Automotive Control

Luigi Glielmo, Ken Butts, Carlos Canudas-de-Wit, Ilya Kolmanovsky,
Boris Lohmann, and Greg Stewart

Automotive: Control Systems in Millions of Copies

Here *automotive* refers to the application field of vehicles on tires, such as cars, trucks, and motorbikes and related infrastructures. (Although some undergrounds run on tires, such as in Paris, we did not include those vehicles and transportation systems! To avoid ambiguity, one could add the requirement of steerable wheels.) Because of the large number of consumers involved, and hence the economic significance of the entire supply chain, the automobile is the symbol of modern-era *homo sapiens,* certainly in developed countries and increasingly in emerging regions. Historically, the automotive industry was not a major user of advanced controls, but the situation began to change several decades ago with the advent of cheaper, smaller, and better embedded processors and other developments. Today control is pervasive in automobiles, and all major manufacturers and many of their suppliers have invested significantly in Ph.D.-level control engineers. Indeed, over the last decade or more, the automotive industry has become one of the foremost industry sectors in terms of the importance accorded to advanced control technology.

> *Over the last decade, the automotive industry has become one of the foremost industry sectors in terms of the importance accorded to advanced control technology.*

On the one hand, because of the successes we will discuss later, mechanical engineering is now much more aware of the possibilities offered by combining mechanical design and control design than was the case just a few years ago. Hence the design of a new engine, or a new subsystem, is performed through dynamical simulations on powerful platforms where control algorithms can be included from the early phases. On the other hand, applying the control-based approach to complex systems is difficult, since control synthesis requires abstraction and usually simplifications that are not so obvious. Roughly speaking, one could say that a sound control-based innovation requires at least a good Ph.D.-level researcher working on it. To make things worse, we must consider that any development in the industry needs to be overseen from early conception to industrialization and maintenance over years; hence the control machinery, often captured only after adequate training, has to be somewhat translated and made understandable to all people in the workflow, a hard but crucial task for achieving widespread market penetration. Another way to put it, according to an automaker expert, is that model-based control design procedures are lengthy and difficult to include in a production schedule. Here are a few numbers to start with: for an engine management electronic control unit (ECU), more than 100 inputs and outputs need to be handled; some 100 system functions need to be implemented; some 1,000 pages of specifications need to be understood; some 10,000 parameters need to be calibrated (hundreds of kilobytes); some 100,000 lines of code need to be written (many megabytes) [1].

In addition, although the costs of sensors and actuators tend to decrease, the high volumes of production (millions of units) and the tight margins of this business suggest a careful evaluation of the return on investment before industrialization of a new control concept.

From: *The Impact of Control Technology*, T. Samad and A.M. Annaswamy (eds.), 2011. Available at www.ieeecss.org.

What are the societal goals in this sector? From a broad perspective, automotive transportation should be efficient, sustainable, and safe, partly because of environmental concerns and partly because of the large number of automobile-related fatalities and injuries worldwide. Economic considerations of manufacturers, suppliers, and consumers must also be taken into account. All aspects are then related to the vehicle itself and to the interrelation among vehicles and between vehicles and the transportation infrastructure.

As consequences of those goals, a list of top-level requirements can be delineated, such as higher engine performance, in terms of tradeoffs among power, fuel needs, and emissions reduction; increased reliability, safety, and passenger comfort; and a longer expected lifetime (strongly connected with a heavy reduction of maintenance and repair costs). Fulfilling these expectations also requires faster and cheaper vehicle development.

Successful Applications

The emissions reduction successes obtained in the automotive field are strictly related to control applications. For example, the operation of three-way catalytic converters, which managed to dramatically reduce emissions by spark-ignited engines, depends on the precision with which the mixture of fuel and air is close to stoichiometry. The ordinary mechanical carburetor could not achieve the necessary precision, and hence “electronic injection” was introduced, where the fuel is injected in precise quantities related to the amount of aspirated air. Typical control problems in this context are control of the injectors, an electromechanical device, and estimation of the air flow, which in early applications could not be directly measured. Interestingly, the idea of “injecting” fuel rather than letting it be aspirated is not a recent one; it was suggested by mechanical engineers at Bendix in the 1950s but failed commercially due to insufficiently robust components. The first solid-state systems were developed in the 1970s.

Now all new engine concepts, such as homogenous charge-compression ignition (HCCI), are mechatronic designs where the role of control is crucial. Another increasingly important control-based engine technology is variable valve actuation (VVA) or variable valve timing (VVT) (Fig. 1), which tends to detach engine valves closing and opening from the camshaft. This is crucial for cylinder-by-cylinder and stroke-by-stroke combustion control since it is possible to adapt the inflow and outflow of the air to the cylinders to the rotational velocity of the engine, the torque requested by the driver, and so on.

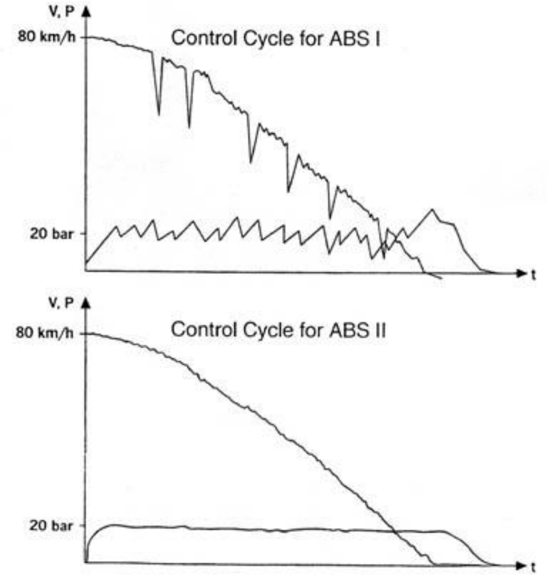
New engine concepts, such as homogeneous charge-compression ignition (HCCI), are mechatronic designs where the role of control is crucial.

The control approach has gained wider visibility among nonexperts as a result of high-impact applications such as the antilock braking system (or *Antiblockier* system in German, ABS in any case) (Fig. 2), electronic stability control (ESC), and the automatic manual transmission. From another perspective, the success of control applications is apparent in that they become mandatory through specific legislation (as will soon happen for ESC) or, conversely, specific legislation calls for the development of control products to meet constraints, typically on emission levels.

Source: www.fiat.it

Figure 1. Fiat VVA valve opening schematic (MultiAir).

The X-by-wire concept, aimed at eliminating mechanical connections among components and facilitating the exchange of information among the various subsystems, has already resulted in successful applications or, in safety-critical areas where it cannot be totally applied, inspired improvements. For example, through drive-by-wire, the torque requested by the driver, originally implicit in the cabled throttle command, becomes a numerical value that can be transmitted to the engine ECU (as a reference value to be tracked) or the ESC (as a known disturbance input), thus enabling coordination of the subsystems and hence more effective operation of the entire system. The steer-by-wire idea is still considered audacious in commercial vehicles, but it can be found in simplified versions as active steering, where the mechanical connection between steering wheel and tires is kept but an electromechanical system enables additional turning of the wheels, possibly depending on the speed of the vehicle. Additional degrees of freedom can be added on four-wheel steering systems where, for example, the rear wheels can turn in the same or the opposite direction as the front wheels, depending on the kind of maneuver and the velocity. Power steering, once an ingenious hydraulic device, is now electromechanical. On some devices, for example, an algorithm controls the steering ratio; on others it modulates the assisting torque.



Source: www.bmwusa.com

Figure 2. Evolution of BMW ABS from version I to version II: Speed and braking pressure.

Note, however, that consumers do not always perceive the control part of the technology (often included in the more generic term *electronic*), although the word *control* has largely made its way to the general public, especially through driver assistance products. Obviously, success also depends on the introduction of new or cheaper sensors (for example, radars, lidars, and cameras for driver assistance).

As in other sectors, the control methodologies used have ranged from standard regulators to optimal control, in relation also to the availability of suitable models for the problem at hand. Sometimes the solution is reached through ad hoc, perhaps nonoptimal but effective, solutions and then improved with more sophisticated control methods. The list of applied control methods (from simple gain scheduling to proportional-integral-derivative (PID), or various forms of optimal control) has widened over the years with the dispersion of graduates in the industry. The list of new methods successfully developed in the automotive control field goes from hierarchical control structure (distributed on various layers) to gain-scheduled PIDs, passing through artificial intelligence control schemes such as neural networks and fuzzy-logic-based controls (to represent experts' knowledge). Virtual sensors (that is, subsystems and/or algorithms that exploit mathematical models to estimate process variables or operating conditions) play a large part in this scenario. Virtual sensors are widely used because they are cheaper than real ones (which often may not be physically feasible), can have a faster response compared to physical sensing devices, and can be more accurate (or better calibrated) than real sensors. Control methodologies such as Kalman filters, state observers, or online system parameter identification are successfully applied in designing virtual sensors.

Market Data and Socioeconomic Effects

Because control technology is hidden, collecting data on its market penetration is not straightforward, and often the data are extracted by taking a broader view. In a report by the European Commission, a relatively good close-up has been compiled for monitoring and control (M&C), therein defined as “the control of any system, device or network through automated procedures, managed by a control unit with or without the capability to display information” [2]. Eleven M&C application markets are defined: environment, critical infrastructures, manufacturing industries, process industries, buildings, logistics and transport, electric power and grid, vehicles, household appliances, healthcare, and home. The M&C market for vehicles “represents expenses by vehicle manufacturers for inside produced [vs. aftermarket products] vehicle embedded solutions. . . . World leaders are Bosch, Continental AG, Delphi, Denso, etc.” The primary market for vehicles is represented by in-car systems, accounting for 95%; the remaining 5% represents vehicles such as aircraft, buses, trucks, and railways. The market’s total world value exceeded €56 billion in 2007 (see Table 1), which is 28% of the total M&C world market (about €188 billion), and the European share is equal to about €17 billion, or 30% of the vehicle world market.

Table 1. World and European Vehicle M&C Markets (2007, in million Euros) [2]

Area	Hardware	Software	Services	Total
World	32489	2076	21842	**56407**
Europe	9873	631	6637	**17141**

Table 1 categorizes the market into hardware, software, and services. Tables 2, 3, and 4 illustrate how each of these groups is subsequently divided into solutions and list respective market values worldwide and in Europe. Note that the “control layer” is the largest value category. Aspects of control technology are also included in other categories.

Table 2. World and European Vehicle M&C Markets: Hardware (2007, in million Euros) [2]

Area	Control Layer	Interfaces Layer	Network	Computing Systems	OS and Drivers	Total
World	19534	2515	2515	2648	5277	**32489**
Europe	5936	764	764	805	1604	**9873**

Table 3. World and European Vehicle M&C Markets: Software (2007, in million Euros) [2]

Area	Communication Software	Application and Visualization	Total
World	1017	1060	**2076**
Europe	309	322	**631**

Note: "Communication Software" and "Application and Visualization" do not seem related to core control engineering software [2].

Table 4. World and European Vehicle M&C Markets: Services (2007, in million Euros) [2]

Area	Application Design	Integration, Installation, and Training	Communication and Networking	Maintenance, Repair, and Overall	Total
World	5148	5745	5720	5229	**21842**
Europe	1564	1746	1738	1589	**6637**

The report also suggested a market growth of 5.1% annually until 2020. This optimistic forecast was made in 2007, before the big financial crisis hit the car industry in 2008. Still, the numbers appear to be gigantic and suggest another way to look at future perspectives of automotive control applications: How many vehicles are on the road these days? *The Wall Street Journal* estimates the number at 800 million (counting cars and light trucks), compared to 650 million in 2000, and there are expected to be more than one billion by 2020—again, optimistic (or pessimistic for environmentalists!) [3]. Older cars have no electronic control units or lines of codes, but now even low-end cars can boast 30 to 50 ECUs governing windows, doors, dashboard, seats, and so on, in addition to powertrain and vehicle dynamics; luxury cars can mount more than 70 and as many as 100 ECUs. Analysts seem to agree that some 80% of all automotive innovations are driven by software. A recent article reports that "a modern premium-class automobile probably contains close to 100 million lines of software code" [4]. Some analysts disagree on the 100 million figure; others believe cars will require 200 to 300 million lines of software code in the near future. What seems undisputable is that the amount of software on a car is comparable with that on a civil aviation aircraft. Furthermore, according to the same article, the cost of electronics (hardware and software) in a vehicle now accounts for 15% of the total cost and can be estimated at 45% for hybrid electric vehicles (HEVs), where software plays a greater role—for example, the GMC Yukon hybrid automobile features a two-mode hybrid automatic transmission whose control software design took 70% of the total staff hours [4]. However, not all ECUs and software on board are related to control functions. One report estimates that about 36% of the automotive electronics market is not related to controls (but rather to security, driving information systems, and body). The part that is related to controls breaks down as follows: safety functions, 16%; chassis/suspension functions, 13%; and powertrain functions, 35% [5].

Another interesting way to quantify the impact of automotive controls relies on cost-benefit analyses, often performed by government agencies to support and justify legislation on safety and environmental protection. The *eImpact* project (funded by the European Commission within the broad objective of halving automotive-related fatalities) [6] aimed at assessing the socioeconomic effects of intelligent vehicle safety systems (IVSSs) and their impact on traffic, safety, and efficiency, focusing on 12 different technologies:

1. Electronic Stability Control (ESC)
2. Full Speed Range ACC (FSR)
3. Emergency Braking (EBR)
4. Pre-Crash Protection of Vulnerable Road Users (PCV)
5. Lane Change Assistant (Warning) (LCA)
6. Lane Keeping Support (LKS)
7. Night Vision Warn (NIW)
8. Driver Drowsiness Monitoring and Warning (DDM)
9. eCall (one-way communication) (ECA)
10. Intersection Safety (INS)
11. Wireless Local Danger Warning (WLD)
12. Speed Alert (SPE)

The assessment procedure followed the scheme in Fig. 3.

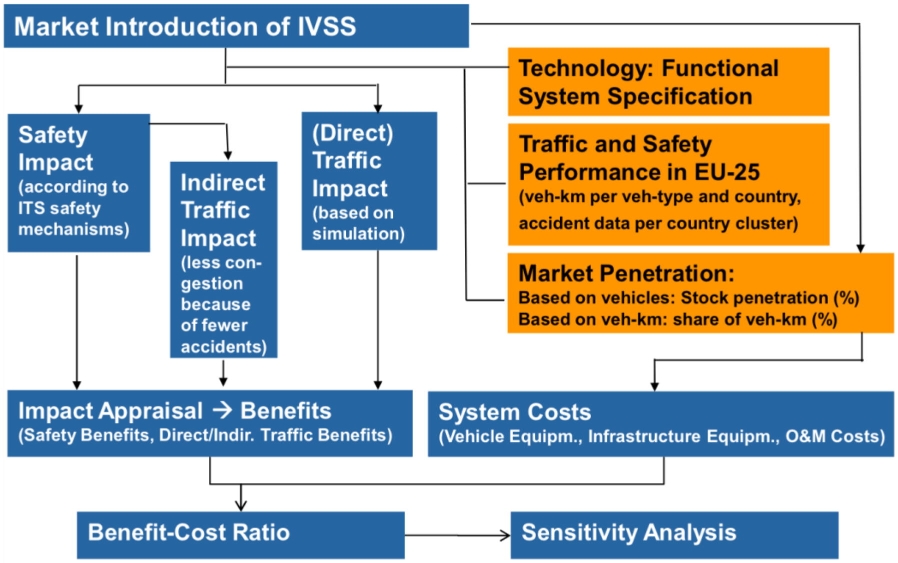
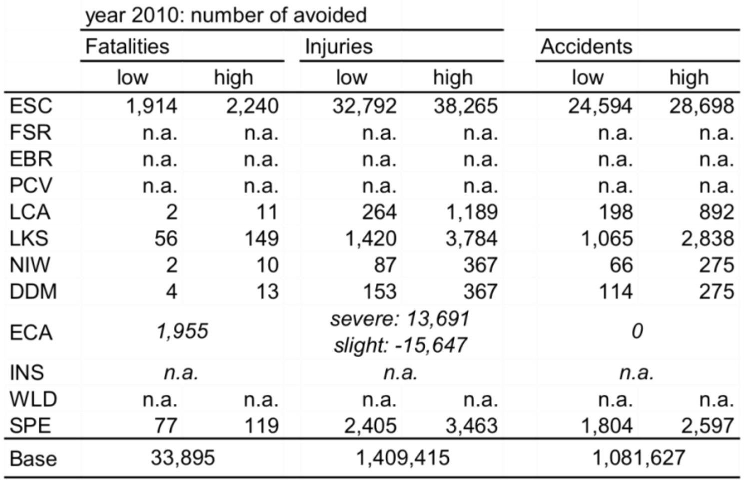


Figure 3. Cost-benefit assessment procedure [6].

For further details regarding the procedure, see [6]. Here we provide some of the conclusions from the report. First, Tables 5 and 6 show the estimated number of avoided fatalities, injuries, and accidents for each of the IVSS technologies for 2010 and 2020. Note that not all technologies were considered available in 2010.

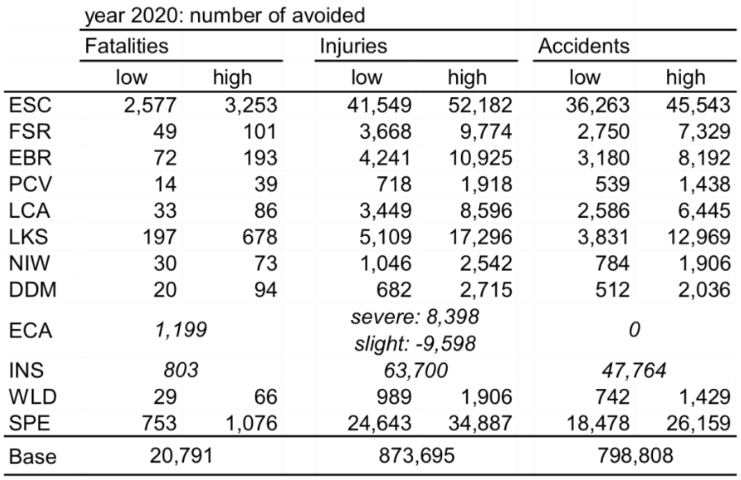
Table 5. Number of Avoided Fatalities, Injuries, and Accidents for Each IVSS in Year 2010 [6]



	year 2010: number of avoided					
	Fatalities		Injuries		Accidents	
	low	high	low	high	low	high
ESC	1,914	2,240	32,792	38,265	24,594	28,698
FSR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
EBR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PCV	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LCA	2	11	264	1,189	198	892
LKS	56	149	1,420	3,784	1,065	2,838
NIW	2	10	87	367	66	275
DDM	4	13	153	367	114	275
ECA	*1,955*		*severe: 13,691* *slight: -15,647*		*0*	
INS	*n.a.*		*n.a.*		*n.a.*	
WLD	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
SPE	77	119	2,405	3,463	1,804	2,597
Base	33,895		1,409,415		1,081,627	

Note: "Low" and "high" refer to penetration extent, related to the absence or presence of incentives.

Table 6. Number of Avoided Fatalities, Injuries, and Accidents for Each IVSS in Year 2020 [6]



	year 2020: number of avoided					
	Fatalities		Injuries		Accidents	
	low	high	low	high	low	high
ESC	2,577	3,253	41,549	52,182	36,263	45,543
FSR	49	101	3,668	9,774	2,750	7,329
EBR	72	193	4,241	10,925	3,180	8,192
PCV	14	39	718	1,918	539	1,438
LCA	33	86	3,449	8,596	2,586	6,445
LKS	197	678	5,109	17,296	3,831	12,969
NIW	30	73	1,046	2,542	784	1,906
DDM	20	94	682	2,715	512	2,036
ECA	*1,199*		*severe: 8,398* *slight: -9,598*		*0*	
INS	*803*		*63,700*		*47,764*	
WLD	29	66	989	1,906	742	1,429
SPE	753	1,076	24,643	34,887	18,478	26,159
Base	20,791		873,695		798,808	

Note: "Low" and "high" refer to penetration extent, related to the absence or presence of incentives.

The above estimates are then used to compute benefit-cost ratios, with monetary values assigned to each type of event. Various other direct and indirect costs are also factored in, including indirect costs arising from the traffic congestion caused by an accident. The results of the cost-benefit analysis are reported in Table 7. Note that the cost-efficiency of a technology can increase, decrease, or remain unaffected by the penetration rate.

Table 7. Synopsis of Benefit-Cost Ratios [6]

	2010		***2020***	
	Low	**High**	**Low**	**High**
ESC	4.4	4.3	3.0	2.8
FSR	n.a.	n.a.	1.6	1.8
EBR	n.a.	n.a.	3.6	4.1
PCV	n.a.	n.a.	0.5	0.6
LCA	3.1	3.7	2.9	2.6
LKS	2.7	2.7	1.9	1.9
NIW	0.8	0.9	0.7	0.6
DDM	2.5	2.9	1.7	2.1
ECA	2.7		1.9	
INS	n.a.		0.2	
WLD	n.a.	n.a.	1.8	1.6
SPE	2.2	2.0	1.9	1.7

Note: “Low” and “high” refer to penetration extent, related to the absence or presence of incentives.

Challenges and Research Opportunities

Certainly, the automotive field remains interesting to control engineers due to an abundance of problems where the model-based approach can make a difference, provided we manage to find good models and suitable control design techniques.

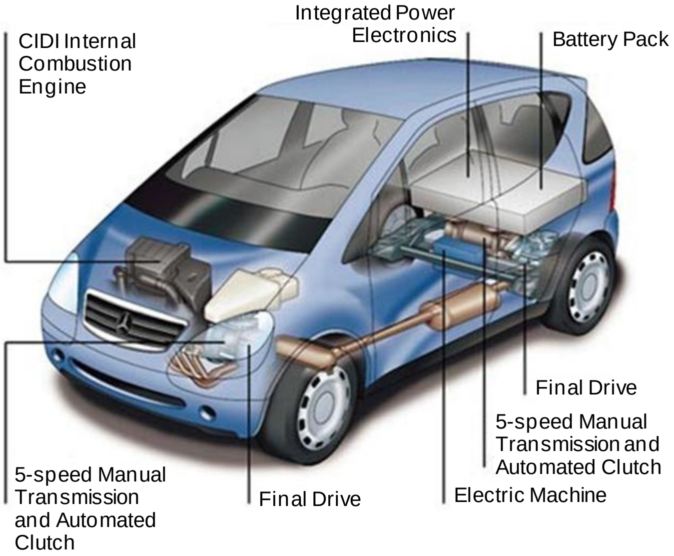
Electric vehicles (EVs) and hybrid electric vehicles (HEVs) are designed, prototyped, and produced in a variety of configurations. Almost every classical carmaker has an HEV project (even Ferrari has started its own “green” 599), and new companies like Tesla Motors aim their efforts directly at all-electric sport cars with incredible speed and mileage performances. The possible architectures of the vehicle (series or parallel configurations, four independently motored wheels, active differential, energy recovery with supercapacitors or flywheels, and so on) suggest a variety of problems, subproblems, and possibilities for innovation. Think of the general issue (sometimes called *energy source fragmentation*) of coordinating the different power sources (batteries, fuel, regenerative braking, solar panels) so as to trade off between autonomy and performance with the constraint of maintaining a reasonable state of charge (SOC) of the battery.

Source: Toyota

Figure 4. The Toyota Prius.

Performance goals can be cast in the form of power split control. Although engine development is pointing toward downsizing for minimizing fuel consumption, coupling it with an electrical motor greatly improves driveability and gives a very small engine the feel of a much larger one, appealing to the driver looking for low CO_2 emissions. Yet another variation on the theme is designing controllers that yield good fuel economy during unknown driving cycles without conflicting with driver aspirations in terms of driving fun; additional challenges come in the form of constraints on powertrain activity, such as Stop&Start functionality or dual-clutch gear shift.

The battery management system (BMS) is mandatory since damaged cells in a battery pack cannot simply be replaced with fresh ones, and this makes the battery one of the costliest and most delicate car components. The BMS objective is to maintain the health and safety of the battery pack through careful charge, discharge, measurement, and estimation to guarantee the affordability of the entire vehicle system. An interesting component of any BMS is a virtual sensor: the SOC estimator. Indeed, although batteries are ubiquitous as the core power source/storage system in small modern electronic devices ranging from cell phones to power tools, in large power grids, and in HEVs, one of the most difficult tasks in battery control applications is the correct estimation of the SOC. This is true for two reasons: first, battery charge and discharge states are definitions based more on manufacturer specifications than on an effective and universally accepted index; second, measuring such an index is difficult because of the highly nonlinear behavior of the battery during operation.



Source: Daimler

Figure 5. The Mercedes-Benz M-Class HyPer, a new hybrid concept vehicle.

Simple voltage-based charge gauges can be cost-effective for small toy rechargeable cells, but definitely not for the $30,000 battery pack of the Tesla Roadster, which requires a dedicated SOC estimator to accurately and reliably measure the health status of every single lithium-ion cell on board. The new-generation SOC virtual sensors are based on an electrochemical mathematical model of the single cell and extended Kalman filters for current/voltage feedback SOC estimation. In particular, for lithium-ion cells, the lithium concentration inside the two electrodes is of great interest not only because this value is closely related to the SOC, but also because the ability to estimate an excess or shortage of this concentration can avoid early aging and prevent battery malfunctions and safety hazards.

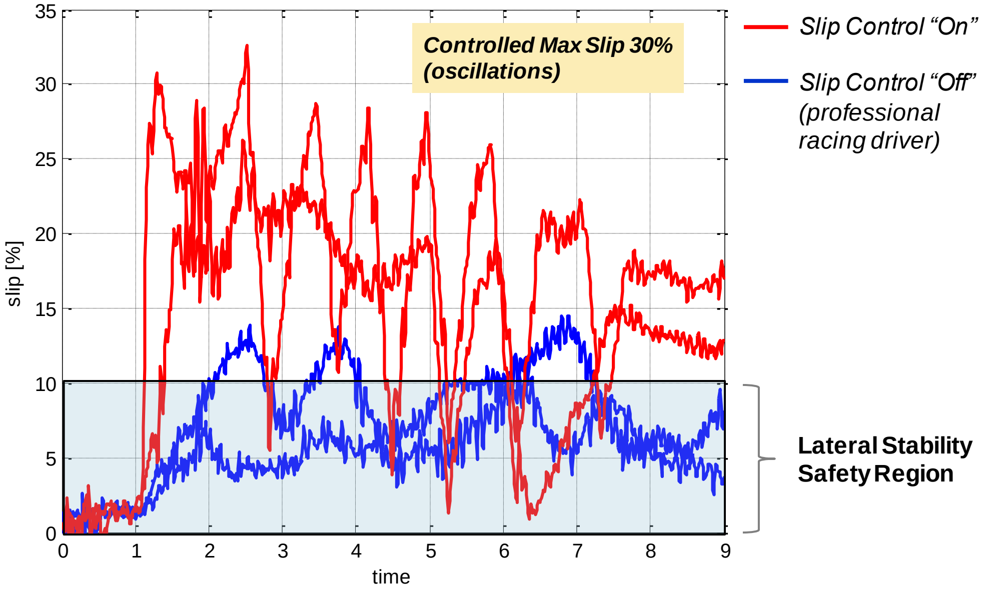
Battery packs composed of thousands of cells connected in series and in parallel have a global state of health equal to that of the weakest cell in the group because damaged cells cannot simply be replaced with new ones. Therefore, ensuring the equalization of the cell-to-cell SOC and maintaining the entire pack in good condition with respect to temperature, stress, and aging is one of the major challenges for hybrid vehicle control applications. Indeed, extended Kalman filtering of large-scale systems (derived from distributed parameter models) can be one of the most effective control tools for solving such a problem.

As mentioned earlier, the camshaft can be replaced with variable valve actuators, allowing for electronically controlled variable valve timing. This new generation of engines greatly improves on the conventional camshaft by better balancing the competing criteria of idle speed stability, fuel economy, and torque performance. VVAs are already used in production vehicles, but they need further improvement, for example, in the area of impact velocities between the valve, valve seat, and the actuator itself, which must be reduced to avoid excessive wear on the system and ensure acceptable noise levels. Another area of improvement is the opening and closing of the valves, which must be both fast and consistent with the strokes to avoid collision with the pistons and reduce variability in trapped mass.

Numerous control engineering challenges can be found working with the machinery on motorbikes or, more generally, on tilting vehicles. These vehicles (including electric versions), which are increasing in popularity because of their urban agility, are commonly found in two-wheeled versions but are now also commercially available in three-wheeled versions such as the Piaggio MP3 (see Fig. 6) and have been prototyped in four-wheeled versions. Estimation and control of the roll angle is a difficult problem, especially with low-cost inertial sensors; and with only two wheels (and sometimes only one in wheelie and stoppie maneuvers!), the problem of estimating the velocity of the bike is even more arduous so that traction control and ABS still provide challenging opportunities for improvement (see Fig. 7). According to specialists, though, the ultimate control problem is active yaw-roll control by coordination of brakes and traction control, which is extremely challenging since the system is not completely controllable.

Source: www.gizmag.com

Figure 6. A three-wheeled tilting vehicle.



Source: Politecnico di Milano

Figure 7. A motorbike TC in production features only raw limitations of slip peaks.

The development of new low-cost components (sensors, actuators, and microprocessors) will sustain control system market penetration and possibly the development of more sophisticated and effective control algorithms, typically characterized by significant computational loads. Nowadays the complexity of automotive control software is not related to the algorithm and its code but more often to its data, that is, the large and ever-growing number of (larger and larger) look-up tables used by gain-scheduled controllers. Further, these large tables have to be filled with numbers through lengthy calibration procedures. Thus, opportunities exist not only for reducing the use of look-up tables by means of different control algorithms, but also for devising better calibration/optimization algorithms and tools to fill the look-up tables, possibly online, during experiments on the test bench or the vehicle, rather than in the intervals between experiments, which is the current practice.

Another aspect to be considered is the need for validation and verification (V&V) procedures behind any control engineering achievement in the automotive field and the relative proportions of the various competencies required. According to one interview, “control engineering” accounts for only 25% of the production effort; software implementation and integration accounts for 30% and validation and testing for 45%—but the proportions of the latter two activities are expected to decrease whereas the proportion of effort devoted to control engineering is expected to increase. One specialist noted a preference for software being written by control engineers rather than by computer engineers, but this is seldom the case. The reason for this may be a (cultural) barrier on the part of control engineers, which can be partially overcome by a deeper awareness of the specific V&V tools now available, as well as by the availability of popular control design packages. On this same “software side” of control engineering, another challenge is presented by the rapidly growing complexity of the systems, which is exacerbated by the presence of legacy systems developed over the years. As a consequence, it is not unusual that new control algorithms, rather than being appropriately embedded into the existing code, are more or less added to it. To cope with this problem, efforts are under way in the automotive industry to establish an open and standardized automotive software architecture, notably AUTOSAR (AUTomotive Open System ARchitecture), that will “create a basis for industry collaboration on basic functions while providing a platform which continues to encourage competition on innovative functions“, e.g. [1] and [7]. In Fig. 8, notice the boxes on sensors and actuators and think of the “application software component” as the piece of code containing the control algorithm.

Conclusions

The role of control technology in automotive vehicles and infrastructure will continue to widen as a necessary consequence of societal, economic, and environmental requirements. The application area will attract attention from control scientists and specialists not only for the difficult problems that need to be solved, but also because of the high volumes of production and the large number of players (from global automakers to local or specialized ones, suppliers, developers, and so on) in search of innovation and in competition for market share. However, again because of the large volumes, control experts will have to pay more attention to the entire software development cycle, since validation and verification, as well as calibration and maintenance, are crucial and sometimes very expensive items for this industry. An insufficient awareness of those aspects may slow penetration of our concepts and methods into this area, so integral to our current way of life.

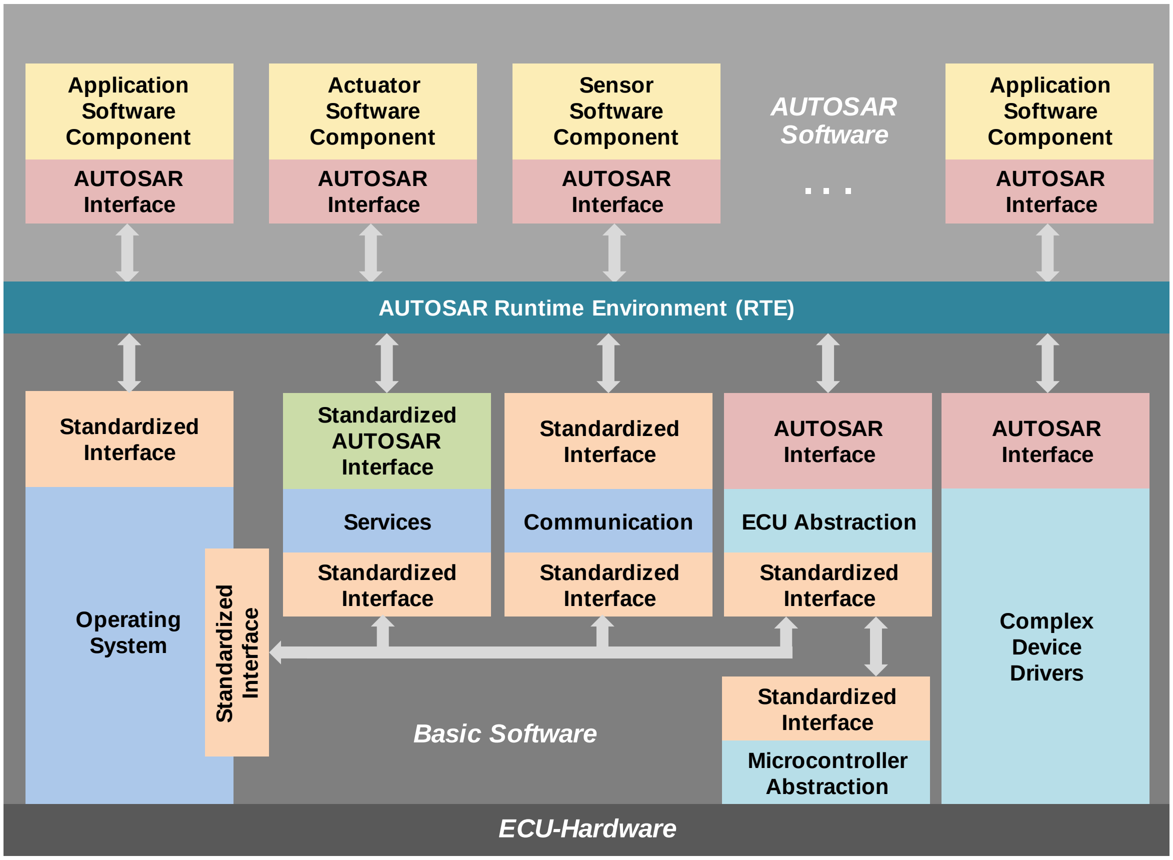


Figure 8. AUTOSAR software architecture.

Acknowledgments

Initial discussions that helped shape this report were held at the Berchtesgaden workshop with the following group members: Juergen Ackermann (DLR), Ken Butts (Toyota), Carlos Canudas-de-Wit (CNRS), Luigi Glielmo (Università del Sannio), Ilya Kolmanovsky (University of Michigan), Boris Lohmann (Technical University of Munich), and Greg Stewart (Honeywell). This work also includes direct and indirect contributions by many others besides those in the working group: Paolo Coeli (Centro Ricerche FIAT), Erik Coelingh (Volvo Car Corporation), Marika Di Benedetto (Università dell'Aquila), Paolo Falcone (Chalmers University), Raymond Freymann (BMW Group), Ruggero Frezza (M31, formerly at Università di Padova), Davor Hrovat (Ford Motor Co.), Mrdjan Jankovic (Ford Motor Co.), Jan-Ola Olsson (Volvo Car Corporation), A. Philips (Ford Motor Co.), Sergio Savaresi (Politecnico di Milano), Ralf Schwartz (AUDI), Malcolm Smith (University of Cambridge), C. Stephens (Ford Motor Co.), Tariq Samad (Honeywell), and E. Tseng (Ford Motor Co.). We wish to thank Luigi Iannelli (Università del Sannio at Benevento) and new Ph.D. graduates Angelo Palladino, Giovanni Palmieri, and Carmelo Speltino for useful discussions and reading.

Selected recommendations for research in automotive control:

- Powertrain architectures with multiple power sources are becoming increasingly popular; these will require sophisticated coordinated control approaches to manage the heterogeneous power sources.
- Correct estimation of the state of charge of a battery is one of the most difficult and important research needs in battery management systems for electric and hybrid-electric vehicles.
- Motorbikes and tilting vehicles represent an emerging and exciting opportunity for control technology, especially for active yaw-roll control.

References

[1] ETAS Group. The ECU Tool Company: Standardization and Partnerships in the Automotive Software Industry [Online], 2007. Available at http://www.imhtwk.de/resources/ETAS+Automotive+Standards+and+Partnerships.2.2-c.pdf.

[2] J. Pereira (ed.). "Monitoring and Control: Today's Market and Its Evolution till 2020, " Luxembourg: Office for Official Publications of the European Commission, 2009.

[3] J.B. White. "One billion cars," *The Wall Street Journal* [Online], April 17, 2006. Available at http://online.wsj.com/public/article/SB114487401909024337-ouwLdesvUMPaejrsk_WhxkaZzNU_20060516.html?mod=tff_main_tff_top.

[4] R.N. Charette. "This Car Runs on Code," *IEEE Spectrum,* February 2009.

[5] Taiwan External Trade Development Council. "Automobile Components & Auto Electronics Industry: Analysis & Investment Opportunities," January 2008.

[6] H. Baum, T. Geißler, U. Westerkamp, and C. Vitale. Cost-Benefit Analyses for Stand-Alone and Co-operative Intelligent Vehicle Safety Systems, version 2, report D6 within eImpact, Information Society and Media project funded by the European Commission, 2008.

[7] Autosar Technical Overview [Online]. Available at http://www.autosar.org/index.php?p=1&up=2&uup=0.

Related Content

The *Impact of Control Technology* report also includes more than 40 flyers describing specific "success stories" and "grand challenges" in control engineering and science, covering a variety of application domains. The ones below are closely related to the topic of this section.

Success Stories

- Active Safety Control for Automobiles – *L. Glielmo*
- Automated Manual Transmissions – *L. Iannelli*
- Control for Formula One! – *M. Smith*
- Coordinated Ramp Metering for Freeways – *M. Papageorgiou and I. Papamichail*

Grand Challenges

- Advanced Driver Assistance Systems Through Massive Sensor Fusion – *L. Glielmo*
- Vehicle-to-Vehicle/Vehicle-to-Infrastructure Control – *L. Glielmo*

These flyers—and other report content—are available at http://ieeecss.org/main/IoCT-report.