Synthesis for Idle Speed Control of an Automotive Engine

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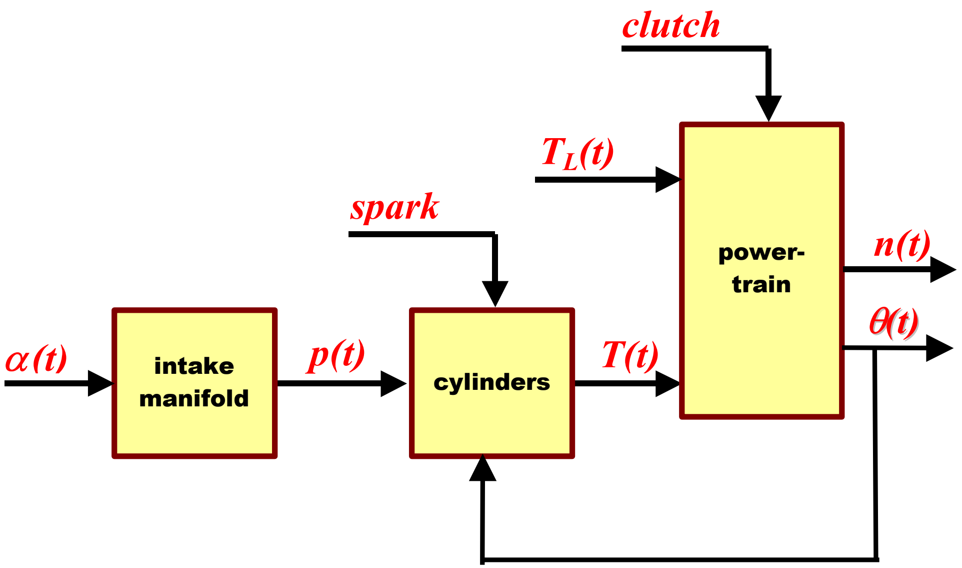
"Idle Speed Control" Case Study



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 $\alpha(t)$

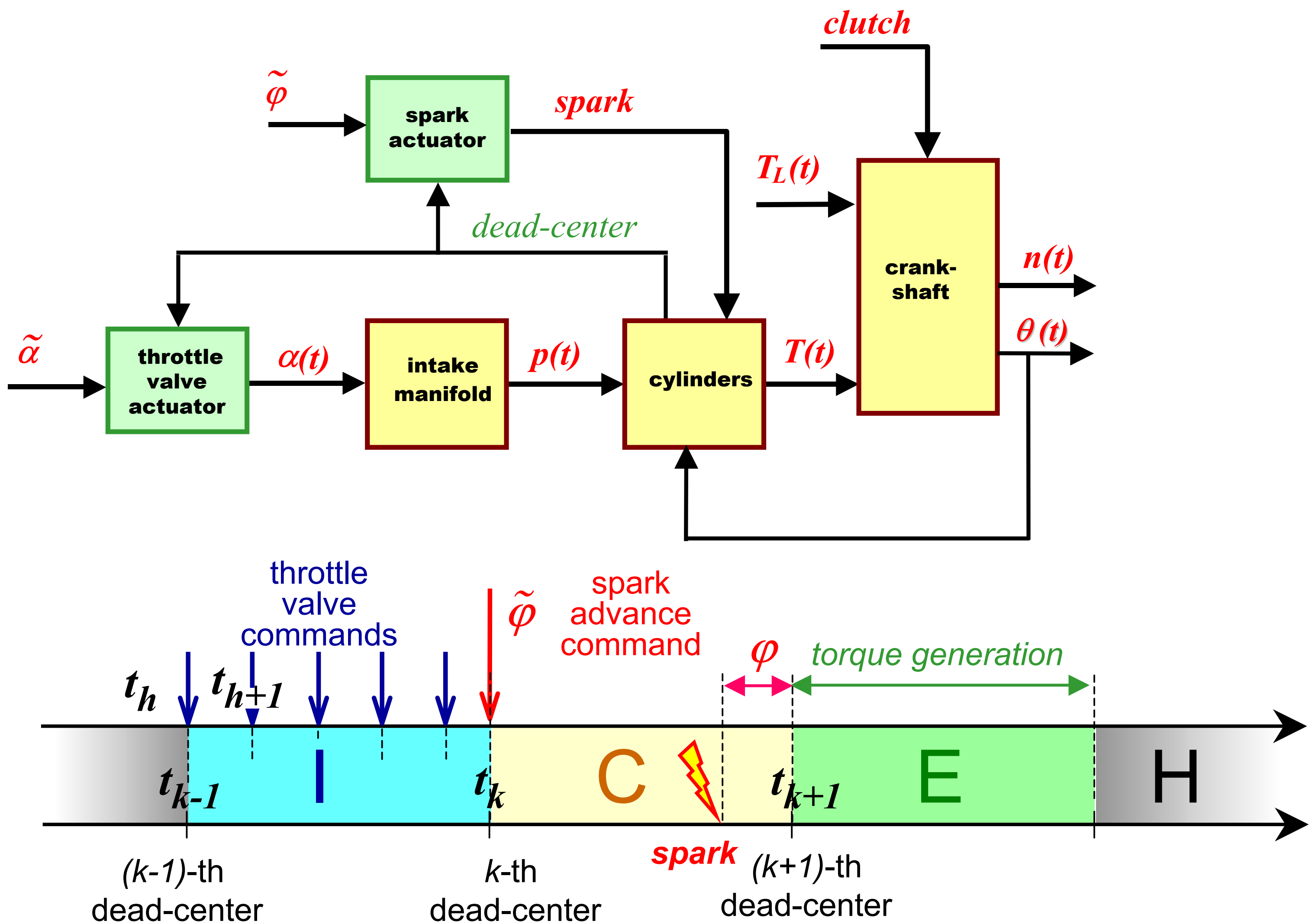
that maintain the crankshaft speed $n(t)$ in the given range $n_0 \pm \Delta$ under

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

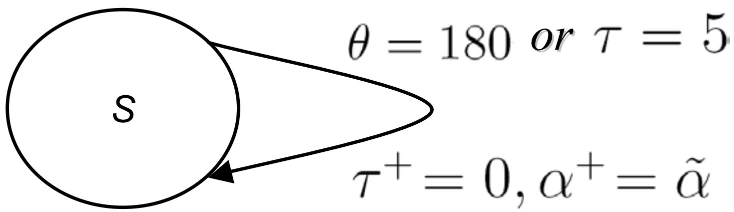
Controls	Time / Value
ignition *spark*	disc / disc
throttle α	cont / cont

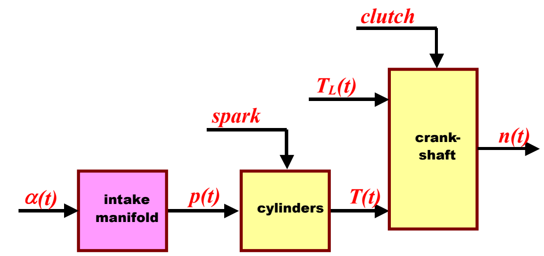
Disturbances	Time / Value
clutch *clutch*	disc / disc
load torque T_L	cont / cont

Throttle valve and spark ignition actuators



Throttle valve actuator and intake manifold model

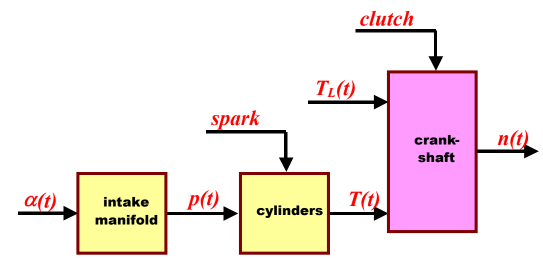




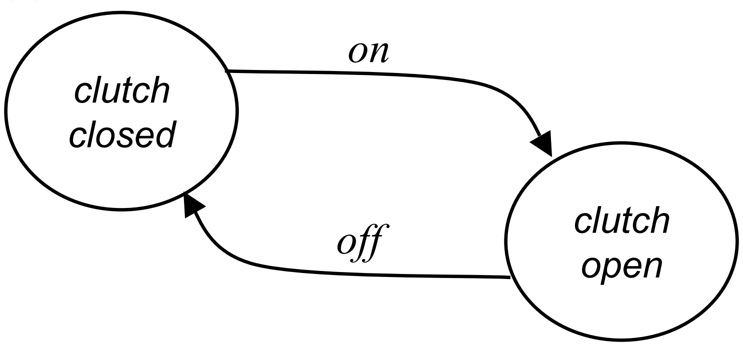
$$\dot{\tau} = 1000$$

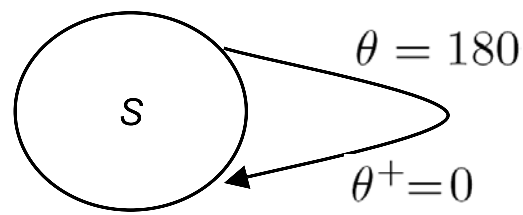
$$\dot{p}(t) = a_p(p(t) - p_0) + b_p(\alpha(t) - \alpha_0)$$

Crankshaft model



$$\dot{n}(t) = a_n^L n(t) + b_n^L[T(t) - \bar{T}_p - T_l(t)]$$

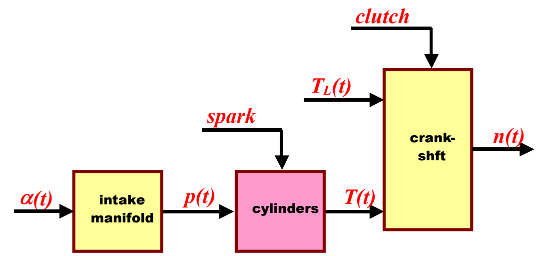


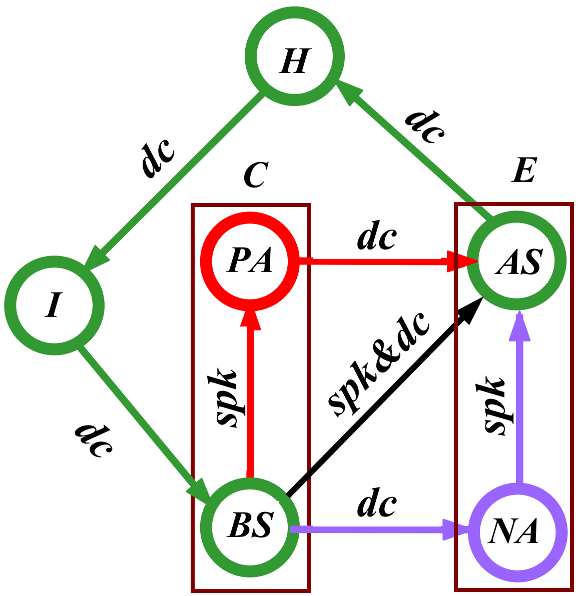


$$\dot{n}(t) = a_n n(t) + b_n[T(t) - T_p - T_l(t)]$$

$$\dot{\theta}(t) = 6n(t)$$

Single cylinder FSM: engine cycle





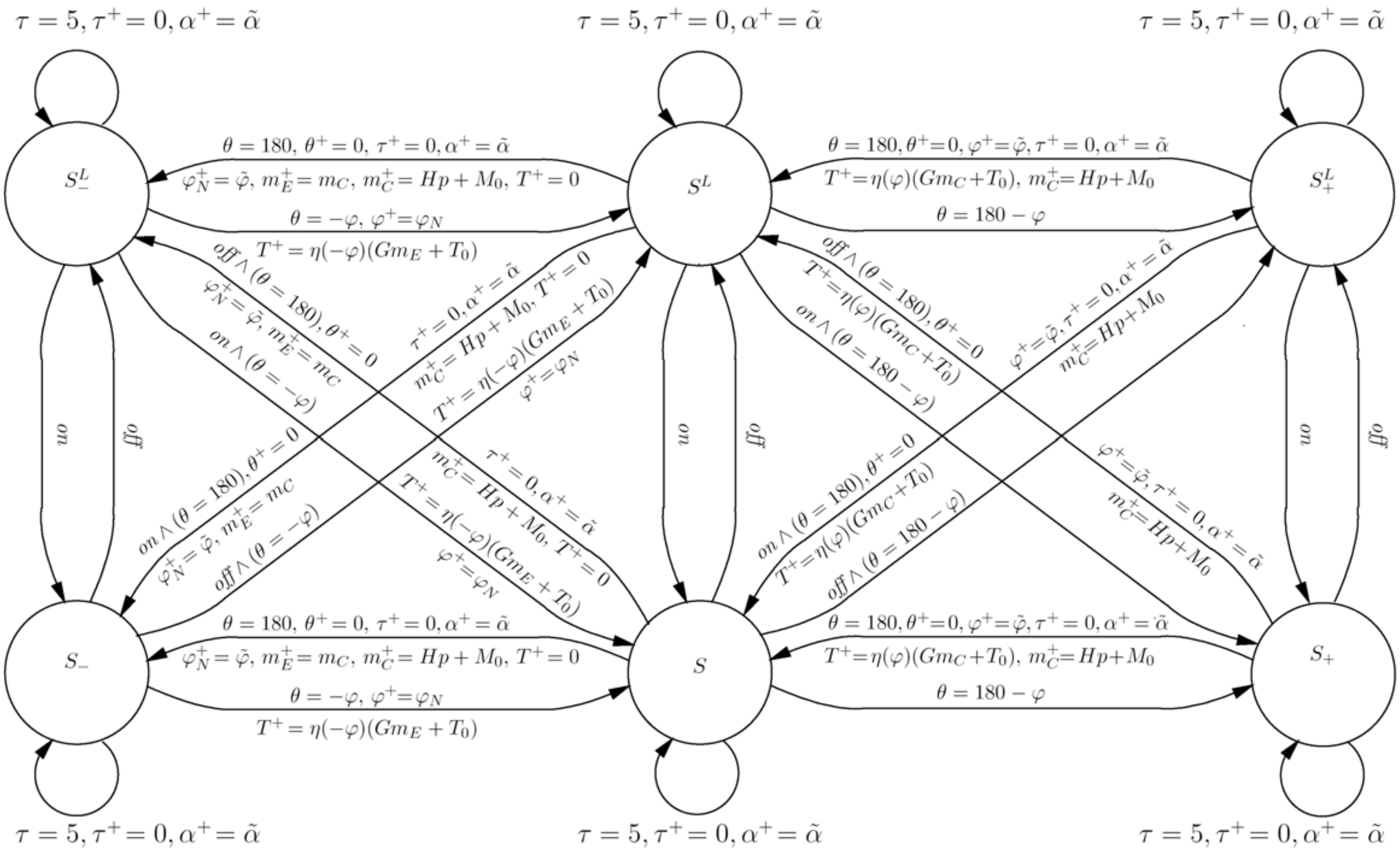
positive spark advance

negative spark advance

$\mathbf{I \rightarrow BS}$	$m := f_m(p, n)$
	$T_C := G^c f_m(p, n) + T_0^c$
$\mathbf{C \rightarrow E}$	$T_C = 0$
$\mathbf{BS \rightarrow PA}$	$\varphi := 180 - \theta$
$\mathbf{C \rightarrow AS}$	$T_E := (G^e m + T_0^e)\eta(\varphi)$
$\mathbf{NA \rightarrow AS}$	$T_E := (G^e m + T_0^e)\eta(-\theta)$
$\mathbf{AS \rightarrow H}$	$T_E = 0$

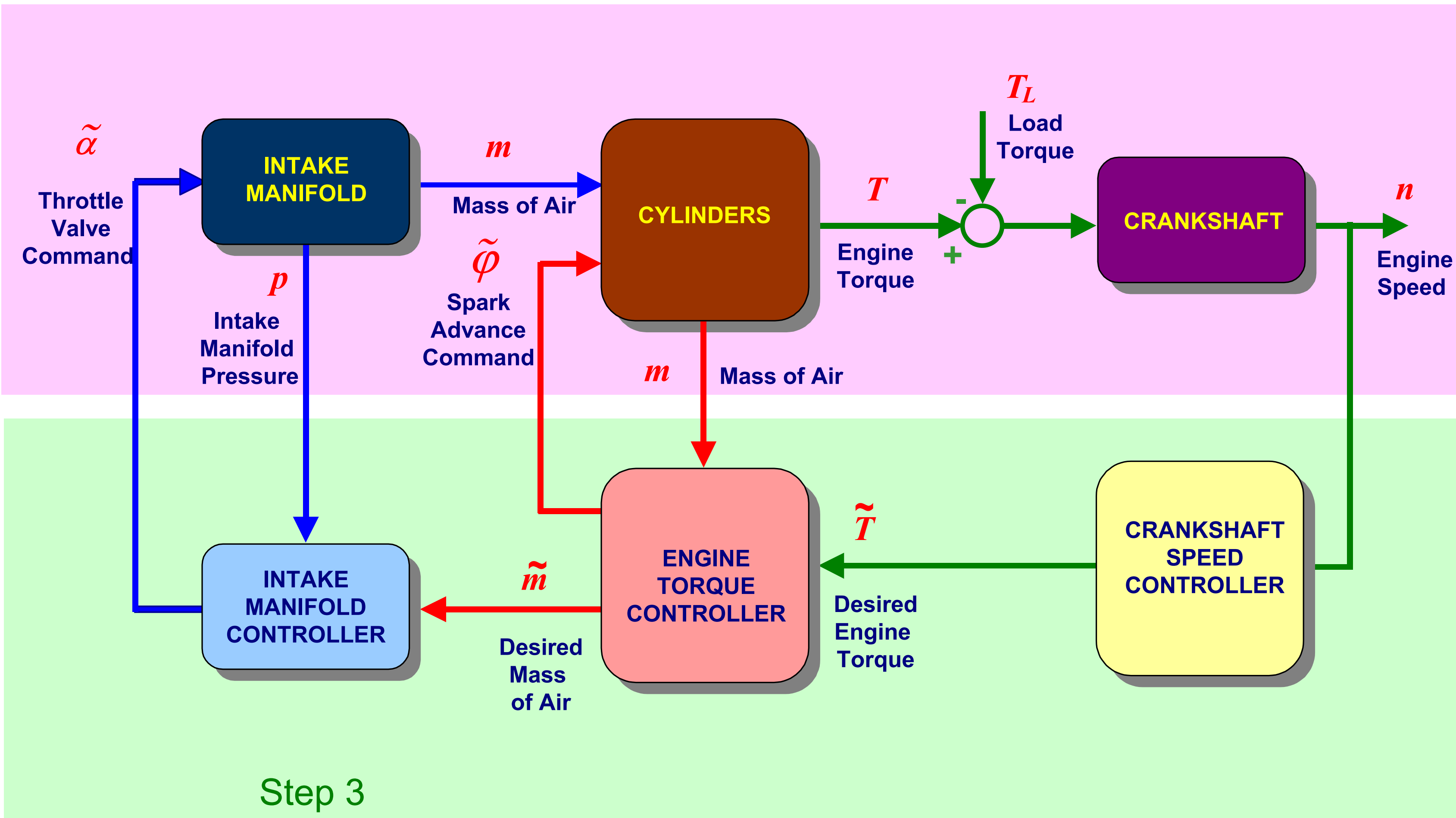
Piecewise-affine hybrid system model

$$\dot{\tau} = 1000 \qquad \dot{n}(t) = a_n^L n(t) + b_n^L[T(t) - T_p - T_l(t)]$$
$$\dot{p}(t) = a_p(p(t) - p_0) + b_p(\alpha(t) - \alpha_0) \qquad \dot{\theta}(t) = 6n(t)$$



$$\dot{\tau} = 1000 \qquad \dot{n}(t) = a_n n(t) + b_n[T(t) - T_p - T_l(t)]$$
$$\dot{p}(t) = a_p(p(t) - p_0) + b_p(\alpha(t) - \alpha_0) \qquad \dot{\theta}(t) = 6n(t)$$

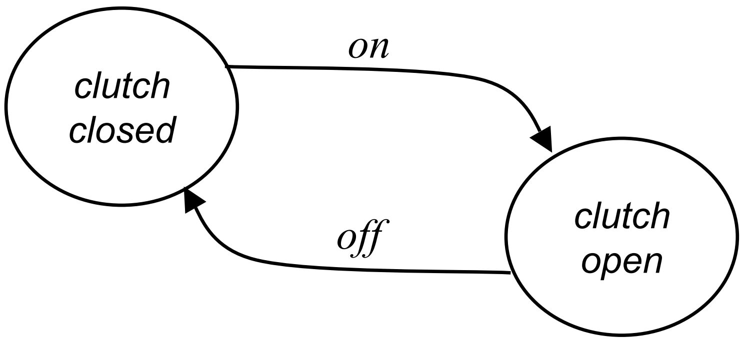
Idle Speed Controller Design



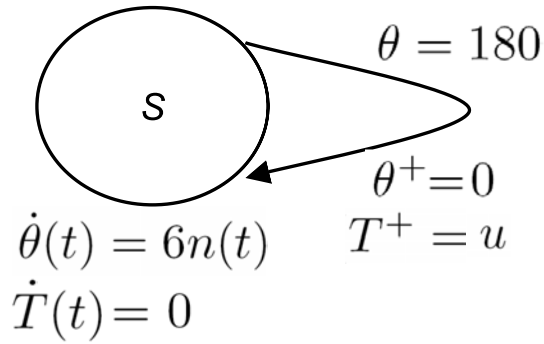
Step 1: Crankshaft speed controller

- **Consider the crankshaft model with states** (n, ϑ, T)

$$\dot{n}(t) = a_n^L n(t) + b_n^L [T(t) - \bar{T}_p - T_l(t)]$$

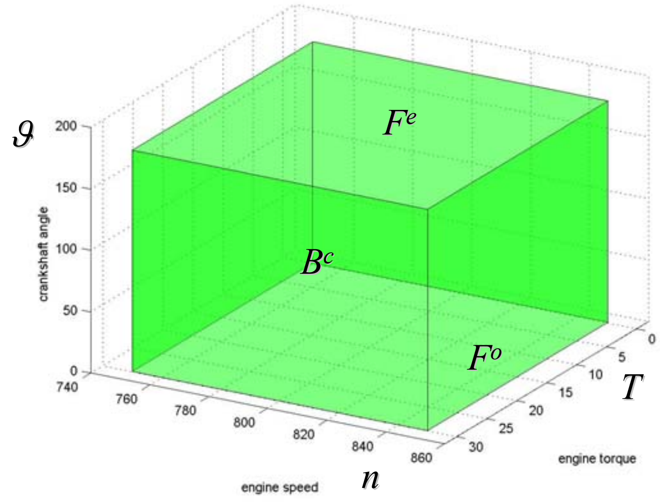


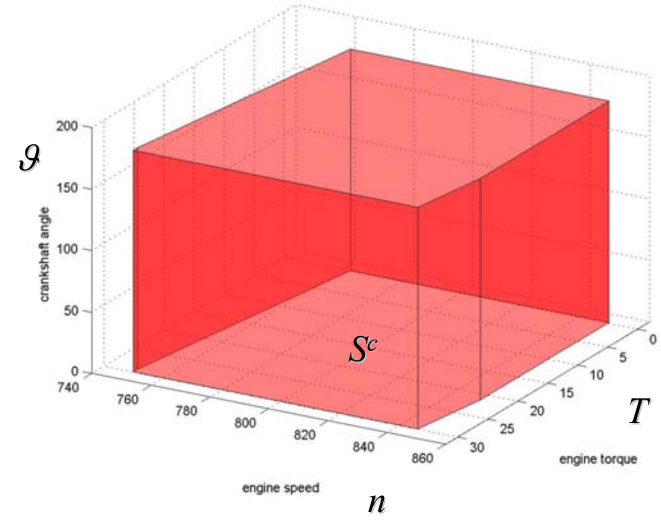
$$\dot{n}(t) = a_n n(t) + b_n [T(t) - T_p - T_l(t)]$$



- **Problem: Find a control strategy for the resets of the engine torque T such that the crankshaft speed $n(t)$ is maintained bounded to $[750, 850]$.**

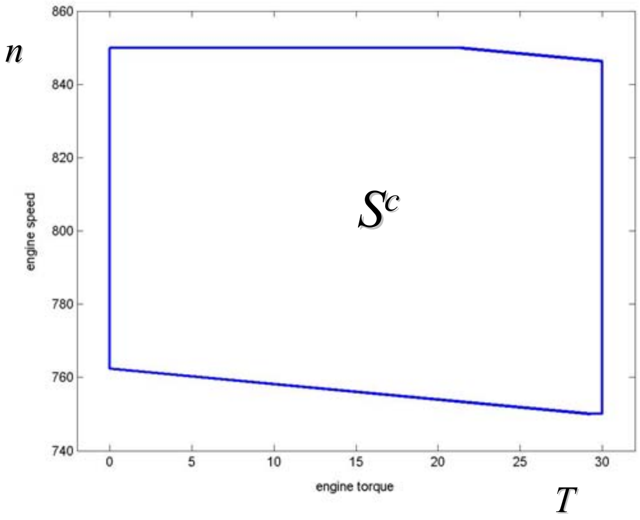
Crankshaft speed constraint satisfaction

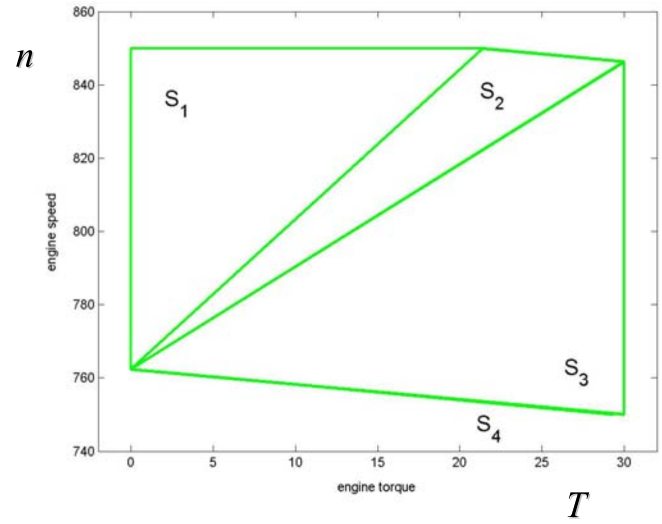




- **Consider the state space** (n, ϑ, T)
  - **If the exit facet from** B^c **is** $\vartheta = 180$**, then** $n(t)$ **belongs to** $[750,850]$ **for** $\vartheta : 0 \rightarrow 180$
  - **If** (n_0, T_0) **belongs to** S^c**, then** $\vartheta = 180$ **is the unique exit facet from** B^c
- **Hence,**
  - **If at each dead-center** (n, T) **belongs to** S^c**, then** $n(t)$ **always belongs to** $[750,850]$**.**

Step 2: Engine torque controller





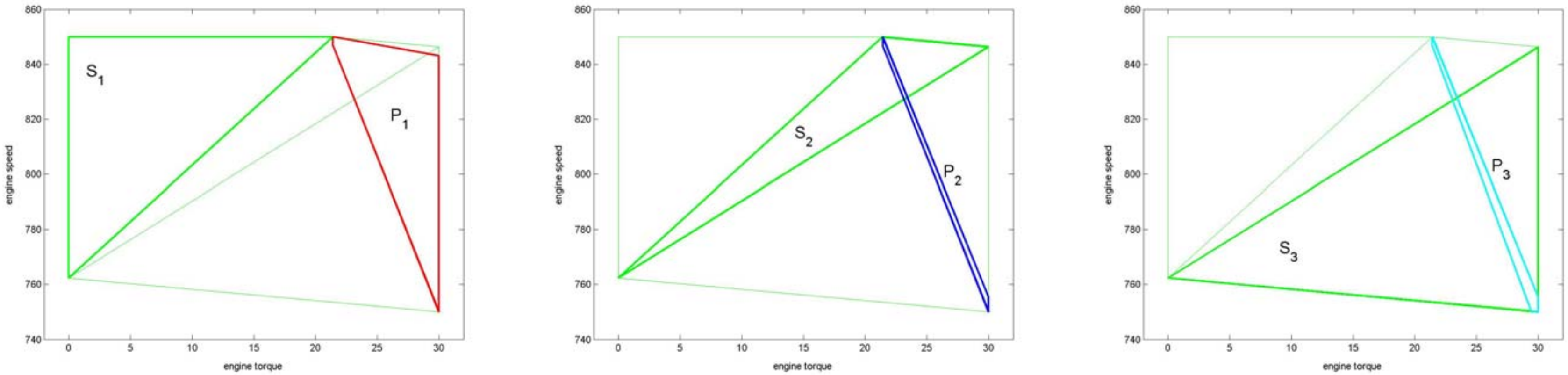
- **Problem:** find a robust controlled invariant set contained in S^c, for a model of the crankshaft evolution between dead-centers

$$n(k+1) = a_d(k)n(k) + b_d(k)(T(k) - T_p - T_l(k))$$
$$T(k+1) = u(k)$$

- **Time-varying parameters represent dependence from dead-center times**

$$a_d(k) = e^{a_n(t_{k+1}-t_k)} \qquad b_d(k) = -[1 - e^{a_n(t_{k+1}-t_k)}]b_n/a_n$$

Robust invariance via triangularization



- **Approach:**
  - S^c **is partitioned in simplex:** S_1, S_2, S_3 **and** S_4.
  - **a feedback** u **is designed s.t.** $S_1, S_2, S_3 \rightarrow S_2 \cup S_3$ **, i.e.** $S_2 \cup S_3$ **is a robust invariant set**

$$u(k) = g_p(n(k), T(k)) = F_p \begin{bmatrix} n(k) \\ T(k) \end{bmatrix} + h_p \qquad \text{for } (n, T) \text{ in } S_p$$

- **Robustness with respect to**
  - **Load toque disturbance, clutch disturbance, dead-center time and parameters uncertainties.**

Implementation of the affine controller

- **Feedback $u(k)$ is implemented in terms of engine torque** $T = \eta(\varphi)(Gm + T_0)$

Since spark advance efficiency is bounded to the interval $[0.6, 1]$ then

$$0.6(Gm + T_0) \leq g_p(n, T) \leq (Gm + T_0) \qquad \forall (n, T) \in S_1 \cup S_2 \cup S_3$$

- **Air-fuel mixture mass is regulated to the interval** $[m_{min}, m_{max}]$ **with**

$$m_{min} = \frac{1}{G}\left[\left(\max_{v_i \in S_1, S_2, S_3} F_p v_i + h_p\right) - T_0\right], \qquad m_{max} = \frac{1}{0.6} m_{min}$$

- **Engine torque is controlled by the spark advance feedback** $\tilde{\varphi} = \begin{cases} \phi_1 & \text{if } \phi_1 \geq 0 \\ \phi_2 & \text{if } \phi_1 < 0 \end{cases}$

$$\phi_1 = \eta^{-1}\left(\frac{F_p[n(t_k) \quad T(t_k)]^T + h_p}{Gm_C(t_k) + T_0}\right)$$

positive spark advance

$$\eta(\phi_2)(Gm_C(t_k) + T_0) = \frac{1 - e^{a_n \frac{30}{n(t_k)}}}{1 - e^{a_n\left[\frac{30}{n(t_k)}\left(1 - \frac{\phi_2}{180}\right)\right]}}\left[F_p\begin{pmatrix} n(t_k) \\ T(t_k) \end{pmatrix} + h_p\right]$$

negative spark advance

Step 3: Intake manifold controller

- **A feedback** $\alpha(k) = f_1 p(k) + h_1$ **is designed to control** p **to the target interval**

$$p_{min} = \frac{m_{min} - M_0}{H} \quad \text{and} \quad p_{max} = \frac{m_{max} - M_0}{H}$$

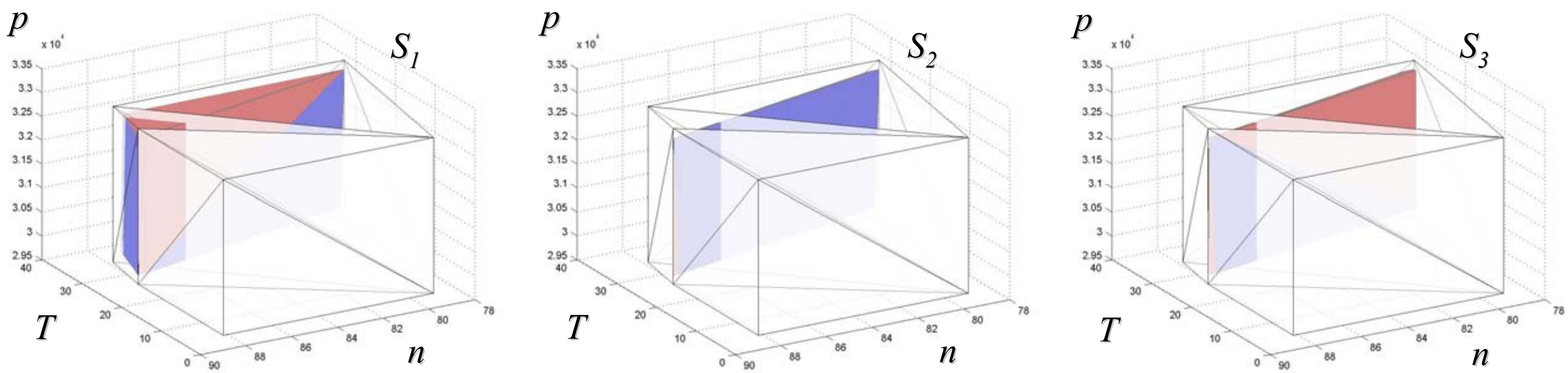
- **The throttle valve feedback is implemented in the** *5msec***-sampling as follows**

$$\alpha(t_h) = \frac{\bar{p}(k+1) - e^{a_p \tau} p(t_h) + (1 - e^{a_p \tau}) p_0 + [1 - e^{a_p \tau}] b_p / a_p \, \alpha_0}{-[1 - e^{a_p \tau}] b_p / a_p}$$

where $\tau = \frac{30}{n(t_h)} \left(1 - \frac{\theta}{180}\right)$ **is the estimated time to the next dead-center and**

$$\bar{p}(k+1) = e^{a_p \frac{30}{n(t_k)}} p(t_k) - \left[1 - e^{a_p \frac{30}{n(t_k)}}\right] \frac{b_p}{a_p} \left(f_1 p(t_k) + h_1\right)$$

Robust invariance for the closed loop system

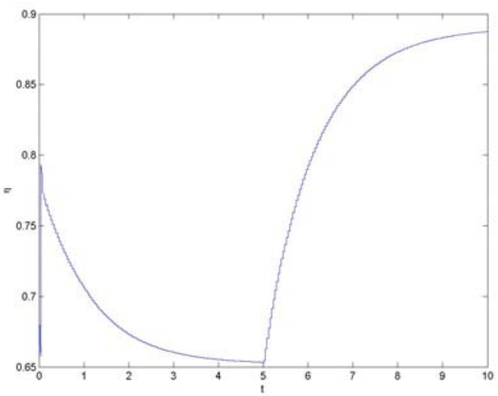


- Robust invariance of the computed subset of the state space, under
  - Clutch and torque load disturbances
  - Dead-center time interval length uncertainties
  - Parameter uncertainties

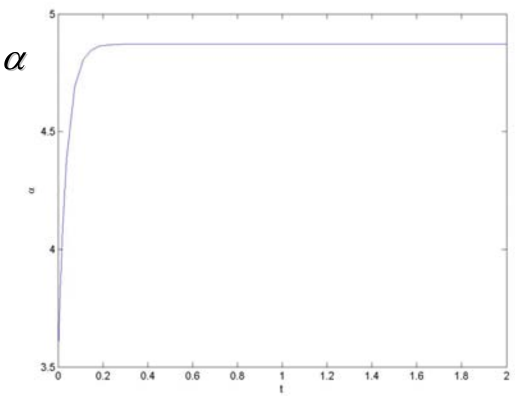
for the closed-loop system obtained with the proposed controller has been verified.

Simulation results

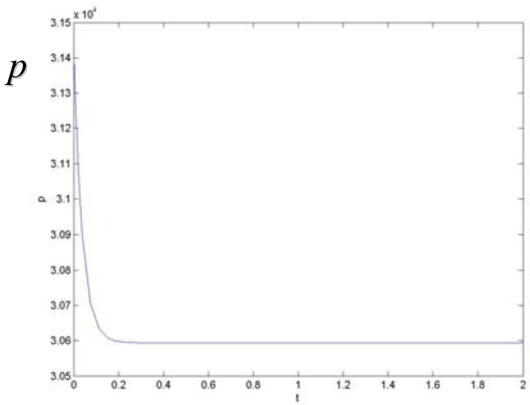
η



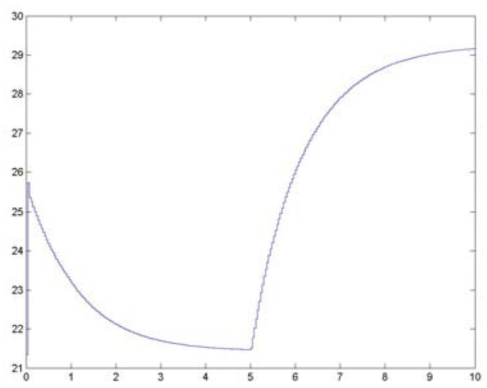
α



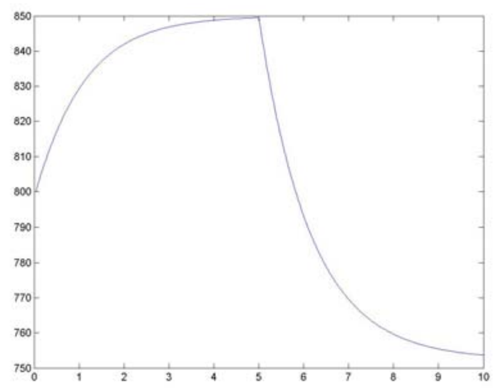
p



T



n



Conclusion

- Idle speed control has been formulated as an affine hybrid system control problem on polytopes.
- The approach to controller synthesis is a combination of
  - Back-stepping procedure and interactive design
  - Control for affine systems on polytopes
  - Theory of invariant sets
- Input and state constraints are handled by
  - Partitioning the space in polytopes
  - Designing feedback controls for each polytope such that the state of the closed loop system is driven only on those polytopes for which constraints are verified
- Future work: introducing performance specifications