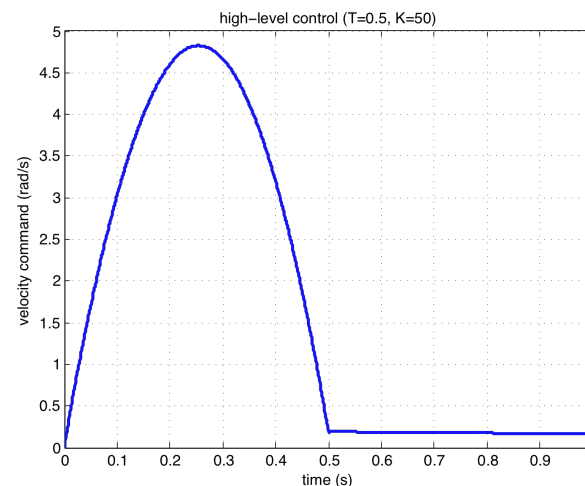
Simulation results

rest-to-rest motion from downward to horizontal position

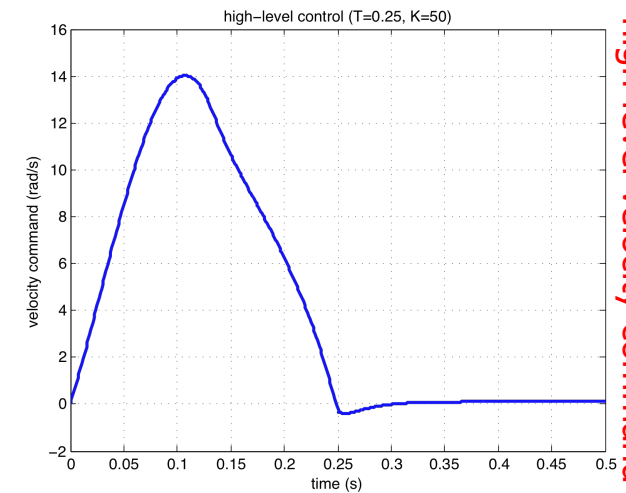
■ in $T = 1$ s



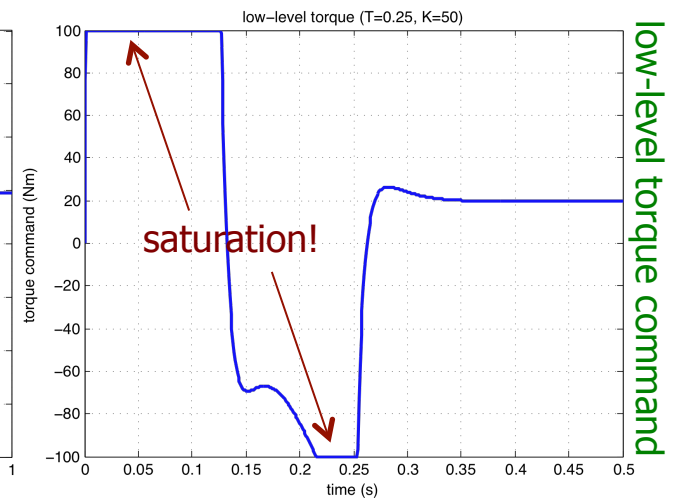
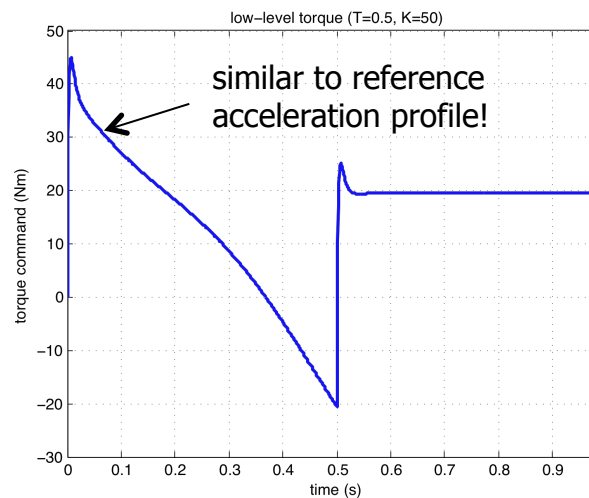
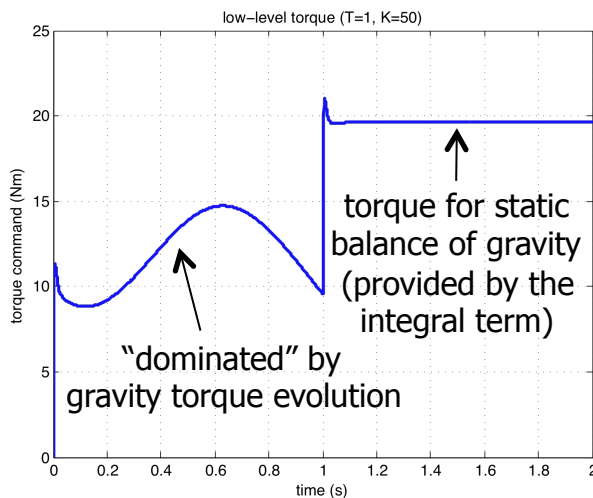
■ in $T = 0.5$ s



■ in $T = 0.25$ s



high-level velocity command



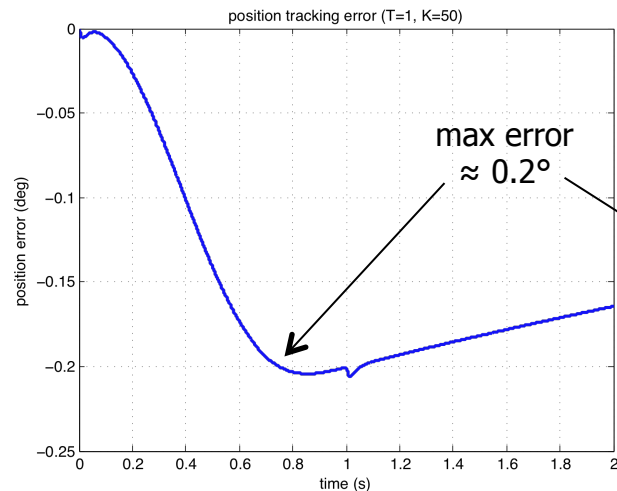
low-level torque command



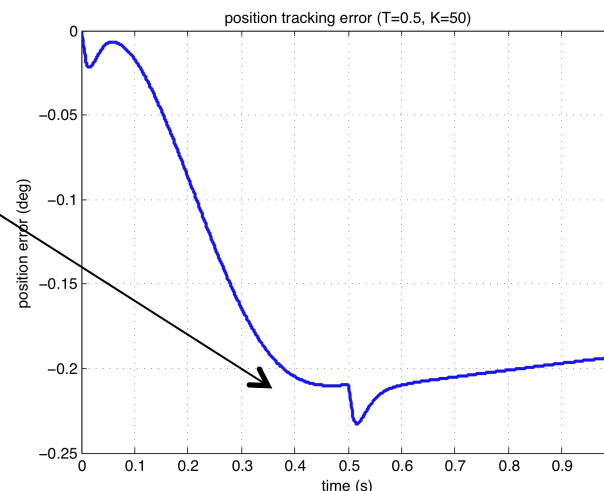
Simulation results

rest-to-rest motion from downward to horizontal position

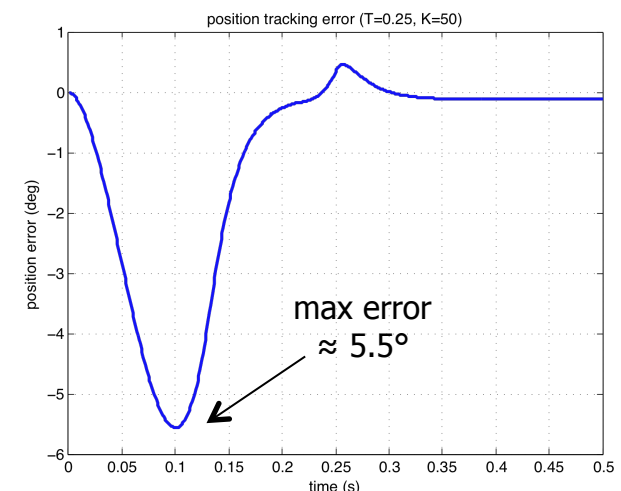
■ in $T = 1$ s



■ in $T = 0.5$ s



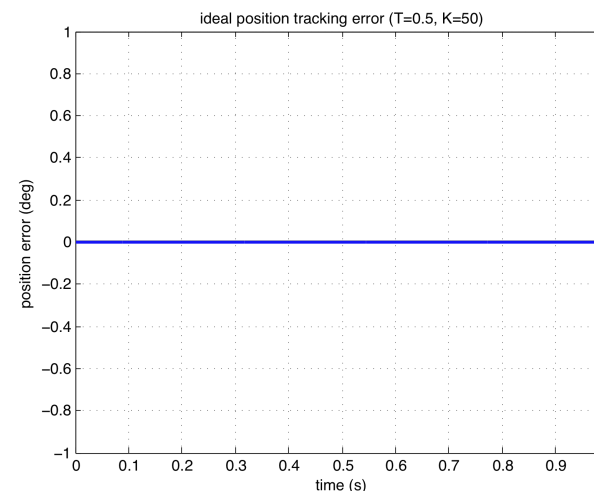
■ in $T = 0.25$ s



real position errors increase when reducing too much motion time
(\Rightarrow too high accelerations)

while **ideal** position errors
(based only on kinematics)
remain always the same!!

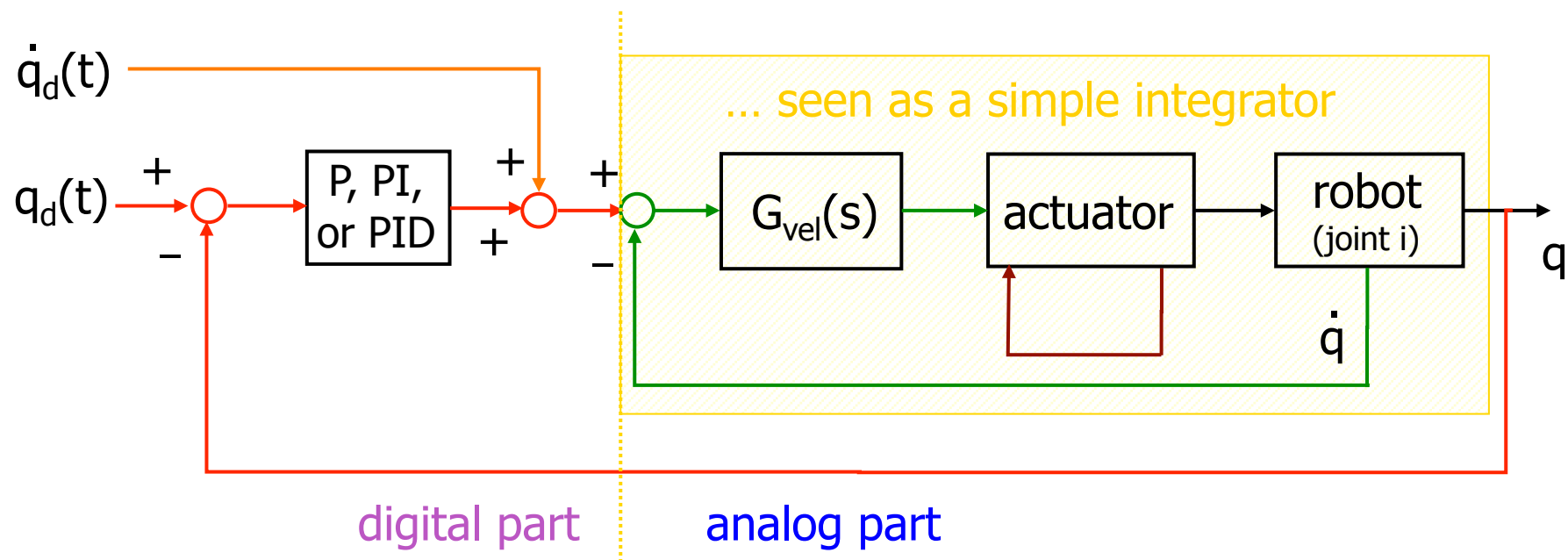
*here, $\equiv 0$ because of the initial matching
between robot and reference trajectory*





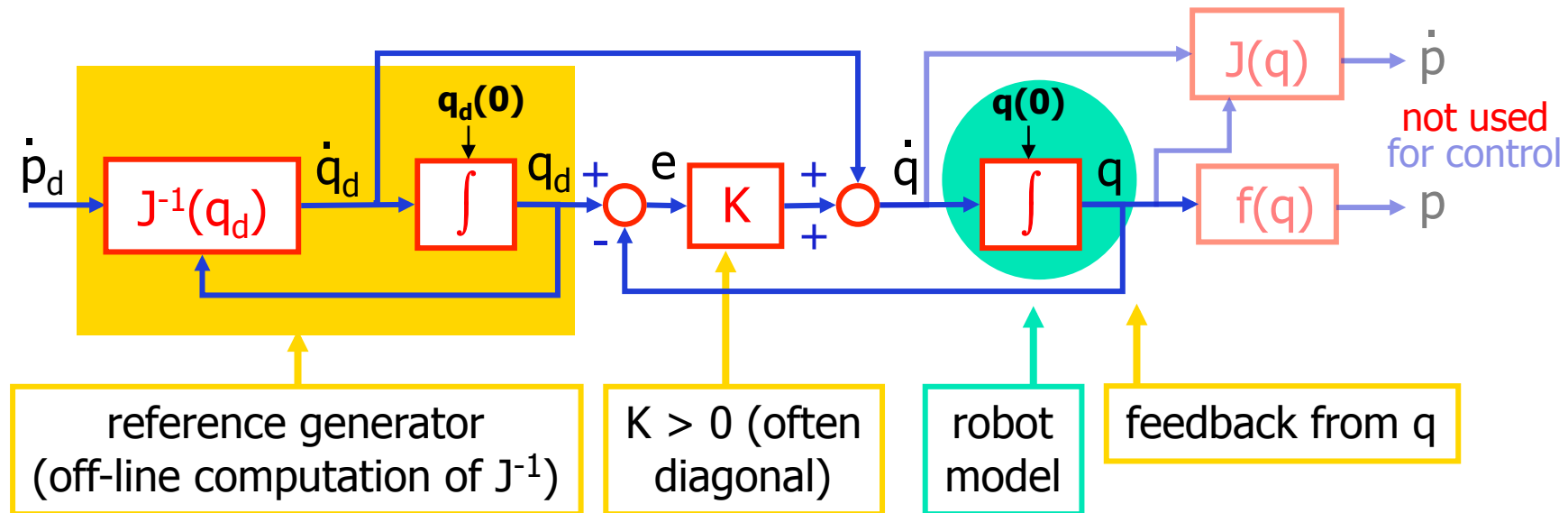
Control loops in industrial robots

- **analog** loop of large bandwidth on motor **current** (∞ torque)
- **analog** loop on **velocity** ($G_{vel}(s)$, typically a PI)
- **digital feedback** loop on **position**, with **velocity feedforward**
- this scheme is local to each joint (**decentralized** control)





Kinematic control of joint motion



$$e = q_d - q \quad \Rightarrow \quad \dot{e} = \dot{q}_d - \dot{q} = \dot{q}_d - (\dot{q}_d + K(q_d - q)) = -K e$$

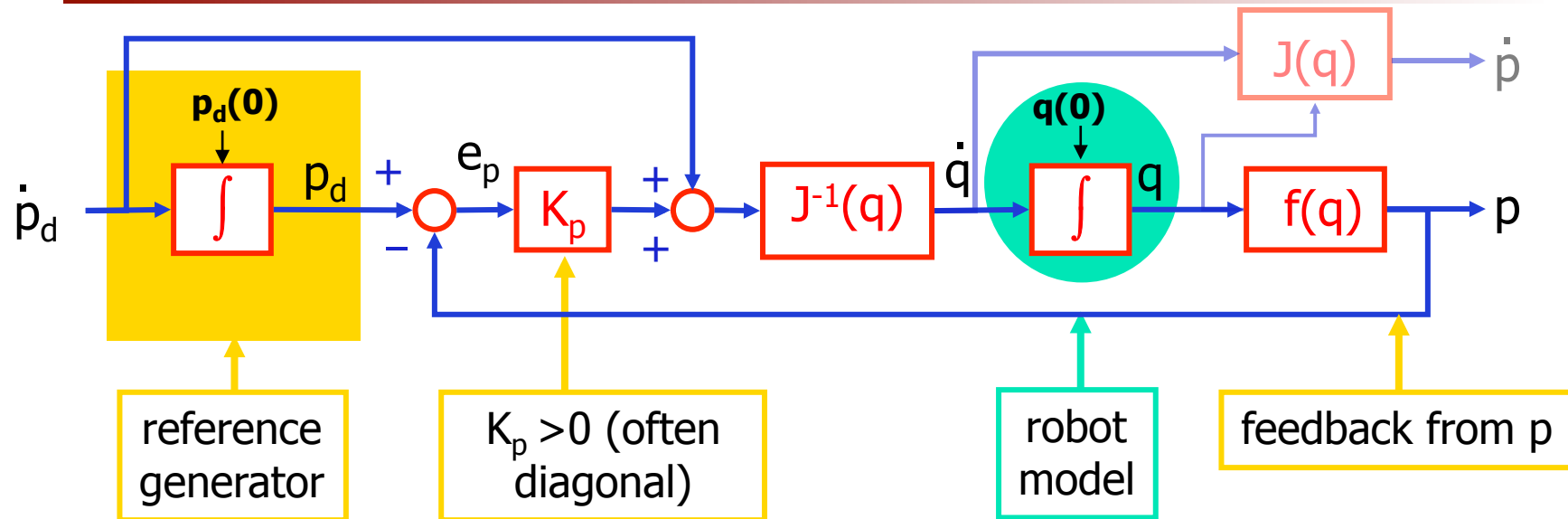
$e_i \rightarrow 0$ ($i=1, \dots, n$)
exponentially,
 $\forall e(0)$

$$e_p = p_d - p \quad \Rightarrow \quad \dot{e}_p = \dot{p}_d - \dot{p} = J(q_d)\dot{q}_d - J(q)(\dot{q}_d + K(q_d - q))$$

$$\begin{matrix} q \rightarrow q_d \\ e_p \rightarrow J(q)e \end{matrix} \quad \Rightarrow \quad \dot{e}_p \approx -J(q)K J^{-1}(q) e_p$$



Kinematic control of Cartesian motion



$$e_p = p_d - p \quad \rightarrow \quad \dot{e}_p = \dot{p}_d - \dot{p} = \dot{p}_d - J(q) J^{-1}(q) (\dot{p}_d + K_p(p_d - p)) = -K_p e_p$$

- $e_{p,i} \rightarrow 0$ ($i=1, \dots, m$) exponentially, $\forall e_p(0)$
- needs on-line computation of the inverse^(*) $J^{-1}(q)$
- real-time + singularities issues

(*) or pseudoinverse if $m < n$

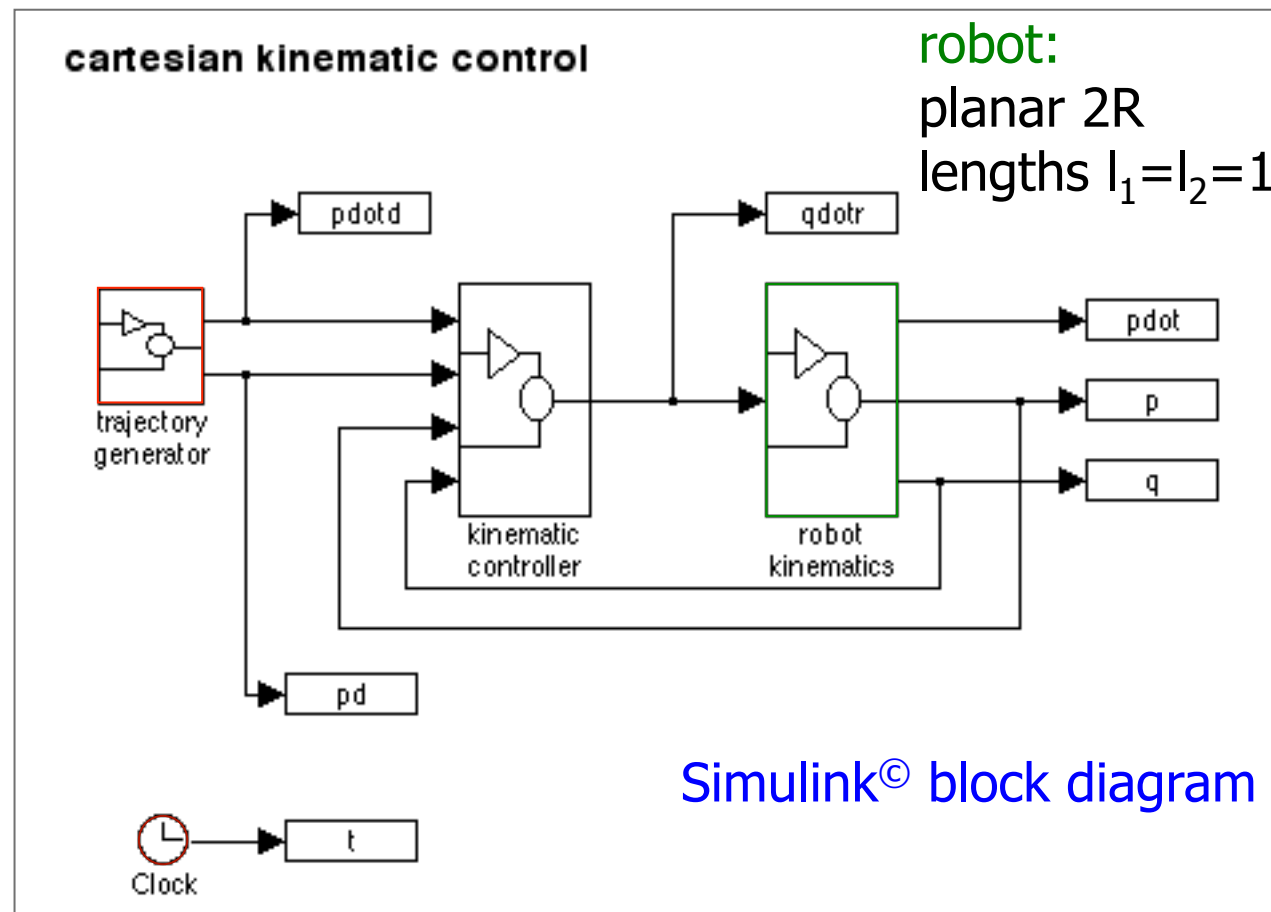


Simulation

features of kinematic control laws

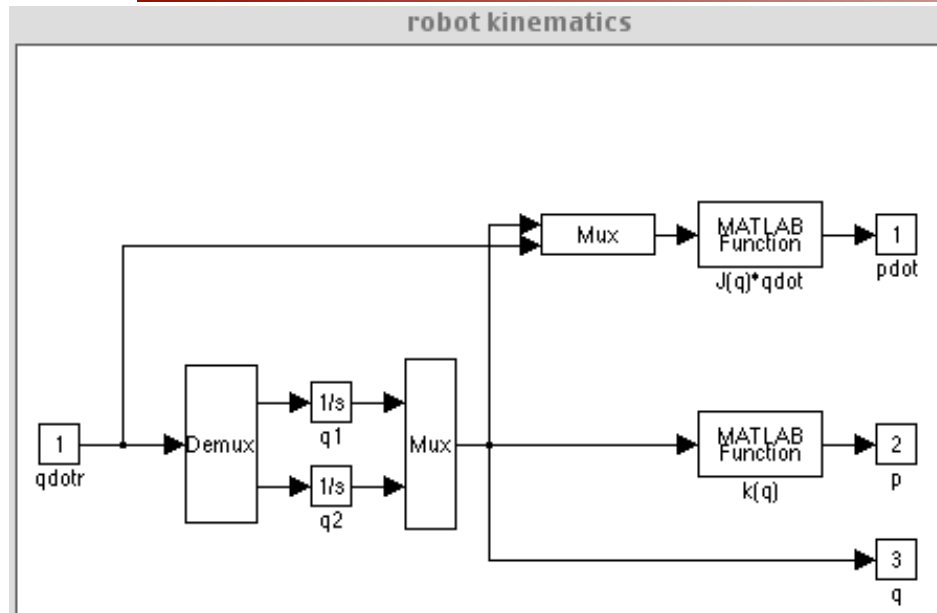
desired reference trajectory:
two types of tasks
1. straight line
2. circular path
both with constant speed

numerical integration method:
fixed step
Runge-Kutta
at 1 msec





Simulink blocks



calls to Matlab functions

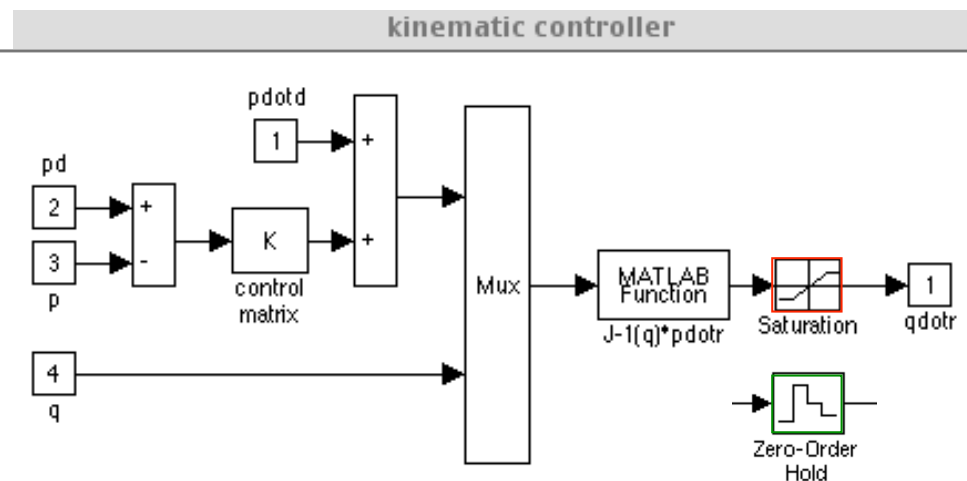
$$k(q) = \text{dirkin (user)}$$

$$J(q) = \text{jac (user)}$$

$$J^{-1}(q) = \text{inv(jac) (library)}$$

- a **saturation** (for task 1.)
or a **sample and hold** (for task 2.)
added on joint velocity commands
- **system initialization** of kinematics data, desired trajectory, initial state, and control parameters (in **init.m** file)

never put "numbers" inside the blocks !





Matlab functions

dirkin.m

```
function [p] = dirkin(q)

global l1 l2

px=l1*cos(q(1))+l2*cos(q(1)+q(2));
py=l1*sin(q(1))+l2*sin(q(1)+q(2));
```

jac.m

```
function [J] = jac(q)

global l1 l2

J(1,1)=- l1*sin(q(1))- l2*sin(q(1)+q(2))
J(1,2)=- l2*sin(q(1)+q(2));
J(2,1)=l1*cos(q(1))+l2*cos(q(1)+q(2));
J(2,2)=l2*cos(q(1)+q(2));
```

init.m

```
% controllo cartesiano di un robot 2R
% initialization

clear all; close all
global l1 l2

% lunghezze bracci robot 2R

l1=1; l2=1;

% velocità cartesiana desiderata (costante)

vxd=0; vyd=0.5;

% tempo totale

T=2;

% configurazione desiderata iniziale

q1d0=-45*pi/180; q2d0=135*pi/180;

pd0=dirkin([q1d0 q2d0]');
pxd0=pd0(1); pyd0=pd0(2);

% configurazione attuale del robot

q10=-45*pi/180; q20=90*pi/180;

p0=dirkin([q10 q20]');

% matrice dei guadagni cartesiani

K=[20 20]; K=diag(K);

% saturazioni di velocità ai giunti (input in deg/sec, convertito in rad/sec)

vmax1=120*pi/180; vmax2=90*pi/180;
```

init.m
script
(for task 1.)



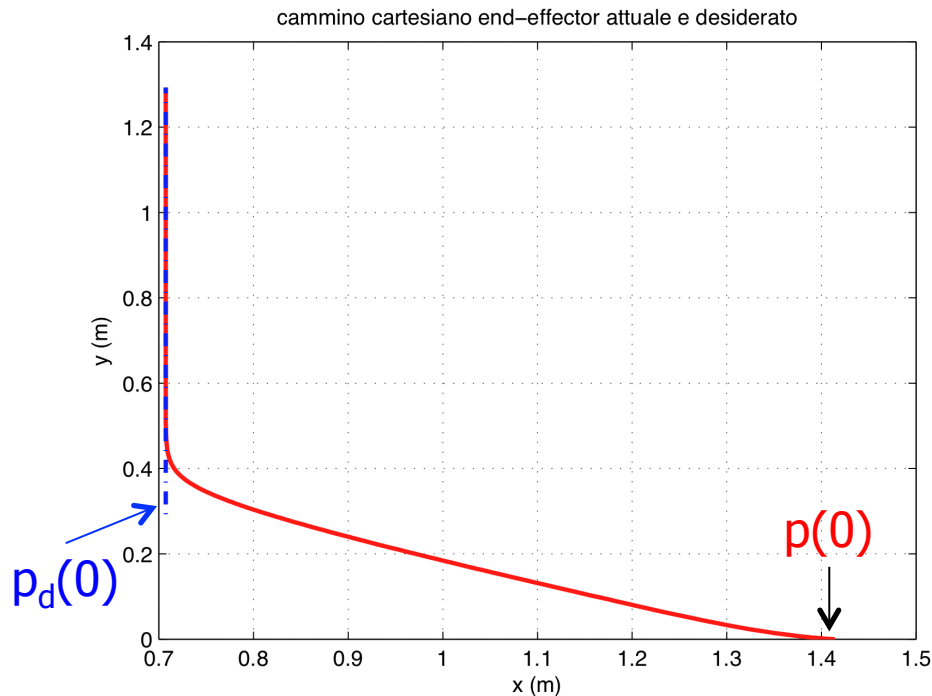
Simulation data for task 1

- **straight line** path with constant velocity
 - $x_d(0) = 0.7 \text{ m}$, $y_d(0) = 0.3 \text{ m}$; $v_{y,d} = 0.5 \text{ m/s}$, for $T = 2 \text{ s}$
- large initial error on end-effector position
 - $q(0) = [-45^\circ \ 90^\circ]^T \Rightarrow e_p(0) = [-0.7 \ 0.3]^T \text{ m}$
- control gains
 - $K = \text{diag}\{20,20\}$
- (a) **without** joint velocity command saturation
- (b) **with** saturation ...
 - $v_{\max,1} = 120^\circ/\text{s}$, $v_{\max,2} = 90^\circ/\text{s}$

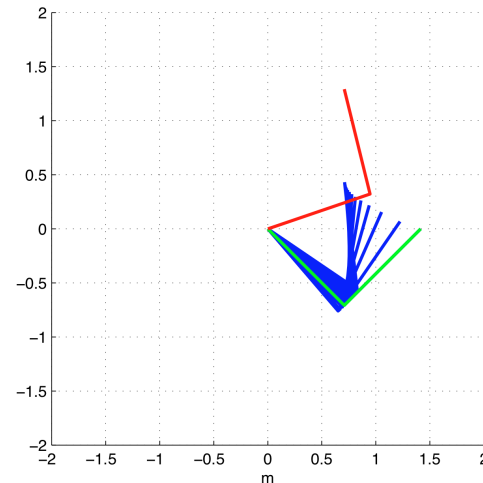


Results for task 1a

straight line: initial error, **no** saturation

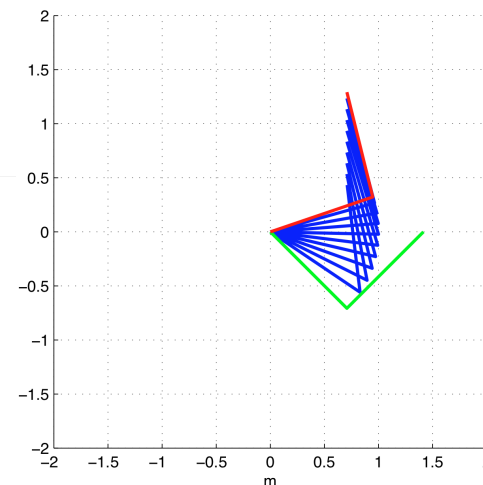


path executed by the robot end-effector
(**actual** and **desired**)



initial transient phase
(about 0.2 s)

stroboscopic view of motion
(**start** and **end** configurations)

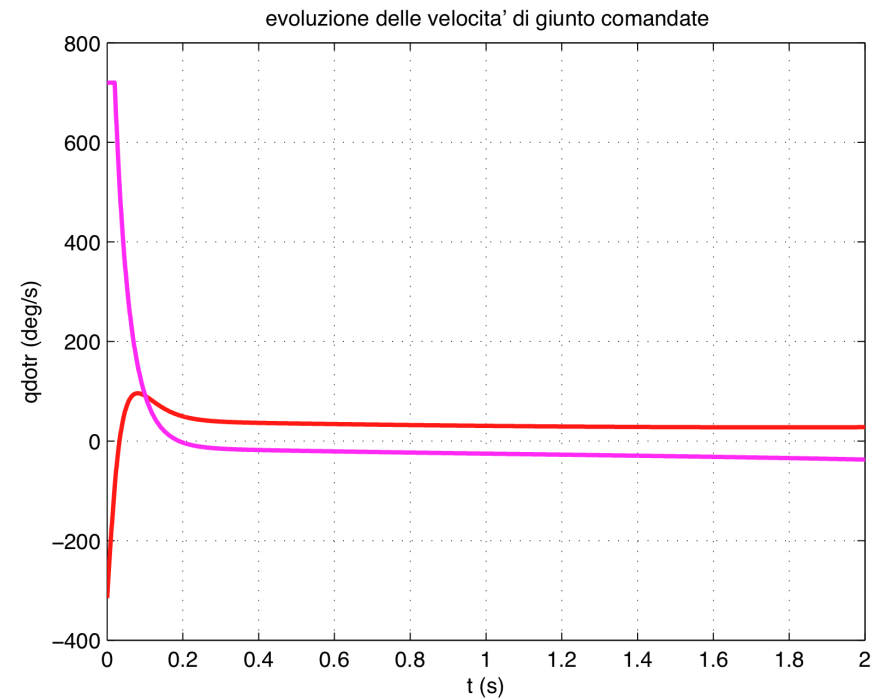
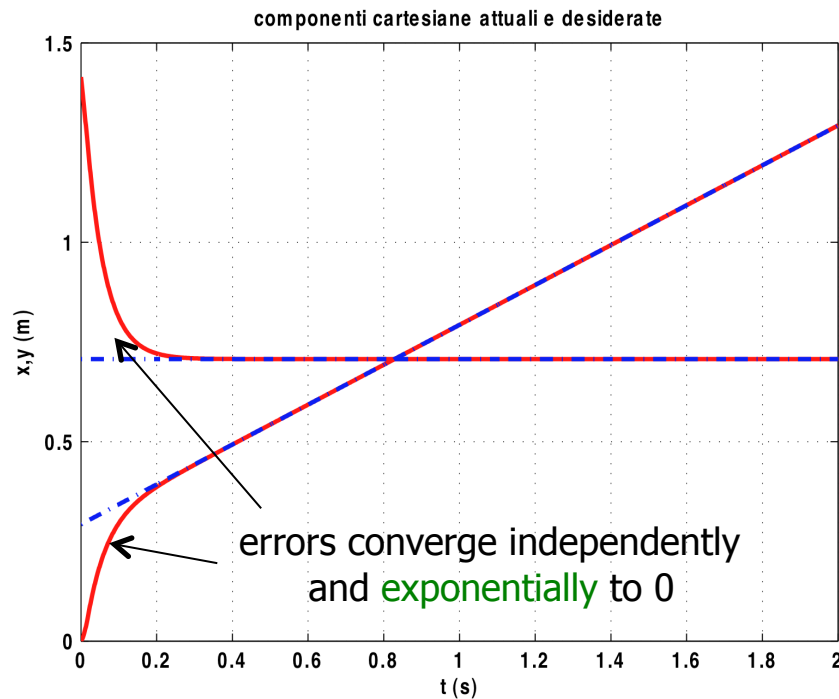


trajectory following phase
(about 1.8 s)



Results for task 1a (cont)

straight line: initial error, **no** saturation



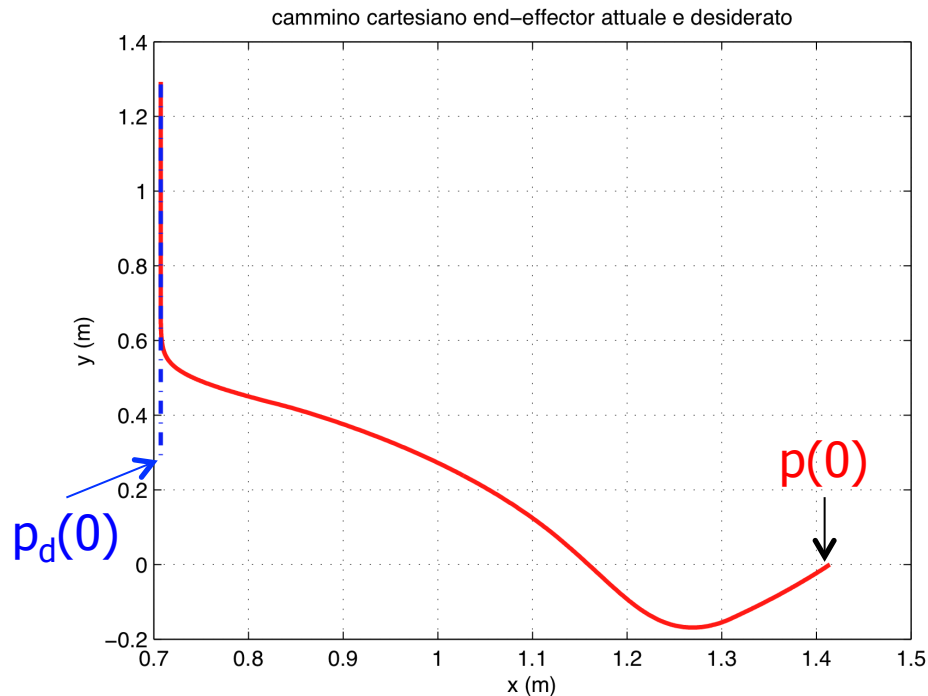
p_x, p_y actual and desired

control inputs \dot{q}_{r1} , \dot{q}_{r2}

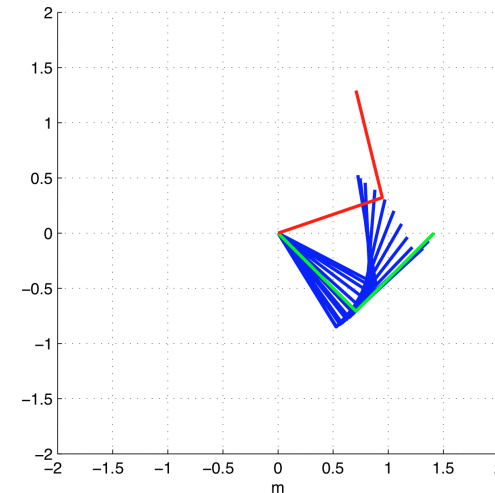


Results for task 1b

straight line: initial error, **with** saturation

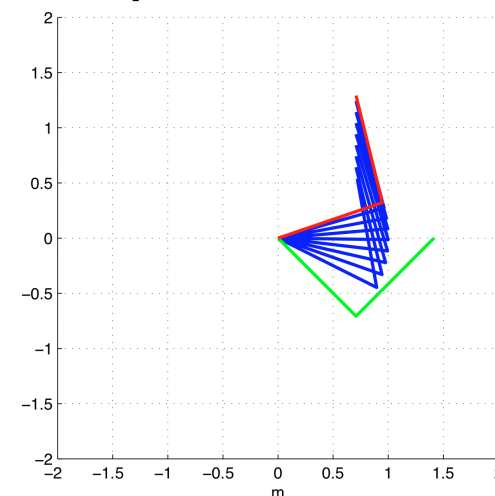


path executed by the robot end-effector
(**actual** and **desired**)



initial
transient
phase
(about 0.5 s)

stroboscopic view of motion
(**start** and **end** configurations)

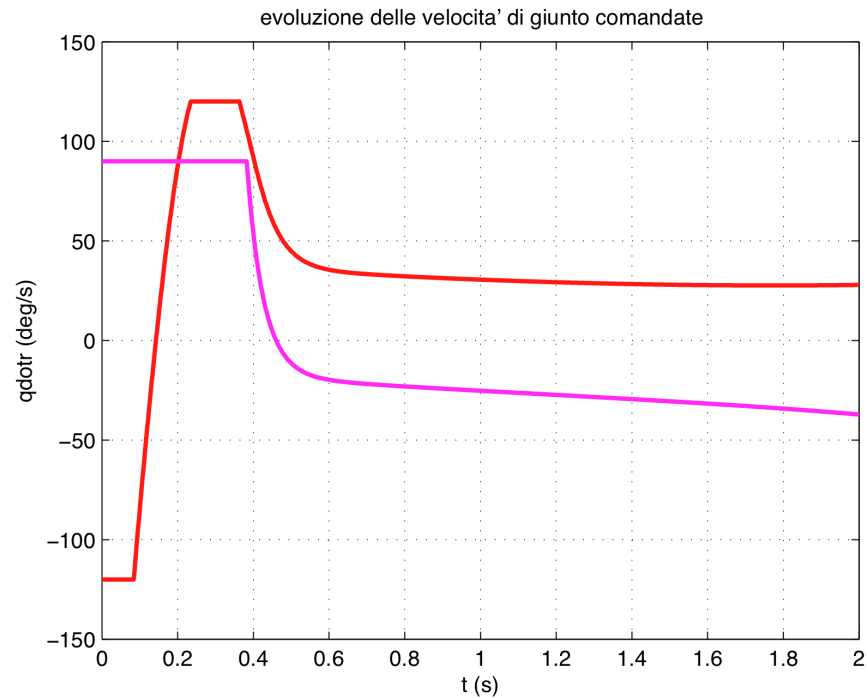
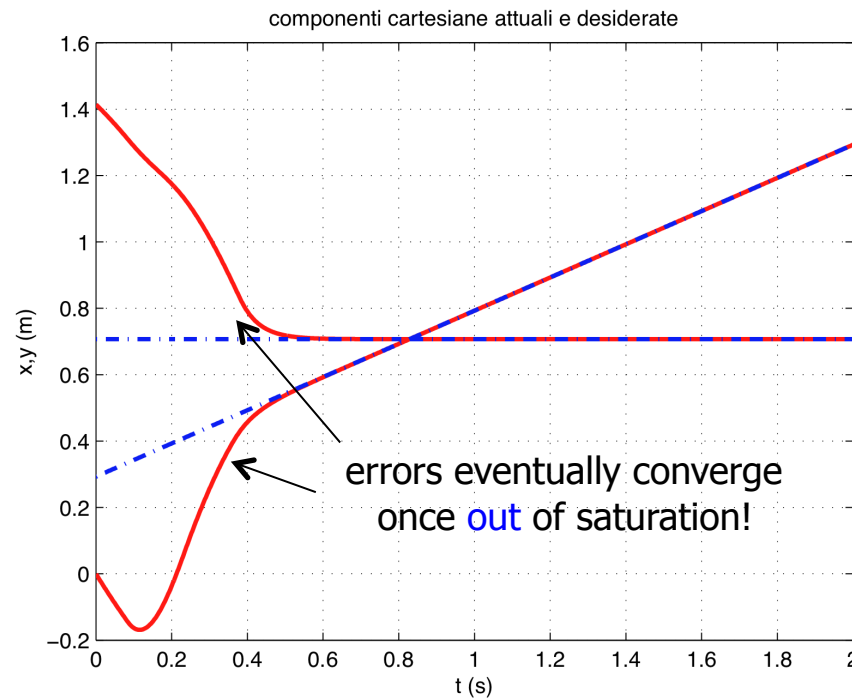


trajectory
following
phase
(about 1.5 s)



Results for task 1b (cont)

straight line: initial error, **with** saturation



p_x , p_y **actual** and **desired**

control inputs \dot{q}_{r1} , \dot{q}_{r2}
(saturated at $\pm v_{max,1}$, $\pm v_{max,2}$)



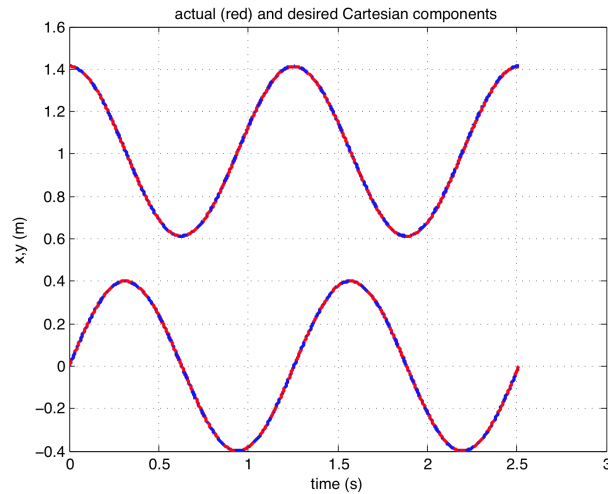
Simulation data for task 2

- **circular** path with constant velocity
 - centered at $(1.014, 0)$ with radius $R = 0.4$ m;
 - $v = 2$ m/s, performing **two** rounds $\Rightarrow T \approx 2.5$ s
- **zero initial error** on Cartesian position (“match”)
 - $q(0) = [-45^\circ \ 90^\circ]^T \Rightarrow e_p(0) = 0$
- (a) ideal **continuous** case (**1 kHz**), even **without** feedback
- (b) **with** sample and hold (ZOH) of $T_{\text{hold}} = 0.02$ s (joint velocity command updated at **50 Hz**), but **without** feedback
- (c) as before, but **with** Cartesian feedback using the gains
 - $K = \text{diag}\{25, 25\}$

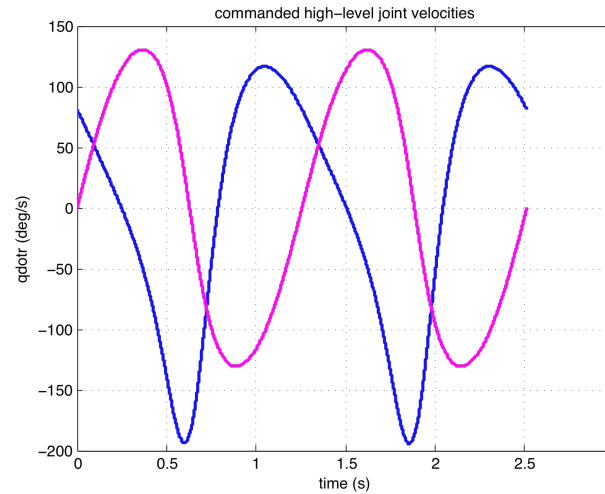


Results for task 2a

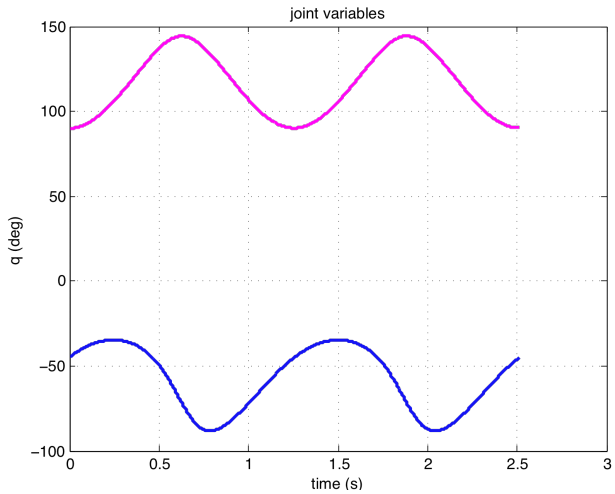
circular path: no initial error, **continuous** control (ideal case)



p_x, p_y **actual** and **desired**

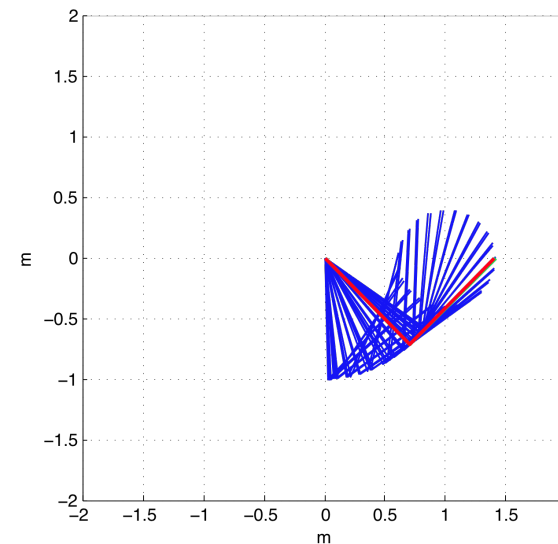
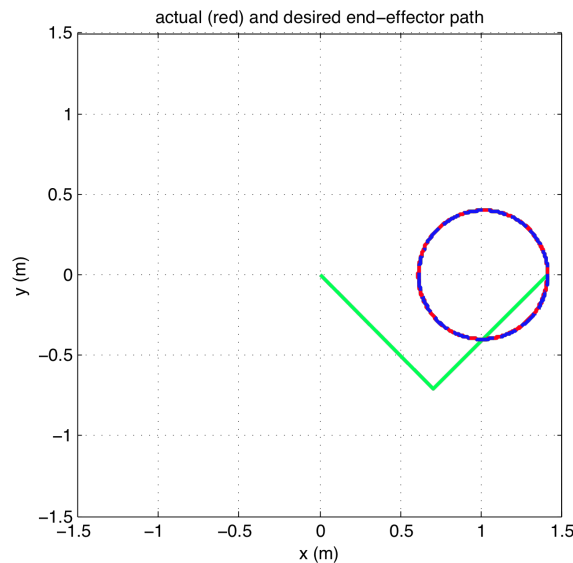


control inputs $\dot{q}_{r1}, \dot{q}_{r2}$



joint variables q_1, q_2

zero tracking error is kept at all times

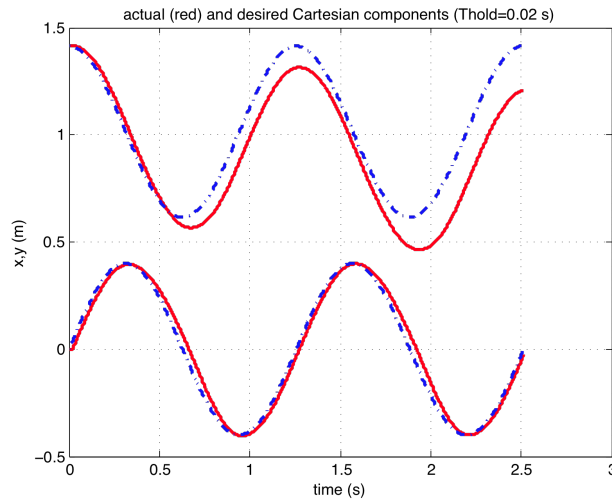


final configuration (after two rounds) **coincides** with **initial** configuration

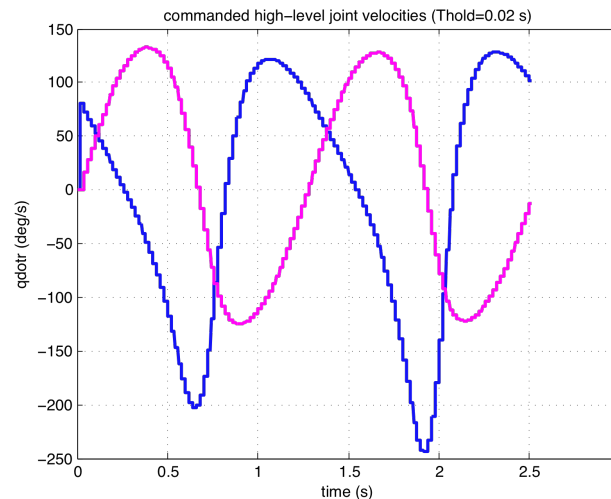


Results for task 2b

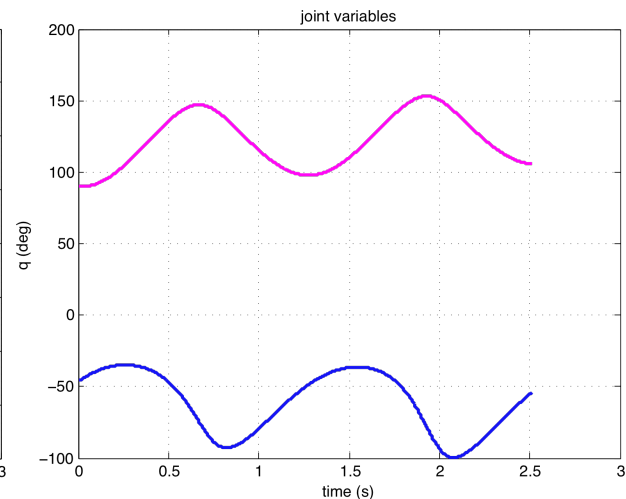
circular path: no initial error, **ZOH** at 50 Hz, **no** feedback



p_x, p_y **actual** and **desired**

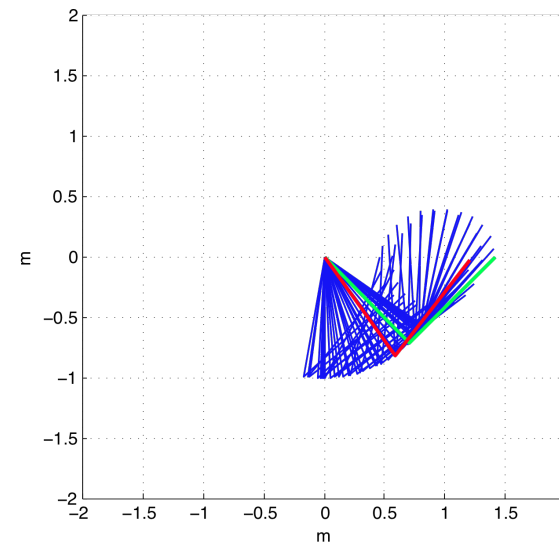
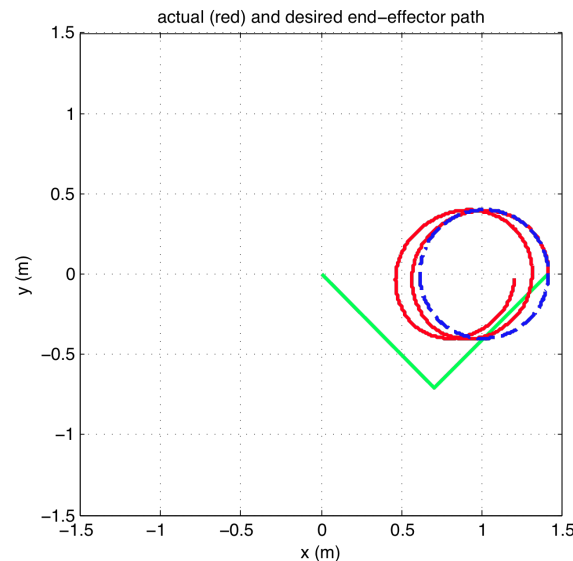


control inputs $\dot{q}_{r1}, \dot{q}_{r2}$



joint variables q_1, q_2

a **drift** occurs along the path due to the "linearization **error**" along the path tangent

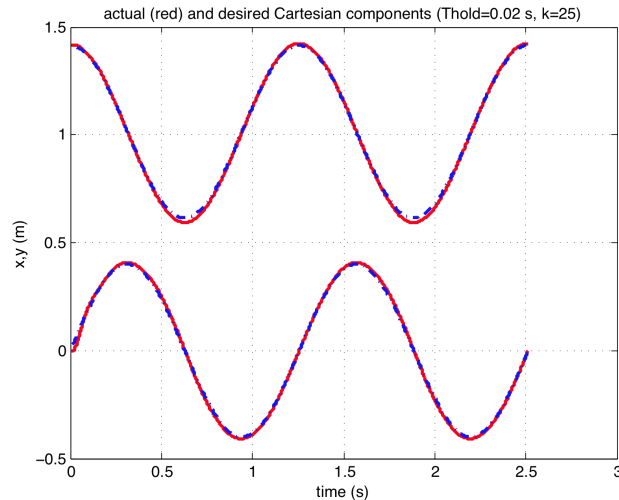


final configuration (after **two** rounds) differs from **initial** configuration

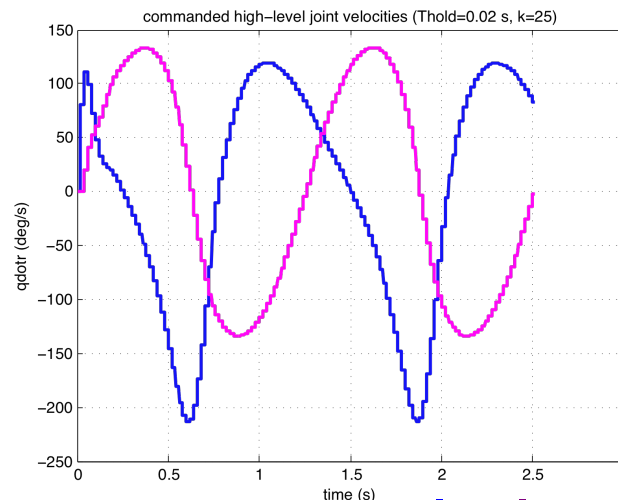


Results for task 2c

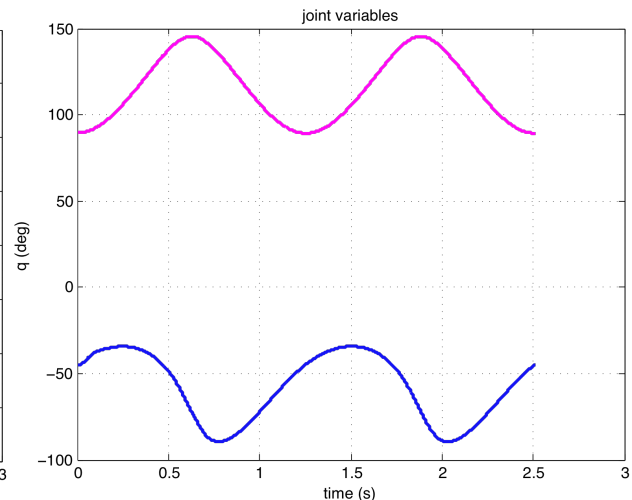
circular path: no initial error, **ZOH** at 50 Hz, **with** feedback



p_x, p_y **actual** and **desired**

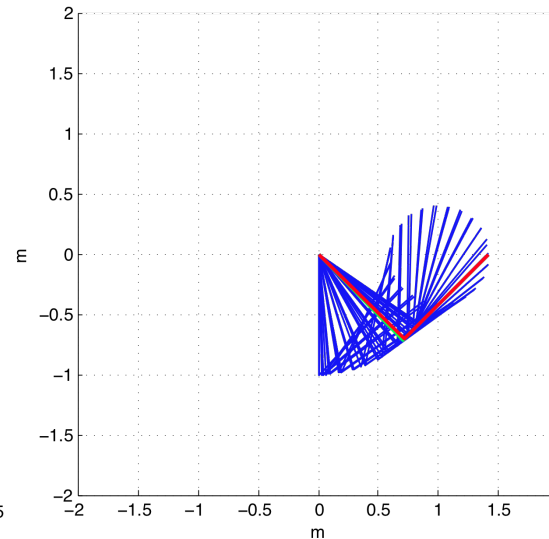
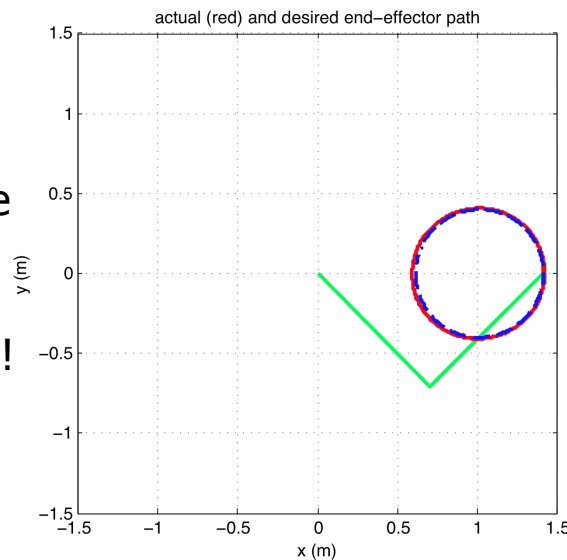


control inputs $\dot{q}_{r1}, \dot{q}_{r2}$



joint variables q_1, q_2

(almost) the same performance of the continuous case is recovered!!

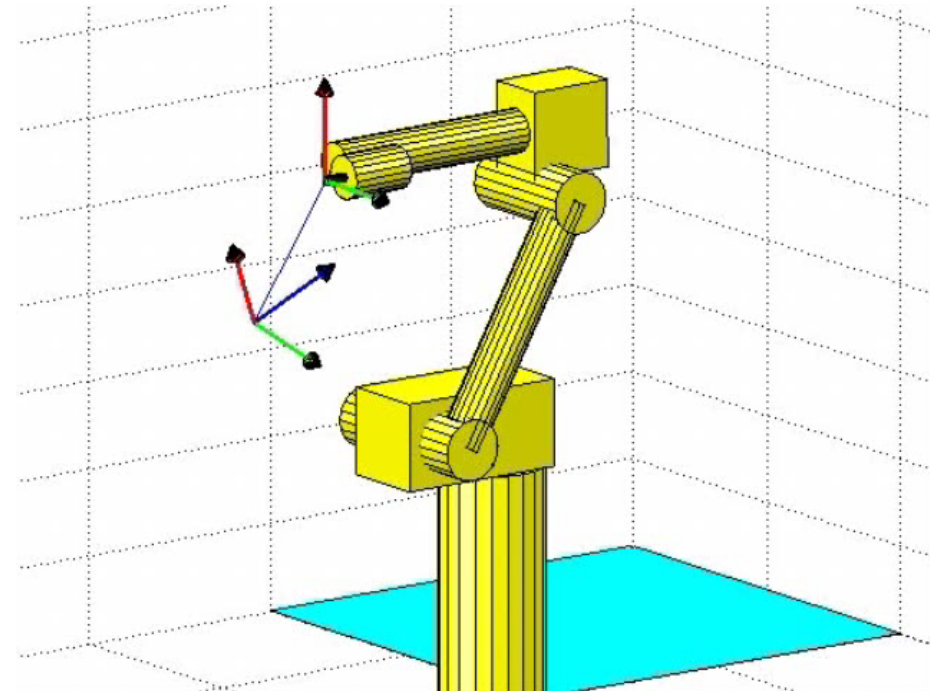
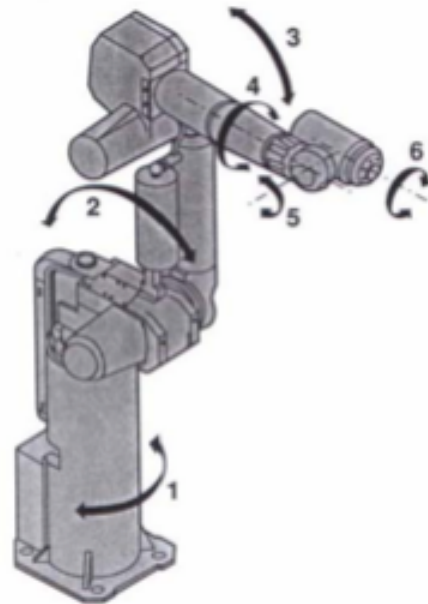


note however that **larger P** gains will eventually lead to **unstable** behavior (see: stability problems for discrete-time control systems)



3D simulation

video



kinematic control of Cartesian motion of Fanuc 6R (Arc Mate S-5) robot
simulation and visualization in Matlab

Kinematic control of KUKA LWR



video



Discrete-Time Redundancy Resolution
at the Velocity Level with Acceleration/Torque
Optimization Properties

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September 2014

kinematic control of Cartesian motion with redundancy exploitation
velocity vs. acceleration level