Adaptive/Self-Tuning PID Control by Frequency Loop-Shaping

Elena Grassi,	ASU
Kostas Tsakalis,	ASU
Sachi Dash,	Honeywell HTC
Sujit Gaikwad,	Honeywell HTC
Gunter Stein,	Honeywell HTC

Outline

- Problem Description: PID Tuning from Input-Output data
- Frequency Loop Shaping
  - Off-line tuning
  - Target loop selection, 1st-2nd order targets
- Direct Adaptation of the PID parameters
  - Cost functional
  - Regressor generation via filter banks
  - Adaptation
  - Performance Monitoring Implications
- Simulation Results
- Conclusions

Problem Description

- Industrial Applications
  - Large number of PID loops, often poorly tuned
  - Reliability and expediency requirements
- A Variety of PID Tuning Strategies
  - Complete or partial models. (System identification-based vs. crossover properties)
  - Control objectives (Time-Frequency domain)
  - Direct and indirect approaches to adaptation
- Frequency Loop Shaping
  - Accounting for uncertainty, several successful applications

FLS PID Tuning (batch/off-line)

- System ID-modeling from I/O data
- Nominal model & uncertainty bounds
- Control Objective
  - Loop-shaping (sensitivity targets)
  - Disturbance attenuation subject to bandwidth constraints
  - Guide: “Robust Stability Condition”
- On-line version via indirect adaptation
  - Update plant model, re-tune controller
  - Complete solutions can be computationally demanding
  - Simple models => off-line construction of look-up table for the PID gains

Target Loop Selection and FLS PID Tuning

- Typical Targets: $\frac{\lambda}{s}, \quad \frac{\lambda(s+a)}{s^2}, \quad \frac{\lambda(s+a)}{s(s+\varepsilon)}, \quad \cdots$
  - Target order depends open-loop/closed-loop bandwidth ratio (for input disturbance attenuation)
  - Uncertainty constraints and RHP pole-zero limitations
  - More difficult cases via LQ or full-order controller design methods e.g., K=lqr(A,B,Q,R), target: [A,B,K,0]
- FLS Tuning: convex optimization in the frequency domain

$$\min_{\theta_{pid}} \left\| S(GC(\theta_{pid}) - L) \right\|_{L_\infty} \quad s.t. \quad \theta_{pid} \quad constr.$$

$$\min_{\theta_{pid}} \left\| S(GC(\theta_{pid}) - L) \right\|_{L_2} \quad s.t. \quad \left\| S(GC(\theta_{pid}) - L) \right\|_{L_\infty} \leq b, \quad \theta_{pid} \quad constr.$$

  - L=loop gain, S=sensitivity, T=complementary sensitivity

Direct Adaptation with an FLS objective

- Construction of the estimation error (at the plant input)

$$e_e = S(CG - L)[u] = SC[y] - T[u]$$

$$\left\| S(CG - L) \right\|_{L_\infty} = \sup_{u \neq 0} \frac{\| e_e \|_2}{\| u \|_2}$$

- Approximate sup by using a filter bank

$$\left\| S(CG - L) \right\|_{L_\infty} \cong \max_i \frac{\| SCF_i[y] - TF_i[u] \|_2}{\| F_i[u] \|_2} \leq \max_i \frac{\| SCF_i[y] - TF_i[u] \|_{2,\delta}}{\| F_i[u] \|_{2,\delta}}$$

  – F_i: band-pass filters, $\|.\|_{2,\delta}$: exponentially weighted 2-norm

Direct Adaptation with an FLS objective (cont.)

- Optimization problem

$$\min_{\theta \in M} \max_{i} \frac{J_{i,k}(\theta)}{m_{i,k}}$$

$$J_{i,k}(\theta_k) = \sum_{n=0}^{k} \lambda^{k-n} \, | z_{i,n} - w_{i,n}^T \theta_k |^2$$

$$m_{i,k} = \lambda m_{i,k-1} + | F_i[u]_k |^2$$

$$z_{i,k} = TF_i[u]_k \, , \quad w_{i,k} = SC_\theta F_i[y]_k$$

- Recursive computation of $J_{i,k}$
- Optimization: min-max of quadratics

Direct Adaptation details

- Recursive computation of $J_{i,k}$

$$J_{i,k+1}(\theta) = \hat{J}_{i,k+1} - S_{i,k+1}^T(\theta - \theta_k) + \tfrac{1}{2}(\theta - \theta_k)^T P_{i,k+1}(\theta - \theta_k)$$

$$\hat{J}_{i,k+1} = \lambda J_{i,k}(\theta_k) + | z_{i,k+1} - w_{i,k+1}^T \theta_k |^2$$

$$P_{i,k+1} = \lambda P_{i,k} + 2 w_{i,k} w_{i,k}^T, \quad S_{i,k+1} = R_{i,k+1} - P_{i,k+1}\theta_k, \quad R_{i,k+1} = \lambda R_{i,k} + 2 z_{i,k} w_{i,k}^T$$

- Each $J_{i,k+1}$ is quadratic in the parameters: minimize the maximum by, e.g., computing a descent direction and performing a line search

Adaptive FLS Properties

- Excitation requirements
- Effects of disturbances and unmodeled dynamics (SNR)
- A dead-zone condition: update when

$$S_{i,k}^{T} P_{i,k}^{-1} S_{i,k} - 2d_0^2 m_k > 0$$

  - Update when the error operator gain drops by at least d_0
- Input Saturation does not affect updates
- Linearization offsets (estimation or high-pass filtering)
- The cost functional provides a measure of tuning confidence
  - Feasibility of performance monitoring

Example

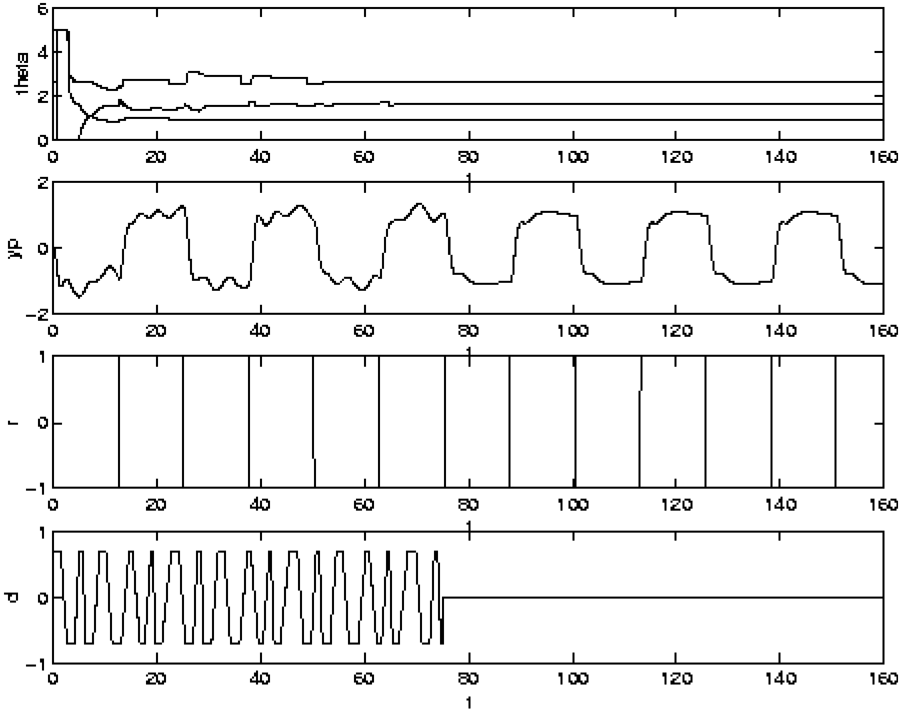
- Simulation Results for the following plant and target loop:

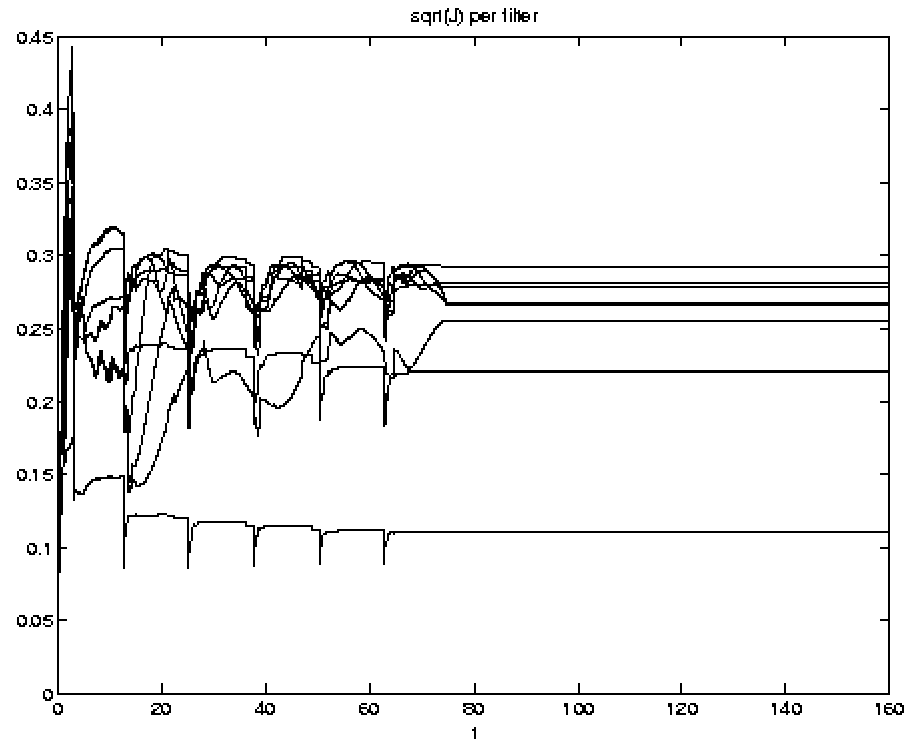
$$G(s) = \frac{1}{(s+1)^3}, \quad L(s) = \frac{1}{s}$$

- Square-wave reference input.
  - Excitation injected at the plant input for $t<75$.
- PID gains converge approximately to the off-line tuning.
- Cost functional has a maximum of 0.3^2, same as the off-line fitting error.

Simulation Results

- Left: Parameters, output, reference, excitation.
- Right: Square-root of cost functional.





Conclusions

- Direct adaptation of PID parameters with an FLS objective
  - FLS: Operator gain interpretation of fitting error
- Recursive implementation for on-line tuning
- Use of a filter bank to approximate the min-max objective
- Quantitative measures of tuning confidence
  - Gain of the error system

Future work:

- On-line monitoring of performance
- On-line adaptation of objective (target loop) based on the cost functional values