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Hybrid Controller Synthesis for Idle Speed Management of an Automotive Engine[1]

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Abstract

The specification for the idle control problem for automotive engines is to maintain the crankshaft speed within a given range in the presence of load changes. A new cycle-detailed hybrid model of the engine that captures well the interactions between the discrete phenomena of torque generation and spark ignition, and the continuous evolution of the power-train and air dynamics, is proposed. The maximal robust–controlled invariant set that satisfies the specification is determined and the maximal controller for the engine in idle is presented.

1 Introduction

The synthesis of a control strategy for an internal combustion engine in the idle regime is one of the most challenging problems in engine control. The goal is to maintain the engine speed as close as possible to a reference constant engine speed despite load torque disturbances (i.e. the air conditioning system, the steering wheel servo-mechanism) and engagements and disengagements of the trasmission occurring when the driver operates on the clutch. In order to achieve the best fuel economy, the reference engine speed is chosen at the minimum value that yields acceptable combustion and emission quality, and noise, vibration and harshness (NVH) characteristics.

Assuming a stoichiometric air-to-fuel ratio[2], stability of the engine speed is achieved by controlling the amount of air supplied to the engine and the spark ignition times. In modern cars, the amount of air is controlled by directly acting on the throttle via a DC or a stepper motor (electronic throttle control). This control can provide large control authority but it is relatively slow since it is subject to the dynamics of the cylinders filling and the delay due to the mix compression. On the contrary, spark control is much faster and is actuated by anticipating/retarding the spark ignition with respect to a nominal retard from the maximum spark-to-torque efficiency value. Hence, sudden loads can be much better compensated with spark ignition than with air inflow, while air inflow can be used to control the engine in steady state. However, spark control has a limited authority since combustion inefficiency and catalyst overheating must be avoided.

A survey on different engine models and control design methodologies for idle control is given in [1]. Both time–domain (e.g. [2]) and crank–angle domain (e.g. [3]) average–value models have been proposed in the literature. Mean value engine models [4] describe the dynamic time development of the average values of some engine variables and can be used for control design, when engine speed fluctuations due to cycle-to-cycle variations in the combustion process are not considered. More recently, cycle accurate models have been investigated [5] in order to reduce the periodic speed variations due to torque fluctuations.

Several control design techniques have been applied to the idle control problem. A typical control consists of a PID control [6] for the air loop, a P control for the spark loop and several feedforward compensation schemes which use accessory load and enviromental information. Since the goal is to regulate the engine speed to its reference value, the integral part of the air control loop is the core of this strategy and several efforts were made to tune the PID control in order to minimize some appropriate cost functions. Other optimization-based methods have been used: in particular the optimal LQ-based [7] control was demonstrated to achieve better performances with respect to conventional PID controller, and H_∞ methods were applied in order to achieve a more robust control design [8]. Controllers based on the μ-synthesis technique were proposed, to ensure stability also when large plant perturbations or uncertainties are present [9]. Additional improvements

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[2]Air-to-fuel is usually controlled to achieve desired emission performances and not for speed regulation.

are possible when some loads are measurable. In [2], an ℓ_1 optimal control minimizing the excursion of the engine speed has been proposed when a bounded load torque accessible to measurement is present.
In this paper, the idle control problem is specified as the one of keeping the crankshaft speed within a specified range, robustly with respect to load torque disturbances. In order to design a controller able to reduce substantially emission and gas consumption while maintaining idle regime stability, an accurate cycle-to-cycle model of a four–stroke gasoline engine is here proposed. The model has a "natural" hybrid representation because (i) pistons have four modes of operation corresponding to the stroke they are in, and (ii) power–train and air dynamics are continuous–time processes. In addition, these processes interact tightly: in fact, the timing of the transitions between two phases of the pistons is determined by the continuous motion of the power–train, which, in turn, depends on the torque produced by each piston. The adoption of a hybrid formalism allows to describe the cyclic behavior of the engine, thus capturing the effect of each spark ignition on the generated torque, the interaction between the discrete torque generation and the continuous power-train and air dynamics, and the discrete changes in the power-train. The torque that is generated by each piston and applied to the engine crankshaft can be assumed to be a function of the spark ignition time, and of the air-fuel mixture mass loaded in the cylinder during the intake phase so that it can be modified by appropriately acting on the throttle valve and on the spark ignition times. Hence, the outputs of the hybrid controller are the input voltage to the DC motor moving the throttle valve (continuous-time variable) and the spark ignition times for the four spark plugs (discrete-time variables). The problem of maintaining the crankshaft speed within a given range is then formalized as a safety specification for the hybrid closed-loop system. A *safety specification* is a state-invariance property, specifying a set of good states within which the closed-loop system must remain. The problem is equivalent to compute the maximal controlled invariant set contained in the good states and robust with respect to the actions of the disturbance. A systematic procedure for computing the maximal safe set has been recently proposed by Tomlin, Lygeros, and Sastry [10]. This set consists of all the hybrid states for which there exists a hybrid control strategy (the maximal controller) that maintains the state in the set of good states forever, in spite of any discrete and continuous disturbance. The procedure is not guaranteed to terminate in a finite number of steps. By applying this procedure to the hybrid model of the engine, the maximal safe set for the idle control is determined. Moreover, from the maximal safe set, the entire set of possible controllers that satisfy the constraints (maximal controller) is computed. Then, an optimal controller can be selected by minimizing a cost function and performance issues can be considered on the basis of the previous results. To summarize our main contribution, the use of a hybrid framework, where discrete and continuous signals are modeled in a separate but integrated manner, is a definite advantage over other approaches since it allows us to solve exactly the control problem while other approaches, where the system is approximated by either continuous [5], or discrete sampled [3] representations, obtain approximate solutions. This allows us to determine exactly the best achievable performance of the closed–loop system, that is the maximum admissible load torque or the minimum reference engine speed attainable. The paper is organized as follows: in Section 2 the hybrid model for a four cylinder SI engine is presented. In Section 3 the maximal controller is presented, and it is applied to gauge the extreme performances of the control system.

2 Hybrid model of the engine

In this section, a hybrid system that describes the behavior of an automotive 4-cylinder engine in idle is illustrated. Figure 1 shows the interactions between the three main subsystems which compose the engine: the intake manifold, the cylinders and the power–train.
The pressure p of the intake manifold depends on the throttle valve angle α and determines the mass of air-fuel mixture m loaded by the cylinders. In each stroke of the 4–stroke engine cycle, the cylinders evolution is described in terms of the angle $\theta \in [0, 180]$, which represents the location of the piston within the given stroke. The torque T generated by the cylinders depends on both the mass m and the spark ignition time. Finally, the power-train dynamics and the crankshaft revolution speed n, controlled by the generated torque T, are subject to the sum of load torques T_l and depends on the position of the clutch. The gear is supposed to be in idle position. A detailed description of these three subsystems and of a hybrid model of a power–train equipped with an N–cylinder 4–stroke engine can be found in [11]. That description follows the tagged-signal model (TSM) formalism proposed by Lee and Sangiovanni–Vincentelli [12], which allows the authors to describe formally systems represented as interacting processes of heterogeneous models of computation. A combination of Finite State Machines (FSMs), Discrete Event Systems (DESs) and Continuous–Time Systems (CTSs) is used to describe the behavior of the engine and the power–train.

The hybrid model of the engine in idle is characterized by a set of discrete modes (corresponding to the FSM states), a set of continuous variables (subject to a continuous–time dynamics, CTS) and a set of symbolic constants (whose discrete–time evolution is described by a DES). The control inputs are: the throttle angle

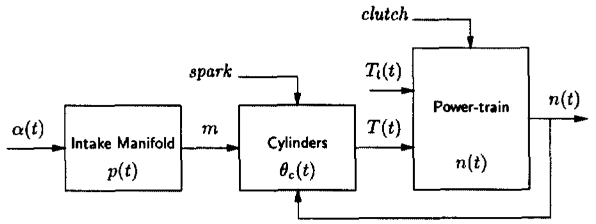

Figure 1: The engine blocks.

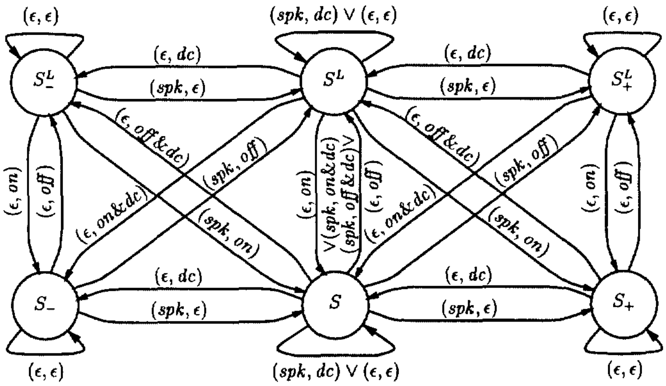

Figure 2: Engine FSM.

α and the spark command *spark*(which can be applied from 20^0 before the end of the compression stroke to 15^0 after the beginning of the expansion stroke). The disturbance inputs are: the load torque T_l (assumed to be nonegative and upper bounded by some T_l^M) and the *clutch*. Hence, the controller and the environment act on the system with two kinds of inputs: the continuous inputs, α and T_l, affect the continuous dynamics; the discrete inputs, *spark* and *clutch*, determine the discrete mode transitions, the resetting of continuous variables and the setting of symbolic constants. This modeling formalism combines the features of [13] with elements of the hybrid dynamics of [10]. The formal definition and the behavior of this hybrid model is analogous to the one described in [14], with the separation between continuous variables and symbolic constants explicitly introduced here (see also [11]).

The engine FSM has six modes S_-, S, S_+, S^L_-, S^L, and S^L_+, see Figure 2. The three modes S_-, S, and S_+ are used to describe the interleaving between spark ignitions and dead–centers (the pistons are at their uppermost/lowermost position) in the cylinders evolution and are related to the clutch in open position. Modes S^L_-, S^L, and S^L_+ are the corresponding modes with clutch closed.

The DES has a 4–dimensional state, whose components (T, m_C, m_E, φ) stand, respectively, for the generated torque, the mass of mixture in the cylinder which is in the compression stroke, the mass of mixture in the cylinder which is in the expansion stroke, and the applied spark advance.

The components of the CTS state are: the manifold pressure p, the crankshaft speed n and the piston position θ. Such variables are subject to the following dynamics

$$\begin{aligned} \dot{p}(t) &= a_p p(t) + b_p \alpha(t) && (1) \\ \dot{n}(t) &= a_n n(t) + b_n (T - T_l(t)) && (2) \\ \dot{\theta}(t) &= k_c n(t) && (3) \end{aligned}$$

where, if θ is in degrees and n is in revolutions per minute, then $k_c = 6$, $a_n = -Bb_n$ and

$$b_n = \begin{cases} 1/J & \text{if the clutch is open} \\ 1/(J+J') & \text{if the clutch is closed} \end{cases} \qquad (4)$$

with J (J') and B (B') denoting the inertial momentum and the viscous friction coefficient of the segment of the power-train from the crankshaft to the clutch (of the primary drive-line, respectively). In (2) the DES variable T plays the role of a parameter.

Formally, the overall engine hybrid model is a tuple $H = (\{Q, X, \Xi\}, \{\Sigma_c, U\}, \{M_c^{disc}, M_c^{cts}\}, \{\Sigma_e, D\}, \{M_e^{disc}, M_e^{cts}\}, \{f, \delta\})$, where:

- the **state space** is composed of: the finite set of FSM modes $Q = \{S_-, S, S_+, S^L_-, S^L, S^L_+\}$, the space of CTS variables $X = \{(p, n, \theta) \mid (p, n, \theta) \in \mathbb{R}^3\}$, and the space of DES variables $\Xi = \{(T, m_C, m_E, \varphi) \mid (T, m_C, m_E, \varphi) \in \mathbb{R}^4\}$. An element (q, x, ξ) in the space $Q \times X \times \Xi$ is called a *configuration*;
- the **control inputs** $\alpha(t)$ and *spark* can be described by means of: the domain of continuous input values $U = [0, \alpha^M]$, the finite domain of *discrete control events* $\Sigma_c = \{spk\}$ with $\Sigma_c^\epsilon = \Sigma_c \cup \{\epsilon\}$ being the set of *discrete control moves* and the special ϵ move being the *silent* move; the *discrete controller feasible move function*[3] $M_c^{disc} : Q \times X \times \Xi \to 2^{\Sigma_c^\epsilon} \setminus \{\}$ given in Table 1; the *continuous controller feasible move function* $M_c^{cts} : Q \times X \times \Xi \to 2^U \setminus \{\}$ described as follows: $M_c^{cts}(q, x, \xi) = \{\alpha \mid \alpha \in [0, \alpha^M]\}$, $\forall (q, x, \xi)$;
- the **disturbance inputs** $T_l(t)$ and *clutch* can be described by means of: the domain of *continuous disturbance values* $D = [0, T_l^M]$, the finite set of *discrete disturbance events* $\Sigma_e = \{on, off, dc, on\&dc, off\&dc\}$ (where the events *on* and *off* represent opening and closing the clutch, the event *dc* represents reaching a dead–center when $\theta = 180$, the events *on&dc* and *off&dc* represent the simultaneous occurrence of a clutch operation and a dead–center), and $\Sigma_e^\epsilon = \Sigma_e \cup \{\epsilon\}$ is the set of *discrete disturbance moves*; the *discrete disturbance move function*[4] $M_e^{disc} : Q \times X \times \Xi \to 2^{\Sigma_e^\epsilon} \setminus \{\}$ given in Table 1; the *continuous disturbance feasible move function*: $M_e^{cts} : Q \times X \times \Xi \to 2^D \setminus \{\}$ described as follows: $M_e^{cts}(q, x, \xi) = \{T_l \mid T_l \in [0, T_{lM}]\}$, $\forall (q, x, \xi)$;
- the **transitions** are described by $f : Q \times X \times$

[3]Notice that $M_c^{disc}(S_-, \theta = 15) = \{spk\}$ is a discrete control move required when the spark was not given yet and must be given now, since it is the last valid ignition time instant.

[4]Notice that $M_e^{disc}(S_+, \theta = 180) = \{dc, off\&dc\}$, $M_e^{disc}(S_+, \theta = 180) = \{dc, on\&dc\}$, $M_e^{disc}(S, \theta = 180) = \{dc, off\&dc\}$ and $M_e^{disc}(S^L, \theta = 180) = \{dc, off\&dc\}$ model discrete moves forced by the continuous state.

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	$\{dc, on\&dc\}$

Table 1: Discrete move functions M_c^{disc} and M_e^{disc}.

$\Xi \times U \times D \rightarrow \mathbb{R}^n$ that models the CTS dynamics, which depends on the mode, and the *transition function* $\delta = (\delta|_Q, \delta|_X, \delta|_\Xi) : Q \times X \times \Xi \times \Sigma_c^\epsilon \times \Sigma_e^\epsilon \rightarrow 2^{Q\times X\times\Xi} \setminus \{\}$ modeling the discrete dynamics. For each $q \in Q$, $f(q, x, \xi, \alpha, T_l)$ is given by (1), (2) and (3), where in (2) the parameters a_n and b_n change by (4) according to whether $q \in \{S, S_+, S_-\}$ or $q \in \{S^L, S_+^L, S_-^L\}$. The transition function δ is described in Figure 2 (FSM next-state function $\delta|_Q$) and in Table 2 (CTS state reset function $\delta|_X$ and DES dynamics $\delta|_\Xi$).

3 Idle speed control synthesis

A hybrid controller watches the entire state of the system at all times, and decides whether to (1) take discrete control actions that may cause an instantaneous change in the configuration, or to (2) let time pass and drive the continuous variables by applying a continuous control action. The computation of the maximal robust–controlled invariant set for the idle control problem is reported in Section 3.1. Then, from this computation, the idle speed maximal controller is derived in Section 3.2. Finally, in Section 3.3, using these results the performances achievable by an idle speed controller are discussed.

3.1 Maximal safe set

As a first step in the design of a feedback controller for the engine in idle, we compute the set of hybrid states for which it is guaranteed that a control action that keeps the evolution of the crankshaft speed in a specified range $n_0 \pm \Delta n$, for any action of the disturbances, exists. This kind of problem belongs to the class of *safety* problems: given a set *Good* of permissible configurations, a set of configurations is *safe* if there exists a control strategy that guarantees that all trajectories that start from *safe* will remain within *Good*. The *maximal safe set Safe* is the biggest of such sets and corresponds to the maximal robust–controlled invariant set contained in *Good*.

q	$(spk, clutch)$	$\delta\|_X$	$\delta\|_\Xi$
S	(ϵ, off)		
	(ϵ, dc) $(\epsilon, off\&dc)$	$\theta := 0$	$m_C := k_m p$, $m_E := m_C,\ T := 0$
	(spk, ϵ) (spk, off)		$\varphi := 180 - \theta$
	(spk, dc) $(spk, off\&dc)$	$\theta := 0$	$m_C := k_m p$, $T := G\eta(0) m_C$
S^L	(ϵ, on)		
	(ϵ, dc) $(\epsilon, on\&dc)$	$\theta := 0$	$m_C := k_m p$, $m_E := m_C,\ T := 0$
	(spk, ϵ) (spk, on)		$\varphi := 180 - \theta$
	(spk, dc) $(spk, on\&dc)$	$\theta := 0$	$m_C := k_m p$, $T := G\eta(0) m_C$
S_-	(ϵ, off)		
	(spk, ϵ) (spk, off)		$T := G\eta(-\theta) m_E$
S_-^L	(ϵ, on)		
	(spk, ϵ) (spk, on)		$T := G\eta(-\theta) m_E$
S_+	(ϵ, off)		
	(ϵ, dc) $(\epsilon, off\&dc)$	$\theta := 0$	$m_C := k_m p$, $T := G\eta(\varphi) m_C$
S_+^L	(ϵ, on)		
	(ϵ, dc) $(\epsilon, on\&dc)$	$\theta := 0$	$m_C := k_m p$, $T := G\eta(\varphi) m_C$

Table 2: Transition functions $\delta|_X$ and $\delta|_\Xi$.

According to the idle control specification, define

$$Good = \{(q, x, \xi) \in Q \times X \times \Xi \mid n_0 - \Delta n \leq n \leq n_0 + \Delta n\}. \quad (5)$$

The maximal safe set for the engine hybrid model described in Section 2 and the set *Good* given in (5) has been computed by using the procedure described in full detail in [10, 14]. In [15], the maximal safe set for the hybrid model of the engine restricted to the four modes $\{S,\ S_+,\ S^L,\ S_+^L\}$ has been presented. That result can be extended to the entire model. The complete solution is not reported here due to lack of space.

3.2 Idle speed maximal controller

The maximal controller is the class of all the hybrid static state-feedback control strategies that guarantee that all the trajectories starting in *Safe* remain within *Good*. Hence, extracting the maximal control strategy from the maximal safe set *Safe* amounts to determining for every configuration in *Safe*, what control choices will keep the system in *Safe* (see [14]). The idle–speed maximal controller (T^{disc}, T^{cts}) is defined for each configuration (q, x, ξ) as follows:

1. $spk \in T^{disc}(q, x, \xi)$ if $spk \in M_c^{disc}(q, x, \xi) \backslash \{\epsilon\}$ and for all $\sigma_e \in M_e^{disc}(q, x, \xi)$, $\delta(q, x, \xi, spk, \sigma_e) \subseteq$ *Safe*.
2. $\epsilon \in T^{disc}(q, x, \xi)$ if $\epsilon \in M_c^{disc}(q, x, \xi)$ and

- for all $\sigma_e \in M_e^{disc}(q,x,\xi)\backslash\{\epsilon\}$, $\delta(q,x,\epsilon,\sigma_e) \subseteq$ *Safe*, and
- when $\epsilon \in M_e^{disc}(q,x,\xi)$, there exists a $\alpha \in \{0,\alpha^M\}$ such that for all $T_l \in \{0,T_l^M\}$ the vector $f(q,x,\xi,\alpha,T_l)$ is in the inward tangent space of *Safe* at (q,x,ξ);

3. $T^{cts}(q,x,\xi) = M_c^{cts}(q,x,\xi)$ if $\epsilon \notin T^{disc}(q,x,\xi)$, otherwise, for $\alpha \in \{0,\alpha^M\}$, we have $\alpha \in T^{cts}(q,x,\xi)$ if for all disturbances $T_l \in \{0,T_l^M\}$, the vector $f(q,x,\xi,\alpha,T_l)$ is in the inward tangent space of *Safe* at (q,x,ξ).

3.3 Idle controller performances

By considering the maximum amount of load torque T_l^M as a parameter, we can determine the maximum value of T_l^M for which a non empty maximal safe set (and, hence, at least one controller that satisfies the constraints) exists, that is the maximum admissible load torque for a given specification on the engine speed, $n(t) \in [n_0 - \Delta n \; n_0 + \Delta n]$.

On the other hand, considering the reference engine speed n_0 as a parameter, we can determine the minimum value for which a non empty maximal safe set exists, that is the minimum admissible reference speed n_0 for a given maximum load torque T_l^M and a given range of variation Δn. Indeed, low values of n_0 are interesting to reduce emissions and fuel consumption, but if n_0 is too low the engine may not able to counteract the maximum load T_l^M.

Finally, the design of the idle control is completed by selecting in the maximal controller a particular one which minimizes a specified cost function. To this purpose, an interesting cost function is the energy of the variation of the engine speed with respect to its reference value n_0.

4 Conclusions

The problem of maintaining the crankshaft speed within a given range has been formalized as a safety specification for the closed-loop system modeled as a hybrid automaton, where continuous and discrete variables retain their distinctive nature. By applying a systematic procedure to the hybrid model of the engine, the maximal safe set for the idle control has been determined. Then, the entire set of possible controllers that satisfy the constraints is computed. This is a definite advantage over other approaches that approximate the system by relaxing it to continuous or discrete sampled representations. This result is the first of its kind in idle control, and allows us to determine tightly the maximum range of allowed torque disturbances, given a range of engine speeds, and the minimum allowed reference engine speed for specified sources of disturbance.

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