Model-based control techniques for automotive applications

Fabio Maran

PhD School on Information Engineering
XXV Series, ICT Section
Advisor: Prof. Alessandro Beghi

28th February 2013

DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE

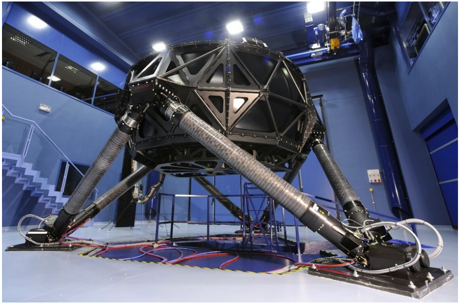
Part I

Model Predictive Control for Motion Cueing

Motion Cueing Algorithm

- Interest in *dynamic* driving simulators is increasing, with research and application in different areas (rehab, prototyping, driving safety, racing).

Ferrari simulator



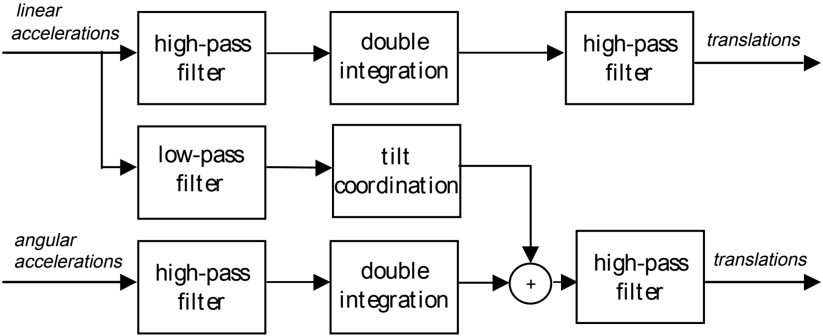
Toyota simulator

Motion Cueing Algorithm

- Interest in *dynamic* driving simulators is increasing, with research and application in different areas (rehab, prototyping, driving safety, racing).
- A successful dynamic simulator platform has to reproduce at best the sensations that the user would have in the real vehicle: this is the task of the Motion Cueing (MC) Algorithm
  - deals with inertial cues
  - strictly related to visual and audio hints
- MC has two purposes:
  - replicate driver's perception
  - keep the platform within its boundaries: Washout Action
- MC generates the trajectories that the platform should track: it acts before the *position-control* layer (usually handled by PLC)

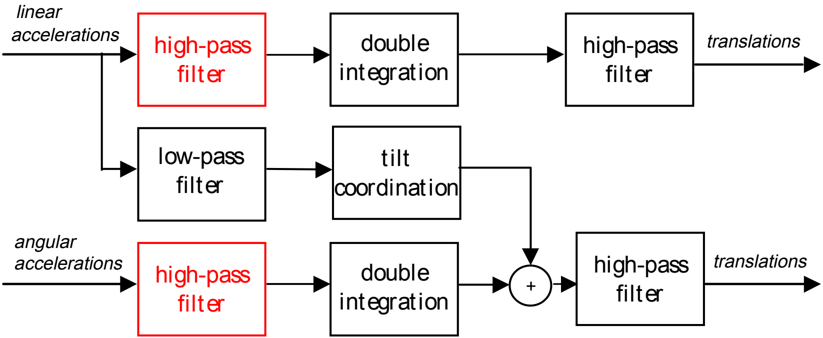
Motion Cueing Algorithm: Classic Approach

Standard (classic) approach: combination of passive filters, both high-pass and low-pass filters



Motion Cueing Algorithm: Classic Approach

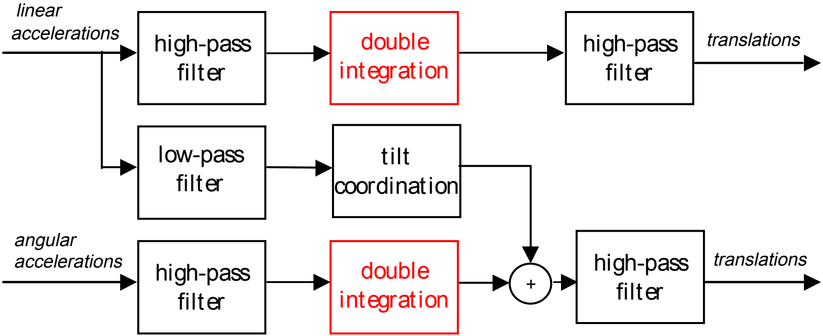
Standard (classic) approach: combination of passive filters, both high-pass and low-pass filters



High-pass filters on linear accelerations and rotations are applied to catch the fast dynamics, traduced into small and fast movements of the platform

Motion Cueing Algorithm: Classic Approach

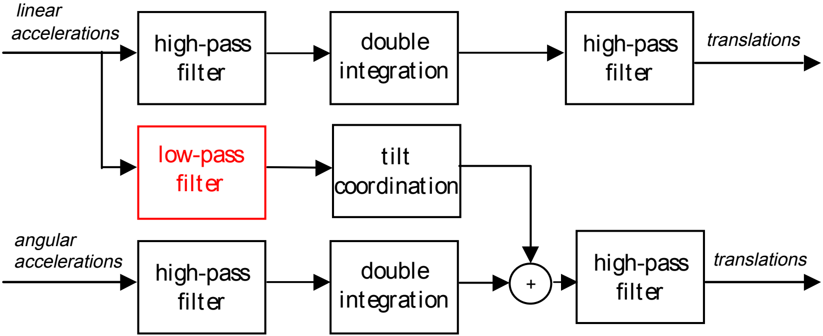
Standard (classic) approach: combination of passive filters, both high-pass and low-pass filters



Double integration is applied to the calculated signals to obtain the linear and angular positions from the accelerations

Motion Cueing Algorithm: Classic Approach

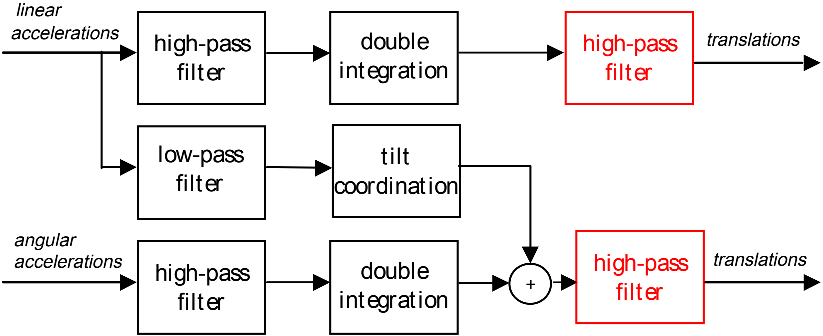
Standard (classic) approach: combination of passive filters, both high-pass and low-pass filters



Low-pass filters on linear accelerations are used for tilt coordination: applying the right visual cues, the low frequencies, progressive accelerations are replicated by *tilting* the platform and exploiting the gravity acceleration

Motion Cueing Algorithm: Classic Approach

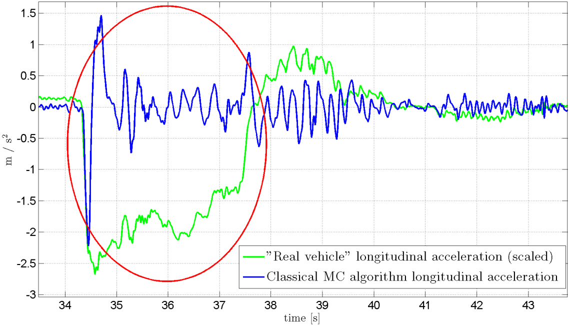
Standard (classic) approach: combination of passive filters, both high-pass and low-pass filters



Washout filters (high-pass with different cut-off frequencies) are then applied to both the linear and rotational signals to assure that physical limits of the platform are not violated

Motion Cueing Algorithm: Problems

- High-pass filtering (HPF) the accelerations gives origin to motion inversion: variations in accelerations around a *positive* value become variations in accelerations around the zero value, leading to *motion sickness*



Motion Cueing Algorithm: Problems

- High-pass filtering (HPF) the accelerations gives origin to motion inversion: variations in accelerations around a *positive* value become variations in accelerations around the zero value, leading to *motion sickness*
- Low-pass filtering (LPF) can introduce delays with respect to video/audio cues and high-frequency components of the motion (motion sickness)

Motion Cueing Algorithm: Problems

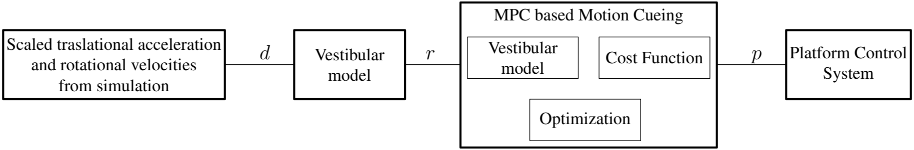
- High-pass filtering (HPF) the accelerations gives origin to motion inversion: variations in accelerations around a *positive* value become variations in accelerations around the zero value, leading to *motion sickness*
- Low-pass filtering (LPF) can introduce delays with respect to video/audio cues and high-frequency components of the motion (motion sickness)
- HPF for the Washout Action makes very hard to exploit all the available working area (no explicit constraints); it may also introduces other false cues

Motion Cueing Algorithm: Problems

- High-pass filtering (HPF) the accelerations gives origin to motion inversion: variations in accelerations around a *positive* value become variations in accelerations around the zero value, leading to *motion sickness*
- Low-pass filtering (LPF) can introduce delays with respect to video/audio cues and high-frequency components of the motion (motion sickness)
- HPF for the Washout Action makes very hard to exploit all the available working area (no explicit constraints); it may also introduces other false cues
- The tuning procedure is counterintuitive (manipulation of filter gains and cut-off frequencies $\Rightarrow$ no physical meaning)

MPC for MC

New approach proposed: Model Predictive Control (MPC) techniques to control the platform motion



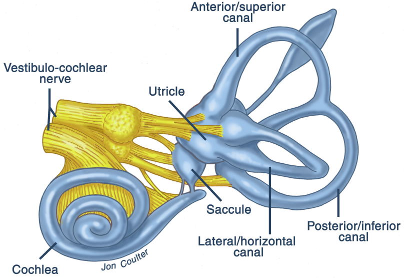
Features

- Model-based: exploits platform (if known) and vestibular system models to calculate reference signals
- Constrained, optimal problem: explicit handling of performance and working area constraints
- Prediction: if available, it allows to improve the platform performance

Vestibular System

The Vestibular System is composed by two sub-systems

- Semi-circular channels: they are responsible for sensing *rotational velocities* applied to the body
- Otoliths: they sense *longitudinal accelerations*



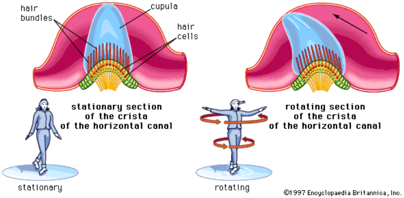
$$\frac{\hat{\omega}(s)}{\omega(s)} = 5.73\frac{80s^2}{(1+80s)(1+5.73s)}$$

$$\frac{\hat{a}(s)}{a(s)} = 0.4\frac{(1+10s)}{(1+5s)(1+0.016s)}$$

Vestibular System

The Vestibular System is composed by two sub-systems

- Semi-circular channels: they are responsible for sensing *rotational velocities* applied to the body
- Otoliths: they sense *longitudinal accelerations*



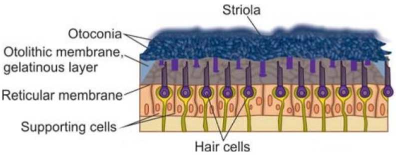
$$\frac{\hat{\omega}(s)}{\omega(s)} = 5.73 \frac{80s^2}{(1+80s)(1+5.73s)}$$

$$\frac{\hat{a}(s)}{a(s)} = 0.4 \frac{(1+10s)}{(1+5s)(1+0.016s)}$$

Vestibular System

The Vestibular System is composed by two sub-systems

- Semi-circular channels: they are responsible for sensing *rotational velocities* applied to the body
- Otoliths: they sense *longitudinal accelerations*



$$\frac{\hat{\omega}(s)}{\omega(s)} = 5.73\frac{80s^2}{(1+80s)(1+5.73s)}$$

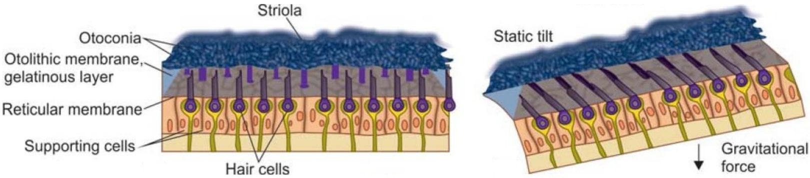
$$\frac{\hat{a}(s)}{a(s)} = 0.4\frac{(1+10s)}{(1+5s)(1+0.016s)}$$

Vestibular system

- Under steady condition the otoliths are incapable of distinguishing translational acceleration from gravity force $\Rightarrow$ rotational and/or visual sensorial information is needed

Vestibular system

- Under steady condition the otoliths are incapable of distinguishing translational acceleration from gravity force $\Rightarrow$ rotational and/or visual sensorial information is needed
- This feature can be exploited when developing motion cueing algorithms: low frequency components of the acceleration can be reproduced by using tilt coordination



Prediction

- Prediction is a crucial aspect of the MPC framework, with immediate advantages for MC applications
    - Better exploitation of the working area (tilt coordination, linear displacement)
    - More effective Washout Action

Prediction

- Prediction is a crucial aspect of the MPC framework, with immediate advantages for MC applications
  - Better exploitation of the working area (tilt coordination, linear displacement)
  - More effective Washout Action
- Real-time application of prediction is a challenging task
  - Human in the loop $\Rightarrow$ hard to calculate a reliable trajectory
  - A high control frequency corresponds to large prediction horizon $N_P \Rightarrow$ higher resolution time

Prediction

- Prediction is a crucial aspect of the MPC framework, with immediate advantages for MC applications
  - Better exploitation of the working area (tilt coordination, linear displacement)
  - More effective Washout Action
- Real-time application of prediction is a challenging task
  - Human in the loop $\Rightarrow$ hard to calculate a reliable trajectory
  - A high control frequency corresponds to large prediction horizon N_P $\Rightarrow$ higher resolution time
- Classic MPC approach: constant reference in the prediction window
  - If system dynamics is "slow" enough w.r.t. the control frequency, tracking performance are not compromised

Prediction

- Prediction is a crucial aspect of the MPC framework, with immediate advantages for MC applications
    - Better exploitation of the working area (tilt coordination, linear displacement)
    - More effective Washout Action
- Real-time application of prediction is a challenging task
    - Human in the loop $\Rightarrow$ hard to calculate a reliable trajectory
    - A high control frequency corresponds to large prediction horizon $N_P \Rightarrow$ higher resolution time
- Classic MPC approach: constant reference in the prediction window
    - If system dynamics is "slow" enough w.r.t. the control frequency, tracking performance are not compromised
- Supposing to have an available reference, a blocking strategy has been studied to improve the computational performance
    - To deal with a larger time window while keeping N_P low enough, different sampling time steps are considered, increasing while receding from the present time instant

Tuning procedure: proposed approach

The tuning procedure has a key role in Motion Cueing systems

Tuning is performed by variating the *constraints*, *weights* and *prediction horizon* N_P values

Tuning procedure: proposed approach

The tuning procedure has a key role in Motion Cueing systems

Tuning is performed by variating the *constraints*, *weights* and *prediction horizon* N_P values

- constraints variations help the exploitation of the working area, preventing undesired behaviour (e.g. motion inversion)

Tuning procedure: proposed approach

The tuning procedure has a key role in Motion Cueing systems

Tuning is performed by variating the *constraints*, *weights* and *prediction horizon* N_P values

- constraints variations help the exploitation of the working area, preventing undesired behaviour (e.g. motion inversion)
- weights variations change the dynamic behaviour of the platform (e.g., "penalizing" the position state variables, more conservative performance are achieved without affecting too much velocities and accelerations perceived)

Tuning procedure: proposed approach

The tuning procedure has a key role in Motion Cueing systems

Tuning is performed by variating the *constraints*, *weights* and *prediction horizon* N_P values

- constraints variations help the exploitation of the working area, preventing undesired behaviour (e.g. motion inversion)
- weights variations change the dynamic behaviour of the platform (e.g., "penalizing" the position state variables, more conservative performance are achieved without affecting too much velocities and accelerations perceived)
- with constant prediction reference, the tracking performance is regulated by manipulating N_P, giving a more flexible algorithm, easily adaptable to different situations (overcoming the difficult in predicting the driver's behaviour).

Tuning procedure: benefits

- The whole procedure is intuitive: it deals with physical values rather than cut-off frequencies as the classical ones

Tuning procedure: benefits

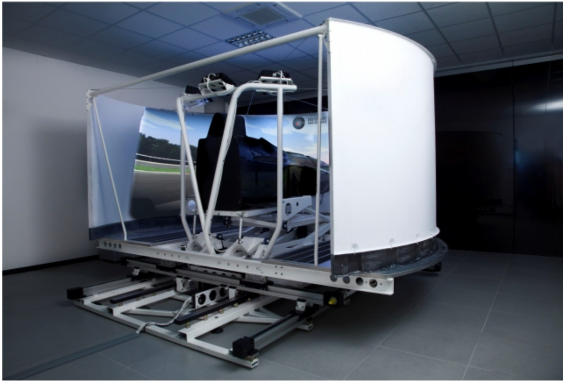
- The whole procedure is intuitive: it deals with physical values rather than cut-off frequencies as the classical ones
- This approach improves the feedback quality from the driver: the suggestions can be traduced in parameters variations in a more natural way (specifying requirements on linear accelerations, angular positions etc.)

Tuning procedure: benefits

- The whole procedure is intuitive: it deals with physical values rather than cut-off frequencies as the classical ones
- This approach improves the feedback quality from the driver: the suggestions can be traduced in parameters variations in a more natural way (specifying requirements on linear accelerations, angular positions etc.)
- The implementation allows real-time variations to the parameters (using a Graphical User Interface)

Real-time application: VI-DriveSIM

New approach to dynamic simulator platforms



Real-time application: VI-DriveSIM

New approach to dynamic simulator platforms

- Compact: can fit a room (4m long, 5.5m wide, 3m high, considering maximum displacements)
- Fast Dynamics with less power consumption: reduced inertia and linear, electric actuators
- Performance: similar to most common racing simulators

Range	Position	Velocity	Acceleration
x	1m	1.3m/s	3.3m/s^2
y	1m	1.3m/s	3.6m/s^2
z	0.3m	0.9m/s	4.9m/s^2
Roll	30deg	112deg/s	600deg/s^2
Pitch	24deg	61deg/s	600deg/s^2
Yaw	50deg	61deg/s	240deg/s^2

Real-time application: implementation

- The application has strict real-time requirements
  - control frequency: 100 Hz
  - sport cars driven by professional drivers ⇒ fast dynamics involved
  - real-time tuning

Real-time application: implementation

- The application has strict real-time requirements
  - control frequency: 100 Hz
  - sport cars driven by professional drivers $\Rightarrow$ fast dynamics involved
  - real-time tuning
- *Quadratic* cost function: quadratic problem

$$J = \sum_{j=0}^{N_P} \delta(j) \left[\hat{y}(k+j|k) - r(k+j)\right]^2 + \sum_{j=1}^{N_C} \lambda(j) \left[u(k+j-1)\right]^2 + \gamma(j) \left[\Delta u(k+j-1)\right]^2$$

Real-time application: implementation

- The application has strict real-time requirements
  - control frequency: 100 Hz
  - sport cars driven by professional drivers ⇒ fast dynamics involved
  - real-time tuning
- *Quadratic* cost function: quadratic problem
- Independence along the degrees of freedom ⇒ model split in *four sub-models*
  - parallel resolution of four optimization problems
  - smaller size for each problem ⇒ faster computation

Real-time application: implementation

- The application has strict real-time requirements
  - control frequency: 100 Hz
  - sport cars driven by professional drivers ⇒ fast dynamics involved
  - real-time tuning
- *Quadratic* cost function: quadratic problem
- Independence along the degrees of freedom ⇒ model split in *four sub-models*
  - parallel resolution of four optimization problems
  - smaller size for each problem ⇒ faster computation
- Online solver: *qpOASES*
  - based on *active-set* with *hot-start* strategy
  - the considered problem is well-suited for such approach (high frequencies ⇒ limited changed between two subsequent problems)
  - a smart choice of weights and constraints (⇒ tuning) assures stability and fast computation
  - open-source, C++ implementation

Results

- Experimental results are performed using a hot-hatch car (Volkswagen Golf R) on Calabogie track (Canada)
- The algorithm is applied to the platform using a GUI developed with MatLab and the implemented and compiled in C++ programming language to improve real-time performances
- The platform is driven by a professional driver
- Since the platform DOFs are almost decoupled, only longitudinal acceleration and pitch velocity are shown

FPGA implementation

- A first FPGA implementation is under development with the collaboration of Imperial College London (Control and Power Group)
- FPGA: Field Programmable Gate Array
  - compromise between general purpose hardware and fully customized hardware
  - consists of *logic blocks* that can be programmatically linked to obtain the desired functions
  - on-board memory elements
- FPGAs are well suited for MPC algorithms
  - large amount of computation for a small amount of I/O
  - provide the precise timing guarantees required for interfacing the controller to the physical system
- Optimization method: interior point
  - polynomial complexity
  - takes advantage of the sparsity structure of the matrices
  - pipelining: exploiting parallelism to keep the linear solver always active

Conclusions and future works

Conclusions

- The MPC algorithm simplify the working area *limits management* and the *tuning procedure*, avoiding undesired behaviours
- The vestibular system model allows to obtain enhanced trajectory references with better exploitation of *tilt coordination*
- The algorithm is already applied to the real platform, with real-time implementation

Future works

- Introduce real-time prediction, taking advantage of repetitive laps (racing application)
- FPGA integration with the real platform, to test the performance improvement of an hardware-based implementation
- Application of the algorithm to different devices

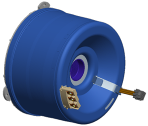
Papers

- F. Maran, A. Beghi, M. Bruschetta, D. Minen, M. Baseggio, M. Pozzi: *Study on the Next Generation Motion Cueing for Driving Simulator*. JSAE Annual Congress, Tokio, May 2011.
- F. Maran, A. Beghi, M. Bruschetta: *An MPC approach to the design of motion cueing algorithms for driving simulators*. Convegno Annuale dei Docenti e Ricercatori Italiani in Automatica, interactive session, Pisa, September 2011.
- F. Maran, A. Beghi, M. Bruschetta, D. Minen, M. Baseggio: *An MPC approach to the design of motion cueing algorithms for driving simulators*. 14th IEEE Intelligent Transportation Systems Conference, Washington DC, October 2011.
- F. Maran, A. Beghi, M. Bruschetta, D. Minen. A *Model-based Motion Cueing strategy for compact driving simulation platforms*. Driving Simulation Conference 2012 - Europe, Parigi, September 2012.
- F. Maran, A. Beghi, M. Bruschetta. *A real time implementation of MPC based Motion Cueing strategy for driving simulators*. IEEE Conference on Decision and Control (CDC 2012), Maui, December 2012.

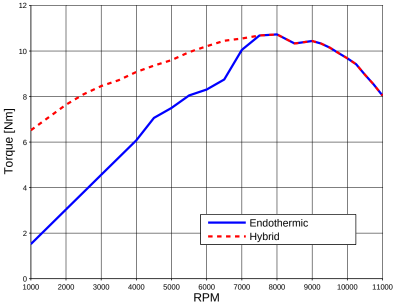
Part II

Control Techniques for an Hybrid Sport Motorcycle

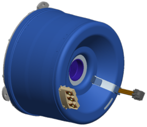
Electrification of a 125cc motorcycle: Aprilia RS125



Improvement in torque performance ⇒



Electrification of a 125cc motorcycle: Aprilia RS125



Main project goals

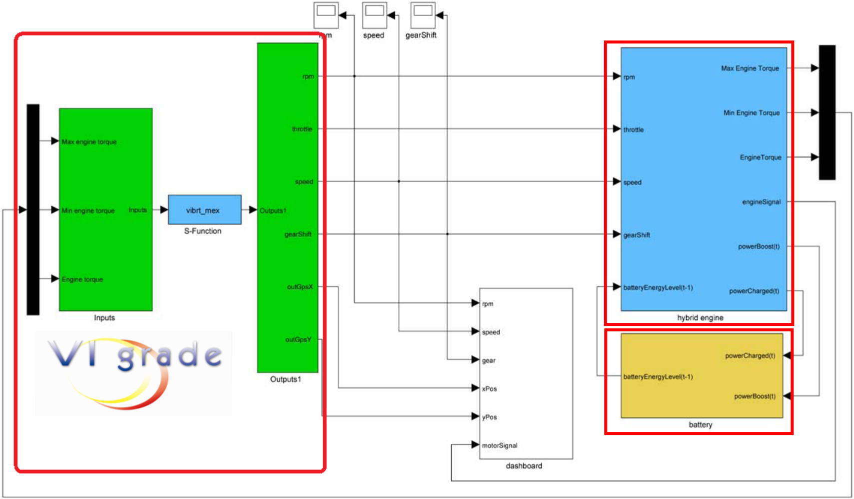
- Control strategies development
- Virtual environment for test and performance evaluation

Virtual Environment

- Motorbike and rider model: VI-Grade tools
- Battery model
- Hybrid engine model

Virtual Environment

SIMULINK implementation

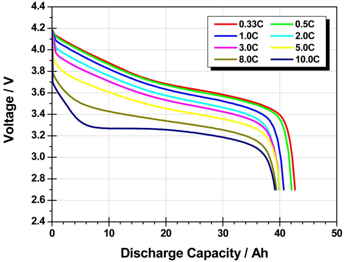


Battery model: discharge

- Lithium-Polymer cell (by Kokam)
- No test-bench available for batteries
- Available informations: datasheet charge/discharge curves
- Polynomial fitting of the reference curves

What are the values of interest?

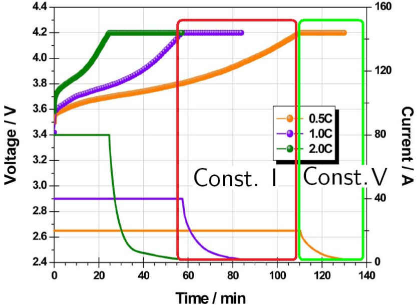
- Voltage V as a function of *State of Charge* (SOC)
- Discharge characteristic $V(SOC)$ immediately available

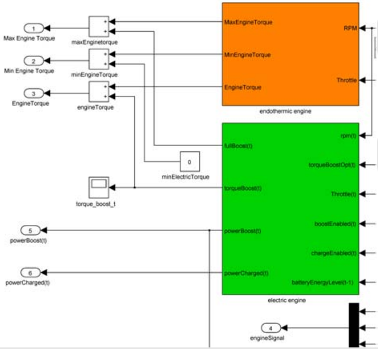


Battery model: charge

Charge curve

- Two distinct charge stages: constant current I ($SOC < 90\%$), constant V ($SOC > 90\%$)
- Given $V(t)$ and $I(t)$ $\Rightarrow$ $\left.\begin{array}{l} P(t) \text{ (power)} \\ E(t) \text{ (energy)} \end{array}\right\}$ $V(E) \Leftrightarrow V(SOC)$





Endothermic engine

- Torque map-based

Electric motor

- Charging/boosting operation modes
- Charging/boosting power estimation
- Different settable boost maps

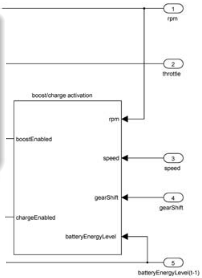
Hypotheses

- Negligible dynamics of the electrical machine
- Current transient respected (ideal charge control)
- Model based estimation of the charging power status

Hybrid engine model: activation strategy

Activation signal: evaluation of the speed derivative

- Charge activation during deceleration or constant speed
- Boost activation during acceleration



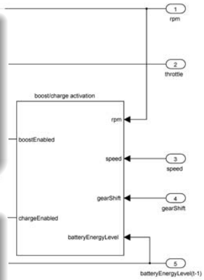
Hybrid engine model: activation strategy

Activation signal: evaluation of the speed derivative

- Charge activation during deceleration or constant speed
- Boost activation during acceleration

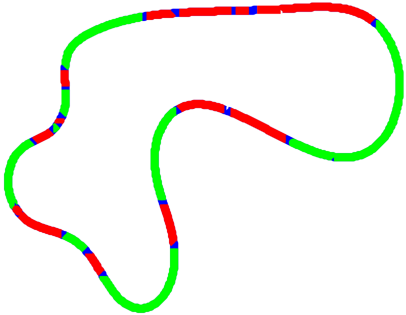
Gear shift control

- Speed decreasing during up-shift
- Problem: *high frequency* variations in activation signal
- Solution: *temporized disabling* of boost/charge when up-shift occurs



Results: simulation

- Virtual track with features similar to a urban path



Results: simulation

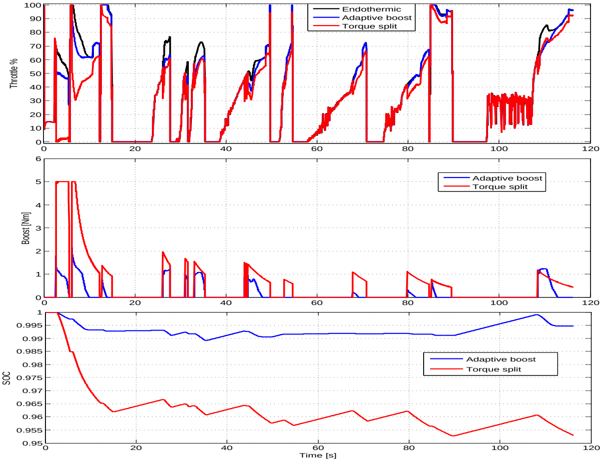
- Virtual track with features similar to a urban path
- Virtual driver performance regulated by using gear shift maps
- Problem: the virtual environment requires a fixed speed profile for the virtual driver. How to evaluate boost performance?

Results: simulation

- Virtual track with features similar to a urban path
- Virtual driver performance regulated by using gear shift maps
- Problem: the virtual environment requires a fixed speed profile for the virtual driver. How to evaluate boost performance?
- Solution: we compare the different throttle requests from the virtual driver for the endothermic and hybrid vehicles with the same speed reference

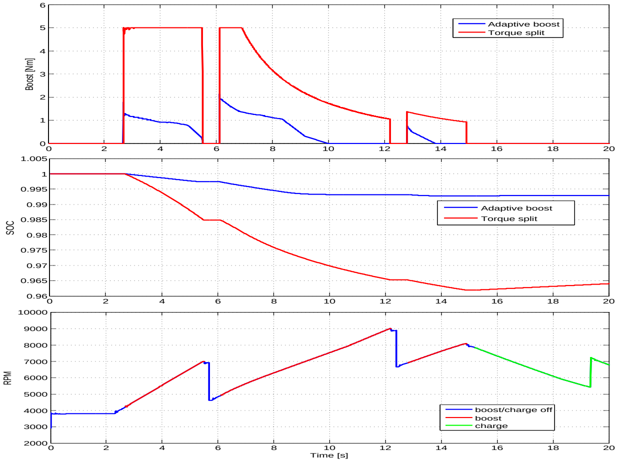
Results: control strategies comparison

- Stability of the motorcycle confirmed (smooth torque variation)
- Improvement in performance: throttle demand reduction
- Torque split allows a better battery exploitation



Results: control strategies comparison

- Stability of the motorcycle confirmed (smooth torque variation)
- Improvement in performance: throttle demand reduction
- Torque split allows a better battery exploitation



Conclusions and future works

Conclusions

- Polynomial battery model
- Driver-oriented analysis via a flexible virtual prototyping tool
- Effective battery management and performance improvement
- Optimal control strategy: regulation of contribution from the two engines
- Prototype implementation: on-track test

Future works

- Development of different boost-maps
- Auto-switching of boost-maps based on the driving style
- Refinement of the torque split strategy
- Model-based predictive control on the electric machine

Papers

- F. Maran, A. Beghi, A. De Simoi: *A VI-BikeRealTime based simulation environment for assessing power management strategies in hybrid motorcycles*. 4th Vi-Grade Users' Conference, Udine, October 2011.
- F. Maran, A. Beghi, A. De Simoi. *A Simulation Environment for Assessing Power Management Strategies in Hybrid Motorcycles*. 9th International Conference on Modeling, Optimization & SIMulation, Bordeaux, June 2012.
- F. Maran, A. Beghi, A. De Simoi. *A Virtual Environment for the Design of Power Management Strategies for Hybrid Motorcycles*. 3rd International Conference on Circuits, Systems, Control and Signals, Barcellona, October 2012.

Thank you for the attention!

Fabio Maran

PhD School on Information Engineering
XXV Series, ICT Section
Advisor: Prof. Alessandro Beghi

fabio.maran@dei.unipd.it

DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE