# A state-of-the-art survey on vehicular mechatronics focusing on by-wire systems.

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**Abstract**

This report is the result of a survey of the current state of the art/ practice in vehicular mechatronics. It summarizes a large quantity of scientific papers and theses, as well as white papers and field trips to manufacturers.

Mechatronics is a multi-domain discipline which is the result of the evolution of the single-domain engineering disciplines mechanics, electronics, information processing and control. Mechatronics is central for most new innovations in automotive products; "according to manufacturers statements, about 90% of all innovations for automobiles are due to electronics and mechatronics" [41]. The consequence of this is that vehicular mechatronics has become an important field of research.

Since this is an incredibly broad field of research, the focus of this report has mainly been on brake and steering systems but the report also covers a wider more general scope of systems. The report covers a wide range of subjects within vehicular mechatronics, e.g. everything from legislative requirements to actual prototypes.

One of the conclusion drawn in this report is that there is a lack of research with a more holistic approach to the systems. Most research only treat individual systems and omit the level of integration and interplay between subsystems and engineering domains which is typical for modern vehicles. There is also a lack of result validation in real conditions; most research are only evaluated through software simulations or in best case with hardware-in-the-loop simulations. Another problem is that most research focus on single aspects like e.g. fuel consumption when there is a lot more properties which need to be taken into account.

# Contents

# Abbreviations

| Abbreviation | Explanation |
|---|---|
| ABS | Anti-lock Brake System |
| ACC | Adaptive Cruise Control |
| AFS | Active Front Steering |
| ASIL | Automotive Safety Integrity Levels |
| ATC | Automatic Traction Control |
| AUTOSAR | AUTomotive Open System Architecture |
| CAN | Controller Area Network |
| CBIICS | City-Bus Information Integrated Control System |
| CMM | Capability Capture Model |
| CMMi | Capability Capture Model Integration |
| CPU | Central processing unit |
| DAS | Distributed Application Subsystem |
| DC | Direct Current |
| DD | Deep Discharge |
| DECOS | Dependable Embedded Components and Systems |
| E/E | Electrical/Electronical |
| ECU | Electronic Control Unit |
| EHPS | Electrohydraulical Power Steering |
| EMB | Electromechanical Brake |
| EMS | Electromechanical Power Steering |
| EPA | Environmental Protection Agency |
| EPG | Exhaust Pressure Governor |
| EPS | Electrically Assisted Power steering |
| ESP | Electronic Stability Program |
| ETA | Event Tree Analysis |
| EV | Electric Vehicle |
| FAA | Front Axle Actuator |
| FCV | Fuel Cell Vehicle |
| FEM | Finite element method |
| FIR | Finite Impulse Response |
| FMEA | Failure Mode and Effects Analysis |
| FO | Fail-Operational |

| | |
|---|---|
| FS | Fail-Safe |
| FSLI | Fail-Silent |
| FTA | Fault Tree Analysis |
| FTP | Federal Test Procedure |
| FTT-CAN | Flexible Time-Triggered communication on CAN |
| FUDC | Federal Urban Driving Schedule |
| GM | General Motors |
| HA | Hazard Analysis |
| HEV | Hybrid Electric Vehicle |
| HIL | Hardware-In-the-Loop |
| HPS | hydraulic power steering |
| HRB | Hydrostatic Regenerative Brake System |
| HWA | Hand Wheel Actuator |
| IDIOM | Integrated Design and Optimization of Mechatronic Products |
| ISO | International Organization for Standardization |
| KTH | Kungliga Tekniska Högskolan |
| MD | Micro Discharge |
| MEMS | Microelectromechanical systems |
| MR | Magnetic Responsive |
| MTTF | Mean Time To Failure |
| NEDC | New European Driving Cycle |
| NVH | Noise, vibration, and harshness |
| OASIS | Optimization of Auxiliary Systems In hybrid heavy vehicleS |
| OEM | Original Equipment Manufacturer |
| PLA | Product Line Approach |
| RAMS | Reliability, Availability, Maintainability, Safety |
| RBS | Regenerative Brake System |
| SAE | Society of Automotive Engineers |
| SEI | Software Engineering Institute |
| SIL | Safety Integrity Level |
| SBA | Simulator Brake Actuation |
| SOC | State Of Charge |
| TCS | Traction Control System |
| TFD | Tactile Feedback Device |
| TMC | Tandem Master Cylinder |
| TMR | Triple Modular Redundancy |
| TTCAN | Time-triggered CAN |
| VEB | Volvo Engine Brake |
| VCB | Volvo Compression brake |
| VDI | Verein Deutscher Ingenieure |

# Chapter 1

# Introduction

## 1.1 General Overview

The consequent evolution of the single-domain engineering disciplines mechanics, electronics, information processing and control is merged into the multi-domain discipline called "mechatronics[1]". However, mechatronics is not just the design of systems incorporating these disciplines, it's rather their intelligent mutual interaction and integration. According to [95], the development of mechatronic systems involves finding an optimal balance between the basic mechanical structure, the implementation of sensors and actuator, the automatic digital information processing and overall control, whose synergy results in innovative solutions. Applying control strategies is a core feature of mechatronic products. Also, as described in chapter 3, a new level of safety diagnosis and fault tolerance needs to be considered.

Due to the wide scope of mechatronics as a holistic engineering discipline, its field of application and a corresponding list of examples is broad. However, some examples of mechatronic products are for instance computer hard drives, service robots and digital cameras. Furthermore, mechatronics also spans the component level; besides integrated hydraulic or pneumatic servo drives, one can also refer to automatic gearboxes, magnetic gearings and MEMS as mechatronic products.

According to Dieterle [13], the main drivers for the next generation of mechatronic products are the so-called "market pull" (i.e. market requirements) and "technology push" (technological trends). He points out some trends up to the year 2020: New products shall be cheaper, smaller and provide advanced functionality with software dominating function and quality of these systems. Furthermore, as

[1] The term mechatronics was first used by the Japan based Yaskawa Electric Corporation in 1969, [28].

electrical/electronical (E/E) systems will successively replace mechanical/hydraulic systems, Moore's law (performance of electronic circuits doubles every 18 months) will stay valid. Besides, Dieterle states that the wish for physical mobility will remain dominant (despite Internet, Virtual Reality, etc.) and that the customers require more individualized products according to their specific wishes and needs.

This report is developed within the KTH ("Kungliga Tekniska Högskolan", Royal Institute of Technology) projects *OASIS* (Optimization of Auxiliary Systems In hybrid heavy vehicleS) and *IDIOM* (Integrated Design and Optimization of Mechatronic Products). It seeks to give an overview of current technologies in the vast field of automotive mechatronics. Therefore, not only the state of art is covered but also the current state of practice.

## 1.2 Vehicular Mechatronics

The last section gave a quick overview on mechatronic systems. However, it did not yet discuss the field of vehicular mechatronics in detail, although this area is probably one of the more extensive ones. Isermann writes in [41] that "according to manufacturers statements, about 90% of all innovations for automobiles are due to electronics and mechatronics".

Automotive mechatronics is a driving factor for the development of new vehicle features as well as it pushes the general development of mechatronic systems. Literatures e.g. [40], refer to the anti-lock brake system (ABS) as the first mechatronic product in vehicles, introduced by the Robert Bosch GmbH in 1978. Another well known early example is the automatic traction control (ATC) also termed as traction control system (TCS)[2]. Yet another well established mechatronic product in vehicles is the mechatronic suspension, which was introduced in 1999 by Mercedes. One other example would be the common rail injection for Diesel engines, which uses piezoelectric injectors for precise high pressure diesel injection into the engine (1997).

Among more recent developments are for instance the second generation of automatic motor stop systems (2006, series use from 2008), which shuts down the engine whenever the car is at standstill to save fuel consumption. By means of a so-called integrated starter-generator the engine can be restarted in shorter time compared to conventional starters. Another field which makes use of the mechatronic integration can be found in the driver assistance area: the so-called adaptive cruise control (ACC) regulates the vehicle's speed according the possibly slower traffic ahead. In

[2]The ATC/ TCS feature is also known by even more names, in use by the individual car manufacturers. Popular alternatives are *ASR* (Mercedes, Volkswagen), *DTC* (BMW), *TRC* (Toyota), *TCSS* (GM), and *TRACS* (Volvo)

today's systems (from around 1998) the velocity is not only adjusted by controlling the engine throttle but also by actively utilizing the vehicle's brakes autonomously.

The value of the electronic and mechatronic components of today's cars is about $20-25\%$ of the total price, with a tendency towards $30-35\%$ in 2010. A higher-class passenger car contains about 2,5 km of cables, about 40 sensors, $100-150$ electromotors, commonly four bus systems with over 2500 signals and $45-75$ micro-ECUs (Electronic Control Unit) [41].

## 1.3 Scope Definition

This report has a rather broad scope, covering all kinds of mechatronic systems in vehicles, however it also focuses more in detail on two mechatronic systems, the first being as the consequent continuation of the more and more complex ABS and ESP (Electronic Stability Program) function, mechatronic brake-by-wire system. The other mechatronic system to be discussed more in detail are mechatronic steering systems. While hydraulic assisted power steering has been in use since the 1940s, electrically assisted power steering, EPS only goes back to around 1996. The parallel combination of electrical and hydraulic power steering in larger cars can be used for automatic parking, among others, [110]. A more recent development is the so-called active front steering (AFS), where a certain driver steering demand can be superimposed by an electrically controlled steering angle so that higher dynamic steering is possible.

## 1.4 Requirements

Innovation in the field of vehicular mechatronics is often driven by demands on higher safety, lower costs, and higher performance. The public's increasing environmental awareness as well as stricter legislation puts demands on energy efficiency and reduction of emissions.

The introduction of safety systems such as seatbelts, airbags, or anti-lock brakes has most likely saved thousands of lives and lowered the consequential damage for society. This motivates further research in this very area. Demands on cost and performance are mainly due to the steadily increasing costumer expectations as well as the economical strive for revenue.

# Chapter 2

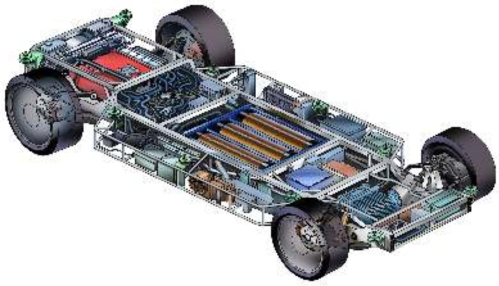
# Products/Prototypes

## 2.1 Vehicles

Full-by-Wire vehicles are still only in the concept level, and none of this kind of vehicles has been produced yet, although the concept of a Drive-by-Wire car is not new. During the early 1990s the Swedish automobile company SAAB built a prototype Drive-by-Wire car based on a SAAB 9000 with a joystick as steering input [9], [87]. The prototype was part of the European Prometheus research project. [109].

Another well known Full-by-Wire vehicle concept is the GM (General Motors) Hy-wire, see Figure 2.1a. The Hy-wire is a fully functioning concept car which uses by-Wire technology for all of its subsystems. systems. The body of the car is interchangeable since the chassis with a height of 11 inches contains most of the electronics and mechanics used to control the vehicle, see Figure 2.1b. The by-wire system also allowed the design engineers to free up a lot of space in the driver/ passenger compartment as well as made it easy to switch between left- and right-hand drive. The vehicles power plant is a hydrogen fuel cell capable of delivering 94 kW power continuously. The concept was first presented in 2002 and the overall project goal was to have such a car in production by 2010, which apparently failed as there is no car on the market today. Other GM concepts, like the Sequel, use technologies such as fuel cells which were originally developed for the Hy-wire concept car [25], [81].

(a) Picture of Hy-wire interior.



(b) Hy-wire chassis.

Figure 2.1: GM Hy-wire. Images courtesy of GM.

## 2.2 Braking

### 2.2.1 General Overview of Electromechanical Brake Systems

Electromechanical brake systems (EMB) are based on electromechanical actuators and communication networks instead of conventional hydraulic or electrohydraulic devices. They can increase comfort of the vehicle and decrease the cost associated with design, manufacturing, assembly, and maintenance. EMB systems can also eliminate the environmental concerns caused by the oils in hydraulic systems. EMB systems offer easy connection with other vehicular systems, enabling better integration with vehicle traction and stability control. They can also provide better control of the pedal stiffness, the vehicle stability, and the brake force distribution. Other advantages of the EMB systems are the elimination of complex and heavy mechanical or hydraulic parts, and enhanced diagnostic capabilities of the braking system. Further merits are the easier adaptation of assistance systems (e.g. the anti lock system or the electronic stability program (ESP)) without any additional mechanical or hydraulic components. Also, the efficiency and stability of the brake control improved due to the quick and accurate generation of brake torques by electric motors [112].

### 2.2.2 Regenerative brake systems

Probably one of the most important applications of vehicular mechatronics can be found in hybrid vehicles and regenerative brake systems. Studies have shown that a significant fraction of energy is consumed in braking especially when the vehicle is driven in cities where a stop-and-go driving pattern is common. It is calculated that in a typical driving cycle, a city bus runs 25% of the time at idle speed, 69%

of time is used for acceleration and deceleration, and only 5% of the time the bus travels at constant speed [92]. The importance of regenerating brake energy shall be demonstrated even more by considering the following results from different studies.

In the FTP75 (Federal Test Procedure) urban driving cycle it is shown that about 40% of the kinetic energy is consumed by braking [24]. In another study it is shown that City buses with a regenerative braking system (RBS) can reduce the fuel consumption by 15%-20% in a typical urban driving cycle [116]. The consumed energy during braking is reported as about one third up to one half of the energy of the vehicle's power plant for a passenger car in the EPA75 (Environmental Protection Agency) driving cycle [23]. According to another study, while braking a HEV (Hybrid Electric Vehicle) city bus, nearly 53% of the total kinetic energy is wasted as heat energy [92].

In [2], it is shown that the fuel efficiency can be increased by 20% to 50% for a passenger car in the FUDS (Federal Urban Driving Schedule) driving cycle, (depending on motor size) by using a RBS. Another estimation states that 59% of the energy can be saved when using regenerative brakes in city buses [108]. Some older studies show less increase in efficiency, such as 15% [99] and 4%-19% [76] depending on the powertrain modules applied and the regenerative model used for the predictions in the FUDS cycle. However, even that number corresponds to a considerable amount of energy. In terms of emissions, urban transport is estimated to account for up to 16% of the global $CO_2$ emission, of which up to 40% is due to energy dissipated in friction brakes [44]. It has been shown that the driving range of electric vehicles (EV) can be increased by 8%-10% if using a RBS [115], so that for pure innercity driving the driving range is estimated to be extended by 14% to 40% [55]. In [113] it is shown that for a hybrid electric city bus in China, the fuel economy can be improved from 9.6kg/100km to 7.9kg/100km, while the battery SOC (State Of Charge)is kept around 47%.

One important factor which needs to be considered when designing hybrid vehicles and their subsystems is the price factor. For example, a hybrid city bus costs $200,000 more than the conventional version [17], thus the usage of new systems to increase the fuel efficiency should be available at a reasonable price. It should be noted that while regenerative braking has the potential of saving fuel, it may also do more harm than good as a result of additional weight, a less than ideal charge/discharge efficiency on the batteries or the storage flywheels, as well as the limited fraction of the entire driving cycle when regenerative braking can be utilized. If regenerative braking can have a net benefit, it would be on a heavy vehicle such as a municipal bus because of the frequent stop and go requirements due to both traffic lights and passengers [108].

### 2.2.3 Design aspects

There are two basic concerns in the brake system design for EVs, HEVs and FCVs (Fuel Cell Vehicle). The first one (1) is to properly applying a braking force on front and rear wheels to quickly reduce the vehicle speed, and meanwhile, maintaining the vehicle traveling direction stable and controllable through the steering wheel on various road conditions. The other one (2) is to recover as much braking energy as possible in order to improve the energy utilization efficiency, especially while driving in a stop-and-go pattern in urban areas [14], [16], [111].

To attain the first point and by considering the fact that safety is the most important factor in braking systems, brake systems with mechanical backup is still preferred over by-wire systems since they have been proven to be reliable. Thus the brake system in hybrid electric vehicles will be laid out as a so-called hybrid brake system. There are different configurations for such hybrid brake systems. As for instance, a parallel brake system, which retains current mechanical systems, but adds on electrical regenerative brakes on the front wheels. This system is based on the conventional hydraulics brake, however the friction brake and the regenerative brake are working in parallel.

Another possible realization is series braking or the fully controllable hybrid brake system. Such a system allows control of each wheel individually as it is based on a Brake-by-Wire system. Compared to the parallel braking approach, it is able to regenerate more energy but is also more complicated [72].

When discussing RBSs in detail, they may be divided into two different systems: series braking with optimal braking feel, and series braking with optimal energy recovery [16]. A comparison of series braking with optimal braking feel, series braking with optimal energy recovery, and the above mentioned parallel braking has shown a capability of recapturing 30%, 36%, and 15%, respectively, of the overall output electric energy. These amount of energy savings in addition to other advantages of hybridization correspond to a total improvement of 32.7%, 34.3% and 19.6%, respectively, in fuel economy compared to a conventional braking system on a city bus [88].

To satisfy (2), that is recovering as much braking energy as possible, suitable power management controllers should be used in the brake system design for EVs, HEVs and FCVs. Here, the battery and super capacitors are the important components. The batteries may be used in two modes: deep discharge (DD) as in an EV, and micro discharges (MD) around an average value of the SOC e.g. 50% or 60%. The DD mode allows a pure electrical mode but limits the lifetime of the batteries. The MD mode is typical for hybrid mode driving, where it allows a more reasonable lifetime of the batteries and also an optimization of their efficiencies. Furthermore, a combination of these modes is mentioned in literature [4].

### 2.2.4 Control strategies

The control problem of the RBS in HEVs can be defined as having three main objectives. First, the driver's demand of the overall braking force according to the driver's action and the vehicle state should be identified. Secondly, the driver's demand of the braking force by distributing braking power between service brake and auxiliary brakes (e.g. retarders) should be satisfied. This is to be achieved by means of an appropriate energy management strategy for the best fuel economy without damaging the components of the vehicle. Third, the braking power distribution should be done properly by coordinately controlling the braking components' state aiming for good drivability and appropriate braking force [48].

Overall control strategies of most brake blending systems are as follows: When the demanded deceleration is little, only the auxiliary brake system is in use, e.g. the engine braking in conventional heavy vehicles. When the deceleration increases, the braking force of the front and rear shaft will be controlled according to the ideal braking force distribution curve. This distribution should follow the idea that the frictional braking force is only applied if the demanded braking force exceeds the available retardation force of the RBS. That is, depending on the amount of braking force needed, the control system will either apply the front RBS only, or a superposition of the RBS and the mechanical braking system together (considering that the totally available braking force equals the sum of regenerative braking force and mechanical braking force) [45].

A lot of research on the optimum regenerative brake strategy is currently done. These so-called power management control strategies can be divided into three main categories: fuzzy logic or neural network techniques, rule-based strategies, and static optimization methods [59]. Built upon fuzzy logic, in [114] a two-input one-output Mamdani's fuzzy inference system [62], is developed for the regenerative braking model. Also, in order to maximize the brake recuperation fuzzy control methods were used to control and distribute the torque (for the example case of stopping a city bus) between electric motors, hydraulic retarder and friction brakes [70]. Fuzzy logic has also been used in other research [57], [61], [71], [120], [118]. Apart from RBS control, fuzzy control strategies are also used for other applications like vehicle stability control in hybrid vehicles [36], [50], [51], [52], [58], [79], [122].

In [91] the Lyapunov method has been used in order to design a brake torque controller for a hybrid electric bus. Using control points on the control strategy curve as design variables, a regenerative hybrid brake system is optimized in order to regenerate more energy [46]. The brake curves show the relation of front and rear brake forces.

In [119] an agent-based power management is used to improve fuel economy. The method also extends the life cycle of the fuel cell engine by letting the fuel cell engine work within its designated operating range. Agents have a certain level of autonomy, which means they can make decisions without a central controller or commander. To achieve this, a set of rules and a control algorithm module are proposed. Furthermore, agents are able to perceive environmental changes and to respond to them. In multi-agent systems, agents can communicate mutually and work together to achieve a global objective .

Another algorithm which is reliable as well as easily applicable and has been used to enhance the energy efficiency of a front and rear wheel drive parallel HEV-Van is the so-called rule based algorithm [30]. However, this algorithm has mainly been used in the early stage of HEV system development. To improve the vehicle performance and to decrease the energy loss of the components, however, it is necessary to introduce optimized approaches so that the energy management system could distribute the demanded power more efficiently [117].

Alternative strategies for controllers are common look-up-tables [45] or so-called dynamic programming. With the latter method, a reduction of fuel consumption of 2% was achieved for a passenger car in the New European Driving Cycle (NEDC), even without predicting the driving cycle [54]. However, as for city buses the driving cycle is know before, dynamic programming can be used to efficiently switch between the two sources (combustion engine and electric motor) [47], [80]. A so-called Model Predictive Control has been used to regenerate the maximum energy during braking [18]. Genetic algorithms are another way to optimize the control strategy in hybrid vehicles [68], [83].

Besides the regenerative braking and the main brake system, another important part of a heavy vehicle's brake system is the so-called retarder, which is used to minimize pad wear, brake fading and also reduces fuel consumption. It is essential that the blending between the main brakes and the retarders gives the best braking performance in the aspects of safety, comfort, energy consumption and the like. Retarders can be primary retarders, secondary retarders and engine braking. For instance, Volvo trucks use a so-called VEB (Volvo Engine Brake), an EPG (Exhaust Pressure Governor), or the VCB (Volvo compression brake (playing with valves in the engine, using exhaust valve) as engine braking. In hybrid vehicles, the electric motor acts as an additional retarder when regenerating energy. Its main advantage is its quicker response time and that it can be controlled for better comfort.

When talking about the recovery of brake energy, it must be stated that this does not necessarily imply that the energy being recovered is electric energy. Also, not all hybrid vehicles are electric hybrids [27]. The recovery of the brake energy through a Hydrostatic Regenerative Brake System (HRB) is another alternative. These systems have some advantages over the electric regenerative system, in particular their hydraulic accumulators have considerable advantages over batteries with respect to brake energy recovery. Also, hydraulic components already in series production can be used, making it more cost efficient. Retrofitting the HRB system requires only small changes to the vehicle. In a study in [6] it is shown that the fuel consumption can be reduced by 30%. Using an energy regeneration system for bus brakes based on “the electric controlled compressed gas energy storage technology” is another way and it can save more than 10% of energy according to [121].

### 2.2.5 Brake systems in product state

In the following some examples of mechatronic brake system products are to be presented. Note that most information is obtained from the manufacturer directly and may thus be biased.

Vienna Engineering has developed a mechatronic brake system, termed the VE-mechatronic brake, shown in Figure 2.2. It is claimed that this brake system needs low electric actuation energy (for example only 5W) and low actuation force (for instance as low as 100N) depending on design specification. This brake system is self enforced and it does not have locking problems as stated by the manufacturer. It shall also be possible to use it as parking brake. The size of the VE-mechatronic brake is compatible with the conventional hydraulic brakes so that it fits in a standard wheel rim. According to Vienna Engineering the cost of VE brake system is less than conventional brakes as it does neither need any brake cylinder, booster, brake fluid nor a parking brake cable, vacuum pump and the like. As claimed it is also a suitable choice for hybrid electric vehicles in terms of brake blending for RBS. Furthermore, it can properly simulate the brake feeling for driver [84].

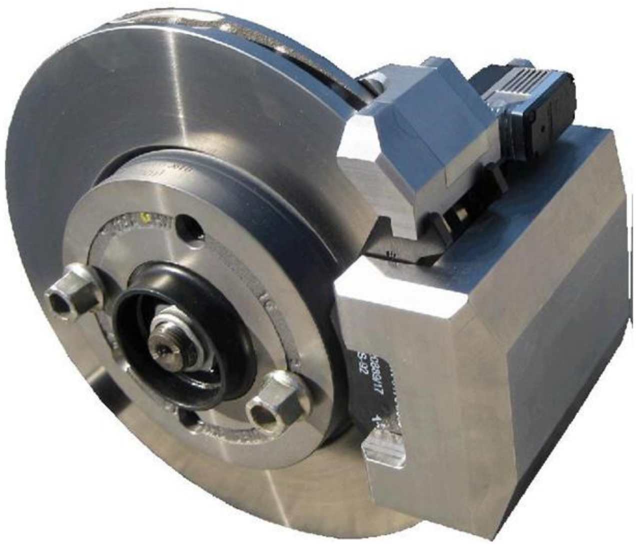


Figure 2.2: Vienna engineering brake caliper. Figure from [84].

Haldex has developed an electromechanical brake system for heavy vehicles (see Fig. 2.3 and Fig. 2.4). By using this brake system, the stopping distance of vehicles may be reduced up to 14% compared to conventional brakes equipped with electronic stability control (ESC) system. As the system is compact and available as a presetup wheel module, it can be seamlessly integrated into the existing design concepts without needing to change anything on the axles to install it. According to Haldex their system improves safety of vehicles as a better brake control and will lead to better stability control which outperforms the conventional Anti-lock Brake System (ABS). Also, the brake system can be monitored more easily. Furthermore, as the parking brake in this brake system is purely mechanical, it complies with given regulations. The noise which is present within pneumatic brake systems is reduced to large extend as well. One of the advantages of Haldex' EMB actuator is the fact that the brake is self enforcing. Doing so, the motor itself only needs little energy to activate braking by pushing the brake pad towards the brake disc and establishing contact with the latter. The actual braking/ self enforcement is achieved using the phenomenon of friction; the brake pad will follow the disc rotation and eventually wedge (using a seesaw-like construction which increases brake force). Theerfore it can be used in the today's heavy vehicles which use 24V power without changing the electrical system. The peak energy consumption is below 300W, and in steady state mode is below 5W. The life cycle costs are low, with the number of components being reduced in general. For hybrid vehicles, this brake system can increase the regenerative braking performance to regenerate more kinetic energy without risking damage to the electrical system as a consequence of electrical overload [29].

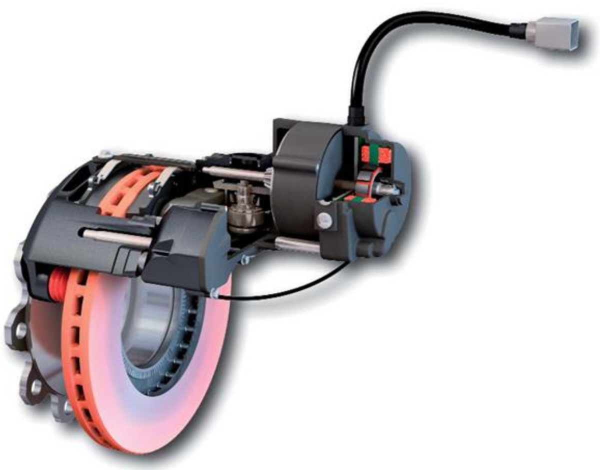


Figure 2.3: Haldex Electromechanical Brake (EMB) system. Figure from [29].

TRW Automotive developed a regenerative-capable electronic stability control system for hybrid electric vehicles which is also a good example of electrohydraulic

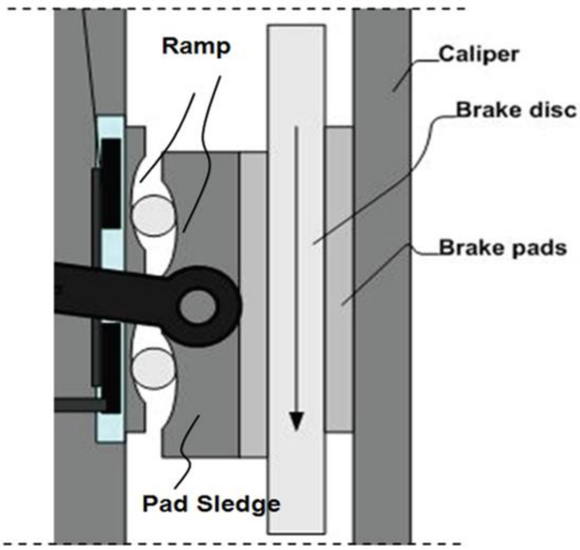



Figure 2.4: Draft showing the principle mechanism behind the self enforcing brake. Figure from [29].

brake systems (see Figure 2.5). It is fully compatible to regenerative braking in HEV vehicles without changing the pedal feel compared to conventional brakes. It is based on the common 12V system and replaces the traditional brake actuation system including boosters, master cylinders and vacuum pumps with an electro-hydraulic control unit. Moreover, the brake system enhances noise, vibration and harshness of the system and so achieves a smooth and quiet braking. The main goal to develop such systems is to have a series regenerative brake system, in order to achieve the maximum regenerative energy effectiveness. This is achieved by always using the maximum possible braking effect of the generator at each time while the friction brake only provides the remaining braking portion. The system is developed by only slightly modifying existing components and it has proven to be optimum in terms of component cost as well as development effort. A more detailed description of system functionality is given in [104].

Continental has developed an electrohydraulic combi brake system for passenger cars and light trucks. It is a combination of a conventional hydraulic brake at the front and electromechanical brake actuators at the rear. According to Continental, this system can improve the brake performance, noise and vibration, as well as it also has a good pedal feel. Since this system also has the ability of regenerative braking it is a suitable option to use in hybrid vehicles to reduce the fuel consumption and decrease the $CO_2$ emission. Fuel economy is also contributed to by reducing residual torque [11].

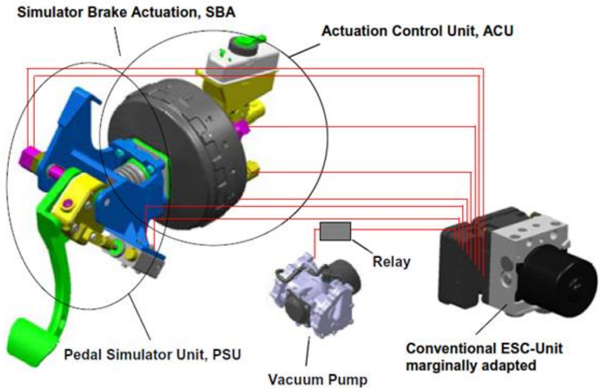



Figure 2.5: Principle sketch of the Regenerative Brake System (RBS). Figure from [104].

VDO Automotive AG is another company which has developed an electronic wedge brake system which is compliant to the common 12V power system (see Figure 2.6 and Fig. 2.7). Their brake approach is described as a modular system which is fitted to the wheels. It consists of brake pad, the wedge attached to the wedge-bearing mechanism, the mechanical power transmission between the two electric motors, and a sensor system for monitoring movement and force. During braking, a brake pad which is attached to a wedge is pressed between the brake caliper and the brake disk. Due to the rotation of the wheel, the effect of the wedge will be intensified automatically, allowing to gain almost any level of braking with only little difficulty. This system can be used as an automatic parking brake. The VDO brake system eliminates the hydraulic pipes, brake cylinder and brake boosters [69].

## 2.3 Steering

### 2.3.1 Overview of steering systems

Conventional steering systems can be divided into two categories which are the rack and pinion steering system as well as the ball and nut steering system. The latter is used for higher steering forces than the former. It is important to note that both systems are purely mechanical. The loss of steering control due to failures in the steering system like breaking or locking up the system are usually not considered for these systems, as these mechanical systems are designed with sufficient safety margins. Furthermore, the manufacturers' long experiences and given standards ensure these systems to be very reliable.

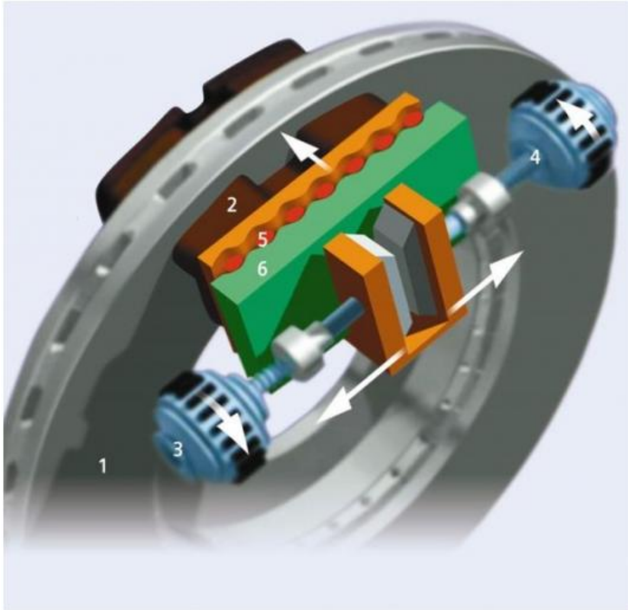



Figure 2.6: VDO electronic wedge brake (EWB). Parts: 1 - brake disk; 2 - brake pad; 3 - electric motor; 4 - electric motor; 5 - rollers; 6 - wedge-shaped inclined faces. Figure taken from [93].

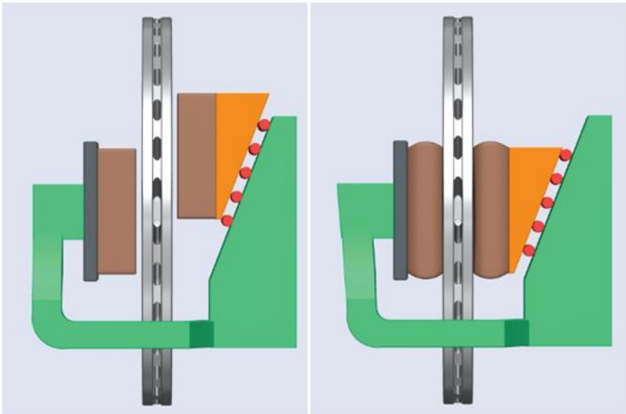


Figure 2.7: Wedge principle used in the electronic wedge brake (EWB). Figure from [93].

Modern steering systems are usually hydraulic power steering systems. These systems consist of a mechanical steering system plus a hydraulic system which usually consists of a V-belt drive hydraulic pump. Such systems are used to assist in such a way that the effort to steer the car can be reduced. In case of a failure in the hydraulic system (e.g. leakage in hydraulic lines), the only "problem" which may occur is an increase in steering effort for driver.

Because of, among others, simplifications made possible by modular design as well as possible energy saving issues, new steering systems being developed today. These systems can be divided into the three following categories: Electromechanical/Electrohydraulical power steering systems (mechanical/hydraulical systems with electrical boosting), Steer-by-Wire systems with hydraulic back up and full Steer-by-Wire systems. So-called electrohydraulic power steering systems are the same as a conventional hydraulic power steering where the hydraulic pump is driven by electrical power instead of by the vehicle engine. It can save up to 75% of energy depending on load distribution and control strategy. In the case of failure, again only the steering effort of the driver is increased. Electric power steering is a combination of a mechanical steering system with an electrical motor which, instead of a hydraulic system, boosts the steering force. It is stated that such systems can decrease the fuel consumption up to 80%. Further, these systems are more environmentally friendly than the hydraulic systems as no hydraulic fluids are necessary. Installation costs can be kept low, as the Electric power steering systems can also be used as a ready-to-install module on different cars. Like the already mentioned systems, in case of failure in the electrical system the driver will have to use more effort to steer, however, no safety issues of magnitude will occur [31]. Figure 2.8 classifies different steering systems considering the source of energy used for the actual steering. In the Figure 2.8, EAS means electric angle assisted system, HPAS means hydraulic power assisted system, EHPAS means electrohydraulic power assisted system and EPAS means electric power assisted steering system. In the electrical power assisted category, the electric motor can reduce the driver effort by applying extra torque either on steering column, pinion or rack. In the dual-pinion system, the electric motor is mounted on a seperate pinion on the rack. In the full power steering (Steer-by-Wire) category, HPS means hydraulic Steer-by-Wire system, EPS means electric Steer-by-Wire system and EHPS means electrohydraulic Steer-by-Wire system. The physical Scheme of the different steering systems is presented in Figure 2.9.

### 2.3.2 New steering systems

In future steering systems, which are currently in research, the steering column will be omitted so that there is no direct mechanical connection between steering wheel and driven wheels. In the case of certain failures within the system, this may lead to serious problems for the vehicle, requiring serious considerations in the design process of these systems. The advantages, however, are the improvement of steering comfort, the possibility to have a variable steering ratio, reduction of injuries in accidents due to the missing steering column, and better steering behavior in oversteer and understeer situations. It can also provide more design freedom of

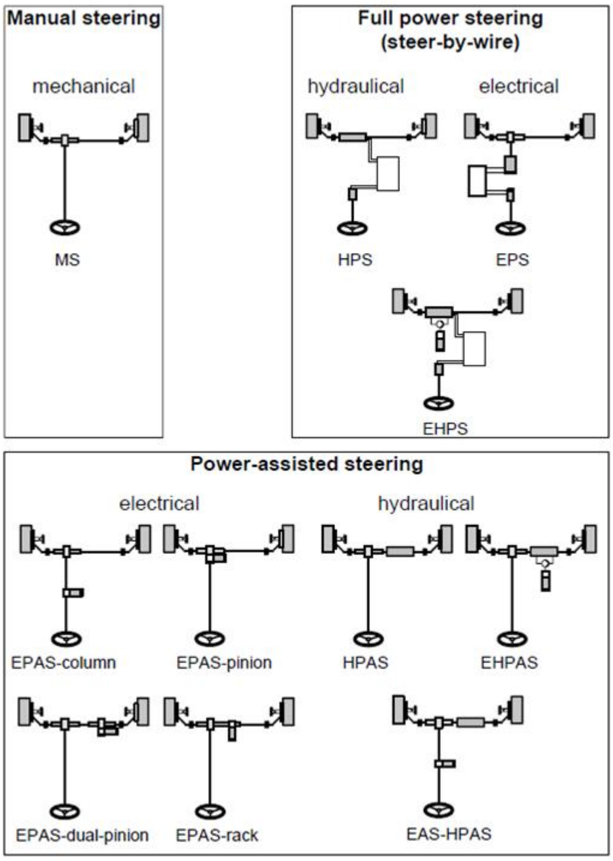



Figure 2.8: Classification of steering systems based on the source of energy and steering assist method. Figure from [37].

the engine compartment [31].

Other general benefits of X-by-Wire systems also apply to Steer-by-Wire system; for instance vehicle dynamics improvements, emission reductions, weight reductions, improvements in fuel efficiency, and improvements of NVH (Noise, Vibration, Harshness) performance [5], [56], [77].

Weight reductions are especially important when it comes to hybrid vehicles; extra weight can easily outweigh the efficiency benefits gained through hybridization. The efficiency gain by downsizing the hybrid electric power train by 30 to 40% can be totally offset by an increased weight of electrical energy storage [43].

In terms of cost efficiency Electrically Powered Hydraulic Steering is, according to [26], the best solution to apply as a combustion engine independent steering system on hybrid electric vehicles. Hydraulic power assisted steering is a proven technology, however only with very poor energy performance in the conventional

(a) Mechanical steering system

(b) Hydraulic power steering

(c) Electrohydraulic power steering

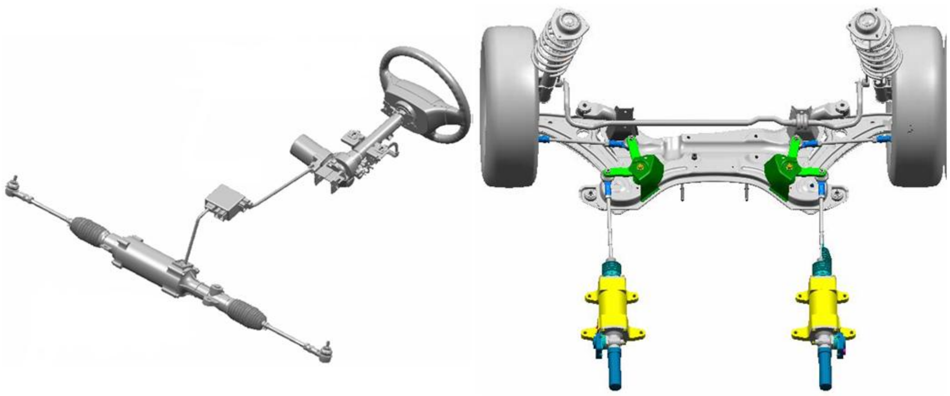
(d) Electrical power steering

Figure 2.9: Different steering systems. Figure from [31].

cases. In [106], it has been shown that by replacing the hydraulic power steering systems in passenger cars with electric power assisted steering systems one would save about 90% of the fuel consumed by the conventional hydraulic power steering system. This reduction in fuel consumption translates to a reduction of 0.3 - 0.5 l/100km. In another study on passenger cars in a FTP-75 (Federal Test Procedure) driving cycle, [107], it is shown that by using electrohydraulic power steering and electric powered steering, overall fuel consumption of the vehicle can be improved by 1% and 1,7% respectively compared to conventional hydraulic power steering systems .

Steer-by-Wire systems can be divided into two categories. The first category describes systems where the two wheels are connected with the steering rack. In contrast, the second category includes the systems in which the wheels are connected to two independent motors. The second method has the advantage that the left and right wheels are controlled independently in an optimal way [77]. Figure

2.10 illustrates both mentioned steering systems.



(a) Integrated Steer-by-Wire system (b) Independent-type Steer-by-Wire System

Figure 2.10: Different types of Steer-by-Wire systems. Figure from [77].

One main issue in using electromechanical steering systems is to simulate the steering feedback in order to provide a proper feeling to the driver. To simulate the steering feeling, four main methods are used: a model-based approach, a torque sensor-based method, a torque-map method, and a direct current measurement method. In the model-based method there is no need for a torque sensor and the force feedback is based on a disturbance observer which considers the aligning torque as the source of disturbance. In the torque-map method, a map for steering wheel torque based on different signals, e.g. vehicle velocity and steering wheel angle, is constructed. In this method, the computations for calculating torque is avoided. In the torque sensor-based method, as its name implies, a torque sensor is used. In the direct current measurement method the current which is consumed by the motor is measured to allow the produced torque to be calculated [74].

LORD Corporation produced a tactile feedback device (TFD) that uses a magneto-rheological (MR) technology which can mime the steering feeling for the driver. According to the company, the MR solution has several advantages over other types of torque generating devices (e.g. electromagnetic friction brakes or motors), for instance a smooth torque with no stick-slip or cogging is generated while also being more energy efficient [56]. The Linde Material Handling GmbH uses the LORD TFD Steer-By-Wire devices to provide tactile feedback for its Steer-by-Wire reach trucks. Replacing the hydraulic steering system with a Steer-by-Wire system enabled Linde to design a lighter vehicle with a smaller footprint and fewer parts. It also reduced electricity usage, and extended the battery life, while improving the quality of the steering feel.

There are some disadvantages with using a motor for the road feedback feeling; for instance, an oscillatory feeling, and improper and potentially dangerous acceleration of the steering wheel by the motor may occur when the driver's hands are released from steering wheel too quickly. The inherent safety problems of the motor-based active steering wheel can be eliminated by a semi-active steering wheel with two magneto-rheological brakes used for reactive torque generation [78].

### 2.3.3 Steering system products

It shall be noted that although Steer-by-Wire systems have many advantages, they have still not been put into production in cars and trucks since more proof of reliability and further development is needed. Therefore, power steering systems are usually chosen over Steer-by-Wire systems [105]. Still, there is a number of Steer-by-Wire prototype systems for road vehicles.

SKF manufactures a Steer-by-Wire plug-and-play module as shown in Figure 2.11. It can sense the change in angular position (how far the steering wheel is turned and in which direction), angular velocity and angular acceleration of the rotating shaft. This module uses several identical sets of sensors that operates independently, making it fail-safe (see also chapter 3). Its application areas include forklift trucks, harvesters, tractors, road rollers and electric carts. SKF claims that this system can save up to 60% of energy required for steering compared to conventional hydraulic steering. The module is maintenance free and there is no need for lubrication and steering torque adjustment [94].


Figure 2.11: The SKF Steer-by-Wire plug-and-play module. Figure from [94].

Delphi Corporation has produced a so-called E-steer system for passenger cars that incorporates the steering gear, electric assist mechanism and also an electronic controller. It eliminates the need of a power steering pump, hoses, hydraulic fluids, pulleys and drive belts. In the E-steer system, an electric motor is mounted onto an intermediate shaft which is attached to the rack and pinion gear system. The sensors in this system measure the steering shaft torque and steering wheel position. By using these inputs and other system variables, the amount and direction of steering assist will be determined. Delphi has also an alternative system closer to a full Steer-by-Wire system which is called Quadrasteer. In this rear steering system there is no mechanical joint between the driver and the steering subsystem [21].

Ognibene S.p.A. has developed a fully functional Steer-by-Wire driving control unit for agricultural tractors. It fulfills all practical requirements for off-road use, as well as all legal requirements for on-road use. Ognibene collaborated with TTControl-TTTech to design the bus architecture based on the Time-Triggered Protocol (TTP). They have used a distributed redundant real time system to achieve a very high degree of fault tolerance. Functional units are grouped into subsystems and each subsystem is mapped onto one or more electronic control units. There are redundant inputs from sensors, redundant outputs to actuators, and each subsystem is distributed on more than a single electronic control unit [100]. Again, see chapter 3 for details on safety and fault tolerance.

## 2.4 Other by-Wire systems

Apart from Brake-by-Wire and Steer-by-Wire systems, other X-by-Wire subsystems has been developed recently. Lindner et al.[60] describe requirements and a solution for a Shift-by-Wire system (currently in production and use today in several BMW car models) that replaces the classical mechanical Bowden-wire based system. The paper states that great weight has to be put into choosing the right shift-pattern to gain customer acceptance. Electromagnetic blocking actuators are used to give the right controller-feel and to block functions depending on the current state. The actual input sensing is taken care of with redundant digital switching Hall effect sensors and certain conditions have to be met before an input is accepted in order to prevent erroneous shifting. The input is transmitted to the ECU controlling the gearbox actuation over either of two redundant CAN-buses. Some of the advantages gained by using this system instead of more conventional ones are, as stated in the paper, increased comfort, no mechanical constraints on positioning of gearbox and lever as well as significant weight reductions.

While the above stated research introduces a gear selector for Shift-by-Wire application only, Kirchner et al. with GM Powertrain, [53], present concepts of a Full-by-Wire powertrain. That is, not only the gear shift is laid out X-by-Wire, but also a Clutch-by-Wire system is introduced. However, for the sake of the driver's convenience, the actual operating devices (gear lever and clutch pedal) remain unchanged so that the driver does not need to adapt to a new system. Moreover, as there is no mechanical connection and as the force-displacement characteristics of the devices show only little hysteresis, both pedal and gear lever may be designed only with regard to comfort purposes. Nevertheless, GM found that the haptics of a gear shift essentially needs to be velocity dependent. In this way, the driver is able to relate the shifting speed with the synchronization force and therefore it is possible to distinguish a slow upshift from a faster downshift by haptics. With respect to heavy vehicles' range-change transmission the authors stated that although the underlying concept of actuation is similar to passenger cars' single-range transmission, different aims are followed: while for the latter ones shift haptics and noise are important, for heavy vehicles mainly a driver-friendly shifting is sought. By applying a Full-by-Wire powertrain it would be possible have the advantages of both manual and automatic shifting.

A more unconventional X-by-Wire system is introduced in a paper by Nguyen et al.[73]. The so-called Observe-by-Wire system uses a force feedback system as a haptic interface to the driver to increase safety. The feedback force is calculated from a number of proximity sensors. A forklift truck where proximity sensors are mounted on the forks is used for prototyping. This allows the vehicle to sense the distance from the fork to nearby objects, which can be hard to see by bare-eye when fork has been lifted up high, and feedback it to the driver. An interesting find from the prototype is that safety as well as operating performance is increased. Further, it was found that feedback forces need to be adjustable due to that different people have different sensitivity to this kind of feedback.

# Chapter 3

# System Architecture

## 3.1 System Design

One possible classification of distributed systems is to divide them into two categories; federated and integrated. Federated systems are characterized by having a separate dedicated processing system for individual application, whereas an integrated system architecture has several applications integrated on a single or more processing units [82].

The federated architecture has historically been preferred for safety critical systems since it has a natural separation of subsystems and allows for isolation of faults and complexity management. Integrated systems, however, have the advantage of massive cost reduction as well as other benefits such as e.g. space reduction [82].

An important factor in the system architecture design for future cars is the constantly growing number of features depend on mechatronic systems. A new architecture must be versatile enough to handle the demands of the foreseeable future.

In 2005 Peti et al. [82] suggested an integrated system architecture called DECOS which supposedly provides a foundation for integrating criticality-mixed subsystems while supporting applications with high dependability requirements (up to maximum $10^{-9}$ failures per hour). The architecture builds upon a concept described as: "The complexity of a large real-time computer system can only be managed, if the overall system can be decomposed into nearly-independent subsystems with linking interfaces that are precisely specified in the value and time domain".

The DECOS architecture denotes each individual subsystem as a Distributed Application Subsystem (DAS), and an example of a such could e.g. be a Steer-by-Wire system. The architecture provides a number of core services like fault isolation and diagnosis as well as high level services like virtual networking. See Figure 3.1 for an overview of the DECOS Integrated System Architecture.

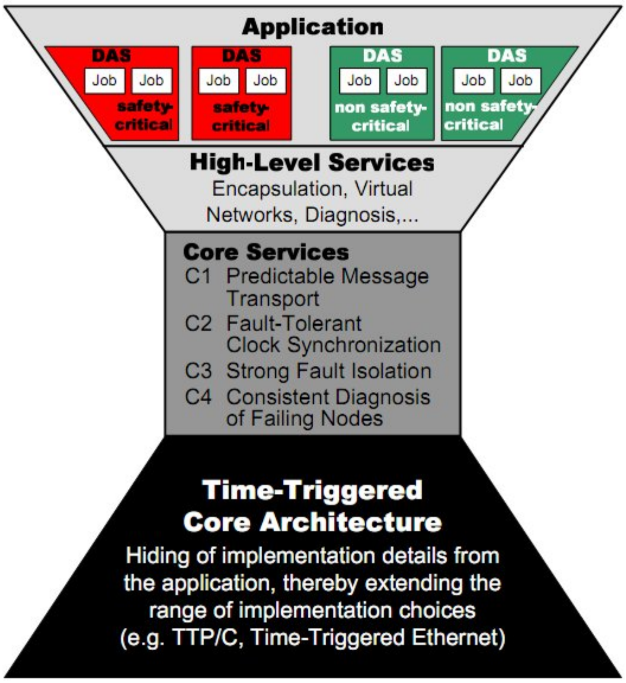



Figure 3.1: The DECOS Integrated System Architecture. Figure from [82].

The design flow specified in the architecture allows the system to be designed upon a top-down approach. See Figure 3.2 for a design flow example.

The advantage of this architecture is that a DAS is somewhat contained in its own allowed space while at the same time several DAS's can be run on the same physical ECU. This of course provides space and cost benefits compared to traditional federated systems. The isolation of the individual components also lessens the complexity in analyzing the system compared to traditional integrated architectures.

In [89], Santos et al. develop and discuss a modular control architecture applied in a small electrical vehicle equipped with X-by-Wire systems. Again, they indicate that with decoupling safety-related systems from a mechanical backup it is inevitable to have a sophisticated overall control architecture. This is also true as the performance gap between mechanical and electrical systems increased, so that the driver "cannot cope with non-assisted systems in a safe way".

As will be shown in the next section, Santos et al. apply the concept of redundancy in order to provide fault-tolerance and to make the respective systems safe. For communicating among all modular functions the FTT-CAN has been used. Here, critical nodes (i.e. those nodes which implement safety related functions as well

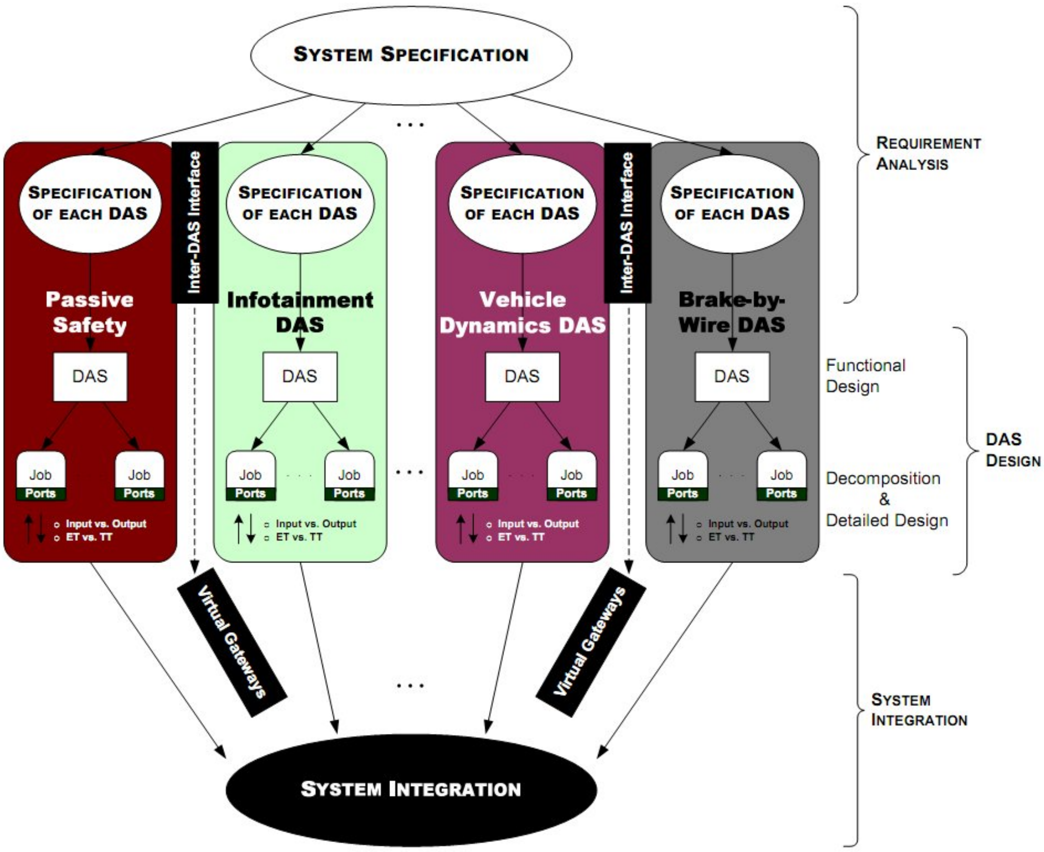



Figure 3.2: DECOS Design flow example. Figure from [82].

as the FTT-CAN master node) are implemented twofold. Non-safety-critical nodes are however not redundant but at least connected to two buses in order to tolerate bus partitioning. Also, using the FTT-CAN, jitter and end-to-end delays (which closed loop controllers are sensitive to) can be minimized imposing phase control both on the system tasks and messages. The actual control of the braking algorithm is carried out by specific ECUs interconnected by a subnetwork.

The Steer-by-Wire system is set up In a similar way. It is broken down into two distinct subsystems (steering wheel handling and haptic force feedback; and road wheel sensor interfacing and steering motor control) and also gathers data from different subsystems.

With X-by-Wire systems another important component is the energy management strategy. In the mentioned project of Santos et al. a specific ECU is devoted to control the energy flow between the sources (batteries, super capacitors, solar panels) and the motors with the aim of maximizing autonomy and longevity of all subsystems.

## 3.2 Fault-tolerance and Safety

Mechatronic systems are to replace purely mechanic, hydraulic and pneumatic systems. However, the transition towards such systems should not only incorporate improvements on the feature side. New mechatronic products also need to be at least as safe as any conventional systems. Although X-by-Wire systems can prevent up to 30% of traffic fatalities if they are used in the safe and proper way (which is the same percentage as airbags give [10]), the safety of these systems needs to be guaranteed to prevent system failure which could cause serious damages. Therefore, for new mechatronic systems it is essential to be designed highly fault tolerant. This means that a single failure of one component must not lead to a failure of the whole mechatronic system. Also, it must be ensured that a system failure does not lead to a state in which human life, economics or environment are endangered, [98].

In order to lessen the risk of failure of mechatronic components, two conceptual ideas are given: *perfection* and *redundancy*. The former seeks to avoid failure by overdesign, careful inspection, etc. which in most cases is not economically reasonable and is thus seldom followed. The idea behind *redundancy* is that failure of components is considered from the very beginning, which in turn results in a dynamically changing structure of the overall system.

In automotive applications the probability of failure should be much less than $10^{-7}$ faults in one hour of operation. This can also be stated in terms of the so-called safety integrity level (SIL) where the maximum bound of $10^{-9}$ fault/hour corresponds to SIL4. For example, a steering system should comply with SIL4 [38]. If a Steer-by-Wire system is used, several electronics components will be involved in the system and it is difficult for single individual components to reach this previously mentioned high level of safety. There are different ways to solve this issue. One of them is to implement redundancy in the system by adding similar components or in other word making it fault-tolerant. Another way would be to add redundancy by adding a different kind of system, e.g. adding a mechanical backup to the electronic system and making this electronic system fail-safe [90].

A measure of the reliability with respect to random failures is given by the MTTF (Mean Time To Failure) which is the time period in which there is a 37% chance that the component is still functioning. However, for safety-relevant systems all aspects of reliability, availability, maintainability, and safety (RAMS) essentially need to be considered. With the terms *system integrity* and *system dependability* [38], two procedures to meet safety requirement in technical disciplines are given. According to [42], "safety and reliability are generally achieved by a combination of fault avoidance, fault removal, fault tolerance, fault detection and diagnosis, automatic supervision and protection". Further, it is stated that "fault avoidance and removal has to be accomplished during a design and testing phase." In order to investigate the effects of faults on safety and reliability, various analysis methods have been developed. The most common ones are as follows:

- reliability analysis,
- event tree analysis (ETA) and fault tree analysis (FTA),
- failure mode and effects analysis (FMEA),
- hazard analysis (HA),
- risk classification.

When talking about redundancy it is crucial to discuss its structures. The two common ones are *static* and *dynamic redundancy*. For *static redundancy* multiple parallel modules are concurrently active, using the same input signal. Their output is fed to a voter in order to decide on the correct signal. To further improve redundancy even the voter can be set up redundantly [75] . Hoseinnezhad et al. use a fuzzy voter as an improved method in decision making, resulting in an up to 82% reduction of the voting error compared to regular majority voting [35]. On the other hand, so-called *dynamic redundancy*, requires less modules at the expense of higher information processing; there is only one active module and in case of failure the system will switch to a backup unit instead. However, this implies that any failure has to be detected safely. Depending on whether this reserve unit is continuously in operation or not, this structure is called *hot* or *cold standby*, respectively. Rooks et al. propose a duo duplex system, that is evaluating two channels with each of them containing two redundant controllers [85]. Fault tolerance with dynamic redundancy and cold standby is attractive for mechatronic systems due to the fact that many sensor signals and embedded computers are readily available so that fault detection can be improved considerably by applying process-model-based approaches [42].

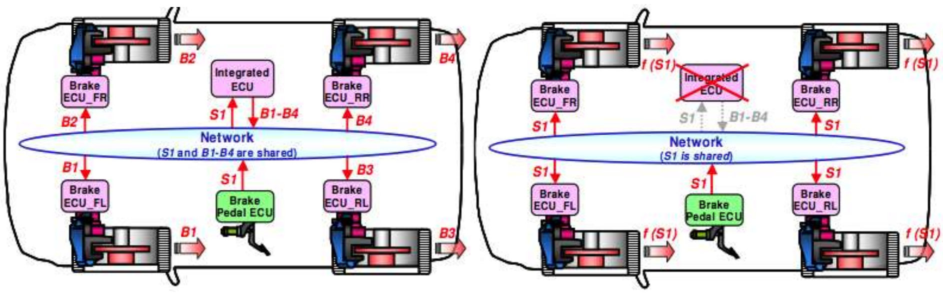
The level of redundancy is limited mainly due to cost, space and weight issues. Therefore three common levels of degradation can be defined:

- fail-operational (FO): one failure is tolerated,
- fail-safe (FS): upon the first failure the component enters a safe state,
- fail-silent (FSLI): upon the first failure the component stays in a passive mode and thus does not wrongly influence other components.

It must be stated that the various components of a fault tolerant (mechatronic) product are based on different levels of redundancy. This idea is handled by an automatic fault management system. Besides fault tolerant components such as sensors, actuators, and communication, this fault management system also covers fault detection and fault handling.

It has been pointed out that X-by-Wire systems should be laid out redundantly, as such systems are safety-critical. Also, the sensors in such systems need to continuously provide their measurement data as the overall control relies on these values. Therefore, it is important to compensate for occasionally missing data due to sensor failures or errors in communication of such safety-critical sensors . In [34] Hoseinnezhad et al. develop a FIR (Finite Impulse Response) filter approach which implements a multistep ahead prediction. According to the authors the prediction filter outperforms comparable prediction methods (e.g. linear smoothed Newton filter, Newton polynomial predictive filter, nonlinear filtering upon neural networks, etc.) in terms of computational overhead with at least similar prediction performance. Hence, missing data can be predicted and compensated for in real time contributing to an increased overall system safety.

One way to increase redundancy, as described by Matsubara et al.[65], would be to use a network centric architecture where instead of having several redundant central ECUs doing control calculations and then sending actuator values over a bus to the actuator ECUs, the actuator ECUs are capable of reading the sensor data directly from the bus and doing simplified control calculations in the case of a central ECU failure. This architecture would be especially useful for Brake-by-Wire systems, as they naturally have actuator redundancy. Even with a central ECU failure and three brake actuator ECU failures, the vehicle would still be able to do limited braking with this architecture. See Figure 3.3 for an example of a network centric Brake-by-Wire system architecture.




(a) Normal operation (b) In case the integrated ECU has failed

Figure 3.3: Example of network centric Brake-by-Wire system. Figure from [65].

Another less conventional method to increase fault-tolerance is so-called analytical redundancy, which is a way to reduce the number of sensors which needs to be used in a system (e.g. Steer-by-Wire system) by using models to calculate what a sensor value should be based on other sensors values [3]. One way of adding actuator redundancy is to use a system with a different functionality to backup the a system. An example could be the usage of a brake system to steer the vehicle using asymmetric brake application in case of failure in steering system and another would be using alternative control surfaces of an aircraft to compensate for loss of others, e.g. using ailerons to compensate for rudder malfunction[15].

Redundancy can be designed into all different product levels, including chip-level like Hitachi which has created a chip with built in dual redundant CPUs as well as other fault-tolerance improving technologies,[49]. The advantage with this method is having redundancy at a relatively low-cost which is the key in vehicle mechatronic systems.

Since modern mechatronic products use increasingly complex software, the trustworthiness of them gets harder and harder to prove. The trustworthiness of any software depends on a number of attributes [32]:

- Safety, i.e. the absence of catastrophic environmental consequences,
- Quality of Service, i.e. which includes availability, reliability and performance,
- Security, i.e. the absence of unwanted access to the system,
- Privacy, i.e. the absence of unwanted disclosure of information from the system.

Security and safety are growing concerns when embedded systems are getting more and more interconnected since the ECUs get more and more control of the different actuators available in the vehicle.

When it comes to redundant computer systems, e.g. TMR-systems (Triple Modular Redundancy), it is also important to have software diversity, which means that the computers should not run exact duplicates of each other's software. This is because there might be programming mistakes that will cause the same error on all the redundant computers, hence causing the system to fail. It is also recommended that the different computer firmwares should be written in different programming languages since there might also be language specific faults due to e.g. compiler design.

Current automotive digital communication architectures are typically based on Controller Area Network (CAN) technology. This technology may not be adequate for the demands of X-by-Wire systems, and therefore technologies such as Time-triggered CAN (TTCAN), Byteflight, and FlexRay are more suitable in automotive digital communications [21] which some of them like FlexRay are currently being used for some applications.

# Chapter 4

# Legislation & Standards

Apart from technical issues which should be considered when new braking and steering systems are designed, also legislation and standards have to be taken into account to be able to use new braking and steering systems in products.

## 4.1 ECE 13 & 79

For designing steering systems, old legislation emphasized that there should be a positive mechanical link between the steering control (steering wheel) and the road wheels. Newer regulations allow steering systems without any mechanical connection between steering control and wheels. However, there are other rules that have to be followed, some of them being that the steering system should have tendency of self-centering and no unusual vibration should be felt at the maximum speed of the vehicle. There should also be a continuous relationship between the steering control deflection and the steering angle (except for full power steering systems when the vehicle is stationary and the system is not energized). If the engine or transmission fails, no immediate change should occur in the steering angle and if any failure happens in the control transmission, it should still be possible to steer to some amount. If any failure in the energy source of the control transmission occurs, it should be possible to steer. Also, the electric steering system should be protected against excessive energy supply [101].

When it comes to brake systems there is also a number of rules that have to be followed, some of them as described in [102] being:

- The brake system should be able to control the movement of vehicle and halt it safely, speedily and effectively whatever its speed, load and road gradient are,

- The parking brake, which should able to hold the vehicle stationary on slopes, should be purely mechanical,
- The operation of electric regenerative brakes should not be affected by electric and magnetic fields,
- When the parking brake is released, the braking system should be able to generate a static total braking force even when the ignition and start switch are switched off, or the key is removed.

## 4.2 AUTOSAR

In order to be able to cope with the growing complexity of electrical and electronical (E/E) systems, many vehicle manufacturers have decided to comply with AUTOSAR (AUTomotive Open System Architecture). So, considering AUTOSAR for developing new X-by-Wire systems is important. AUTOSAR is an open and standardized automotive software architecture for automobile manufacturers, suppliers and tool developers [33]. It makes it easier to exchange and update software and hardware over the service life of the vehicle, which forms the basis for reliably controlling the growing complexity of the E/E systems in motorized vehicles. The standard comprises a set of specifications describing software architecture components and defining their interfaces [20]. The main purpose of the standard is to manage the growing complexity of automotive electronic architectures. It is very important to build a common architecture and a common understanding of how electronic control units (ECU) cooperate on the same functions. It can also be used to separate the software from the hardware in order to allow software reuse and smooth evolutions which limits re-development and validation. AUTOSAR allows multiple different functions, i.e. different software modules to coexist on the same ECU independently from the supplier of either part, [22].

Overall objectives of AUTOSAR as described in [67] can be concluded as:

- Implementation and standardization of basic system functions as an OEM wide "Standard Core" solution,
- Scalability to different vehicle and platform variants,
- Transferability of functions throughout network,
- Integration of functional modules from multiple suppliers,
- Maintainability throughout the whole “Product Life Cycle”,

- Increased use of “commercial off-the-shelf hardware”,
- Software updates and upgrades over vehicle lifetime,
- Consideration of availability and safety requirements,
- Redundancy activation.

The main working topics of AUTOSAR are architecture, methodology and application interfaces. AUTOSAR only considers the information exchange of the building blocks of the implemented design. The information about what the electrical/electronical (E/E) system should fulfill is not considered in this standard. Support of general architecture decisions is not implemented either. AutoSAR defines a software component technology for developing application software as well as it proposes a standardized ECU software architecture. Furthermore, it suggests a methodology with predefined templates how to exchange design information between actors [97].

AUTOSAR aims to be prepared for the upcoming technologies and improves cost efficiency without compromising quality. It is also a key enabling technology to manage the growing electrics/electronics complexity [1].

## 4.3 ISO 26262

Safety is a very important aspect of every industrial product. To standardize the functional safety (i.e. the absence of unreasonable risk due to hazards caused by malfunctioning behavior of systems) in the E/E and programmable electronic systems, the IEC 61508 has been in use since the mid-1980’s and recently been updated to the second edition [38]. The ISO 26262 standard [39] is an adoption of IEC 61508 so it can be used in the E/E systems in road vehicles. E/E systems have provided several new functionalities in the vehicles like driver assistant systems; vehicle dynamics control systems, and active and passive systems. The new development of these systems and integration of them requires specific safety system development processes and criteria to show that these systems are behaving safely. As in any other system, whenever software content and mechatronic systems are used, there is always risk of systematic and random failure in the system. The ISO 26262 is proposed to provide guidance to avoid these risks. This standard is intended to be used for safety related systems which include one or more E/E systems which are installed on passenger cars with a maximum gross weight of 3.5t. The standard is planned to be extended for heavy vehicles by 2013. ISO 26262 considers the possible dangers which can be caused by the malfunctioning of the safety related E/E systems. Hazards from electric shock, fire, smoke, heat, radiation, toxicity, flammability, reactivity, corrosion, release of energy, and similar hazards are not considered unless they are caused by a malfunctioning of safety related E/E systems.

The ISO 26262 provides an automotive safety life cycle (management, development, production, operation, service and decommissioning) and supports tailoring the necessary activities during these life cycle phases. Furthermore, it provides an automotive specific risk-based approach for determining risk classes (so-called Automotive Safety Integrity Levels, ASILs), and uses the ASILs for specifying an item's necessary safety requirements for achieving an acceptable residual risk. Moreover, the standard also provides requirements for validation and confirmation measures in order to ensure a sufficient and acceptable level of safety.

ASIL specifies the item's or element's necessary requirements of ISO 26262 and safety measures for avoiding an unreasonable residual risk. Four ASILs are defined: ASIL A through ASIL D, where ASIL A is the lowest safety integrity level and ASIL D the highest one. In addition to these four ASILs, the class QM (Quality Management) indicates no requirement according to ISO 26262. The severity of a potential danger is estimated using a severity class of S0, S1, S2 and S3. Class S0 means that the hazard is only limited to material and does not involve humans. The other severity classes are shortly defined in Figure 4.1.

| Class | S0 | S1 | S2 | S3 |
|---|---|---|---|---|
| Description | No injuries | Light and moderate injuries | Severe and life-threatening injuries (survival probable) | Life-threatening injuries (survival uncertain), fatal injuries |

Figure 4.1: Severity classes. Figure from [39].

The probability of exposure in operational situations is estimated by means of so-called probability classes E0, E1, E2, or E3. Class E0 is used for situations that are suggested during hazard and risk analysis, but are considered to be extremely unusual. Other classes can be decided based on the Figure 4.2.

| Class | E0 | E1 | E2 | E3 | E4 |
|---|---|---|---|---|---|
| Description | Incredible | Very low probability | Low probability | Medium probability | High probability |

Figure 4.2: Probability of exposure. Figure from [39].

The controllability of dangerous events, caused by the driver or other traffic participants, can be estimated using the controllability classes C0, C1, C2 and C3 which are shown in Figure 4.3.

| Class | C0 | C1 | C2 | C3 |
|---|---|---|---|---|
| Description | Controllable in general | Simply controllable | Normally controllable | Difficult to control or uncontrollable |

Figure 4.3: Controllability of dangerous events. Figure from [39].

The ASIL should be determined using the severity (S), probability of exposure (E) and controllability (C) in accordance to the Figure 4.4.

| | | C1 | C2 | C3 |
|---|---|---|---|---|
| S1 | E1 | QM | QM | QM |
| | E2 | QM | QM | QM |
| | E3 | QM | QM | A |
| | E4 | QM | A | B |
| S2 | E1 | QM | QM | QM |
| | E2 | QM | QM | A |
| | E3 | QM | A | B |
| | E4 | A | B | C |
| S3 | E1 | QM | QM | A |
| | E2 | QM | A | B |
| | E3 | A | B | C |
| | E4 | B | C | D |

Figure 4.4: ASIL determination. Figure from [39].

The safety life cycle which includes the main activities during the concept phase, the product development phase and after the start of production (SOP) phase are shown in Figure 4.5. In this figure, the numbers in the blocks correspond to the specific chapter in the standard document which is referred to [39].

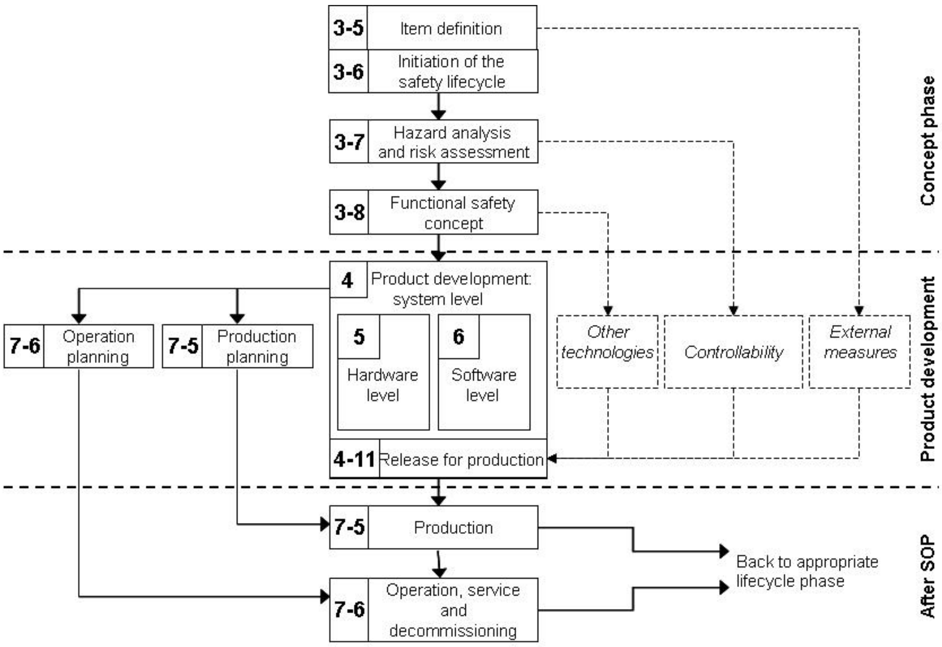



Figure 4.5: Safety life cycle. Figure from [39].

# Chapter 5

# Methodology

## 5.1 Development methodology and multi-domain optimization

Since mechatronic product development is a wide area, it is (almost) impossible to define one fixed optimized generic development method to use.

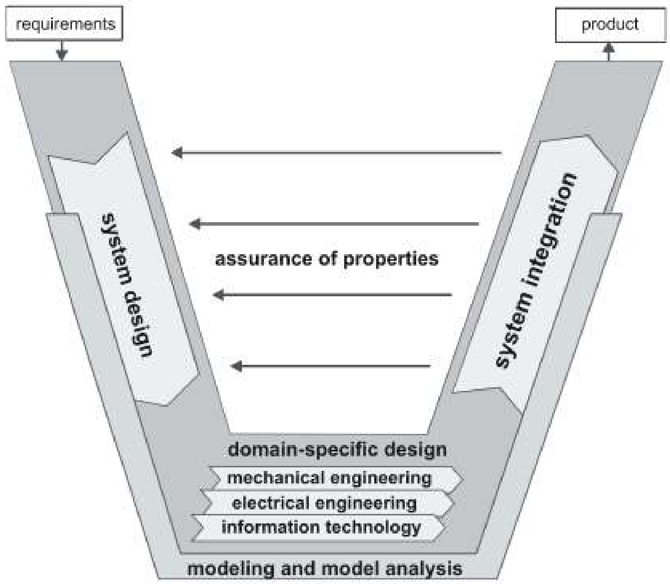



Figure 5.1: The V-model as a macro-cycle. Figure from VDI 2206 [96].

However, one of the more commonly used methods is the V-model, which is recommended by VDI. The VDI 2206 [96] proposes to use conventional problem solving on micro-level and the V-model on a macro-level. Figure 5.1 describes the V-model; the horizontal axis describes project completeness and the vertical axis describes the abstraction level. The main idea is to verify each step on the right side against its corresponding requirements on the left side. The VDI 2206 also proposes an iterative V-model where the macro-cycle is repeated several times with increasing product maturity, see Figure 5.2.

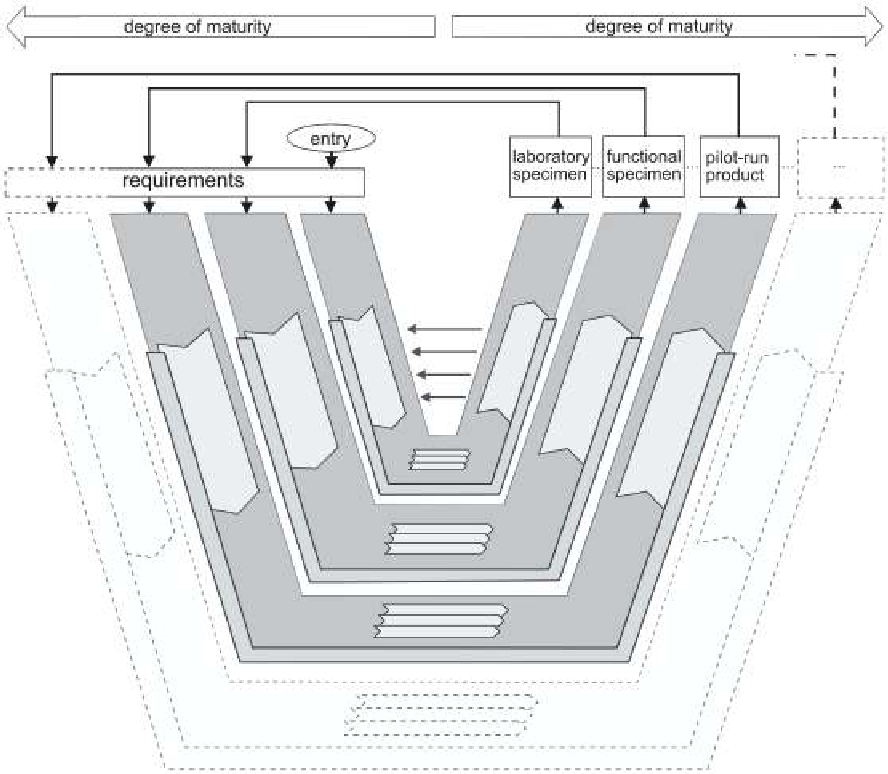



Figure 5.2: Iterative macro-cycle V-model. Figure taken from VDI 2206 [96].

The traditional design methods for mechatronic systems are usually fairly sequential [7], [8], [86]. The different engineering domains are treated as separate designs, e.g. mechanics, electronics and control systems are designed and optimized individually and then integrated with each other. Usage of off-the-shelf components instead of custom components is also quite common, leaving out an all optimization step together.

Fredrik Roos proposes an alternative model-based design methodology [86]. This design methodology uses a combination of static models which describe relationships between different physical parameters, and dynamic models which describe the components' behavior. By using this method, optimization using genetic algorithms with regards to properties such as cost, weight and performance is possible. The genetic algorithm gives a global system optimum instead of local component optimums which would have arose by optimizing the components individually.

Behbahani et al. [7], [8] describe a method to optimize a mechatronic system with respect to multiple criteria. To take the different criteria into account a so-called Mechatronic Design Quotient is used. This multi-criteria quotient is calculated through aggregation by a non-linear fuzzy integral, which makes it possible to weigh a combination of off-the-shelf components against other combinations. Optimization carried out via a niching genetic algorithm, which in comparison to a standard genetic algorithm lets several “eco-systems” (also called niches) evolve parallel to each other. The niches have small differences in their initial conditions and when the evolutionary cycles are completed the top “ elite” candidates compete against each other to generate a winning candidate based on the Mechatronic Design Quotient.

As pointed out in [13], the Robert Bosch GmbH started the initiative “Systems Engineering Mechatronic” in order “to cope with the challenges of system design and complexity handling”. This approach is based on the above introduced V-model. Key elements of this initiative are that physical/ mathematical models are to be used whenever possible. However, as some physical processes are very complex (e.g. combustion processes) they can not be used for an efficient product design of such systems. It is then pointed out that information systems need other methods of modeling, which is also holds for mechatronic systems with a high part of information technology. Furthermore, it is stated that a mechatronic system and its components shall be tested against the requirements specification. Apart from that, an overall computer aided engineering tool infrastructure is required, for instance by coupling commercially available tools via scripts for parameter exchange. Another key of the “Systems Engineering Mechatronic” is that standardized base models for different technologies have to be available so that fast or virtual rapid prototyping is enabled with a high reuse of these models. Apart from that it is significant that one can exchange models quickly between different tools in horizontal direction (“e.g. in a one-dimensional simulation level between tools for hydraulic simulation and electronics simulation”) as well as in vertical direction (“e.g. between three-dimensional and one-dimensional hydraulic simulation tool”).

According to Bosch the application of Systems Engineering Mechatronic yields different benefits. For example it is said that by using rapid prototyping the design quality can be increased already in early phases, and the design efficiency can be increased (as a result Bosch was able to reuse up to 80% of the design models). Also, it is pointed out that different variants of a certain design were developed easily as they all base on a stable set of construction elements. In general, it is stated that the system design has become more flexible due to the model-based system design description.

The role of software is special in mechatronic systems in such a way that the software design must take physical border conditions into account. There are already some software methodologies for software-intensive systems of high complexity (e.g. Product Line Approach (PLA) and Capability Maturity Model (CMM), both designed at the Software Engineering Institute (SEI), Pittsburgh, USA). However, as these approaches do not consider “classical” mechatronic aspects, they cannot be used for mechatronic development and rather an integrated concept considering “classical mechatronic” next to software aspects is needed.

## 5.2 Tools

During product development, simulation is usually an important step. Due to the multiple-domains included in mechatronic product design, it is difficult to do proper simulations of the whole system. Well proven tools exist for the individual domains, e.g. SPICE simulators for electronics, FEM-tools for structural analysis, software simulators, etc. Tools designed specifically for multi-domain simulation exist, but are usually limited in comparison to domain-specific tools.

One possibility is to interconnect existing domain-specific tools through a common software framework as is introduced by Farkas et al. in [19]. Similar approaches are being developed in several institutes around the world, including KTH.

*Something about Ahsans work?*

Another consequent idea to optimize mechatronic systems from a holistic point of view, is that the developers should be able to model and simulate any part of the system within one environment and easily be able to exchange them, which is achieved by a so-called model-based design.

As long as there is no single environment simulation toll available, one usually applies a specialized software tool in order to model certain components in detail, next to a general modeling/ simulation environment. This so-called co-simulation requires the special tool being interfaced with the general simulation environment used for holistic modeling. However, this becomes difficult as it needs to be controlled what actual data both tools are allowed to exchange, and which of the tools performs a certain calculation.

To overcome those apparent problems of co-simulation, Mathworks introduced the Simscape software accompanied with the Simscape language which allows to even model in detail within a single environment [66], [64]. Here, the system is rather modeled upon its actual structure than on the underlying mathematical physical description, which the tool itself takes care of.

Although only a single environment is used, still different domains may be coped with easily. The different components are represented by nodes in a network of physical components. This network is then analyzed using Kirchoff's law in an analogue manner to analyzing electrical networks. In contrast to Mathworks' Simulink, in Simscape equations may be expressed implicitly. That is, unlike common programming languages, the equation does not simply assign values of variables. Rather a mathematical relation between the parameters, the variables and their derivatives is established, which is defined within each component. In doing so, each component is only defined once, however, may be used throughout different systems, as only the underlying relation is evaluated.

MapleSim is also a modeling software used to model multi-domain physical systems. It uses symbolic computational techniques to model the multi-domain systems. This software, like SimScape, uses a drag-and-drop method to build models. The equations of system are produced automatically in MapleSim [63].

Dymola is another example of modeling softwares which is used for modeling and simulation of dynamic behavior of complex multi-domain systems [12]. Dymola uses the Modelica modeling language which is an object oriented language for physical modeling. Dymola consists of different libraries of components from different domains such as mechanical, electrical, control, pneumatic, powertrain, vehicle dynamics and the like. Dymola is also very good software to be used for hardware-in-the-loop (HIL) simulations. Some of the main Dymola features are the handling of large and complex multi-domain systems, fast simulations, symbolic preprocessing, the capability of implementing user defined components, 3D animation and real time simulation. A brief comparison of the mentioned modeling and simulation software is done in Figure 5.3 [103].

| *Aspect* | *Chapter* | **SimMechanics** | **MapleSim** | **Dymola** |
|---|---|---|---|---|
| **User friendliness** | 1 | □ | □ | □ |
| **Simulation performance*** | 1 | - | □ | + |
| **Overall performance** | 1 | - | + | + |
| **Verification & error handling** | 2 | + | - | + |
| **Numerical accuracy** | 3 | + | □ | □ |
| **Visualization** | 4 | □/- | n.a. | + |
| **Parametrisation** | 5 | □ | □ | □ |
| **Exporting & interchangebility** | 6 | - | □ | + |
| **Closed loop systems** | 7 | + | - | □ |

**+**: above average
**-**: lower than average
**□**: average

* only minor differences occured

Figure 5.3: Comparison of SimMechanics, Dymola and MapleSim, Figure taken from [103].

# Chapter 6

# Conclusions

From this study it can be concluded that most published research focuses on single or few aspects of the systems, e.g. fuel consumption. However, to analyze if these systems are viable for use in a real production vehicle, there is a wide range of properties which needs to be considered in conjunction with other aspects such as safety and regulations, cost, applicability, etc. Therefore more research needs to be conducted on each individual aspect as well as the combination of them before common application of these systems is possible. Further on, it would seem a good idea to take a wider array of properties into account already from an early state in future research.

Another conclusion that can be drawn is that most research is only evaluated by software simulations or in some cases hardware-in-the-loop simulations. Thus a large share of published research in the area misses the all important validation in real conditions. There are even some aspects like passenger comfort which are not usually considered in the simulations and can only be studied in full extent in real tests.

The consistency of new technologies with new regulations and standards is an important aspect which is not considered in most of the research. Researchers usually focus on the theoretical and scientific aspects of new technologies and do not care about the legislation and standards, which is one of the most important factors which can decide whether a technology can be used in production or not.

Also, focus is often laid on individual systems whereas when these systems are used in real conditions, they are required to coexist and work in synergy with a large number of other systems. That is, the aspect of integrating an individual system into the overall vehicle environment is often omitted.

For some systems like electromechanical steering, only a little research has been conducted so far. There is a wide range of research areas such as the effect of electromechanical steering systems (especially Steer-by-Wire systems) on fuel consumption, safety, cost, packaging, etc. for which more research is needed.

Although a large portion of traffic consists of trucks and heavy vehicles, however, the percentage of papers about the application of mechatronic systems on these vehicles is considerably low compared to the number of articles about passenger cars. So, more research is needed in this area since improvements in this area can affect the whole transportation system.

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