Idle Speed Controller Design and Verification for an Automotive Engine

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Outline

- The idle speed control problem
- Hybrid model of the engine
- Previous work: maximal safe set computation
- Controller design
- Formal verification of the closed-loop system behavior
- Conclusions

Idle Speed Control

Objective: ***maintain the crankshaft speed within a specified range, when the accelerator pedal is released and the gear is not engaged (idle).***

- **Plant Modeling:**
  - **Survey paper** *[Hrovat & Sun, 1997]*
  - **Time-domain average models** *[Butts et al., 1999]*
  - **Crank-angle domain average models** *[Yurkovich & Simpson, 1997]*
- **Control Techniques:**
  - **Multivariable control** *[Onder & Geering, 1993]*
  - **μ-synthesis** *[Hrovat & Bodehimer, 1993]*
  - **L_1 control** *[Butts, et al., 1999]*, **Hinf control** *[Carnevale & Moschetti, 1993]*
  - **Sliding-modes control** *[Kjergaard et al, 1994]*
  - **LQ-based optimization** *[Abate & Di Nunzio, 1990]*

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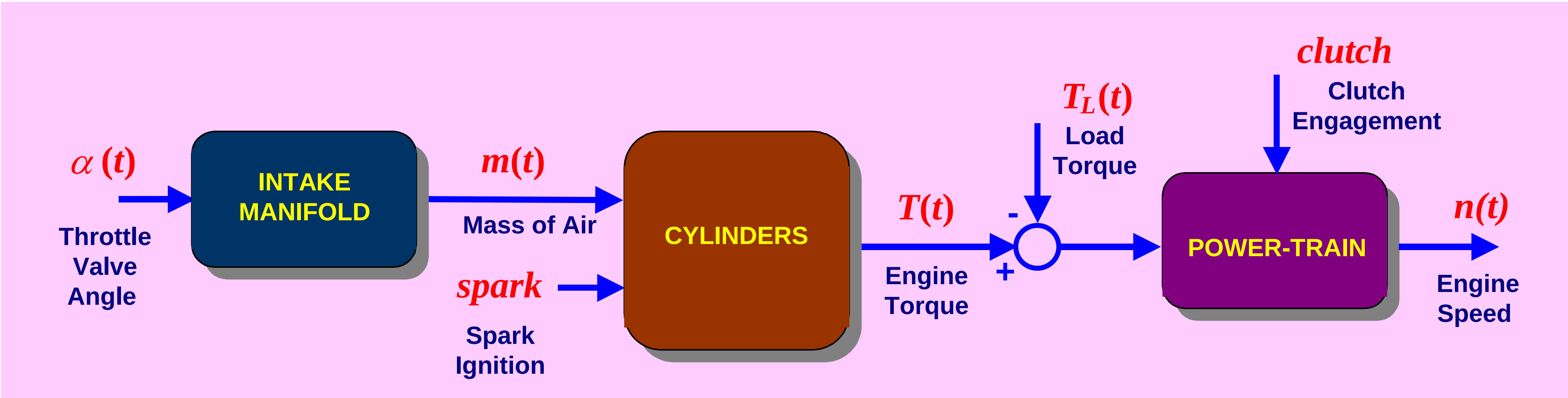
Engine Hybrid Model (no GDI)



Controls	Time / Value
ignition *spark*	disc / disc
throttle α	cont / cont

Disturbances	Time / Value
clutch ***clutch***	disc / disc
load torque T_L	cont / cont

Control Problem

*Find feedback controls (**spark**, α) that maintain the engine speed **n** within a given range $n_0 \pm \Delta$ under any action of (**clutch**, T_L).*

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Engine hybrid model: intake manifold & power-train

Intake Manifold

Throttle angle α in $[0, \alpha_M]$

State	Time / Value
manifold pressure p	cont / cont

$$\dot{p}(t) = a_p p(t) + b_p \alpha(t)$$

Power-train

The gear is not engaged.

$$a_n = -B b_n$$

$$b_n = \begin{cases} 1/J & \text{if clutch pedal is pressed} \\ 1/(J + J') & \text{if clutch pedal is released} \end{cases}$$

States	Time / Value
crankshaft speed n	cont / cont
crankshaft angle θ	cont / cont

$$\dot{n}(t) = a_n n(t) + b_n (T(t) - T_L(t))$$

$$\dot{\theta}(t) = 6n(t), \quad \text{if } \theta = 180 \text{ then } \theta := 0$$

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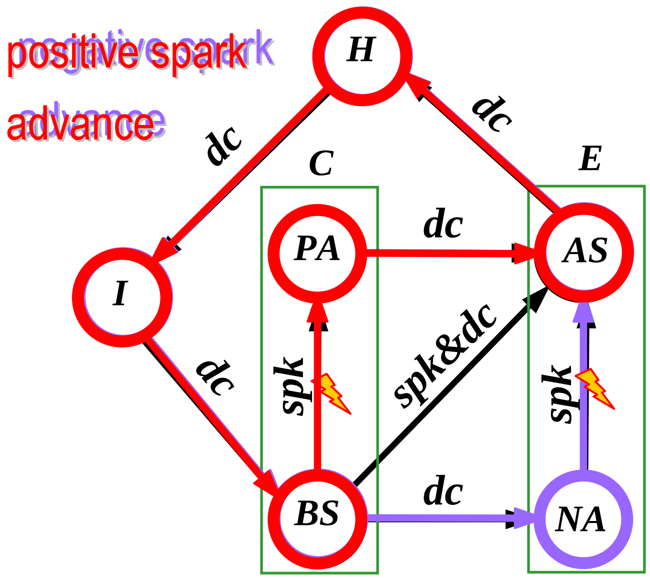
Single cylinder FSM: engine cycle

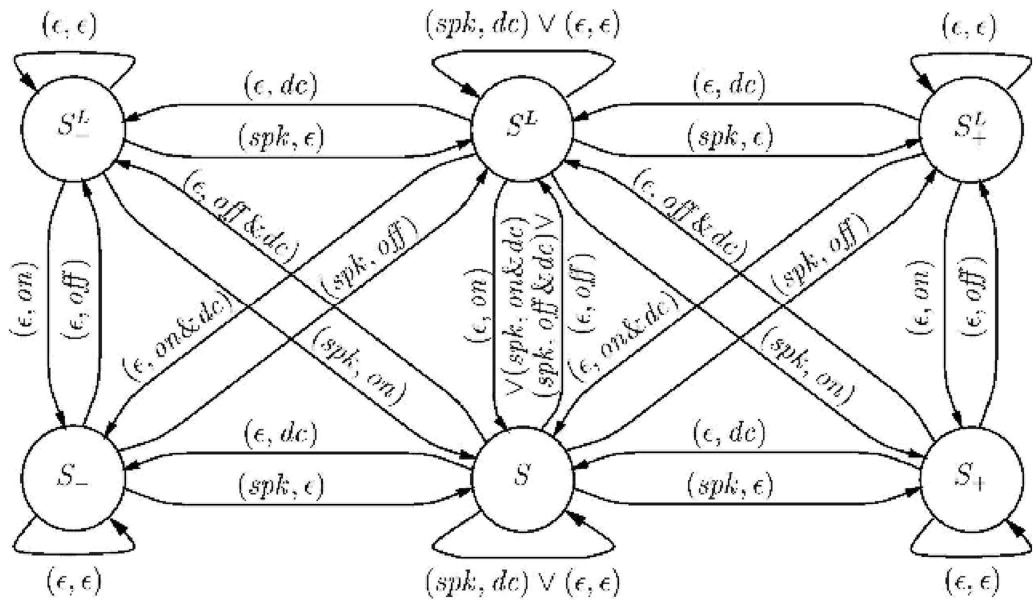


States	Time / Value
mass of air m	disc / cont
generated torque T	disc / cont
spark advance angle φ	disc / cont

$\mathbf{I} \rightarrow \mathbf{BS}$	$m := c_p \eta_v(p) p$
$\mathbf{BS} \rightarrow \mathbf{PA}$	$\varphi := 180 - \theta$
$\mathbf{PA} \rightarrow \mathbf{AS}$	$T := T_{\text{pot}}(m)\, \eta_c(\varphi - \varphi_{\text{opt}}, m) = T_{\text{gen}}(m, \varphi)$
$\mathbf{NA} \rightarrow \mathbf{AS}$	$\varphi := -\theta$ $T := T_{\text{gen}}(m, -\theta)$
$\mathbf{AS} \rightarrow \mathbf{H}$	$T := 0$

stoichiometric fuel injection.

4-Cylinder Engine Hybrid Automaton



$$\dot{p}(t) = a_p p(t) + b_p \alpha(t)$$
$$\dot{n}(t) = a_n n(t) + b_n (T - T_L(t))$$
$$\dot{\theta}(t) = 6n(t)$$
$$a_n = -B b_n \qquad b_n = \begin{cases} 1/J \\ 1/(J + J') \end{cases}$$

q	θ	M_c^{disc}	q	θ	M_e^{disc}
S	$[0,160)$	$\{\epsilon\}$	S	$[0,180)$	$\{\epsilon, off\}$
	$[160,180]$	$\{\epsilon, spk\}$		180	$\{dc, off\&dc\}$
S^L	$[0,160)$	$\{\epsilon\}$	S^L	$[0,180)$	$\{\epsilon, on\}$
	$[160,180]$	$\{\epsilon, spk\}$		180	$\{dc, on\&dc\}$
S_+	$[0,180]$	$\{\epsilon\}$	S_-	$[0,15]$	$\{\epsilon, off\}$
S_+^L	$[0,180]$	$\{\epsilon\}$	S_-^L	$[0,15]$	$\{\epsilon, on\}$
S_-	$[0,15)$	$\{\epsilon, spk\}$	S_+	$[0,180)$	$\{\epsilon, off\}$
	15	$\{spk\}$		180	$\{dc, off\&dc\}$
S_-^L	$[0,15)$	$\{\epsilon, spk\}$	S_+^L	$[0,180)$	$\{\epsilon, on\}$
	15	$\{spk\}$		180	$\{dc, on\&dc\}$

q	$(spk, clutch)$	$\delta\vert_x$	$\delta\vert_z$
S	(ϵ, off) (ϵ, dc) $(\epsilon, off\&dc)$	$\theta := 0$	$m_C := c_p\eta_v(p)p,$ $m_E := m_C,\ T := 0$
	(spk, ϵ) (spk, off)		$\varphi := 180 - \theta$
	(spk, dc) $(spk, off\&dc)$	$\theta := 0$	$m_C := c_p\eta_v(p)p,$ $T := T_{gen}(m_C, 0)$
S^L	(ϵ, on) (ϵ, dc) $(\epsilon, on\&dc)$	$\theta := 0$	$m_C := c_p\eta_v(p)p,$ $m_E := m_C,\ T := 0$
	(spk, ϵ) (spk, on)		$\varphi := 180 - \theta$
	(spk, dc) $(spk, on\&dc)$	$\theta := 0$	$m_C := c_p\eta_v(p)p,$ $T := T_{gen}(m_C, 0)$
S_-	(ϵ, off)		
	(spk, ϵ) (spk, off)		$T := T_{gen}(m_E, -\theta)$
S_-^L	(ϵ, on)		
	(spk, ϵ) (spk, on)		$T := T_{gen}(m_E, -\theta)$
S_+	(ϵ, off) (ϵ, dc) $(\epsilon, off\&dc)$	$\theta := 0$	$m_C := c_p\eta_v(p)p,$ $T := T_{gen}(m_C, \varphi)$
S_+^L	(ϵ, on) (ϵ, dc) $(\epsilon, on\&dc)$	$\theta := 0$	$m_C := c_p\eta_v(p)p,$ $T := T_{gen}(m_C, \varphi)$

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Previous Work

- In ***HSCC2000***, the idle speed control was formalized as a safety problem and the maximal safe set was obtained by applying TLS' procedure [HSCC98].
- In ***ACC2000***, some linearity assumptions in the model used in HSCC2000 had been removed and the final result was obtained.

Control Problem

Given a value of n_0, Δ and T_L^M, determine whether there exist

- an ignition control *spark* and
- a throttle control $\alpha(t)$

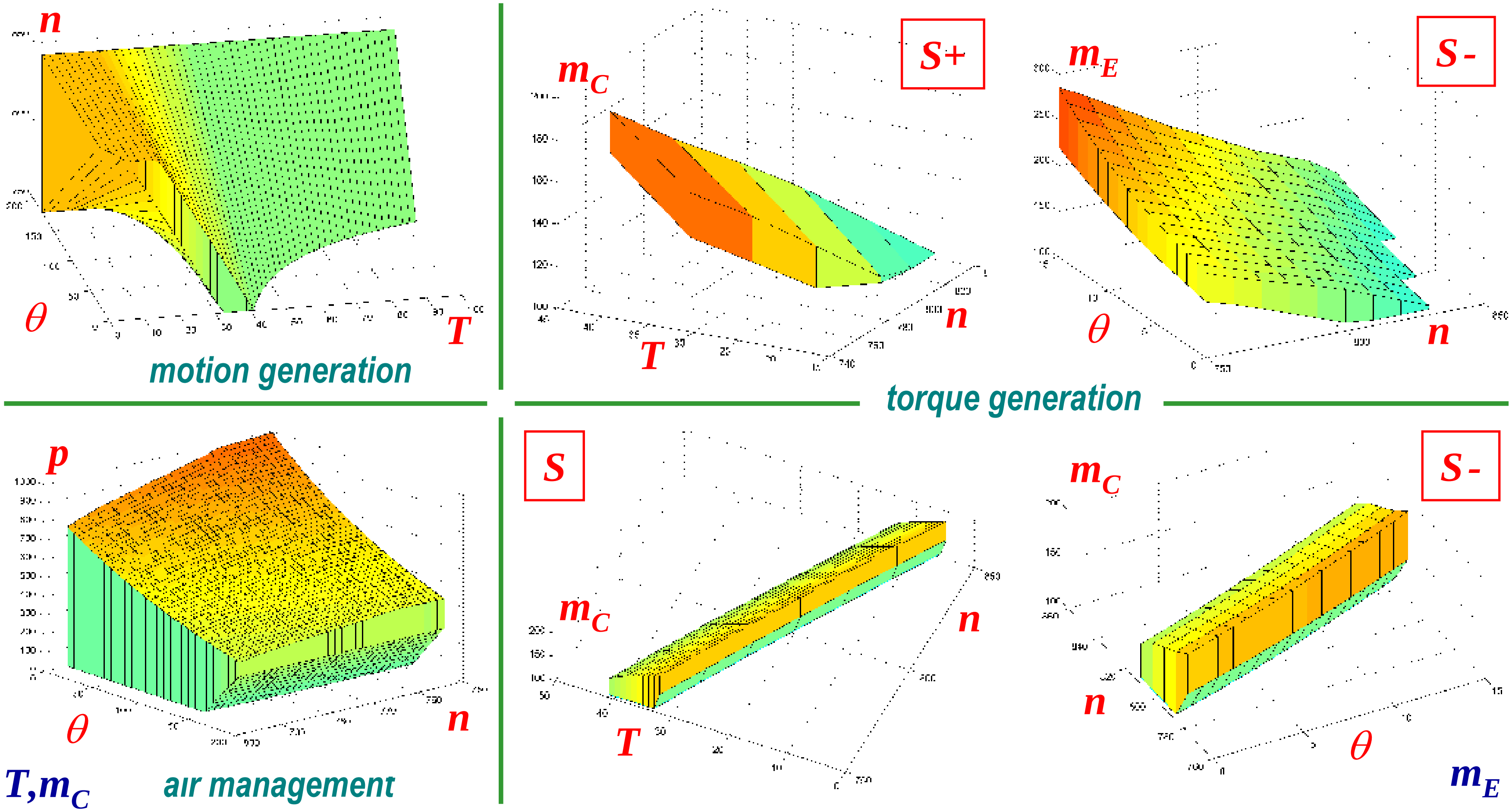
that maintain the crankshaft speed $n(t)$ in the given range $n_0 \pm \Delta$ under

- any driver's action on *clutch* pedal,
- any load torque $T_L(t)$ in $[0, T_L^M]$.

Latest Results

- Spark ignition and throttle valve actuator dynamics have been introduced.
- A particular idle speed controller has been designed.
- Formal verification of the proposed idle speed controller has been performed.

Idle Speed Control: Maximal Safe Set



Specification: *maintain $n(t)$ within the specified range $n_0 \pm \Delta n$ given T_l^M.*

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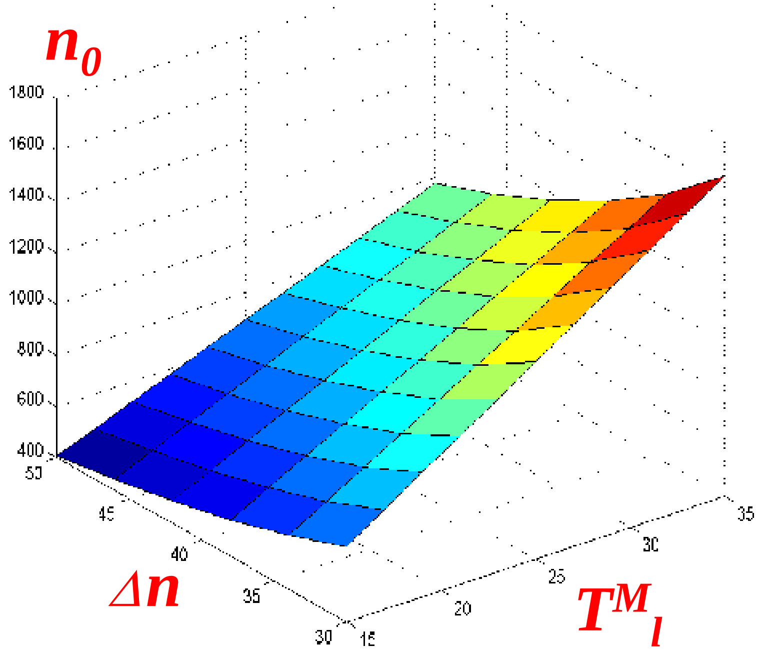
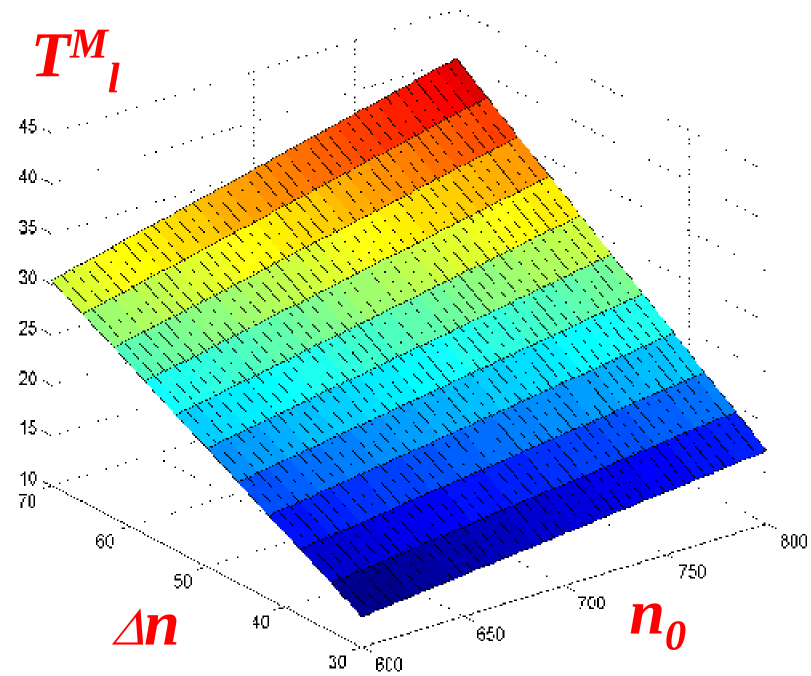
Idle Speed Control: Performance Analysis





- ***minimum*** *nominal engine speed* n_0 *for which the safe set is not empty, given a range* Δn *and an upper bound on load torque* T_l^M.

- ***maximum*** *upper bound on load torque* T_l^M *for which the safe set is not empty, given a range* Δn *and a nominal engine speed* n_0.

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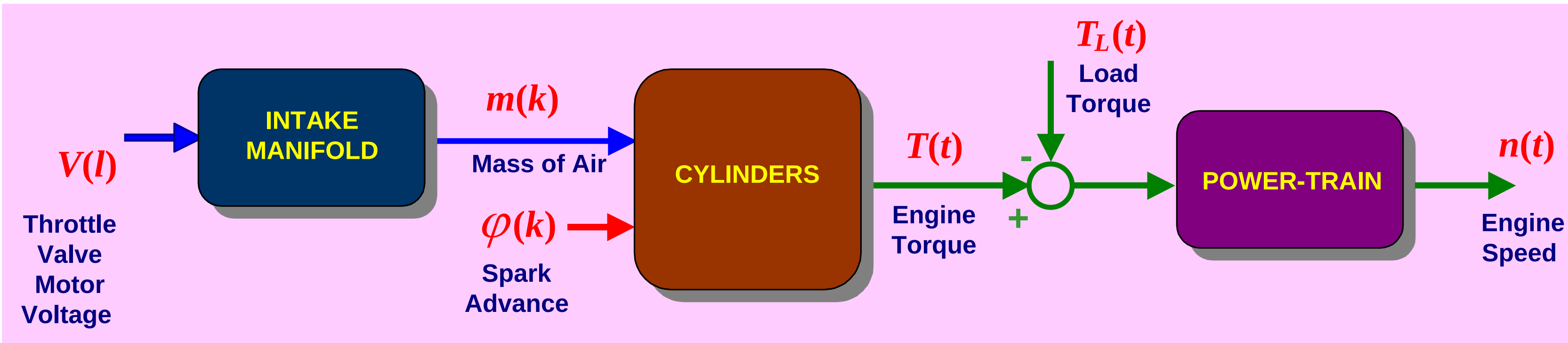
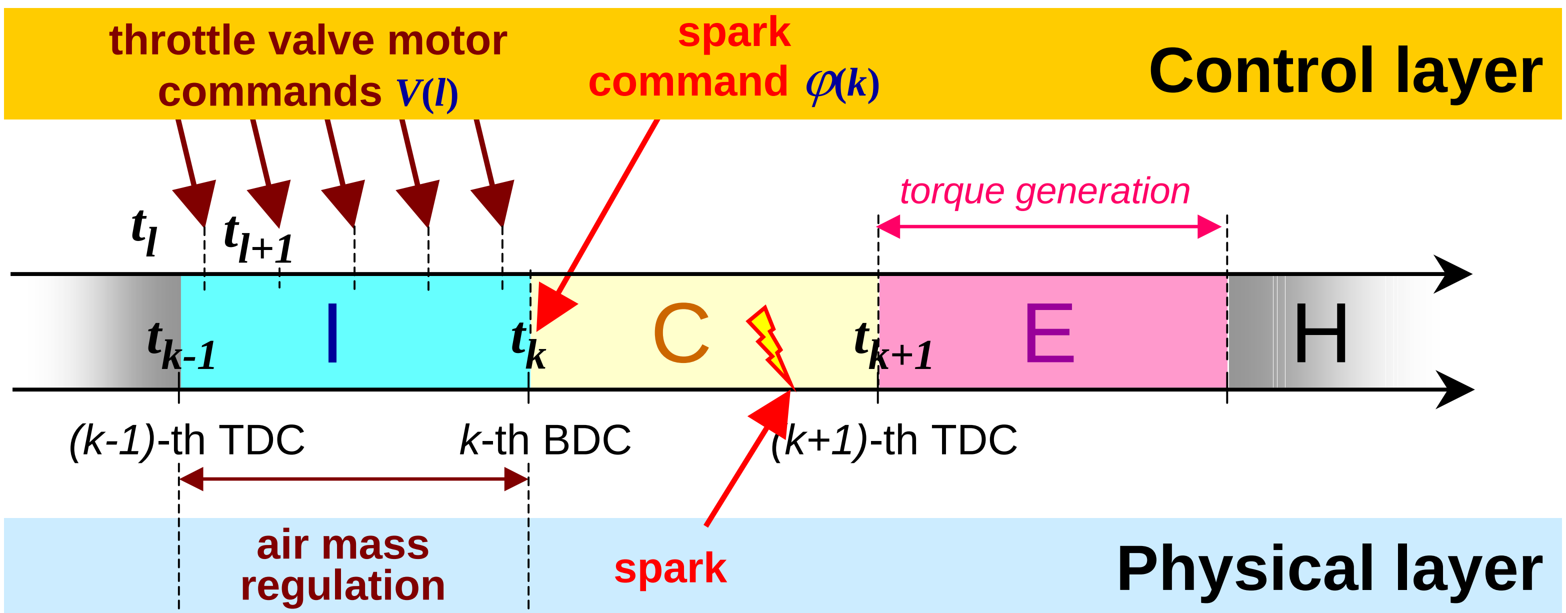
Actuators Dynamics and Input Timing





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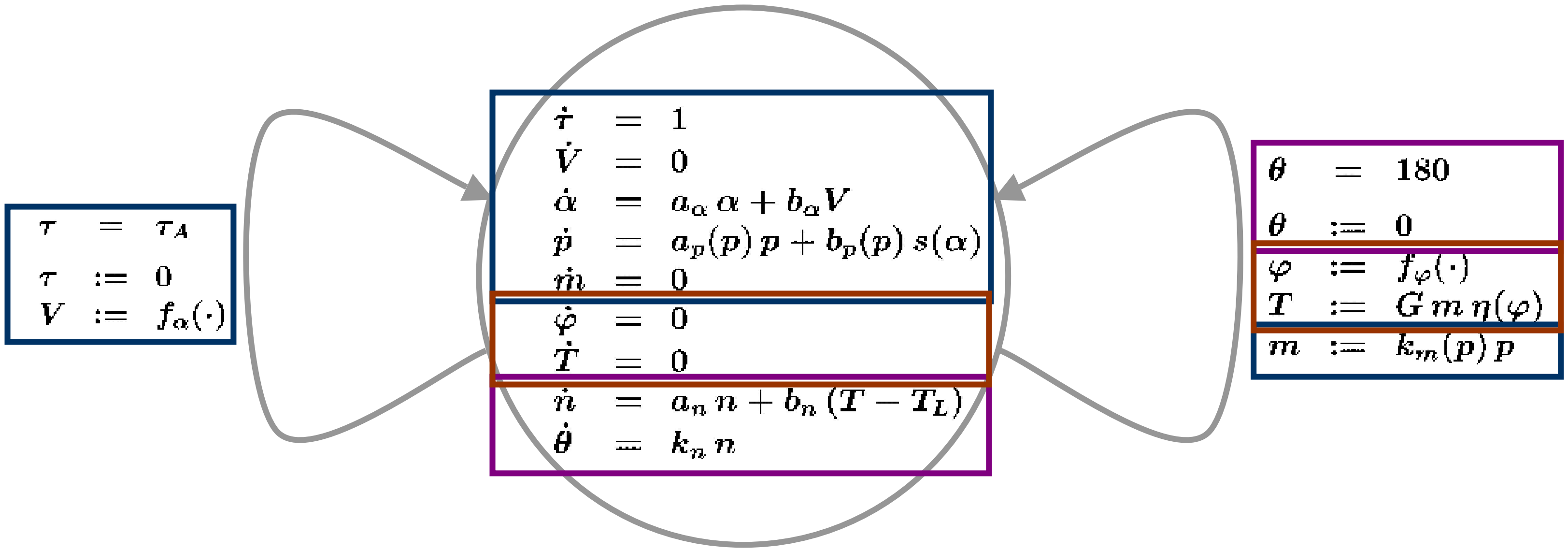
Engine hybrid model with actuators



intake manifold

cylinders

power-train

- intake manifold dynamics
- engine speed and crankshaft angle dynamics
- torque generation dynamics
- cylinders filling dynamics
- spark actuation delay
- dead centers events generation
- throttle valve actuator dynamics

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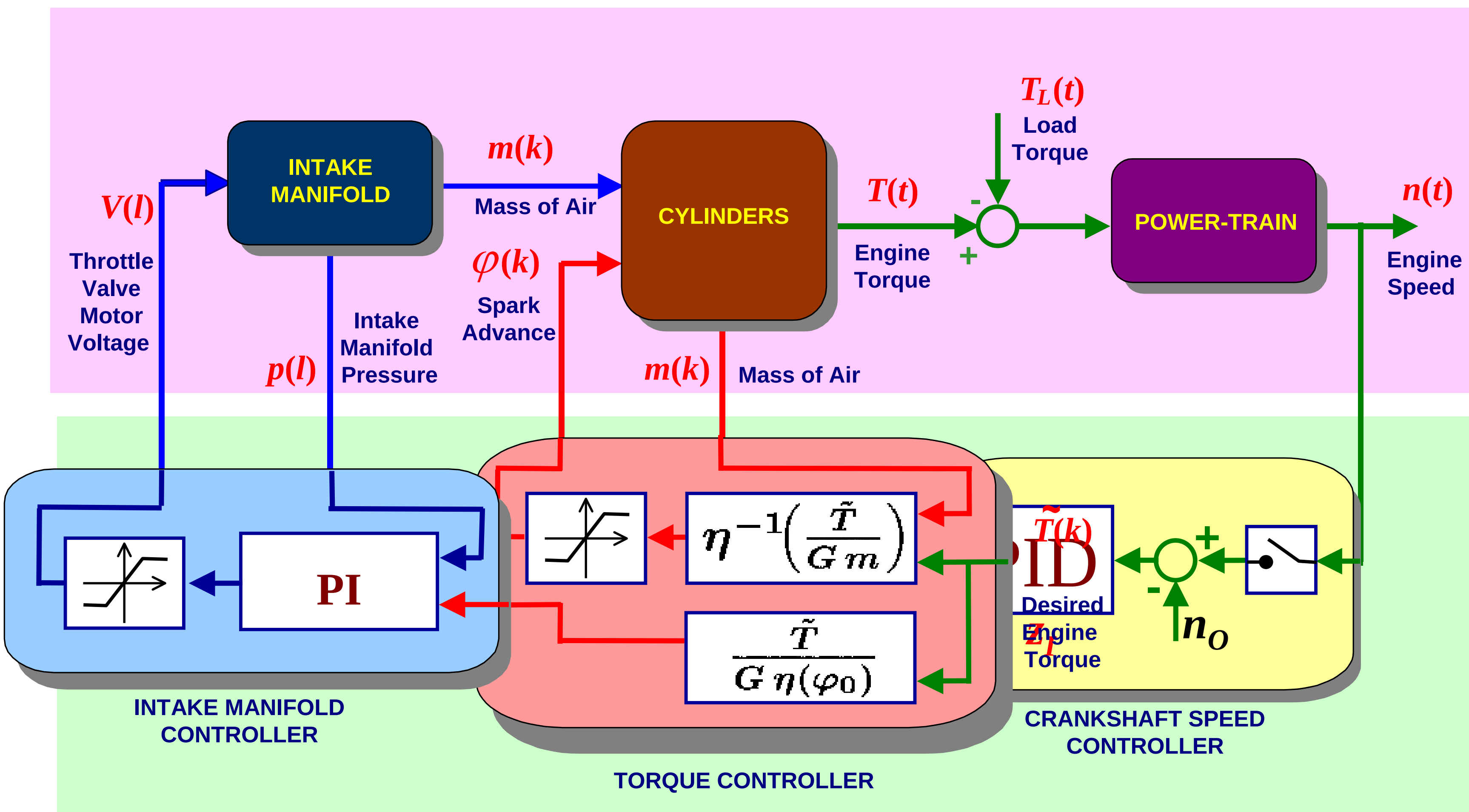
Idle Speed Controller Design



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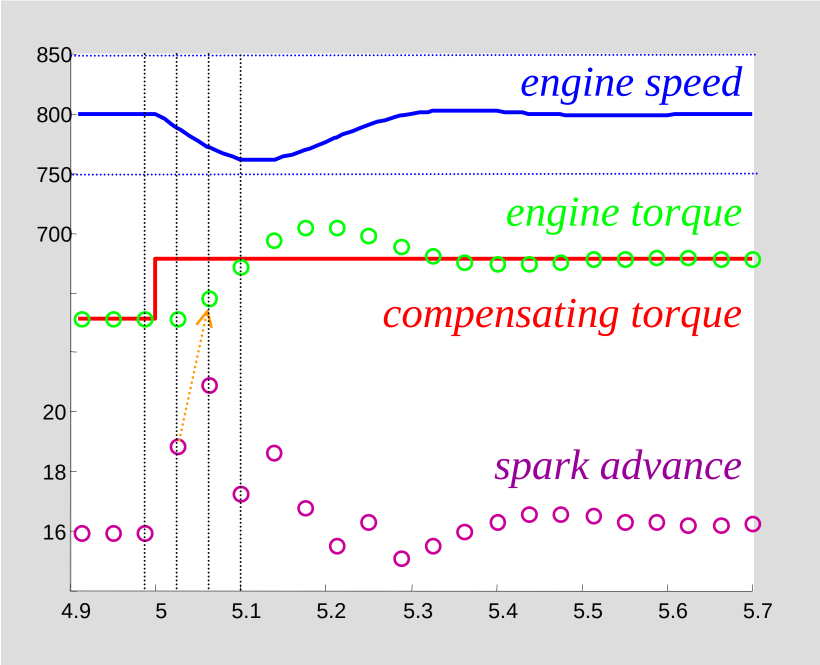
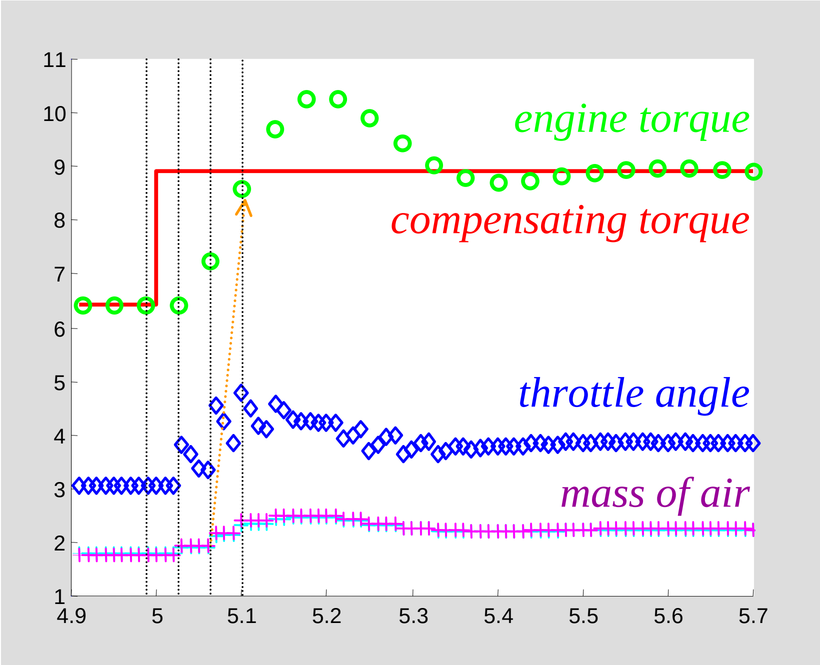
Closed-loop System Simulations





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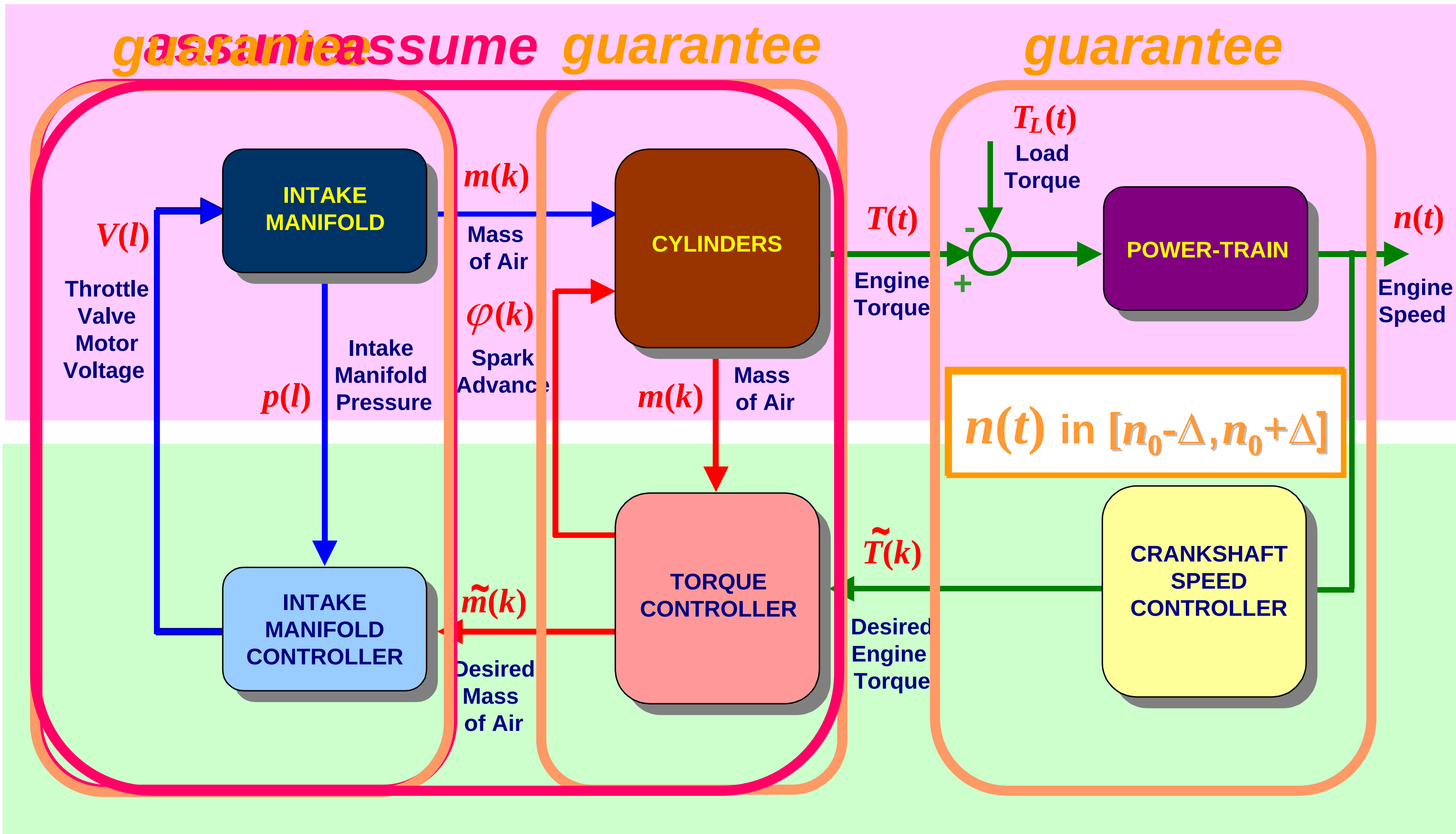
Idle Speed Controller Verification



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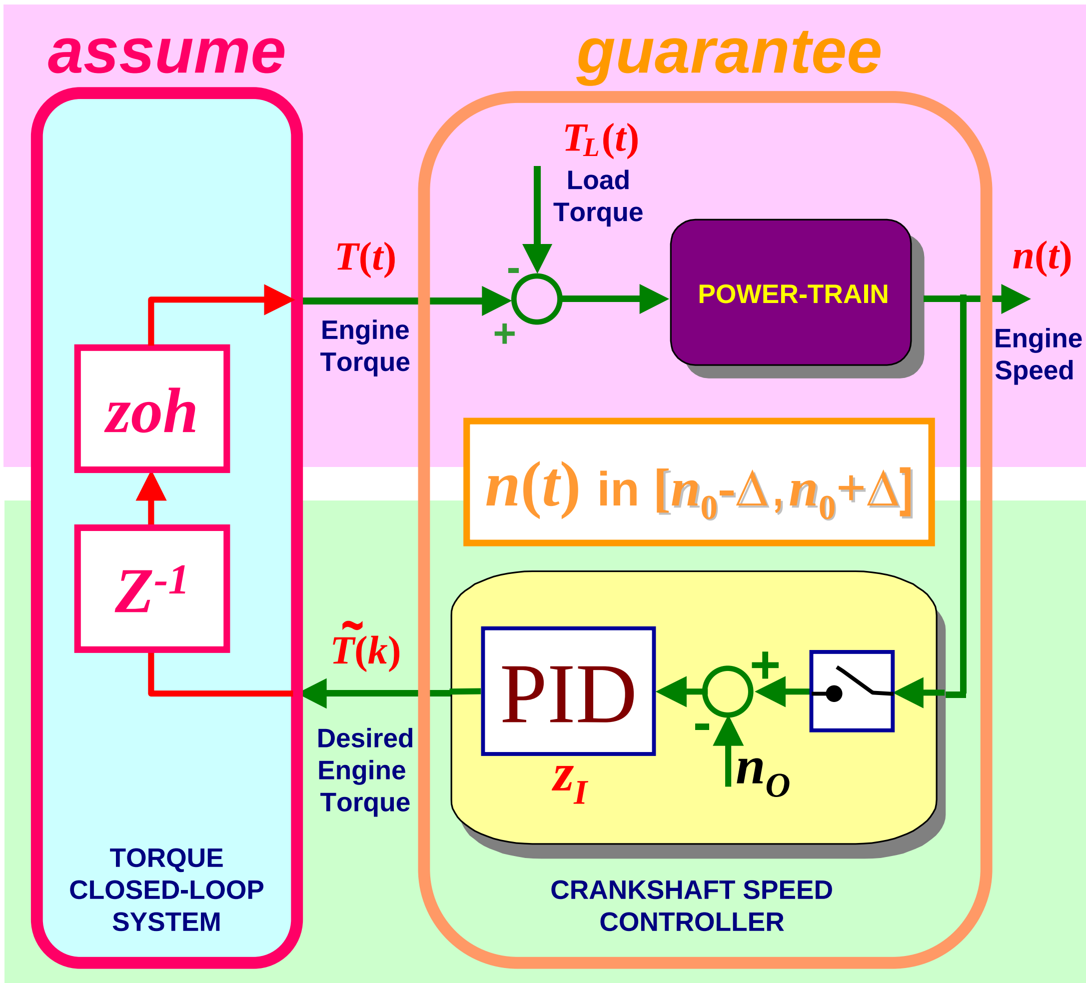
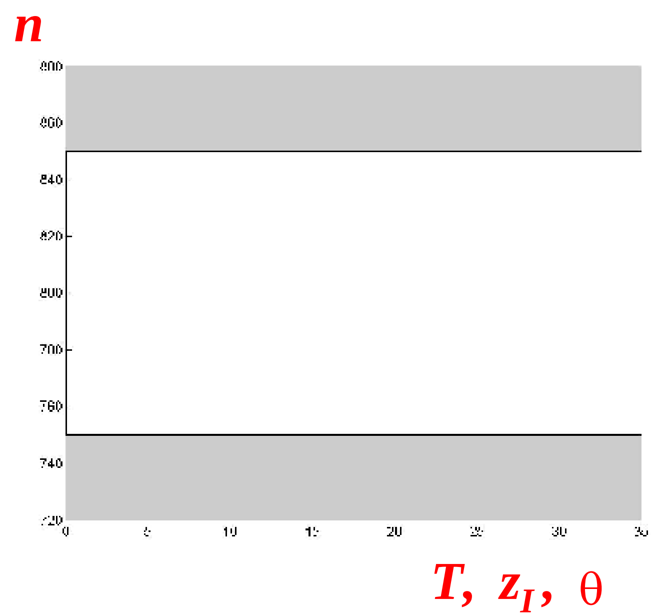
Crankshaft Speed Controller Verification





- **Step 1:** sufficient conditions for the correct evolution between two successive dead-centers.
- **Step 2:** admissible integrator initialization values guaranteeing sufficient conditions computed in Step 1.

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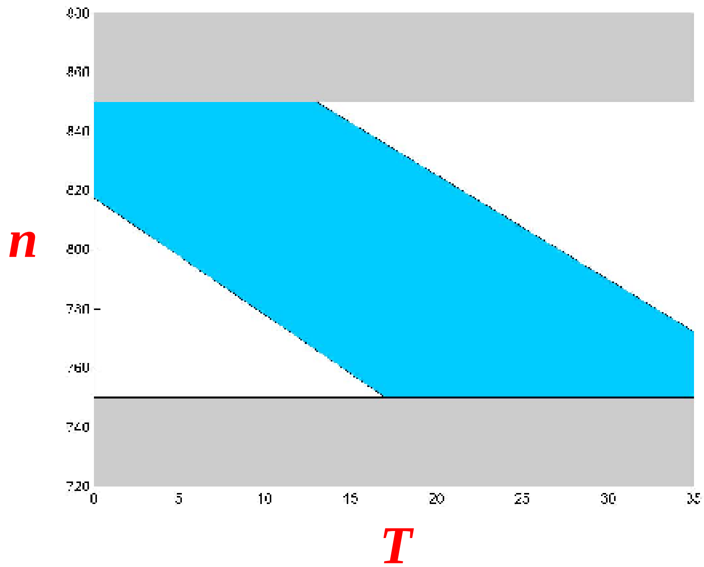
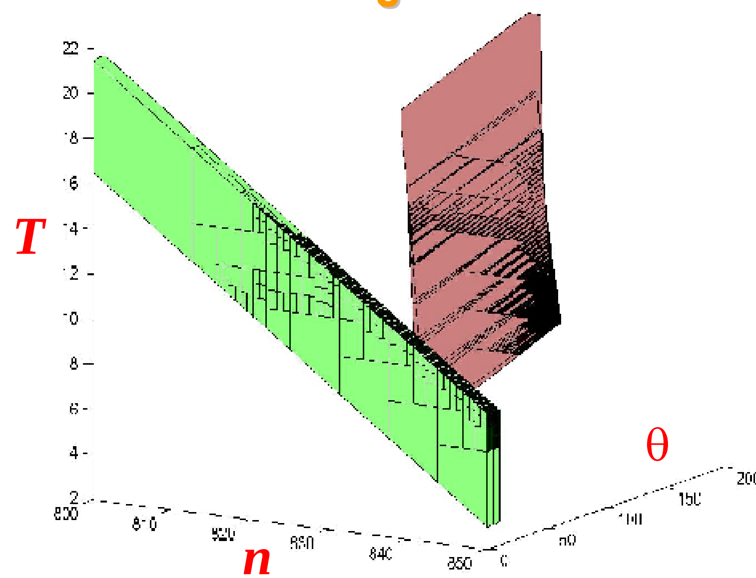
Step 1: Safe set between two dead-centers

During the continuous evolution between two successive dead-centers, the controller is safe provided that

- at each dead-center, the substate (n,T) is inside the blue region.





- The (n,T) safe set has been computed analytically in the continuous time domain considering the worst
  - load disturbance $T_L(t)$ in [$0,5$] Nm
  - dead-center time in [$30/750$, $30/850$]

- CheckMate [CMU] has been used to verify the (n,T) safe set between two dead-centers and some partial results have been obtained.

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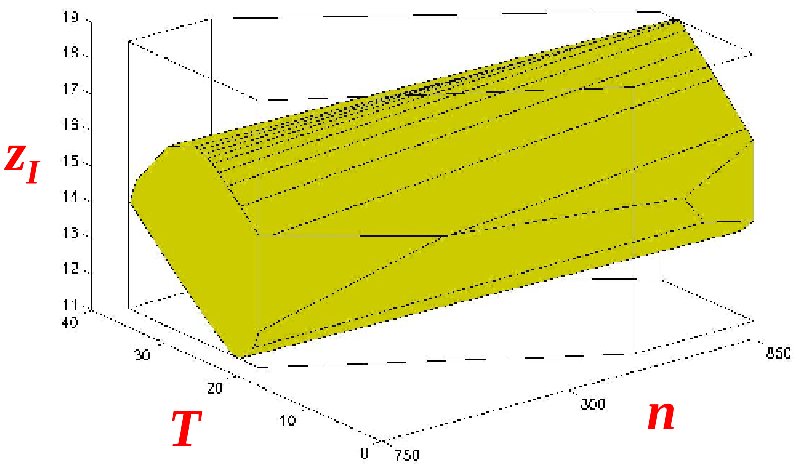
Step 2: Safe set on dead-center events

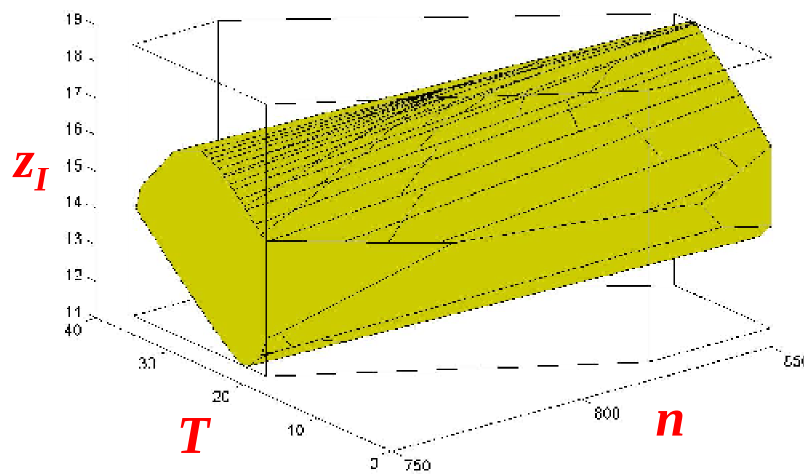
Admissible integrator initialization values guaranteeing that at each dead-center the the substate (n,T) is inside the region computed in Step 1 are obtained

- by computing the maximal safe set on the dead-center events domain

Backwards Reachability has been used

Hp: load disturbance $T_L(t)$ in $[0,5]$ Nm





- Assuming dead-center time = *30/800*
- convergence in 14 steps
- # of constraints 29

- Assuming dead-center time in [*30/799,30/801*]
- convergence in 14 steps
- # of constraints 125

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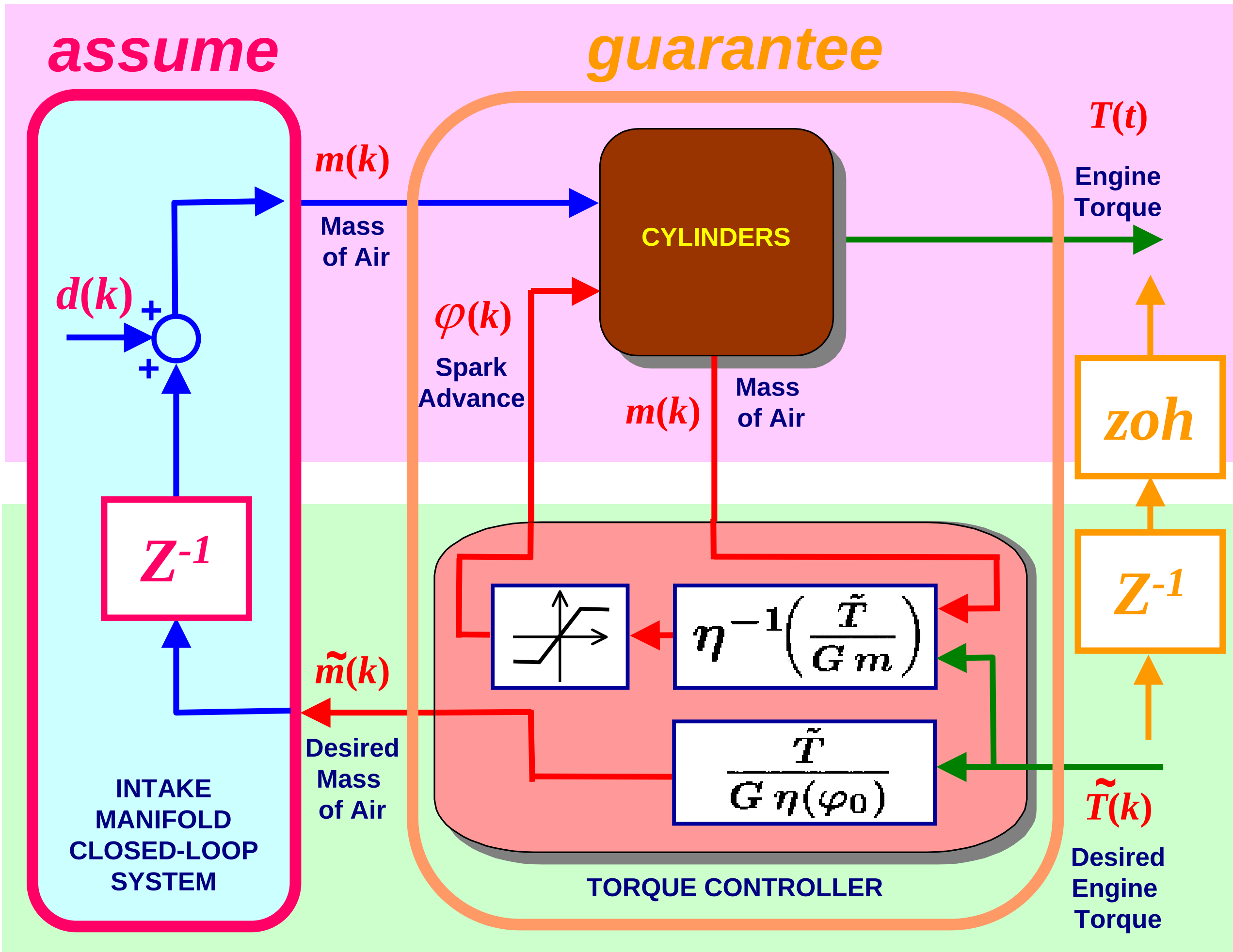
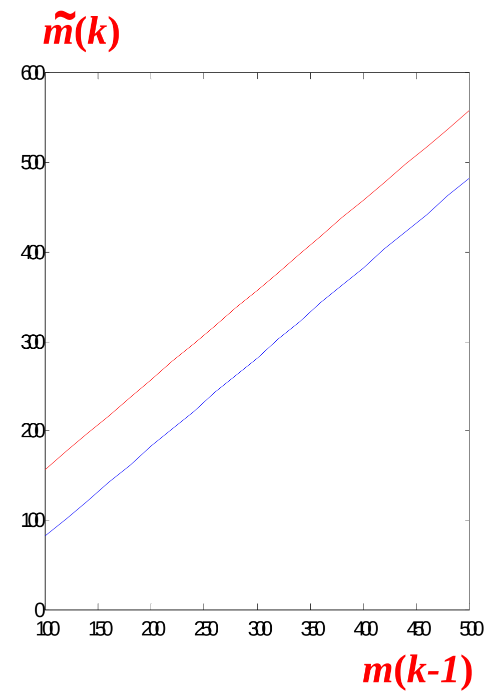
Torque Controller Verification





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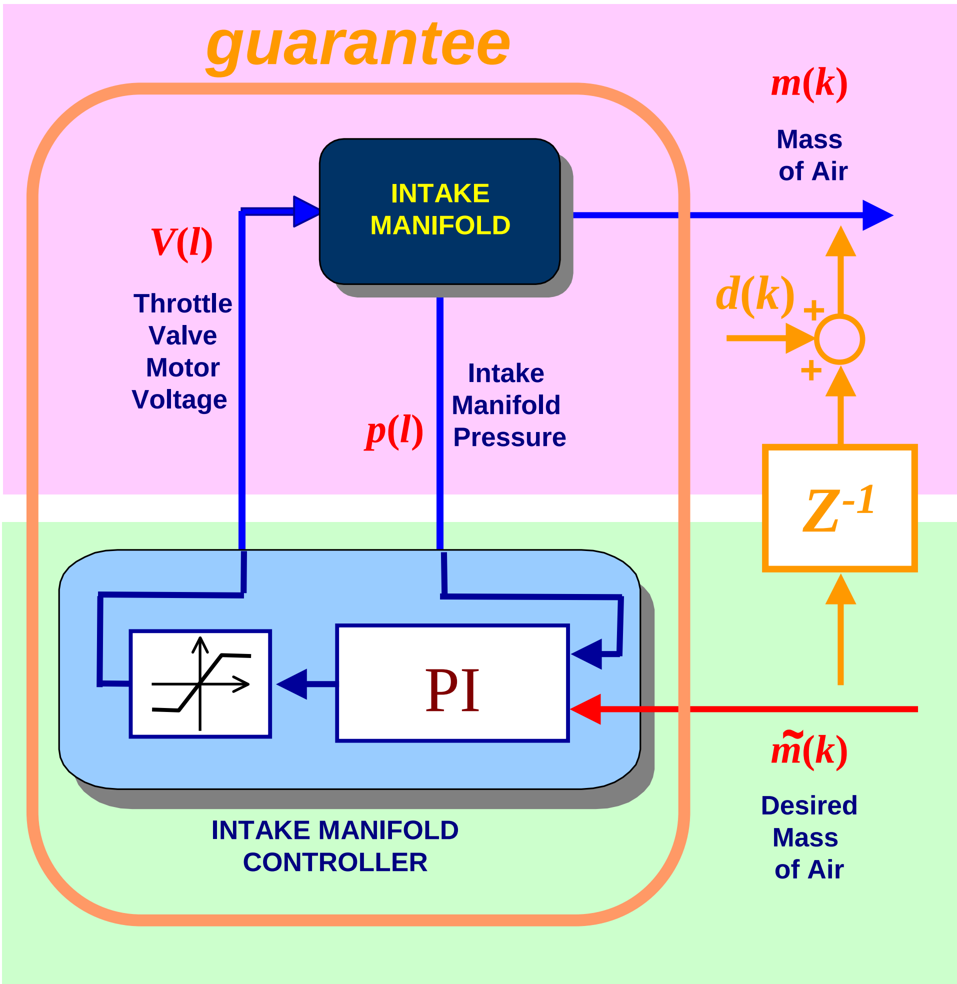
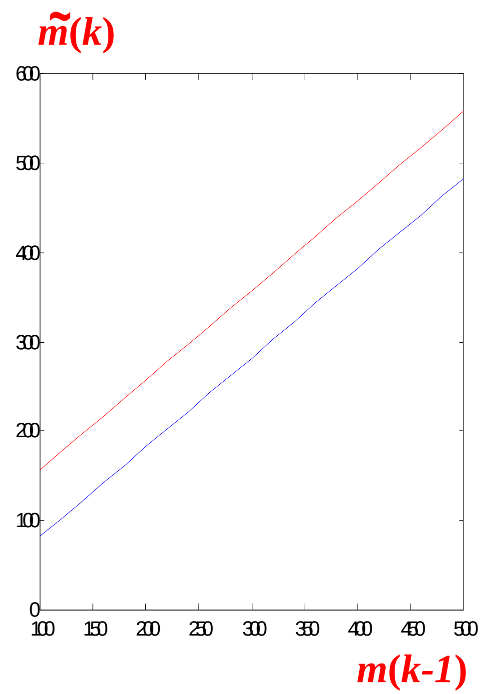
Intake Manifold Controller Verification





Conclusions

- A hybrid automaton that models the behavior of a 4-cylinder engine in idle has been presented. The model describes the nonlinear phenomena in the torque generation process and the spark and throttle valve actuators dynamics.
- By exploiting the decomposition of the plant in three subsystems (intake manifold, cylinders and power-train), an idle speed controller has been designed.
- The correct behavior of the closed-loop system has been formally verified by using an assume-guarantee approach.
- Design and verification of idle speed controllers for GDI engines are currently under investigation.