THE IMPACT OF AUTOMATIC CONTROL ON RECENT DEVELOPMENTS IN TRANSPORTATION AND VEHICLE SYSTEMS

Status report prepared by the IFAC Coordinating committee on Transportation and Vehicle Systems

Uwe Kiencke *(University of Karlsruhe),* **Lars Nielsen** *(University of Linköping),*
Robert Sutton *(University of Plymouth),* **Klaus Schilling** *(University of Würzburg),*
Markos Papageorgiou *(Technical University of Crete),* **Hajime Asama** *(University of Tokyo)*

Abstract: Throughout the field of transportation and vehicle systems control is gaining importance. This report focuses on the current key problems engineers in this field are facing and highlights some major recent accomplishments. The driving forces behind the increasing use of control are the rising need for transportation services and the demand for a higher safety level. While each domain takes specific approach to deal with these demands, a general trend towards automatic co-pilots or even autopilots is visible. In the automotive domain, this is aided by the design of drive by wire systems. In other fields like marine or aerospace systems, the focus of research is on the swarming behavior of multiple vessels. New sensors and networking will also enable more efficient traffic flow control, which will allow for a better use of the resource network capacity. Another trend in the vehicle systems sector is the modeling of nonlinear system behavior, which is starting to replace look-up tables in real time systems. A forecast on future trends is given at the end of the report.

Keywords: Transportation, vehicle systems, automotive, aerospace, marine systems, intelligent autonomous vehicles, traffic control

1. INTRODUCTION

In today's globalized world, mobility of people and goods has become an essential necessity. We rely on vehicles and transportation systems to not only take us to our jobs and homes every day, but also to supply us with everything from the most basic commodities to the most exotic specialty products. The systems we rely on to accomplish this have grown and evolved over decades with control playing a crucial and ever more important role. Today, transportation and vehicle systems in every form include control systems. Some of the problems faced by engineers are very specific to the application domain while many of them are common to all modes of transportation.

This paper therefore reviews current key problems and general trends and accomplishments shared by all transportation applications as well as those, which are specific to selected certain fields. The fields included are the following:

Automotive Systems:
All aspects concerning automotive vehicles, including engines, vehicle dynamics and in-car electronics are considered.

Marine Systems:
Touches on topics of interest in surface and underwater vessels including navigation and control of marine systems.

Aerospace Systems:
Deals with aspects of dynamics, control, and mission control of aeronautical and space related systems including missiles, aircraft, and satellites.

Transportation Systems:
Addresses ground transportation systems (road and guided transport) and air traffic control systems for

both passengers and transported goods with regard to modeling, simulation and control. Also addresses common aspects and generic techniques for all transportation modes.

Intelligent Autonomous Vehicles:
Includes mobile robots on land, at sea, or in space. Addresses perception, architectures, planning, motion control, navigation techniques, tele-operation, and practical applications.

2. CURRENT KEY PROBLEMS

Throughout the field of transportation and vehicle systems some general trends can be universally observed. The demand for transportation, for example, is increasing for all modes of transportation and types of vehicles. This need for mobility of persons and goods and the corresponding increase in traffic causes serious congestion, safety and environmental problems in all modes of transportation as described e.g. in the European Commission's "*White Paper – European Transport Policy for 2010*". For economical and ecological reasons or simply due to a lack of space, expansion of traditional transportation infrastructure cannot be the only answer to this problem. The scientific-technical community attempts to address and solve these problems in an intelligent way, i.e. via employment of new technologies and advanced methodologies. These include driver assistance systems, reliable information perception and accident avoidance systems.

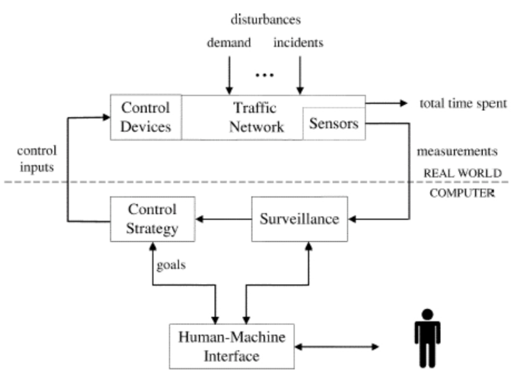

Figure 1: The control loop in traffic control

Another significant trend that can be observed throughout the transportation field is the growing interest in autonomous or semi-autonomous vehicles. This encompasses completely autonomous systems such as unmanned underwater/surface vehicles in marine systems as well as only partially autonomous or supervised autonomous systems. Although standard in aerospace for many years, these supervised autonomous systems are fast gaining ground in consumer level applications such as automotive. This calls not only for increasingly better modeling of systems but also creates new challenges for human-machine interfaces and communication.

The main challenge for completely autonomous vehicles is a high capacity power source where a major breakthrough in battery technology and/or a shift to other power sources is needed. Another restricting factor is the limited capabilities of onboard navigation, guidance and control as impressively demonstrated in the recent DARPA Grand Challenge where no vehicle was able to autonomously complete a 300 miles obstacle course. The last, and very significant set of challenges for completely autonomous vehicles are the legal responsibilities and liabilities that come from autonomous operation.

A trend towards better modeling of systems can be seen throughout the entire field of vehicle systems. While hard real time control systems like engine control are usually look-up tables today, the use of modeled processes in control bears the advantage of easy adaptation through parameters of the model.

While fly-by-wire systems have been state of the art in aviation for some time now (they were first introduced in the late 70's), drive-by-wire systems for cars are still a research topic. In contrast to the development of fly-by-wire systems, where the high-integrity of the systems was a crucial issue, drive-by-wire systems have to meet high levels of safety, reliability and availability while simultaneously adhering to cost sensitivity of the automotive sector. In order for drive-by-wire systems to gain customer acceptance, they will not only have to be safe but also provide added value for the customer. This can be achieved through a combination of drive-by-wire and advanced driver assistance systems, which are not possible with conventional steering and brakes. These systems can provide functions like automated parking, automated lane keeping during highway travel, and automated speed adjustment based on road signs which can be analyzed by the driver assistance system.

Driver assistance systems are themselves a major focus of research. This is in large part due to three recent developments:

1. First there is the afore mentioned planned use of drive-by-wire systems in future cars which will enable driver assistance systems to have more far reaching control over the vehicle.

2. With the planned use of new sensors like IR cameras and RADAR, future driver assistance systems will be able to detect and recognize more objects in the environment of the car faster than the driver especially in unfavorable conditions like fog and rain.

3. The third factor contributing to the interest in driver assistance systems is the large increase in computing power of embedded systems.

The major challenge presented by driver assistance system is efficient merging of the combination of several different sensors in order to optimally assist the driver in a given situation. Combining and weighting the information given by the various sensor types is crucial and not only requires large amounts of computing power but also advanced approaches like Kalman filtering or Bayesian networks.

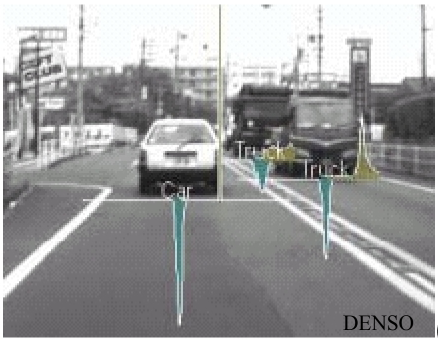

Figure 2: Bayesian network analysis of a traffic situation

Another major challenge in the automotive control field is including cylinder pressure in engine control since this pressure allows closed-loop control of the combustion cycle. Closed-loop control produces more efficient and therefore more environmentally friendly combustion. A number of approaches are taken at the moment including modeling based on the ion current in the spark plug and including a sensor in the combustion chamber. The reason behind this development is not only a pull from the customer side with customers demanding more fuel-efficient vehicles but also a push from both lawmakers requiring lower emission of harmful substances such as soot and NOx and the automotive industry which is committed to limiting green-house gases like CO2.

The long tradition of autonomous control in aerospace nevertheless also cumulated recently in very successful combined autonomy/tele-operations-architectures as successfully proved by NASA's Mars rover operations since January 2004 on the surface of Mars. Therefore it would be desirable to enhance cross-fertilization between terrestrial and space control applications.

With recent interest in supply chain management from companies around the world, large scale transportation systems are getting more and more attention. Supply chain management identifies inventory as a factor which drives cost and therefore tries to minimize inventory at all stages of the supply chain of a product while adhering to certain constraints. With smaller inventory, the transportation of raw materials and goods becomes a crucial factor for the success of a business. It has to be reliable, flexible and fast. This poses a great challenge to the design of large scale transportation systems like roads and train networks and the intermodal management of fleets and the flow of goods and raw materials.

3. RECENT MAJOR ACCOMPLISHMENTS, TRENDS

Although there are several difficult challenges facing vehicle and transportation systems, there have nevertheless been significant accomplishments within recent years. Furthermore several trends are now recognizable within a broad class of vehicles and transportation systems.

3.1 Marine Systems

During the last decade there has been a rapidly growing interest in the design and development of autonomous marine craft. These craft are unmanned underwater vehicles (UUVs) and unmanned surface vehicles (USVs). Many accomplishments have been realized, but this area of marine control systems design will continue to be one of the key areas for research and application both in the military/naval and industrial sectors for the foreseeable future.

The dynamic characteristics of an UUV presents a control system design problem which classical linear design methodologies cannot easily or effectively accommodate. Fundamentally, UUV dynamics are nonlinear in nature and are also subject to a variety of disturbances such as varying drag forces, vorticity effects and currents. Therefore they offer a challenging task in the development of suitable algorithms for motion and position control in the six degrees of freedom in which such craft operate, and are required to be robust in terms of disturbance rejection, varying vehicle speeds and dynamics. It should be noted that the term "unmanned underwater vehicle" as used here is a generic expression to describe both an autonomous underwater vehicle (AUV) and a remotely operated vehicle (ROV). An AUV is a marine craft which fulfils a mission task without being constantly monitored and supervised by a human operator, whilst an ROV is a marine vessel that requires instructions from a human via a tethered cable or an acoustic link.

Although ROVs play an important role in the offshore industry, their operational effectiveness is limited by the tethered cable, and the reliance and cost of some form of support platform. Even though AUVs cannot be considered as being commonplace at this moment, they are thought by many to be the future technology to provide essential platforms for instruments and sensors for various kinds of subsea missions. These missions include environment forecasting, policing exclusive economic zones and under-ice operations as well as ocean basin monitoring.

Earlier in this discussion a *prima facie* case has been made regarding the need for ongoing research into robust control algorithms for AUVs. Also of paramount importance for this type of vehicle is the requirement for it to be equipped with a robust navigation subsystem that accurately determines its current position. High accuracy can be gained by employing costly inertial systems. However, as the popularity and use of AUVs increases so will the demand for continued high navigational accuracy but at low cost. The solution to this ongoing problem lies in the use of inexpensive sensors being used in multi-sensor data fusion (MSDF) algorithms. Without doubt, the development of MSDF algorithms is a priority for research. In addition, as the navigation aspects of an AUV improve the guidance laws are becoming more sophisticated.

Although AUVs are seen as having great potential, such craft cannot be deployed in shallow or inland waters to undertake, for example, surveying and pollutant tracking tasks. As a result, operational costs are currently high as SCUBA divers or special vessels containing a number of people have to be employed for these applications. Hence the interest in providing such services at low cost via USVs which are capable of operating in river systems, and littoral and deep water. USVs can also be usefully commissioned for search and rescue missions, police, and custom and excise operations, and a variety of deterrent, attack and covert military roles.

The dynamic characteristics of USVs vary depending upon whether it is a mono or twin hull vessel. However, irrespective of the hull configuration, they all exhibit highly nonlinear behavior. Further complications arise with these vehicles when attempting to control the surge, sway and yaw modes owing to underactuation. In many cases, underactuated USVs are more easily served using nonlinear control theory. Thus underactuated marine systems and the application of nonlinear control theory in the design of their control systems is in the light of recent success considered as a necessary field of continued research.

It may be argued the navigation of an USV is less of a problem than that of an AUV because of access to GPS information. To a certain degree this may be true, however, they can be required to operate in areas of non-existent / degraded GPS reception. Thus the navigation of USVs is still difficult and thereby since intelligent dead reckoning algorithms are being applied more frequently for such vessels as well as AUVs.

The navigational aspects of an USV can be further complicated if it operates in a pack with similar vehicles. This can be further exacerbated if the pack or an individual also has to be linked with other airborne and / or subsea autonomous assets. Hence as USVs can be engaged in multi-entity operations, research into network centric systems is essential along with that for robotic co-operative and swarming behavior.

3.2 Automotive Systems

In the automotive field there is an increasing trend to use physical models instead of look-up tables. Physical models provide better information over a wider range of parameter variations than look-up tables. Look-up tables typically contain vehicle and engine dynamics. This trend is largely due to two factors: The first is the need for adaptive control. The adaptation is used to control e.g. aging of components (long term adaptation) or to configure the model for different cars. The second is the rapid proliferation of powerful embedded components which allow for calculation of complex models in real-time. Since this trend is likely to continue, the model based approach will probably replace look-up tables in hard real time fields like suspension and even engine control.

Diesel engines are rapidly gaining popularity (especially in Europe) mainly because of their lower fuel consumption. A current field of interest is to make the distribution of fuel in the cylinder as homogeneous as possible thereby allowing for cleaner burning. This is usually done by using a common rail (a common supply line, which provides high-pressure fuel for all cylinders) with increased pressure (up to 2000 bar) and a very thin nozzle. Automatic control is employed to find the optimum solution for how much fuel is injected at what time into the combustion chamber.

A major downside of diesel engines is the relatively high emission of possibly harmful particles (soot). In certain metropolitan areas, like central Tokyo, a legal limit for the particle content of exhaust of diesel-fueled trucks has been introduced recently, with more areas expected to follow suit. Current particle filters tend to clog up over time and have to be cleaned either using an additive substance in the fuel or higher exhaust temperatures to burn the residue. While the first method only requires the filter and the additive, which has to be refilled during maintenance, and is therefore suitable for refitting kits, the second requires changes in the motor management and is therefore only an option for new cars. However since the approach using increased exhaust temperature does not require an additive and is therefore more suitable for long maintenance intervals, it is the focus of research at the moment.

Homogeneous Charge Compression-Ignition (HCCI) on the other hand are the latest development for diesel (CI-compression ignition). At part load they have the potential to run as efficient as a diesel engine with extremely low particle and low NOx emissions. They are very difficult to operate in transients. In order for HCCI engines to live up to this potential, detailed modeling of the injection and combustion process is necessary.

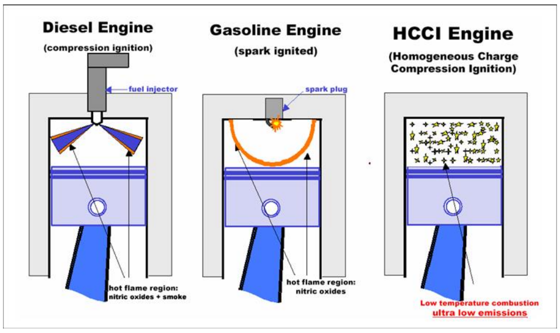

Figure 3: Homogenous Charge Compression-Ignition

Also a clear trend towards the use of driver assistance systems is visible. Mainly due to increased traffic, drivers have to deal with a rapidly growing amount of information while driving. Systems, which will assist the driver such as adaptive cruise control, will gain momentum in the near future, fueled by research in sensor data fusion. Using techniques like Bayesian Networks or Kalman Filtering, sensor data fusion delivers improved data quality from COTS (Commercial Off-The Shelf) sensors, which is especially important in a cost sensitive market segment like automotive systems. The major improvement of fused data over separate algorithms for each sensor is the inherent weighting function which always prefers the sensor combination which is best suited for the current conditions. This feature is essential to safety-relevant systems. In addition to sensor data fusion, the application of 'new' sensors like RADAR or LIDAR or other, radically new sensors will further improve the quality of data. With the improved quality of car data, new driver assistance systems such as automated parking or the electronic tow bar (automated convoy driving on highways) can be implemented. The electronic tow bar is the automotive equivalent of the 'swarming behavior' described in the marine systems chapter. It will take the important step from independent driver assistant systems to networked driver assistant systems. The networking will be ad-hoc, which allows for frequent changes in the network structure. All of these driver assistance systems will help to minimize stress on the driver and let him focus on possibly dangerous traffic situations.

GPS-based onboard navigation systems are now found in a significant percentage of new cars as well as planes (for taxiing). In addition to current static or adaptive route calculation, future navigation systems are likely to provide the possibility for dynamic route calculation which considers the implications of routing recommendations on the future traffic situation. These systems will also be offered as offboard navigation systems with a small embedded system onboard which serves mainly as a human-machine interface. The main route calculation will be done offboard and will be transmitted to the current local position through a broadband connection. Such offboard or even decentralized routing requires new algorithms which are able tot ake feedback into account, which will require advanced optimization and control techniques and should especially be useful in urban settings. In connection with portable and wireless systems, this also allows for intermodal navigation. Intermodal navigation combines different modes of transportation such as subway, car and train in one journey in order to find an optimal (that is fastest, shortest or cheapest) route. This lets customers profit from the advantages of traveling with different transportation carriers.

3.3 Aerospace

Challenging control applications are based on a long tradition in the Aerospace community, relating to aircraft as well as spacecraft. Current interesting trends take advantage of new navigation capabilities (GPS, GALILEO), improved telecommunication infrastructures for tele-operations (IP in space). There are also promising interactive architectures, which combine autonomy approaches with human tele-operations. This allows to most efficiently perform space missions by limiting the need for operators on the ground to perform routine tasks. In general while interplanetary space missions offer still significant challenges for autonomy, while autonomous control in Earth orbiting spacecraft is successfully handled more as work relieve for tele-operators. In general, autonomous vehicles are fast gaining importance in the aerospace sector, for example for the observation of disaster zones, reconnaissance and other applications.

An area of increasing interest to control concerns high precision formation flying of spacecraft while attitude control system designs are challenged by increasing accuracy demands.

Another trend in the aerospace sector is the application and integration of new sensor technologies. These are mainly based on nanotechnologies and strongly contribute to mass reduction which is a main concern in the design of spacecraft. These new sensors also fuel the general trend towards smaller and therefore lighter spacecraft. This new type of spacecraft raises the demand for appropriate new control concepts.

Since China send an astronaut into orbit aboard the Shenzhou 5 in October 2003, there is a renewed international interest in manned space missions. With a manned mission to Mars and the planet's exploration being the long-term goal of several nations, the moon has also become an intermediate target for manned missions.

Figure 4: The mars rover

There is also a growing interest in supersonic transport. The goal here is to develop a transporter with a cruising speed of up to Mach 2.2 and a range exceeding 10,000 km/h. This presents a challenge in the field of basic aerodynamical design.

In commercial aviation, in-flight communication has gained importance over the last few years and has become a priority for airplane companies. After the transition from analog to digital optical fiber communication the next step will be to provide passengers with in-flight Internet access through a satellite link. This will also enable the widespread use of in-flight telemedicine which will not only help to increase passenger safety but will also avoid the diversion of airplanes for medical reasons.

In order to increase efficiency in commercial aviation, both major OEMs presented their new concepts lately. Both of these concepts will provide an increased range over today's planes which will allow them to reach more destinations non-stop and thus saving time. The concepts also promise lower noise emission as well as increased fuel efficiency which will be at the same level as roughly the same level as modern turbo-diesel cars (fuel consumption per passenger).

3.4 Transportation Systems

Traffic congestion in road networks and motorway networks has become a major plague of modern societies that degrades infrastructure use and negatively affects both economic development and the environment. Continuous research and development work toward optimum utilization of the available nominal network capacity is supported via recent advances in computing, surveillance and communication technologies (transport telematics). Major challenges when developing control systems for road traffic are due to the large-scale, distributed character of the process under control, the presence of strong nonlinearities, unexpected disturbances and strict constraints, as well as the involvement of human decision makers (drivers) at the process level.

These conditions result in several very specific challenges within the transportation systems field. The first environment which has to be dealt with is the urban road network. It is characterized by a high level of utilization at peak times which usually leads to the congestion of roads. In this scenario, the design of a traffic sign control strategy which allows for the optimum utilization of the road network is the major challenge.

The second important scenario which poses a challenge is the design of control systems for large-scale motorway systems. It includes several variables such as ramp metering as well as speed and lane control.

An actuator input, which can prove very useful in both settings is the use of driver information and road guidance systems. These systems use a combination of variable message signs (VMS), on-board equipment and mobile route planners to control the flow of traffic. These systems are especially useful if feedback from all (or at least the large number of) cars is provided to the control system which can in turn adapt both routes for single cars through route guidance systems (off-board navigation) and speed limits for all cars on a given road section. This way, an integrated traffic control system which employs a variety of actuators (traffic signs, VMS, route guidance) can be created. This integrated traffic control system helps to maximize the synergistic effects while minimizing the interference between the subsystems, which can lead inferior solutions in the decoupled case.

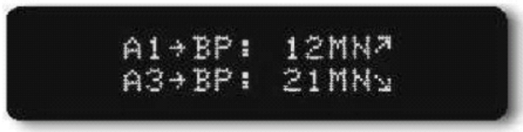

Figure 5: A variable message sign (VMS) indicating travel times on alternate routes

Modern freight transportation and logistics are increasingly influenced by the booming of information and communication technologies, satellite navigation systems and related developments. The presence of congestion in all transportation modes as well as the need for efficient treatment of unexpected disturbances in real-time call for re-assignment, re-scheduling or re-distribution procedures represents major methodological challenges which are due to the inherently combinational (discrete) character of the involved processes. Specific subareas of this significant application field that is located at the edge between (combinatorial) optimization and control (to account for real-time actions) include vehicle routing, fleet and crew management, intermodal transportation, terminal management, supply chain optimization, city logistics and freight intelligent transportation systems.

3.5 Intelligent Autonomous Vehicles

Intelligent autonomous vehicles have been mentioned in most of the sections above. This indicates, that intelligent autonomous vehicles are not just a stand-alone research topic anymore, but that they have become integral part of the research in the application domains.

One major point in the recent years was the increasing maturity of especially airborne autonomous vehicles, which have become commonplace in reconnaissance. Also the successful mars rover mission has proven the maturity of autonomous (or at least partly-autonomous) vehicles. Despite the fact that there are still challenges, great progress has been made in the intelligent autonomous vehicles perceive their environment. Using cameras with image processing and other sensors like RADAR, intelligent autonomous vehicles are able to determine their position and plan routes. As mentioned above, this does not quite hold for ground vehicles yet.

A trend for all land, sea and airborne intelligent autonomous vehicles is that research into swarming behavior of these vehicles promises improvements and poses new challenges for the research community.

3.6 Distributed Systems

A trend which can be observed throughout the entire transportation field is the tendency of modern electronic systems to be increasingly distributed. Connecting independent control units, networking has become an indispensable part of system design. With the proliferation of 'smart sensors' and 'smart actuators', communication over the network is fast becoming an integral part of modern electronic systems. This trend is likely to continue and we will likely see truly distributed systems, that is systems with distributed hardware, control and data. Moreover there is a tendency to distribute functions, control algorithms and data dynamically over a network which will lead to better hardware usage.

This distribution on the other hand creates new problems which are not present when designing monolithic systems. While data consistency in not a problem in a non-distributed system, the transport delays caused by sending data over a network can cause inconsistencies in identical functions. This is especially important in safety relevant systems like drive-by-wire. In order to avoid these negative effects of distribution a "best practice" for the design of distributed systems is needed.

4. FORECAST

While the majority of transportation and vehicle systems have been controlled almost exclusively by humans (driver, pilot or captain) at a high level, automatic control will probably achieve a much more significant role in control of all modes of transportation. Automatic control will most likely extend its influence from the lower levels like engine control in automobiles to much higher levels and more complex functions. Through this trend the research in autonomous intelligent vehicles in combination with lessons learned from robotics might affect research throughout the transportation sector.

Depending on the special circumstances presented by each mode of transportation, future research topics and anticipated developments which will occur in coming decades will no doubt differ for each field. Nevertheless, we can confidently predict that several advances will become commonplace in the fairly short-term future. These include driver assistance systems which will improve overall safety and operating economies, but which still leave the driver in full control of the vehicle (navigation systems, etc.). The next logical step is the development of co-pilot and autopilot systems. Modern aerospace and marine systems already include auto pilot systems. Research in these areas therefore focuses strongly on autonomous vehicles with control systems in full control of the vehicle. This trend is also fuelled by the need to better utilize the scarce resource network capacity. A prerequisite for this development is design and implementation of by-Wire control of vehicles with a high level of safety and integrity in the fields where they are not already commonplace today.

The research on transportation systems might help to improve the traffic situation in all modes of transportation. The traffic modeling and control will likely show best results in the automotive sector, where improvements through variable message signs and off-board navigation will probably yield the best results in addressing traffic saturation phenomena.

Including public transportation in these systems will create intermodal navigation systems which promise to further increase the efficiency of traffic guidance systems. Traffic control strategies designed via the application of powerful and systematic methods of optimization and automatic control will likely replace heuristics wherever possible in the long run.

More powerful embedded control systems, new and networked sensors and actuators will change the field of vehicle and transportation systems. These two factors will both enable and demand the use of more complex control strategies replacing in large parts the simplistic approaches used today because of the constraints imposed on vehicle systems.

But not only are the sensors likely to be networked, new sensor types, e.g. based on nanotechnology, and sensors which have become mature or affordable enough for mass production will probably change the field of vehicle and transportation systems. This, along with other trends like sensor data fusion, will allow new levels of autonomy in vehicles.

5. CONCLUSION

In the field of vehicles and transportation systems, great progress has been made over the last couple of years, with control at the very forefront. Automatic control will also help to fuel advances in this sector in various forms from the modeling of traffic flow to integration of new sensor information and from engine control to autonomously operating intelligent vehicles. New and emerging trends show promising results for solving some of the fields more fundamental questions.