Ph.D. Course on

Hybrid Systems

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Continuous systems controlled by discrete logic  Embedded systems

- micro-processors with an inherently discrete behavior (e.g. due to finite precision computations and quantization of signals) embedded in a physical device
- integrated with the physical world (continuous environment) through actuators and sensors
- sharing data and resources by a networked architecture (networked embedded systems)

Characteristics of embedded systems

Real-time operation
- Must finish operations by deadlines.
- Hard real time: missing deadline causes failure.
- Soft real time: missing deadline results in degraded performance.
Automotive applications

- Air Bags
- Traction Control
- Automatic Parking
- Anti-lock Brake
- Navigation Systems
- Emission Control
- Tire Pressure Monitor
- Climate Control

Continuous systems controlled by discrete logic

Embedded systems

- Adaptive Cruise
- Night Vision
- Drive by wire
- Back-up collision sensor
- Rain-sensing Wipers
Coordination of multi-agent systems

- predefined set of commands (speed change, short cut, detour...) issued by air traffic controllers to pilots to avoid conflicts
- sequencing of aircraft landing to some airport (distance to avoid turbulence caused by preceding aircraft, timing constraints)
Continuous systems controlled by discrete logic

Switching control

Control of a complex plant:
different controllers designed for different control modes (different models),
switching rule coded by a DES (e.g. flight control)
Continuous systems controlled by discrete logic

Switching control

Logic that selects which controller to use

Bank of controllers
Engine and power-train hybrid model
Why a hybrid model?

- Torque generation problem has a natural hybrid representation
  - the cylinders have four modes of operation corresponding to the stroke they are in
  - drive-line and air dynamics are continuous-time processes
  - the timing of the transitions between two modes of each cylinder is determined by the continuous motion of the drive-line
  - the motion of the drive-line depends on the torque produced by each cylinder (piston)
This stroke of the piston begins at T.D.C. and ends at B.D.C. In this stroke the intake valve is open and the piston pulls an air-fuel mixture into the cylinder by producing vacuum pressure into the cylinder through its downward motion.
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This stroke begins at B.D.C and ends at T.D.C.
In this stroke the piston compresses the air-fuel mixture. Both the intake and exhaust valves are closed during this stage.
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In this stroke the piston compresses the air-fuel mixture. Both the intake and exhaust valves are closed during this stage.
This is the start of the second revolution of the four stroke cycle. At this point the crankshaft has completed a full revolution. While the piston is at T.D.C. the compressed air-fuel mixture is ignited by a spark plug, forcefully returning the piston to B.D.C.
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This stroke produces mechanical work from the engine to turn the crankshaft...
The piston once again returns from B.D.C. to T.D.C. while the exhaust valve is open. This action expels the spent air-fuel mixture through the exhaust valve.
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CONTROL VARIABLES

SPARKING TIME

THROTTLE MOTOR VOLTAGE
**Throttle motor dynamics**

\[ \dot{\alpha}(t) = a_\alpha \alpha(t) + b_\alpha V_\alpha(t) \]

\( V_\alpha(t) \) \text{ throttle motor voltage}

\( \alpha(t) \) \text{ throttle angle}

**Air dynamics**

\[ \dot{p}(t) = a_p(n, p)p(t) + b_p(n, p)\alpha(t) \]

\( p(t) \) \text{ manifold pressure}
The torque generated by each piston at each cycle depends on the thermodynamics of the air–fuel mixture combustion process.

- Quantity of **air** and **fuel** loaded in the cylinder
- **Ignition time**

The quantity of air loaded into each cylinder at the end of the intake run depends on the evolution of the intake manifold pressure and the crankshaft speed.

\[ m(t) = w[p(t), n(t)] \]

The amount of fuel injected is such that the air-to-fuel ratio is 14.64 (the mix is said to be at stoichiometry)

- **Maximum combustion efficiency**
- **Minimum emissions**

\[ T_{pot}(m) \text{ maximum potential torque} \]
Spark ignition must occur at every cycle. Intuitively, it should occur exactly when the piston reaches the TDC.

To achieve maximum fuel efficiency: produce a spark before the piston ends the compression stroke (*positive spark advance*).

To reduce drastically the value of the torque: produce a spark after the piston completed the compression phase and is in the expansion stroke (*negative spark advance*).

\[
T(m, \varphi) = T_{pot}(m) \eta_c(\varphi)
\]
Torque generation

\[ T(m, \varphi) = T_{pot}(m) \eta_c(\varphi) \]

- \( T_{pot}(m) \): Depends on the evolution of the throttle
- \( \eta_c(\varphi) \): Depends on spark ignition time
negative spark advance: the spark is given after the TDC between C and E

positive spark advance: the spark is given before the TDC between C and E

$I \rightarrow BS: \quad m = w [p(t), n(t)]$

$BS \rightarrow PA: \quad \varphi = 180 - \theta(t)$

$NA \rightarrow AS: \quad \varphi = -\theta(t)$

$I, BS, PA, NA, H: \quad T = 0$

$AS: \quad T = T_{pot}(m) \eta_c(\varphi)$

Torque generation
Power-train dynamics

\[
\begin{bmatrix}
\dot{\alpha}_e(t) \\
\dot{n}(t) \\
\dot{\omega}_p(t)
\end{bmatrix}
= A
\begin{bmatrix}
\alpha_e(t) \\
n(t) \\
\omega_p(t)
\end{bmatrix}
+ bT(t) + b_0
\]

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

\(\theta(t)\) crankshaft angle

\(n(t)\) crankshaft speed

\(\alpha_e(t)\) torsion angle

\(\omega_p(t)\) wheel speed

\(T(t)\) torque generated by the engine
Hybrid modeling of the plant

The need (and the benefit) for a hybrid model:

• Cut-off control (*comfort control*)
• Actual gear identification (*emission control*)
Driver releasing the gas pedal (tip-out).

- Intuitive solution: cutting fuel injection as soon as the gas pedal is released (*shut-off*).
  - very simple
  - minimizes fuel consumption and emissions
  - but, elasticity of the power-train may produce unpleasant oscillations of the car compromising driving comfort

- Present solution: open loop air and fuel modulation.
  - power-train state not taken into account

- Control Problem: Control the longitudinal oscillations of the car.
Shut-off strategy

unpleasant oscillations!
Control design

• Minimize the peak of the acceleration until it is below the threshold of acceleration perception
• The control problem can be simplified considerably by relaxing the plant hybrid model to the continuous time domain
• The solution is then modified to make it feasible for the hybrid model taking into account torque generation constraints:
  - bounds
  - synchronization
  - delays
• Only two values for the injection are considered: $j = 0$ and $j = 1$
• The optimal spark advance is used
• The decision about injection is synchronized with cylinder phases so that its effect on power-train is delayed by three phases
Control design

\[
\begin{bmatrix}
\dot{\alpha}_e(t) \\
\dot{n}(t) \\
\dot{\omega}_p(t)
\end{bmatrix} = A \begin{bmatrix}
\alpha_e(t) \\
n(t) \\
\omega_p(t)
\end{bmatrix} + bT(t) + b_0
\]

\[\lambda(A) = \{-2.67 \pm 21.54j, -0.054\}\]

Isolate the oscillations from monotone behavior by natural mode decomposition.
Optimal Control

\[ b^T \perp x = 0 \]

\[ T = T_{pot}(m) \]

\[ v^T x = 0 \]

\[ T = 0 \]
Control design

\[ \lambda(A) = \{-2.67 \pm 21.54j, -0.054\} \]

Isolate the oscillations from monotone behavior by natural mode decomposition.
Experimental Results

**Test:** at *Magneti-Marelli Engine Control Division* on a commercial car, a 16-valve 1400-cc-engine car. The engine control electronics is a 4-LV Magneti Marelli on-board computer based on a 25-MHz 32-bit Althair Motorola microprocessor with fixed-point arithmetic unit.
Experimental Results

Implemented strategy by Magneti Marelli
Results: better performance: for a commercial car, 50% of memory occupation for data and 75% of memory occupation for code, 1% CPU utilization (Motorola 68020)
Actual engaged gear identification

Driver acting on the clutch pedal and on the gear lever.

- Control Problem: Identify the engaged gear from the measurement of the crankshaft and wheels revolution speeds and an estimate of the mean-value of the engine torque.

- Present solution: comparison of the revolution speed of the wheels with the revolution speed of the crankshaft
  - very simple
  - but, elasticity of the transmission shafts and the tires may produce oscillations: large time delays in the identification and errors
Detailed model
Detailed model

Hybrid
Nonlinear continuous-time dynamics
Used for analysis and validation

6048 discrete states
12 continuous states

Plus discontinuities in the driveline due to engine suspension, elastic torsional characteristic, tires, frictions and backlashes.
\[ \dot{\omega}_e(t) = -\frac{b_e}{j_e} \omega_e(t) + \frac{1}{j_e} T_e(t) - \frac{1}{j_e} T_c(t) \]

\[ |T| > \mu_s P_c \quad P_c = 0 \]

\[ \omega_e = \omega_c \quad \text{and} \quad |T| \leq \mu_s P_c \]

\[ T_c(t) = \mu_d P_c(t) \quad T_c = 0 \]

\[ T_c(t) = k_i \alpha(t) + b_i \left( \omega_e(t) - \frac{\omega_w(t)}{\tau_i} \right) \]
Validation with experimental data

Magneti Marelli Powertrain

Hybrid system simulation
Reduced order hybrid model

\[ \omega_e \text{ crankshaft speed} \]
\[ \omega_c \text{ clutch plate speed} \]
\[ \omega_w \text{ wheel speed} \]
\[ \alpha \text{ driveline torsion angle} \]

\[ P_c \text{ connection pressure of the clutch plates} \]
\[ \text{gear lever } \in \{1, 2, 3, 4, 5, RG, N\} \]
\[ T_e \text{ torque generated by the engine} \]
\[ T_w \text{ load torque} = T_{slope} + T_{air} \]
Reduced order hybrid model

7 discrete states:
- 6 gears
- neutral/slip

3 continuous states:
- driveline torsion angle
- crankshaft speed = clutch plate speed
- wheel speed

clutch closed and 1st gear

$q_1$
- lever = N
  - or
  - $P_c = 0$
  - or
  - $|T| > \mu_s P_c$

$q_{RG}$
- lever = N
  - or
  - $P_c = 0$
  - or
  - $|T| > \mu_s P_c$

$q_N$
idle gear or clutch open or clutch slipping
\[
\dot{x}(t) = A_i x(t) + B_i u(t) \\
y(t) = C_i x(t)
\]
\[
x = \begin{pmatrix}
\alpha \\
\omega_e \\
\omega_w
\end{pmatrix}, \quad u = \begin{pmatrix}
T_e \\
T_w
\end{pmatrix}, \quad y = \begin{pmatrix}
\omega_e \\
\omega_w
\end{pmatrix}
\]

\[
A_i = \begin{bmatrix}
0 & 1 & -\frac{1}{\tau_i} \\
-k_i & -b_e + b_i & \frac{b_i}{\tau_i} \\
-k_i & b_i & \frac{b_i}{\tau_i}
\end{bmatrix}
\]
\[
B_i = \begin{bmatrix}
0 & 0 \\
1 & 0 \\
0 & -\frac{1}{j_w}
\end{bmatrix}; \quad C_i = \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]
Validation

Validation on the same experimental data used during the identification

Validation on experimental data different from the previous
Hybrid observer approach

Identification of the actual engaged gear

Identification of the current location of the reduced model

Extension of Failure Detection and Identification techniques:

◊ Is the system obeying some given dynamics?

\[ \dot{z}_i(t) = (A_i - L_i C_i) z_i(t) + B_i u(t) + L_i y(t) \]
\[ \tilde{r}_i(t) = C_i \tilde{z}_i(t) - y(t) \]
Disturbances:

- Crankshaft and wheel speed quantization (1 RPM)
- Wheel speed dead zone (5 Km/h)
- Unknown inputs (torque wheel, pressure clutch, gear level)
- Unmodel dynamics
- Pulsating torque engine

Hybrid observer

- Residual Generator 1st gear
- Decision function
- Location Identification Logic
- DES
- Estimated engaged gear

Crankshaft and wheel speed

Engine torque
Experimental Results

Specifications: identification within 250 msec, with an implementation of the algorithm in discrete-time with a sampling period of 12 msec

Test: at Magneti-Marelli Engine Control Division on a Opel Astra equipped with a Diesel engine and a robotized gearbox SeleSpeed

Validation of the identification algorithm: the estimated engaged gear is compared to the signal on actual engaged gear provided by the control unit of the robotized gearbox.

Results: the algorithm was tested on:
- Several maneuvers
- for a total of 250 gear engagements

Correct identification within 250 msec in 90% of cases
The unsuccessful cases have been obtained in very critical maneuvers such as
- gear engagements during sharp braking
- clutch abrupt releases.

Robust with respect to parameter uncertainties (e.g. vehicle inertia) and time-varying unknown disturbances (e.g. wheel torque and road slope).
Experimental Results
Experimental Results
Transition from second to third gear.