PI Tuning via Extremum Seeking Methods for Cruise Control

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Motivation

- Automated PID Tuning Method
  - Online control synthesis
  - Achieve optimal performance in some sense
  - Reduces calibration time
  - Does not require knowledge of plant
  - Does not require special experiments

- Can ES be used as an adaptive control law?
  - Real-time controller adaptation
  - Varying plant parameters and dynamics
  - Varying disturbance inputs

Reference Paper

PID Tuning Using Extremum Seeking
Online, Model-Free Performance Optimization

Nick J. Killingsworth and Miroslav Krstic

IEEE Control Systems Magazine
February 2006

Literature Review

Closed-loop (model free) PID parameter tuning

Relay Feedback Tuning

- Åström *et al* (1984)
- Leva (1993)
- Voda *et al* (1995)

Unfalsified Control

- Jun *et al* (1999)
- Saeki *et al* (2003, 2004)

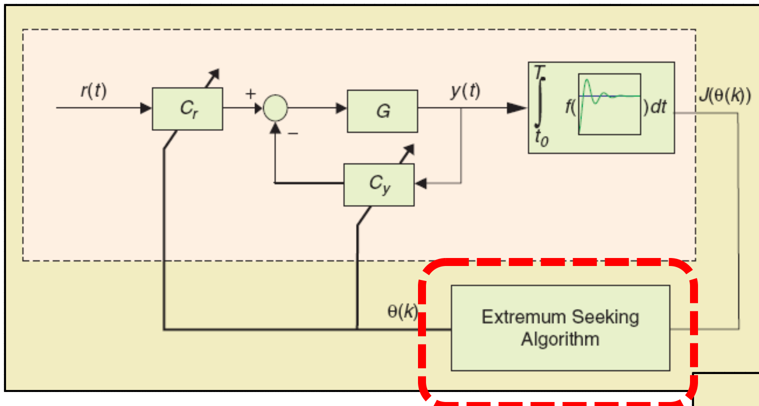
Iterative Feedback Tuning

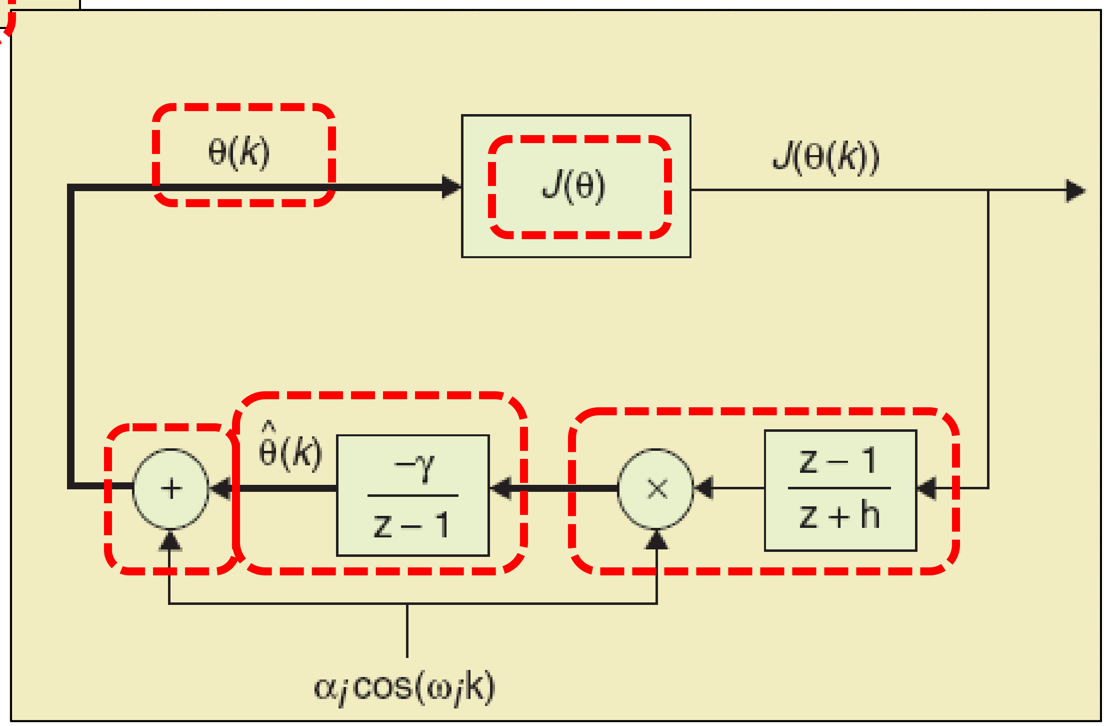
- Hjalmarsson *et al* (1998)
- Lequin *et al* (1999, 2003)

Outline

- Motivation & Literature Review
- Paper Reproduction
  - Extremum Seeking (ES) Algorithm
  - PID Tuning on Sample Plant
  - ES Parameter Sensitivity
- Case Study: Adaptive Cruise Control
  - Cruise Control Model
  - PI Tuning
    - Vary Desired Velocity, Fix Road Grade
    - Vary Road Grade, Fix Desired Velocity
    - Vahidi Road Grade Profile (I-15 near San Diego)
- Summary & Conclusions

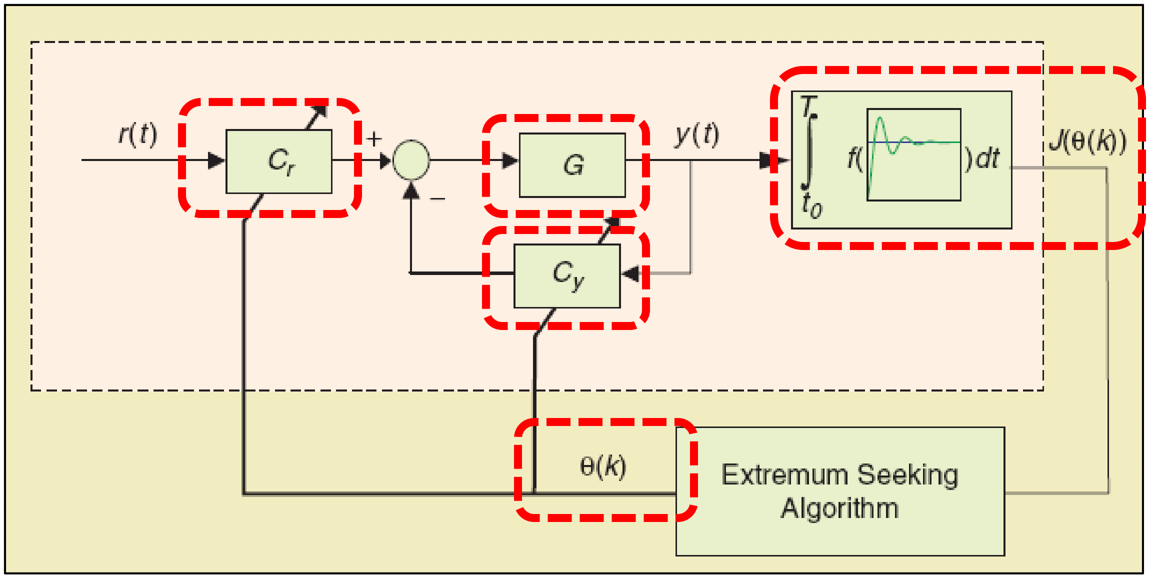
Extremum Seeking Algorithm





- θ PID parameters
- J Cost
- h Washout filter cutoff freq
- ω_i Perturbation freq.
- α_i Perturbation amplitude
- γ Adaptation gain
- $\hat{\theta}$ PID parameters estimate

Control Problem Formulation



Plant:

$$G(s) = \frac{1}{1+20s} e^{-20s}$$

Controller:

$$C_r(s) = K\left(1 + \frac{1}{T_i s}\right)$$

$$C_y(s) = K\left(1 + \frac{1}{T_i s} + T_d s\right)$$

Cost Function:

$$J(\theta) = \frac{1}{T - t_0} \int_{t_0}^{T} e^2(t,\theta)dt$$

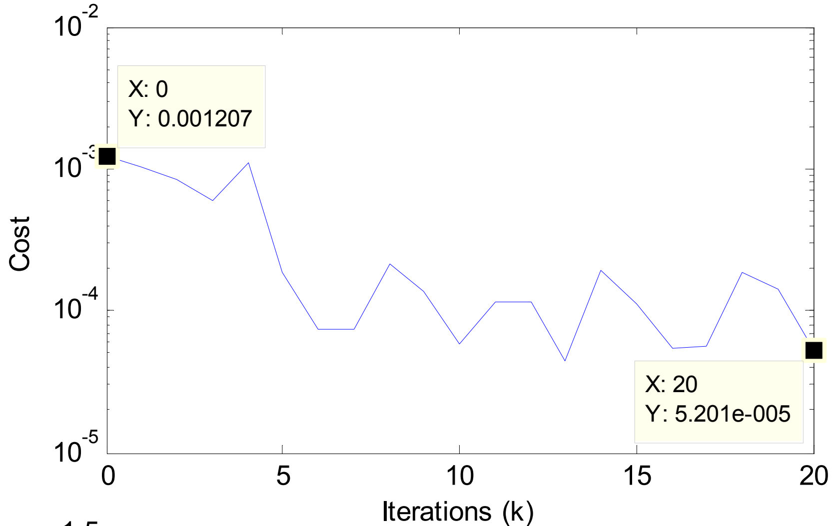
$$e(t,\theta) = r(t) - y(t,\theta)$$

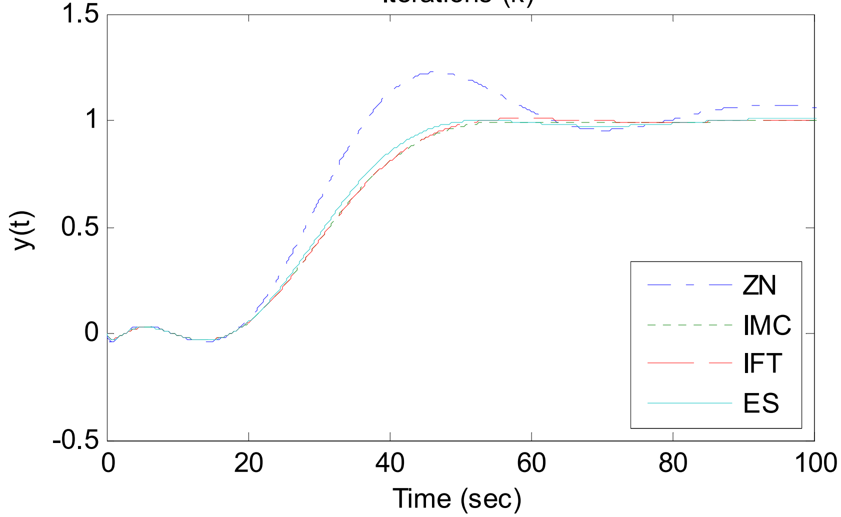
Tuning Parameters:

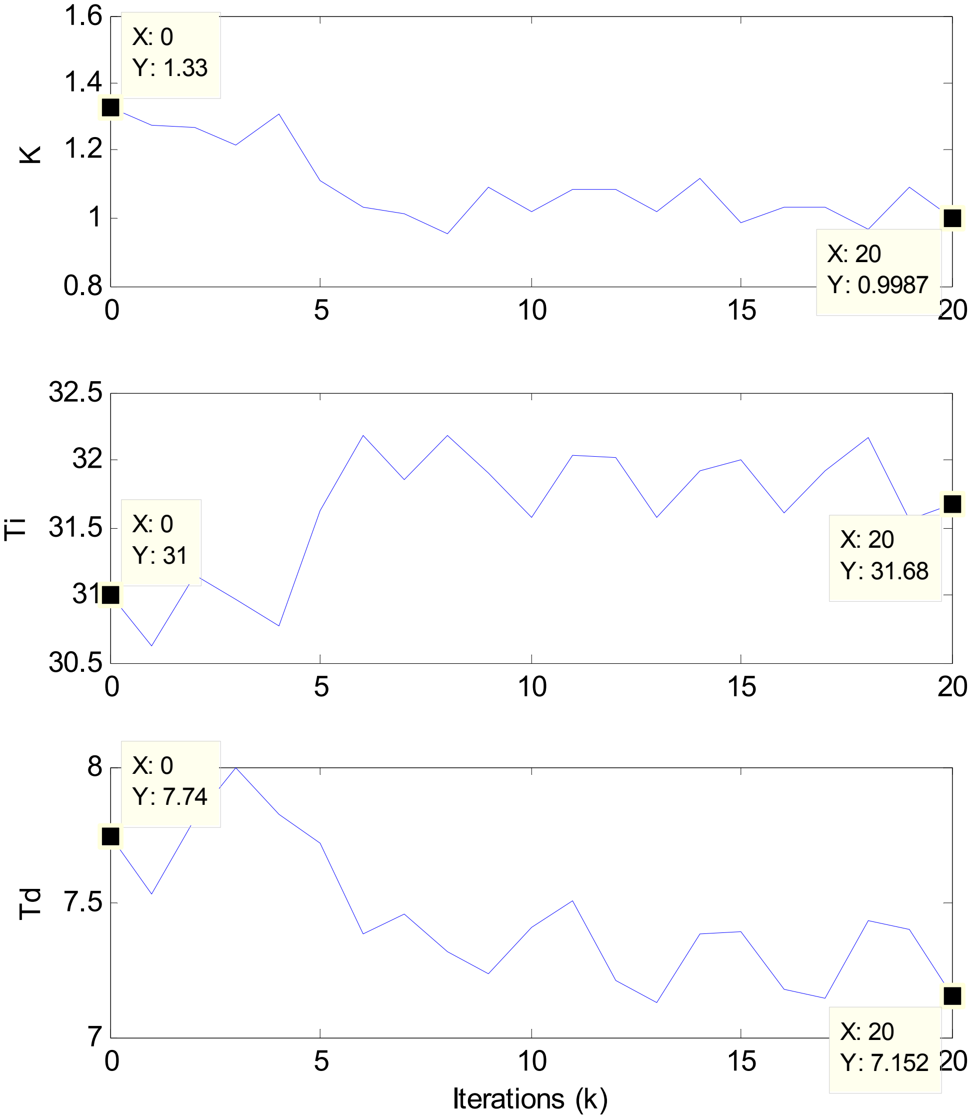
$$\theta = \begin{bmatrix} K & T_i & T_d \end{bmatrix}^T$$

PID Tuning on Sample Plant

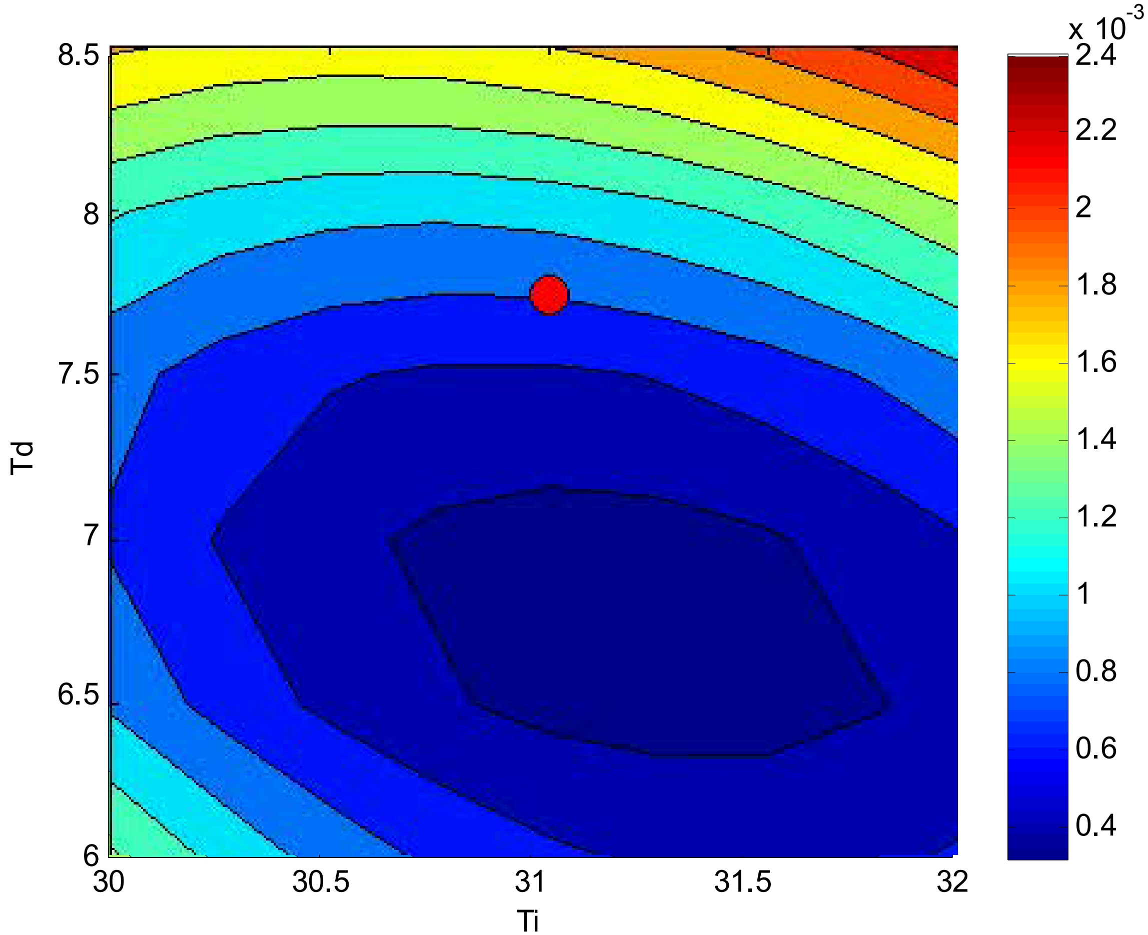
Use Ziegler-Nichols as initial gains







PID Gain Trajectories wrt Cost

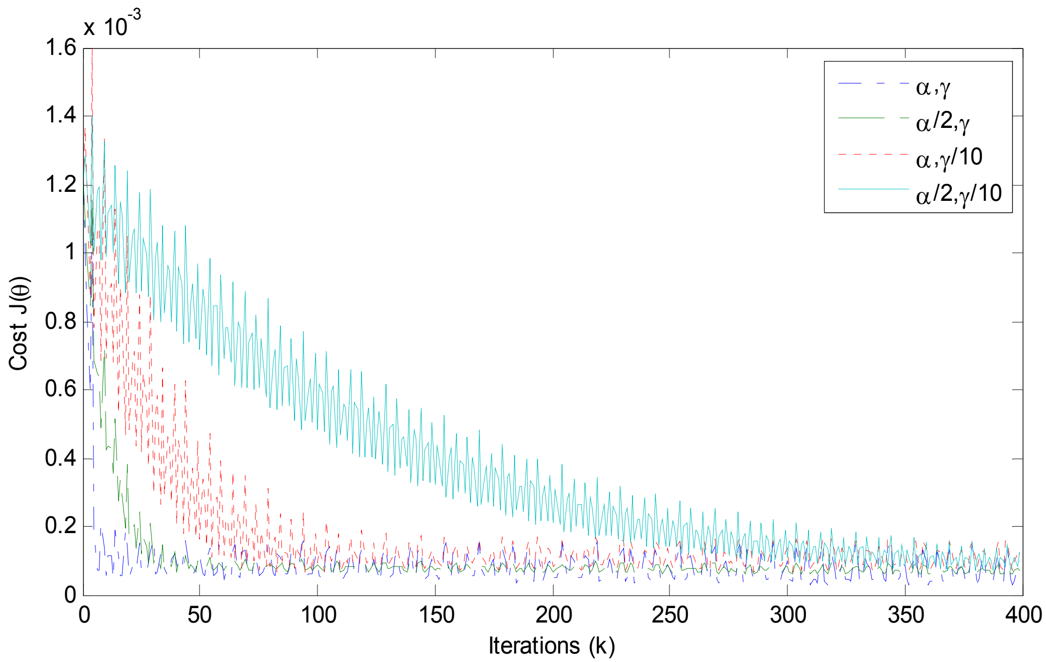


Cross-section of cost as a function of T_d and T_i

Fixed K

Varying ES Parameters

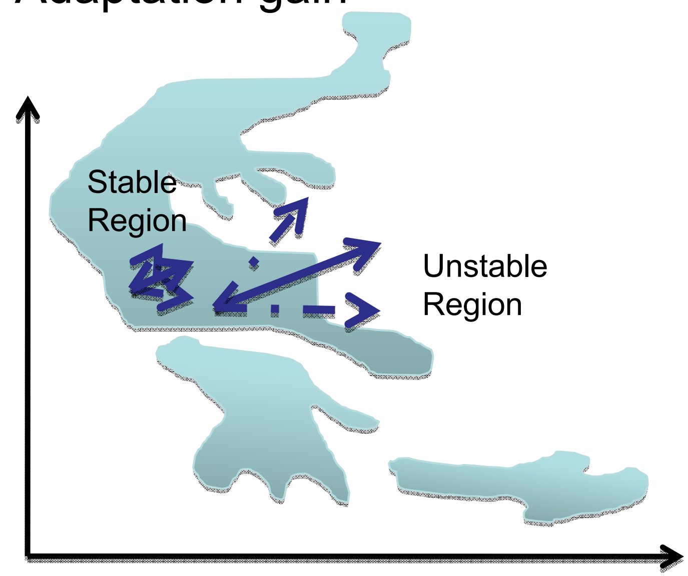
How sensitive are the results to the choice of the ES parameters?



Recall

α_i Perturbation amplitude

γ Adaptation gain



Killingsworth's Answer

"fairly insensitive"

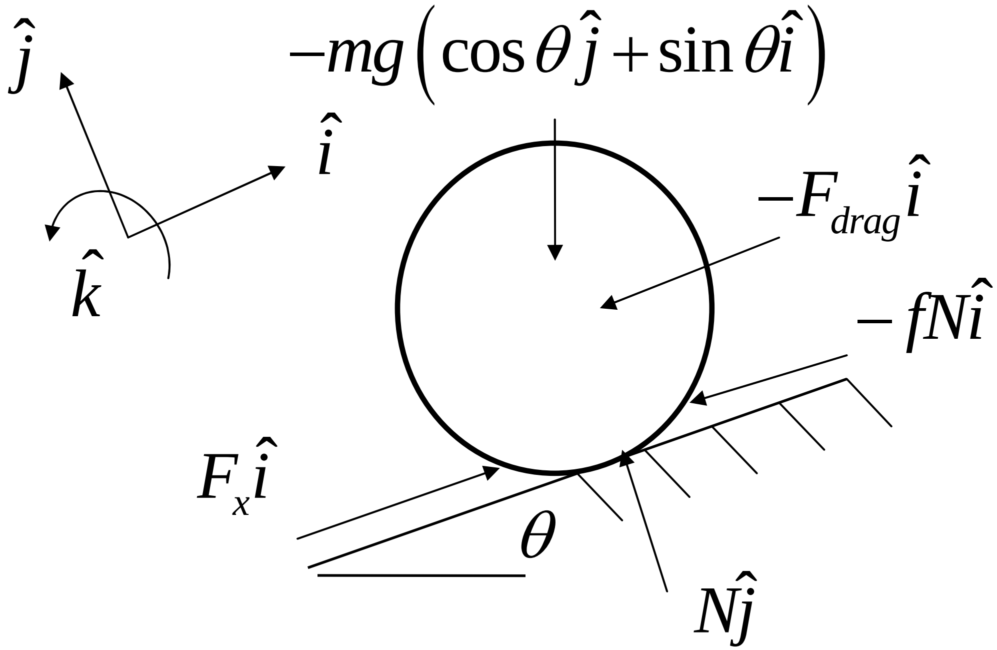
Our Answer

- Insensitive for more conservative values
- VERY sensitive for more aggressive values

Case Study

Adaptive Cruise Control

Vehicle Dynamics Model



Assumptions

- Rolling disk dynamics
- No wheel slip
- No actuator dynamics
- Coulomb friction

$$m\mathbf{a}\cdot\hat{i} = F_x - mg\sin\theta - fN - F_{drag}$$

$$m\mathbf{a}\cdot\hat{j} = N - mg\cos\theta = 0$$

$$F_{drag} = 0.5\rho A C_d\left(v+v_w\right)^2$$

Wind Speed

$$N = mg\cos\theta$$

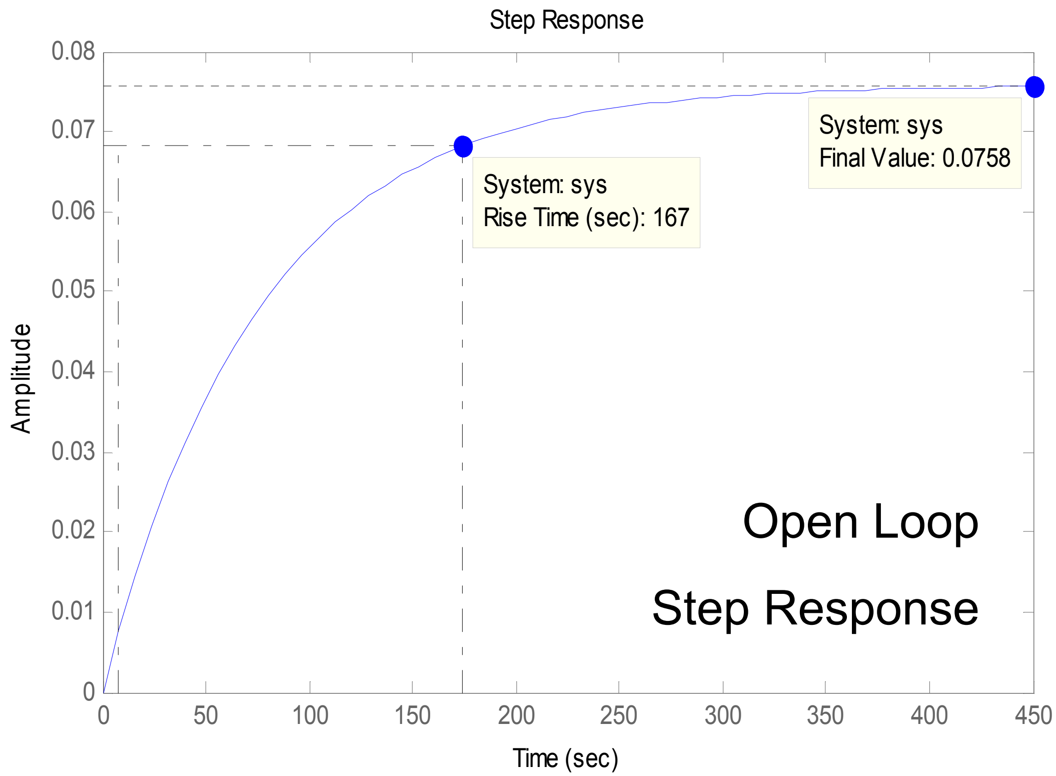
$$\boxed{m\frac{dv}{dt} = F_x - mg\sin\theta - fmg\cos\theta - 0.5\rho A C_d\left(v+v_w\right)^2}$$

Linearization and Ziegler-Nichols

$$\delta\dot{v} = -\frac{1}{m}\rho A C_d \left(v_0 + v_w\right)\delta v + \frac{1}{m}\delta F_x + \frac{1}{m}\left[-mg\cos\theta_0 + fmg\sin\theta_0\right]\delta\theta$$

Variable	Nominal Value
Traction Force, F_x	293 N
Road Grade, θ	0 radians
Wind Speed, v_w	2 m/s
Vehicle Speed, v	20 m/s ≈ 45 mph

$$\frac{Y(s)}{U(s)} = \frac{0.0758}{75.75s+1} = \frac{K}{\tau s+1}$$



Open Loop

Step Response

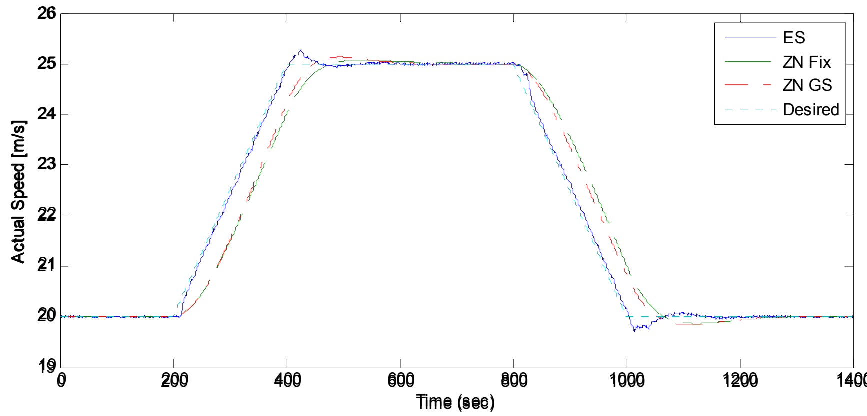
PI Controller:

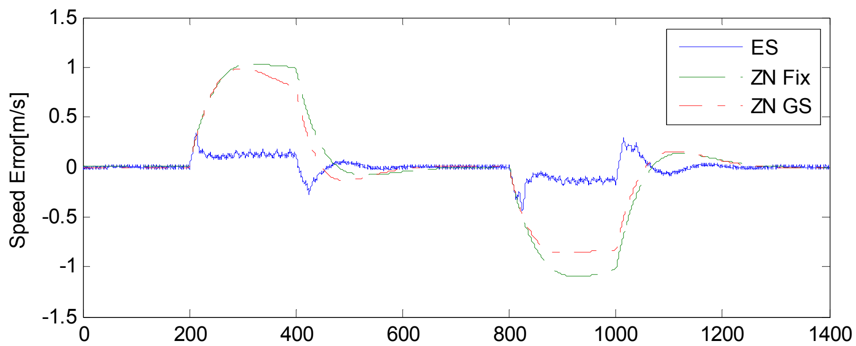
$$C(s) = K_{PI}\frac{\tau_{PI}s+1}{s} \xrightarrow{\text{Ziegler-Nichols}} C(s) = (0.3845)\frac{43s+1}{s}$$

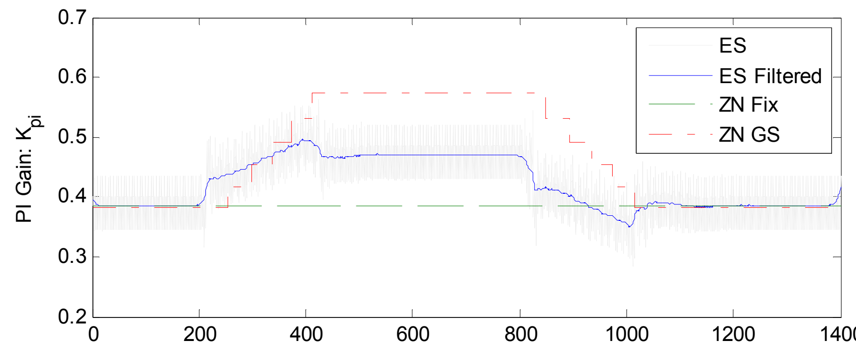
PI Tuning for Cruise Control

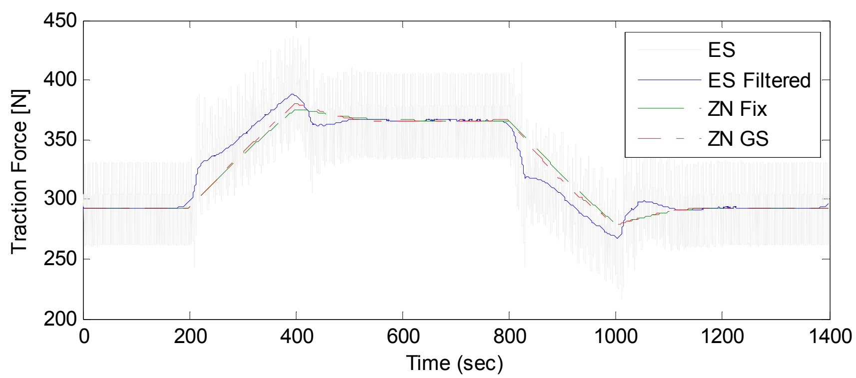
Control Methods

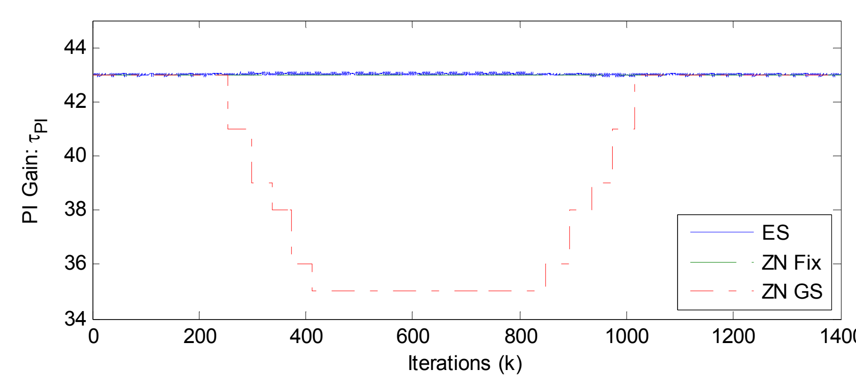
- Extremum Seeking (ES)
- Fixed Ziegler-Nichols Gains (ZN Fix)
- Gain Scheduling (ZN GS)











Summary & Conclusions

- Tunes PID controllers by minimizing a cost function characterizing the desired closed-loop behavior
- Achieves better or comparable results relative to other popular tuning methods
- Improper ES parameters may produce instability
- Successfully performs adaptation for time-varying systems
- Online adaptation does not require models

References

[1] N.J. Killingsworth, M. Krstic, "PID tuning using extremum seeking," *IEEE Control Systems Magazine*, pp 70-79, Feb. 2006.

[2] K.J. Åström, B. Wittenmark, *Computer Controlled Systems: Theory and Design*, 3rd ed. Upper Saddle River, NJ: Prentice-Hall, 1997.

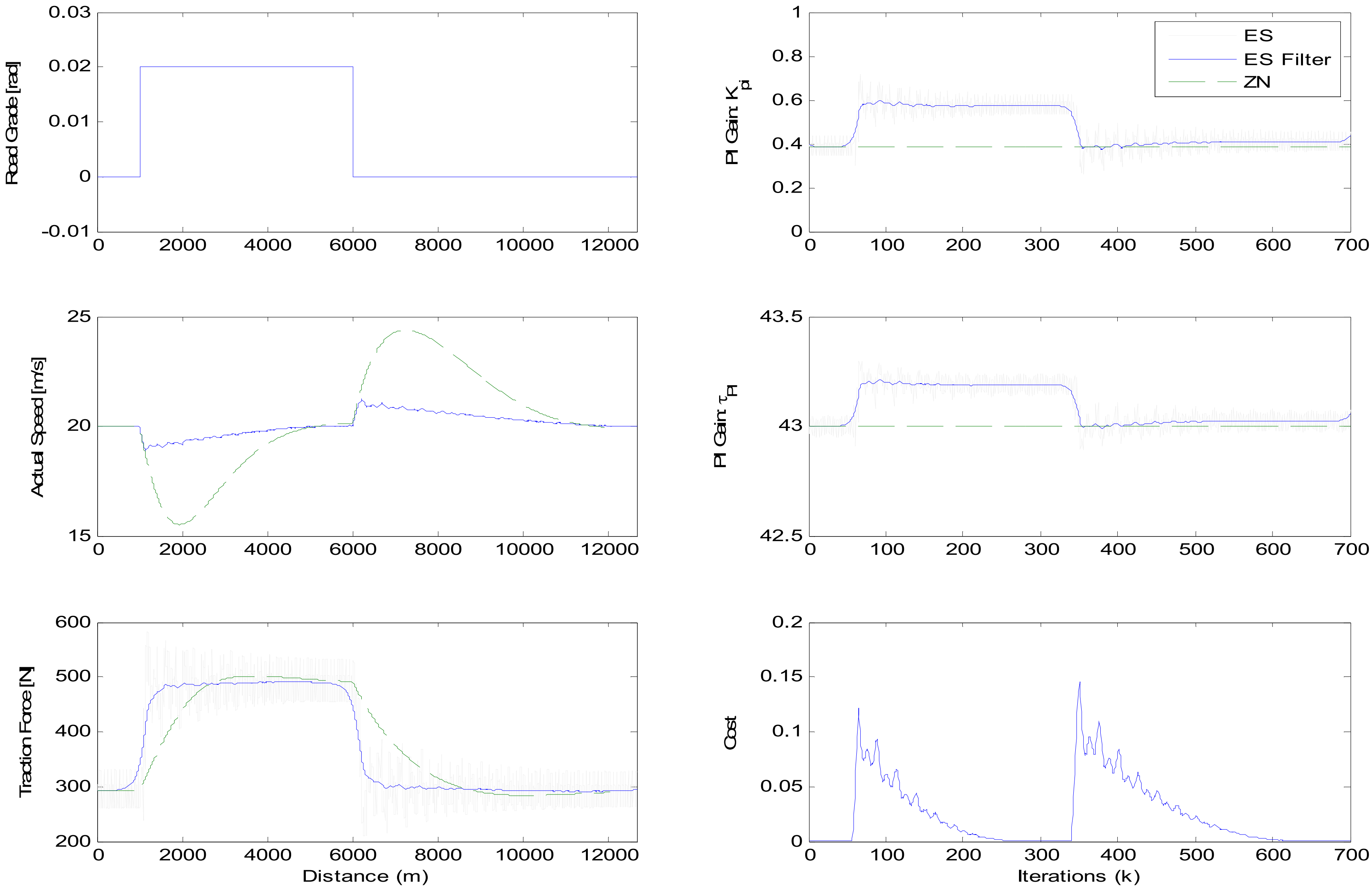
[3] O. Lequin, E. Bosmans, T. Triest, "Iterative feedback tuning of PID parameters: Comparison with classical tuning rules," *Contr. Eng. Pract.,* vol. 11, no. 9, pp. 1023-1033, 2003.

[4] A. Vahidi, A. Stefanopoulou, H. Peng, "Recursive least squares with forgetting for online estimation of vehicle mass and road grade: theory and experiments," *International Journal of Vehicle Mechanics and Mobility*, Jan 2005.

QUESTIONS?

APPENDIX SLIDES

Results: Road Grade Steps



Results: Vahidi Road Grade Profile (Linear Model)