Model-Based Control Techniques
for Automotive Applications

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Summary

Two different topics are covered in the thesis.

Model Predictive Control applied to the Motion Cueing Problem

In the last years the interest about dynamic driving simulators is increasing and new commercial solutions are arising. Driving simulators play an important role in the development of new vehicles and advanced driver assistance devices: in fact, on the one hand, having a human driver on a driving simulator allows automotive manufacturers to bridge the gap between virtual prototyping and on-road testing during the vehicle development phase; on the other hand, novel driver assistance systems (such as advanced accident avoidance systems) can be safely tested by having the driver operating the vehicle in a virtual, highly realistic environment, while being exposed to hazardous situations. In both applications, it is crucial to faithfully reproduce in the simulator the driver's perception of forces acting on the vehicle and its acceleration. This has to be achieved while keeping the platform within its limited operation space. Such strategies go under the name of Motion Cueing Algorithms.

In this work, a particular implementation of a Motion Cueing algorithm is described, that is based on Model Predictive Control technique. A distinctive feature of such approach is that it exploits a detailed model of the human vestibular system, and consequently differs from standard Motion Cueing strategies based on Washout Filters: such feature allows for better implementation of tilt coordination and more efficient handling of the platform limits.

The algorithm has been evaluated in practice on a small-size, innovative platform, by performing tests with professional drivers. Results show that the MPC-based motion cueing algorithm allows to effectively handle the platform working area, to limit the presence of those platform movements that are typically associated with driver motion sickness, and to devise simple and intuitive tuning procedures.

Moreover, the availability of an effective virtual driver allows the development of effective predictive strategies, and first simulation results are reported in the thesis.

Control Techniques for a Hybrid Sport Motorcycle

Reduction of the environmental impact of transportation systems is a world wide priority. Hybrid propulsion vehicles have proved to have a strong potential to this regard, and different four-wheels solutions have spread out in the market. Differently from cars, and even if they are considered the ideal solution for urban mobility, motorbikes and mopeds have not seen a wide application of hybrid propulsion yet, mostly due to the more strict constraints on available space and driving feeling.

In the thesis, the problem of providing a commercial 125cc motorbike with a hybrid propulsion system is considered, by adding an electric engine to its standard internal combustion engine. The aim for the prototype is to use the electrical machine (directly keyed on the drive shaft) to obtain a torque boost during accelerations, improving and regularizing the supplied power while reducing the emissions.

Two different control algorithms are proposed

1. the first is based on a standard heuristic with adaptive features, simpler to implement on the ECU for the prototype;

2. the second is a torque-split optimal-control strategy, managing the different contributions from the two engines.

A crucial point is the implementation of a SIMULINK virtual environment, realized starting from a commercial tool, VI-BIKEREALTIME, to test the algorithms. The hybrid engine model has been implemented in the tool from scratch, as well as a simple battery model, derived directly from data-sheet characteristics by using polynomial interpolation. The simulation system is completed by a virtual rider and a tool for build test circuits.

Results of the simulations on a realistic track are included, to evaluate the different performance of the two strategies in a closed loop environment (thanks to the virtual rider). The results from on-track tests of the real prototype, using the first control strategy, are reported too.

Sommario

Nella tesi vengono trattati due argomenti distinti.

Model Predictive Control applicato al Motion Cueing Problem

Gli ultimi anni hanno visto un'interesse sempre crescente nei confronti dei simulatori di guida dinamici, con lo sviluppo e la diffusione nel mercato di nuovi soluzioni. I simulatori di guida giocano infatti un ruolo fondamentale nello sviluppo di nuovi veicoli e dei vari dispositivi di aiuto alla guida: infatti, da un lato la presenza di un guidatore in un simulatore permette ai produttori in ambito automotive di colmare il divario fra la prototipazione virtuale e i test su strada nella fase di sviluppo del veicolo; dall'altro, i nuovi sistemi di assistenza alla guida (come ad esempio le procedure di advanced accident avoidance attualmente in fase di sviluppo) posso essere testati in totale sicurezza ponendo il pilota in un contesto virtuale altamente realistico, simulando le situazioni di pericolo. In entrambe queste applicazioni risulta cruciale riprodurre fedelmente nella piattaforma la percezione che l'essere umano avrebbe, all'interno del veicolo reale, delle forze agenti sul mezzo e le conseguenti accelerazioni. Questo task deve essere compiuto tenendo conto dei vincoli fisici del simulatore, all'interno dei quali deve avvenire il moto. Le strategie utilizzate per perseguire questo obbiettivo vanno sotto il nome di Motion Cueing Algorithms.

Il presente lavoro intende illustrare una particolare implementazione di un Motion Cueing Algorithm, basato sulla tecnica di controllo nota come Model Predictive Control. Una delle principali caratteristiche di questo approccio è lo sfruttamento di un modello del sistema vestibolare umano, e questo (assieme ad altre features) lo rende differente dalle strategie standard di Motion Cueing: esso permette infatti una migliore realizzazione della tilt coordination e una più efficiente gestione dei limiti di piattaforma.

L'algoritmo è stato testato sperimentalmente su una piattaforma innovativa, dalle dimensioni ridotte, con l'aiuto di piloti professionisti. I risultati dimostrano come l'algoritmo basato su MPC permetta di gestire efficientemente l'area di lavoro del simulatore, limitando la presenza di tutti quei comportamenti tipicamenti associati alla motion sick-

ness, garantendo nel contempo un approccio molto più semplice e concreto alle procedure di tuning, rispetto alle procedure classiche.

In più, la disponibilità di un efficace driver virtuale permette lo sviluppo di strategie predittive affidabili: nella tesi sono riportati alcuni iniziali risultati simulativi in tal senso.

Tecniche di Controllo per un Motociclo Ibrido Sportivo

La riduzione dell'impatto ambientale dei sistemi di trasporto si sta affermando come una priorità sentita a livello mondiale. I veicoli a propulsione ibrida hanno dimostrato avere un grande potenziale a questo riguardo, e svariate soluzioni sono ormai diffuse sul mercato per quanto riguarda i veicoli a quattro ruote. A differenza delle automobili, e pur essendo considerati la soluzione ideale per la mobilità urbana, l'applicazione della propulsione ibrida a motociclette e scooter non ha ancora avuto una diffusione significativa, e ciò è dovuto in gran parte ai grossi vincoli di spazio e all'impatto della propulsione additiva sul feeling alla guida.

In questa parte della tesi viene considerato il problema dell'applicazione della propulsione ibrida a una motocicletta 125cc in commercio, aggiungendo una macchina elettrica al motore termico presente di serie. Lo scopo, per il particolare prototipo, è sfruttare la macchina elettrica (installata in modo solidale all'albero motore) per fornire un incremento alla coppia erogata durante le accelerazioni, migliorando e regolarizzando la potenza della moto e riducendo nel contempo le emissioni di gas nocivi.

Due algoritmi di controllo sono proposti per la gestione del motore elettrico e degli accumulatori

1. il primo è basato su una euristica standard con caratteristiche adattative, più semplice da implementare nella ECU per la prototipazione;

2. il secondo è basato su una strategia di controllo ottimo con lo scopo di gestire in maniera ottimale la coppia erogata da entrambi i motori.

Elemento cruciale è l'implementazione di un ambiente virtuale SIMULINK realizzato integrando un tool in commercio, VI-BireRealTime, per la valutazione degli algoritmi. Il modello del motore ibrido è stato implementato ex-novo, e così anche un (semplice) modello di batteria, derivato con interpolazione polinomiale dalle caratteristiche riportate nei data-sheet. Il sistema di simulazione è completato dalla presenza di un virtual rider e di un tool per la realizzazione di circuiti di test.

Sono riportati i risultati delle simulazioni su un tracciato realistico per valutare le differenti performance delle due strategie in catena chiusa (grazie al rider virtuale). Sono riportati anche i risultalti su pista del prototipo realizzato.

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Part I

Model Predictive Control applied to the Motion Cueing Problem

1

Introduction

In the recent years, *dynamic* driving simulators have been playing an important role in the automotive world. The first applications were in the racing context, focused on driver's training and virtual vehicle set-up. Nowadays, applications of such systems are becoming more and more numerous and diverse, involving field as security control systems (e.g., accident avoidance), medical rehabilitation, virtual prototyping. Automotive OEMs exploit driving simulators to cut down the costs for prototyping, by anticipating the on road vehicle behavior. Furthermore, such systems allow to ease the development process of the various vehicle components, by testing different hardware and software solutions, by resorting to sophisticated Hardware-In-the-Loop (HIL) tools, in a safe and realistic virtual environment. In a different perspective, realistic dynamic simulators are crucial to develop detailed driver behavior models to devise accident avoidance strategies, for example by putting the driver in simulated dangerous condition and measuring his/her reactions. Also, assessment of driver performance under stress conditions (i.e., adverse weather

conditions, endurance driving, etc.) can be more effectively performed by using dynamic simulators with a high degree of immersion into virtual environments. To this regard, ever more effective Hazard Perception Test can be devised and used as requirements for achieving a driver license. In this scenario, the effectiveness of a dynamic platform is deeply related to the capability of reproducing in the most realistic way the feelings that the driver would have inside a real vehicle: this is the role of the *Motion Cueing* (MC) strategy.

Motion Cueing is the name of the algorithms designed for transforming vehicle accelerations into motion commands to the platform, aiming at accurately replicating the forces acting on the driver and guaranteeing that the machine stays inside its physical limits. Clearly, this is a very complicated part of a dynamic simulator, due to the complex nature of the human perception system, which involves different organs and senses. In fact, it is not clear yet, from a physiological point of view, the role and priorities of stimula of different nature to the overall perception of accelerations and force. It is however well established that a coordinated visual-motion action is fundamental for achieving satisfactory performance of a MC algorithm. Given the above motivations the necessity of a perceptive model within the MC algorithm becomes evident.

Beside the improvements realized during the years, in most dynamic simulators the Motion Cueing Algorithms are based on a sequence of passive filters Nahon and Reid (1990) combined together. The standard procedure is implemented as to

- remove low frequency components of accelerations and velocities obtained from the vehicle dynamic model. In this way, only fast variations are kept, which are easier to be reproduced in a limited space environment;

- transfer part of the low frequency translational accelerations to the angular dynamic using a low pass filter (*tilt coordination*). This is a common way of tricking the human perception, with the help of visual cues, to exploit the gravity force to reproduce at least a part of the low frequency accelerations;

- limit the platform motions with a further high pass filter to keep the platform in a neutral position, i.e. eliminating low frequency components that could lead to infeasible positions for the platform actuators. This is commonly called *Washout Action*.

This simple strategy has seen a wide range of implementations over the years (Conrad and Schmidt, 1971; Nahon and Reid, 1990). However, it has some shortcomings:

- being a filtering based approach, it is not possible to guarantee stimuli consistency between the dynamic simulation environment and the real platform movements,

i.e. it is hard to find a good compromise for complex vehicle maneuvers (e.g. a complete track lap in racing applications);

- it cannot explicitly handle hard constraints on the platform movements and accelerations (both regarding actuators limit and perceptive reliability);

- it is not possible to exploit any available information on the driver's behavior in the future;

- the tuning of the algorithm is in general difficult, since it is not easy to give physical interpretation to most of the parameters (principally filter gains and cut-off frequencies).

These elements characterize the most commonly used procedures. Over the years, there have been modifications and improvements, with the introduction of adaptive (Parrish, Dieudonne, Bowles, and Martin, 1975) and optimal control (Sivan, Ish-Shalom, and Huang, 1982) features, but without significantly modifying the main algorithm.

Recently, a novel approach to motion cueing has been proposed by Dagdelen, Reymond, Kemeny, Bordier, and Maïzi (2009) and Augusto and Loureiro (2009), based on a strategy already consolidated in the field of industrial process control, namely, Model Predictive Control (MPC). MPC is a model-based, *constrained*, *optimal* control methodology that allows to effectively handle limits on the working space and to exploit information on future reference signal. In the idea developed in those works the motion cueing strategy integrates a model of the human perception systems and takes advantage of predictions of the future trajectory to fully exploit the platform working area. In these early works, the proposed solutions are not suitable for experimental application in real situations; as they don't take into account many of the aspects that characterize an effective and reliable MC system (e.g., real time constraints, tuning procedures and so on). Moreover, they focus on investigating the prediction capabilities rather than on taking advantage of the optimization approach of MPC.

The MC algorithm described in this part of the thesis has to be considered one of the first real time implementation of an MPC-based Motion Cueing strategy, developed from scratch and eventually run on an experimental environment. The idea of the algorithm comes from the previously cited works, but with a deeply different development and rationale, with each step realized with the final aim of obtaining a procedure ready to be applied in the real world. One of the key elements is the development of a reliable vestibular model. Being a model-based approach, the availability of such information about the dynamics of the human perception allows a great improvement on the reliability of the signals that will be fed to the physical device, in terms of realistic motions. As

already mentioned, in the work by Dagdelen et al. (2009) a first attempt of exploiting such information has been presented, but the simplicity of the illustrated model and the greater emphasis on the prediction phase reported in the paper seems not not provide effective results. Moreover, other MPC approaches as the one by Augusto and Loureiro (2009) seems to make use of reference signals that might result in undesired behaviours. In the present study, a major review of the literature has been carried on, starting from aerospace applications, to derive more detailed models which have been refined with the help of practical tests by professional drivers and medical consultants. The overall modelization is completed by the integration of a (simple) mechanical model of the platform.

The prediction phase is quite a difficult task for this kind of application, involving a human being in the loop (whose behaviour could be hard to anticipate): in this sense, the main idea is to exploit most the *optimal control* aspect of the MPC methodology, together with the natural integration of the *constraints*. The considered cost function, although being quadratic to reduce the complexity of the problem, takes into account the tracking error, the control signal and its derivative (Wang, 2009), aiming at maximizing the performance while keeping the control signals as regular as possible. Constraints are another fundamental feature of the MPC approach: they not only allow to take into account in a rational way the constructive limits of the device, but also to avoid undesired physical behaviours (e.g. different signs of the accelerations with respect to the visual cues) that may lead to sickness and that are very hard lo manage with the traditional methods.

The effectiveness of a MC algorithm is mostly determined by its *tuning* phase. The proposed strategy introduces a newel approach to this crucial step: both the weights in the cost functions and the constraint values become *tunable parameters*. In this way, the parameters that are regulated have an immediate physical meaning, with a double advantage

1. making the learning phase faster for the operator, since everything is much more immediate to understand and intuitive to manipulate;

2. improving the feedback from the driver, whose suggestions can be immediately applied.

In this sense, it will be shown how the length of the prediction window (i.e. the number N_P of future steps taken into account for tracking) becomes an important parameter to be tuned. As common practice in applied MPC, the reference signal is considered to be constant over the prediction window, because of the difficulty of obtaining a reliable

future signal and, most of all, the increase in terms of resolution complexity.

The resolution of the constrained optimization problem is the hardest part of any MPC application, in particular in the presence of strong *real-time* request, as in the case of MC where fast dynamics are involved. Among the different possibilities given in literature (Bemporad, Morari, Due, and Pistikopoulos, 2002; Boyd and Vandenberghe, 2004; Wang and Boyd, 2010), the chosen approach is a particular implementation of the Active Set strategy, qpOASES Ferreau, Bock, and Diehl (2008), which has a number of features well suited for the considered problem.

As a final validation of the research, the algorithm is evaluated on the field by professional test drivers using an innovative dynamic simulator, VI-DRIVESIM (VI-Grade, 2012), which has the advantage of being a small, low cost platform with a high number of Degrees of Freedom (six, almost decoupled)

Some remarks on a possible implementation on FPGA are also given as topics for future research.

The first part of the thesis is organized as follows.

In **Chapter 2** the general Motion Cueing problem is described, with an overview of the most common driving simulator architectures, and a detailed explanation of the classic approach and its problems and limitations.

In **Chapter 3** the proposed Model Predictive Control procedure is illustrated in details. After an introduction on the general MPC framework, the derivation of the Vestibular Model will be presented, and the overall model will be shown. The optimization strategy will be examined as well, and in the end all the features that characterize the tuning procedure and the rationale behind this methodology will be detailed.

In **Chapter 4** the test platform will be presented and the results from simulations and practical tests analysed and compared. Simulation results that take advantage of prediction will be considered too, even if not tested on the real platform. More, a possible hardware implementation will be introduced, based on Field Programmable Gate Arrays (FPGA) devices.

In **Chapter 6** concluding remarks will be given.

5
Conclusions

In this first part of the dissertation, the design of an innovative Motion Cueing algorithm based on MPC techniques has been presented. The use of the MPC has three fundamental motivations:

1. to exploit a model of the human vestibular system to compare the in-vehicle and the in-platform perception;

2. to adopt a suitable technique to efficiently handle hard constraints;

3. to take advantage of a time-domain control that ease the comprehension of the problem and the consequent regulations.

The proposed algorithm represents a novel approach to motion cueing that completely changes the classic paradigms of washout filters: tilt coordination and working area constraints are handled through an optimization procedure without the employment of any filter.

The integration of the perceptive models strongly improves the Motion Cueing effects, helping to prevent incoherent behaviours and allowing to reproduce effective signals to track for the motion controller. The presence of constraints improves the exploitation of the working area without losing physical reliability, enhancing the overall robustness of the problem.

A distinctive point is the ease of tuning procedure. This is a fundamental improvement with respect to the standards in this field, where the lack of "physical connection" between the parameters and the motion behaviour, as well as the complicated integration of the passive filters and the lack of capabilities to deal a-priori with the limitations on the working area made the MC hard to tune and required specialized (and expensive) experts to handle the problems, making the adoption of dynamic simulators difficult in various field. In particular, this approach makes possible the direct interaction with the drivers, in the sense that their feedbacks during the tests can be immediately translated into parameters modification, with a clear improvement in the regulation time. This feature is crucial, as it is been verified that one of the major problems in driving simulators is the *adaptation*: after a certain time on the device, the driver adapts it style and perception to the virtual environment even if it does not reflect the reality (Straus, 2005). This is a problem indeed, hence a fast regulation of the system is necessary.

It is worth noting that, given the high system dimension, although implementing a real time MPC procedure is not a trivial task, the algorithm works at 100 Hz control frequency. This real time capabilities, improved by the explained approximation, made possible the implementation on a small size dynamic driving simulator, namely VI-DRIVESIM, validating the tuning methodology and the performance improvement in a practical environment. Feedbacks from professional test drivers have been encouraging.

The natural development will be the introduction of prediction. As seen, the difficulties in terms of computational time can be overcome by using a *blocking* strategy, but the need for reliable references is an issue. One possible idea is to exploit the availability of a virtual driver (Frezza, Saccon, and Bacchet, 2003; Frezza and Beghi, 2006) to obtain a reliable future trajectory. This information can be integrated in a *stochastic* variant of MPC, and one possible approach could the *tube-based MPC* (Langson, Chryssochoos, Raković, and Mayne, 2004), where uncertainties are taken into account in the problem resolution. A possible improvement can be the introduction of a *learning* procedure, where the algorithm starts by relying its predictive information on the virtual driver, and then adapts itself to the specific user and to its driving style. The first insight about prediction, whose simulation results have been reported, showed encouraging results.

The need for fast optimization would be critical in presence of prediction, and the development of FPGA solutions comes at hand. The first simulation tests are being carried on at the time of writing, and possible improvement in term of speed and cost are being examined. In particular, the newly approach on *first order methods* seems promising (Jerez, Goulart, Richter, Constantinides, Kerrigan, and Morari, 2013): if the constraints on the original problem can be reformulated as to depend only on states $\mathbf{x}$, inputs $\mathbf{u}$ and their (approximate) derivative $\Delta\mathbf{u}$, it is estimated that this approach would require about 1350 resource units, and the time per iteration would be $3-4\ \mu s$ for the complete model and $1-2\ \mu s$ for the subproblems, a significant improvement.

Part II

Control Techniques for a Hybrid Sport Motorcycle

1
Introduction

Transportation systems and efficient energy utilization are two of the most relevant research topics on a world-wide scale, for their economical and environmental impact. In the European context European Union (2011), *fossil fuels*, despite their high levels of pollution, are still extensively used for energy production and transportation. To assure sustainability and more confidence on energy supply, the European Union has studied a careful energetic policy for the next ten years, whose aim is to reduce *greenhouse gas levels* and *energy consumption* by 20% and increase the share of renewables by 20%, all these three targets by 2020.

However, the analysis of current trends show that the second target will not be reached. One of the main causes of such phenomenon is associated with the intense use of energy for *transportation*. Consequently, there is an increasing level of attention on the development of hybrid vehicles, that can help in addressing both the reduction of greenhouse gas levels and the increase of energy efficiency of transportation systems,

hence capturing the interest of international research and vehicles manufacturers.

In general, a hybrid vehicle couples two different propulsion systems, which are made to coexist mainly to *improve performance* and *reduce emissions*. Although various typologies have been studied, the most widespread is the *electric hybrid*, which couples an internal combustion engine to an electric machine powered by the energy stored in dedicated systems (*accumulators*). Depending on the implemented architecture, hybrid electric vehicles are divided into three main categories (Chan, 2007; Chan, Bouscayrol, and Chen, 2010; Ehsani, Gao, and Miller, 2007; Emadi, Rajashekara, Williamson, and Lukic, 2005)

Series Hybrid *Hybrid electric vehicles* (HEV) of type *series*, or *Range Extended Vehicle* (REV), exploit a combustion engine to generate the energy needed to recharge the batteries and to power the electric machine that provides all the motion power (schematics in figure 1.1). The Internal Combustion Engine (ICE), which is not responsible for traction, is forced to operate around the point of maximum efficiency in all driving conditions, by starting it in the case where the state of charge of the battery reaches the established minimum value, and turning it off to the achievement of the maximum charge level. As made clear by the architectural scheme, there is
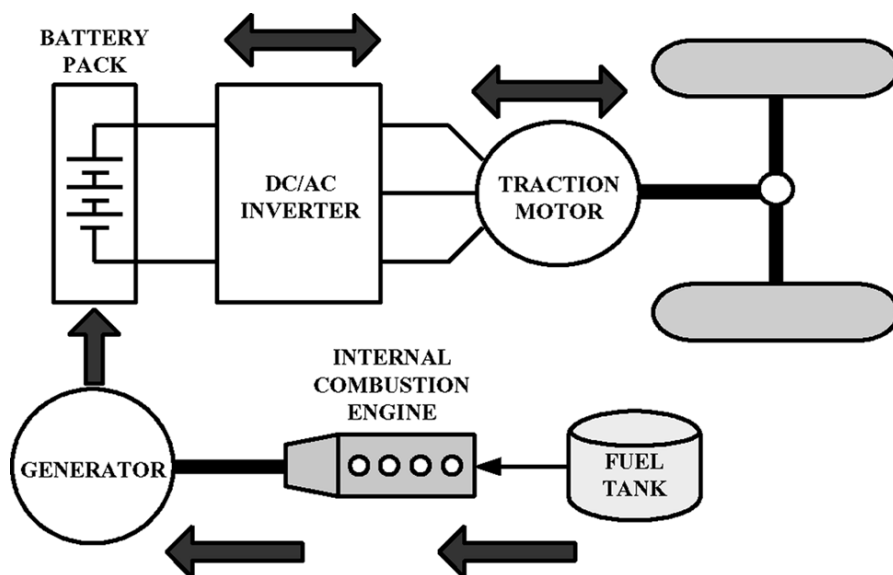
Figure 1.1: Series Hybrid schematics.

not a mechanical connection between the ICE and the wheels: in this way it can operate in optimum conditions of speed and torque to provide only charging power, limiting consumption of fuel and increasing the efficiency. The weak point of this type of hybrid vehicles is the presence of two *dissipative* energy conversion, from

combustion engine to generator and from generator to electric motor. A further disadvantage is the need to size both electrical machines (generator and motor) with respect to the maximum power of the vehicle, which is useful only in rare circumstances, hence making the dimensioning a challenging task. This architecture can be useful in all those contexts in which the driving conditions are clearly defined, such as the urban environment, or if applied to vehicles whose dimensions allow the positioning of the electrical machines which, by acting as a sole source of traction, are very massive (locomotives, buses, trucks, etc.).

Parallel Hybrid HEV in *parallel* configuration are equipped with an internal combustion engine and an electric machine, *both* connected to the drive shaft, which can operate simultaneously or individually depending on driving conditions (figure 1.2). Usually while driving at low speeds, such as in urban environments, the more efficient electric motor is used, while at high speeds ICE is preferred, using the electric machine as a generator to recharge the batteries (with the help of regenerative braking) or to provide boost contributions. To improve efficiency, the parallel HEV are often
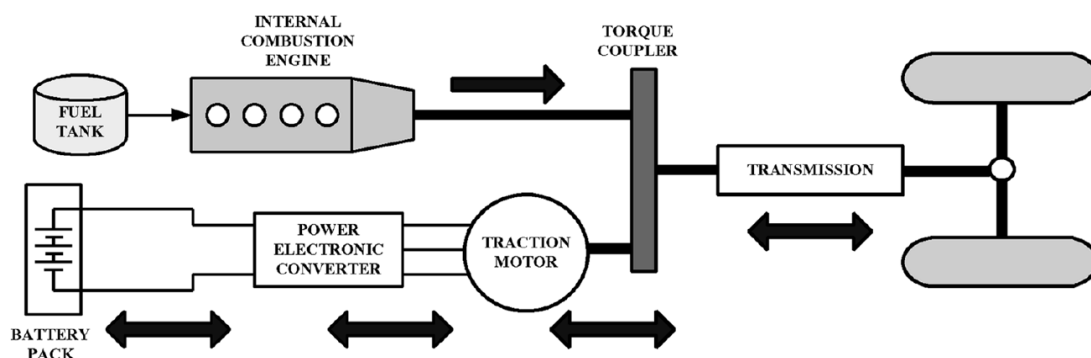
Figure 1.2: Parallel Hybrid schematics.

equipped with *continuously variable transmissions* (CVTs), that allow to optimize the operating point of the internal combustion engine for every possible torque request, hence improving the efficiency and the fuel consumption. The main advantages of the parallel configuration are

1. the presence of a *single energy conversion*, which allows to reduce the dissipation;

2. the use of a single electric machine of *small size*, which allows to reduce costs and space needed for its positioning.

Since it is not the main source of traction, the electric motor is dimensioned to

provide a lower power than the maximum for the vehicle, in this sense this class can be further divided into three categories:

1. *micro hybrid*: equipped with an electric machine of limited voltage and power ($V < 60$ V, $P < 5$ kW), it replaces the alternator, while the propulsion is guaranteed by the internal combustion engine. The electric motor is used for the *start and stop* system, which shuts down the engine when it is not used (as for example at traffic lights) allowing a saving of fuel between 2% to 10%, in the urban cycle. The electrical machine allows a smoother start compared to normal starters and a limited regenerative braking, since it is connected to the motor shaft by means of *belts* (*Belted Starter Alternator* – BAS).

2. *mild hybrid*: these are an evolution of micro hybrid vehicles, using medium voltage and power devices ($V > 100 \div 200$ V and $P > 10 \div 20$ kW). The goal is to get a boost effect using the electric machine to provide an additional torque to the endothermic propulsion during acceleration or braking. This type of vehicle allows to enhance the regenerative braking and, if possible, the operation of the vehicle in "pure-electric" mode at low speeds and loads, with a fuel saving between 10% to 20% in the urban cycle.

3. *full hybrid*: they are equipped with high voltage and power devices ($V > 300$ V and $P > 50$ kW), which can provide the power required to propel the vehicle. In this way it can travel in purely electric mode (*zero emission vehicle*), limited only by the capacity of the batteries, as well as with the internal combustion engine only or a combination of the two. This particular type of vehicles ensures a fuel saving between 20% and 50% in the urban cycle.

Series – Parallel Hybrid HEV of type *series-parallel* (figure 1.1) are a combination of the two previous architectures obtained using a *planetary* transmission that allows to decouple the vehicle speed ω_V from the electric machine and the internal combustion engine ones, respectively ω_E and ω_I. The electric motor can then be used to perform simultaneously the propulsion of the vehicle and the charging of the batteries (*power split*) if $\omega_E < 0$, or the optimization of the working point of the internal combustion engine if $\omega_E > 0$, thus decreasing fuel consumption. In addition, by exploiting a particular locking system, it is possible to disable the electrical machine to obtain a parallel configuration or, by absorbing all the torque provided by the ICE, to operate in series configuration. It is easy to understand that the growing architectural complexity requires sophisticated control systems, making this type of vehicles considerably more expensive than previous ones.
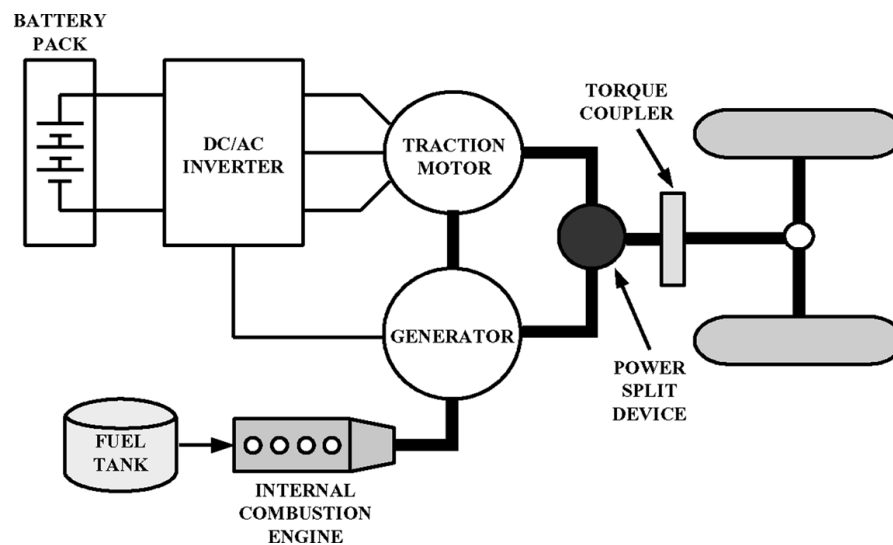
Figure 1.3: Series-Parallel Hybrid schematics.

While many models of hybrid cars have been developed and put on the market in the last few years, hybrid scooters and motorcycles have not seen a large scale production yet, despite their promising peculiarities in terms of fuel economy and environmental impact, and mobility capability. One of the main obstacles to their spreading is the limited autonomy of batteries, an even greater problem for two-wheeled vehicles given the limited available space. The presence of the electric engine and the battery pack makes the problem particularly challenging with motorcycles, since it may affect the rider's driving feeling with respect to an equivalent model provided with an internal combustion engine only. In this sense, an appropriate design of the *Power Management System* is crucial to deal with the requirements of acceptable autonomy of the electric engine and preservation of satisfactory driving feelings, which depends most on the strategy that regulates the instantaneous coupling of the two propulsions.

To this respect, it is important to have a means of evaluating the dynamic behaviour of the motorcycle when it undergoes the hybridization step. It's easy to understand that the presence of an electric machine on the motorcycle can highly modify the vehicle behaviour, e.g. due to the increase in weight and the effects of the additional torque provided by the electric engine. In this context, a *virtual environment* capable of accurately describing the vehicle dynamics is a key feature for testing different engine and power systems management algorithms and their impact on the vehicle manoeuvrability. Moreover, one of the crucial design steps, namely the sizing of the batteries, is usually carried out with static simulations. A standard telemetry is processed off-line, boost and charge steps are identified and *point-wise* energy consumption/recovery values are calculated. Reliability

for this kind of analysis is not assured, since the effects of the boost phase on the vehicle stability and performance is not investigated. A *dynamical simulation* environment can therefore be effective also in this design stage.

In this part of the thesis, we report the activities of a research project aimed at studying the electrification of a commercial 125cc motorcycle. The main focus of is the development of the controller of the Power Management System. Two strategies are proposed, a simpler one based on the evaluation of RPM derivative to select the boost/charge phase for the electric machine, and a more sophisticated *optimal control* strategy studied to obtain the best performance (in terms of available torque) while keeping the battery pack around its optimal operating point. Since the considered vehicle is a sports vehicle, the target is the utilization of the electric engine as a *torque-boost supplier*. Starting from an exiting software tool for simulation provided by VI-GRADE, VI-BIKEREALTIME (VI-Grade, 2012), a flexible SIMULINK environment has been developed. An easily customizable model for the accumulators has been derived, together with a map-based model for the electric engine. Simulations have been carried out using different configuration for the virtual rider tested on different tracks, elaborated with a dedicated tool to evaluate the performance of the control strategies among different driving conditions. The results show that satisfying performance can be obtained, in terms of both available torque utilization and battery management. Finally, the simpler of the two strategies have been implemented in the Electronic Control Unit (ECU) of a prototype and tested on track.

This part of the dissertation is organized as follows.

In **Chapter 2** the different elements of the prototype is described, namely the chosen motorbike, accumulators and electric machine. The work by Ferrari (2010) reports a dimensioning study that defines the selected components.

In **Chapter 3** the proposed control strategies are depicted. In particular, a modelization of the accumulators, based on the information from datasheets is provided, that will be useful for the control strategies proposed. Both the algorithms will be described in details.

In **Chapter 4** some results are illustrated. The SIMULINK -based virtual environment is described and simulations on a digital version of Silverstone (UK) racing track, as well as on a track with urban features are provided. The simulations takes advantage of the presence of a virtual rider, whose importance is crucial to close the loop and validate the proposed control strategies. On road tests are also reported, compared to simulations on the same test track (PIAGGIO test track in Pontedera, Italy). Greater importance will be given on the boost phase, since instruments for

measuring the charge of the batteries in real time were not available at the time of the test.

In **Chapter 5** final remarks will be given.

5

Conclusions

In the second part of this dissertation, the problem of designing and validating a controller for a hybrid sport motorbike has been discussed. Different parts of the hybrid system have been modelized, in particular the accumulators. Their physical characteristics have not been directly measured, due to the lack of a test bench, so a modelization based on the information from datasheet has been proposed. Through this, an estimation strategy for the provided and absorbed power has been implemented.

Two control algorithms have been proposed: the first is an heuristic based on the direct control of the sole electric machine. This strategy sees the intervention of the electric motor only if the endothermic is not able to provide the full torque needed by itself. In this sense it is a conservative controller, from the point of view of electric machine and batteries exploitation. The second one is an optimal control strategy based on the idea of *torque split*: the algorithm acts on the endothermic engine too with the aim of enhancing the use of the electric machine while assuring that the accumulators are not too much

stressed. Both the controllers have adaptive features that help the management with different path profiles.

A virtual, dynamical environment for the test of the hybrid motorcycle has been implemented. The battery model and control strategies have been included in a flexible SIMULINK interface and integrated with a virtual rider tool for testing purpose: simulations have been carried out to validate the battery sizing and the effectiveness of the control, both on stability and power management, with satisfactory results in particular with the optimal control strategy.

Finally, the first of the two control algorithm, easier to realize, has been implemented on the real prototype and tested on a track, with clear improvement in the dynamical performance of the vehicle, in particular at low RPM values.

Next steps will be the improvement of electrical machine and battery models to help improving the reliability of the virtual environment, in order to test different vehicles and different tracks an driving styles. The development of different boost mappings is already on the way, in order to check the performance obtained from the vehicle with more or less conservative exploitation of the electrical powertrain. This feature is already implemented on the virtual environment. Furthermore, studies will be carried on to realize algorithm for the identification of the driving conditions, e.g. using *machine learning* techniques, with the goal of adapting the boost supply to the features of the route and the driving style by automatically selecting the most suitable torque map. Finally, the approach of torque split, which has shown promising results will be refined by introducing more refined system model and cost functions. Model Predictive Control will be discussed as well to manage the electric motor, as proposed by Bolognani, Bolognani, Peretti, and Zigliotto (2009).

Final Remarks

In this dissertation, two innovative control applications in the automotive field have been considered.

The MPC-based Motion Cueing Algorithm was inspired by the need of more effective procedures to exploit dynamic simulator platforms, with respect to more classical approaches. After a review of the existing literature about similar ideas, a thorough analysis of the existing studies on vestibular system has been carried out, with the aim of deriving reliable models to be integrated in the MPC framework (Beghi, Bruschetta, Maran, Minen, Baseggio, and Pozzi, 2011). The complete system for the algorithm has seen the coupling with a simple mechanical model, in order to be as general as possible, easy to be integrated in existing devices by generating *references* for the motion controller (usually PLCs), rather than control the actuators themselves (Baseggio, Beghi, Bruschetta, Maran, and Minen, 2011). If further information on these components are available, the model can be revised and customised. The problem has been formulated as a Quadratic Programming problem, for which many solvers are available. The chosen one is based on *Active Set* strategy, and is able to work in real-time. The overall procedure introduces a new concept for the tuning phase, where constraints and weights of a cost function are manipulated to get the desired behaviour. This methodology has the advantage of being intuitive and fast to adapt to the needs of the specific driver (Beghi, Bruschetta, and Maran, 2012a). Finally, the proposed MC algorithm has been implemented and tested on a real platform, with satisfactory results (Beghi, Bruschetta, Maran, Minen, Baseggio, and Pozzi, 2012b).

The control strategies for the hybrid motorbike have been elaborated with the goal of obtain an increase in terms of low-RPM torque performance, avoiding safety issues and excessive battery consumption. To this aim, after a study of the specific components of the prototype, a model for the accumulators has been derived, that makes use of the

information from the data-sheets. Two controllers have been proposed, a simpler, heuristic one that uses the electrical machine when the endothermic engine can not provide the requested torque, and a more sophisticated one based on a optimal *torque split* control strategy, that manages both the powertrains to achieve the best combination possible in terms of performance and fuel savings, while preserving the battery pack from excessive stress (Beghi et al., 2012c). A simulation environment has been implemented to test the proposed strategies: it integrates the battery model and a virtual rider that closes the loop in order to validate the algorithms (Beghi et al., 2012d). Finally, the heuristic strategy has been implemented in the Electronics Control Unit of the prototype and tested on track, with satisfactory results.

Both the topics have studied from scratch, innovative algorithms have been designed and after being validated via simulation, implemented and tested on the field.

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