Automation and Robotics Lab.

Μια προσπαθεια για την επιτευξη ανθρωπινης επιδοσης σε ρομποτικές εργασίες με νέες μεθόδους ελέγχου

Towards Achieving Human like Robotic Tasks via Novel Control Methods

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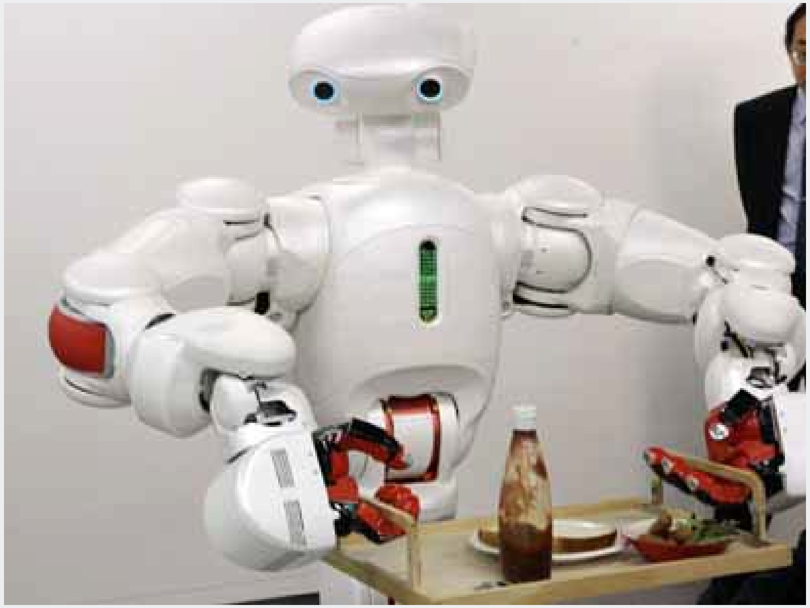
Current Trends in Robotic System Development

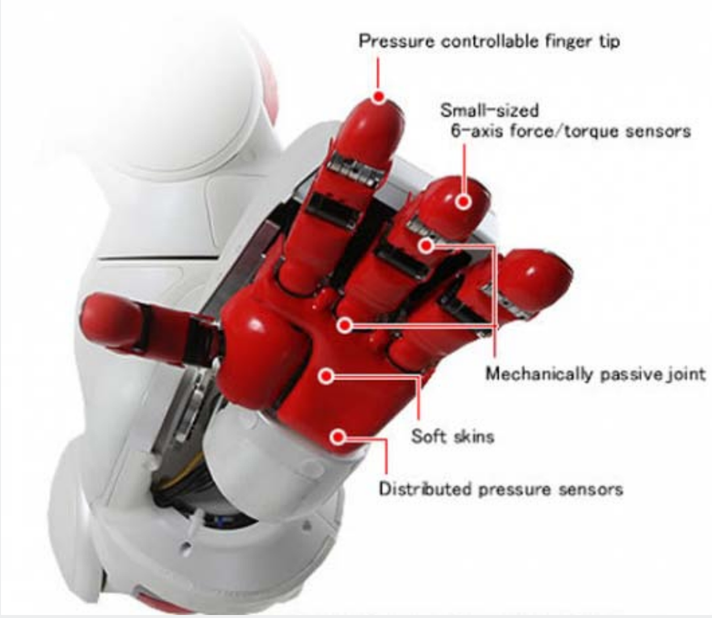
Robotics Research Goal

Build robots to assist humans, navigate around human spaces, deal with human tools, do bimanual manipulation, deal with deformable objects, manipulate objects blindly etc. with human like dexterity.

➡ Implementation of soft components at various levels

- ✓ materials
- ✓ sensing
- ✓ actuation





Soft actuation

Low stiffness ⟷ Low gear ratios / High back drivability

Associated with uncertainties

- Robot Inertias, couplings, nonlinearities
- Load and external force disturbances

➡ adversely affect performance (speed and accuracy)

Associated with increased model complexity ⟷ *increased control complexity*

Variable stiffness actuators — VIA, antagonistic muscles or tendons

Can we guarantee prescribed, time dependant performance bounds in robot motion through simple control algorithms ??

Control objective

Design a simple controller that guarantees Prescribed Performance

In terms of:

- Maximum overshoot
- Minimum speed of convergence
- Maximum steady state error

Irrespective of (not affected by):

- Model uncertainties
- Bounded disturbances

So far robot control solutions guarantee stability and convergence but not prescribed transient performance

- Joint or end-effector position error ? yes
- Contact force error ? yes
- Actuator stiffness? I do not know yet

Prescribed Performance

$$\rho(t) = (\rho_0 - \rho_\infty)e^{-\lambda t} + \rho_\infty$$

Max initial error

$$\rho_0 > |e(0)|$$

- *min speed of convergence*

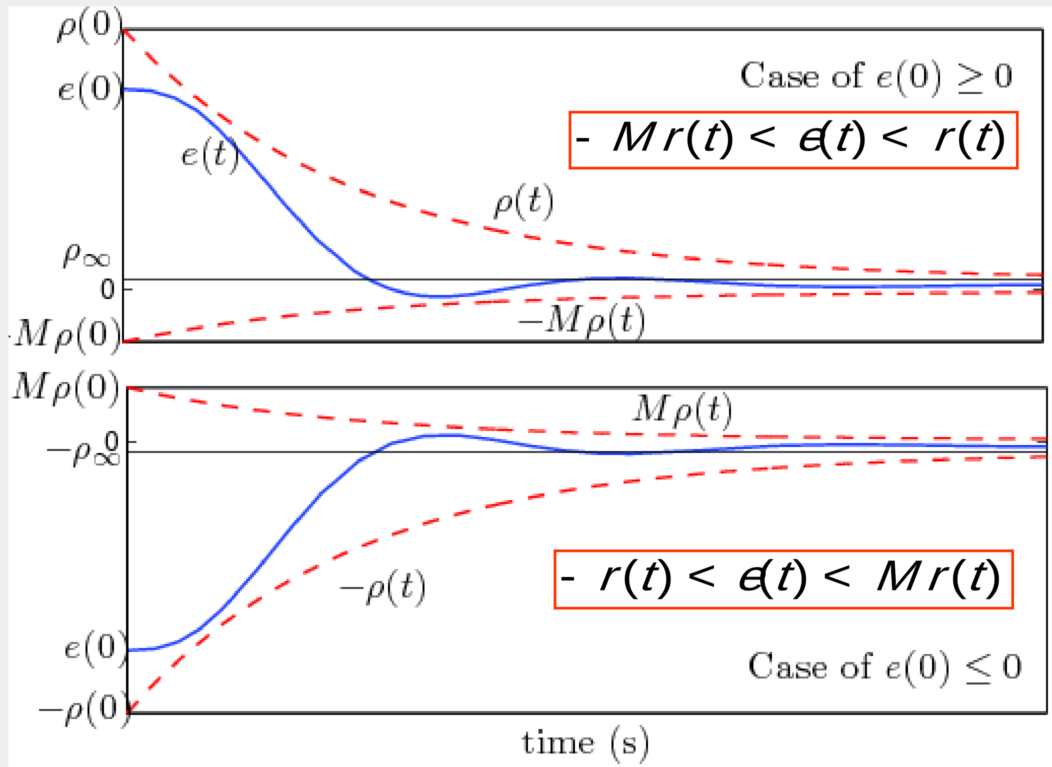
- *max steady state error*

$$\lim_{t \to \infty} \rho(t) = \rho_\infty > 0$$

- *Overshoot* $0 \leq M \leq 1$

- *Performance bound functions*

$$M\rho(t), \rho(t)$$

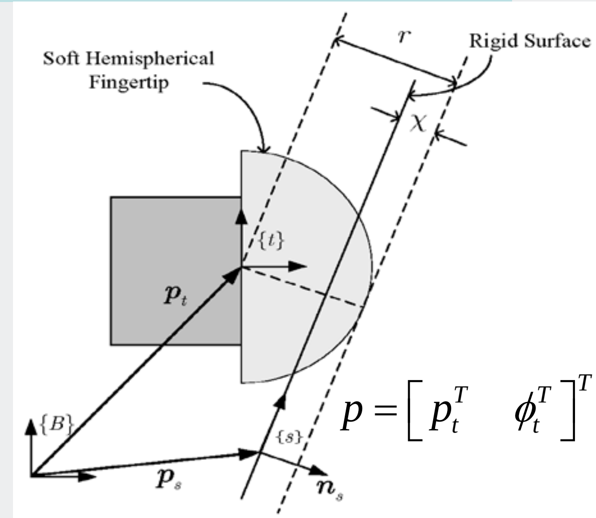


Contact Maintenance

$$e_p = Q(p - p_d)$$

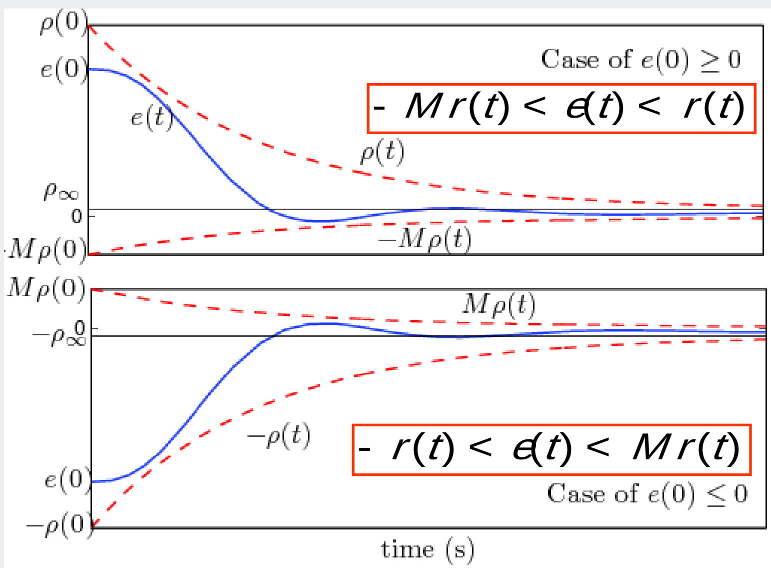
$$e_f = f - f_d$$

$$f = \begin{cases} f(\chi) > 0 & \chi > 0 \\ 0 & \chi = 0 \end{cases}$$



$$r(t) = (r_0 - r_\infty)e^{-\lambda t} + r_\infty$$

$f(t) > 0$ $\quad -M_f \rho_f(t) < f(t) - f_d(t)$



$e_f(0) \geq 0$ $\quad M_f \rho_f(t) < f_d(t)$

$OK \quad for \quad M_f = 0$

$e_f(0) \leq 0$ $\quad -\rho_f(t) < f(t) - f_d(t)$

$$\rho_f(t) < f_d(t)$$

Basic Idea: Error Transformation

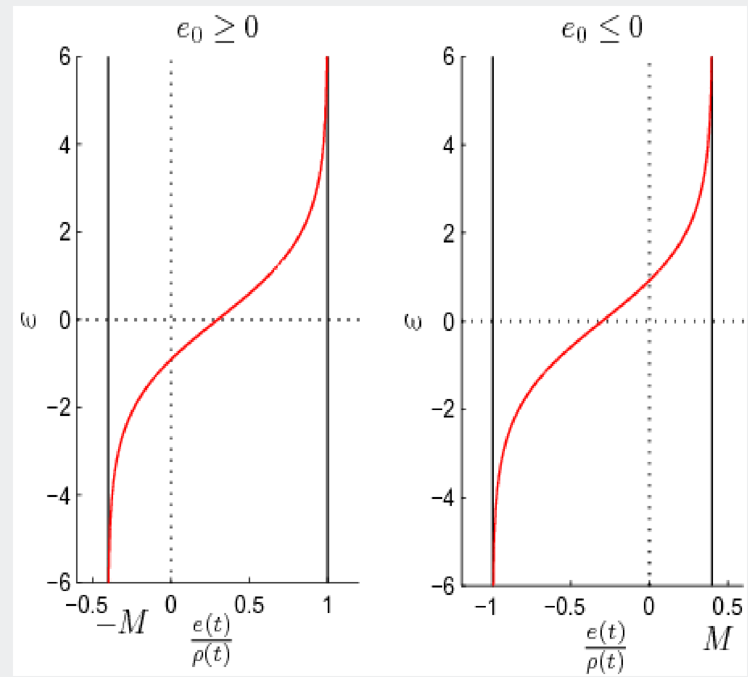
Modulate the position error using the performance function $\dfrac{e(t)}{r(t)}$

Define a bijective map of the performance region:

$(-M,1)$ or $(-1,M)$ to $(-\infty,\infty)$

$$e(t) = T\left(\frac{e(t)}{r(t)}\right)$$

$$-M < \frac{e(t)}{r(t)} < 1 \qquad -1 < \frac{e(t)}{r(t)} < M$$



$$T_a\left(\frac{e}{r}\right) = \ln\left(\frac{M + \frac{e}{r}}{1 - \frac{e}{r}}\right) \quad \text{in case} \quad e(0) \geq 0$$

$$T_a\left(\frac{e}{r}\right) = \ln\left(\frac{1 + \frac{e}{r}}{M - \frac{e}{r}}\right) \quad \text{in case} \quad e(0) \leq 0$$

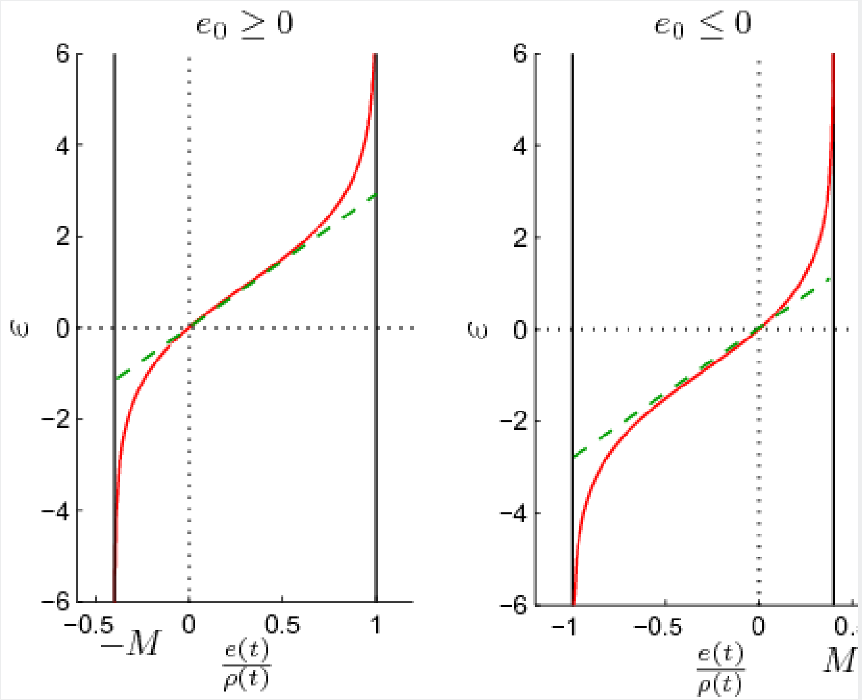
The inverse transformation exists and it is bounded $\left|T^{-1}(e)\right| < 1$

IEEE TAC 2008

- or a shifted transformation such that $T(0) = 0$

$$T_b\left(\frac{e}{\rho}\right) = \ln\left(\frac{M + \frac{e}{\rho}}{M\left(1 - \frac{e}{\rho}\right)}\right) \quad \text{in case } e(0) \geq 0$$

$$T_b\left(\frac{e}{\rho}\right) = \ln\left(\frac{M\left(1 + \frac{e}{\rho}\right)}{M - \frac{e}{\rho}}\right) \quad \text{in case } e(0) \leq 0$$



$$-M < \frac{e(t)}{\rho(t)} < 1 \qquad -1 < \frac{e(t)}{\rho(t)} < M$$

Boundedness of ε(t) achieves PP for e(t).

$$|\varepsilon| > \frac{4}{(M+1)\rho(t)}|e|$$

- in a multi dof system

$$\varepsilon_i(t) = T\left(\frac{e_i(t)}{\rho(t)}\right)$$

$$J_{Ti} \triangleq \frac{\partial T}{\partial(e_i/\rho)}\frac{1}{\rho} > 0$$

$$\varepsilon(t) = \begin{bmatrix}\varepsilon_1 & \ldots & \varepsilon_n\end{bmatrix}^T \quad \Rightarrow \quad \dot{\varepsilon} = J_T(t)\left[\dot{e} + \alpha(t)e\right]$$

$$J_T(t) = diag\begin{bmatrix}J_{T1} & \ldots & J_{Tn}\end{bmatrix}$$

$$\rho(t) = (\rho_0 - \rho_\infty)e^{-\lambda t} + \rho_\infty$$

$$\rho_0 > \max\left(\left|e_i(0)\right|\right)$$

$$\alpha(t) \triangleq -\frac{\dot{\rho}(t)}{\rho(t)}$$

$$0 < \alpha(t) < \lambda$$

$$\lim_{t\to\infty}\alpha(t) = 0$$

Robot Joint Position Regulation

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + C_v\dot{q} + g(q) + F(t) = u(t)$$

$F(t)$ Any bounded model error or disturbance

$q_d = const$

Typical regulator structure: $u = -K_p e - K_v \dot{q} - v$

Positive Definite Diagonal Matrices

Setting: $v = -g(q)$ or $v = -g(q_d)$, $e = q - q_d$ Conventional PD controller

$$v = K_I \int_0^t e(t)dt$$

PID controller with local asymptotic stability

$$v = K_I \int_0^t y_0(t)dt$$

$$y_0 = \dot{q} + a s(e)$$

PID controller with global asymptotic stability

Saturation function

$$U(q) - U(q_d) - e^T g(q_d) \geq -c_g \|e\|^2$$

$$e^T\left(g(q) - g(q_d)\right) \geq -c_g \|e\|^2$$

Prescribed Performance Regulator

TP-PID

$$u = -K_p e - K_v \dot{e} - K_e J_T(t) e(t) - K_I \int_0^t y(t)\,dt$$

TP - term

K_p, K_v, K_e, K_I Diagonal positive definite gain matrices

k_p, k_v, k_e, k_I Minimum diagonal entries

$$y(t) = \dot{e} + k(t) e = J_T(t)^{-1} \dot{\varepsilon}$$

$$k(t) = a(t) + b$$

$$b = 0 \quad in\,case\,of\; T_a\left(\frac{e}{\rho}\right)$$

SYROCO 09

$$b > 0 \quad in\,case\,of\; T_b\left(\frac{e}{\rho}\right)$$

ICRA10

PP Regulation Stability Result

Using TP-PID control law with a choice of gains satisfying

$$k_p > 2c_g$$

$$k_v > (\lambda + \beta)\left(\lambda_H + \rho_0 \sqrt{n} c_0\right) + \frac{\sqrt{2}\lambda_H \lambda}{4}$$

$$\left\| C(q,\alpha)\beta \right\| \leq c_0 \left\| \alpha \right\| \left\| \beta \right\|$$

$$\lambda_H = \max_q \left\{ \lambda_M \left(H(q) \right) \right\}$$

It is proved that

(a) all signal in the closed loop are bounded

(b) Position error remains in the performance region at all times without even approaching its boundary, hence prescribed performance is guaranteed

$$-M\rho(t) < e(t) < \rho(t)$$

$$-\rho(t) < e(t) < M\rho(t)$$

(c) the joint velocity asymptotically converge to zero $\dot{q} \to 0$

(d) the error asymptotically converge to zero $e \to 0$

Provided transformation $T_b(.)$ is used in all joints and disturbance F is constant

Remarks on Prescribed Performance Regulator

TP-PID

$$u = -K_p e - K_v \dot{q} - K_e J_T(t)\varepsilon(t) - K_I \int_0^t y(t)\,dt$$

Structure — Simple PID-type regulator with minimum robot information required to satisfy theorem conditions

Gain tuning — Significantly simplified as it is not related to performance
Choose values that lead to reasonable input torques

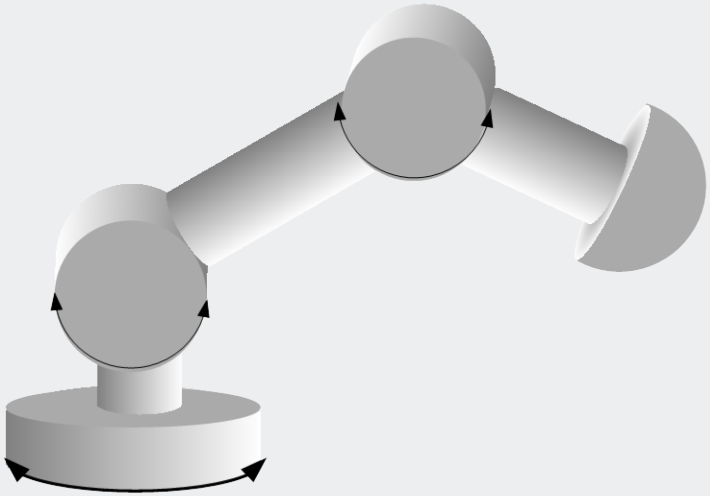
TP - term — Is responsible for the prescribed performance stability result

I - term — Compensates for any bounded constant disturbance and hence Is responsible for the asymptotic convergence of the joint velocity and error to zero

Omitting the I - term — Prescribed performance of joint error is guaranteed as well as the uub of joint velocity

Omitting the K_p- term — Possible when using the shifted transformation T_b , replacing the lower bound of K_p with a K_ε lower bound.

Simulation Example



masses $m_1 = 0.5\ \mathrm{kg}, m_2 = m_3 = 1\ \mathrm{kg}$

lengths $l_2 = 0.3\ \mathrm{m}, l_3 = 0.2\ \mathrm{m}$

Inertias
$$\begin{cases} I_{z1} = I_{z2} = I_{z3} = 6.25\,10^{-4}\ \mathrm{kgm}^2 \\ I_{x2} = I_{x3} = I_{y2} = I_{y3} = 0.081\ \mathrm{kgm}^2 \end{cases}$$

Initial joint positions $q(0) = [0\ \ 30\ \ 10]^T\ \mathrm{deg}$

PID Simulation Results – Regulation task

Set-point

$$q_d = [\,30\ \ 60\ \ 40\,]^T \deg$$

$$q(0) = [0\ 30\ 10]^T \deg$$

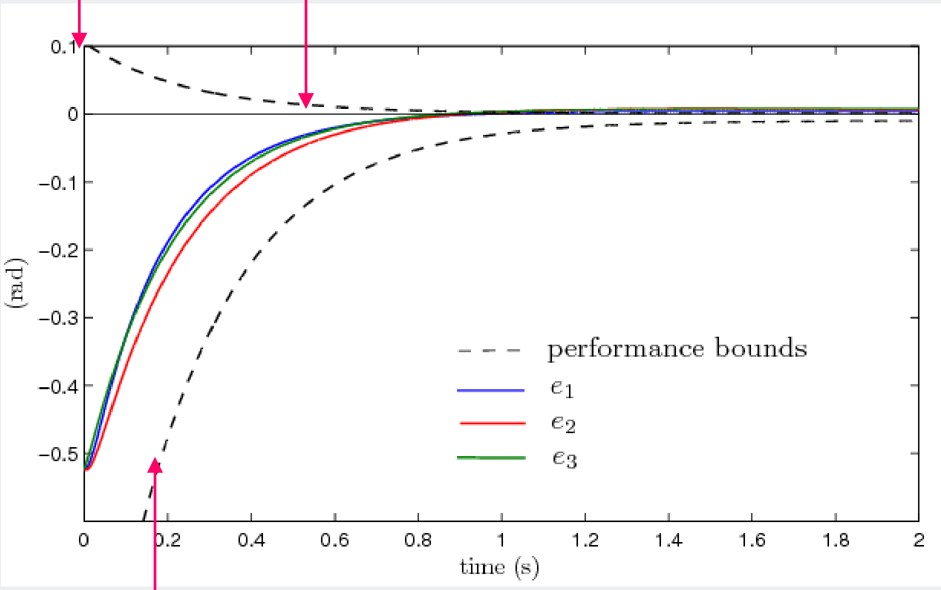
PID gains

$$K_p = 50I_3$$

$$K_v = 5I_3, K_I = \mathrm{diag}[2, 20, 2]$$

Overshoot Index

$M = 0.1$ $M = 0$



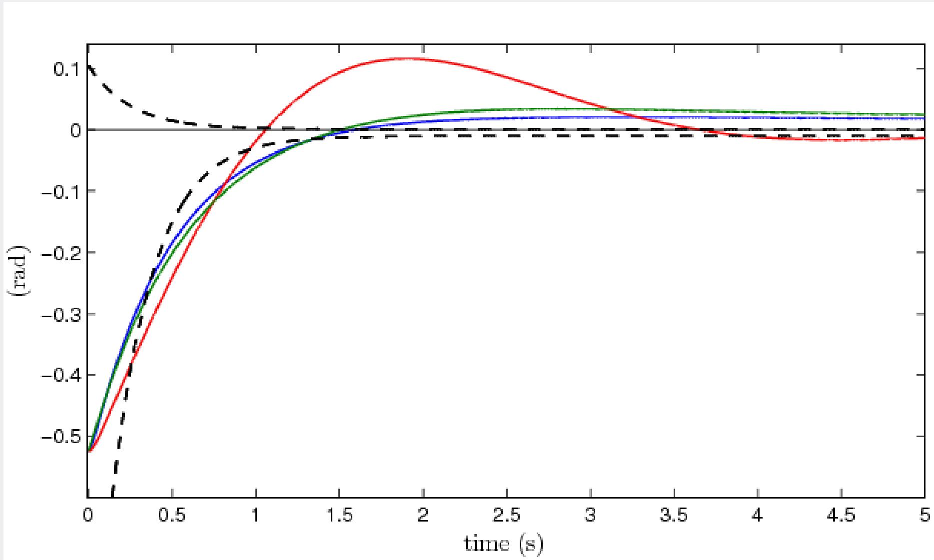
Performance function

$$r(t) = (r_0 - 10^{-2})e^{-4t} + 10^{-2}$$

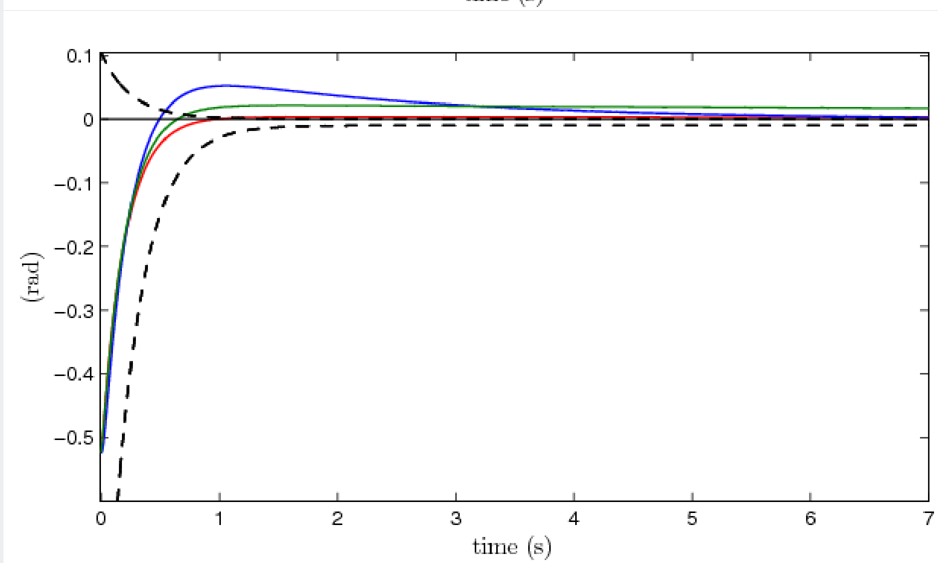
$$r_0 = 2e_{0i} = \frac{p}{3}$$

PID state and gain sensitivity – Regulation task

PID



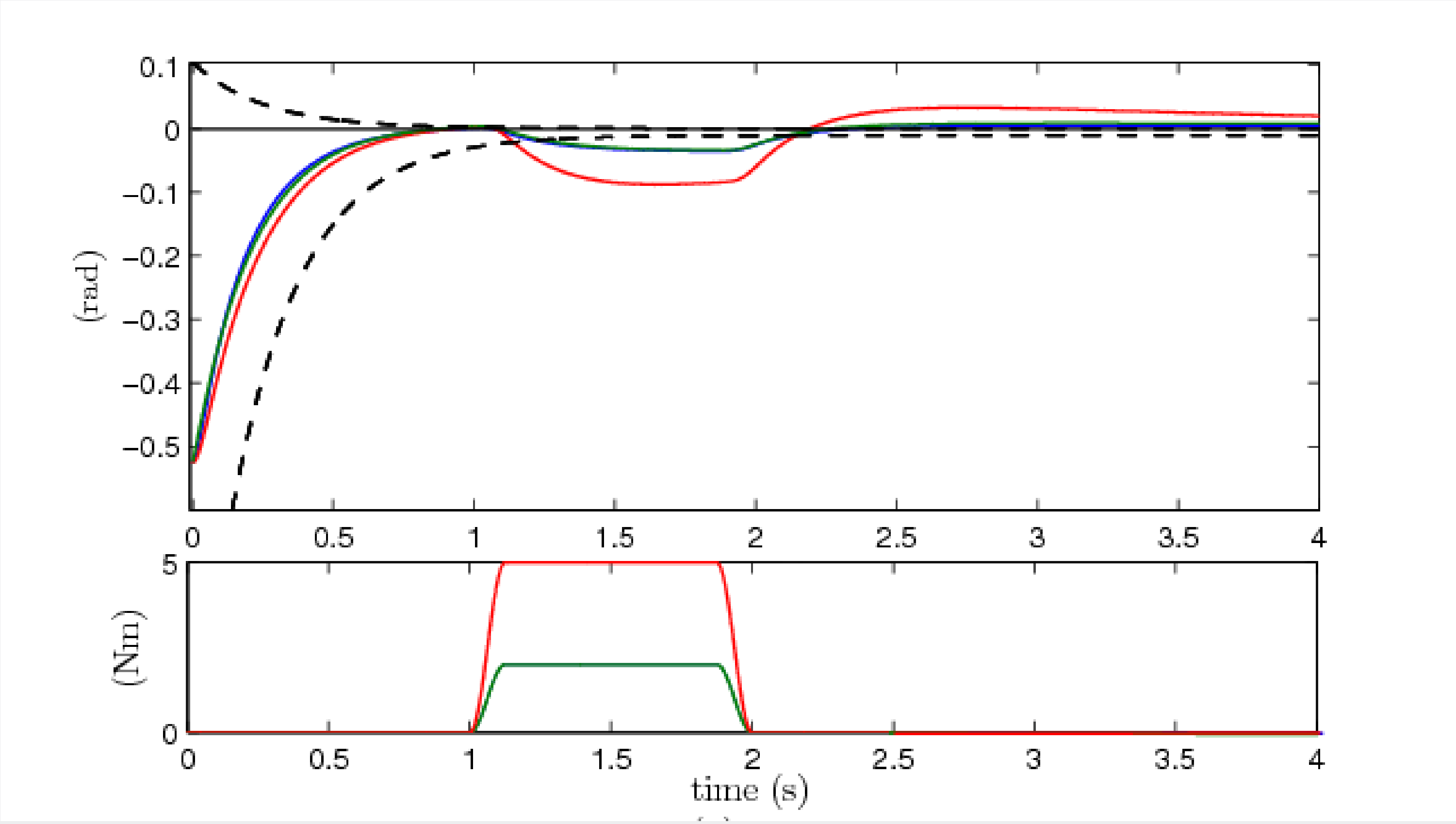
Reduce K_p from 50 → 20



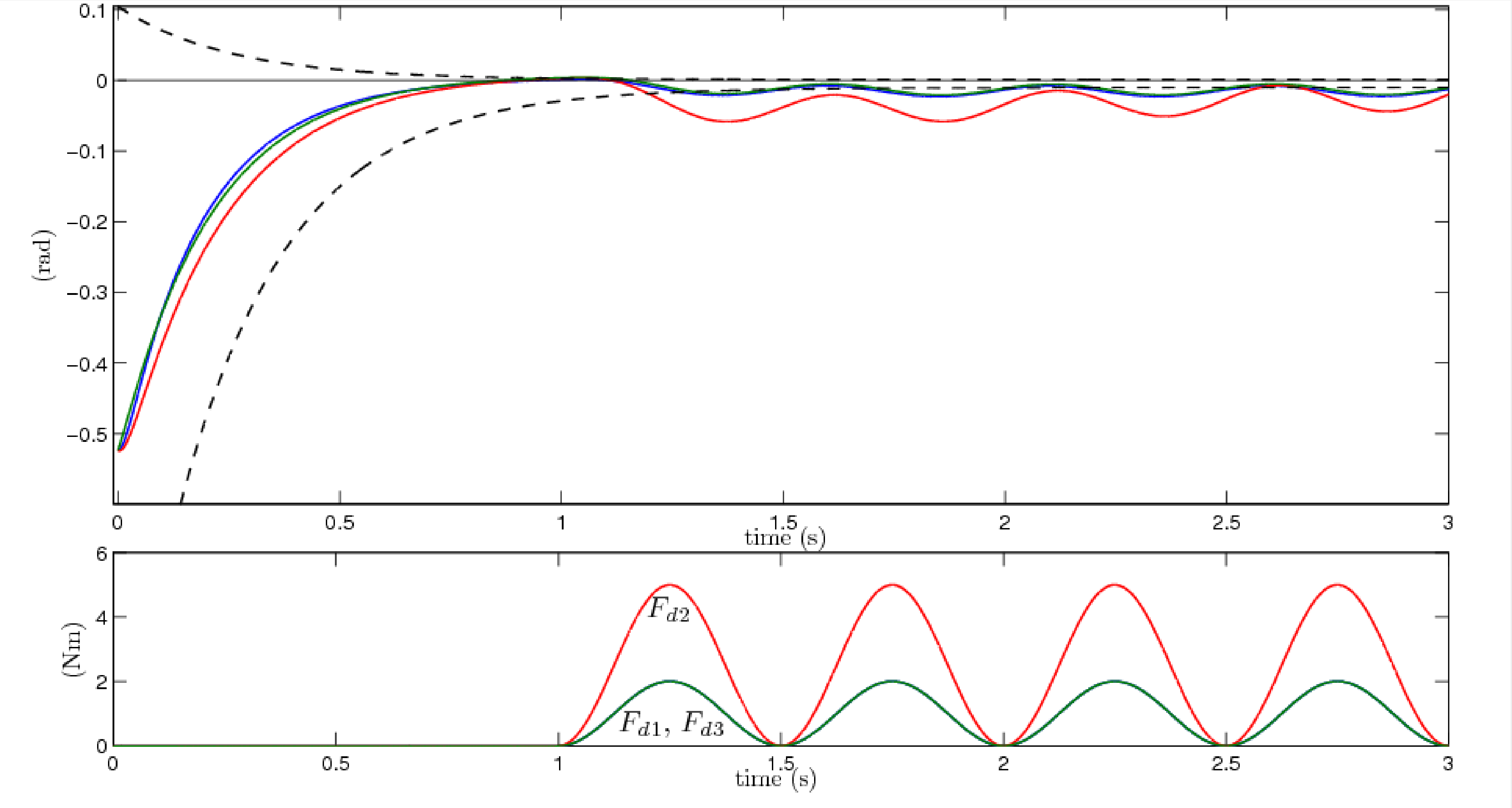
Change initial configuration

$$q(0) = \begin{bmatrix} 0 \\ 30 \\ 10 \end{bmatrix} \rightarrow q(0) = \begin{bmatrix} 30 \\ 60 \\ 40 \end{bmatrix}$$

PID robustness – Constant disturbance



PID robustness – Time varying disturbance

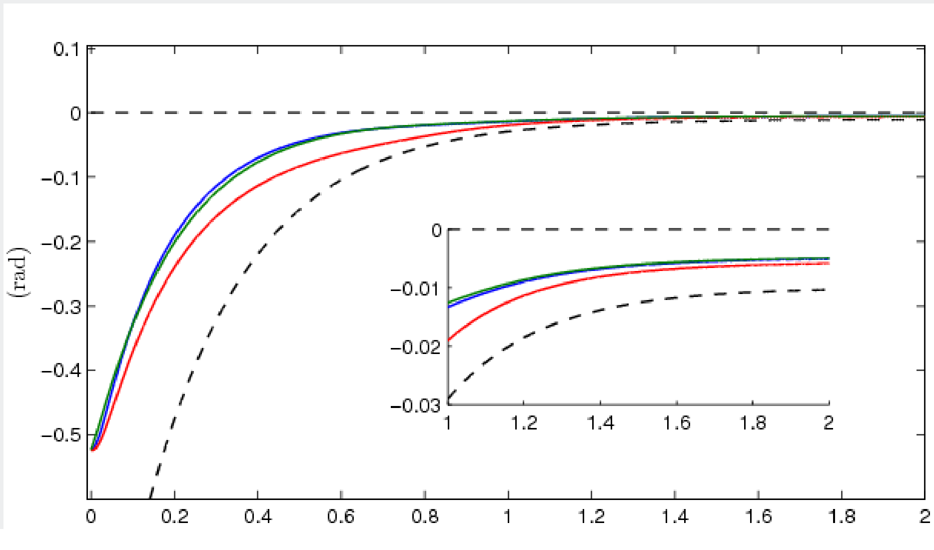


TP-PID – Regulation Task

TP-PID $u = -K_p e - K_v \dot{e} - K_e J_T(t)\varepsilon(t) - K_I \int_0^t \varepsilon(t)\,dt$

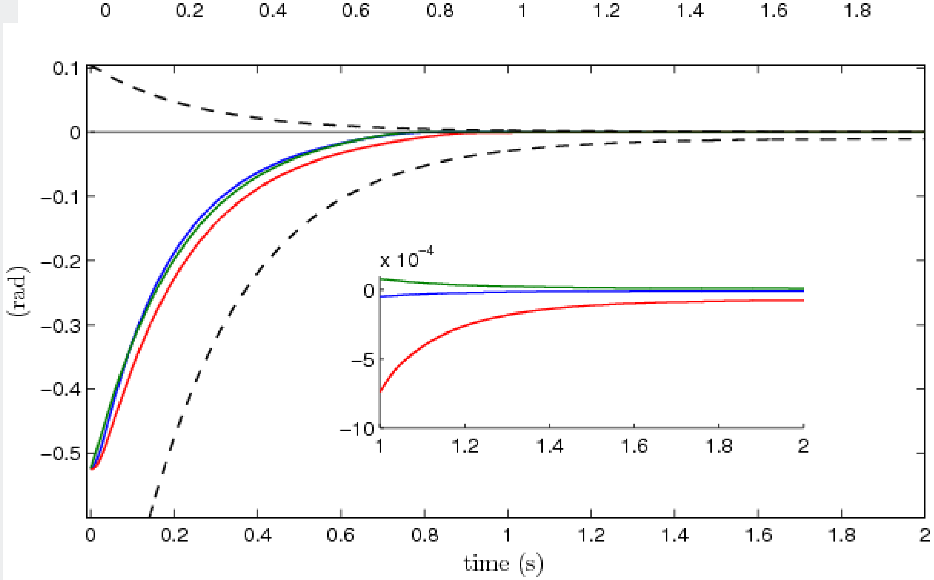
$K_e = 0.01 I_3 \quad b = 1$

$T_a(X)$



With the original transformation zero overshoot can be prescribed

$T_b(X)$



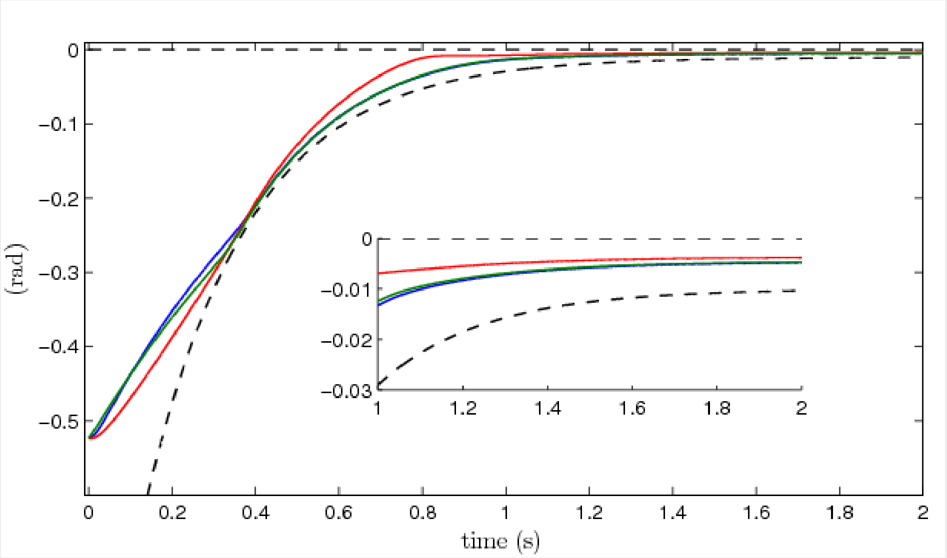
With the shifted transformation convergence to zero allows a wider steady state performance band to cater for noisy measurements

TP-PID – Gain sensitivity $K_p = 20I_3$

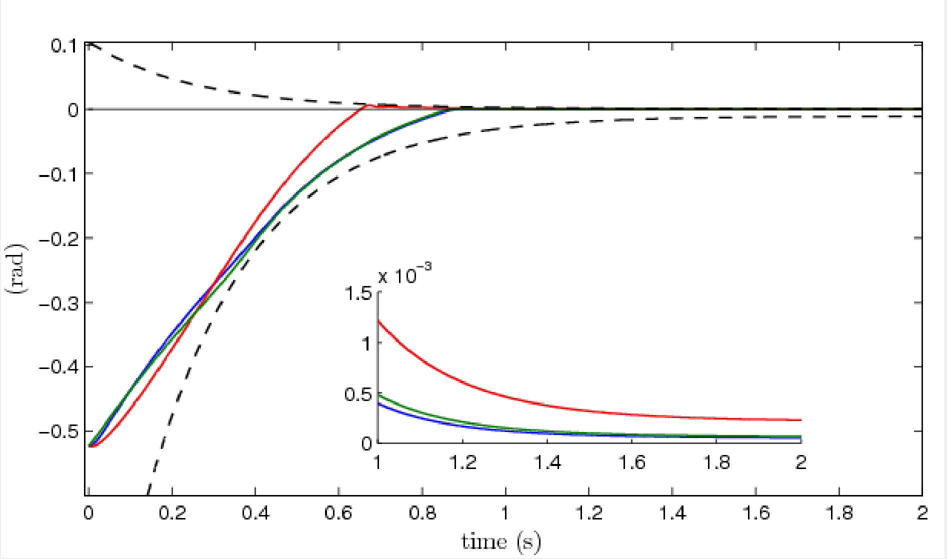
TP-PID

- Gain tuning is significantly simplified

$T_a(X)$



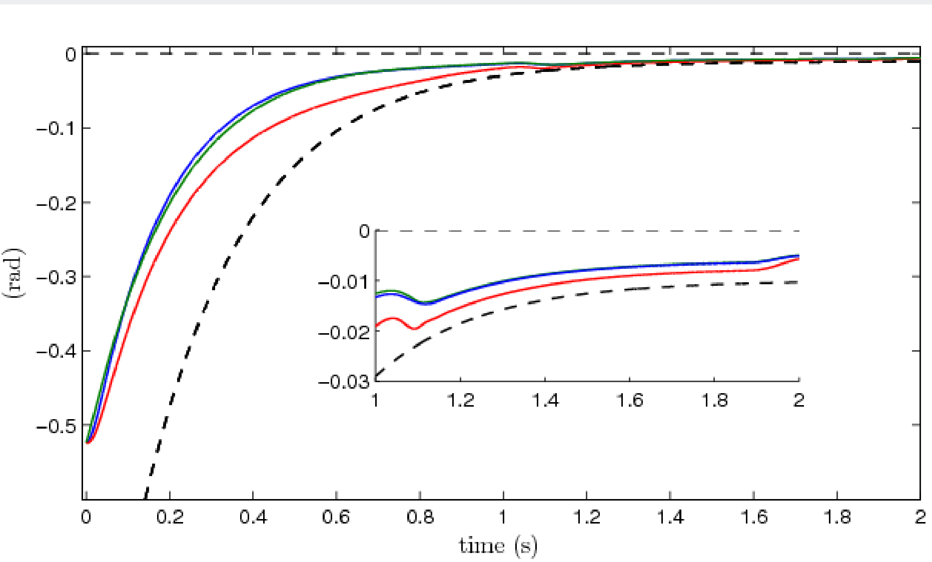
$T_b(X)$

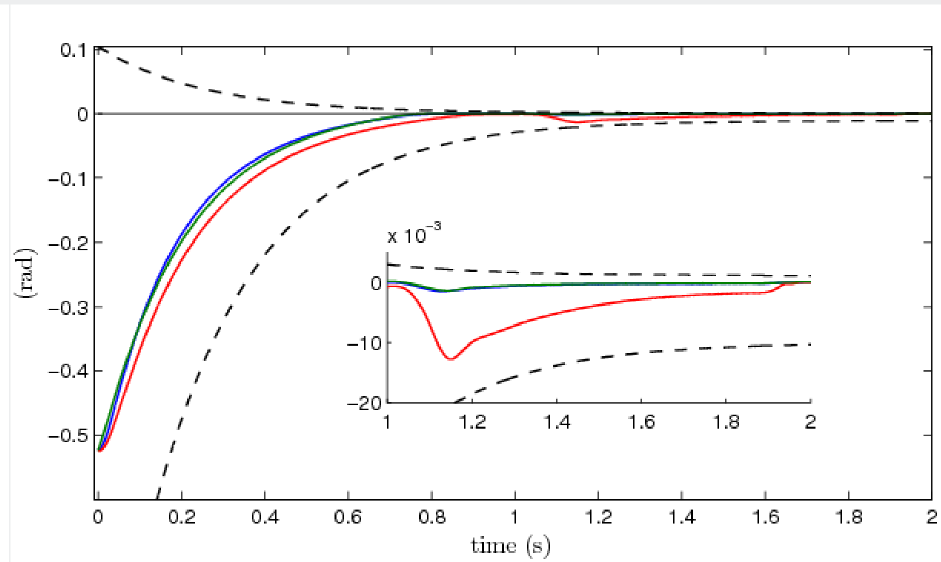


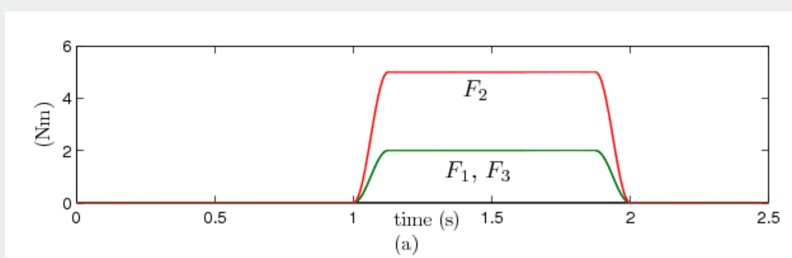
TP-PID – Constant disturbances

T_a(X

T_b(X

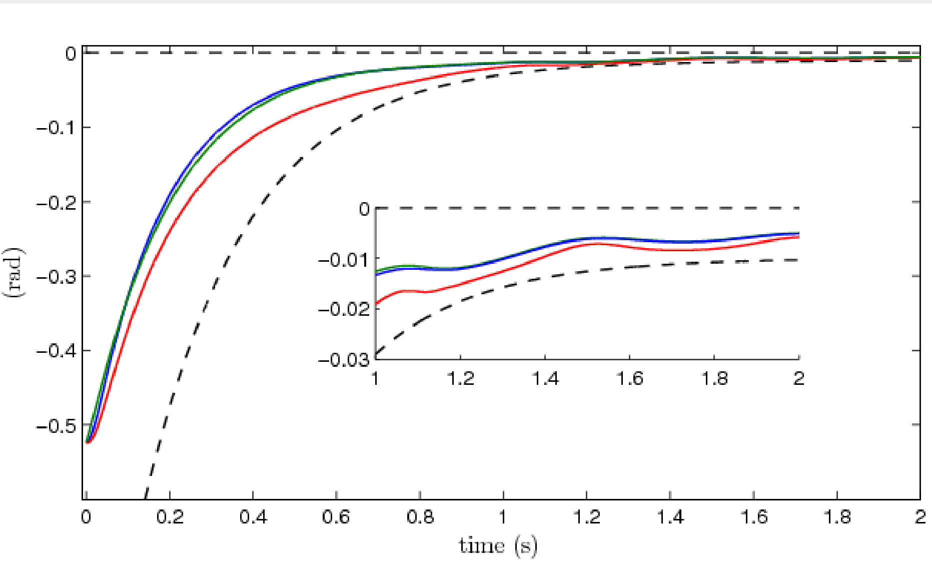


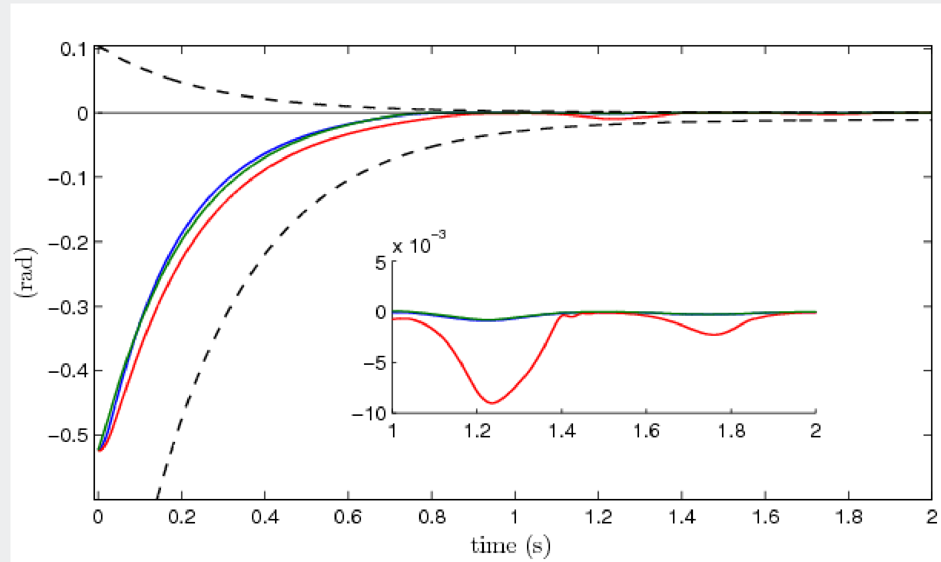




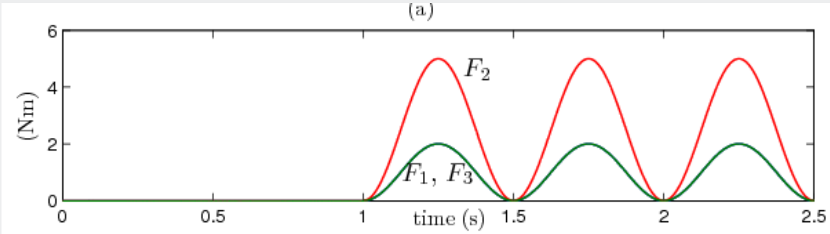
TP-PID – Time-varying disturbances

$T_a(X)$ $T_b(X)$





(a)



(b)

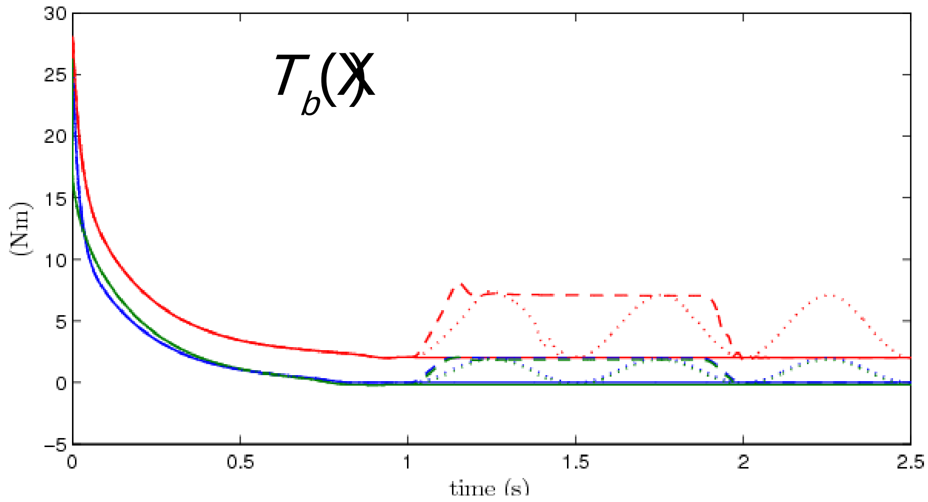
With the shifted transformation choice we still get practical convergence despite time varying disturbances

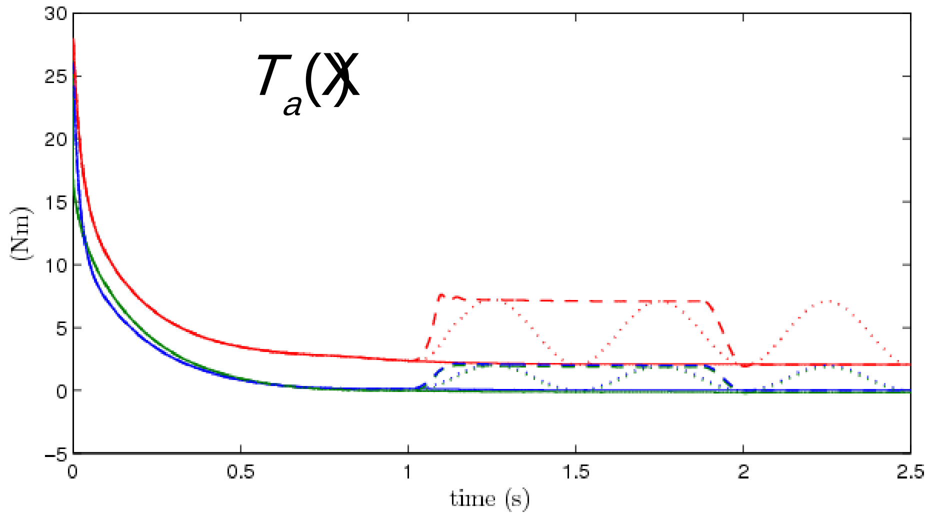
Is such a performance and robustness achieved with increased control effort? *no*

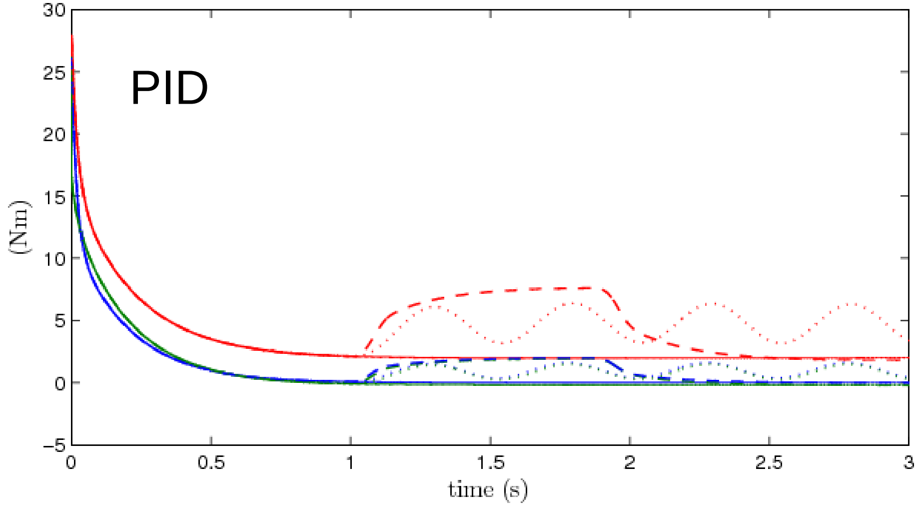
Simulation – Input torques

TP-PID

- Comparable control effort with PID







Can we achieve the same results in a trajectory tracking task keeping such a simple control structure?

yes

Prescribed Performance Tracking

$q_d(t) \in C^2 \qquad q_d, \dot{q}_d, \ddot{q}_d \in L_\infty \qquad \Phi(t)$

TP-PD $\quad u = -K_p e - K_v \dot{e} - K_e J_T(t)\varepsilon(t)$

$$\varepsilon_i(t) = T_b\left(\frac{e_i}{\rho(t)}\right)$$

- using the shifted transformation

Using TP-PD control law with a choice of gains satisfying

$$k_v > (\lambda + \beta)\left(\lambda_H + \rho_0\sqrt{n c_0}\right) + \frac{\sqrt{2}}{4}\lambda_H \lambda + \frac{1}{2}\left(c_0 v_d + 1 + 4c_0^2 v_d^2\right)$$

It is proved that

(a) Position error remains in the performance region at all times without even approaching its boundary, hence prescribed performance is guaranteed

$-M\rho(t) < e(t) < \rho(t)$

$-\rho(t) < e(t) < M\rho(t)$

(b) $e(t)$ $\dot{e}$ are uniformly ultimately bounded with respect to a set involving control gains and system constants

Simulation – TP-PD Tracking (1)

Desired positions (dotted lines)

$$q_d = \begin{bmatrix} 5 \\ 35 \\ 15 \end{bmatrix} + \begin{bmatrix} 30 \\ 20 \\ 40 \end{bmatrix} (1 - \cos(2\pi t)) \text{ deg}$$

Gains

$$K_v = 5I_3, K_p = 50I_3, K_e = 0.1I_3$$

Overshoot Index

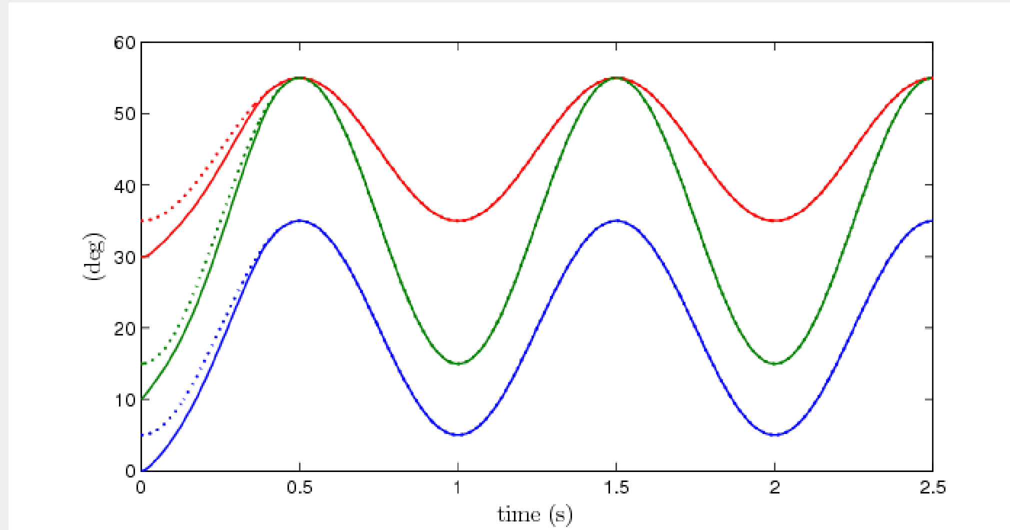
$$M = 0.1$$

Performance function

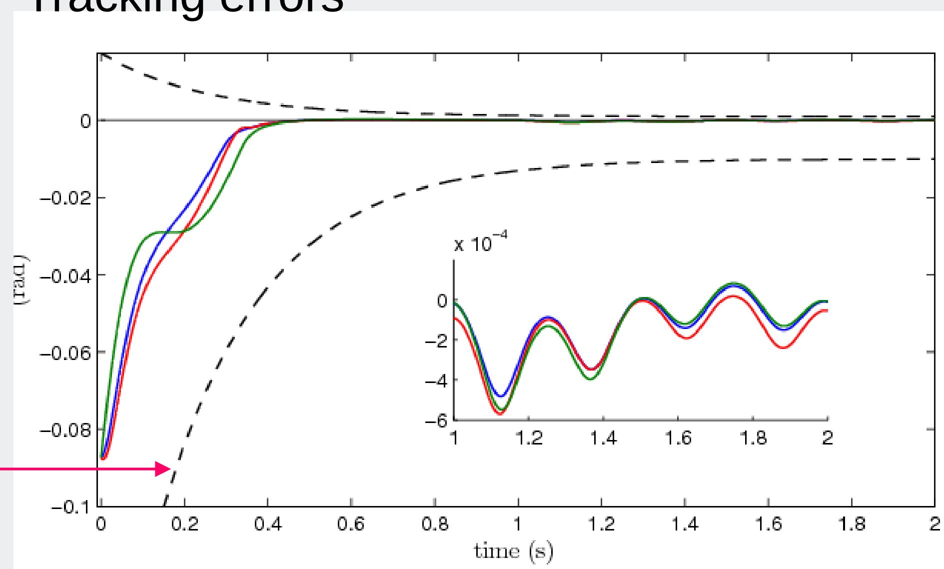
$$\rho(t) = (\rho_0 - 10^{-2})e^{-4t} + 10^{-2}$$

$$\rho_0 = 2e_{0i} = \frac{\pi}{18}$$

Desired and output trajectories

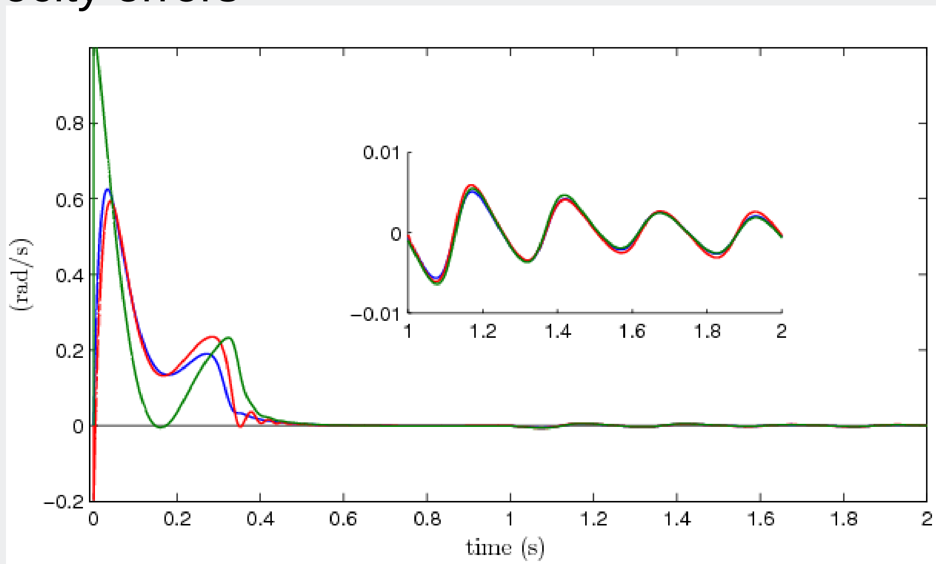


Tracking errors

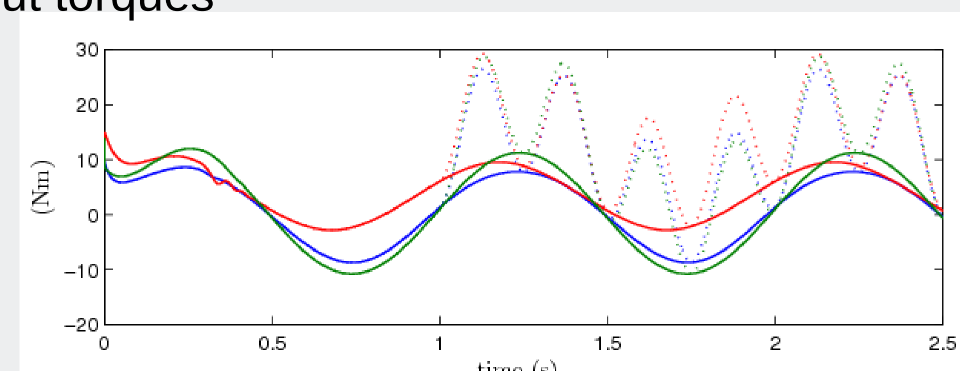


Simulation – TP-PD Tracking (2)

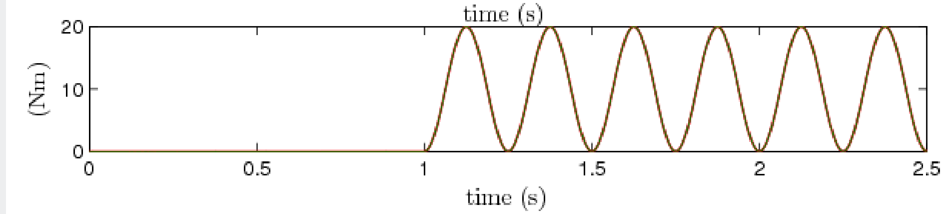
Velocity errors



Input torques



Disturbances ➡



Can a model based controller be endowed with prescribed performance guarantees?

yes

Model based control structures endowed with prescribed performance guarantees

Reference Velocity

$$\dot q_r = \dot q_d - \alpha e - \beta J_T^{-1}\varepsilon$$

Model based control structure (Slotine&Li)

$$u = Z(q,\dot q,\dot q_r,\ddot q_r)\hat\theta(t) - k_p v - Ds$$

$$Z(q,\dot q,\dot q_r,\ddot q_r)\theta = H(q)\ddot q_r + C(q,\dot q)\dot q_r + g(q)$$

$$s = \dot q - \dot q_r = \dot e + \alpha e + \beta J_T^{-1}\varepsilon$$

Parameter update laws

$$\dot{\hat\theta}(t) = -\Gamma Z^T s - K\hat\theta$$

$$\Gamma > 0$$

$$\|F(t)\| \le \bar F$$

Conventional Controller	Prescribed Performance Controller
$0 < \alpha \quad const$ $v = 0$	$\alpha = -\dfrac{\dot\rho(t)}{\rho(t)}$ $v = J_T\varepsilon$

Model based control structures endowed with prescribed performance guarantees

Reference Velocity

$$\dot{p}_r = Q\left(\dot{p}_d - \alpha e_p\right) + n\left(\dot{\hat{\chi}}_d - \beta\left(\chi - \hat{\chi}_d\right)\right)$$

Model based control structure

$$u = M\ddot{q}_r + C\dot{q}_r + F_q + g + J^T n f_d + J^T Q F$$
$$- D s_q - k_f J^T n v_f - k_p J^T Q v_p$$

ICRA09

Adaptive laws for uncertainties

$$\dot{\hat{h}} = -\gamma\left(\dot{f}_d + \beta f_d\right)\left(e_f + k_f v_f\right) \qquad \left(f = k_s \chi,\ h = k_s^{-1}\right)$$

Parametric uncertainty

$$f(\chi) = Z_f^T(\chi)\theta_f$$

MSC09

Structural uncertainty

$$\dot{f}(\chi) = \partial f(\chi)\dot{\chi} \qquad \partial f(\chi) = \theta_f^T Z_f(\chi) + w_f(\chi)$$

IEEE Trans. NN 2010

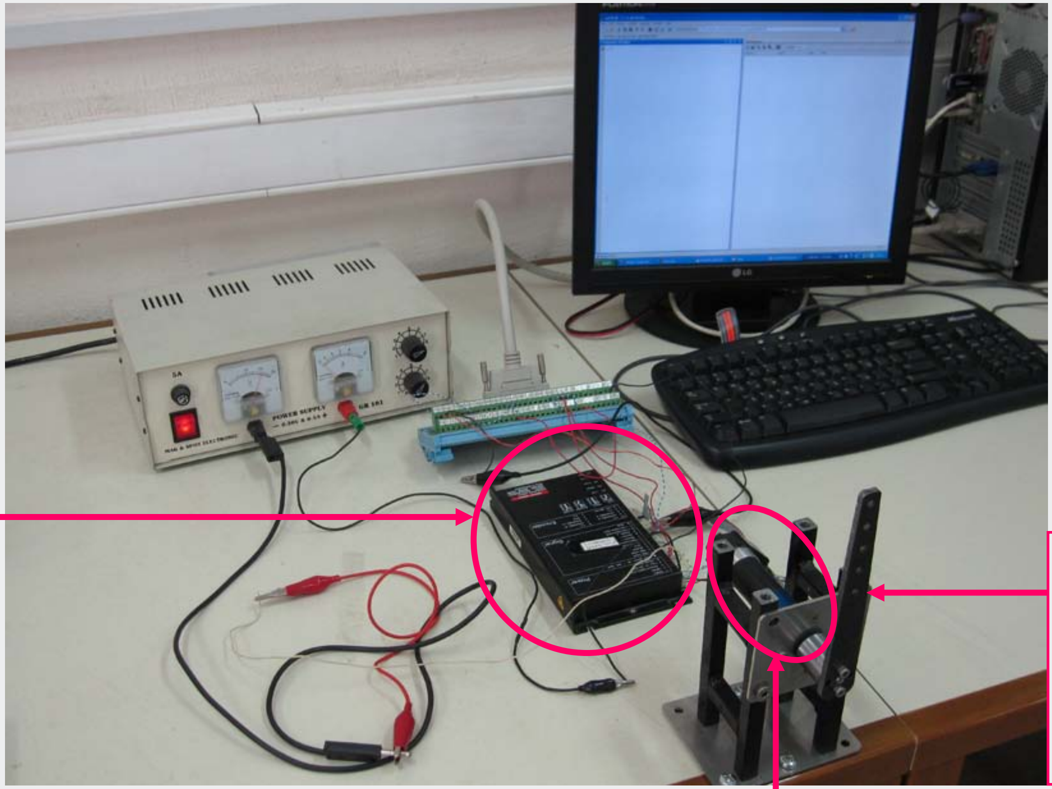
Conventional Controller	Prescribed Performance Controller
$0 < \alpha, \beta \quad const$	$\alpha = -\dfrac{\dot{\rho}_p(t)}{\rho_p(t)} \qquad \beta = -\dfrac{\dot{\rho}_f(t)}{\rho_f(t)}$
$v_p = e_p$	$v_p = J_{Tp}\varepsilon_p$
$v_f = e_f$	$v_f = J_{Tf}\varepsilon_f$

Is it possible to design a prescribed performance guaranteeing controller that is completely model knowledge free?

Yes *First results in MED10*

More in upcoming publications

One degree of freedom Experimental setup



Maxon Motor's analogue ADS Servoamplifier 50/5 in current mode (internal current loop)

link length: 15 cm
total mass: 145 g

Dc motor (Faulhaber 2342024CR) equipped with an incremental encoder and a low rate reduction gear box (1:14),

Experiment – Regulation

PID controller

$$u_{PID} = -k_v\left\{T_v(\dot{e} + k_p e) + \int_0^t (\dot{e} + k_p e)\,dt\right\}$$

$k_p = 9.5,\ k_v = 1.5574,\ T_v = 0.314$

TP-PID controller

$k_e = 0.02,\ k_v = 0.9,\ k_p = 10,\ k_I = 1$

$b = 1$

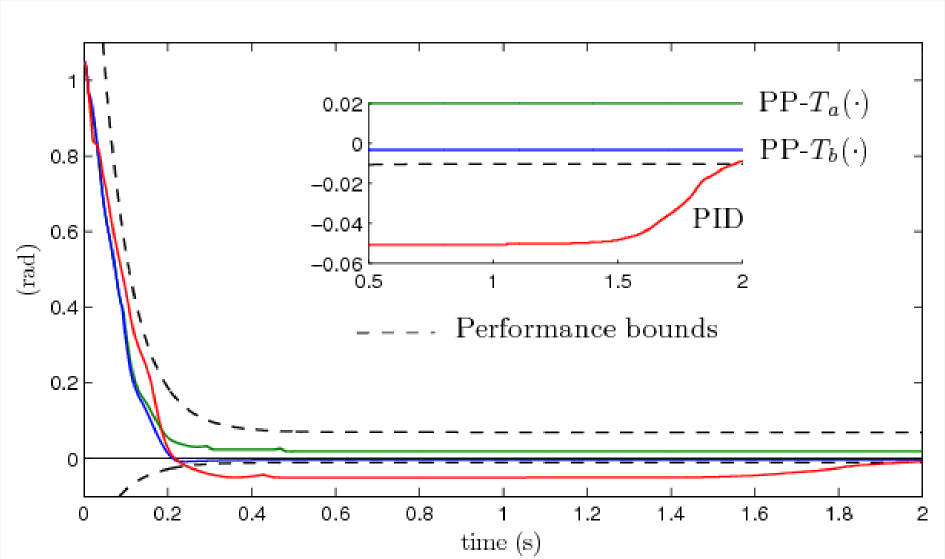
Performance bounds

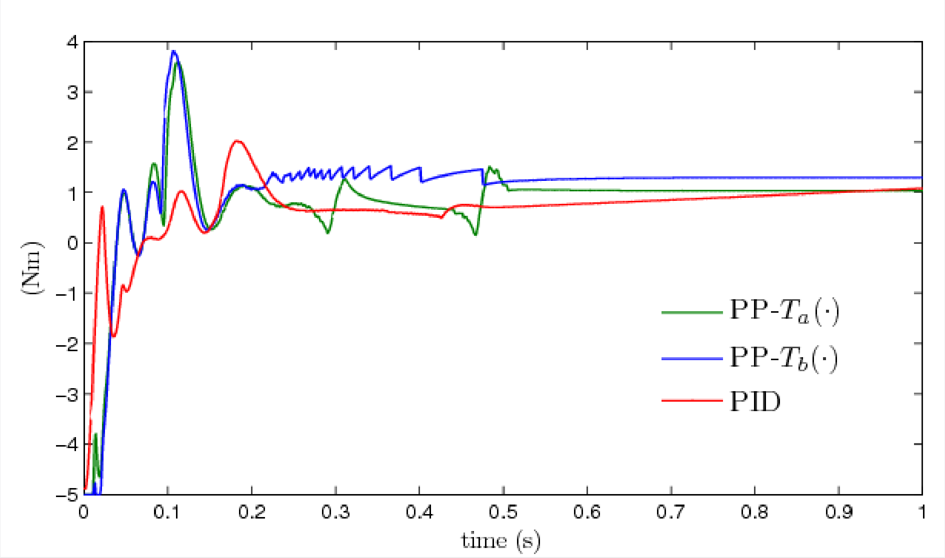
$M = 0.15$ for $T_b(\cdot)$

$r(t) = (2 - 0.07)e^{-14t} + 0.07$

Convergence in less than 0.4 s

Less than 5% of the setpoint error





Experiment – Tracking

Desired trajectory

$$q_d = -30\cos \pi t \text{ deg}$$

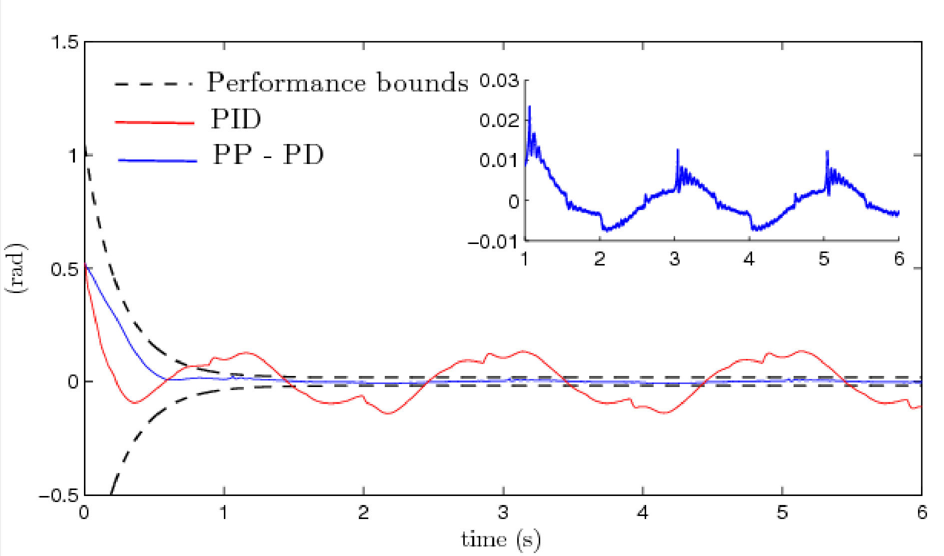
Control gains

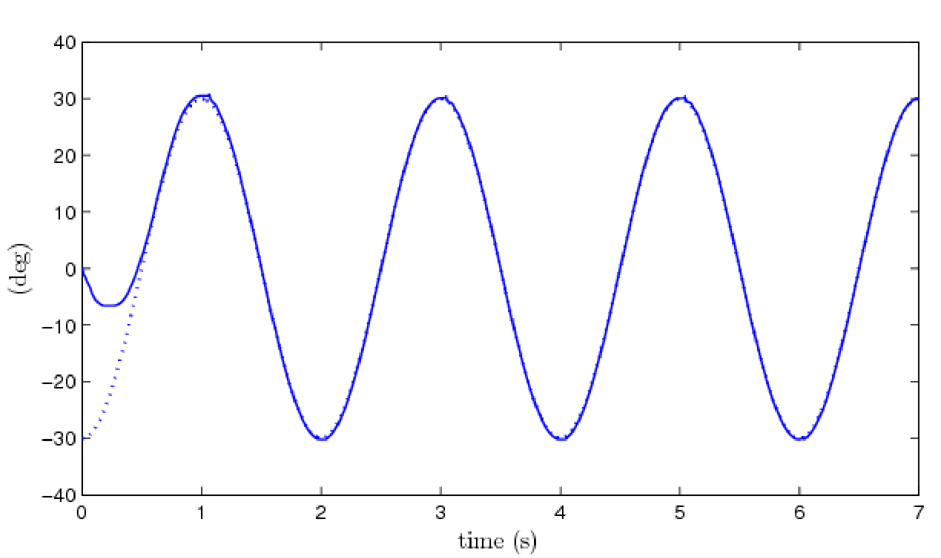
$$k_v = 0.5, \quad k_p = 2, \quad k_e = 0.008$$

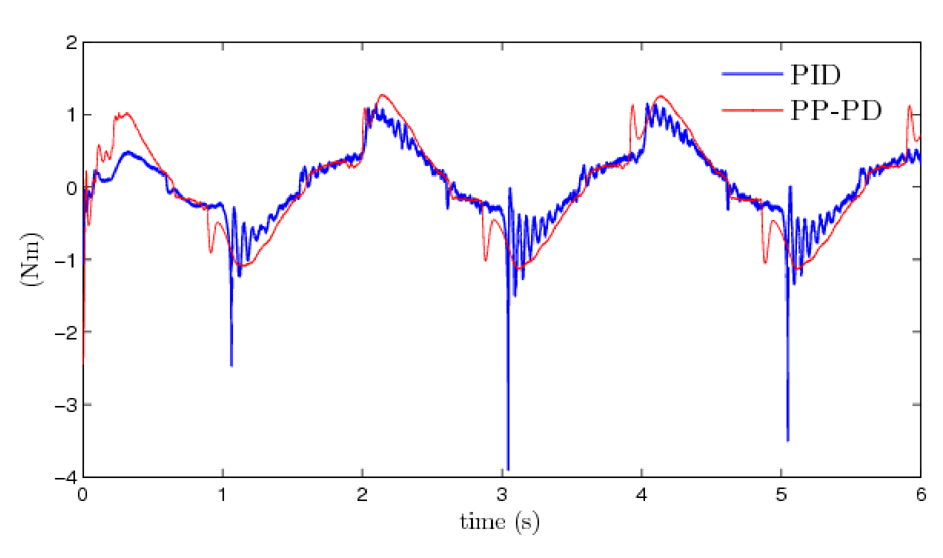
Performance bounds

$$r(t) = \left(\frac{\pi}{6} - \frac{\pi}{180}\right)e^{-4t} + \frac{\pi}{180}$$

$M = 1$ Symmetric performance envelope







Conclusions & Future Application

- Prescribed performance controllers incorporate performance quality constraints via an error transformation

- Prescribed performance controllers guarantee transient and steady state in complex nonlinear uncertain robotic systems

- Prescribed performance controllers can be model free

- Prescribed performance controllers have been applied in robot position regulation and tracking and in robot force/position tracking guaranteeing contact maintenance

Future Applications

Stiffness performance guarantee

Rolling motion guarantee

Publications

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THANK YOU FOR YOUR ATTENTION

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Talk Outline

Current Trends in Robotic System Development-Soft Robotics

Prescribed Performance-Basic Idea

PP Model free Joint Position Regulation & Tracking

Model based control structures endowed with prescribed performance guarantees

Experimental Results

Conclusions and Future Work