Demonstrating Optimum HCCI Combustion with Advanced Control Technology

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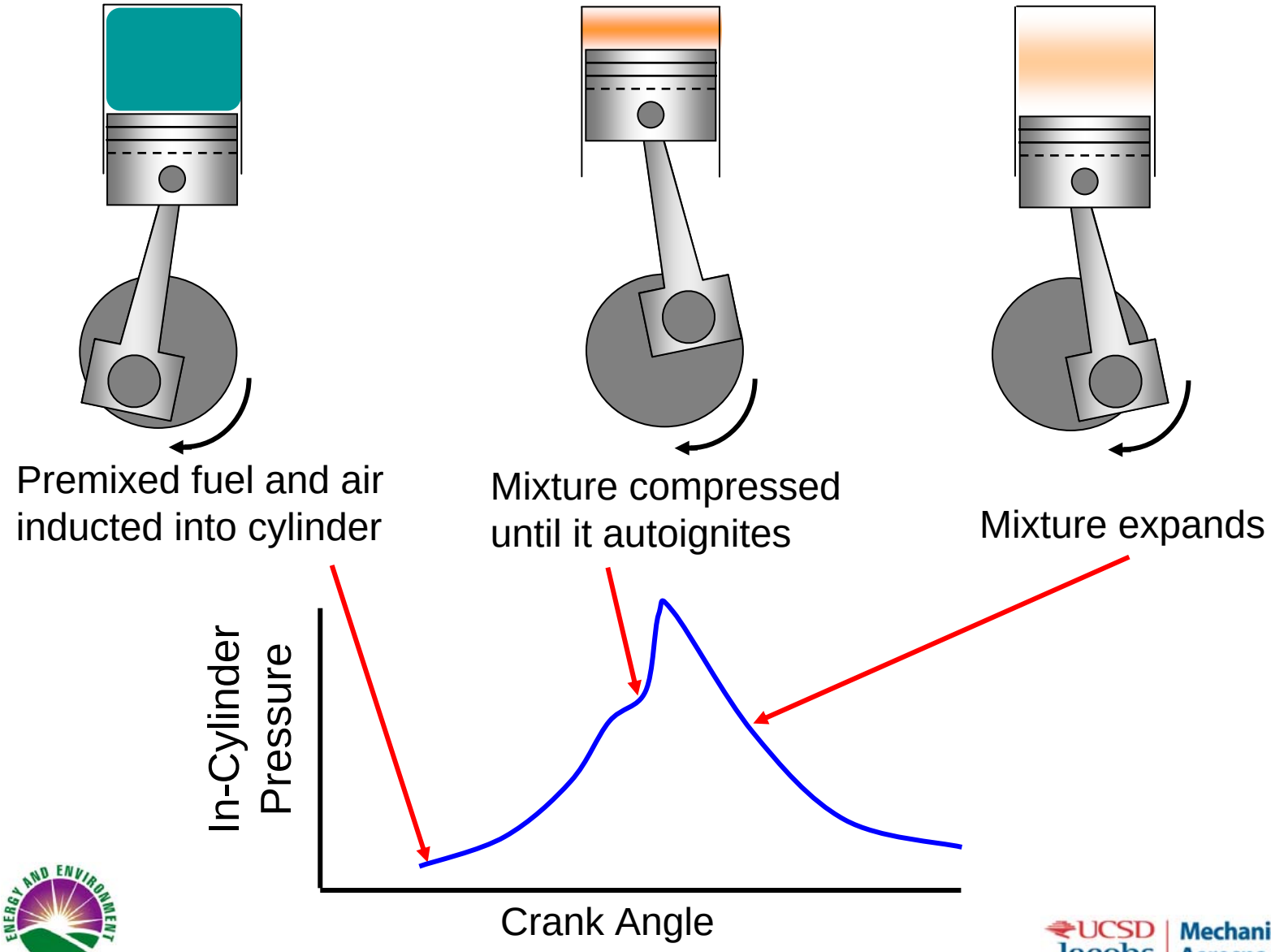
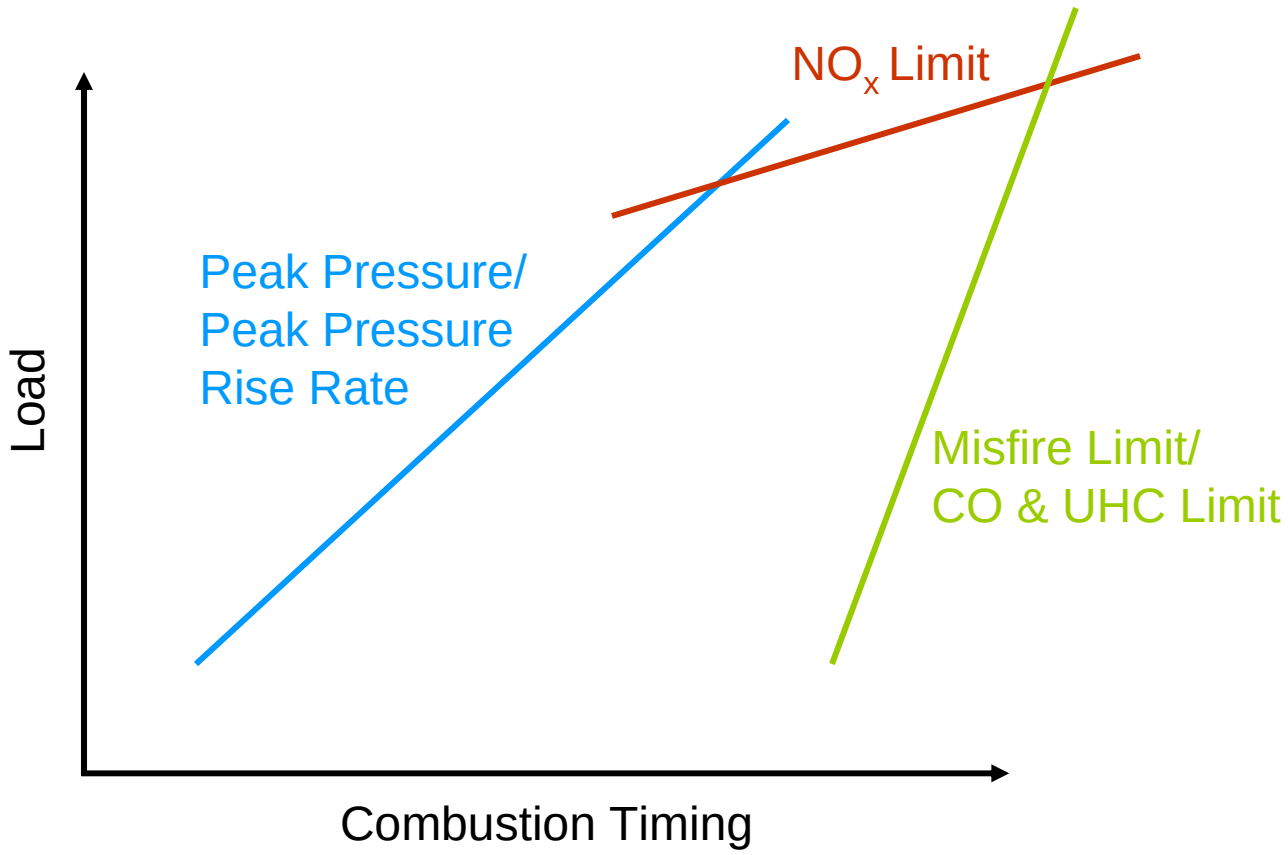
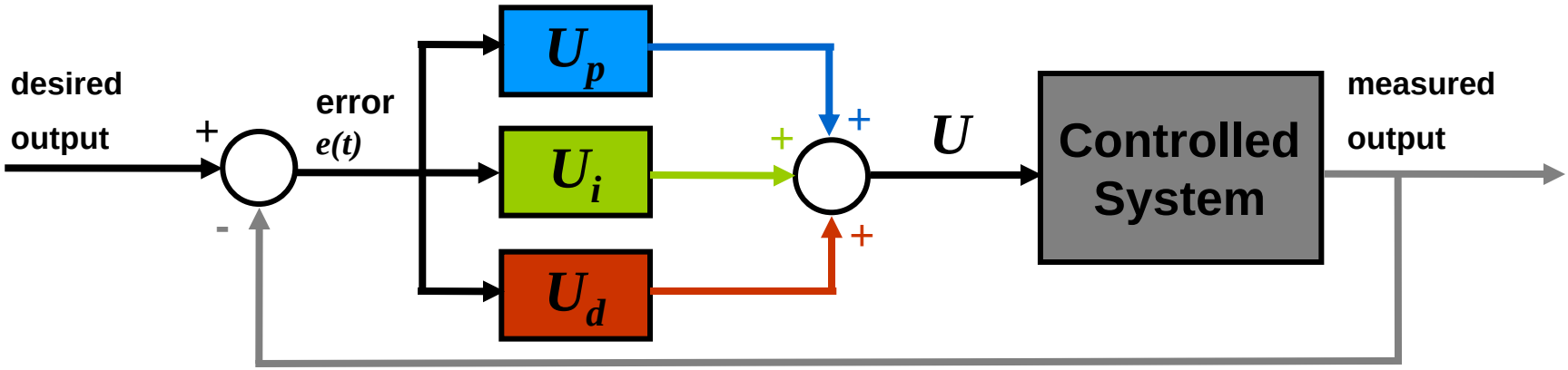
HCCI combustion occurs when premixed mixture autoignites, no direct trigger to initiate combustion



There is a window of allowable HCCI engine combustion timings due to constraints



A Proportional-Integral-Derivative (PID) controller has three terms



- Proportional to error: $u_P(t) = Ke(t)$

- Integral of error : $u_I(t) = \frac{K}{T_I}\int_0^t e(s)ds$

- Derivative of error: $u_D(t) = KT_D\frac{de(t)}{dt}$

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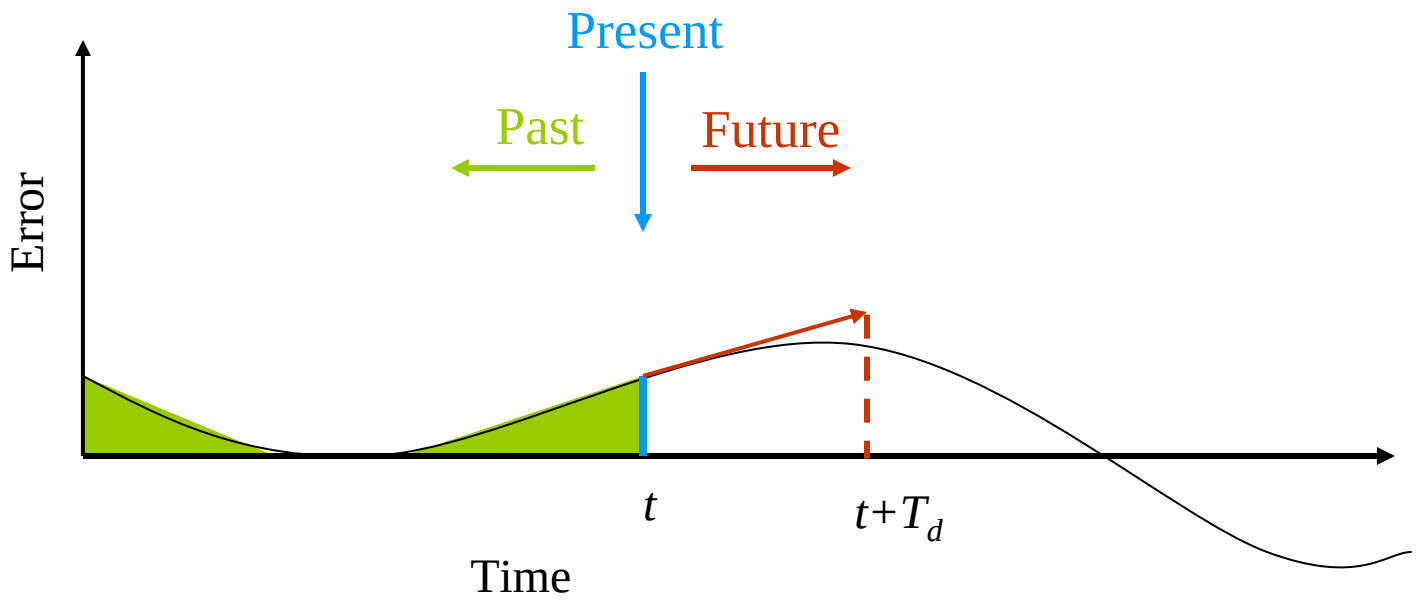
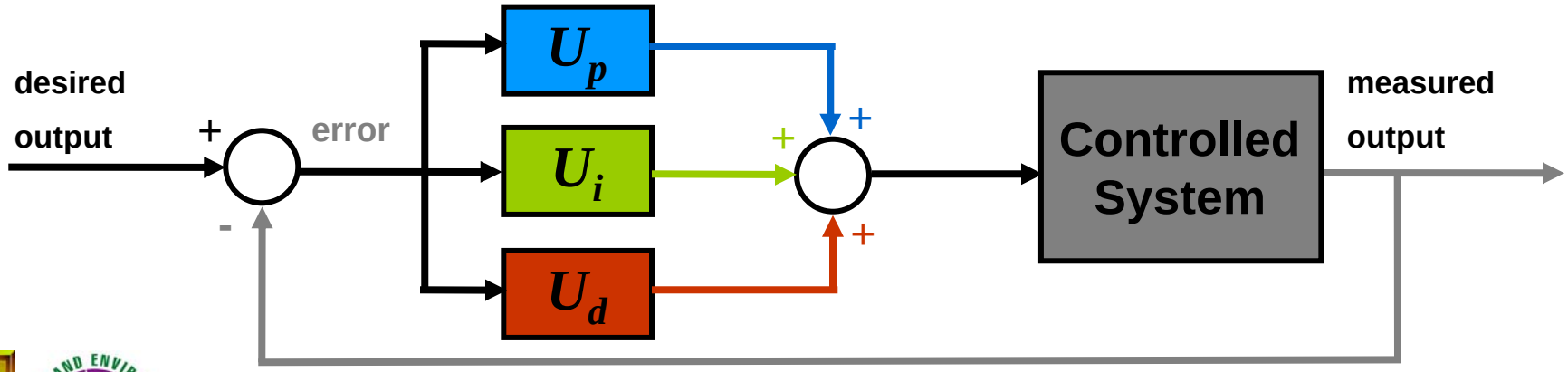
PID controller takes control action based on past, present, and future control errors





Gain scheduling of PID parameters required due to nonlinear nature of HCCI engines

Gain Scheduled PID Parameters (K, T_I, T_D)

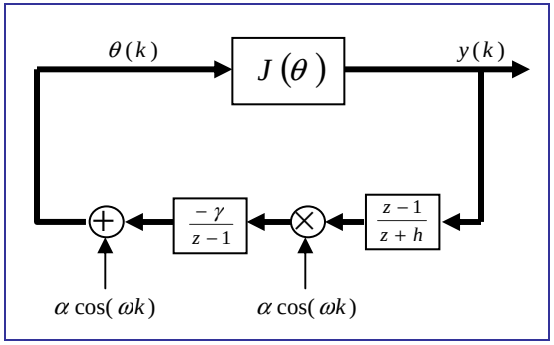
IMEP / RPM	0-1 [bar]	1-2 [bar]	2-3 [bar]	3-4 [bar]
0-1000	$PID_{1,1}$	$PID_{1,2}$	$PID_{1,3}$	$PID_{1,4}$
1001-2000	$PID_{2,1}$	$PID_{2,2}$	$PID_{2,3}$	$PID_{2,4}$
2001-3000	$PID_{3,1}$	$PID_{3,2}$	$PID_{3,3}$	$PID_{3,4}$
3001-4000	$PID_{4,1}$	$PID_{4,2}$	$PID_{4,3}$	$PID_{4,4}$
4001-5000	$PID_{5,1}$	$PID_{5,2}$	$PID_{5,3}$	$PID_{5,4}$

Online non-model based controller tuning methods are desirable

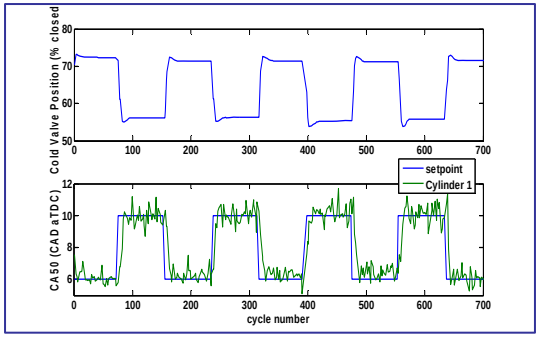
- Many methods have been developed
  - Model based methods
    - Model must be derived or estimated
    - Controller parameters calculated offline
  - Non-model based methods
    - Require offline calculations
  - Extremum Seeking
    - Non-model based
    - Online tuning procedure


We have applied extremum seeking to tune HCCI combustion timing controller

Experimental HCCI engine setup



Extremum seeking controller tuning scheme



Experimental controller tuning

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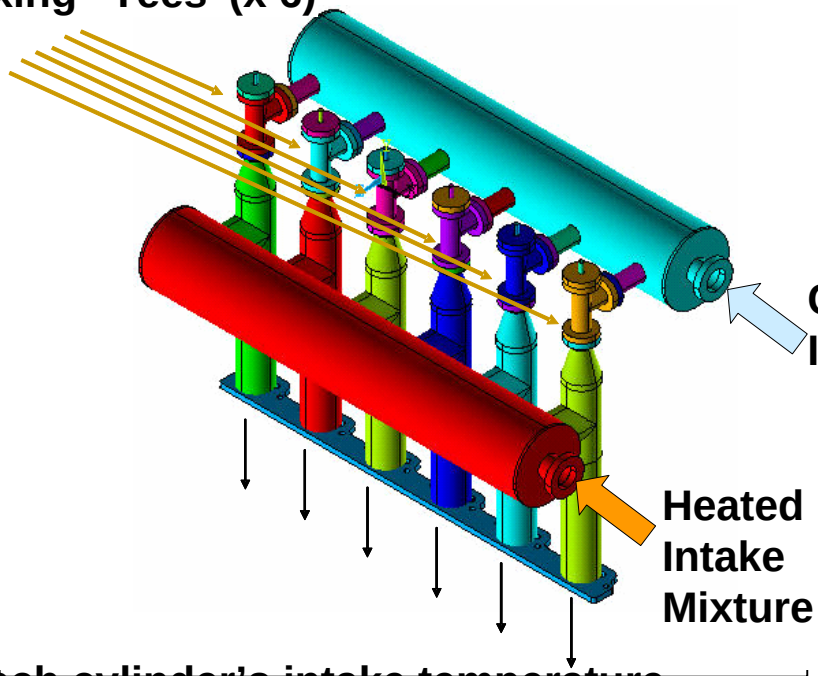
Caterpillar 3406 operated at LLNL the platform for control experiments

- Converted 3406 spark ignited engine
- 15L 6-cylinder engine

Intake temperature effective means to control combustion timing

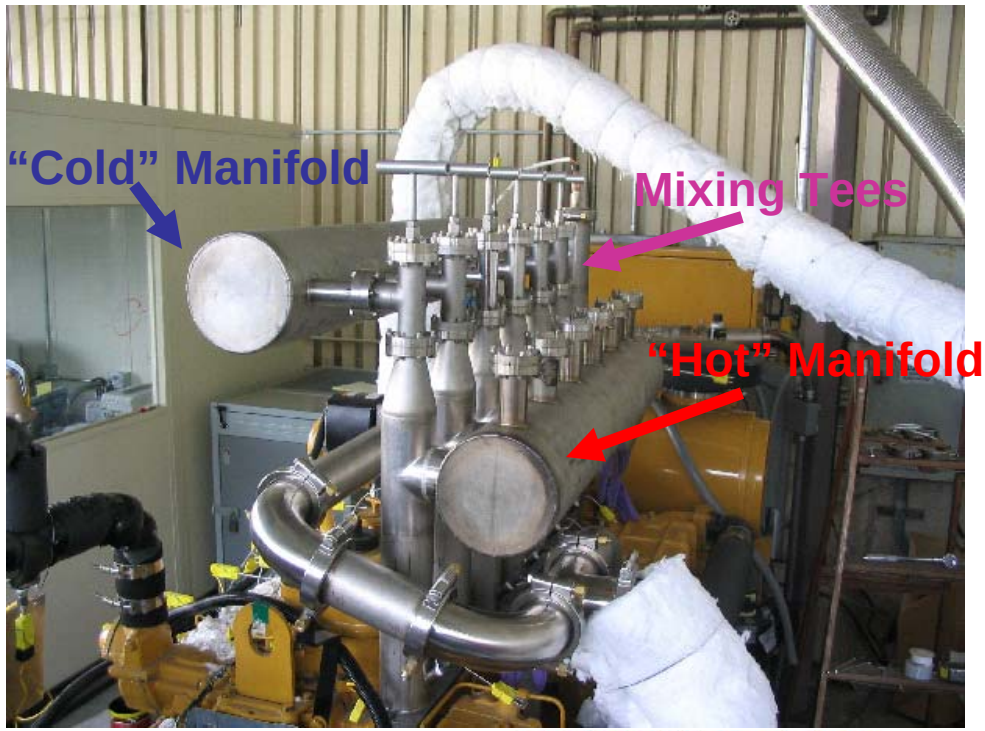
Mixing “Tees”(x 6)



Cooled Intake Mixture

Heated Intake Mixture

Each cylinder’s intake temperature controlled individually



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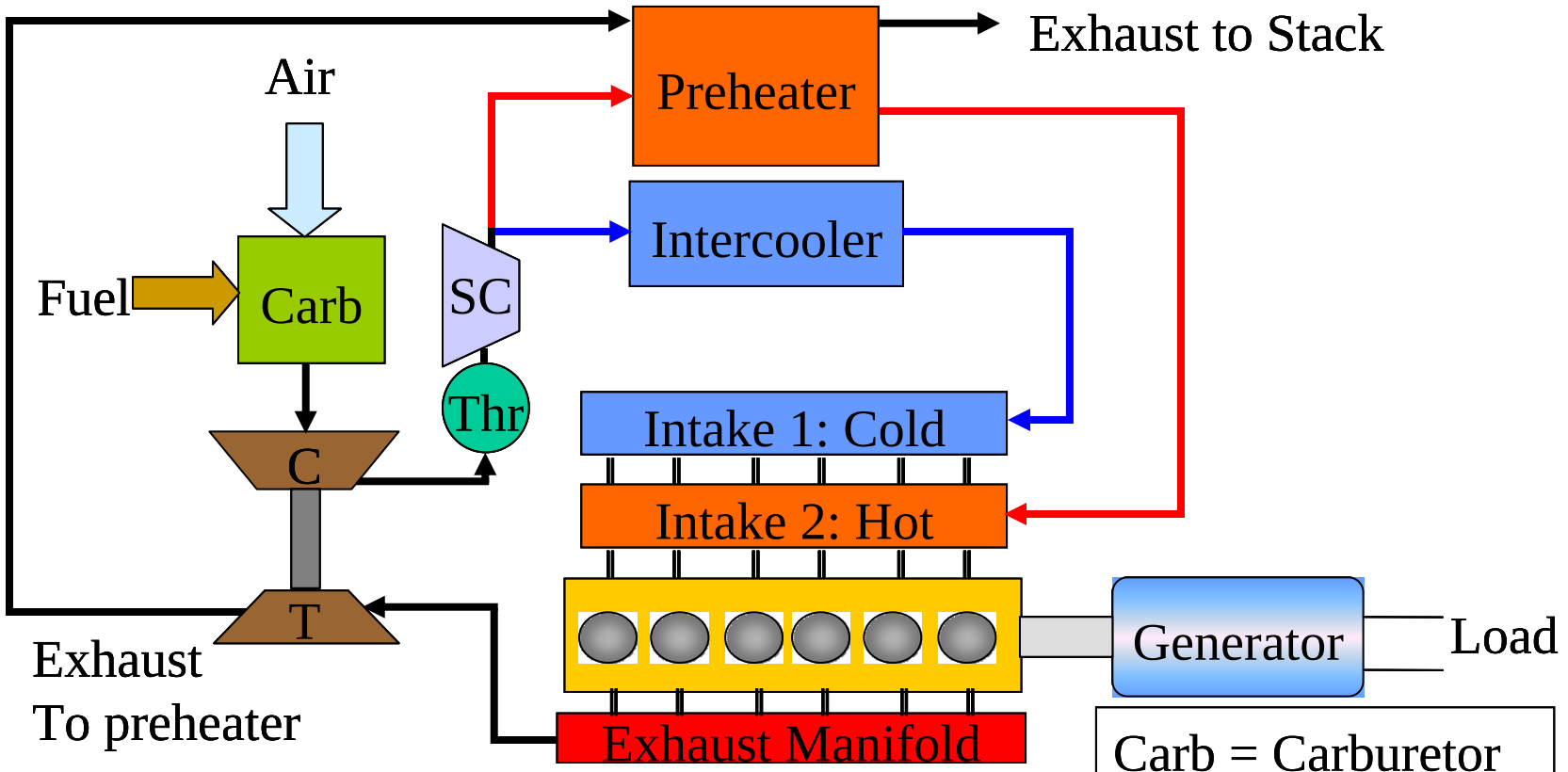
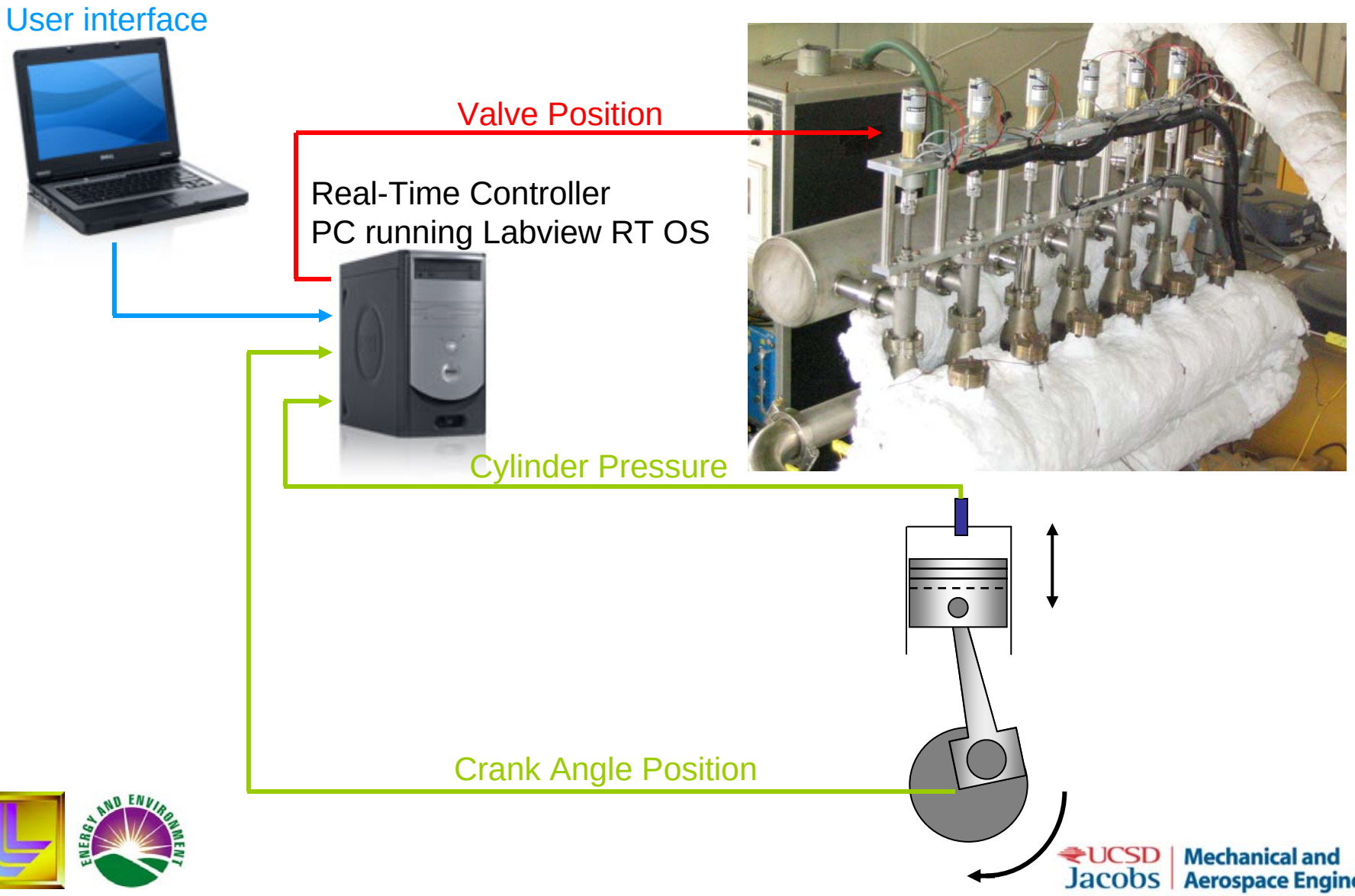
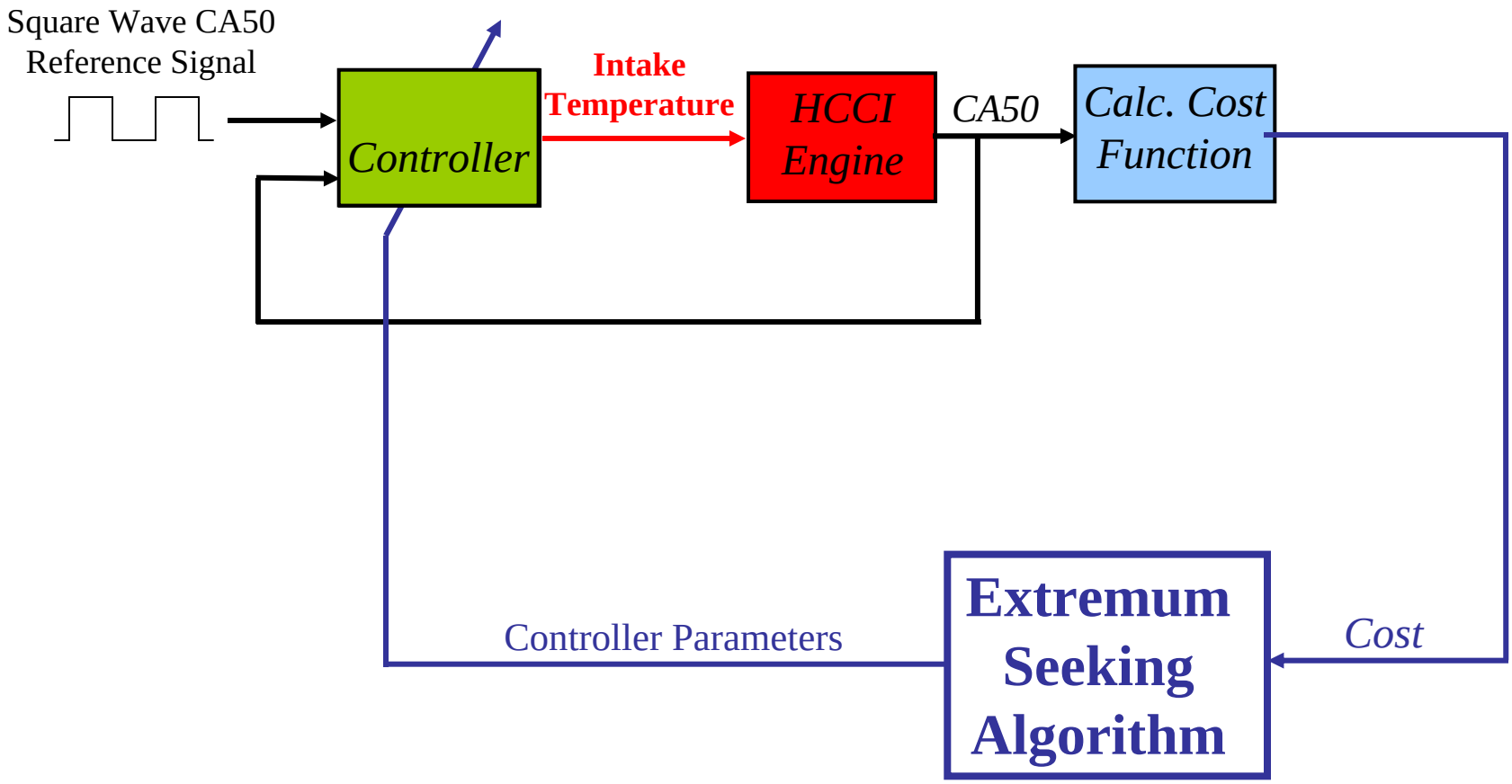
Schematic of the HCCI engine and thermal management system used in experiments



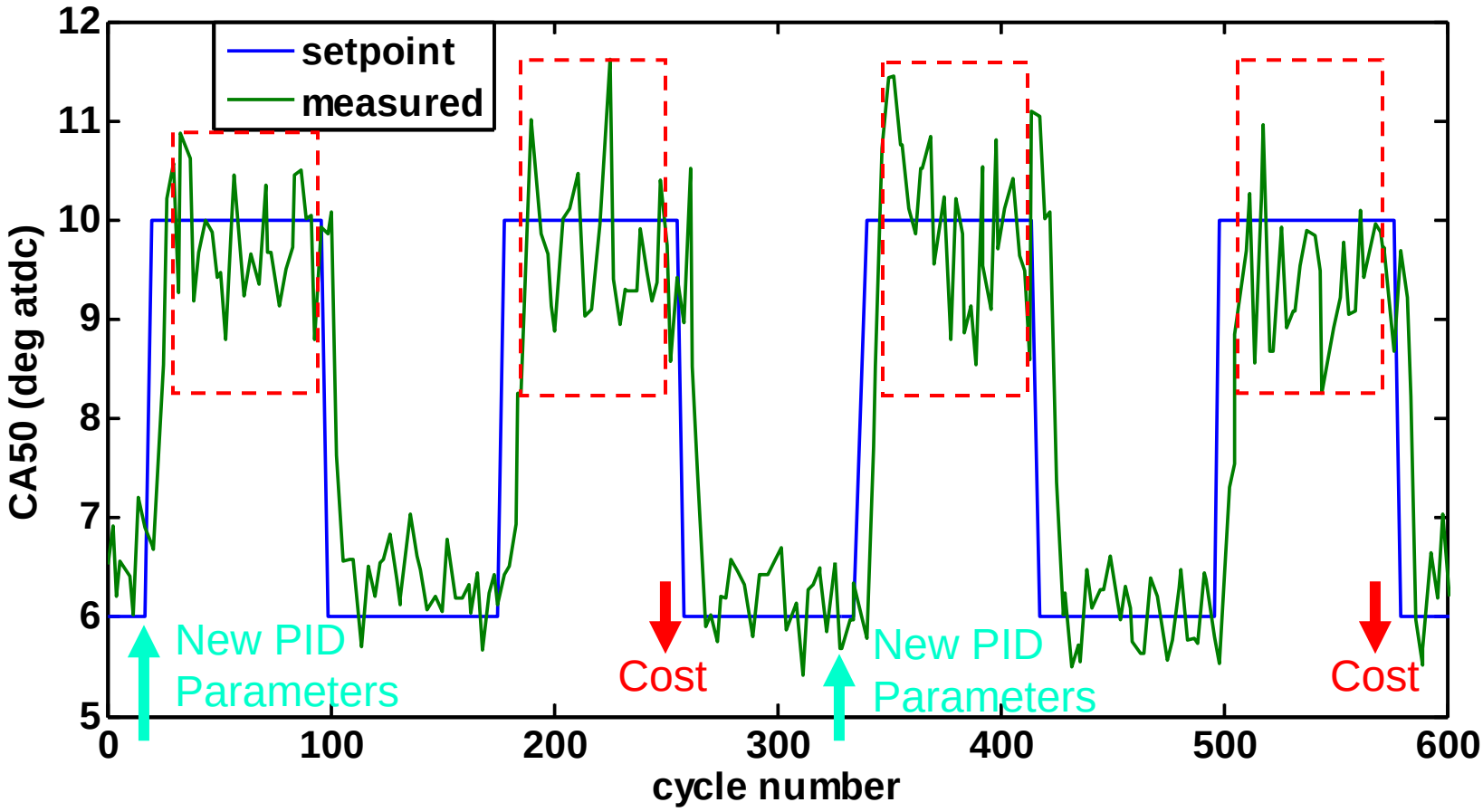
Real-time control system utilizes cylinder pressure measurements as feedback signal



Extremum seeking minimizes cost function by tuning the controller parameters

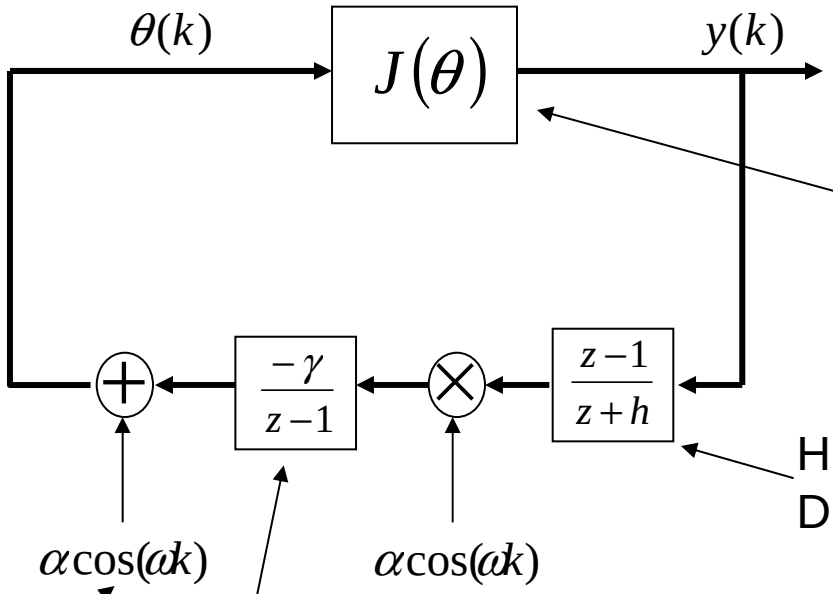


Cost function calculated as combustion timing responds to square wave setpoint change



Combustion timing varied from 6 to 10 CAD ATDC, cost function only calculated at later timing (10 CAD ATDC)

Extremum seeking: non-model-based optimization method



Function we are trying to optimize

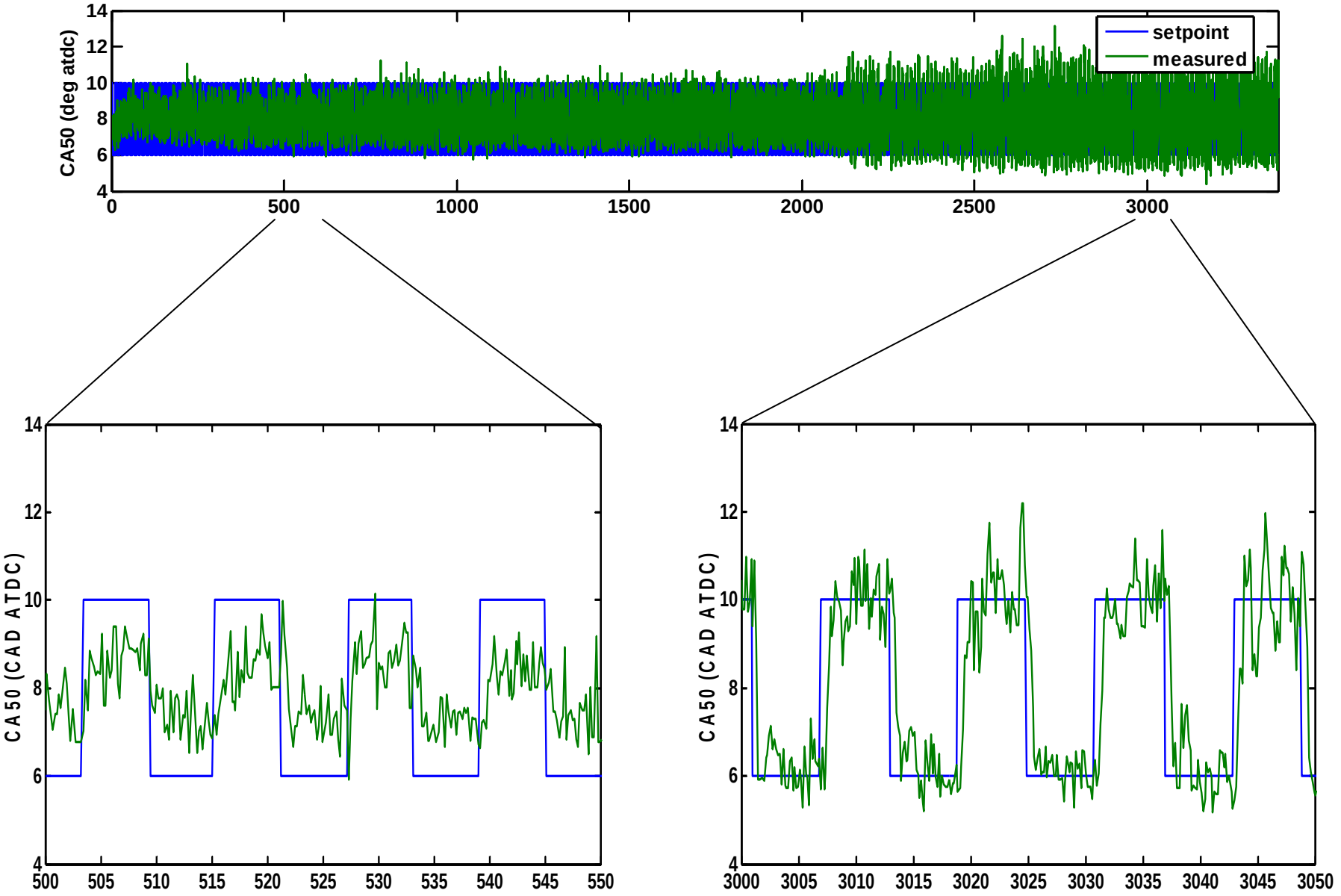
High Pass Filter removes DC component of output $y(k)$

Demodulate by multiplication with $\alpha\cos(\omega k)$, this picks out portion of output due to perturbation, $\alpha\cos(\omega k)$

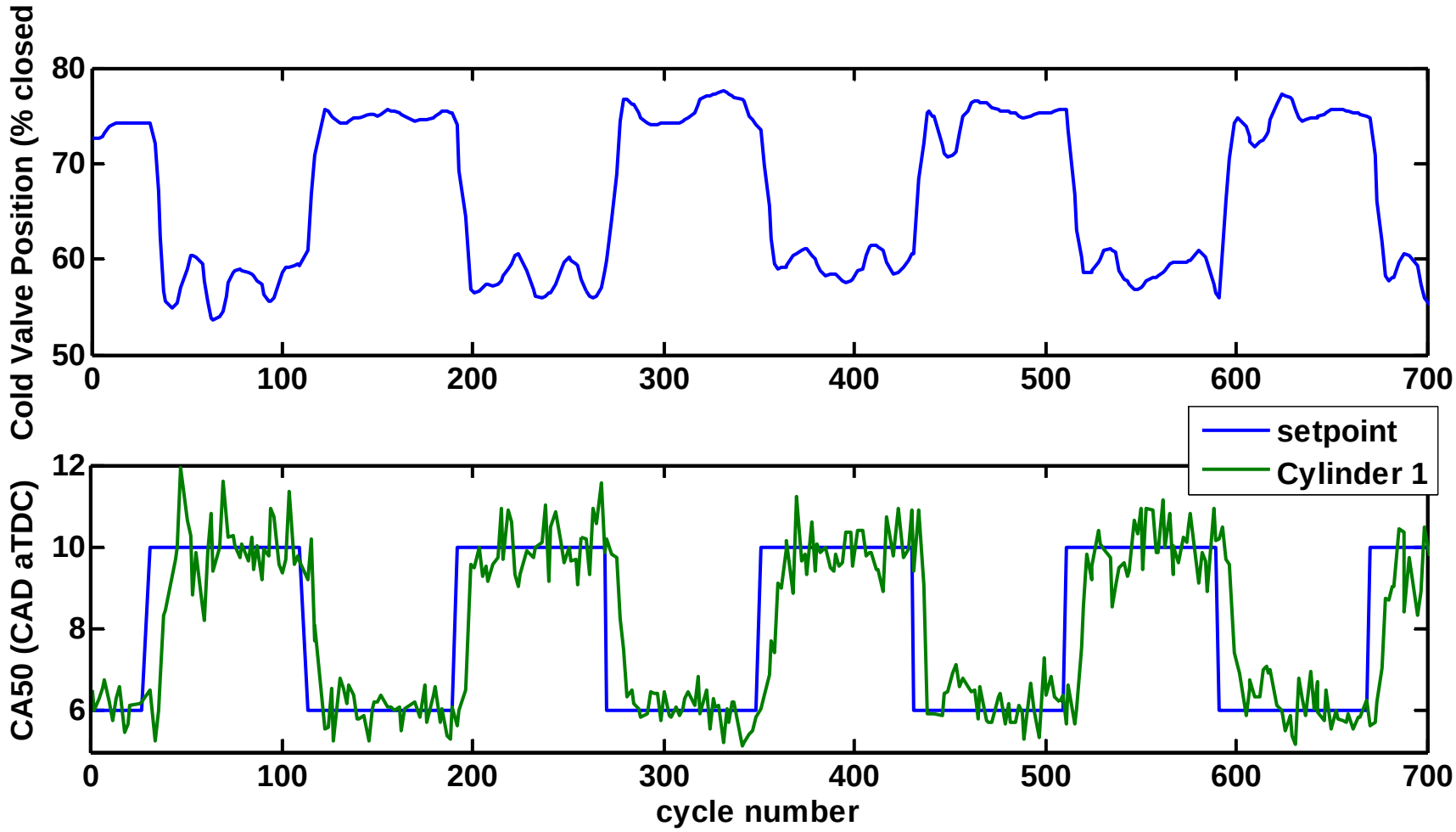
Perturb system in order to generate gradient

Estimate of gradient is then integrated to yield a new θ closer to θ^*

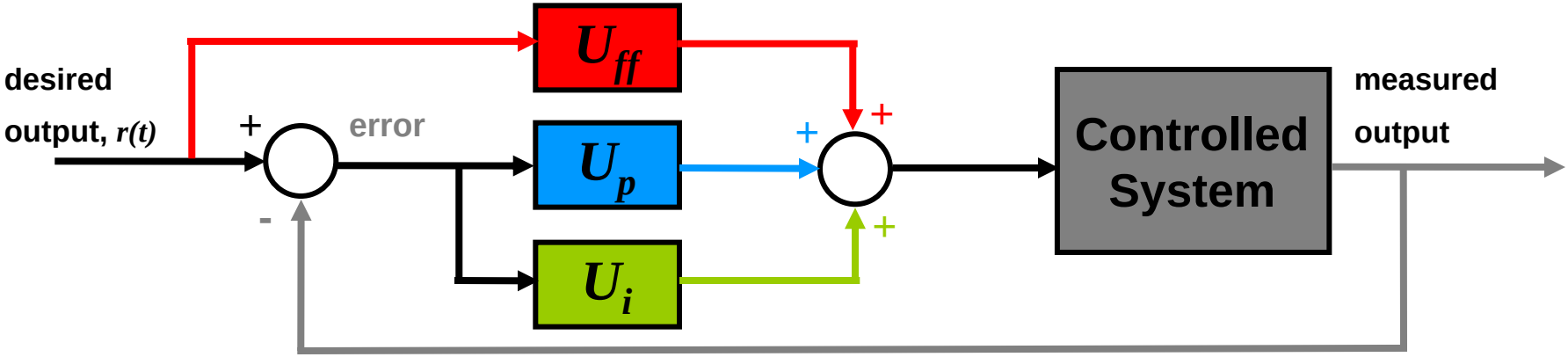
Extremum seeking used to tune a PI controller for improved setpoint response of combustion timing



PI controller tuned for fast setpoint response results in high controller gains



A feedforward term was added to the PI controller



- Constant feedforward term: $u_{ff}(t) = K_{ff} r(t)$

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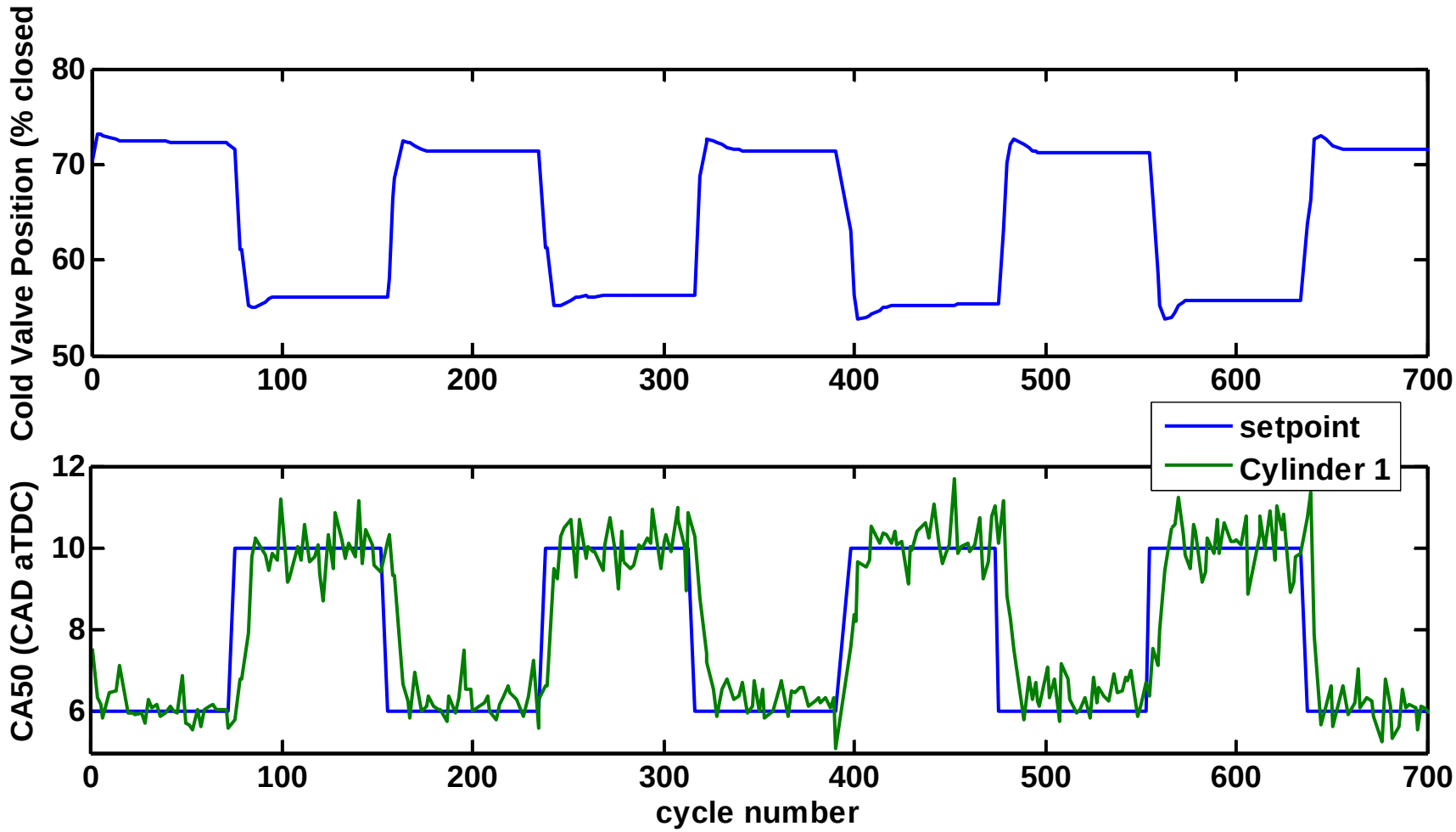
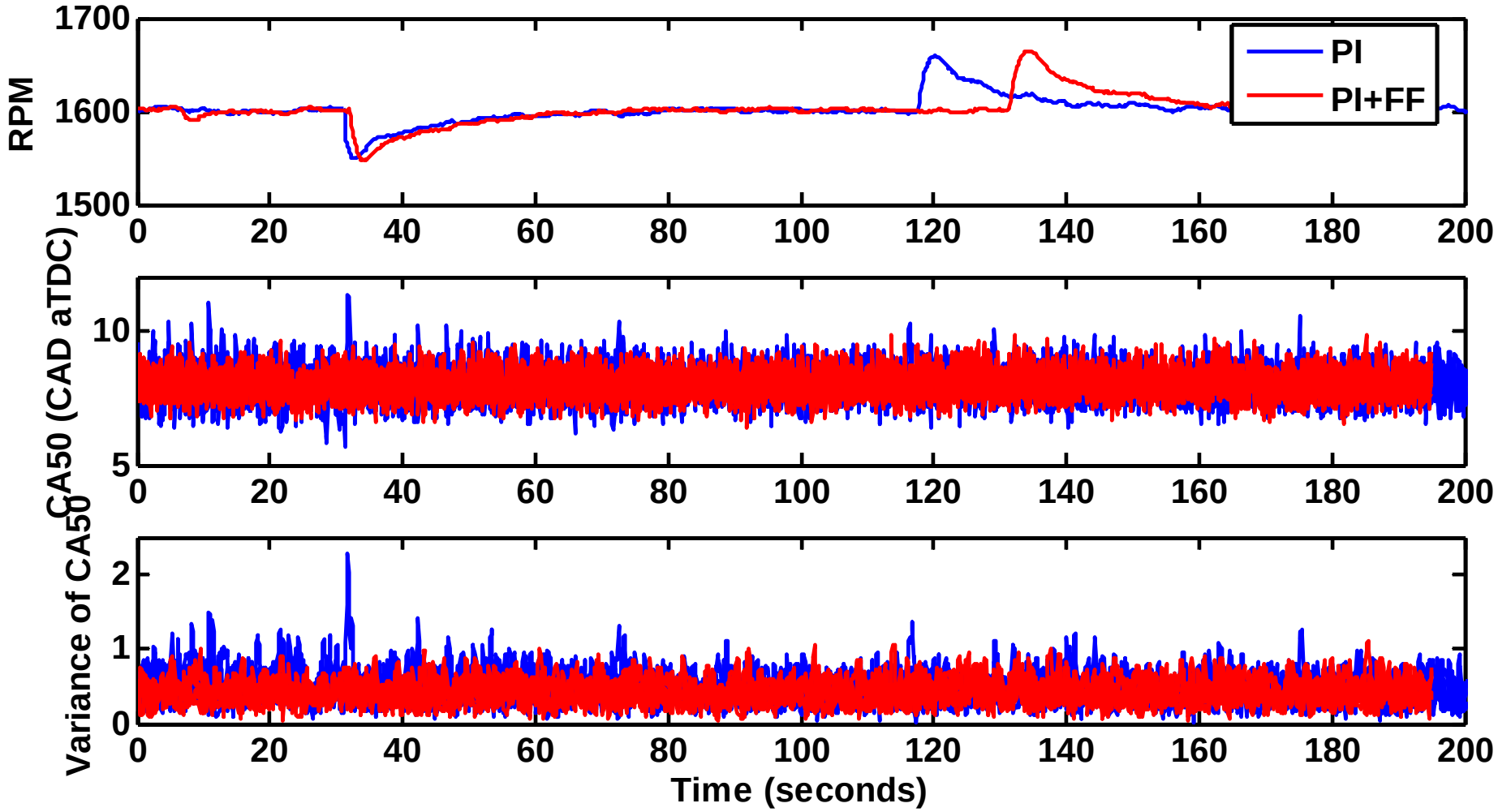
PI + feedforward controller tuned using ES
feedforward results in less high frequency gain



ES optimized PI and PI+FF controllers able to hold constant combustion timing during load disturbance



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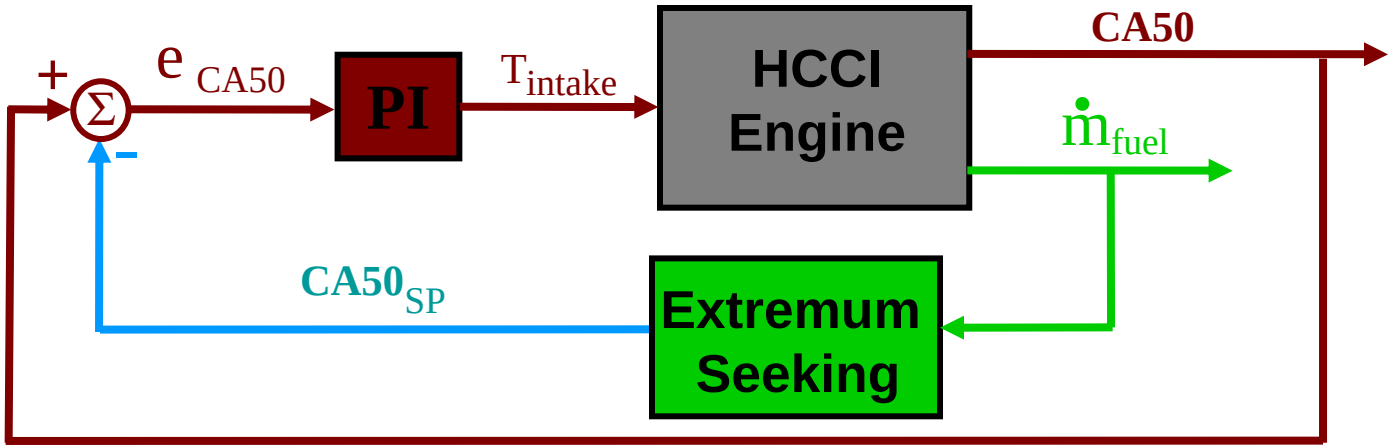
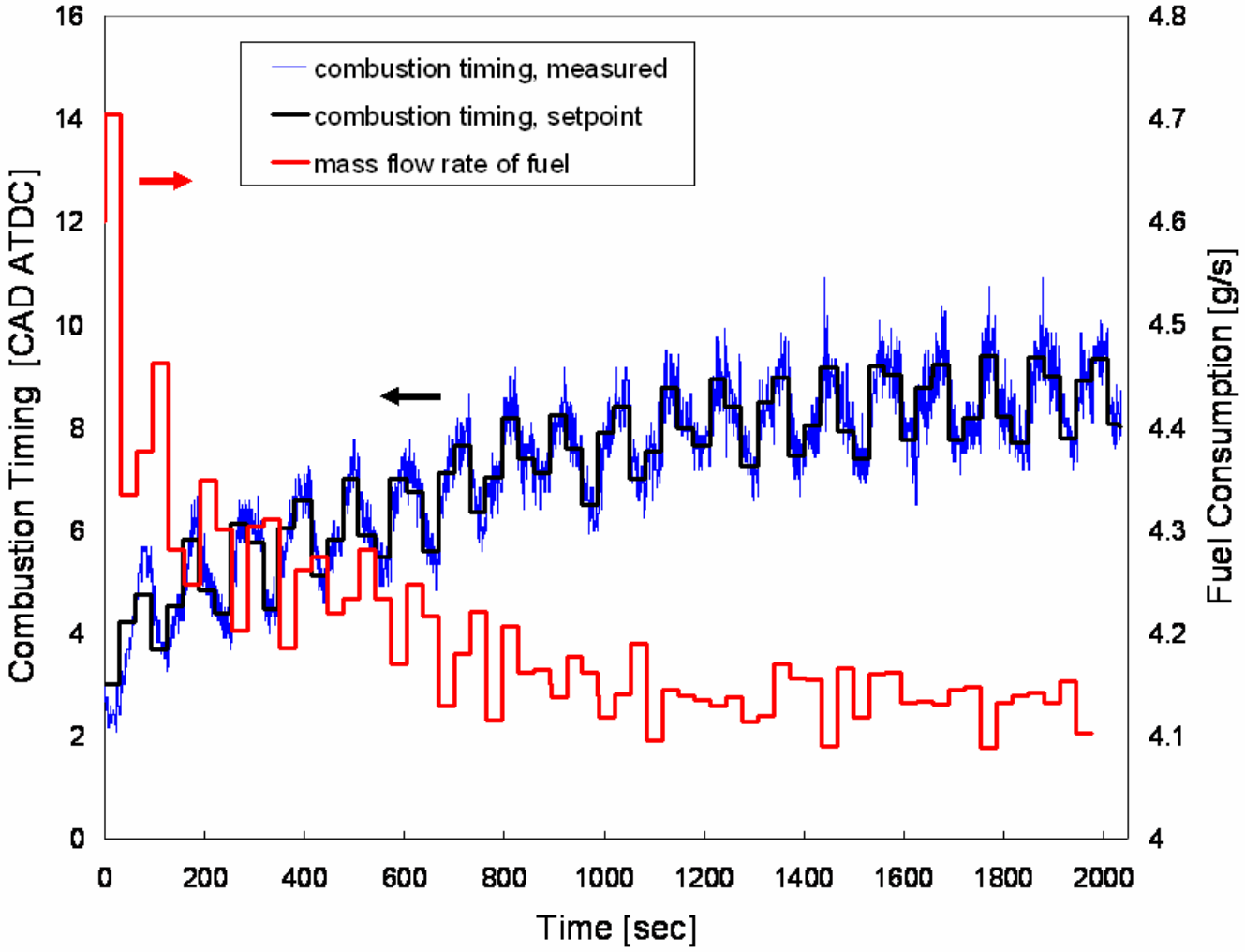
ES scheme used to minimize fuel consumption of experimental HCCI engine by determining optimal combustion timing setpoint



ES delays the combustion timing 6 CAD reducing fuel consumption by more than 10%



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Extremum Seeking is a useful tool for rapidly improving HCCI controller performance

- We use ES to tune various forms of PID controllers while the engine is operating
- ES can also be used to optimize performance parameters (such as minimize fuel consumption)
- ES greatly aids in automating and optimizing the development of controllers for nonlinear systems like HCCI engines


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