A Perspective View on
the Future of Control in Transportation Systems

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1 A workshop to unravel the issue

Modern transportation systems rely extensively on electronic devices, computer systems and sophisticated algorithms to run and be run. In fact, transportation systems simply would not work without combinations of electronic sensors, processors and "hidden intelligence" that govern their correct functioning and make up their control systems. Over the recent years automatic control has entered all vehicles, on roads, railways, air and space, and their infrastructure. A large part of future development will rely on more complex and effective control systems and diagnostic functionalities able to improve travelers' safety and comfort, performance of the transportation system and vehicles interactions with one another and their surroundings.

This report is a synthesis of the *IEEE Control Systems Society International Workshop on The Future of Control in Transportation Systems*, held at the University of Sannio in Benevento, Italy, on May 27–29, 2010 (subsequently the "Workshop"). The Workshop was a by-invitation event which was an outgrowth of the "IEEE International Workshop on the Impact of Control: Past, Present and Future" held in Berchtesgaden, Germany, October 2009. This Workshop was focused on current and future challenges in *road, railway, aircraft vehicles and transportation systems*. Participants discussed common problems across these application area, and drew attention to specific area in need of research and advances by academia, industries, private and government funding agencies.

The main goal of the Workshop was to bring together a group of leading researchers and practitioners in control science and engineering to broadly address the future of control in transportation systems. The 38 attendees represented Europe, USA and Asia. Their presentations and discussions focused on topics such as successful practical applications of advanced control, new and emerging control technologies, and obstacles that limit the practical impact of controls research in transportation systems.

This Workshop report summarizes deliberations and recommendations for cross-institutional collaborations in controls, specifically targeting industrial, academic, and governmental cooperation. This report is available on the web sites of the IEEE Control Systems Society (CSS), the Group for Research on Automatic Control Engineering at the University del Sannio (GRACE), the Hungarian Academy of Science and the University of Minnesota Aerospace Engineering and Mechanics.

2 Impact of control and expected benefits

The wide application of industrial and academic research results to control of transportation vehicles and systems has already demonstrated the potential impact and benefits of control in this area. For instance, *safety* and *comfort* have been continuously improving due to the design and implementation of dedicated control strategies. Designers recognize the potential benefits of control already starting from the conception of new and renewed vehicles and transportation

infrastructures. There is enormous potential for advances in control to benefit the safety and comfort for future transportation systems. Moreover there is the need for new ideas and solutions from the research community to address the challenging problems facing the transportation community.

The global evolution of transportation systems is putting increased emphasis on the potential impact of control on other correlated and sometimes conflicting objectives, such as *efficiency* and *environment*. Several problems still need advances to provide solutions related to close-to-optimal compromises. For instance, the adoption of a new perspective on the control strategies design at the vehicle level can still provide improvements in vehicle performance by reducing at the same time emissions, noise and fuel consumption. Analogously, at the *systems of systems* level it is important to study operational procedures able to increase capacity and throughput flows by minimizing congestion, traffic and travel time under fairness constraints.

3 Transportation challenges driving control perspectives

Advances in all engineering fields today will require cross-fertilization between theory and practice to achieve real progress and advancements. Future transportation vehicles and infrastructures will require control theorists to adopt a new perspective to address these new problems. Control researchers will need to work with researchers across different disciplines to craft solutions acceptable to the needs of the transportation community.

Looking at transportation systems, huge improvements are still possible on methodologies and tools for *high integrity control systems development*. To this aim, three main features should underpin the control system design procedures for future transportation systems: *modularity*, *integration*, and *scalability*. For each module, it is fundamental to start with the theoretical understanding and validation of industrial practices, trying to adopt processes and tools (physical and empirical modeling, simulation, analysis, design, verification, validation) that match the level of expertise (development/calibration) and allow modularity through the use of common or understandable languages at different levels of abstraction. An architecture driven development approach (description, data to address system scale/complexity, visualization, analysis) should be adopted to allow the integration of the modules. This would contribute to the definition of standard design procedures to address certification, validation and verification challenges. This is also a possible route for the formulation of more formal procedures to improve scalability: component → application → vehicle → vehicle to infrastructure → vehicle to vehicle.

Looking forward, the control of transportation systems should increase *flexibility*, thus allowing robust handling associated with the increased *complexity* of future vehicles and infrastructures. Examples of the growing complexity include coordination of multi-vehicle networks, sensor fusion, environmental uncertain-

Reconfigurable control systems
Observability/controllability of cell models
Centralized *vs* decentralized control
Cooperative and heterogeneous systems opportunities
Control design accounting for elastic demand and multi-modal approach
Data aggregation for control
Control of switched and hybrid systems
Consensus control
Constrained optimization techniques
Development, calibration, and coordination of control systems
Gray-box (physics-based and phenomenological) modeling
Verification and validation
Life cycle management
Calibration
Hardware-in-the-loop testing
Efficient control computational resources and algorithms

Table 1: Control research areas for future transportation systems

ties, heterogeneous control problems, human interactions, autonomous vehicles.

4 Emerging controls in transportation systems

Control engineering is widely applied in transportation systems. New challenges rise from the forecast of the transportation scenario in next decades and offer great opportunities for the controls field. Workshop attendees have pointed out some of the most challenging control problems and promising techniques which could help address future applications of onboard and systems of vehicles controls. Table 1 summarizes the control areas identified as important to continued advancement of transportation vehicles and systems.

The following sections consider the application domains discussed at the Workshop, i.e., automotive, aerospace and railways. Relevant open problems and promising control techniques are identified based on the consensus of the group discussions.

4.1 Advances and perspectives in automotive control

The topics of the onboard automotive control session at the Workshop focused on the current status and importance of vehicle control, and future trends. Part of the motivation of this section is to influence the direction of control technology development to help solve some of the current, as well as emerging, problems in transportation systems. The ten presentations (the list of participants is provided in Section 6) broadly covered the topics ranging from global, societal drivers of new automotive technologies to the issues in modeling, optimization,

control design, diagnostics, calibration, robustness, validation, and life cycle management. This section provides a very broad overview of the topics and discussions.

There is a very complex set of requirements imposed on today's automotive vehicles by customers and government regulators. The requirements include regulations on safety, emissions, fuel economy (or CO_2 emissions), end-of-life disposal, recycling, as well as customer preferences for fuel economy, availability, performance, and comfort. To address these issues, the automotive industry has embraced high levels of technology content mainly in the form of intelligent devices that are invariably computer controlled. For example, inside the powertrain, this content includes new engine optimization devices (variable valve timing and lift, direct injection, sequential turbo-charging, charge motion control valve, etc), more efficient and more complex transmissions (six, seven, and eight speed; power-shift), new propulsion systems (hybrid-electric), as well as advanced gasoline and diesel exhaust after-treatment systems. The area of active safety has also witnessed major advances from new technologies that include adaptive cruise control with collision prevention, roll stability control, vehicle dynamic (yaw) control, tire pressure monitoring, etc. Finally, there is new functional content with a significant control component such as the parallel park assist system that parks the vehicle semi-autonomously when prompted by the driver's command. With all this electronic and controls content, a typical 2010 sedan has approximately ten times the complexity of the Space Shuttle as measured by the number of on-board computers or the numbers of lines of embedded software code that implements these algorithms.

Systems inside the vehicle employing feedback control include mechanical, chemical, and electrical components. These controllers use sensors that measure flows, pressures, temperatures, gas concentrations, currents, voltages, accelerations, and finally relative position and range information from on-board lasers and cameras. A single control system could interact with very diverse sets of physical and functional subsystems, from thermodynamics and power electronics to image processing units. A salient feature of automotive technology is that system cost is a major factor in its adoption. It is imperative to deliver as much content as possible without a significant increase of the vehicle price.

Development, calibration, and coordination of control systems present major challenges from the complexity standpoint. As much as one can point to the unquestionable successes of the automotive control community to deliver the required content, Workshop participants have voiced the community's concerns that the level of complexity being reached exceeds the capability of the current tools, processes, and workforce.

The automotive control community has turned to modeling and model based control design to address challenges of control design. In general, one can divide the models into physics-based and phenomenological. The examples of the former are thermodynamic or body-dynamic models, while the latter are black-box models such as those often used for engine emission formation. In many cases, the used models are "gray-box" blends between the two types. The physical component of the model is used to reduce the amount of expensive and time

consuming experimental data collection, while the phenomenological, or data driven component assures desired accuracy of representation.

The methods and processes that form the model based control design (MBCD) framework were one recurring theme of the Workshop presentations. The use of a plant model in the control design step of the MBCD process represents a classical approach for control engineers. Automotive examples were presented of the application of Proportional Integral Derivative controllers, feedforward, Smith Predictor, model predictive control, state estimators and observers. The models are used to support various steps of the MBCD process including controller calibration, verification, validation, and life cycle management. With the models of the system to be controlled and the controller itself available, one can combine hardware and models in different ways to perform complete model based, hardware-in-the-loop, or software-in-the-loop testing. Models need to be of different complexity and accuracy levels to support their diverse uses. One challenge in MBCD is scalability of model based verification and validation between component, application, vehicle, vehicle-to-infrastructure, and vehicle-to-vehicle levels. Another challenge is efficient development of accurate models—that is, with minimal use of expensive experimental facilities—and their proper management at varying levels of fidelity.

The presence of a large body of legacy control content and embedded software that interacts with any new functionality is among the challenges facing control engineers. Redesigning the legacy content is often difficult because the original requirements may not be available or complete, as the existing legacy version is likely to have been obtained through an evolution-like process with numerous small improvements and fixes. Another challenge of control system design is the reduction in time for controller tuning/calibration. Introduction of more complex systems coincided with shortening of the product development cycle. The paradox is that there is, in general, less time available to tune more advanced new controllers than the simpler controllers they are replacing. One could argue that the need for fast turnaround time for tuning advanced controllers—in particular in response to a late hardware change—has not received significant attention by the control research community.

In view of the interaction of many systems in delivering complex vehicle functions, it is not surprising to find that networked control systems have become more representative of the systems in vehicles. Of particular interest are safety, security, reliability, and robustness of such systems. To connect these challenges to the discussion in the previous paragraph, we note that making the networked systems significantly cross-dependent may lead to a late hardware change in one system creating a cascade of changes that propagates through the network from the source and back. One can see how such a situation may significantly increase complexity and cost of the networked system design process.

Another unique aspect of automotive control is that the vehicle control system significantly interacts with the human operator in delivering desired behavior and important functions. In contrast to most other cases of such interactions, for example in aerospace, one cannot expect that the human operator of a passenger vehicle be specially trained. Road and traffic conditions during use also

Control of new engine optimization devices
Advanced control of complex transmissions
Hybrid vehicles
Electric vehicles
Emission control
Active safety
Collision prevention
Vehicle dynamics
Park assist systems
Human-vehicle interaction

Table 2: Opportunities for new automotive onboard controls

Advanced transportation management (AdTM) systems
Sensor technologies in AdTM
Car2Car and Car2Infrastructure communications
Ramp metering algorithms in AdTM
AdTM variable velocity control
Real-time traffic modeling, prediction and control
Fleet management for public transportation
Real-time passenger information systems
Accident detection
Integration of motorway and urban traffic
Infomobility/user services/logistics

Table 3: Opportunities for new systems of vehicles controls: *automotive*

can vary significantly. The diversity of operators and conditions leads to a number of questions around human-machine interactions and how much authority and autonomy to give to the vehicle control system relative to the operator.

A different aspect of human-machine interaction is a group of users interested in customizing the performance of their vehicles. Traditionally, these users are enthusiasts who replace engines, add turbochargers or superchargers, change mufflers, etc. One presentation discussed an opportunity that arises with computerized control of the vehicle functions. In this case, users may be interested in employing their personal computer, connected through an auto maker-provided interface to at least some vehicle systems, to customize the operation to their taste. A number of opportunities exist for control application within the *automotive* transportation area: some of the topics of interest are reported in Tables 2 and 3.

In summary, the control content in automotive vehicles is increasing in size and complexity at a very fast rate. The growth poses significant challenges, many of which are discussed above. We hope that this report would provide inspiration to the broader control engineering community to help meet these

challenges.

4.2 Advances and perspectives in aerospace control

The aerospace session of the Workshop consisted of ten presentations, one from each of the organizations taking part in the working group (see the list of participants in Section 6 of this report). These presentations served as a starting point to establish a common ground and initiate the discussion. Subsequently, the goal of the working group activity was to provide a unified view on the following points:

- Identify the aerospace application areas for which further developments of control can have a major impact and how can the expected benefits be defined;

- Identify the applications in aerospace controls;

- Determine the challenges and open issues expected to require attention from the research community in the near future;

- Identify actions the controls community can take to facilitate the development of aerospace control technology, with specific reference to the interaction between academic and industrial players.

This section provides a summary of the results of the discussion on these topics. In particular, even though most of the academic research activity in aerospace controls focuses on vehicle control and optimization, the panel members addressed both problems arising at the level of the individual vehicles and problems related to air traffic management. In this respect, this report aims at providing a complete coverage of such problems, even though time limitations did not allow an in-depth exploration of interactions between single and multi-vehicle control issues.

Impact of control and expected benefits

The first issue addressed by the working group has been the assessment of the areas in which controls can be mostly beneficial. The main priority of aircraft builders and operators and of air traffic managers is, as has always been, *safety*. In this respect, it has been pointed out during the meeting that aerospace vehicles (aircraft and rotorcraft) as well as the entire traffic management system are currently already designed to achieve a remarkably high safety level; hence, in this respect, further improvements are likely to come only from significant technological investments and/or radical departures from current architectures and methodologies. Advanced controls can contribute to safety improvements both at the level of the individual vehicle and at the traffic management one, by increasing the reliability of individual vehicles and by improving the quality of operation of the traffic management system. In particular, automatic systems

that further reduce the burden on the crew and help them make correct decisions, and fault detection/identification/reconfiguration systems designed to react to technical problems as soon as they occur can significantly contribute to the improvement of aircraft safety.

Similar considerations apply as far as *efficiency* is concerned. In this respect, the priority is to improve vehicle performance and to increase the capacity of the air traffic system as a whole. A number of technologies can be deployed to this goal, we will discuss below some of the potentially more interesting ones.

One of the key issues for the future of aeronautics is the *environmental impact*. Indeed, aircraft noise and emissions still represent a political and social issue and a major nuisance to people living close to airports. In recent years the aeronautics sector has made increasing efforts towards a sustainable approach to air traffic by developing quieter engines with reduced damaging emissions, using materials which are either recyclable or have minimal environmental impact, optimizing operational procedures and improving land planning and use around airports. Advanced controls can also contribute significantly to reducing vehicle emissions and noise; furthermore, control-based approaches to air traffic management can contribute to the reduction of air traffic impact.

Finally, *affordability* and *reduced time to market* are additional issues which can benefit from the adoption of advanced control methodologies to improve the design process rather than focusing only on controls as a means to improve the product performance. Indeed, as will be further highlighted, some steps in the design and implementation of aircraft control systems remain to date extremely time consuming and costly. In particular, verification and validation constitute a critical issue in this respect and should be tackled as a priority.

Emerging applications

Control technologies have been at the core of aeronautics and space systems since the very beginning and have evolved alongside all the other aerospace-specific disciplines and technologies throughout the 20th century. A number of innovative applications however are emerging in recent years, and the working group has tried to provide an overview of them.

Concerning *aircraft control*, we first mention the so-called performance-centered control, i.e., a novel viewpoint in the design of aircraft control systems in which the emphasis in the design is put on the actual performance of the closed-loop system as measured, using different metrics simultaneously, to account for the areas identified above (safety, efficiency, environmental impact, etc). In the framework of traffic management a similar, integrated view of the problem is the so-called gate-to-gate control approach.

More specific advances are related to new technologies which are either needed by new developments in the field, such as active loads control, or that will be potentially beneficial in the long run as far as efficiency is concerned, e.g., active flow control. The former would allow control of the aeroelastic response of aircraft and flutter suppression beyond what has already been demonstrated in terms of e.g., gust alleviation, which has been successfully implemented on

aircraft. Similarly, active flow control is a technology aimed at altering a natural fluid flow allowing increases in efficiency and a reduced environmental impact. Significant progress has been made in control theory for optimal and automated design of closed-loop controllers that can be applied to flow control systems, given a sufficiently accurate and efficient model of the system.

Concerning *air traffic management* (AirTM): the need for new operational concepts and systems is emerging, so as, e.g., to permit aircraft to operate in all weather conditions and to fly closer together at low risk (control of position relative to other aircraft, so allowing optimal and efficient airspace allocation). More specifically, the main emerging applications can be shortly summarized as follows.

- *Four dimensional trajectory (4DT) control*: A 4DT is a description of the flight path of an aircraft as a four-dimensional continuum from its current position to the point at which it shuts down at its destination (i.e., unlike 3DT, every point on a 4D trajectory is precisely associated with a time). In this respect one can define an optimal 4DT as a 4D trajectory which, if flown, would result in the most efficient use of the available resources. In this framework, a number of specific challenges can be formulated, such as 4DT generation, navigation and tracking.

- *Handling uncertainty*: Uncertainty can arise in multiple forms. The main issue is of course weather, which remains a major disrupting factor for aircraft operations and a source of discomfort (and danger) during flight. However, also human error and intentional adverse actions (e.g., terrorism, spoofing) need to be taken into account.

- *Control-based AirTM*: Control-based approaches to AirTM can provide efficiency and safety benefits at various levels. For traffic flow management the issue is how often to run demand/capacity and response strategy models, considering time to implement coordinated decisions across domains. Similarly, control based methods can be exploited for separation assurance and collision avoidance, providing complementary advisories to controllers and pilots.

Unmanned Aerial Vehicles (UAVs) have been playing an increasing role and attracting a lot of attention from the research community in aerospace control. Indeed, the remote and/or autonomous operation of such vehicles poses a number of challenges, some of which have been progressively addressed in the last few years, while others remain open. Among others, emerging applications in this area are related to the management of UAV access to airspace, possibly sharing the same airspace as conventional civil and military aviation, and new applications of unmanned vehicles, moving from the military to the civil domain, such as, e.g., cargo transport.

Finally, recent technological developments are paving the way to (more or less radically) *new architectures* for aircraft: in this respect, the trends towards more electric aircraft, which will enable new and different approaches to control

systems design and deployment, and the specific issues arising in the design of so-called optionally piloted vehicles have been discussed.

Challenges and open issues

The discussion of the working group has been particularly fruitful as far as the definition of the main challenges and open issues for future research are concerned. Most of all, the interaction between academic and industry/agency members of the working group has made it possible to highlight issues which are not frequently treated in the academic control engineering literature but are strongly felt as highly important in industry in order to enable some of the expected benefits identified above. For the sake of conciseness, the numerous issues which emerged in the discussion have been synthesized into four main items, as follows.

- *High integrity control systems development* (e.g., safety-critical systems). This topic is related to the various aspects arising in the design of aircraft and rotorcraft control systems, when viewing the design process *as a whole* instead of focusing on the specific task of control law design as is common practice in the academic control engineering community. Indeed, when this viewpoint is adopted, the classical problems associated with control law design methods and tools (covering various aspects, such as modeling, simulation, analysis, design, verification, validation) result in a much wider panorama, in which other problems and additional constraints come into play. The most critical aspects appear to be certification challenges, and policy and legacy issues causing implementation constraints. While the latter have a tight connection with control law design, the former, equally important, are frequently (if not systematically) neglected in academic work. The group felt strongly that industry desires development of design approaches which can facilitate the verification & validation (V&V) tasks, currently the most demanding, time consuming and costly ones in the development of aircraft control systems—more on this issue can be found in the third item of this list, where the interaction with other disciplines is discussed. Similar comments apply to the problem of life cycle management. Another area which still poses significant challenges in spite of extensive research work in recent years is the one of, broadly speaking, analytical redundancy, i.e., fault detection and isolation, fault-tolerant control, health monitoring. Finally, an interesting aspect which arose from the discussion is the problem of providing theoretical validation to industrial practices which are frequently employed in the implementation of control systems (and usually provide simple, satisfactory solutions to practical problems) but are usually not taken into account at the design stage.

- *Flexible operation design.* Overall aircraft performance would benefit by improving control systems design methods. Flexible operation design provides a set of control methods, concepts and approaches which can be

deployed in order to bring the notion of performance as usually intended in the control community closer and closer to the actual needs of aeronautical applications. As far as individual vehicles are concerned, the key approaches which have been highlighted by the discussion are multi-attribute optimization (which enables effective tradeoff analysis between multiple performance criteria at design time), the inclusion of variables measuring environmental performance in the design of the on-board control system, and the adoption of adaptation techniques which would allow to online modify tradeoffs between otherwise conflicting objectives, such as noise and vibrations, power requirements, emissions, etc. Note that the notions of flexible operation and adaptivity are being assessed and developed also in the rotorcraft field, see for example the recent DARPA "Mission-Adaptive Rotor" program, which aims at achieving the flexible operation goal by suitably combining design choices with the implementation of adaptive control schemes. Concerning the air traffic management side, on the other hand, the key challenge is represented by the development of advanced methods and tools for trajectory planning.

- *Complexity.* The design, implementation and verification of aerospace control systems are characterized by a significant level of complexity manifested in multiple different ways. First of all, the use of mathematical modeling methods and tools from different disciplines at various levels of the design can lead to difficulties in managing the overall process. In addition, when viewing the design process as a whole a number of different disciplines are involved, the boundaries among which can pose significant challenges to overcome. A typical example, as far as V&V is concerned, is the interplay between control and computer engineering, an area which is attracting increasing attention from the two communities. Additional challenges in this respect are introduced by the tradeoffs between distributed/centralized control and coordination which arise in the development of advanced control-based schemes for Air Traffic Management (AirTM) and of multi-vehicle networks.

- *Human-centered automation and control.* Finally, a key point to be addressed in future research for aerospace controls is related to the interaction between advanced, complex automation and control systems with human operators: pilots and crews for the case of the individual aircraft, and air traffic controllers as far as AirTM is concerned. Currently the situation is quite different in the two domains, as the level of automation on the individual aircraft is already far more advanced than it is in the typical air traffic control room. However, recent studies have shown that the interaction between pilots and onboard automation systems is more critical than frequently anticipated at design time and training needs are sometimes underestimated, leading to potential problems and, sometimes, to accidents when automation executes an unexpected action (commission), or fails to execute an action (omission) that is anticipated or expected by one or more of the pilots. It can be easily foreseen that similar issues will

arise in AirTM as automation progresses over time and human operators move to increasingly outer (higher level) control loops.

4.3 Advances and perspectives in railway control

The Workshop represented an unusual occasion for sharing knowledge among experts in the field of railway systems and control engineering. The session participants (the complete list in Section 6) were mechanical engineers with expertise in railway vehicle dynamics, researchers working on the railway traffic management and signaling, and control scientists, as well. The presentations focused on specific control problems of electrical and mechanical subsystems as well as on more general and systemic issues. This section will provide a short overview of the session discussions and conclusions.

It is undoubted that control systems methodologies and technologies have not permeated into the railway community as strongly as already occurred for other transportation areas. Indeed, compared to the automotive and aerospace fields, only few academic control groups dedicate their research to railway applications. This was also reflected in the session participants affiliations: most of the contributors were from industry. The session conclusions reassert the need for more control people to work on railway systems: railway control systems design can get wide benefit from the control theorists contribution so as to improve classical and sometimes obsolete solutions.

Railway systems are complex due to the composition and interrelations among subsystems at heterogeneous levels. Generally, the most important subsystem in railway system is the subsystems for safety. For example, brake system, signaling system, telecommunication system running gears, and so on. The subsystem which the attention of railway engineers has been focused on is, of course, the locomotive that implements the propulsion functionality meaning, nowadays, electrical traction for most of the applications. At this level many control problems are related to the performances and the correct behavior of the electrical traction. However the locomotive is not the only component of interest since the presence of rolling stocks influences the dynamic behavior of the overall vehicle. Hence vehicle dynamics aspects are also very important from a control design perspective, with issues at least as complex as the analogous counterpart of the automotive field. Finally, at a compositional higher level, several trains access the same common resource, i.e., the railroad. Thus, control theory has a role to play in the management of the rail traffic and signaling. These topics are explored in more detail in the following paragraphs.

Challenges and open control issues for electrical systems

Most of the classical and modern railway propulsion systems are based on electric traction. Therefore motion control and control of power electronics systems are fundamental control engineering applications in the railway field. Challenges from the control perspective can be synthesized in the following three main items.

- *Electrical traction system.* Electrical traction is based on several components and subsystems that convert electrical energy to mechanical energy. Such conversion has to be controlled in order to achieve desired performances and maximum efficiency. Thus, advanced control for power converters like the propulsion inverter but also the four quadrants chopper, the auxiliary inverter or the braking chopper are fundamental applications in the electrical traction chain. Modeling and control of new traction motors like permanent magnet motors, are challenging issues directly related to faster and more efficient trains.

- *Energy management.* Cost savings and efficiency improvements can be achieved through smart control algorithms for both on-vehicle and vehicle-to-infrastructure energy management systems. Examples of promising applications in this field are: active filtering, which can avoid or reduce the size (and cost) of passive filters; supercapacitors and on-board batteries, which can increase the efficiency and the flexibility of energy flows management; advanced control of the train operations, which can optimize the infrastructure energy management.

- *Frequency domain issues.* Aspects more related to passengers comfort, such as acoustic noise or electro-magnetic interference reduction, can also be successfully addressed by control theory and frequency analysis of non-linear systems, e.g., employing suitable modulation techniques and control algorithms. Such applications are subject to constraints dictated by regulations and this can strongly motivate improvement as it happens in the automotive field as a consequence of regulations on emission control.

Possible solutions to the above mentioned problems need to satisfy strict requirements, such as robustness to failures of physical devices and safe behavior under hard operating conditions. Therefore testing, verification and validation represent key issues for controlled systems also in the railway field, where real experimentation is much more difficult and expensive with respect to other transportation fields, such as the automotive industry. Hence rapid prototyping and hardware-in-the-loop methodologies are becoming more and more useful for the design cycle of railway control systems.

Control problems arising from mechanical railway engineering

From the viewpoint of vehicle dynamics, the compatibility between high-speed stability and curving performances is a difficult task ahead for urban railway, especially subway systems, which have high-speed sections in suburbs and tight curve sections in urban areas. In general, railway vehicles are designed based on the high speed performance as the fundamental specification, and the curving problem is addressed only after high speed performance of the train has been attained. When vehicles run on a tight curve section, many undesirable phenomena are observed such as: high frequency "squeal noise", loud flange noise, excessive rail-wheel wear, noise and vibration generated by rail corrugation, etc.

Various countermeasures have been tried and applied to solve these problems by many challengers among vehicle dynamics engineers but the search for the best solution is still an open problem for the community.

Research has been focused on optimization of the self steering mechanical system design. Indeed, railway vehicles turn thanks to the effect of a mechanical feedback due to the self steering system: the position of the wheelset is automatically and naturally controlled to the balanced position by the difference of the contact point circle diameter of the inner wheel and the outer wheel. The difference depends on the relationship between the lateral position of the wheelset and the conicity of the wheel tread. The self steering system performs very well and is a very reasonable method, but its effectiveness needs a large conicity. On the other side, the large conicity comes at the expense of the high speed stability of the vehicle. Due to this trade-off, the design solution of the wheel tread shape is limited to relative gentle curves with radius more than approximately 300 m.

Drastic improvement in curving performance would benefit from active steering control. Active steering bogie trucks are categorized into two types. One is the semi-active steering, where the steering angle is enlarged by the inner forces of the bogie truck that can be achieved by the electronic control, thanks to the variation of the characteristic of a suspension component, e.g., a damper. The alternative is active steering which steers the wheelset through actuators thus avoiding the controllability limitations intrinsic to the semi-active approach. Generally speaking, the idea of semi-active steering is an extension of the self-steering system with a softening of the primary suspension; active steering systems, instead, require the development of a more complex feedback controller which fully actuates the steering on the basis of current measurements and estimations. Recently, test results to evaluate the active steering bogie truck with electrical or hydraulic actuators replacing the linkages have met with great success. Although semi-active or active steering systems are very effective methods to improve the curving performance of the bogie truck, implementation of these new techniques requires great changes, large-scale investments and the safety risk inherent in transition to a new system. Hence railway operation companies, being conservative in nature, are reluctant to install such innovations.

A relevant phenomenon for railway vehicle performance is the friction between wheels and rail since it plays a very important role in processes such as adhesion, rolling contact fatigue, wear and noise generation. Some of those processes have contradicting consequences somehow: on one hand high friction is required to reduce adhesion loss;[1] on the other one low friction minimizes the wear at the wheel flange-rail gauge corner contact. Anyway there exist friction modifiers (special materials for wheel-rail lubrication) that can be applied to the wheel-rail contact so as to generate the required coefficients of friction. To implement the concept of friction control, researchers devised an onboard system which sprays, onto the top of the low rail as a mist, a friction modifier through a

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[1]In the railway terminology the friction available, and needed, between wheel and rail during traction and braking operations is known as adhesion; a form of adhesion loss is due, e.g., to wheels slipping in acceleration or skid in deceleration.

nozzle behind the last axle of train, and the following train receives the benefit of it. The advantages of this onboard friction control system are as follows: the friction modifier can be supplied onto the rail uniformly through the curve by controlling its amount proportionally to the vehicle's velocity; the train with the friction control device can supply the friction modifier immediately at any curve of the service line where the wheel-rail contact condition needs improvement; and the supply of the friction modifier or the maintenance of the device could be performed in an equipped place of a car depot. In order to obtain enough effect, appropriate amount of friction modifier is required: if the amount of supply is excessive or consumption between a spray to the next is too little, the friction modifier cannot play the expected role because the friction coefficient is too low. Thus attention is devoted to develop a control algorithm deciding the amount of friction modifier to spray according to the measurements coming from the field. In this way it is possible to improve the curving performances and to reduce both noise and rail vibration.

Railway system of systems

The last aspect discussed within the railway session has been related to the so called "system of systems" point of view. Systems of systems consist of components that themselves are systems able to operate independently. By looking at a geographically extended railway infrastructure with several trains running at the same time, it is apparent that the system of systems point of view can be applied.

The automatic train control is mostly based on new technologies like signaling and telecommunication, electronic beacons, GPS. Command and control of rolling stocks accessing a common railway infrastructure are very important issues for satisfying requirements in terms of safety, availability and punctuality, and capacity. The European Railway Traffic Management System (ERTMS) has been developed in order to address the issue mentioned above and taking into account also interoperability, different standards and the integration of old and new applications. These issues give rise to important control engineering problems. For instance the need for a reliable and precise position information suggests an interesting and challenging position estimation problem. Determining the actual train position in all situations, even when the GPS signal is not available or when the beacon signaling is not enough accurate, is a tough problem where control theory might give a significant help. This issue parallels similar issues for automotive vehicles and unmanned air vehicles.

Optimal management of the railway traffic, meaning also route optimization, is another difficult and challenging issue similar to that one of air traffic management in terms of performances and requirements, but also very different in terms of constraints.

Advanced control for power converters
Active noise reduction
Active filtering
Efficient energy management
Energy saving
Onboard energy storage and reuse
Robustness under failures and asymmetries
Control of new traction motors

Table 4: Opportunities for new railway onboard controls

Curving performance
Friction control, active tilting, active steering
Active train suspension
Distributed and synchronized generation and propulsion

Table 5: Opportunities for new railway vehicle system

Summary

In summary, the railway session of the workshop highlighted how control engineering can represent a relevant added value in several applications related to railway systems. Tables 4, 5, and 6 identify some of the most relevant problems of interest for control theorists.

The common issue associated with all problems discussed in the railway session is that control engineering is just starting to being successfully applied within the railway community. Hence there is great potential for advances and the application of advanced control technology to railways vehicles and their transportation systems. A closer look at such applicative domain is worthwhile to control experts.

Train position estimation under sensor uncertainties
Dynamic optimization of scheduling
Route optimization
Railway traffic management system
Energy savings through signaling
Speed optimization
Railway safety critical analysis
Centralized traffic control
Automatic train protection, operation and supervision

Table 6: Opportunities for railway systems of vehicles

5   Potential actions

Several actions were identified to focus transportation controls research, facilitate the exchange of ideas between academia and industry and the interplay between research and education. This section offers opportunities to address these issues.

A limitation of related research which emerged from the discussion is the lack of a unified view of the development process for transportation control systems on the academic side. An effective instrument to overcome this difficulty could be the definition of benchmark problems, with the following specific features. First of all, the benchmark problems should be defined *across disciplines*, i.e., they should involve all the (diverse) technical and scientific communities which contribute to the actual design and implementation of a real control system. This means, for example, to combine control, human factors, software engineering, certification aspects and others. Furthermore, such benchmarks should be formulated with industry, to ensure that they are relevant to the actual needs of the automotive, aerospace and railway communities. This of course has a number of implications in terms of handling of intellectual property, but there should be ample background to deal with such aspects in previous experience on occasion of this type of exercise within the European Union Framework Programs. A useful tool for this purpose might be represented by dedicated (CSS sponsored) workshops, aimed at analyzing in greater depth the various aspect which have emerged from the discussion of this workshop and at defining benchmarks. In view of the above discussion, the workshop should not only involve industrial and academic partners from the control community but also include specialists from all the relevant, related disciplines.

Encouragement of industry papers in special conference sessions and special journal issues is another approach to improve the industry/academia connection. These sessions might capture common industrial practices and make them available to the control community.

Similarly, efforts should be made to encourage and support international collaboration: indeed, it is easy to anticipate that facing the challenges and open issues identified above, such as high-integrity development and flexible operations design, will require international cooperation.

Finally, on the education side, the main goal which emerged from the discussion would be to broaden control education trying to ensure that the entire development process of control systems is included in control curricula. This, in particular, would imply to include at least the basics of all the above mentioned disciplines (e.g., computer science, human factors, application domains) into existing curricula. While this is an extremely challenging objective, in view of the traditional organization of academic curricula at most engineering school, it would likely be worthwhile, in view of both the competitive advantage this would provide to students and of the benefits for industry.

6 Workshop participants

The list of participants divided into the three working groups.

- Aerospace

  - Ciro Amitrano, SAM Aerospazio, Italy
  - Gary Balas, University of Minnesota, Minnesota, USA
  - Johann Bals, German Aerospace Center, Germany
  - Richard Barhydt, NASA, Virginia, USA
  - Federico Corraro, CIRA, Italy
  - John Hansman, MIT, Massachusetts, USA
  - Marco Lovera, Politecnico di Milano, Italy
  - Andres Marcos, DEIMOS-SPACE S.L., Spain
  - Roberto Palumbo, CIRA, Italy
  - Peter Seiler, University of Minnesota, Minnesota, USA
  - Balint Vanek, Hungarian Academy of Sciences, Hungary
  - Shuguang Zhang, Beihang University, China

- Automotive (vehicle-infrastructure)

  - Carlos Canudas de Wit, CNRS, France
  - Carmen Del Vecchio, University of Sannio, Italy
  - Mariano Gallo, University of Sannio, Italy
  - Luigi Gortan, MIZAR, Italy
  - Markos Papageorgiou, Technical University of Crete, Greece
  - Yi Zhang, Tsinghua University, China

- Automotive (vehicle-controls)

  - Ivan Arsie, University of Salerno, Italy
  - József Bokor, Hungarian Academy of Sciences, Hungary
  - Francesco Borrelli, University of California at Berkeley, California, USA
  - Pandeli Borodani, Centro Ricerche FIAT, Italy
  - Ken Butts, Toyota, Michigan, USA
  - Luigi del Re, Johannes Kepler Universität, Austria
  - Giovanni Fiengo, University of Sannio, Italy
  - Mrdjan Jankovic, Ford, Michigan, USA
  - Sergio Savaresi, Politecnico di Milano, Italy

- Stefano Scala, ELASIS, Italy
  - Greg Stewart, Honeywell, Canada

- Railway

  - Luigi Accardo, AnsaldoBreda, Italy
  - Luigi Iannelli, University of Sannio, Italy
  - Kosuke Matsumoto, Tokyo Metro, Japan
  - Ciro Nappo, AnsaldoBreda, Italy
  - Fabio Senesi, Rete Ferroviaria Italiana, Italy
  - Francesco Vasca, University of Sannio, Italy

- Cross-area participants

  - Luigi Glielmo, University of Sannio, Italy
  - Alkis Konstantellos, European Commission, Belgium
  - Roberto Tempo, IEEE CSS and CNR, Italy

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