Hybrid Systems in Automotive Engine Control

PARADES G.E.I.E.

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PARADES: Project on Advanced Research of Architecture and Design of Electronic System

Magneti Marelli Powertrain

ST Microelectronics

Cadence Design System

Italian National Research Council

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Outline

- Automotive engine control
  - overview of a direct injection engine
  - design methodology
- Hybrid engine model
- Hybrid control synthesis and verification
- Idle speed control
- Driveline observer design

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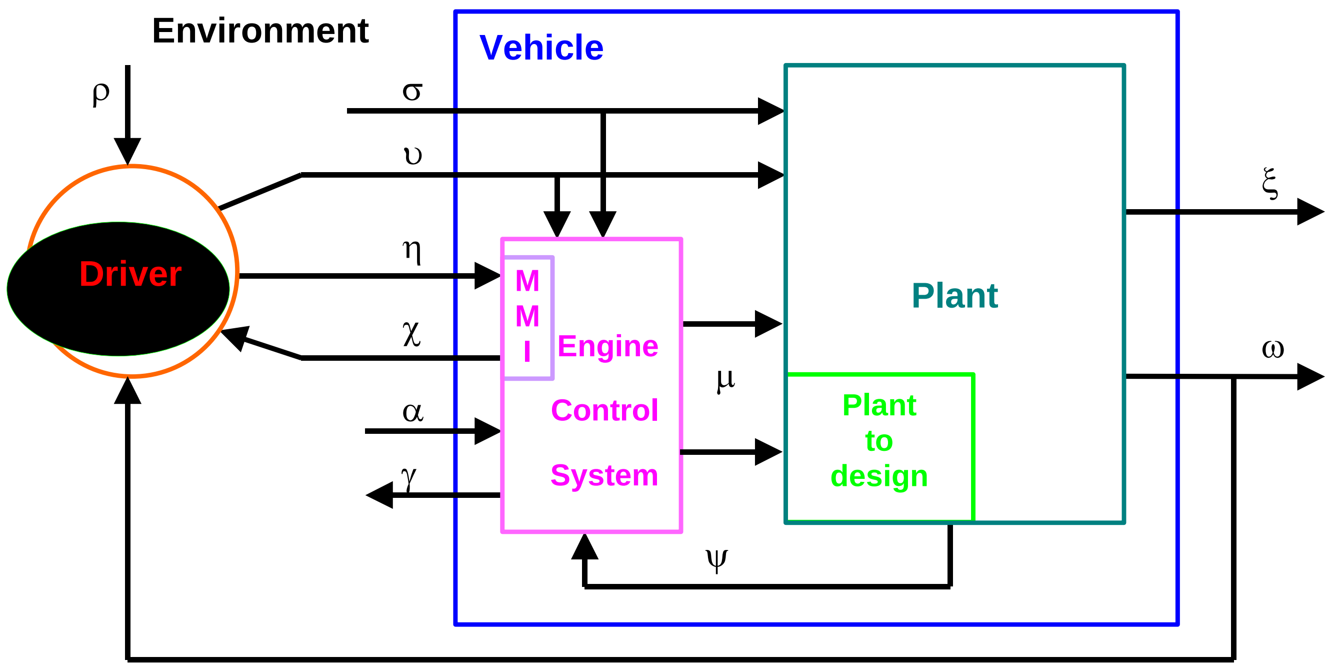
Power-Train Embedded Controller

- Electronic device controlling internal combustion engine and gearbox
- The goal
  - offer appropriate driving performance (e.g. torque, comfort, safety)
  - minimize fuel consumption and emissions
- Relevant characteristics
  - man-in-the-loop system
  - safety requirements
  - strictly coupled with mechanical parts
  - hard real-time constraints
  - complex algorithms for controlling fuel injection, spark ignition, throttle position, gear shift …
  - large parameters distribution, time dependency, unknown disturbances
  - low cost

Engine Control System Design

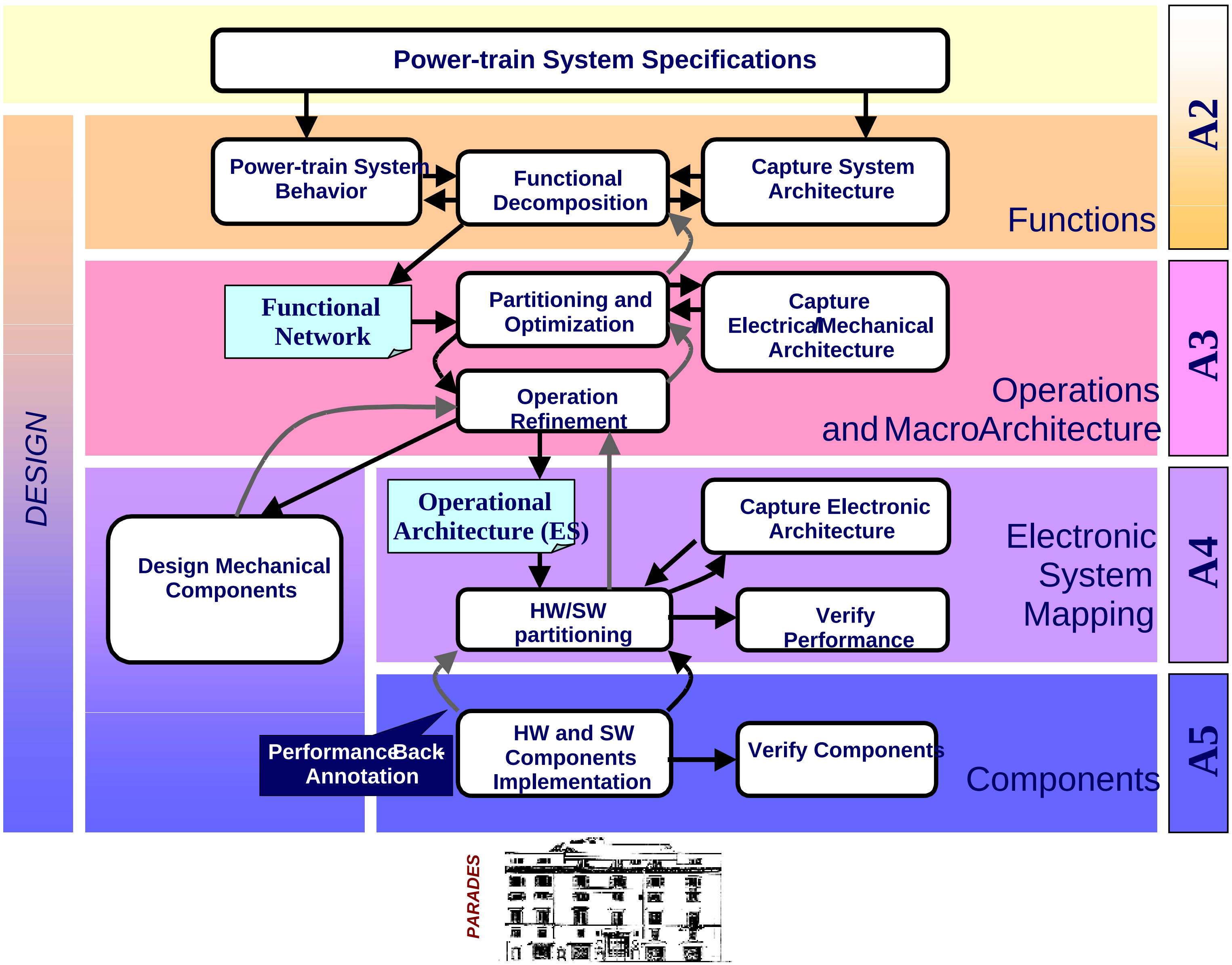


Why Designing Hybrid Control Algorithm for Engine and Power-train Controls?

- **Specifications**
- **Control and disturbance inputs**
- **Physical processes in the plant**
- **Handling of asynchronous signals**
- **Description of the HW/SW implementation constraints**

input	value	time
Throttle valve	Continuous	Continuous
Fuel injection	Continuous	Discrete
Spark ignition	Discrete	Discrete
Clutch	Discrete	Discrete
Gear	Discrete	Discrete
Resistant torques	Continuous	Continuous

Design Methodology (PARADES-Magneti Marelli)



Power-train Control Problems Classification

Control Problems / Controlled Variable	Regulation	Tracking
Engine Speed	idle speed	rpm tracking
Traction Force	force transients	force tracking
Vehicle Velocity	cruise control	
	idle with gear in	

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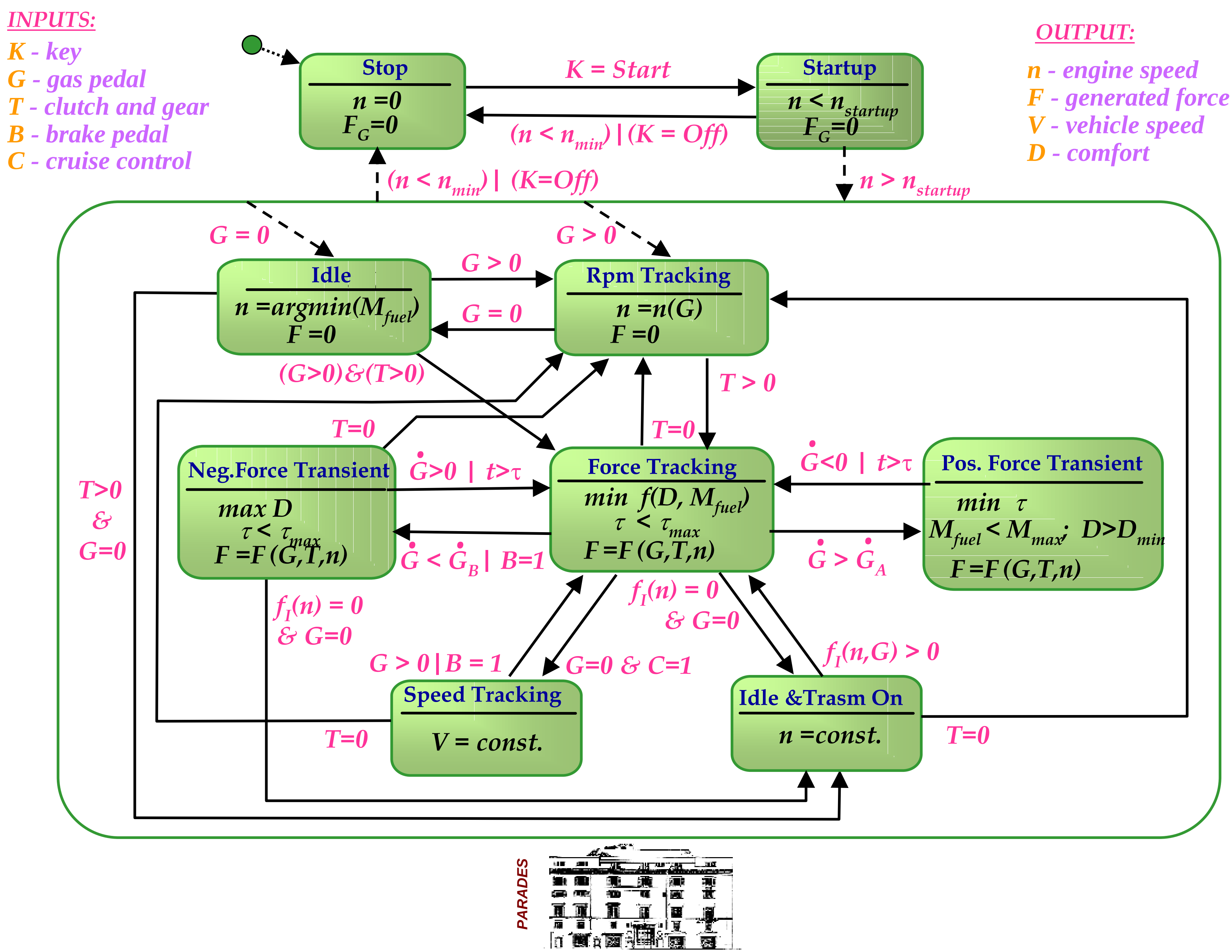
INPUTS:
K - key
G - gas pedal
T - clutch and gear
B - brake pedal
C - cruise control
OUTPUT:
n - engine speed
F - generated force
V - vehicle speed
D - comfort
Stop
n =0
F_G=0
K = Start
Startup
$n < n_{startup}$
F_G=0
$(n < n_{min}) | (K = Off)$
$(n < n_{min}) | (K=Off)$
$n > n_{startup}$
G = 0
G > 0
Idle
$n = argmin(M_{fuel})$
F =0
G > 0
G = 0
Rpm Tracking
n =n(G)
F =0
(G>0)&(T>0)
T > 0
T=0
T=0
T>0
&
G=0
Neg.Force Transient
max D
$\tau < \tau_{max}$
F =F (G,T,n)
$\dot{G}>0$ | $t>\tau$
Force Tracking
min $f(D, M_{fuel})$
$\tau < \tau_{max}$
F =F (G,T,n)
$\dot{G}<0$ | $t>\tau$
Pos. Force Transient
min τ
$M_{fuel} < M_{max}$; $D>D_{min}$
F =F (G,T,n)
$\dot{G} < \dot{G}_B$ | B=1
$\dot{G} > \dot{G}_A$
$f_I(n) = 0$
& G=0
$f_I(n) = 0$
& G=0
G > 0 | B = 1
G=0 & C=1
$f_I(n,G) > 0$
Speed Tracking
V = const.
T=0
Idle &Trasm On
n =const.
T=0
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System Specifications

- $J\{\}$ and J_{max} : performance index and threshold
- z : object variable
- v_{rif} and x_{rif} : reference trajectory in a given class

$$J\{z(t)\} \le J_{\max}$$

$$z(t) = \varphi\left(v_{rif}(t), x_{rif}(t), t\right)$$

- **Ex. Idle specs:** Accelerator and clutch released, idle gear, water temperature greater than 60°, z=engine rpm; $J(z) = |z(t+2) - 500|$ and $J_{max} = 20$.

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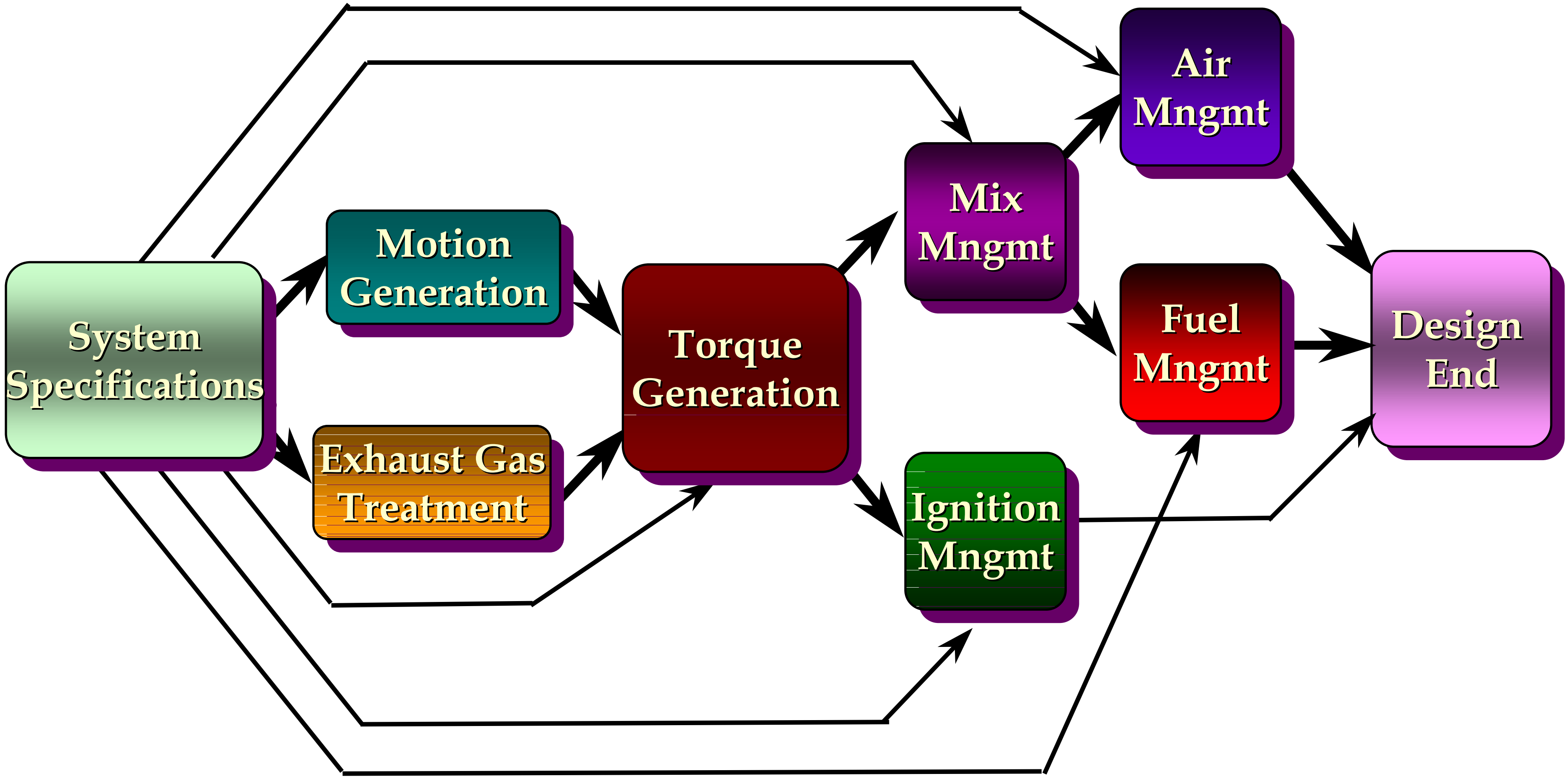
From System Specification to Functions

- Decompose the system into Functional Architecture
  - early detection of design-constraint conflicts
  - to tackle the complexity of the design of control algorithms
  - inside on the physical processes
- Performance is guaranteed by estimating each function behavior and by a trade-off process guided by the function interaction graph
- Simulation of the design alternatives and evaluation of cross dependencies
- Provide implementation independent solutions

Design of Functions Desired Behaviors



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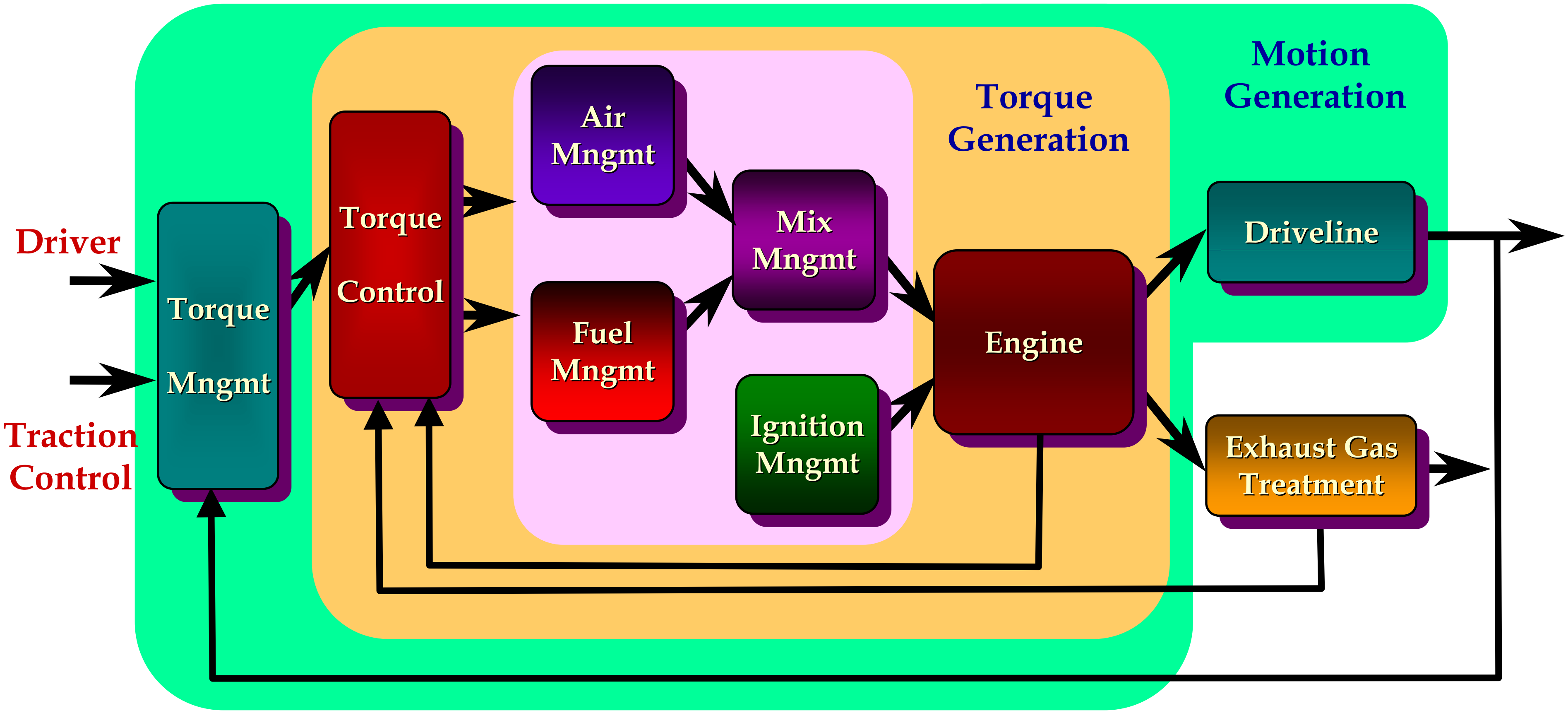
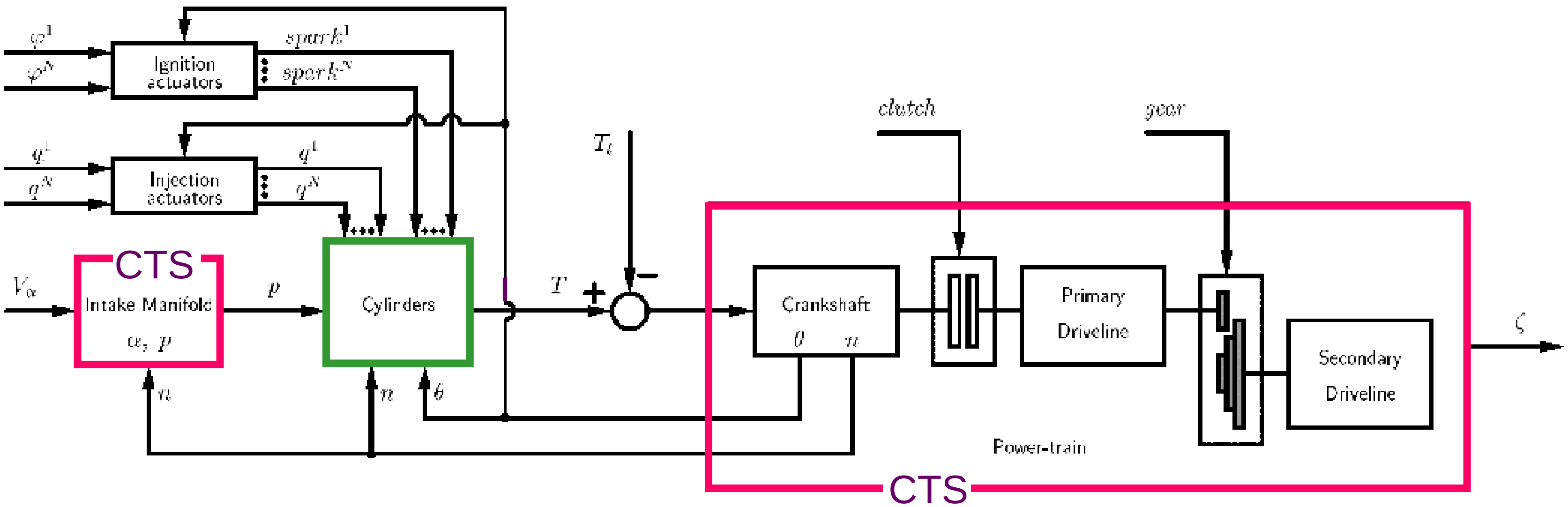
Design of Operations



- For each function control algorithms has to be designed to achieve the desired functional behavior.

Engine and Power-train Model



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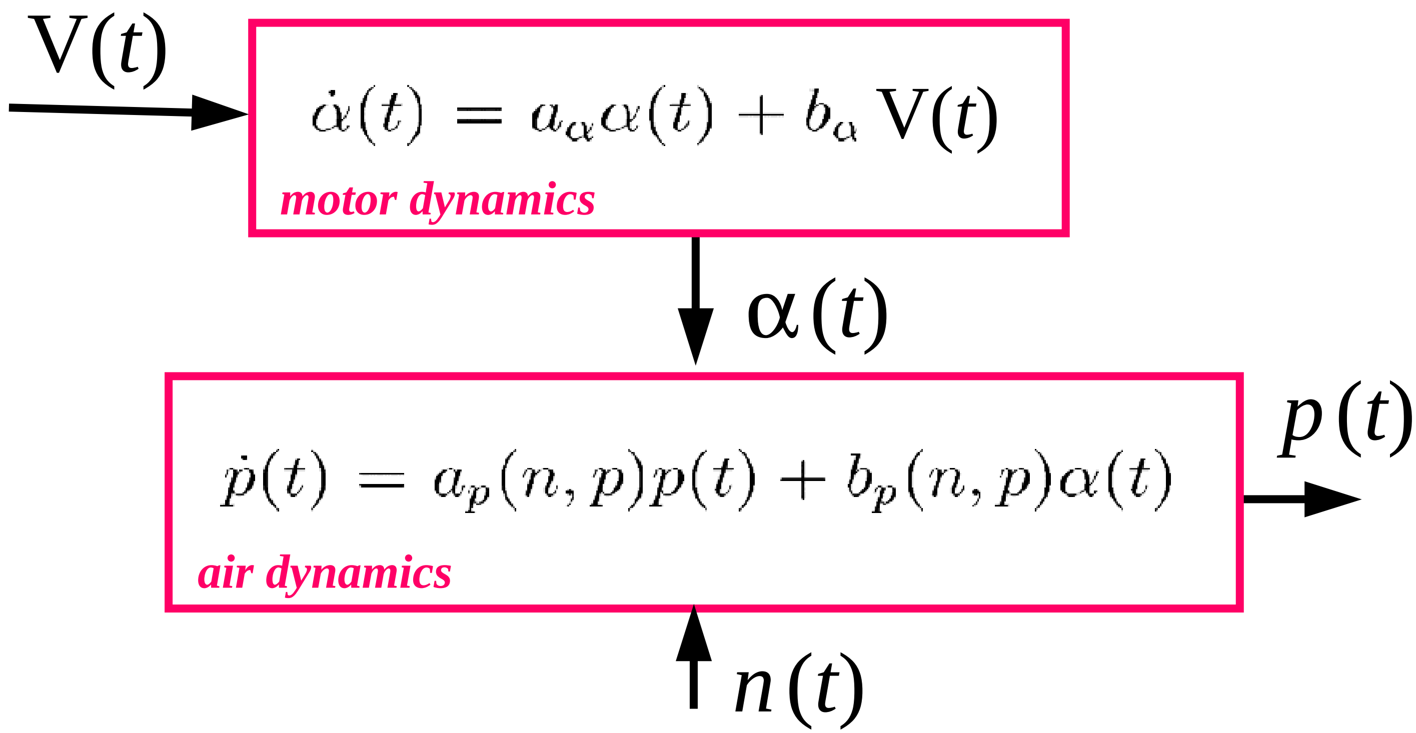
Intake Manifold



V(*t*) *- throttle motor voltage*

n **(*t*)** *- crankshaft speed*

α **(*t*)** *- throttle angle*

p **(*t*)** *- manifold pressure*

Power-train

$T(t)$

$$\begin{bmatrix} \dot{\alpha}_e(t) \\ \dot{n}(t) \\ \dot{\omega}_p(t) \end{bmatrix} = A \begin{bmatrix} \alpha_e(t) \\ n(t) \\ \omega_p(t) \end{bmatrix} + b\,T(t) + b_0$$

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

$\zeta(t)$

power-train dynamics

$\zeta(t)$

$\theta(t)$

***T* (t)** *- generated torque*

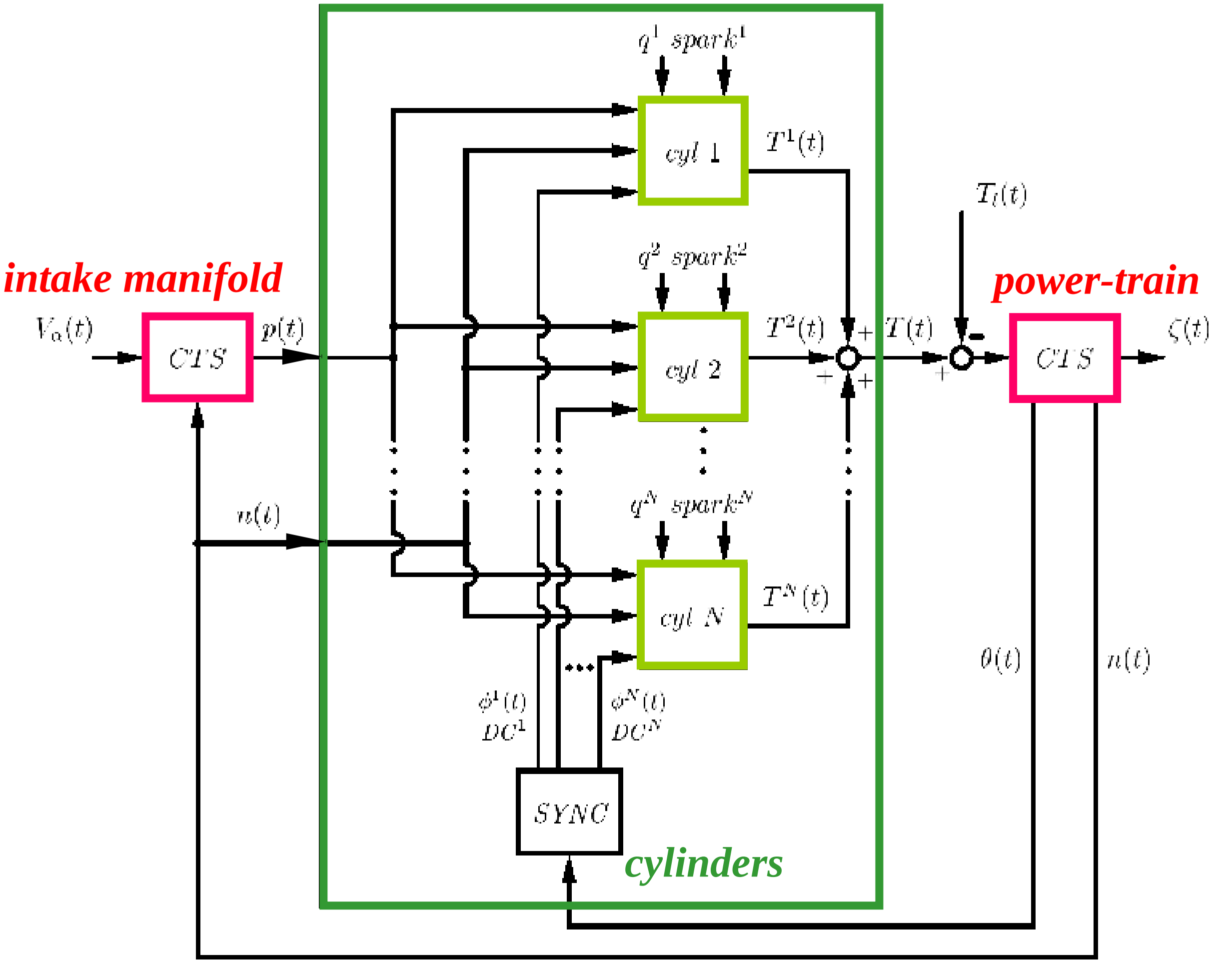
***θ* (t)** *- crankshaft angle*

α_e(t) *- torsion angle*

***n* (t)** *- crankshaft speed*

ω_p (t) *- wheel speed*

Engine and Power-train Model



Hybrid Systems in the Tagged-Signal Models (TSMs) Framework

Hybrid systems can be seen *as formalisms* for describing a complex system using combinations of models of computation when a single one is not powerful, expressive or practical enough.

- An event e belongs to V x T: V is the set of values and T is the set of tags i.e.
  - universal time (T is the set of real numbers)
  - discrete time (T is a totally ordered discrete set),
- a signal is a set of events,
- a process with N channels is a subset of the set of N-tuples of signals.

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Models of Computation

- A *Finite State Machine (FSM)* is a synchronous TSM process in which the tags take values in N and the inputs, outputs and states assume finite values.
- An *Sequential System (SS)* is a synchronous TSM process in which the tags take values in N and the inputs, outputs and states assume values on infinite sets.
- A *Discrete-Event System (DES)* is a timed TSM process in which the tags are order-isomorphic with N (and denotes instants of time).
- A *Continuous-Time System (CTS)* is a timed TSM process in which the tags take values in a connected set on which a metric is defined.
- A *Discrete-Time System (DTS)* is a synchronous DES.

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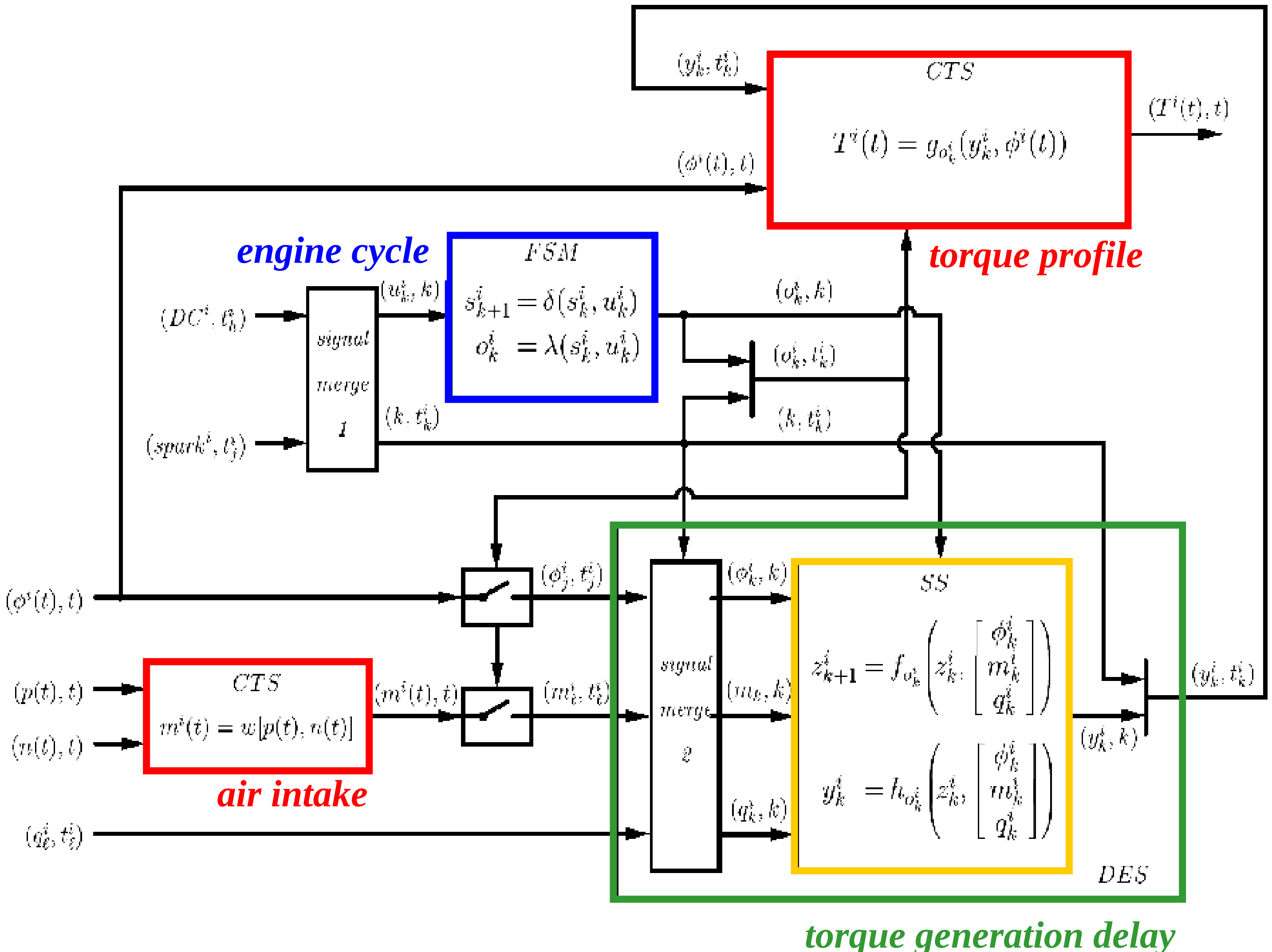
Hybrid Tagged-Signal Model of a Single Cylinder



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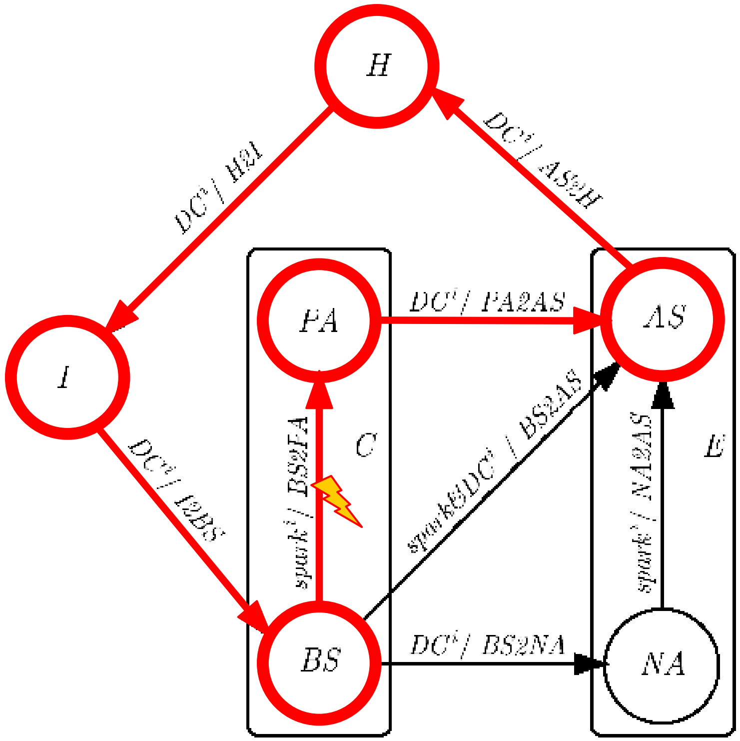
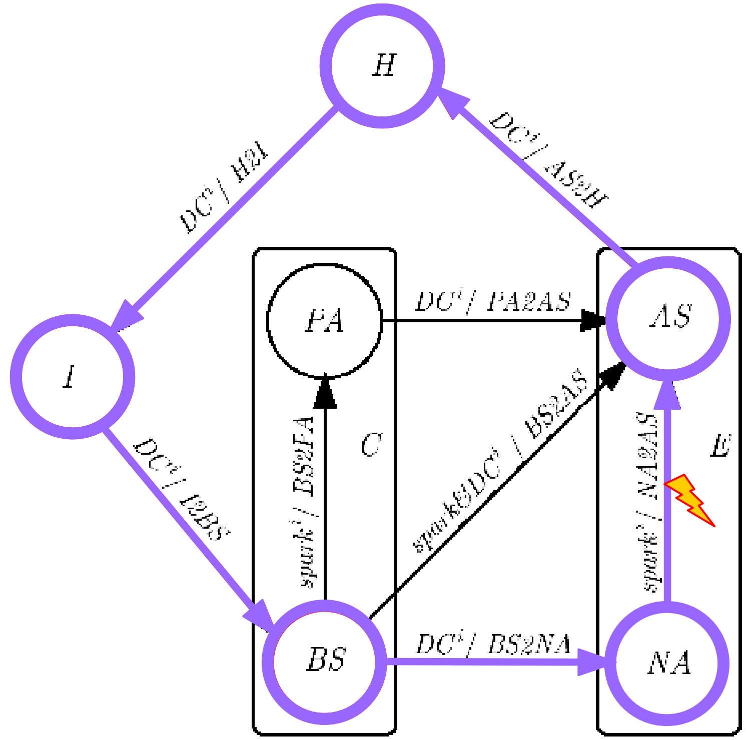
Engine Cycle (FSM)





- **positive spark advance:**

the spark is given before the TDC between the compression and expansion strokes.

- **negative spark advance:**

the spark is given after the TDC between the compression and expansion strokes.

Torque Generation Delay (SS)

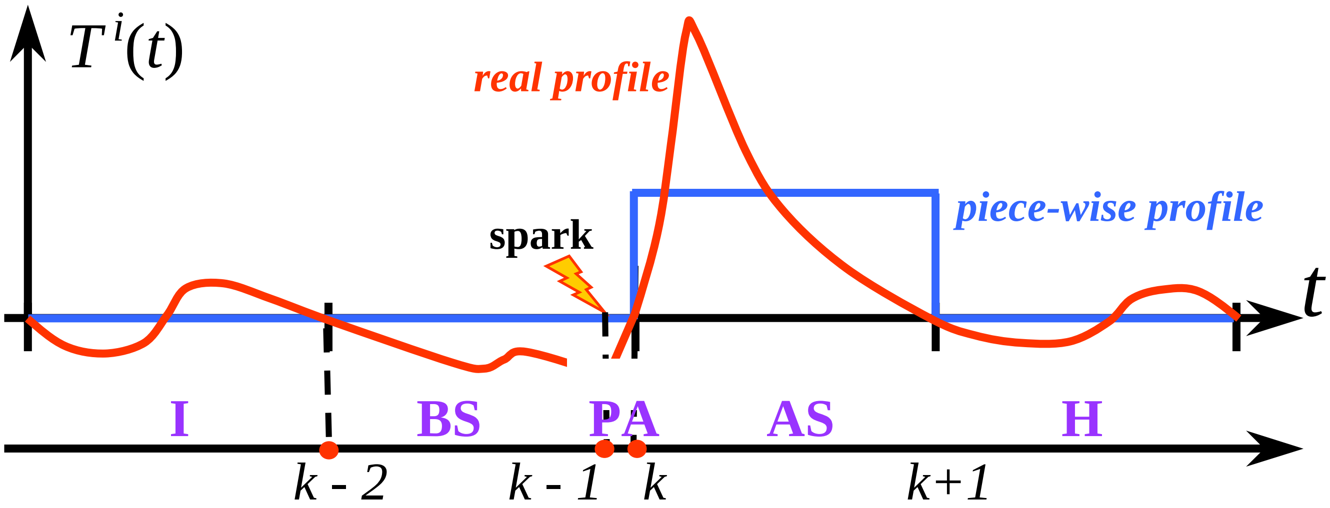
Sequential System

$$y_k^i = (m^i, q^i, \varphi^i) = (m_{k-2}^i, q_{k-2}^i, 180^o - \phi^i(t_{k-1}))$$

Torque Profile (CTS)

Continuous-Time System

$$T^i(t) = g_{o_k^i}(y_k^i, \phi^i(t))$$



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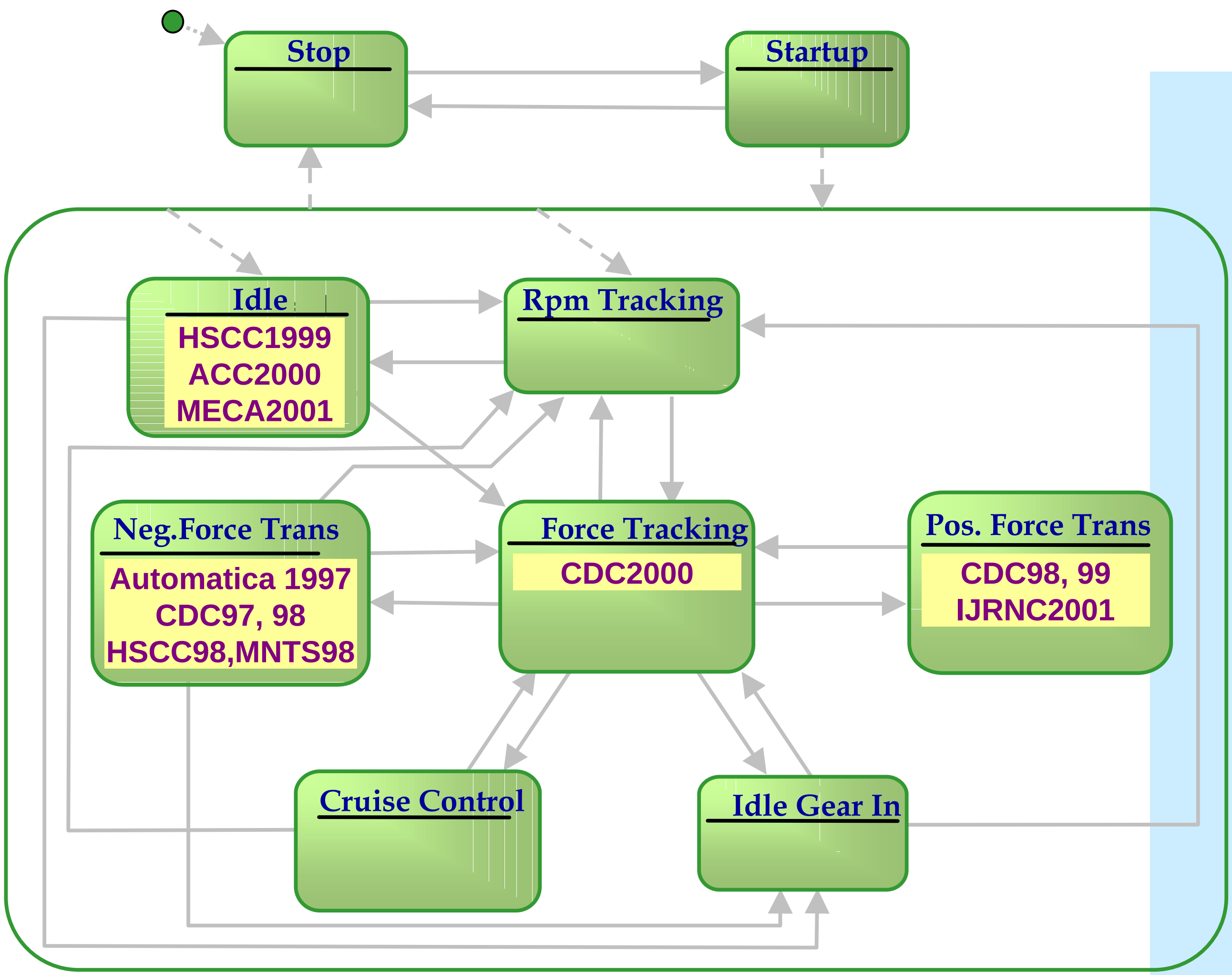
Control Algorithm Design



Open Projects

- Formal verification
  - automatic tools
  - idle speed control MECA01
  - force transients
- Design of a hybrid observer for the driveline ECC01
- Cruise control design
- Misfire diagnosis
- Switching strategies between controller modes

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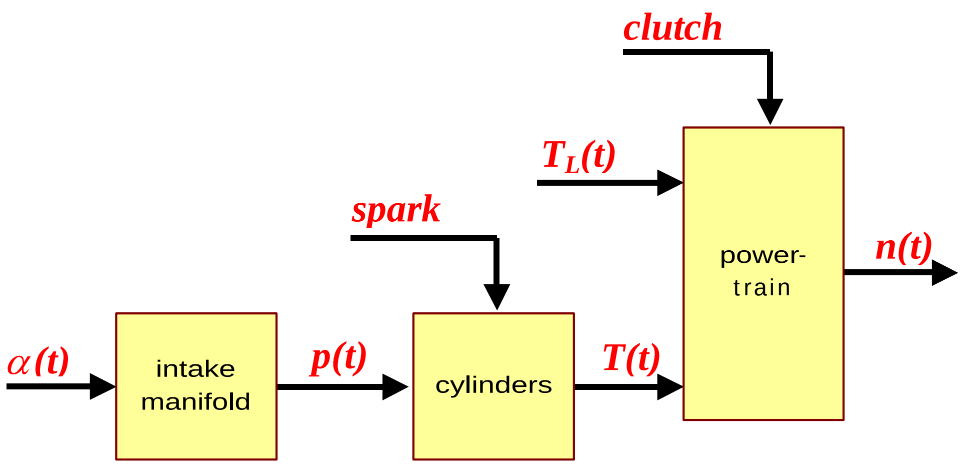
Idle Speed Control

Maintains the crankshaft speed within a specified range.



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

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 $[0, T_L^M]$.

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Cut-off Control (no elect. throttle valve)

Driver releases completely accelerator pedal: no torque is requested.

- **Plant inputs:** fuel injection $q(k)$ and spark ignition *spark*
- **Control problem:** reduce fuel injection to zero minimizing driveline oscillations

  assuming

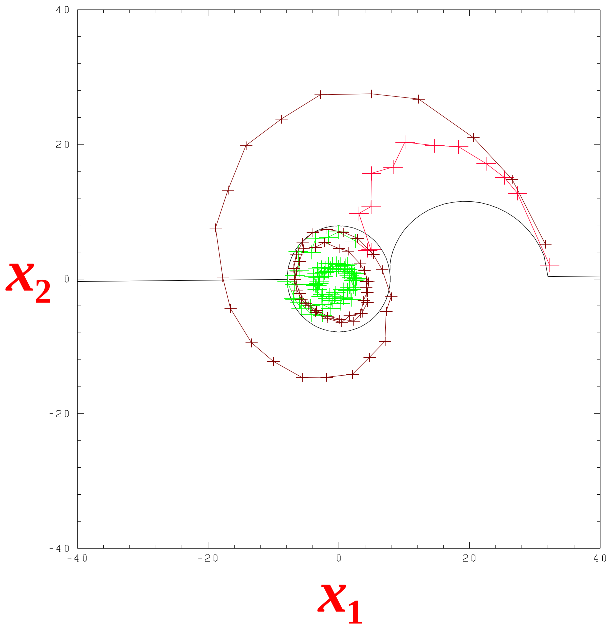
  - air manifold dynamics at rest, i.e. $m(k)=m_0$,
  - either no fuel injection or stoichiometric air-fuel mixture, i.e. $q(k) \text{ in } \{0, m_0 / (A/F)_{stoic}\}$
- **Approach:** design

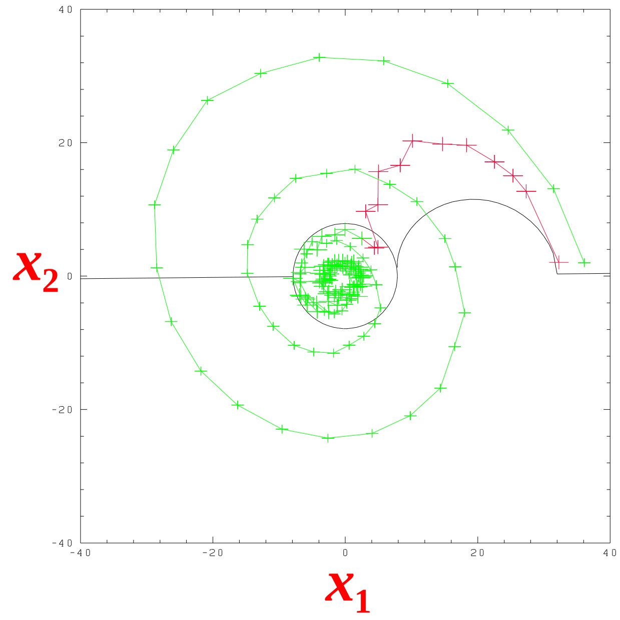
  (*1*) a minimum-time torque control $u(t)$ for the *motion generation* subsystem.

  (*2*) feedback controllers for the *torque generation* subsystem ($q(k)$, and *spark*) that produce the torque $u(t)$,

  (*3*) provide conditions that ensure convergence of the closed-loop hybrid system.

Cut-off Control: Experimental Results





- *comparison between the proposed cut-off control and a currently implemented open-loop strategy.*
- *comparison between the proposed cut-off control and a sharp cut-off.*

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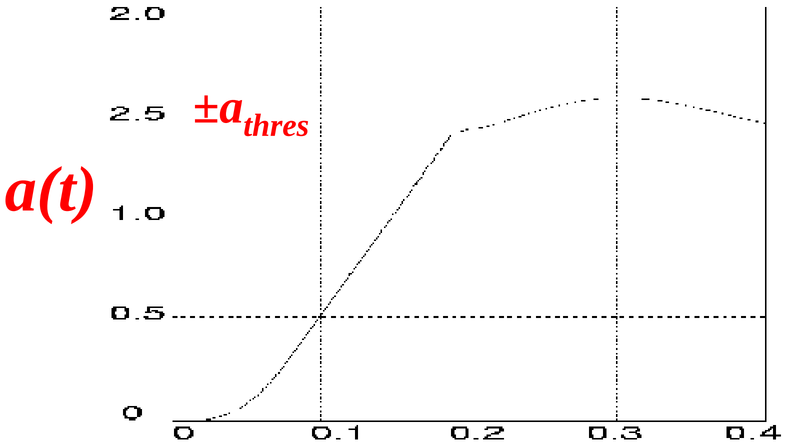
Force Transient Control (GDI engine)

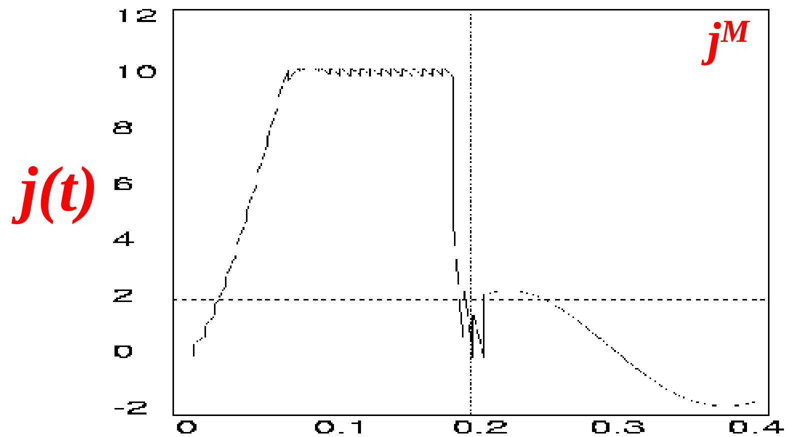
Driver pushes fast accelerator pedal requesting a new value of engine torque.

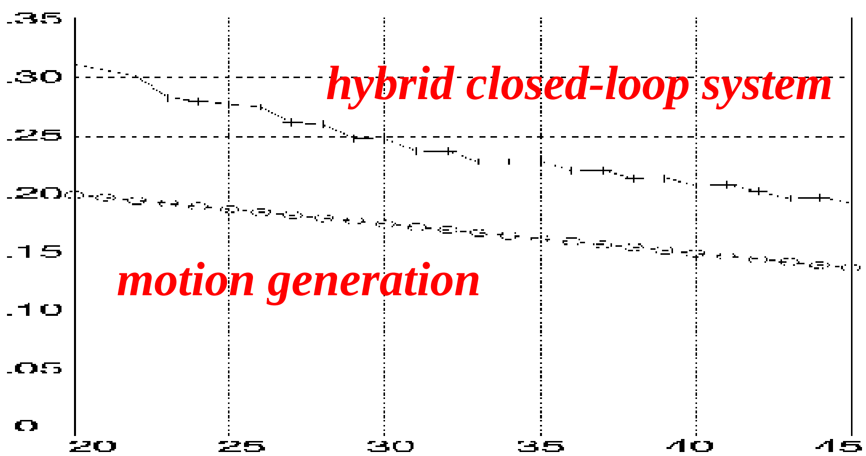
Plant inputs: throttle valve $\alpha(t)$, fuel injection $q(k)$ and spark ignition $spark$.

- **Control problem:** produce as soon as possible the requested torque T^R, satisfying the following constraints
  - vehicle oscillations under perception threshold $|a_{osc}(t)| \leq a_{thres}$,
  - bounded vehicle jerk $0 \leq j(t) \leq J^M$,
  - bounded air-fuel ratio $(A/F)_{min} \leq m(k)/q(k) \leq (A/F)_{max}$.
- **Approach:** design
  - (1) a minimum-time torque control $u(t)$ for the *motion generation* subsystem.
  - (2) feedback controllers for the *torque generation* subsystem ($q(k)$, and $spark$) and the *air management* subsystem, $\alpha(t)$, such that the engine torque T tracks u,
  - (3) provide conditions that ensure convergence of the closed-loop hybrid system.

Force Transient Control: Simulation Results







Comparison: ***time to the target set for***

- ***the motion generation subsystem minimum-time control***
- ***the hybrid closed-loop system***

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A/F Control during Engine Torque Transients (multipoint injection system)

Driver pushes fast accelerator pedal requesting a new value of engine torque.

- **Plant inputs:** throttle valve $\alpha(t)$, injection times $\Delta(k)$.
- **Control problem:** produce as soon as possible the requested torque T^R,

  satisfying the following constraints

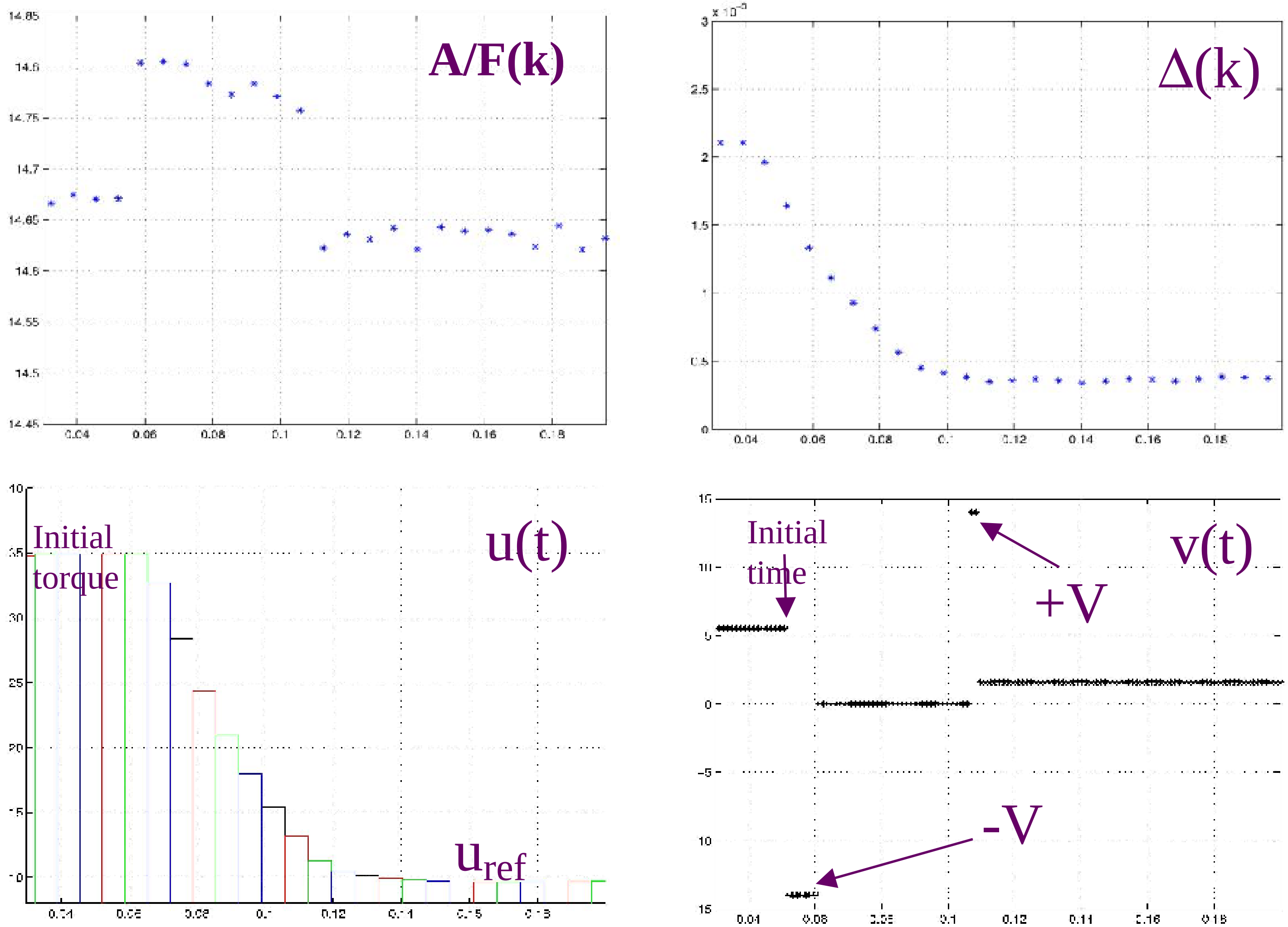
  - vehicle oscillations under perception threshold $|a_{osc}(t)| \le a_{thres}$,
  - bounded air-fuel ratio $(A/F)_{min} \le m(k)\,/\,q\,(k) \le (A/F)_{max}$.
- **Approach:** design

  (*1*) a minimum-time constrained control for $\alpha(t)$ and $\Delta(t)$ in the continuous-time domain

  (*2*) mapping of the continuous solution into the hybrid domain

  (*3*) provide conditions that ensure convergence and constraint satisfaction for the closed-loop hybrid system.

Simulations



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Force Tracking Control (GDI engine)

Driver moves accelerator pedal generating on-line a desired engine-torque signal.

- **Plant inputs:** throttle motor $V(t)$, fuel injection $q(k)$, and spark ignition *spark*.
- **Control problem:** track the requested engine-torque $T_{ref}(t)$ satisfying
  - air-fuel ratio constraint $(A/F)_{min} \leq m(k)/q(k) \leq (A/F)_{max}$,
  - saturation of the catalytic converter oxygen storage mechanism $l_{min} \leq l(k) \leq l_{max}$.
- **Approach:** design a 2-nested loop tracking controller

(*1*) the outer one for the *torque generation*, which achieves tracking of $T_{ref}(t)$ *by* $T(t)$, satisfies the constraints, and generates a reference manifold pressure $p_{ref}(t)$,

(*2*) the inner one for the *air management*, which achieves tracking of $p_{ref}(t)$ *by* $p(t)$.

Then,

(*3*) analyze the behavior of the closed-loop hybrid system and provide sufficient conditions for tracking of generic reference torques $T_{ref}(t)$.

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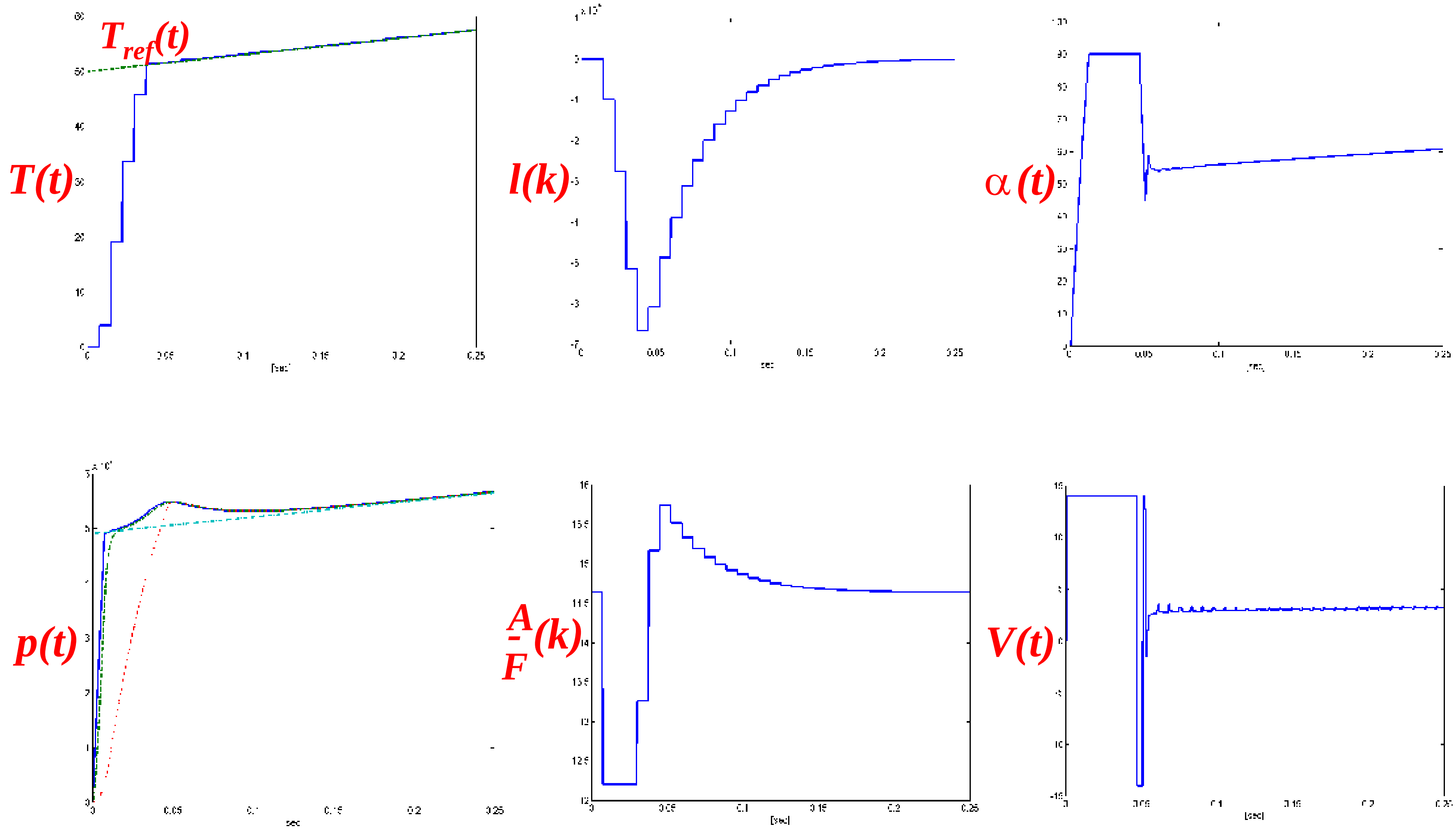
Force Tracking Control: Simulation Results



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Cruise Control System

Regulate vehicle speed to a desired value set by the driver.

- **Control problem:** design an engine torque feedback control that steers the car to a desired velocity and maintains it, robustly with respect to driving conditions and torque disturbances.
- **Several operation modes:**

  off, regulation, acceleration, deceleration, stand-by, override
- **Man-machine interface problem** (safety and comfort):

  e.g., switching between driver and ECU controlling the engine torque in the outer loop.
- **Safety relevant application:**

  the ECU has complete control of the longitudinal motion of the car (no driver in the loop).

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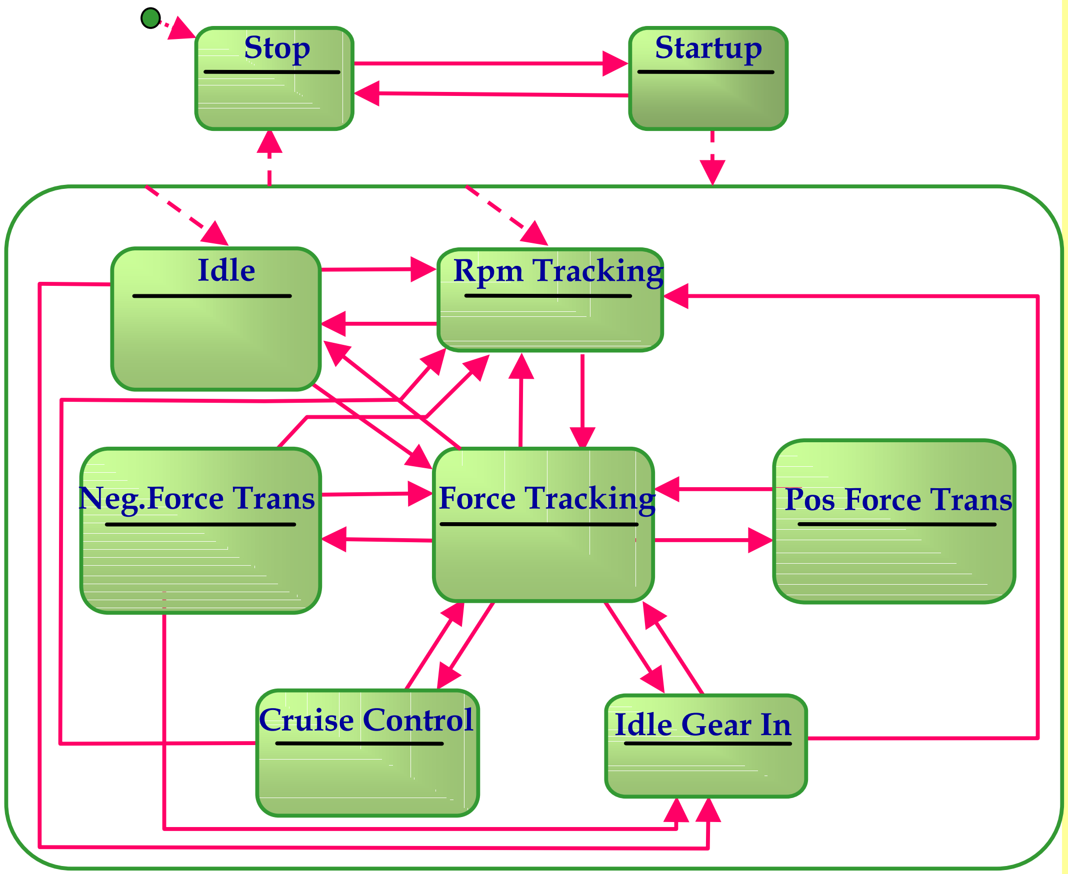
Switching Strategies between Controller Modes



- The driver selects the operation mode by acting on pedals, levers and consoles. In each mode,
  - different controlled variable
  - different objective (performance).
- The control system has to provide proper switching between the operation modes, ensuring
  - safety and comfort.
- This involves the design of
  - switching conditions
  - control algorithms that drive the system from one mode to another.

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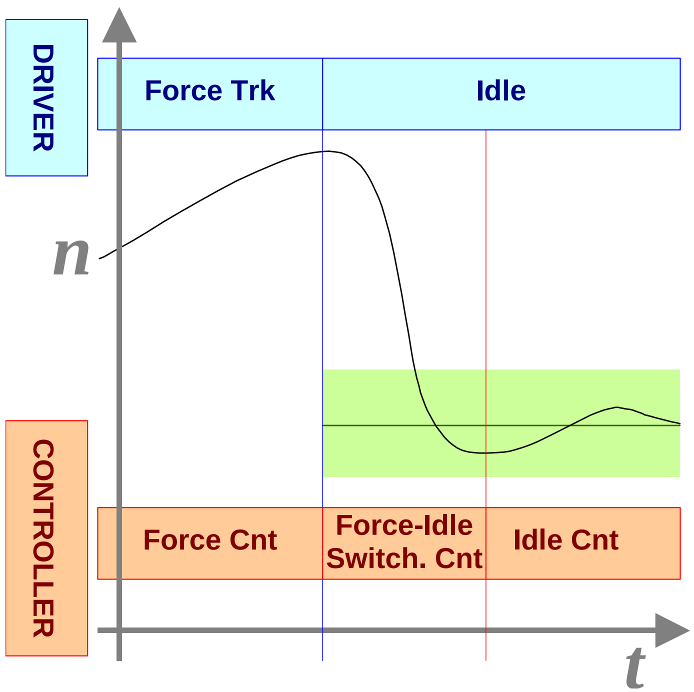
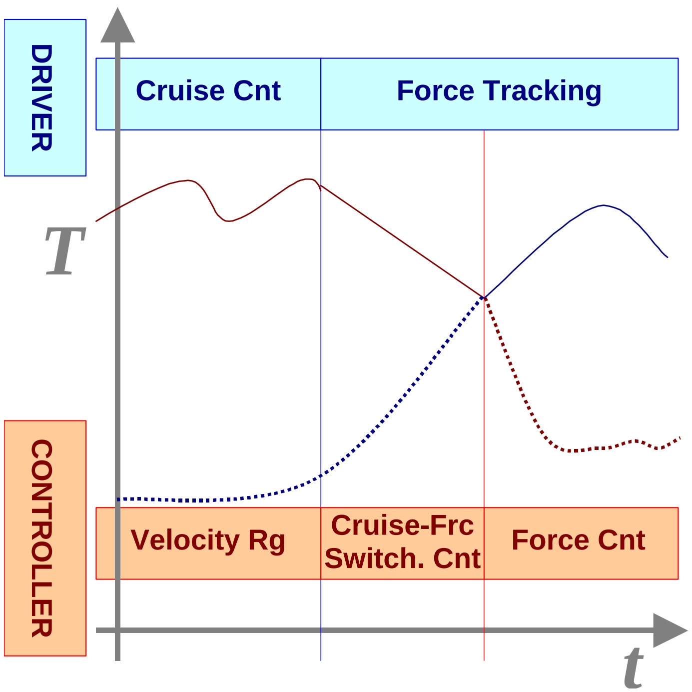
Switching between Controller Modes

◆ Force Tracking ➡ Idle



◆ Cruise control ➡ Force tracking



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Formal Verification

- Synthesis of maximal controller satisfying a safety property by iterative removal of unsafe states
  - Application to idle speed control
  - Simplified synthesis procedure for systems with lower bounds on event separation

- Verification of safety properties based on computation of states reached over time
  - Evaluation of available tools to verify control strategies:

    Checkmate (CMU)
    - idle speed control
    - force transient control
  - Definition of new computational engines based on different data structures