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Upgrade of the E/E Architecture of an electric test vehicle with drive-by-wire component

Design of an Active Front Independent Steering System equipped with steer-by-wire technology

Relatori:
Prof. Mauro Velardocchia
Dr. Ing. Antonio Tota
Prof. Dr. rer. nat. Frank Gauterin
Dipl. Ing. Till Böse

Candidato:
Marco Obertino
ID: S296009

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Abstract

In recent years, the development of autonomous driving has emerged as a promising area of research in the automotive field. The interest is mainly due to the need for more comfortable, safe and efficient driving systems to integrate onboard of novel car concepts, such as Drive-by-Wire (DBW). Despite not being a recent concept, in light of its application within the Aerospace sector, the few present examples in the automotive environment still integrate a mechanical backup line to meet the safety requirements.

Aiming to overcome this limitation, the work presented focuses on the design of an Active Front Independent Steering system (AFIS) equipped with Steer-by-Wire (SBW) technology. After a first analysis of the system's software component, including EE-architecture and communication protocols, the attention shifts to the drawing of the hardware part on the SolidWorks platform, with the assembly of the 3D model. The final step is the study of the control system and embedded communication network. For this purpose, the CANopen protocol was identified as the best compromise between available resources, flexibility and potential.

The results of this research underline the potential of steer-by-wire technology and the proposed steering system. Similarly, the critical points and complexity in setting up and managing the control system are highlighted, while providing interesting and consistent insights into its implementation. However, the practical implementation of this technology on a real vehicle requests further extensive research into control approaches and safety considerations.

Keywords: Drive-by-Wire, Steer-by-Wire, EE-architecture, Autonomous Driving, CANopen;

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This is for you.

Contents

1 Introduction

1.1 Motivation

In recent years, technological innovation has led to significant changes in most industrial sectors. Underlying this development is the desire to achieve an ever-higher level of automation, which can bring improvements in working comfort, safety, decision-making and operational speed.

In this group of industries, the automotive sector stands out as one of the most rapidly expanding. Within this field, an increasingly relevant topic is autonomous driving (AD), which has been at the centre of many debates from the very beginning. Although until recently it seemed to be something mysterious and intangible, today AD is becoming a part of normal city traffic, as reported in the prediction graph in Figure 1. Specifically, six levels of AD have been identified and the distinction has been made according to the driving capabilities of vehicles as described in [1]. However, the path to a fully autonomous vehicle network, in which drivers become passengers and vehicles interact with each other on the road, is still a long one. The only certainty is that the benefits so far are considerable and the promises for the future are as challenging as they are exciting. Indeed, car designers are striving to build ever safer and more intelligent vehicles.

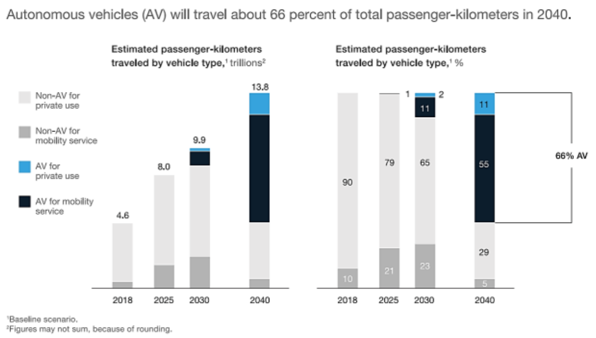


Figure 1: Forecast of AD spread [2].

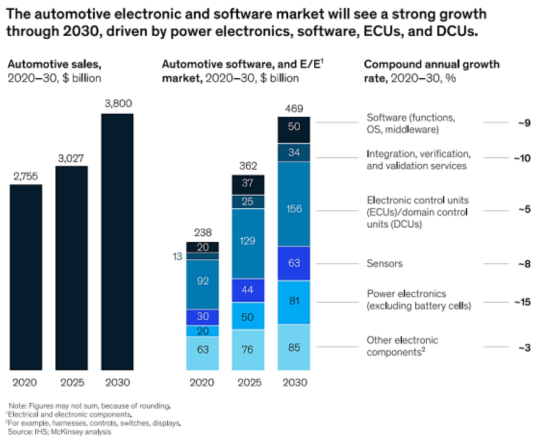


Figure 2: Growth in vehicle electronics [2].

Part of the evolution of AD are all those systems that have been and will be introduced in vehicles to improve individual functionalities. Generally, these types of systems aim to reduce the number of mechanical components in favour of electrical and electronic devices. This trend is confirmed by the investments made in this sector, as illustrated by Figure 2. The latter are the basis on which to build driverless vehicles in which a central computer connected to the various Electron Control Units (ECUs) issues commands to actuators and receives feedback from sensors. Thanks to this internal network called EE-Architecture (EEA), the diagnostic system functions on a completely different level than in the case of the mechanical implementation of the respective functionalities. As the number of electronic components increases, the number of parameters that can be monitored also increases, allowing the services offered by the vehicle to be improved, but above all to ensure safer driving [3].

One system that is gaining popularity as a sub-part of the big AD revolution is Drive-by-Wire (DBW). It is inspired by the fly-by-wire technology used in aviation and initially referred only to the vehicle's propulsion system [4]. Subsequently, its area of application expanded to include steering, braking and shift systems, thus defining four main branches of DBW: Steer-by-Wire (SBW), Throttle-by-Wire (TBW), Brake-by-Wire (BBW) and shift-by-wire [5]. These technologies involve the replacement of mechanical connections between actuators, such as between the steering wheel and the rack, in favour of electrical connections and offer a multitude of benefits that will revolutionise the automotive landscape. Firstly, DBW streamlines the entire manufacturing process by reducing complexity, making assembly more straightforward, and simplifying maintenance and tuning procedures. Furthermore, it diminishes the physical effort required for engaging vehicle inputs, offering the possibility of customisation through haptic technology. This innovation also grants designers newfound interior design freedom, enabling creative input mechanism placements. Moreover, drive-by-wire paves the way for automation in driving functions, enhancing overall vehicle safety. By removing mechanical linkages, it allows to reduce cabin noise and to improve crash safety by minimizing floor openings. Notably, it enables computer-controlled corrections in vehicle controls, enhancing safety through features like Electronic Stability Control (ESC), Adaptive Cruise Control (ACC), and Lane Assist Systems (LASs) [6].

However, it is essential to acknowledge that each implementation of drive-by-wire introduces additional actuators within the vehicle, leading to increased energy consumption. For example, these systems incorporate actuator motors to generate the required wheel-turning torque and feedback transducers to replicate the sensation of the road on the steering wheel [5].

In terms of safety, drive-by-wire systems demand redundancy in driver input sensors, vehicle communication networks, actuators, and other critical components [7]. This replication of functions is essential in fulfilling strict automotive safety regulations like ISO 26262, which require drive-by-wire systems to exhibit both fail-operational and fail-safe behaviour [8].

Within this context, in the past few years the FAST department of the University Karlsruhe Institute of Technology (KIT) has invested resources to pursue and deepen the knowledge in the x-by-wire field. The goal of this research effort is to gather the knowledge on the hardware and software logic currently available for these systems from different sectors of application (aerospace, automotive, robotic, etc.) and contribute to DBW research and development with novel proposals and experimental prototypes in the near future.

1.2 Project overview

The present thesis work is part of a project on sustainable mobility and production promoted by several local authorities in the German region of Baden-Württemberg. The founders of the project are the Ministry of Science, Research and Art of Baden-Württemberg, the University of Stuttgart, and the Karlsruhe Institute of Technology, which have set up a research platform for the development of new technologies called 'Innovation Campus Future Mobility' [9]. The aim is to promote research in the field of intelligent mobility and production through interdisciplinary projects that have as their merging point the desire to build a sustainable future, as schematically summarized in Figure 3. As presented in Figure 4, a test vehicles were also developed for the demonstration and early validation of the research results.

In particular, the project on which the research team of the FAST department of KIT University is working is the 'BUP24 - E/EeVee' [10]. This project focus on the integration of new hardware and software components into the demonstrator to enable the testing of new driving functions based on electrical signals. The first step to explore is the installation of electronic devices such as control units and sensors, to create an internal vehicle communication network called EE-architecture. Once a solid EEA is built, the following step is to investigate important autonomous driving topics such as drive-by-wire and over-the-air updates, which is going to be partly addressed in this document.

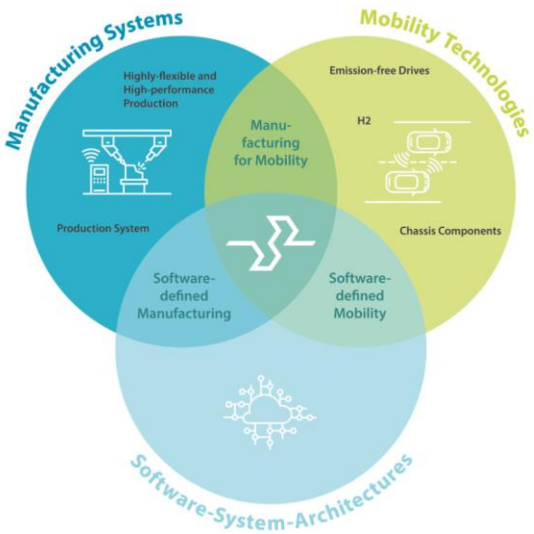


Figure 3: ICM research fields [9].

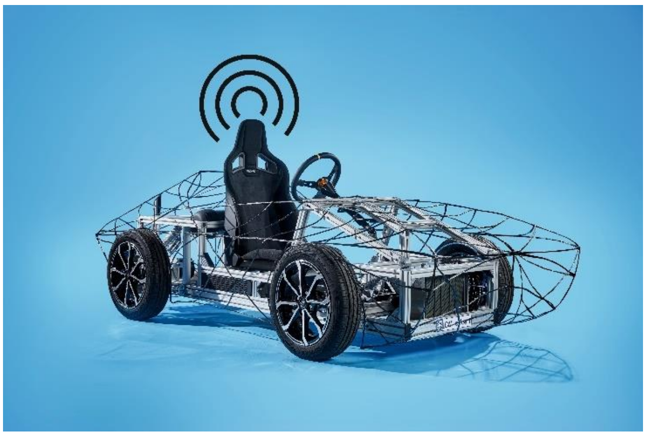


Figure 4: eVee test vehicle [10].

1.3 Objectives

The main goal of this research is to design and size an Active Front Independent Steering (AFIS) system equipped with steer-by-wire technology for the eVee test vehicle introduced in the section above and further discussed in section 3.3. The study aims to evaluate both the hardware and software components of the system in order to identify the solution that is best suited to the case under analysis.

For the software component, careful research was required into the most widely used EE-architecture and communication protocols in order to lay the basis for further consideration of the most feasible and promising solutions to adopt for the test vehicle. A different approach was used for the hardware component, which had already been partly analysed by a previous project that allowed this second study to start from an advanced stage [11]. After considering and comparing different steering system alternatives, the previous work produced some preliminary suggestions and guidelines for the path to follow moving forward. The tasks undertaken during this research meant to deepen and reshape the aforementioned draft trying to enhance and improve the initial proposal so as to be able to proceed with the detailed design of the individual components.

The feasibility and operability of the mechanism was then assessed by means of the 3D CAD design platform Solidworks, which was adopted for the construction of the system and the operation of its motion.

The results aimed to highlight the advantages and disadvantages of the proposed solution. Furthermore, they should allow vehicle designers to identify critical elements and the main challenges to be faced when designing viable alternatives.

Demonstrating that steering systems with SBW technology are already at an advanced stage of development and have potential advantages in terms of performance and operation is crucial for the future of this project and similar studies in the field of autonomous driving.

1.4 Thesis outline

Chapter 1 – Introduction

The motivations behind the development of new technologies in the automotive field, which justify the pursuit of studies in innovative driving systems such as drive-by-wire, are introduced here. Additionally, a description of the project and the core topic of this research is provided. Lastly, the objectives and milestones established to fulfil the research's purpose are articulated.

Chapter 2 – State of the Art

The state-of-the-art section encompasses, a historical overview of the evolution of EE-architecture, the underlying theory, and a review of the most popular communication protocols for the chosen application. The working principle and the main components of a steer-by-wire system are extensively covered to ensure a thorough understanding of the topic. Several examples of applications already available on the market and many projects that are working towards the same final goal of smart and safe mobility are included to provide a reference point of the current industrial and academic research efforts.

Chapter 3 - Active Front Independent Steering

This chapter explores the concept of active front independent steering. The assets and advantages that this system can offer when combined with steer-by-wire technology are outlined. The well-known Ackermann Steering System is discussed, so as to examine its limits, and potential solutions to overcome them. Lastly, a brief summary of the steering system proposed by an earlier in-house research work in the FAST department of KIT is provided.

Chapter 4 – Active Front Independent Steering with SBW

This chapter contains an extensive discussion of the front wheel independent steering system equipped with steer-by-wire, which was developed for the eVee test vehicle. First, a detailed explanation of its operation and the design procedure followed for the sizing of each component is provided. Afterwards, the assembly procedure and fastening systems are analysed in detail. Each section is complemented by 3D CAD model renderings generated through the Solidworks software platform, facilitating comprehension and visualization of the system.

Chapter 5 – Control System

This chapter provides a summary of the key requirements that a SBW system must fulfil, along with guidance on selecting and integrating one of the most promising advanced control systems reported in the existing literature. Additionally, it outlines the rationale for opting to use CANopen as the communication protocol, especially in the context of the system under examination. To enhance understanding, the chapter presents a system flowchart that illustrates the connections and data exchange among various devices within the network. It concludes by offering recommendations on parameter settings to assist in the future development of the system software.

Chapter 6 – Conclusion and Future work

This chapter reviews the achievements of this project. Furthermore, to highlight both the potential advantages and limitations of the proposed system, a critical analysis of the studied steer-by-wire (SBW) system and the approach employed for its implementation is provided. In addition, recommendations for future work regarding potential improvements of the steer-by-wire steering system and future steps that should be undertaken are discussed.

2 State of the Art

This chapter aims to provide an overview of the EE-architecture concept, its relevance and its temporal and technological evolution. Background information is then provided on communication protocols, their characteristics, and main fields of employment, with the aim of identifying those that are best suited to the application under analysis. Finally, a description of the steer-by-wire technology, its operation logic and its components shed light on the reasons that drive further research in this field.

2.1 EE-Architecture

Generally, the automotive EE-Architecture (EEA), also known as Electric and Electronic Architecture, is a network infrastructure, used to interconnect and organize ECUs and mechanical/electronic components [12]. The difference between electric and electronic is:

- Electric refers to the fundamental principles of electricity. The way it is generated and distributed. It also includes the design and operation of the electrical circuits.
- Electronic refers to the hardware parts that use electric power to work. Examples of these devices can be transistors, diodes and integrated circuit that can perform logic functions process data and manage electrical signals to undertake specific tasks.

The concept of EEA in automotive field encloses the engine management system, safety systems such as airbags and anti-lock brakes (ABS), entertainment systems, navigation systems, climate control, and lighting systems.

The control system has to coordinate all the functions and ensure that they work together efficiently and reliably. There are laws and requirements that the architecture must meet during the design and implementation such as ISO 26262, the basic standard for functional safety of electrical and electronic systems, which is schematically summarized in Figure 5, with its different areas of legislations [13].

Figure 5: Standard for EE systems functional safety [13].

The development of the EE-architecture is part of a strong technological innovation that sees the software part as the heart that drives the advancements in autonomous driving, connectivity, electrification, and intelligent driving. This trend has led companies to invest on the software evolution of vehicles, trying to decouple as much as possible the software part from the hardware in order to proceed freely in the development of both branches. Therefore, the definition of the structure and operational logic of the EEA is presently in progress [14].

In the early days the number of mechanical and hydraulic components far exceeded the number of electronic components, but the current trend states that electricity and electronic devices are becoming increasingly important changing the concept of vehicle.

This technological transition led to an increasing number of ECUs, which initially worked independently and were directly connected to actuators in a so-called 'Point to Point' configuration. This set-up was sustainable as long as there were few functionalities to control and coordinate. With the introduction of more demanding safety requirements and the need to reduce greenhouse gas emissions, the amount of information to manage increased exponentially. This resulted in the introduction of a more efficient communication system based on a central gateway connected to several sub-networks. As all information passed through this central unit, the need soon arose to divide the system into domains consisting of control units with similar functions that are interconnected via bus system. In this way, communication became faster, and the role of the central gateway was limited to domain management. Examples of domains may be body, powertrain, chassis, infotainment, ADAS and telematics domains.

Nowadays the process is moving toward ‘Vehicles centralized’ or ‘Zone-based architecture’ that suggests integrating not only similar or closely related functions, but also creating domains based on the physical location of components within the vehicle. In accordance with Zhu et al. [12], the requirements that drive the evolution of EE-architecture include the following:

- Interconnection of ECUs.
- Improvement of automobile performances, such as braking, stability, safety and economy.
- Reduction in the cost and weight in automotive manufacturing.
- High bandwidth and low latency of in-vehicle communication.
- Connectivity with the outside.
- Flexible decoupling of hardware and software.

In modern vehicles, the EE-architecture is becoming increasingly complex due to the integration of these advanced features. The step-by-step EEA evolution is displayed in Figure 6.

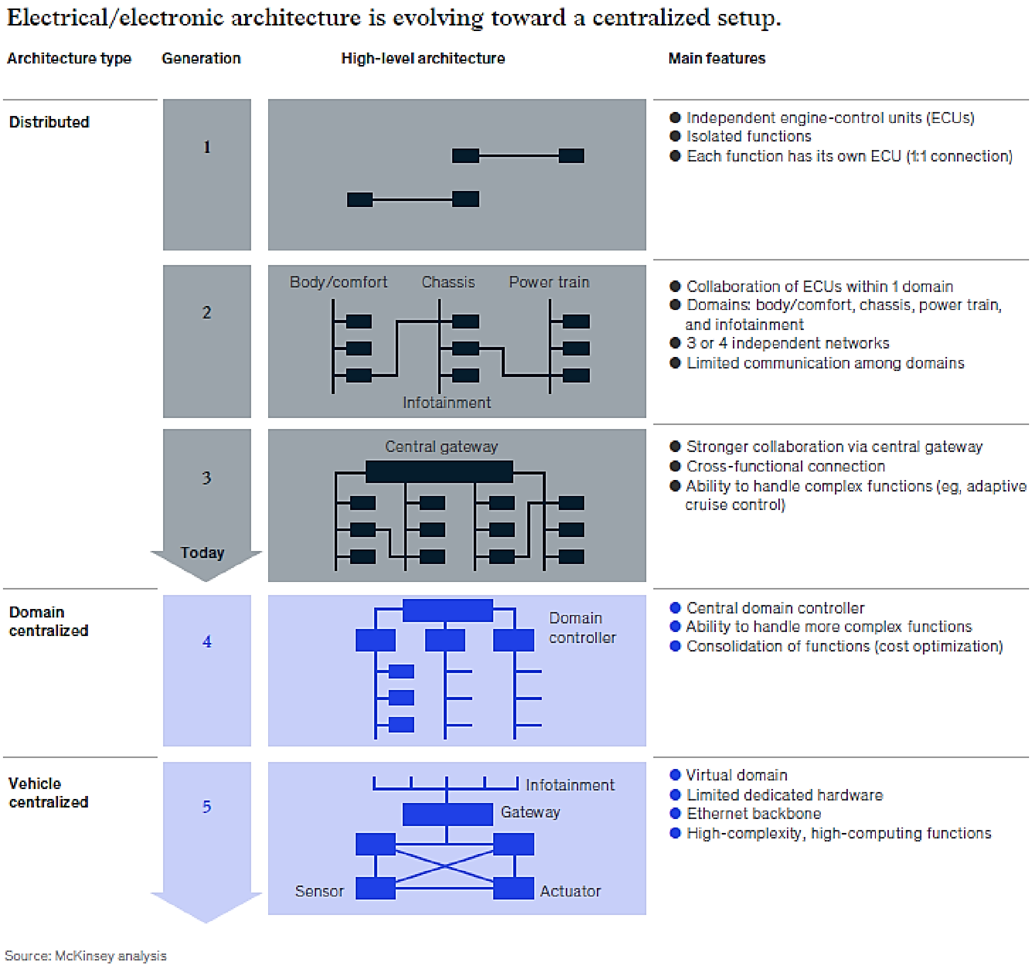


Figure 6: EE-Architecture evolution [14].

2.2 Communication protocols

Due to the need to transmit more and more information, in ever-shorter times and with increasingly stringent reliability and efficiency requirements, the way of transmitting information has undergone many changes over the last decades. Specifically, there was a shift from a "Signal-Based Communication" to a "Service-Oriented Architecture" approach.

In signal-based communication, the sender transmits the data across the network whenever the values are updated or modified, even if any node in the network does not request the data. It is still used on classic bus systems like CAN, LIN, FlexRay and MOST. In these automotive solution hardware and software are tightly linked, therefore the communication among Electronic Control Units (ECUs) is statically defined [15]. This represents one of the main limits of this approach, to assume that the software will remain unchanged throughout its operational lifespan. Another limit is that the nodes are burdened with data they may never need or utilize.

Due to dynamic customer requirements and market changes, significant improvements in computational performance and more flexible communication approaches are needed. Furthermore, the ability to update or introduce new applications throughout the entire lifespan of a vehicle is essential. Service-Oriented Architecture (SOA) concept was born to meet these requests.

SOAs allow dynamic communication relationships at run time without static dependencies mapped on ECUs. Therefore, it introduces more flexibility, less dependence between hardware and software and easier integration of external services and on-demand functions. The access to the information over the entire vehicle is simplified, expedited, and the data can come from internal control units or Over-The-Air (OTA) by an Original Equipment Manufacturer backend [16].

To enable effective communication among software components across different networks, a middleware solution becomes crucial. It serves as a bridge between different software applications or systems, allowing them to communicate, exchange data, and work together effectively even if they run on different platforms, use different programming languages, or following different communication protocol. An example of such middleware is the Scalable Service-Oriented Middleware over IP (SOME/IP) [17].

Communication protocol requirements

In this process of continuously improving of autonomous intelligence, the enhancement in perception and decision-making capabilities requires the support of the underlying architecture. The vehicle requires large-bandwidth, low-latency, scalable and flexible EE-architecture. In this way, the features requested by automotive EEA can be summarized as follows [12]:

- Bandwidth
  The signal's bandwidth refers to the frequencies within which a system maintains a certain performance level. With the escalating data from a growing array of sensors, the bandwidth of conventional in-vehicle networks becomes a constraining factor.
- Wiring complexity and cost
  The multiple standards of wiring in vehicles and the various wired/wireless cabling have made the wire harness more complicated and costly than ever. Moreover, the wire harness and the wire system are ranked as the third most expensive and the third heaviest component in vehicles, respectively (with the powertrain being first and the chassis second in both cost and weight). As such, reducing the wire system weight can contribute to fuel efficiency directly [18].
- Deterministic latency
  Latency is another critical measurement in in-vehicle networking since most of the safety-related modules and powertrain as well as chassis controls all have strict delay requirements for the sake of reliability guarantee. Latency can be affected by various factors, especially when communications take place across different domains.

- Flexible architecture
  Typically, new vehicles come equipped with the latest software updates before departing the factory. By collecting and analysing new data during operation, however, systems can also be continuously optimized beyond the originally provided software over the entire life cycle of a vehicle. This approach enhances the performance of current systems while also facilitating swift integration of innovations into individual vehicles via purchased upgrades. This concept is commonly referred to as over-the-air updates [19].
- Security
  Today's vehicles are expected to connect with one another wirelessly and even be connected to the Internet directly. As such, a vehicle is no longer an isolated system. This may lead to a greater threat to the safety of drivers and passengers. Further, like any computers connected to the Internet, connected vehicles can be attacked, hijacked, and jeopardized remotely by malicious users [16].

As mentioned before, the communication between the different ECUs occurs via different bus systems which differ mainly in the features previously listed. The most relevant communication protocols are:

- CAN, Controller Area Network.
- LIN, Local Interconnect Network.
- FlexRay.
- MOST, Media Oriented Systems Transport.
- Automotive Ethernet.

2.2.1 CAN

CAN network has long been used to transmit most in-vehicle communication signals. It is an asynchronous serial bus network which was developed by Robert Bosch in 1980’s to interconnect devices, sensors, and actuators in a system [20].

Although many different networks have been developed afterwards in response to some requirements that CAN does not meet, CAN still retains the popularity in automotive networks, particularly in powertrain system and upper body electronics. As reported by Zheng et al. [21], the main reasons of its extensive use are:

- Cost-effectiveness.
- Mature full-scale tool chains of CAN system, from data dictionary design to production code automatic generation, from network simulation to software validation, which imply high reliability.
- It does not require any global timer nor centralized coordinator to regulate the communication. Each individual node synchronizes its time with the talker when

receiving messages. Conventionally, CAN nodes access the network on event-triggered basis, which means every node has the equal right to try to access the bus when the transmission event is ready, and the bus is idle. But when multiple nodes initiate attempts at the same time, they need to compete for the access through a non-destructible Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme, the lower the message ID the higher the priority to transmit. This type of Media Access Control (MAC) brings great flexibility in network design, but may raise also big problems when stringent determinism is demanded as for safety-related applications.

- Another reason for CAN's dominance in the past years is its acceptable capabilities of noise-resistance and fault-tolerance. CAN network uses Unshielded Twisted Pair (UTP) which has higher resistance to external common-mode interference than untwisted cables such as those in LIN network. Further, they can lower the radiation of high-frequency noises.
- Additionally, most CAN transceivers today provide extra means to detect and report different kinds of physical layer failures. They are helpful in maintaining robust operation of the network.

Moreover, CAN network may come with various topologies depending on the different physical layers adopted. The most widely used CAN network is high speed CAN which allows data transfer rates up to 1 Mbps. The least popular low-speed fault-tolerant CAN is characterized by a baud rate between 40 kbps to 125 kbps [18], [21].

Admittedly, CAN is the dominant automotive network, but it still has some critical drawbacks, especially for high safety applications as previously discussed by Zheng et al. [21]:

- Indeterminism is an inevitable problem of conventional CAN due to the nature of its arbitration mechanism. In such a mechanism, the lowest ID will always win access to the network, and the other messages will have to wait for the bus to become idle even when they contain more urgent signals.
- Byzantine General Problem is another critical problem on how the sender and receiver can reach mutual consensus on the integrity and authenticity of the messages transmitted in between. Since the acknowledgement in CAN network does not signify which node it comes from, the publisher cannot always ensure its message has been correctly received by all the designated nodes in the same (sub)network.
- Furthermore, the unprotected sixth bit of End-of-Frame (EOF) may cause inconsistency among different nodes, because the receiver only checks form error up to the sixth bit of EOF field and leaves the seventh bit as "don't care" value.

- CAN also lacks means to handle Idiot Bubbling Failure. A bubbling idiot station (with a sufficiently low ID) may trash the whole network by repeatedly sending useless messages too frequently and suppress normal communication between other stations.

In order to overcome these drawbacks, different from the event-triggered approach, the concept of time-triggered networks was proposed to improve the performance of in-vehicle networks, such as TTP (Time Triggered Protocol), TTCAN (Time Triggered CAN), CANopen, FlexRay, and TTEthernet (Time Triggered Ethernet) [12]. In a time-triggered approach, the transmission and reception of data takes place at predefined time intervals. Every device or node within the network is aware of this timetable and adheres to it rigorously. In this way, the likelihood of conflict or collision between data packets and network access contention by different devices is minimised. Time-triggered networks prioritize determinism, which means that the timing of data transmission is highly predictable, leading to a consistent and reliable communication pattern. They are well-suited for applications with stringent timing requirements, such as real-time and safety-critical systems [22].

2.2.2 CANopen

Special emphasis is placed on the CANopen communication protocol, both because of the interesting features it has to offer and because such features will be useful at a later stage of this project.

Built on top of the Controller Area Network (CAN) protocol, CANopen is a high-level application layer and communication protocol. While CAN protocol has already been introduced in the previous section, it might be useful to introduce some basic concepts about embedded networking to better understand the CANopen definition.

The international standard ISO/IEC 7498 delineates network communication into seven distinct layers. Figure 7 displays the ISO 7-layer network reference model. Each of these layers has its own specific functions and responsibilities, but not all layers are always implemented for embedded networking applications. A communication protocol that functions above the CAN network's physical layers and basic data link is referred to as a "higher-layer protocol". User-developed software or standardized protocols like CANopen can handle the higher layers. CANopen is an open standard currently maintained and improved by the non-profit association CAN in Automation (CiA), which has made available thousands of pages of specification including communication and device profiles for different industries. Moreover, as reported in [23], it is “open” in many ways:

- It doesn’t involve any license fees.
- It facilitates the integration of both CANopen-compliant and proprietary CAN nodes into a unified network, fostering developers to adopt CANopen in their devices and

systems without encountering proprietary limitations. It can be also linked to networks with other protocols via gateways and bridges. This interoperability reduces integration challenges and costs.

- CANopen comprises a concise set of essential functionalities alongside an extensive array of optional features, allowing for easy expansion and customization tailored to specific applications.

Other notable advantages offered by the CANopen protocol are scalability and real-time communication. The scalability feature implies the possibility of easily adding or removing devices, offering a flexibility that is desirable in dynamic industrial settings where the number of devices may change over time. As far as real-time communication is concerned, there is no general specification on the speed required for a control system to be defined as a 'real-time system'. It should simply be able to meet the application's requirements.

Finally, it is useful to know that in CANopen there are three different types of "identifier", according to Pfeiffer et al. [23]:

- The Node ID is used to identify a specific CANopen node. Up to 127 nodes are allowed in a CAN network.
- The Index and Subindex within the Object Dictionary, represented by a 16-bit and 8-bit "identifier" respectively, serve the purpose of identifying precise variables within a node. Further elaboration on the Object Dictionary will follow shortly.
- The COB ID and CAN message ID both refer to identifiers used to distinguish different messages or data frames within a CAN network, and they are unique values.

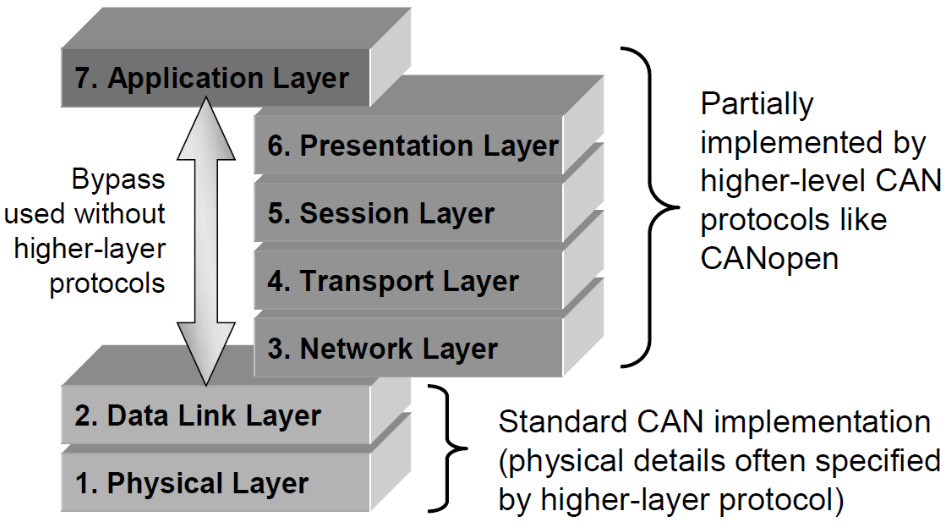


Figure 7: The ISO 7-layer Reference Model [23].

To summarize, CANopen provides a standardized framework for the exchange of data and commands among devices in a CAN network. These devices encompass sensors, actuators, controllers, and other industrial equipment. Thanks to the robustness and reliability of the

CAN lower layers combined with the flexibility of the CANopen application layer and the interoperability provided by the CANopen profiles, CANopen is known for its versatility and nearly limitless applications.

Object Dictionary

The Object Dictionary (OD) is one of the core aspects of any CANopen node. The Object Dictionary encompasses all parameters defining the functionality of a CANopen device, covering communication, process data, configuration options, and diagnostic details. Structured as a lookup table, each parameter is accessible via a 16-bit index and an 8-bit sub-index. Each entry within this table can contain a variable of any type, either pre-defined (Standard or Complex) or specified by the manufacturer, with variable lengths. Additionally, the Object Dictionary serves as storage for node-specific application data, accessible for reading and writing by other CANopen nodes across the network. The presence of comprehensive descriptive information or minimal data within the Object Dictionary hinges on the specific application's needs, adhering to the network design prerequisites. However, some information in the Object Dictionary is mandatory and must be present. The CANopen features implemented by the node typically determines which information is required.

An example of the OD structure is reported in Table 1. A comprehensive discussion can be found in [23].

Table 1: Object Dictionary organization [19].

Index Range	Description
0000h	Reserved
0001h – 0FFFh	Data Types
1000h – 1FFFh	Communication Entries
2000h – 5FFFh	Manufacturer Specific
6000h – 9FFFh	Device Profile Parameters
A000h – FFFFh	Reserved

To effectively monitor, analyse, and configure the parameters of each CANopen node, it's essential to have a file format that can be electronically read. CANopen provides two separate file formats for this intent: Electronic Data Sheets (EDS) and Device Configuration Files (DCF).

The format of the DCF closely resembles that of the EDS. However, their intended uses differ significantly. Various commercial software tools are readily available to facilitate the creation and maintenance of EDS files. The concept revolves around the utilization of an EDS by a CANopen configuration tool or master, enabling the identification of accessible parameters within a node. Additionally, the DCF can be utilized to store or retrieve the values associated with these OD entries. Consequently, it becomes possible to save and restore all settings of a node [23].

Access to CANopen Object Dictionary

Once the features of the nodes have been defined through the OD, it is necessary to have a method to access them, so that they can be shared across the network. CANopen protocol defines different types of communication objects:

- Service Data Objects (SDO): SDO is a key feature of the CANopen protocol offering a means to enable generic access to a CANopen node's Object Dictionary. It is a mechanism for exchanging data between devices on the CANopen network, allowing one device to read or write specific parameters or objects in the Object Dictionary of another device. SDO operates through a request-response framework. The device that wants to access data (the client) sends an SDO request message to the target device (the server) specifying the data object's index and sub-index in the Object Dictionary. Subsequently, the server processes the request and returns a response message. This response contains the requested data or, in the case of a successful write operation, an acknowledgment. Each SDO request and response message encompasses 8 bytes of data [24].

  To accommodate larger data objects, SDO messages support data segmentation. Messages can be divided into multiple frames, and the receiver reconstructs these segments to restore the complete data object. However, it's worth noting that the request-response mechanism and data segmentation employed by SDO messages introduce some overhead and latency. Hence, while it might be feasible to construct a communication system solely reliant on SDO communication, more effective communication methodologies complement SDO. In CANopen, the Process Data Objects (PDOs) serve as this streamlined and efficient method for transmitting process data.
- Process Data Objects (PDO): In the CANopen protocol, PDOs are used for efficient and real-time communication of process data between devices on the network without the request-response overhead associated with SDOs. PDO communication is typically divided into two categories, Transmit PDOs (TPDOs) and Receive PDOs (RPDOs).
  - TPDOs are used by a device to send process data, status information, sensor readings, or control commands on the network from one device to others in real-time applications.
  - RPDOs are used by a device to receive data from one or more remote devices on the network to be processed or used by the receiving device.

Figure 8 presents a graphical explanation of the PDO communication structure.

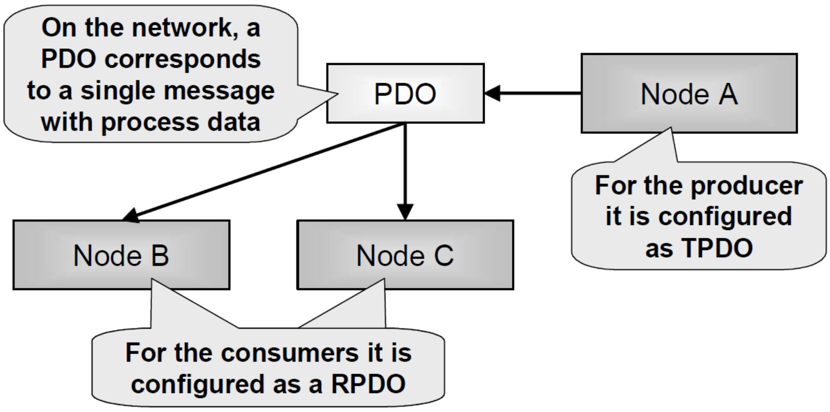


Figure 8: PDO communication [23].

Additionally, each PDO has two sets of configuration parameters: communication parameters and mapping parameters. Communication parameters define how the PDO should be transmitted or received within the network, and include:

- CAN Object Identifier (COB ID), which is a message identifier used for each PDO. A default configuration known as the "pre-defined connection set" specifies the default assignment of COB IDs to respective nodes.
- Transmit Trigger Options, as CANopen support all major transmit trigger methods, including:
  - Event driven (Change of State with “Inhibit Timer” to avoid the indeterminism).
  - Time driven (Event Local Timer in milliseconds).
  - Individual polling (not used).
  - Synchronized or grouped polling (SYNC signal produced on a fixed time basis to synchronize devices data).
  - A combination of them (implemented using the transmission type “manufacturer specific” as they are not part of the CANopen specification).

The PDO mapping parameters define which Object Dictionary entries are mapped in a PDO. The PDO comprises a sequence of 64-bit entries populated one by one with data extracted from the Object Dictionary entries specified within the single mapping parameters [25].

It's important to emphasize that the mapping for a Process Data Object (PDO) often varies between the Transmit PDO (TPDO) and Receive PDO (RPDO) sides. When a receiving device views the PDO as an RPDO, it's possible that certain data elements are immediately utilized as outputs to drive actuators. Meanwhile, some data may be stored locally for subsequent processing, and a portion of the data might never be used at all. Consequently, this can lead to a wholly distinct set of PDO mappings on the receiving end. However, all the process data variables must be mapped in RPDOs, also the "unwanted" ones. CANopen support multiple "dummy" entries for this kind of process data [23].

Network Management (NMT)

The CANopen network management is based on a master/slave approach. The device possessing NMT master functionality manages the CANopen NMT slave devices. [26] Every CANopen slave node must implement an NMT state machine that allows the slave to be in different operating states, as explained in Figure 9, which may be:

- Pre-operational.
- Operational.
- Stopped.

Some of these state transitions can occur automatically, initiated by the slave devices themselves, while others necessitate the reception of the corresponding Network Management (NMT) Master message. NMT commands issued by NMT master devices can be directed at individual nodes or broadcasted to all nodes simultaneously. Confirmation of these NMT commands at the application program level is accomplished through the Heartbeat message.

The Heartbeat method serves as a monitoring mechanism to verify the availability of any CANopen device within the network. It consists of a concise one-byte message conveying the current state of the associated NMT slave device. This Heartbeat message is accessible to all other nodes in the network. The transmission frequency of Heartbeat messages is configurable, typically achieved through the heartbeat-producer-time parameter specified within the transmitting device's Object Dictionary.

The utilization of CANopen communication depends on the current NMT state, as outlined in Table 2. After the power-on switch is activated, the CANopen slave node initiates the complete application, encompassing the CAN/CANopen interfaces and communication protocols. Once successfully initialized, the node produces and sends a boot-up message, transitioning into the pre-operational state. During the pre-operational state, the NMT slave device remains ready for optional configuration and activation by the NMT master device. Alternatively, there's the choice to configure an NMT slave device to initiate autonomously. Once in the operational mode, a CANopen node operates at full capacity, performing all the designated input and output functions for which it was designed. The primary distinction between the pre-operational and operational states is the addition of PDO communication, enabling the node to exchange and work with process data. Finally, the NMT stopped state can be utilized to halt a device from communicating SDO and PDO messages. It just accepts the NMT message and continues to produce the Heartbeat message [23].

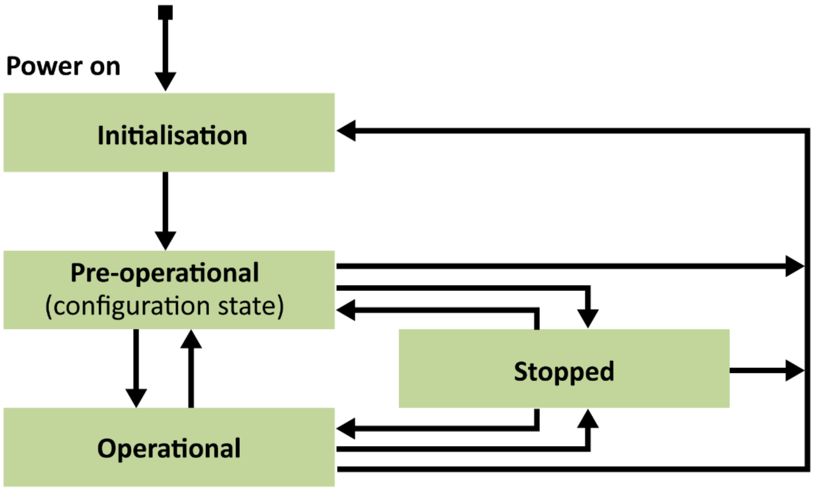


Figure 9: NMT slave state machine [23].

Among the CANopen communication modes listed in Table 2, the Emergency message (EMCY) has not yet been introduced. The error register is a variable that's part of the CANopen object dictionary in every CANopen slave node, and it plays a pivotal role in controlling the emergency state machine. When an error is detected, the CANopen device activates the emergency service and dispatches an 8-byte EMCY message. In most cases, emergencies are reported just once. The indicated emergency state remains active until the node utilizes another emergency message to clear or reset that particular emergency condition. These detected anomalies may relate to various aspects, including the CAN data link (for instance, recovery from a bus-off state or an error passive mode indication), the CANopen application layer (such as exceeding PDO length or encountering an RPDO timeout), or the device's own application (like mains voltage irregularities or over-temperature conditions). In addition to some general emergency error codes, CANopen profiles also define specific additional codes for particular applications and use cases.

Table 2: NMT state dependent communication [23].

CANopen communication	Inizializing	Pre-operational	Operational	Stopped
Boot-up	X			
SDO		X	X	
EMCY		X	X	
SYNC/TIME		X	X	
Heartbeat		X	X	X
PDO			X	

Device and system configuration

An “embedded system” is an appliance consisting of many microcontrollers which, through communication channels, form the so-called “embedded networking”. To enable the system to fulfil the purpose for which it was created and to function reliably, the individual nodes of the network must be informed about their role, what information they should send and receive, and the timing with which to transmit it. This management and coordination task is performed by the control system. There are different types of control systems depending on the relationship between the network nodes, including:

- Traditional or Master/Slave control system.
- Distributed or Masterless control system.

Since CANopen is primarily designed around a master/slave communication model, the focus will be on this control system.

Master/Slave control system

A Master/Slave communication model is a common architectural framework used in various types of networks, including CAN. In this model, the network consists of one or more slave devices controlled by a central master node. The master is responsible for managing and coordinating the communication in terms of timing and sequencing of data transmission. It often monitors the network for errors and can take actions to handle and recover from failures. In addition, during network startup, the master can be responsible for configuring and initializing the slaves. Other functionalities are the shutdown and/or reset of individual nodes or the entire network. On the other hand, the slave devices receive messages sent by the master and transmit data requested by the master. Depending on the application, each slave may have device-specific functions, such as controlling motors, sensors, actuators, or other industrial equipment.

The advantage of having a centralized control is that it makes easier to manage and configure the network. It ensures that messages are sent and received at the appropriate times, which is especially important in real-time and time-critical applications. In cases of access contention to the network, the master determines the priority, optimizes the network bandwidth and resolves conflicts using a predefined arbitration process. The master can enforce strict timing and determinism, guaranteeing that time-critical data is sent and received within specified timeframes.

Nevertheless, this control system has certain drawbacks. The master node stands as a singular point of failure within the system. If the master fails, the entire network may be affected with a significant impact on network reliability. Moreover, managing a centralized master in large networks can become challenging, and the network may become less scalable.

As previously mentioned, CANopen relies on this type of control system to manage the network and to configure and programme devices. Specifically, the NMT master device uses both SDO and PDO communication mechanisms depending on the needs and requirements of the network and its devices.

Apart from configuring communication parameters, the majority of CANopen devices require configuration adjustments because they come with default application functions and a multitude of customizable options. In general, two prevalent configuration strategies are employed. In the first approach, system designers configure all CANopen devices to align with the system's specific requirements and securely store these configurations in non-volatile memory. The second option involves configuring all connected CANopen slave devices each time the system is initialized. While this method ensures the system functions as intended, even in the event of device replacement, it relies on the NMT master device, which must maintain configurations for all CANopen NMT slaves.

CANopen networks offer the flexibility to incorporate proprietary devices and application profiles. However, the CiA (CAN in Automation) provides standardized CANopen interfaces for specific classes of devices, such as generic I/O (CiA401), drives and motion control (CiA402), encoders (CiA406), power supplies (CiA453), and many others.

2.2.3 LIN

Local Interconnection Network is a Universal Asynchronous Receiver-Transmitter (UART)-based, single-master, multiple-slave, open-source networking protocol [18]. LIN is a communication network broadly used in the automotive field mainly because its low cost. It is easy to develop and implement and it requires low memory space. Due to its low communication speed and limited capability in fault tolerance, LIN is used in simple applications such as traditional central door lock activation, window lifter control, mirror adjustment, steering wheel button module, and many low refresh rate sensors where stringent timing performance are not required [21].

2.2.4 FlexRay

FlexRay network was invented by a consortium of different companies that aimed to tackling indeterminism, increasing bandwidth, and enhancing fault-resistance of existing networks. It is a dual-channel architecture with a data rate up to 10 Mbps each, which provides reassurance to satisfy the reliability requirements of emerging safety systems such as x-by-wire [21]. The additional channel is designed to be a backup in case of any communication failure in the other. However, due to the independence of the two channels, it is not always necessary for both channels to transmit the same data, which virtually gives FlexRay 20 Mbps transmission bandwidth in extreme, but losing the redundancy. Due to the complexity of hardware (double channel) and software (many parameters to configure that cost huge engineering effort), FlexRay network is still expensive at present [18].

There are some prominent properties regarding FlexRay's transmission capabilities [21]:

- It can transmit both deterministic and dynamic data in the same cycle, which means FlexRay is suitable for time-critical messages and event-driven/triggered ones (i.e. chassis domain).
- It has much greater payload than LIN and CAN.
- It is very flexible in terms of network topologies. FlexRay supports network structures ranging from point-to-point to different star connections, from linear passive bus to hybrid topology, even the connection types can vary between the two channels.
- The FlexRay protocol can also be employed as an in-vehicle network backbone, working in conjunction with existing systems like CAN and LIN.

Based on these properties, FlexRay Network may be one of the most cost-saving networks in automotive applications in the future.

2.2.5 MOST

MOST, short for Media Oriented Systems Transport, represents a significant advancement from the earlier Domestic Digital Bus (D2B) network and is a product of the MOST Corporation [27]. It distinguishes itself within the realm of in-vehicle communication networks due to its remarkable attributes, including significantly enhanced bandwidth, high-speed capabilities, and its adaptability for transmitting various data types.

The latest iteration of this network, MOST150, encompasses both electrical and optical components, making it a dependable choice for transmitting both synchronous and asynchronous data. This technology has garnered considerable attention in the automotive industry, thanks to a multitude of compelling reasons. Moreover, MOST150 facilitates the transmission of audio and video streams that do not necessarily need to be synchronized with MOST's internal timing. It also boasts compatibility with the widely used Ethernet communication protocol, thanks to its support for MAC addressing in packet data transmission.

Another noteworthy feature of MOST150 is its substantial nominal bandwidth, offering a baud rate of 150 Mbps for transmitting large event-oriented data packages. However, it's crucial to emphasize that MOST networks often entail significant costs. The primary cost driver in the physical layer of MOST networks lies not in the Polymer Optical Fiber (POF) cables themselves, but rather in the connectors and transceivers. This is primarily because optical connectors must be shielded and housed in separate enclosures, and the optical transmitter and receiver components typically require distinct packaging [28].

From a safety perspective, MOST150 stands out as an excellent fit for Advanced Driver Assistance Systems (ADAS) due to its exceptional throughput and deterministic behaviour. Firstly, the use of optical cables renders the network immune to electromagnetic interference, and the error rate at the interface is impressively low, standing at less than 10^{-9} [28]. Secondly, features like Cyclic Redundancy Checks (CRC) and the ability to create redundant interconnecting rings further bolster the network's resilience against errors.

However, it is important to acknowledge that the MOST network is not immune to all possible faults and has some critical disadvantages in fault handling. For instance, its ring transmission structure can lead to a complete network shutdown if a single MOST station experiences a defect, unless backup channels are in place. Malicious timing frames can potentially disrupt MOST synchronization, and faulty channel requests may result in bus jamming. Additionally, the limited temperature adaptability of optical fiber may preclude the deployment of MOST cables outside the passenger compartment of vehicles [21].

2.2.6 Automotive Ethernet

Automotive Ethernet denotes the utilization of Ethernet-based communication networks specifically designed for use within vehicles. It is an extension of traditional Ethernet technology, which has been widely used in other big industries such as IT (Information Technology) and Telecommunication.

Automotive Ethernet is designed to handle large amounts of data in modern vehicles, including data from cameras, sensors, and infotainment systems. One of its standout features is its high-speed data transfer, starting at 100 Mbps and potentially going up to 1 Gbps or more [21]. Rapid data transfer is crucial as vehicles increase in complexity and demand higher volumes of data. Automotive Ethernet is also adaptable, allowing for the easy addition of more devices and sensors as vehicle complexity grows. This flexibility helps future-proof automotive networks as new features and technologies are integrated into vehicles.

Another significant advantage is its ability to guarantee specific timeframes for data transmission, known as deterministic communication. This becomes especially crucial for safety-sensitive applications such as ADAS and autonomous driving. Automotive Ethernet offers reliability with low latency, ensuring real-time data is handled efficiently. Moreover, Automotive Ethernet can connect to the Internet Protocol (IP), making it easier to link to external networks and cloud-based services. This connectivity is essential for over-the-air (OTA) updates and vehicle connectivity.

Compared to traditional automotive communication networks like Controller Area Network (CAN) and FlexRay, Ethernet components have become more cost-effective due to their widespread use in other industries, potentially reducing the overall cost of vehicle electronics.

Ethernet facilitates advanced diagnostic and troubleshooting capabilities, simplifying the identification and resolution of network-related issues [21].

In conclusion, Automotive Ethernet is a promising choice for the next generation of in-vehicle networks, beyond CAN and FlexRay. Its high-speed, reliable, and adaptable communication technology positions it as a key enabler for the evolving automotive industry, supporting advanced driver assistance systems, autonomous driving, and connected vehicles.

2.3 Steer-by-wire

The vehicle concept is rapidly evolving. The mechanical component, on which the construction and operation of vehicles has always been based, is being supported and in some cases replaced by electronic systems. The reasons behind this trend are related to the need for constant improvement in terms of efficiency, safety and driving performance.

A striking example of the rise of the electronic component can be seen in the evolution of the steering system. Initially it was purely mechanical, later the hydraulic power-assisted system (HPS) was introduced, then electrohydraulic power-assisted steering (EHPS) and electric power-assisted steering (EPS, Figure 10) entered the market, and now industry is moving towards steer-by-wire (SBW, Figure 11) system [5].

As its name suggests, steer-by-wire is a steering system in which communication between input, the steering wheel angle, and output, the swivel of the front wheels, occurs by using electronic devices. Vehicle models currently equipped with SBW technology have in most cases retained the traditional mechanical steering system as a backup to meet the stringent safety requirements laid down in the risk analysis carried out by ISO 26262 [29]. The standard proposes an Automotive Safety Integrity Level (ASIL) of D, which is the level with the most restrictions on the degree of acceptable failure. Examples of commercial vehicles equipped with the mechanical back-up are the Infiniti Q50 and Q60 produced by Nissan [30]. This hybrid solution is an intermediate step towards the full implementation of the SBW concept in which the mechanical connection is replaced completely by electric sensors and actuators. This would unlock the technology full potential, because maintaining the mechanical connection means increasing weight, volume, and cost, as well as limiting design freedom. Furthermore, with the prospect of using steer-by-wire technology as a steering system for autonomous driving, mechanical back-up can no longer be considered as an alternative for achieving safety requirements since it is based on human-in-the-loop logic [5].

The advantages brought by SBW are multiple. The omission of the mechanical connection between steering wheel and tyres allows a reduction in weight, more flexible design and better space utilisation. The consequence of a lighter vehicle is higher fuel efficiency, while the greater flexibility includes the possibility of being able to install the steering wheel anywhere within the passenger compartment, thus being able to meet specific requirements. In addition, the lack of a steering column leads to further advantages in terms of comfort and safety. Vibrations from the road surface are no longer transmitted to the steering wheel, thus reducing driver fatigue. In a head-on collision scenario, the risk of injury is notably diminished. Another enhancement attributed to SBW technology is heightened maneuverability and driving stability. Given the modular structure of a steer-by-wire system, it's easily adaptable, allowing various drivers to customize the system according to their preferences, ultimately enhancing the vehicle's handling. In addition, the steering ratio can be adjusted to suit the driver's preferences. For example, during a parking manoeuvre it is useful to have a low steering ratio, while during high-speed motorway driving a high steering ratio configuration is safer and more advantageous. This results in reduced steering sensitivity when the steering wheel is near its central position, making it more challenging for the driver to oversteer at high speeds. As the steering wheel is turned closer to its maximum rotation, the wheels become more responsive to steering commands [31].

This technology is exceptionally adept at integrating ADAS systems, thereby guaranteeing an enhanced level of driving safety.. Furthermore, given the configuration of the system, SBW is a strong candidate among all the possible steering systems used in the increasingly popular autonomous driving (AD) or for others advanced steering systems such as four-wheel steering [4].

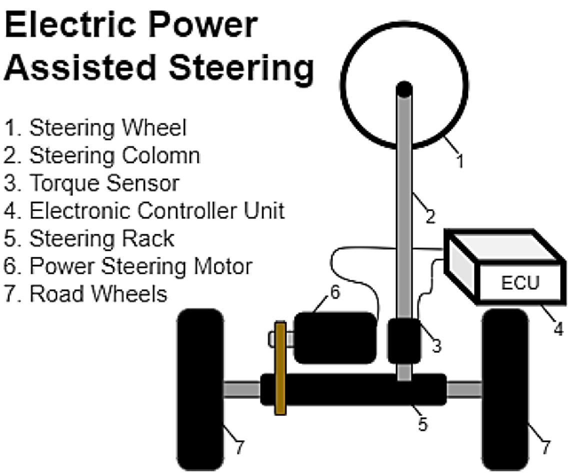


Figure 10: Traditional steering system [32].

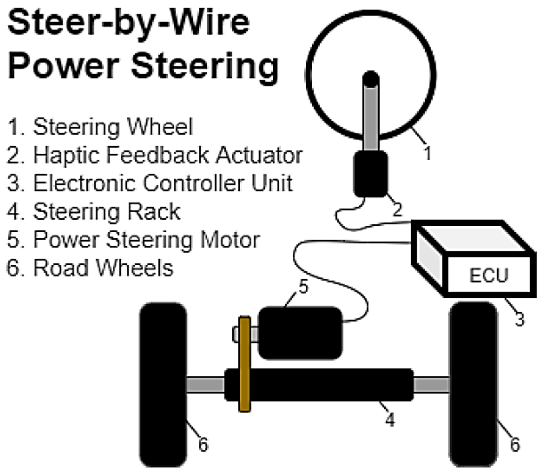


Figure 11: SBW steering systems [32].

Nowadays, there are still some challenges to be addressed before the SBW system can become widespread in the automotive market. These come mainly from the complexity of the control system and the need to achieve a level of safety and reliability that prevents dangerous situations from occurring as a result of hardware or software fault. Furthermore, there are still some shortcomings in recreating a realistic driving feeling, which is now missing due to the lack of the steering column. Finally, being a technology under development, the costs of implementation and maintenance slow down its spread.

Nevertheless, despite few drawbacks, the advantages offered by SBW are an undoubtful proof that research work on this subject must be pursued and the likelihood of seeing vehicles equipped with this technology on the market soon grows [33].

2.3.1 Description of the system

A SBW system can be split into three main subsystems. The first subsection is the human-machine interface device that plays the role of the system's input. The second one is the output of the system that enables the execution of the steering manoeuvre. Finally, there is an intermediate part that connects the entire system. It manages its operation, detects the emergence of errors and allows a continuous update of the system’s software. The block structure can be seen in Figure 12.

Starting with the input block, it consists of:

- Steering wheel.
- Feedback electric motor.
- Angle sensor.
- Torque sensor.
- Rotary speed sensor.

The feedback motor is in charge of simulating the traditional driving feeling experienced by the driver. The sensation of driving can be replicated by directly gauging the resistance torque stemming from the contact between the tires and the road. Alternatively, it can be achieved through a mathematical model that computes the forces influencing the car's wheels, considering dynamic vehicle parameters like speed, front axle positioning, and front tie rod force. Brushless Direct Current (BLDC) motors are often used as feedback motor due to their good power to size ratio and ease of torque and speed control [34].

The task of the three listed sensors is to transmit the input control from the driver to the actuator of the front axle, which is the output of the system. This actuator is usually an electric motor that can be of the same family as the feedback motor (i.e. BLDC), and that adjusts the wheels depending on the angle of the steering wheel, the applied torque and the rotation speed of the steering wheel. It can be installed in a parallel, perpendicular or coaxial configuration to the front axle depending on the steering technology used and the space available. Various steering systems are currently deployed and many of them are presented in Häfele’s research work [11]. Here we just mention the most common ones:

- Rack and pinion.
- Ball screw.

A specific version of the ball screw technology is presented in detail in the following paragraphs as the main topic of the thesis work.

Instead, the management of the system is handled by the ECUs. These are integrated systems that use electrical signals to receive and send information to sensors that are useful for achieving specific tasks. In modern vehicles, the number of ECUs is constantly growing due to the strong technological development and the increasing number of automated functions implemented. The most relevant standard buses for communication are those presented in section 2.2, with a particular interest in TTCAN, CANopen, FlexRay and Automotive Ethernet for steer-by-wire applications [21].

In the specific case of the steering system, the ECU is called the Power Steer Control Unit (PSCU). It works in both communication directions allowing the correct operation of the front axle actuator and the feedback motor connected to the steering wheel. As input data, it uses information from the many sensors in the vehicle system to provide a real overview of the driving situation [32].

Since the steering system is classified as safety-critical and the purpose of SBW is also to improve vehicle safety, it must be able to identify and operate even in the presence of component failure. According to the ASIL-D standard, all components of the steering system must be fault-tolerant, meaning that at least a single failure should not affect the functioning of the system. A popular method to achieve this requirement is the duplication of components, which can be done using replication, redundancy, or diversity. Replication involves the installation of two identical units working in parallel. Redundancy also involves two units, but which alternate in operation if one of them fails. Finally, diversity is based on two dissimilar units operating in parallel and able to perform the task of both units [5]. Figure 13 shows the hardware component of a SBW system, equipped with the redundancy elements.

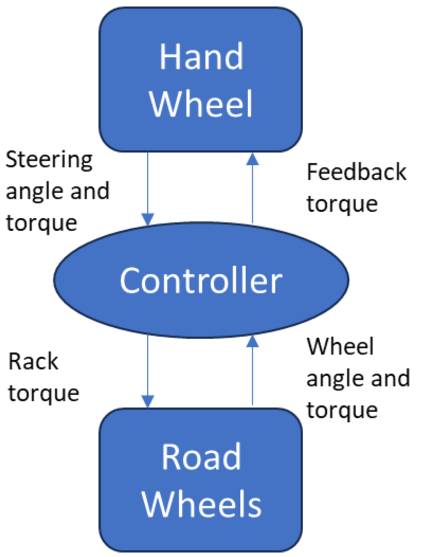


Figure 12: SBW blocks structure.

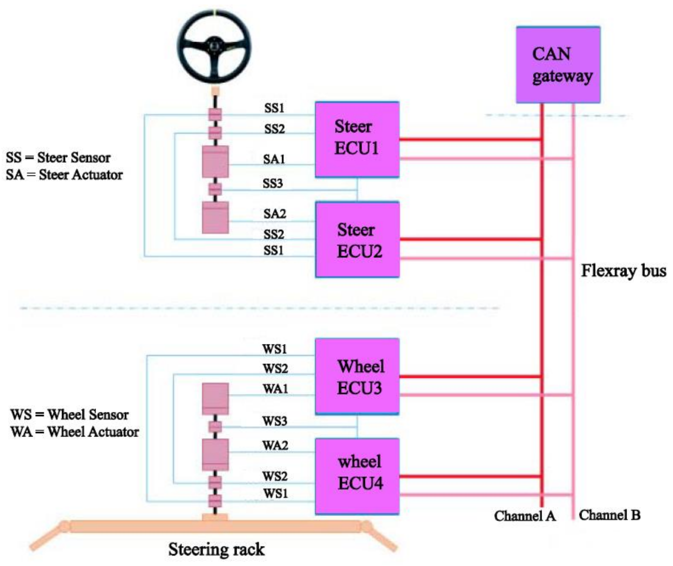


Figure 13: SBW hardware components [34].

2.3.2 SBW control systems

The control system requires special attention as it is responsible for the operation of the entire system and in particular the synchronisation between hand wheel and road wheel. It is particularly complex due to the lack of a mechanical connection, which imposes the need to create a reliable control method capable of tracking the vehicle and providing realistic haptic feedback to the driver. Extensive studies in this field led to the issue of various concepts and philosophies for achieving the aforementioned goal. An overview of the different control method is here introduced, and reported with higher detail in [5]:

- Model-Based Control Technique
  This control system bases its operation on dynamic mathematical models of the vehicle, the steering system and the human-machine interface.
- Torque Map Control Method
  This method uses an empirical approach to determine torque at the wheel. It relies on lookup tables whose data on vehicle dynamics, and in particular torque, come from tests simulating real driving situations.
- Direct Current Measurement Control Method
  Another proposed approach for controlling the SBW system is the use of current sensors and simple algorithms that can artificially calculate and create the drive torque of the frontal axis and the haptic feedback mechanism.
- Torque Sensor-Based Control Approaches
  As the name of this control method suggests, it integrates torque sensors to create closed-loop or open-loop controls for both the steering wheel block and the actuation block. Based on the quantity and variety of sensors integrated, an additional four subcategories of control systems can be delineated. The different configurations, as widely argued by Mortazavizadeh et al. [5], are:
  - Torque sensor on both steering wheel and road wheel
    This first method involves installing a torque sensor behind the steering wheel and one near the wheels on the drive shaft. These two sensors exchange information on the driver's requests and the actual state of the vehicle in order to create a closed-loop control system for both steering wheel and front axle blocks. A graphic representation of it is shown in Figure *14*. Subsequent ones are shown in the Annex 9.
  - Angle Sensor on both steering wheel and road wheel
    The operating principle of this control method is similar to the previous one, with the difference that the drive command and haptic feedback are based on measuring the steering angle, which is then converted into torque using a dynamic mathematical model.

- Angle sensor on steering wheel and torque sensor on road wheel
  This hybrid configuration utilises the steering wheel angle measurement for steering, while the feedback mechanism relies on the torque measurements of the sensor near the wheels. The main problem is that the torque sensor, which is more expensive and more sensitive to working conditions than the angle sensor, works under harsh conditions.
- Torque sensor on steering wheel and angle sensor on road wheel
  In the latter control system, the two sensors are reversed, in favour of greater durability and reliability. Mathematical models are still used to convert the angular signal into a torque signal.

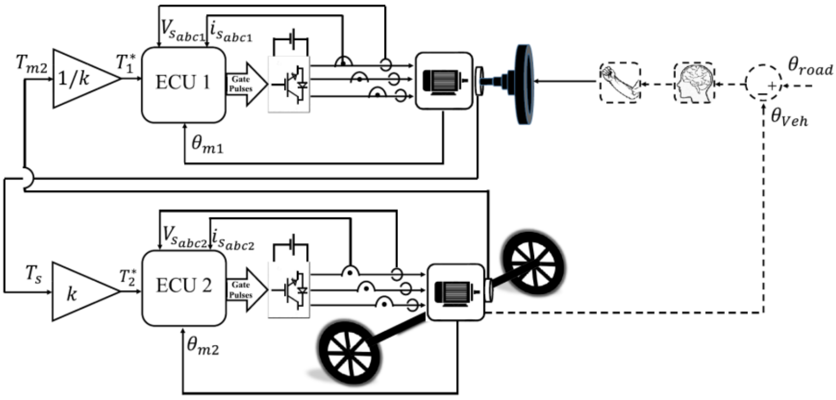


Figure 14: Block diagram of Torque Sensor-Based Control [5].

2.3.3 SBW sensors

It is now clear that SBW systems base their operation on data from sensors, which have the task of instantly detecting and transmitting the status of the entire system to the control unit. Therefore, they play a key role, reason why it is necessary to carefully study which and how many sensors are required by a SBW steering system.

Torque sensor

Within SBW applications, torque sensors play a pivotal role in measuring the applied torque to the steering system. This data holds utmost significance in precisely interpreting the driver's steering inputs and delivering suitable steering assistance or feedback. There are several types of torque sensors which can be used in SBW systems such as Strain Gauge, Magnetostrictive, Hall Effect and Optical Torque Sensors. The commonly used for the steering wheel application is Strain Gauge Torque Sensors (reported for example in Figure 45 available in Annex 9). Their operation relies on strain measurement of a strain gauge. This deformation alters the strain gauges' resistance, which is then measured and converted into an electrical signal. They offer good accuracy, reliability and cost-effectiveness, making them suitable for many SBW applications [35].

Magnetostrictive Torque Sensors and Hall Effect Torque Sensors are based on the behaviour of specific materials when exposed to a magnetic field [36]. This characteristic constrains their application since the interference of external magnetic fields could affect their precision and accuracy. However, thanks to their resistance to harsh working environments, they are a viable alternative for application near the wheels [37].

Finally, optical sensors are able to guarantee higher performance than all other proposed sensors, in some cases even higher than that required for this application, but their restricted use is mainly due to their higher cost and sensitivity to the working environment [38].

As proposed by the steer-by-wire sensor configuration illustrated in Figure 15, one torque sensor is typically located in the steering wheel block, directly on the steering wheel or its shaft, and the latter on the front axle, usually on the steering motor shaft. Placing the torque sensor near the driver's input source ensures accurate measurement of the driver's commands. Placing the other close to the wheels enables the detection of reaction torque from the road-wheel interface, which is useful in recreating a realistic driving feel for the driver. Additionally, this configuration allows for real-time monitoring and adjustment of the steering assistance based on the driver's input and system requirements.

Depending on the SBW configuration, a second torque sensor can be installed close to the road wheels to provide information on the resistant torque to the feedback mechanism.

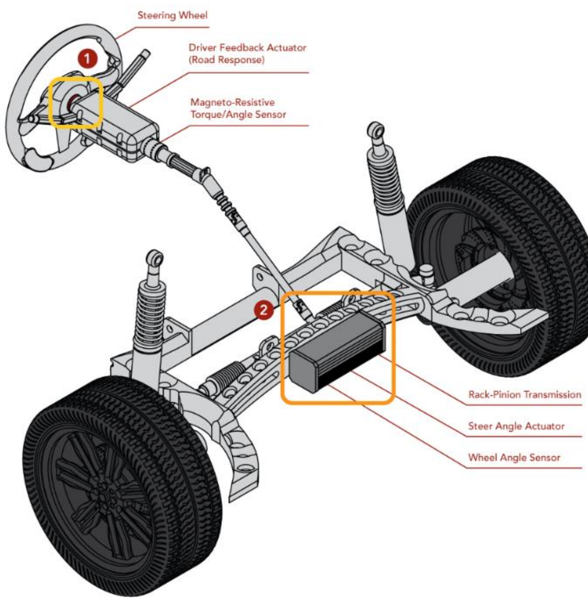


Figure 15: SBW sensors configuration [39].

Steering angle sensor

Steering angle measurements are crucial for various automotive applications, including stability control, driver assistance systems, and many others. Hence, employing multiple angle sensors serves for redundancy and data validation. Typically, the steering control program necessitates two signals from two angle sensors to validate and confirm the steering wheel's position. Usually there is one sensor located behind the steering wheel and the second next to the steering shaft. However, the working conditions of the sensors are very different. The one placed on the shaft must be able to provide reliable measurements even when affected by temperature variations, vibrations, and dust. Different technologies are therefore used depending on the type of application. Primarily, these sensors operate based on optical, magnetic, or inductive principles [40].

Before proceeding with a comparison of the different types of angle sensors, it is important to know what requirements they must fulfil in order to be suitable for the application under analysis. Some of the key requirements are listed here, according to [40]:

- Accuracy: high accuracy is essential for safety-critical applications. To ensure precise control of the vehicle, value within ±0.1 to ±0.5 degrees are required.
- Resolution: resolution refers to the smallest detectable change in the steering angle. It is essential for capturing subtle steering inputs accurately. The resolution commonly varies in a range of 0.1 to 0.5 degrees.
- Linearity: this refers to the relationship between the sensor's output and the actual steering angle. Non-linearities can lead to inaccuracies in control and can affect the performance of safety systems. It is usually within ±0.5% to ±1% of full scale.
- Range: steering angle sensors must cover the full range of motion of the steering system, from full lock left to full lock right. It is typically around ±720 degrees.
- Speed of Response: Quick response is crucial for stability control systems and other safety features. Response times are often in the range of 1 to 10 milliseconds.
- Durability: Automotive environments can be challenging, subjecting components to temperature fluctuations (e.g., -40°C to 85°C), moisture, vibrations, and mechanical stress.
- EMC Compatibility: Electromagnetic compatibility (EMC) is essential to prevent interference from other electronic components in the vehicle. The sensor should be designed to mitigate electromagnetic interference.
- Self-Diagnostics: Steering angle sensors may include self-diagnostic capabilities to detect sensor failures or drift over time. These diagnostics can be part of the overall vehicle health monitoring system.
- Cost: the pricing of steering angle sensors can differ significantly. It's essential to balance sensor performance with cost constraints. High-performance sensors may be more expensive but can be necessary for critical safety functions.

The values given are only indicative as they may depend strongly on the specific application, vehicle type and regulatory standards.

Table 3 shows the main types of angle sensors as a function of some of the parameters discussed above. Starting from these data, some considerations can be made:

- Resolvers are sensors with a very high accuracy, are robust against vibration and are suitable for working in dirty environments. Thanks to these characteristics, these sensors find primary use in applications demanding high precision. However, their use is limited by their size and overall price. They require additional electronics for signal generation and conditioning, which has a significant impact on the final cost [41].
- Optical sensors are very popular in steering angle systems. They have good resolution as well as good accuracy, which makes them suitable for installation behind the steering wheel. In addition, as they are a well-known and popular technology on the market, the costs are relatively low. However, they suffer from some disadvantages such as high sensitivity to dirty environments and vibrations, as well as high power consumption intrinsic to their LED operating system.
- Induction sensors usually have a maximum operating range of less than 120°. In addition, they present the problem of EMC when installed in sensitive automotive areas. Consequently, they are not very suitable for steering system applications.
- Hall sensors are a well-established technology. They can measure angles on a scale of 360°, offer excellent performance in resolution, accuracy and update-rate, and are cost-effective. Unlike magneto-resistive sensors, Hall sensors can be disturbed more easily.
- The best known and most widely used magneto-resistive sensor is the Anisotropic Magneto Resistive (AMR) sensor. It relies on the behaviour of Permalloy thin films when immersed in a magnetic field. They modify their resistance based on the alignment of the field concerning the current's direction. It offers a resolution and accuracy perfectly in line with the requirements for steering systems. However, this measuring system allows to record a maximum angle of 180°.
- The so-called spin-valve Giant Magnetoresistance (GMR) is another magneto resistive principle quite new compared to the principles previously mentioned. It differs from the AMR effect in that it bases its operation on the relative direction of magnetisation of two magnetic layers separated by a non-magnetic layer. For angular measurement, one ferromagnetic layer is rotated in a reference direction, while the second follows the direction of the external magnetic field. Another crucial distinction from AMR sensors is that GMR sensors offer an absolute steering-angle value across the entire steering-angle spectrum, making them suitable for multi-turn sensor applications. The resolution and accuracy are slightly better, and the update time is significantly shorter. These features allow it to be adopted in many

applications including steering angle measurement. Another relevant fact is that this type of sensor is undergoing strong development and promises to achieve even higher performance in the foreseeable future [40].

Table 3: Steering Angle Sensors [40].

Parameter	Optical	Inductive	Hall	Resolver	AMR	GMR
Range	360°	120°	360°	360°	180°	360°
Resolution	3.0°÷0.2° 0.8÷0.06%	< 1.5° 1.25%	< 2.0° 0.55%	< 0.1°	<0.08°	<0.03°
Accurancy at 25°C	3.0°÷0.5° 0.8÷0.14%	< 1.5° 1.25%	< 2.0° 0.55%	< 0.1° 0.028%	1.65° 0.92%	0.9° 0.25%
Accurancy vs Temp.	3.0°÷0.5° 0.8÷0.14%	< 2.0° 1.67%	< 2.3° 0.64%	< 0.1° 0.028%	2.95° 1.64%	1.8° 0.5%
Hysteresis	3.0°÷0.2°	< 0.3°	0.5°÷0.7°	-	0.1°÷0.2°	0.1°÷0.4°
Update Time	Very fast	5 ms	4 ms	100 µs	4.5 ms	82 µs
Temperature (short time)	< 85°	< 125°	125°	125°	125°C (160°C)	125°C (140°C)
Standard sensing condition	No dust	3.3 MHz	50÷100 mT	0.1÷10 kHz	45 mT	30 mT
Interface	Incremental	Analog, PWM	Analog, PWM, SPI	Analog or sensor ASIC	Analog, PWM, SPI	SPI

3 Active Front Independent Steering

The SBW technology described in section 2.3 is already a big step forward in the field of steering systems. It makes it possible to improve safety, comfort and driving performance, but in its basic configuration it still has some deficiencies.

This chapter introduces a steering system known as Active Front Independent Steering (AFIS). In combination with SBW technology, it allows to increase even further the quality and flexibility of steering systems.

3.1 AFIS system

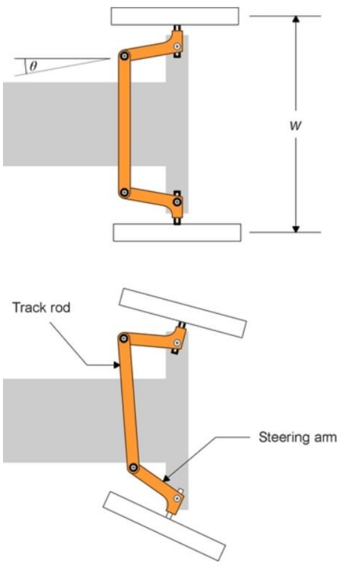
The term Active refers to the possibility of setting up the steering system in the most suitable way according to driving conditions or driver preferences. Active is therefore synonymous with flexibility. In addition to the traditional steering power function, the active steering system can apply the active additional angle to the steering system through the steering motor connected to the driver input, so as to realize functions such as variable transmission ratio and steering intervention stability control. In the latter configuration, the active steering system can not only realize the coordination and unity of the steering ease and the steering feel through the control of the system force characteristics, but also realize the perfect integration of the active safety and the driver steering feel through the control of the system displacement characteristics [42].

Based on the definition of Active Steering System, it can be stated that SBW technology is already part of this group of steering systems. In fact, it can provide most of the functions and benefits mentioned above. The key difference between a traditional SBW steering system and an AFIS system is the ability to manoeuvre the two steering tyres independently. An SBW system involves decoupling the steering wheel block from the actuating block, by removing the steering column and using electronic devices and communication protocols as a means of connection. However, the two components from a hardware point of view are unchanged. Specifically, the front axle is driven by an electric motor, which is mechanically connected to both tyres according to the widely adopted Ackermann steering geometry. This is the geometry implemented in most of today's vehicles as it fully meets the requirements for a reliable and precise steering system but has a relative wheel alignment error during the steering phase. This misalignment can be fixed by decoupling the two tyres, i.e. using AFIS technology.

3.2 Ackermann steering geometry

Nowadays, the most popular steering geometry is the Ackermann steering geometry. It consists of three main elements, which are the central track rod and two steering arms inclined at an angle θ to the longitudinal axis of the vehicle, as shown in Figure 16. This configuration was designed to allow the front wheels to trace two circular paths of different radii. In fact, the radius of curvature of the inner wheel must be smaller than that of the outer wheel to allow the vehicle to follow a circular trajectory with minimal slip. The aim is to have a smooth and free rolling of the tyres, without lateral slip across the road. Minimising this slippage is crucial for better cornering stability and, above all, for managing tyre wear.

The theoretical solution proposed by Ackermann steering is to have a unique centre of rotation for all wheels. Since the rear axle is fixed, the centre lies along the extension of this axle. The front wheels, in order to have the same centre, are rotated by different angles. Specifically, the steering angle of the inner wheel is greater than that of the outer wheel as highlighted in Figure 17 [43].



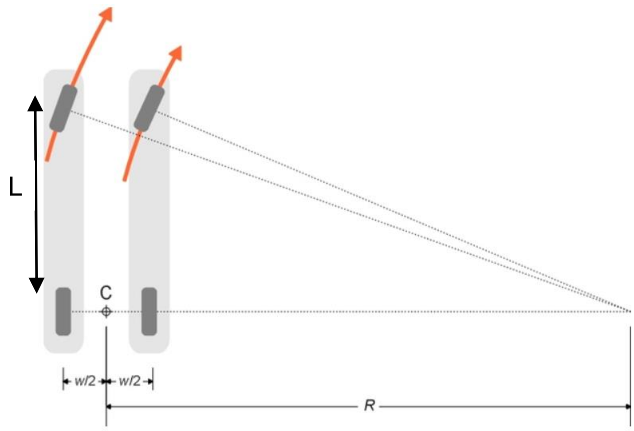


Figure 16: Ackermann steering geometry [43]. Figure 17: Ackerman steering angle [43].

Through trigonometric considerations, the steering angle of both the single-track model and the full model can be calculated. The angle of the single-track model, δ, is known as the Ackermann angle, and can be obtained as stated in equation (1) below [43]:

$$\delta = arctan\left(\frac{L}{R}\right) \tag{1}$$

$$\delta_{i,ideal} = arctan\left(\frac{L}{R - \frac{1}{2}w}\right) \tag{2}$$

$$\delta_{o,ideal} = arctan\left(\frac{L}{R + \frac{1}{2}w}\right)$$

(3)

Where the mentioned symbols are:

- δ, Ackermann or single-track angle.
- $\delta_{i,ideal}$, Ideal steering angle of the inner wheel.
- $\delta_{o,ideal}$, Ideal steering angle of the outer wheel.
- L, Vehicle wheelbase.
- R, Radius of curvature.

The angles obtained through these equations are ideal. The actual mechanical steering system cannot replicate them except for specific turning angles. Once the outer steering angle is set, the inner wheel will always be affected by a positioning error due to the mechanical constraint between the wheels. To better visualise the concept, two pictures comparing real and traditional or real steering are reported below. On one hand, Figure 18 shows how the only position that can guarantee pure rolling is the dead position, in which the wheels are positioned straight ahead. Figure 19, on the other hand, shows how the alignment error of the inner wheel increases as the outer steering angle increases up to a maximum of 10% around an outer angle of 25°.

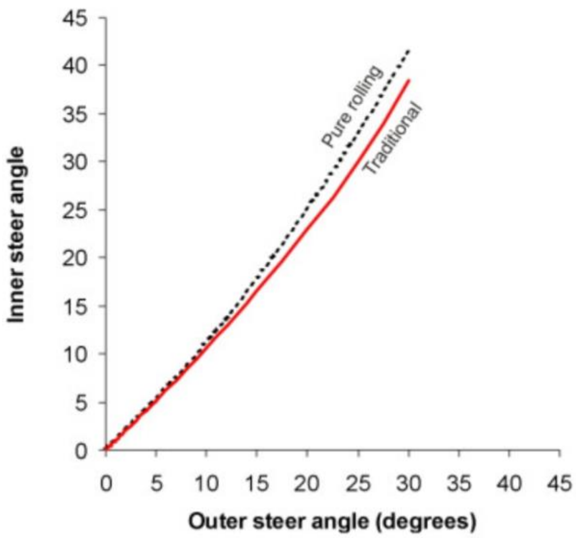


Figure 18: Inner-Outer steering angles [44].

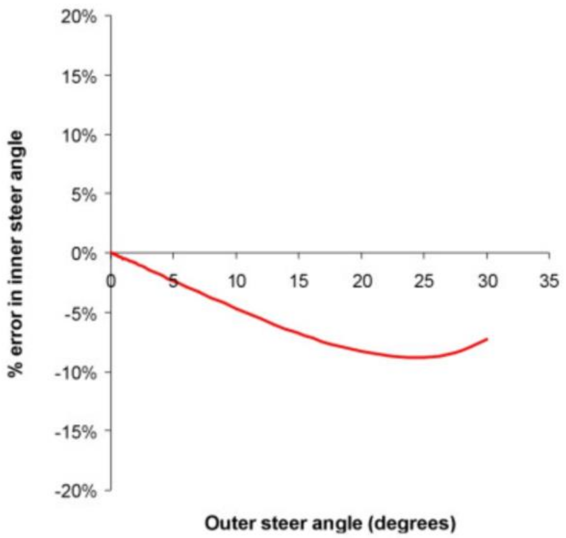


Figure 19: Ackermann angle error [44].

The parameter that can be adjusted to contain the Ackermann error is the steering arm angle θ. In the early models built, for construction simplicity, the angle θ was chosen so that the extension of the two arms met at the centreline of the rear axle (see Figure 21). It was later discovered that by increasing the angle and thus moving the point of intersection of the two arms towards near the front axle, it was possible to reduce the error over the entire range and make it null for specific steering angles other than zero (as depicted by blue line in Figure 22).

A further step was to find an angle θ for which there was asymptotic rolling, i.e. an almost zero error over the entire steering range. Through some geometrical considerations and mathematical reformulations of the ideal and actual steering angles, it was possible to derive the value of θ for which there is asymptotic rolling (graphically presented in Figure 21). With this setup, the error of the internal wheel angle is almost zero for small angles of curvature, but the problem is not yet solved as the error grows exponentially as the outer steering angle increases (as can be seen from the green line of the graph in Figure 22) [44].

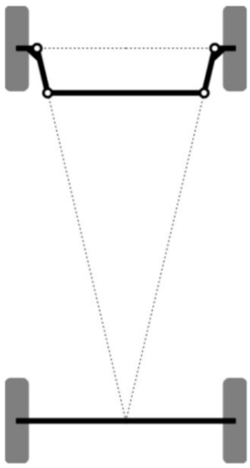


Figure 20: Traditional arm angle [44].

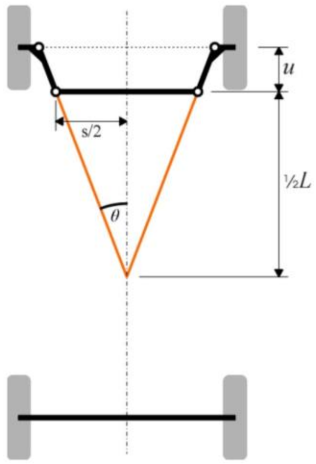


Figure 21: Asymptotic rolling arm angle [44].

In conclusion, a steering linkage that matched the pure rolling dashed curve presented in Figure 18 and that thus would exactly eliminate tyre scrub, cannot be realised with a practical Ackermann steering geometry. Furthermore, the assumption of pure rolling can only be applied at low speeds because the direction in which the wheels point can be assumed to be the same as the direction of motion. At high speeds the wheel slip angles become significant and the number of parameters to be taken into account increase. Foremost among these is the transfer of load from the inside wheel to the outside wheel, with consequent variation of the two slip angles. For this type of analysis, it is necessary to work alongside the study of lateral dynamics to study suspension design.

Coming back to the steering error of the inside wheel, which is intrinsic to Ackermann steering geometry, it can be completely avoided with the use of an AFIS system. This type of computer-controlled steering system can swivel independently the front wheels, thanks to electrically powered actuators. A microprocessor decodes the electrical signal received from the driver's handwheel and adjusts the steering angles based on factors like the vehicle's speed, turning radius, and the wheel loads during that moment [44]. These innovative steering systems are therefore an important turning point towards improved handling, steering precision, durability and safety.

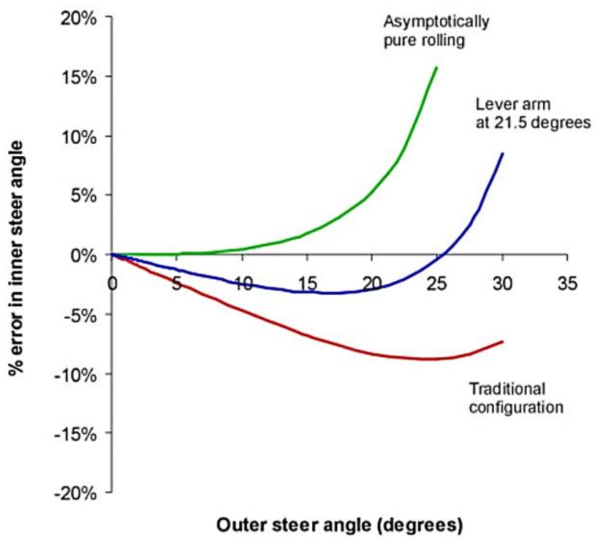


Figure 22: Ackermann steering angle errors [44].

3.3 Previous work and its development

With the purpose of studying a steering system capable of overcoming the mentioned limitations of Ackermann geometry, an AFIS model equipped with SBW technology was proposed by the colleague Finn Häfele at the end of his thesis work (as represented in Figure 23). The focus of his work was the analysis of different steering system configurations available in the literature in order to identify the one that best meet the specific requirements and manoeuvres in accordance with the ISO standard [11]. The steering manoeuvres considered were:

- Standstill
- Driving straight ahead
- Slow cornering
- Fast cornering
- VDA-Test
- Deceleration when cornering
- Acceleretion when cornering
- Steering angle jump
- Steering Oscillation
- Parking Drive
- Driving over a vibrating plate with wetness
- Cornering over a hill
- Cornering over a very rough road
- Cornering on ice/snow

While the different steering systems investigated were:

- Manual
- Power steering
- AFS (Active Front Steering)
- AWS (All-Wheel steering)
- SBW (Steer by wire)
- 4WIS (Four Wheel Independent Steering)
- FWIS (Front Wheel Independent Steering)
- RWIS (Rear Wheel Independent Steering)

The target criteria used to compare the different systems were:

- Quality of the steering while driving (safety and comfort)
- Complexity/Feasibility
- Costs
- Novelty

At the end of the study, the selected steering system was the FWIS in the form of the steer-by-wire concept. It was conceived with the aim of replacing the existing conventional steering system installed on one of the demonstration vehicles built by KIT University. This vehicle is designed with a modular or customisable structure, allowing for easy reconfiguration and adaptation to suit different research objectives or applications. It currently consists of an aluminium chassis, a centrally located driver's seat and four wheels on which the system rides. The propulsion system is an electric motor powered by a battery and driving the rear wheels. In addition to the traditional charging system via the socket, the vehicle is equipped with a fuel cell able to convert hydrogen into electricity. The installed steering system relies on a rack and pinion configuration and allows the front wheels to be steered by a maximum angle of 28° as a result of 2.8 turns of the steering wheel. Finally, the steering system is not equipped with auxiliary power systems. Some of the vehicle characteristics are reported in Table *4* and more details can be found in [11].

The task of the author is to make the draft of the proposed steering model operational and functional by carrying out the appropriate adjustments. To achieve this, a functional and mechanical study was performed on the individual components, how they interact and how they are fastened to the chassis. The aim is to ensure that the system is able to accomplish its assigned task and that it meets standard mechanical design requirements. In the following chapter, the overall FWIS system with SBW concept will be presented component by component.

Table 4: eVee vehicle characteristics

	Vehicle Characteristics	
Wheelbase	1686	mm
Track width	1222	mm
Weight (max)	425 (L6e-B class)	kg
Steering system	Mechanical – Rack and pinion	Front wheels
Propulsion system	Electric motor + Fuel cell	Rear wheels
Suspension system	Double Wishbone Suspension	/

4 Design of SBW Steering System

The focus of this chapter is to describe the steering system designed, conceived as a proposal for a future integration on the test vehicle owned by the FAST department of KIT University. First, based on the knowledge acquired in the preliminary phase of the work, including the requirements and operation of traditional steer-by-wire systems, an evaluation was made on the steering wheel unit. Subsequently, the front axle system was designed and generated in CAD format. It was developed from the draft proposed in the thesis by Häfele [11], according to the schematic reported in Figure 23, which was updated with both physical and conceptual modifications. The initial part of the study dealt with the analysis of the system's operating logic and the forces exchanged within it. Through this process, it was possible to identify the components required for a consistent transmission of motion and an adequate distribution of stresses on the support systems. The next step was the mechanical design of all system components to ensure feasibility. In this way, it was also possible to define the exact characteristics of each component according to the acting loads and the selected materials. Finally, some layout adjustments were made following the study of the assembly procedure.

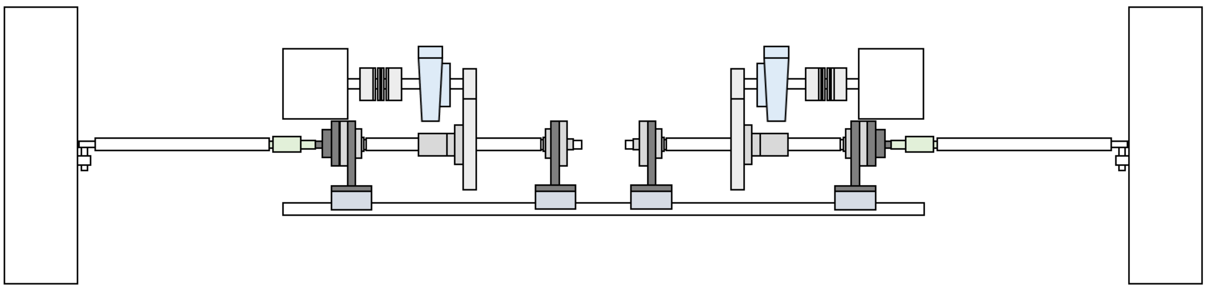


Figure 23: Starting draft of the SBW system [11].

4.1 Steering wheel system

In cooperation with the research group of the FAST department, a FANATEC CSL DD racing wheel equipped with a Direct-Drive system was identified and purchased (see Figure 24 for reference) [45]. The unit consists of a brushless DC motor with a peak torque of 5 Nm, which can be increased up to 8 Nm with the addition of an external kit. Furthermore, it includes an angular position sensor and a torque sensor to measure the steering angle and input torque provided by the driver. The angle sensor is a high-resolution (contactless) Hall position sensor offering a resolution of 0.001 degrees. The model of the torque sensor, however, is not explicitly disclosed by the manufacturer, but it is presumably either the widely used strain gauge torque sensor or, consistent with the angle sensor, it is also a Hall effect sensor. The resolution is 0.001 Nm. It is PC compatible, but extensive research is needed on how to interface it and make it communicate with the whole steer-by-wire system.

Overall, the characteristics of the steering wheel presented adhere to the requirements set out in the research part of this project. The main characteristics of the device are listed in Table 5.

Table 5: Steering wheel system characteristics.

FANATEC CSL DD (5 Nm)		
Feedback motor	BLDC	Direct-Drive
Position sensor	HR contactless Hall effect angle sensor	Res. 0.001°
Torque sensor	Strain Gauge torque sensor	Res. 0.001 Nm
Communication	USB-C to PC	CANopen friendly

Figure 24: FANATEC CSL DD.

4.2 Overall concept of front axle system

Before moving on to a detailed analysis of the front axle individual components, it is important to understand the operation of the entire unit. Since this is a FWIS system, the two front wheels are driven by two symmetrical systems. For this reason, only one side of the entire system is presented (see Figure 25).

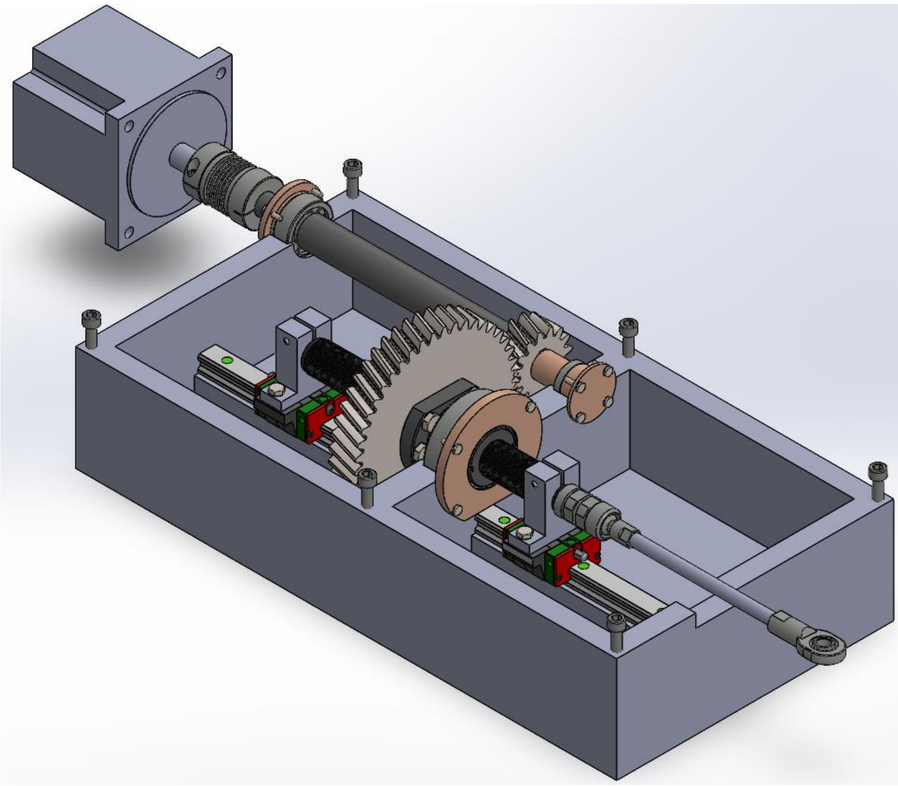


Figure 25: Proposal of SBW model.

It consists of an electric drive system based on a brushless DC motor, which is connected to the input shaft via a bellows coupling. The shaft is positioned between two bearings and a helical gear is splined in the central section. It meshes with a second wheel attached to the flanged nut of a ball screw. The screw acts as a second axis in this parallel-axis configuration. It has axial movement as it is the nut that is axially constrained by a bearing. The nut is therefore free to rotate upon actuation of the gear wheel, but not to translate. What translates rigidly is the screw which, via a ball joint and tie rod, drives the steering arm directly. As supports for the ball screw, in addition to the bearing, two shaft blocks mounted on linear slides are placed. The role of the slides is twofold, supporting part of the radial load from the gear and relaying the position of the road wheel to the electric motor at all times. An absolute magnetic linear encoder was chosen for this type of measurement. The entire system is then placed inside a box that will be fixed to the chassis of the vehicle.

4.2.1 Electric motors

As a FWIS system, the control of the two front steerable tyres must be completely decoupled. Two motors are therefore required, one for each drive wheel. Electric motors have been selected as they are easily to integrate into the vehicle's internal network, have high efficiency, low maintenance costs and are easily controllable in position and rotational speed. In particular, brushless DC motors seem to be promising in the field of SBW technology due to their reliability, precision, power density, efficiency and long life. In addition, the windings are positioned on the stator, improving heat dissipation and overload capacity [46].

In order to know the torque and rotational speed required by the motor, it was necessary to calculate the lateral forces exchanged between the tyre and the road under the worst working conditions in which the vehicle may be operating. For this purpose, a class L6e-B [47] vehicle was considered with a dummy on board weighing more than 95% of the average male adults. In addition, in order to maximise the load on the front axle, the vehicle was placed on an inclined plane with the driving direction towards the valley. The inclination of the plane is 35% as this is the maximum inclination that can be measured worldwide [48]. Finally, since the condition requiring the maximum effort for wheel turning is the static one, the vehicle was at a standstill. Therefore, a static friction coefficient μ = 1 and a triangular load distribution along the linear contact footprint of the wheel were considered. A further assumption was to consider the load evenly distributed over the two front wheels. The resulting force was then applied at 2/3 of the tyre width equal to b = 0.12 m. Given the coefficient of friction and point of application, the torque to be applied to each front wheel in order to change the steering angle under worst-case operating conditions was:

$$F_{G,front,max} = 1553 \text{ N}$$

$$F_y = \mu F_{G,front,max} = 1553 \text{ N}$$

$$M = F_y \cdot \frac{2}{3} b = 125 \text{ Nm}$$

Considering then a distance between the point of action of the tie rod with respect to the steering axle in maximum steering condition equal to r = 0.05 m, the force acting on the tie rod was:

$$F_{tie\ rod} = \frac{M}{r} = 2485 \text{ N}$$

In order to determine the torque transmitted from the motor to the ball screw, a ball screw efficiency of 95%, a pitch p = 10 mm and a pitch diameter d_p = 20 mm were considered. As a result, the maximum torque required of the ball screw was:

$$M_{max} = \frac{F_{tie\ rod} \cdot p}{2\pi \cdot \eta} = 4.5 \text{ Nm}$$

Finally, by using a parallel-axis configuration connected by gears, the torque required by the motor is reduced by a transmission ratio i = 3. In this way, the performance required of the motor is reduced to a value of:

$$M_{M,max} = \frac{M_{max}}{i} = 1.5 \text{ Nm}$$

with the additional benefit in terms of cost.

The rotational speed required of the motor was determined in accordance with the requirements set for a high-speed evasive manoeuvre, which stipulate a steering arm travel speed of v = 130 mm/s [49], which corresponds to a motor rotation speed of:

$$n_{spindle} = \frac{v}{p} = 13 \text{ rps} = 780 \text{ rpm}$$

$$n_{motor} = n_{spindle} \cdot i = 2340 \text{ rpm}$$

A BLDC motor powered at 48 V with a maximum torque of 1.91 Nm and a maximum rotational speed of 3000 rpm was therefore chosen (see Figure 26) [50]. Its datasheet is available in Annex 9.

4.2.2 Bellow joint

The motor output shaft and the system input shaft are coupled by means of a bellows coupling (see Figure 27). It allows axial, radial, and angular movement between the two shafts so that any misalignment due to vibrations and oscillations of the system does not lead to motion interruption or worse, damage to the motor shaft. The chosen coupling is designed to transmit a nominal torque of M_{BJ} = 4.5 Nm and can reach a maximum rotational speed of $n_{max,BJ}$ = 19000 rpm. It is therefore suitable to operate with the selected motor.

Furthermore, knowing the diameter of the motor shaft and after checking the different joint configurations available in the catalogue, the bellows joint with a bore diameter d = 14 mm at both ends was chosen [51]. This value is suitable as it also meets the minimum diameter required at the input shaft of the system to withstand bending and torsion stresses. M3 screws are provided as the shaft fastening system. A technical data sheet for the component is attached in Annex 9.

Figure 26: BLDC motor [50].

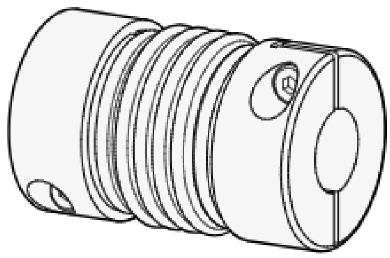


Figure 27: GN 2244 Metal bellow joint [51].

4.2.3 Input shaft

The input shaft of the system was sized to handle torsion and bending stresses. As the torque value applied to the shaft for torsion design, the maximum torque supplied by the motor $M_{M,max}$ = 1.91 Nm was used. On the other hand, the loads considered in the case of bending result from the forces exchanged between the pinion and driven wheel.

The chosen material is a normalised C45 steel and, as a result of the design process, the minimum diameter required is d = 8 mm. For structural reasons and in order to be able to install the pinion using the key, the shaft was designed with different diameter cross-sections. The end coupled with the bellows coupling has a diameter d_1 = 14 mm. The sections dedicated to the bearing seat and the shaft-hub coupling of the pinion has a diameter d_2 = 15 mm. Finally, the centre section has a diameter d_3 = 21 mm, which is equal to the minimum abutment required by the bearing.

The shaft section on which the pinion is installed contains the keyway. It is used as a medium for the transmission of motion between the shaft and pinion. The key was sized to transmit the maximum torque $M_{M,max}$ = 1.91 Nm, and the UNI 6604 5x5x10 key was selected.

Two other interesting sections are those designed to accommodate the axial bearing locking system housings. One of these sections provides a seat for a circlip, while the other involves an M10 threaded section that will mate with a locknut. Figure 28 shows the shaft to ease the understanding of its geometry.

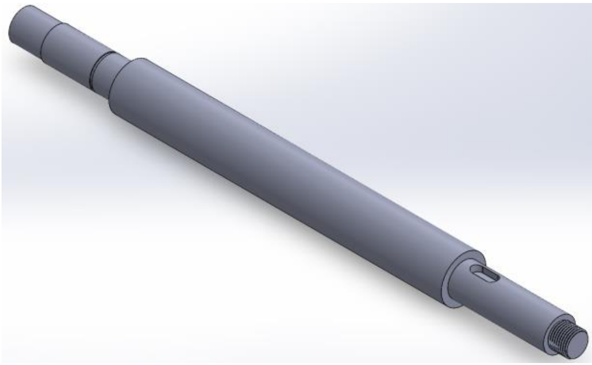


Figure 28: Input shaft of the system.

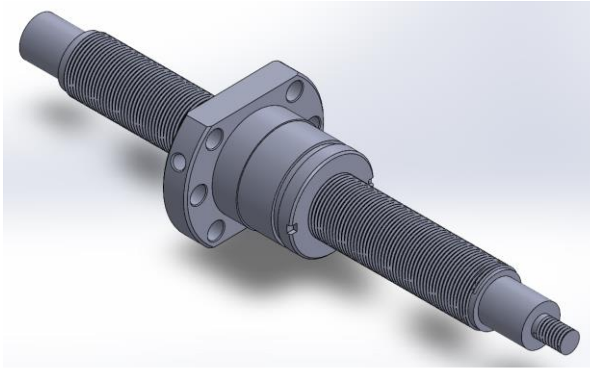


Figure 29: Ball screw.

4.2.4 Gears

Part of the work carried out in [11] was to consider different mechanisms of rotational motion transmission between the two parallel axes. The configurations that emerged as most attractive in terms of performance, simplicity and cost of implementation were belt or gear transmission. The factor that led to a preference for one configuration over the other was the possibility of being able to produce the gear wheels in-house at the FAST department. Specifically, the choice was to use helical gears due to the several advantages they bring to the system. The major ones are a continuous, smooth, and noiseless transmission. A better load distribution allows less tooth wear and therefore a longer service life. In addition, they are compact and guarantee high transmission precision. The advantages listed above come up against a higher cost, but it still completely justifies their use for this application.

The design has been carried out on the pinion, being the smallest wheel, and also the most stressed. The torque considered is the maximum torque that can be delivered by the motor $M_{M,max}$ = 1.91 Nm, the required transmission ratio is i = 3 and, using a normalised C45 steel as material, the diameter and number of teeth shown in the Table 6 were obtained.

Table 6: Gears parameters.

Parameters	Pinion	Driven Wheel
β = helix angle	20°	20°
z = number of teeth	15	45
m_n = normal module	2.5	2.5
b = width [mm]	20	20
d_p = pitch circle [mm]	40	120

4.2.5 Bearings

After an analysis of the operating conditions, including the acting loads, the diameter and the maximum rotation speed of the input shaft, it was possible to proceed with the choice of bearings. For an accurate design, the products and literature made available by the well-known company SKF Group were consulted [52].

Among the various bearing models and configurations suggested in the catalogue, the following solution was identified. As a bearing that can withstand a combined radial and axial load, a single row deep groove ball bearing of the type "61802" was chosen. The other end of the shaft was supported by a single row cylindrical roller bearing of the type 'NU 202 ECP'. The feature of this second device is to have two integral flanges on the outer ring and no flanges on the inner ring. This geometry can accommodate axial displacement of the shaft relative to the housing in both directions caused, for instance, by thermal expansion.

An additional bearing is required to support the flanged ball screw nut. The task of this bearing is to absorb both axial and radial loads as the nut must be axially constrained for proper operation of the mechanism. Part of the radial load also goes on the slides which support the spindle, but the lower this load, the lower the losses due to friction between slides and rails. As done before, a single row deep groove ball bearing was selected, with identification code "6007" [53].

The design of the bearings in terms of lifetime, static load, dynamic load and minimum required load are widely satisfied. Compared to the manufacturer's recommended operating conditions, these bearings can withstand the magnitude of the actual loads acting on the system. This conservative approach was taken to account for uncertainties and unknown in mounting, testing plan definition, and allow freedom for more demanding/stressful future modification.

For the geometry of the bearing seats, the axial and radial fixing systems and the installation procedure, please refer to section 4.3. The datasheets of the three bearings are attached in Annex 9.

4.2.6 Ball screw

Moving on to the second axis, it comprises a ball screw. The reason behind the use of this type of mechanism to transform the motion from rotary to linear is driven by the need to have a smooth and accurate transmission that can work continuously even at high speeds. Precision and accuracy are two fundamental characteristics for a steering system, while a long life allows for reduced maintenance. High speeds are possible thanks to the low friction guaranteed by the interposition of balls between the nut and spindle. A low coefficient of friction limits heat generation significantly, improves system efficiency and enables rapid direction changes that may be required when critical driving situations occur [54].

During the component design procedure, a simple lead screw was also considered. On one hand, it would have allowed a significant cost reduction, and its operation is generally less noisy. On the other hand, it would not have been able to guarantee the performances required for this type of application, both in terms of accuracy and, above all, continuous operation and high speeds. The increased friction and heat generation would have introduced additional problems in terms of service life and maintenance. For these reasons, the lead screw was left aside.

The selected ball screw involves a flanged nut with a threaded internal diameter of d_i = 20 mm and a pitch of p = 10 mm. The choice of the flange configuration was due to the desire to have a large, flat surface that could interface and mesh with the second sprocket. For this purpose, there are bores for M6 bolts on the flange. The pitch corresponds to the path that the spindle takes with each rotation of the nut and was a useful parameter for establishing the number of revolutions required to reach the end stop.

The spindle, through its linear displacement, is the element that controls the swivel angle of the wheels. Accordingly, the length of the threaded section must be such that the maximum required steering angle can be achieved. In everyday vehicles, the latter ranges between 30° and 40° in low-speed or stationary conditions. A further relevant factor to consider is the space available for the tyre to move without impacting the chassis. For the vehicle under study, a maximum steering angle of ± 40° with respect to the straight-ahead condition was considered. Consequently, through trigonometric relations taking into account the relative position between spindle and wheel and the point of action of the steering arm in relation to the steering axis, a spindle stroke of s = 80 mm was calculated. In addition, the spindle is supported at the ends by two support blocks with diameter d_s = 16 mm and width l = 16 mm fastened to the slides. Lastly, the end of the spindle on the wheel side must terminate with an M8 threaded section that fits into the ball joint. This allows the angular displacement between spindle and tie rod required during wheel adjustment. GN 782 Ball Joints have been identified as a suitable component for the system under discussion [55]. The other end of the ball-joint was linked to the tie rod also with an M8 threaded coupling.

Based on the minimum required spindle stroke, the width of the sprocket and flange nut, the width of the two shaft support blocks and the threaded section for coupling with the ball joint, the overall length of the spindle is l_{tot} = 220 mm, as can be seen in Figure 29.

4.2.7 Slides and rails

Two linear guides were chosen as the guiding and support system for the ball screw. They are equipped with two independent rails, both of which hold in place onto the base of the housing by means of M3 screws (see Figure 30). The decision not to use a single rail was mainly due to the need to make the system as compact as possible. Since the size of the driven cogwheel is significant, placing the rail below it may have prevented any interference between the two components, but this would also have increased the vertical development of the system. The length of the rails was established taking into account the overall dimensions of the slides and complying with the stroke required by the spindle to ensure wheel rotation of ±40°.

Two shaft support blocks are secured above the slides to support the spindle and prevent its rotation. Eliminating this degree of freedom is crucial to the operation of the system. Not being able to rotate, under the action of the nut, the spindle tends to translate laterally adjusting the position of the tyre. The torque arising from the nut and counteracted by the shaft support blocks is then discharged through the slides onto the rails. Limiting the distance between the spindle and the rails is also crucial in this regard.

The slides are driven by means of the screw and their position is known at all times thanks to the installation of an absolute magnetic linear encoder. The position information is then sent to the axle drive motor so that it can compare it with the given input and can verify the correct alignment of the wheels with the steering angle. Furthermore, the choice to adopt an absolute magnetic encoder comes from the good compromise it offers between accuracy, reliability, and the ability to work in the presence of vibration or dirt. Finally, there is the possibility to install a redundant sensor on the second slide. Having them mounted one per slide allows to increase the system's safety level, as in the event of one sensor failing, the other can continuously provide the recorded position.

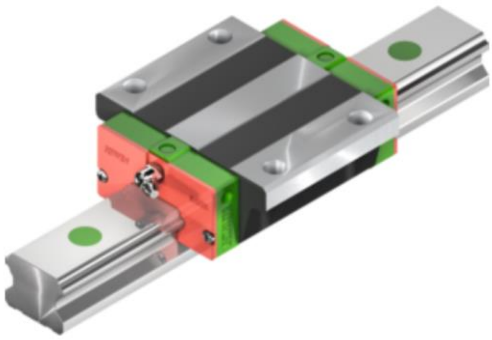


Figure 30: Slide and rail [56].

4.2.8 External box

The entire steering system is housed in a customised box (see Figure 31). Its main function is to support the system, protect it from the external environment and simplify its installation inside the vehicle body. The housing design was carried out according to an assembly approach and in such a way that it may be manufactured using conventional moulding and machine tool processes. Specifically, the walls accommodate the bearing housings and on the lower base there are two guides for placing and fixing the rails. On the upper part, a cover provides access to the system to allow assembly and maintenance. While the two opposite sides are fastened by M6x20 hexagonal socket head bolts. A more detailed view of the geometry of the bearing seats and the respective fixing systems is provided in section 4.3.

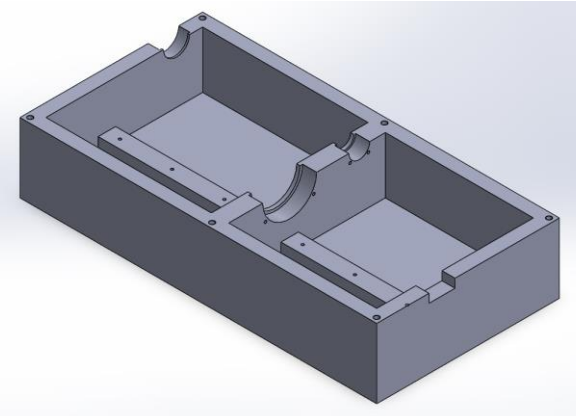


Figure 31: Lower Box.

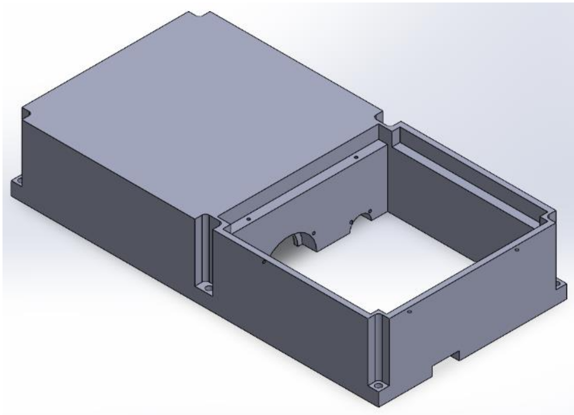


Figure 32: Upper Box.

4.3 Construction of the model

After a detailed description of the individual system components, the attention is now turned to how they interact, respectively the coupling systems, fastening methods and stress distribution.

4.3.1 Input shaft and bearings

The input shaft has the main task of transmitting the rotational motion of the motor to the entire system. To fulfil its duty, it is positioned between two radial bearings and is designed with a cantilever section that is connected to the motor via a bellows coupling. The role of the bearings is to support the shaft and the loads resulting from the motion transmission mechanism. Their ability to withstand axial loads is crucial in this application due to the use of helical gears. Their geometry leads to the formation of an axial load whose direction is a function of the inclination of the chosen helix.

Two different approaches were used for the axial fixing of the bearings. The inner washer of the roller bearing was fastened axially by the shaft shoulder and a circlip. The outer washer, on the other hand, goes against the housing on one side and is retained on the outer side by a specific lid fixed to the housing. In order to protect the bearing from dirt coming from the external environment, a radial shaft seal has been placed in the dedicated housing inside the cap, as highlight in Figure 33.

The ball bearing is mounted between a spacer and a threaded ring nut. The spacer is interposed between the pinion and the bearing so as to perform the dual function of shoulder and axial block. The ring nut is screwed onto the threaded end of the shaft and ensures that it is kept in place even under heavy loading. Lastly, the outer washer of the bearing is clamped between the housing and an outer cap, as shown in Figure 34.

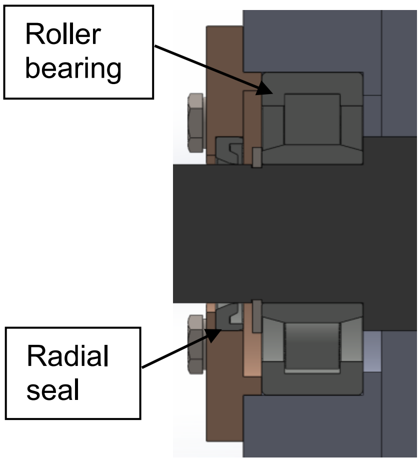


Figure 33: Radial roller bearing on input shaft.

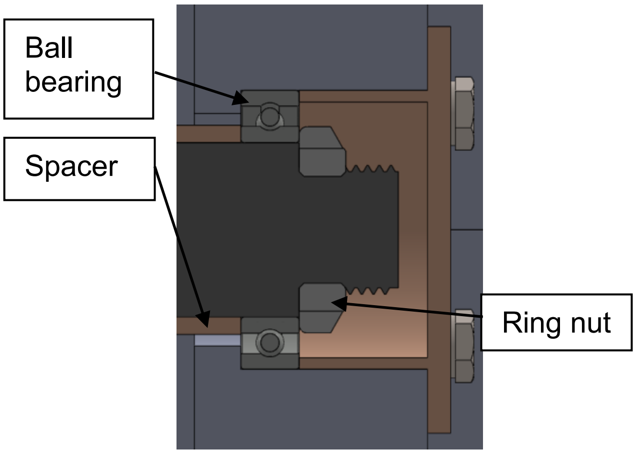


Figure 34: Radial ball bearing on input shaft.

4.3.2 Input shaft and pinion

Following a careful analysis of the different methods of power transmission carried out by Finn Häfele [11], it was determined that the most suitable configuration for the system under consideration is the use of two parallel axes interconnected by a helical gear.

The pinion is mounted on the input shaft, which is driven by the electric motor, while the driven wheel is fixed directly to the ball screw nut using M6x40 bolts.

Aiming to make the system as flexible as possible and to simplify the manufacturing process of the shaft and pinion wheel, the use of a torque transmission key was chosen. In this way, different materials of wheel and shaft could be used, and the production of the two separate components required less technological effort than the production of a wheel and shaft made in one piece. Following the design procedure for the key design, the choice turned to UNI 6404 5x5x10. The section of the shaft-hub coupling is shown in Figure 35.

For the axial locking of the wheel, the shaft shoulder was used on one side, while on the other side the task was accomplished by a spacer of a length equal to the distance between the wheel and the radial ball bearing. This configuration can be seen in Figure 35.

4.3.3 Gears and force distribution

The decision to employ a parallel-axis configuration derives from the possibility of having a gear ratio capable of reducing the torque required from the motor, which consequently can be pick with slightly lower performance and size with the benefit of lower cost. This reduction was achieved through a helical gear with a right-handed helix.

The use of the right-hand helix ensures that the axial load is carried by the single row deep groove ball bearing, which is able to work under both radial and axial load.

Figure 35 shows the distribution of forces on the pinion, shaft, bearing and housing.

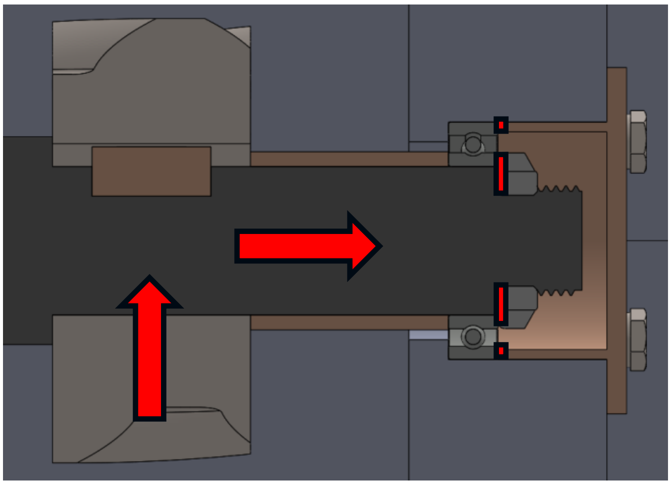


Figure 35: Force distribution from gear to housing.

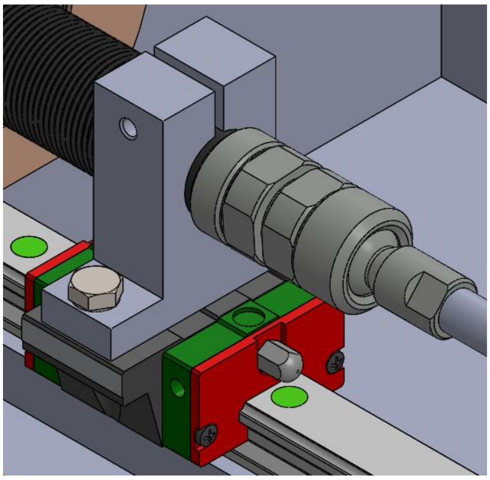


Figure 36: Slide components.

4.3.4 Driven Wheel and Ball Screw Nut

The driven gear is fixed directly onto the flange of the ball screw nut by means of M6x40 hexagon head bolts. In such manner, the motion is rigidly transmitted to the flanged nut, thus minimising losses. The inner diameter of the wheel hub must be large enough to allow the ball screw nut to pass through, which by translating laterally acts directly on the tie rod and thus on the tyre's steering angle. Figure 37 shows the helical gear - ball screw nut fastening system.

In a traditional ball screw application, torque is transmitted to the nut, which consequently rotates and translates along the axis. Since in the system at hand, the nut rotates, but it is the screw that translates, the torque is transmitted from the nut to the spindle and through the spindle to the shaft support blocks. They are attached to the slides by means of M5 screws and have a wheelbase of 41 mm. However, in order to make them suitable for the selected slides, it was necessary to modify the wheelbase to 40 mm. Nevertheless, this type of support makes it possible to minimise the distance between the spindle and rails, thus reducing the arm and consequently the torque acting on the sliding interface between the slides and rails (see Figure 36 for a CAD display of the configuration).

4.3.5 Ball screw nut and bearing

In order to work properly, the ball screw nut must be able to rotate around its own axis without translating laterally. To achieve this, it was mounted on a single row deep groove ball bearing, which allows rotation but no axial movement. To obtain this type of configuration, it was necessary to carry out some machining on the ball screw nut. The outer diameter was reduced slightly to fit the nearest available bearing diameter. In addition, a seat for the circlip, which is useful for the axial locking of the bearing, was made in the outer diameter.

While analysing the bearing fastening system, it can be seen that the housing seat and an outer cap axially clamp the outer bearing washer. Once more, to preserve the bearing, a radial shaft seal was inserted inside the lid. The inner washer, instead, is located between the shoulder of the ball screw nut and the retaining ring. In this way the axial load is discharged onto the bearing and in turn onto the housing.

Figure 38 shows the different components of the system described above.

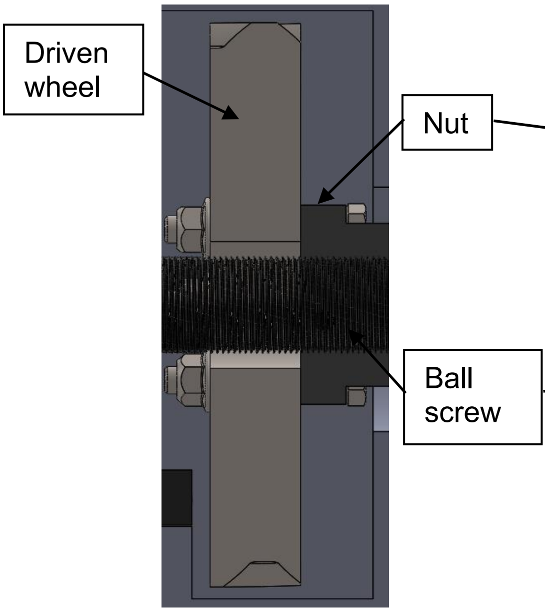


Figure 37: Fixing system of driven gear.

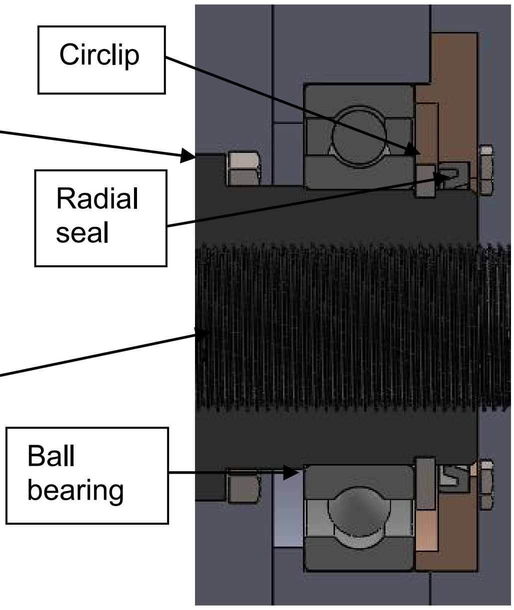


Figure 38: Radial ball bearing on ball screw nut.

4.4 Sensor analysis

The mechanical construction of the system was carried out considering what would be the input and output parameters required for the operation of the technology. As mentioned in subsection 2.3.2, the main sensors of an SBW system are the torque and steering angle sensors. Since the focus of this work liens on the steering axle and not on the steering wheel unit, only the sensors employed in the section of interest are going to be analysed in detail. Particular attention is paid to measuring the angular position of the wheels and the different types of sensors available to achieve this. Due to the relevance of the tyres‘ position reading, which requires extreme accuracy, it was necessary to develop a multi-sensor configuration able to guarantee continuous monitoring of this information with high reliability. The data from the sensors mainly work as feedback for the main ECU to ensure a proper match between the input steering wheel angle and the output steering angle of the wheels.

In the following paragraphs, the steps and considerations made in choosing the type of sensors and the installation site are reported. Specifically, the final configuration employs two sensors, one installed on the motor and the other near the tyres.

4.4.1 Angular sensor on motor shaft

To attain optimal performance, a BLDC motor control system must ensure a smooth startup, consistent commutation, peak efficiency, and the utilization of maximum torque from the electrical power available. The fundamental factor for achieving these objectives lies in accurately determining the rotor's position in relation to the stator. This information empowers the motor control system designer to develop a resilient electrical drive management solution [57].

The electric motor is the link between the input and output of the system. Commands from the driver through the steering wheel are processed by the ECU and sent to the electric motor so that it can steer the wheels. For there to be a correlation between the driver's command and the actual response of the vehicle, a direct relationship between the position of the motor and the steering angle of the wheels must exist, even when power is off.

Most electric motors on the market, including the model selected for this application [50], are already equipped with an internal position sensor, which is usually a Hall effect sensor. However, it provides the relative position of the rotor relative to an initial position defined by the controller during the start-up process. This means that Hall-effect sensors can detect changes in rotor position relative to the sensor position but cannot provide an absolute position of the motor at each instant. Furthermore, when the power is switched off, they do not store the last position [57].

Considering the application in hand, and the fact that the motor has to turn more than 360° to reach maximum steering angle, having a fixed reference is a must. For this reason, it was necessary to find an additional position sensor capable of providing absolute position feedback. The sensors to be considered alongside, or as an alternative to, the Hall sensor are absolute encoders and resolvers. They are able to provide absolute position even with multiple revolutions.

The brushless transmitter resolver stands as the most prevalent type among resolvers. They have a stator-rotor configuration similar to an electric motor, with some differences in the winding arrangement. Their operation relies on electromagnetic induction, and they are able to provide information on angular position and rotational speed. They can achieve an accuracy of between 4' and 20' depending on the variant, consistent with the values given in Table 3. However, they are analogue sensors and, in order to communicate more easily with the control unit, they require a digital converter that can transform the sinusoidal output signal into a binary signal. Given their high accuracy and the complexity resulting from the analogue-to-digital conversion, resolvers are mainly sensors suitable for applications requiring high accuracy and robustness of the signal, where cost is not regarded as a constraint, such as in the aerospace field [58].

Encoders are angular sensors available on the market in two types: incremental or absolute. Another distinction can be made on the operating technology: optical or magnetic. The main differences between incremental and absolute encoders lie in the type of output signal, the position memory, and the ability to detect the direction of rotation. Absolute encoders provide a code signal at the output while incremental encoders provide a rectangular pulse signal. Absolute encoders retain the position even when the power is turned off, whereas incremental encoders do not store this information. Finally, absolute encoders provide an output signal with a '+' or '-' sign depending on the direction of rotation. In contrast, incremental encoders vary the order of the generated signal, but do not vary the form [59]. Consequently, the encoders of interest for the application under examination are absolute encoders.

A comparison between optical and magnetic encoders is carried out in 4.4.2. Typical values for these types of sensors can also be found in the Table 8. The discussion here is limited to a theoretical comparison of the properties of each and the reasons for choosing an optical encoder over a magnetic one. Optical encoders base their operation on a transmitting and a receiving device. This means that they need a clean and protected environment to ensure maximum performance. On the other hand, they are devices that guarantee high accuracy at a lower price than resolvers, also because they are a well-known technology.

Magnetic encoders have experienced a strong development only in recent years due to their ability to guarantee good performance even in harsh working conditions. They rely on variations in an internal magnetic field. These variations are detected by the sensor and converted into position information [60].

Because of the importance of having the most accurate data possible on the motor position and the possibility of ensuring a safe working environment, it was decided to use an absolute optical rotary encoder.

4.4.2 Linear sensor on slide

Following the input command, the motor rotates in response to the driver's request for wheel orientation. There is therefore a direct relationship between motor angle and tyre angle, but for safety reasons it is necessary to have a closed-loop control system. This means that after the motor has actuated the steering, the ECU must receive feedback on the success of the manoeuvre. This feedback must come from a sensor placed as close as possible to the wheels themselves in order to obtain a measurement with high reliability and low uncertainty.

After an analysis of the types of sensors that could be used and the different possible installation locations, the decision was to use an absolute magnetic linear encoder placed on the ball screw support slides.

The initial approach was to find a sensor that could operate as close to the wheel as possible, i.e. on the tie rod or knuckle. This led to the idea of being able to use a single sensor to detect wheel speed and angle. Vehicles are usually already equipped with a speed sensor placed close to the wheels to detect their rotational speed. This data proves valuable for multiple vehicle systems like the ABS system. Implementing this approach can streamline the system by reducing the necessary sensors, simplifying operations, and potentially cutting down costs. Moreover, being installed directly on the position where the wheel steering motion occurs, the measurement could be very reliable. On the other hand, it's important to consider factors such as the resolution and accuracy requirements for each measurement, as the shared use of a single encoder may introduce some trade-offs between the precision of the swivel angle and the speed measurement. Calibration and proper signal processing techniques are necessary to ensure accurate and reliable results for both measurements, without considering that the closer you get to the wheels, the more challenging the working conditions are.

Consequently, a more conservative solution was devised to simplify the installation process, allow the sensors to operate under less hazardous environments, and that would not overlap with other measurements avoiding further complicating the software control system. This alternative involves installing a linear position sensor on the slides that guide the movement of the ball screw. These are located inside the steering system housing, so they are protected from dirt and external agents, and they rigidly follow the linear movement of the spindle, which is mechanically connected to the tyre via the ball joint, tie rod and knuckle. In this way, by measuring the position of the slides, it is possible to obtain the angular position of the wheels with a good degree of resolution, reliability and accuracy. The types of sensors considered are:

- Absolute optical linear encoder
- Magnetic absolute linear encoder
- Linear Variable Differential Transformer (LVDT)

The values in the Table 8 reported in Annex 9, which are in accordance with [61]–[63], allow a direct comparison between these types of sensors from different points of view:

- Working principle
    - Optical Encoder: Optical encoders use a light source and a photodetector to read a patterned scale. The scale consists of alternating opaque and transparent lines.
    - Magnetic Encoder: Magnetic encoders use a magnetic scale with a magnetized pattern and magnetic sensors to detect the position.
    - LVDT Sensor: LVDT sensors operate on the principles of electromagnetic induction. They comprise a primary coil and two secondary coils wound around a core. The core's position dictates the output voltage in the secondary coils.
- Accuracy
    - Optical Encoder: Optical encoders generally offer higher accuracy due to their fine resolution and ability to detect sub-micron movements.

  - Magnetic Encoder: Magnetic encoders have slightly lower accuracy compared to optical encoders, but they can still provide precise measurements.
  - LVDT Sensor: LVDT sensors can achieve high accuracy, typically in the same range of optical encoder (±1 to ±10 microns).
- Durability
  - Optical Encoder: Optical encoders are sensitive to dust, debris, temperature changes and environmental conditions. They require proper sealing and protective measures for reliable performance.
  - Magnetic Encoder: Magnetic encoders are more robust and less affected by environmental factors like dirt, dust, or vibration. They are suitable for harsh working conditions.
  - LVDT Sensor: LVDT sensors are known for their robustness and durability. They can withstand harsh environments, vibrations, and high temperatures.
- Installation and set-up
  - Optical Encoder: Optical encoders require careful installation to ensure the alignment of the scale and the sensor. Misalignment can lead to accuracy issues.
  - Magnetic Encoder: Magnetic encoders are generally easier to install and align. They are less sensitive to misalignment during set-up.
  - LVDT Sensor: Proper alignment is crucial for accurate measurements. They require signal conditioning electronics to convert the sensor's analog output to a usable signal, such as voltage or current. Calibration may be necessary to establish the relationship between the output voltage of the LVDT sensor and the actual linear position.
- Electrical Supply and Output Signal:
  - Absolute Linear Optical Encoders: Optical encoders usually require a DC power supply. The output signal is typically digital.
  - Magnetic Encoders: Magnetic encoders commonly operate with a DC power supply. The output signal can be analog or digital, contingent upon the particular model and its designated application.
  - LVDT Sensors: LVDT sensors operate with an AC power supply. The output signal is an AC voltage that varies linearly with the position of the core.
- Measurable Length/Scale:
  - Optical Encoders: Optical encoders can measure a wide range of lengths, ranging from a few millimeters to several meters, depending on the specific model and scale used.

  - Magnetic Encoders: Magnetic encoders also offer a wide range of measurable lengths, similar to optical encoders.
  - LVDT Sensors: LVDT sensors have a shorter measurable length compared to optical and magnetic encoders. These sensors are readily accessible and capable of measuring movements ranging from a few millimeters to up to ±0.8 meters.
- Speed Range:
  - Optical Encoders: Optical encoders can support high-speed operation, typically ranging from a few meters per second (mps) to tens or even hundreds of mps. The maximum speed is affected by factors such as the encoder design, signal processing, and the mechanical setup of the system.
  - Magnetic Encoders: Magnetic encoders can support high-speed operation, comparable to optical encoders.
  - LVDT Sensors: They are not specifically designed for high-speed measurement applications. Their response time and speed range are typically lower compared to optical and magnetic encoders. LVDT sensors are commonly used in applications where precision and accuracy are prioritized over high-speed operation.
- Cost:
  - Optical Encoder: Optical encoders are generally more expensive due to their higher precision and the complexity of their components. Depending on the features of the model, the price can vary in a rage of 40€ to more than 400€.
  - Magnetic Encoder: Magnetic encoders are frequently favored for applications where exact precision isn't crucial due to their cost-effectiveness. Depending on the features of the model, the price can vary in a rage of 15€ to more than 200€.
  - LVDT Sensor: LVDT sensors generally fall within the mid to high price range in terms of cost. As a rough estimate, LVDT sensors can range from €100 to €1000 or more, depending on the specific requirements and application demands.

In conclusion, the sensor that best seems to meet the system requirements is the absolute magnetic linear encoder. It is able to provide data with precision and accuracy suitable for a measurement used as feedback from the control system. Furthermore, due to their ability to work in harsh environments, they provide good durability, allowing reduced intervention and maintenance costs. They are also easy to install and are most cost effective. The sensor selected is shown in Figure 39 and its features are listed in Table 7.

LVDT sensors have been left aside mainly because of their cost and limited measuring range. Furthermore, their power supply and output are AC current, which makes them less suitable for working within a system supplied entirely with DC current, coming from the battery.

Optical absolute linear encoders were not chosen because the better performance they can provide, compared to magnetic encoders, is not strictly necessary for a feedback application. In addition, due to their slightly higher cost and greater sensitivity, it was preferred to use a solution that would guarantee greater reliability and durability.

Figure 39: Absolute magnetic linear encoder [64].

Table 7: LA 11 characteristics.

LA 11	
Accuracy	±40 μm/m
Resolution	up to 0.244 μm
Speed	up to 7 m/s
Max length	16.3 m
Voltage	4.75 ÷ 5.75 V, 8 ÷ 30 V
Outputs	BiSS-C, SPI slave, SSI

5 Control System

In the previous chapters, a preliminary assessment of all the components required to implement the SBW system was conducted. In particular, a viable configuration of the full front wheel system incorporating motors, actuators and sensors was presented. Looking back at the entire SBW system, the aim is to lay the groundwork for future development of the software module. Indeed, once the hardware components of the system have been selected, it is necessary to define a networking among the various devices, how they communicate, with what timing and what information they must exchange.

5.1 Steer-by-wire control requirements

Before proceeding with the analysis of the proposed communication network and some advice on the set-up procedure customised for the SBW system studied, attention is drawn to what are the main requirements that a SBW system must fulfil and in which way they can be tested and verified. According to Fahami et al. [65], an accurate SBW control system must be able to guarantees:

- Wheel synchronisation and direction control: It is the task of the Master node to constantly control and adjust the steering angle of the wheels, trying to minimise the error in relation to the incoming steering wheel angle.
- Steering wheel self-alignment: The steering wheel in the lack of an applied torque must be able to return to the central position.
- Variable steering ratio: It is one of the main advantages brought by SBW technology and it is the responsibility of the main ECU to adjust the steering ratio value according to vehicle speed and wheel angle.
- Traditional steering feel: the DC motor connected to the steering wheel, under the control of the Master node must provide the resistant torque in order to recreate the traditional driving feeling depending on wheel speed, road surface and external disturbances.

There are many SBW control systems reported in the literature and generally they are closed-loop control systems based on a mathematic model of the system. For instance, the paper published by Fahami at al. [65] presents the control strategy for the wheel synchronization and the variable steering ratio using a PID controller and it introduces a new feedforward variable steering ratio. From the results of this study it is concluded that by mean of the PID control the response of the front tire angle, to an input steering angle step function, is stable even under disturbance and torque, as can be seen in Figure 51 attached in Annex 9, therefore suggesting a promising approach to be followed. In the work of Tumari et al. [66], an application and comparison between PID controller and Fuzzy Logic Controller regarding steering wheel returnability, directional control and wheel synchronisation is proposed. In this study, the Fuzzy Logic Controller displayed better results regarding response time. A force feedback torque estimation and control algorithm are described by Fahami et al. [67]. In this research work a Linear-Quadratic Regulator (LQR) controller with gain scheduling based on steering wheel angle and vehicle speed was implemented, which is an important additional step in the SBW schematic. Huang et al. [68] introduced a Sliding Mode Predictive Tracking Control (SMPC) to enhance the resilience of model predictive control (MPC) against uncertainties in modeling and disturbances within steering control procedures. Lasty, a Sliding Mode-Based Learning Control (SMLC) technique has been developed by Do et al. [69]. The scheme proposed by the authors adapts to different driving conditions and vehicle dynamics. This approach allows the SBW system to learn from previous control experiences and continually improve its response to various road conditions. The experimental results prove that SBW systems equipped with the sliding mode-based learning control show improved tracking accuracy, reduced tracking errors, and better adaptability to changing conditions, as can be seen in Figure 49 and Figure 50 reported in Annex 9.

These learning control would ultimately benefit the project taking in consideration multiple simulation control testing and maybe even road data test drives to train the SBW response.

5.1.1 PID and Feedforward control

By leveraging the valuable lessons learned from studies addressing similar problems to the one currently under examination, it was possible to propose a conceptual control logic schematic. This schematic adopts three PID control blocks and one Feedforward control. The baseline block diagram is presented in Figure 40. The PID controllers are applied to the steering wheel system and the wheels subsystems, whereas the feedforward control acts on the steering ratio.

The idea behind the proposed control logic is to expedite and provide support for the subsequent phases of the project, specifically in controlling the designed steer-by-wire system. The decision to adopt a PID control method is justified by the fact that, of the proposed methods, it is the one easiest to implement and this aspect, especially in a preliminary phase, would allow accelerating the development and testing of the control system. Once its functionality has been verified, it will be possible to enhance it with more refined control methods that require in-depth knowledge of the system and its dynamics. However, the actual implementation and calibration of the gains, parameters, and mathematical relationships are beyond the scope of this research phase. More detailed information and modelling are needed before advancing to controlled response and tuning of the steering dynamic.

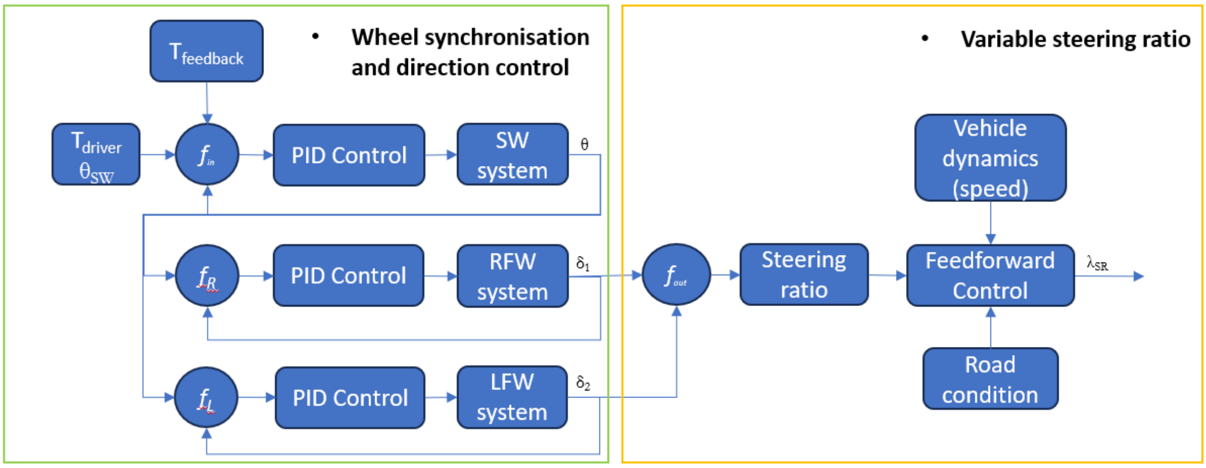


Figure 40: SBW system conceptual control logic.

In this approach, the input parameters are the steering wheel angle and torque applied by the driver. The torque feedback acts as a disturbance and the combination of these inputs feeds the PID which generates the modulated command to drive the steering wheel system at the target value. The latter, in response to the command received, outputs an angle that takes into account stiffnesses, inertias, damping, resistances and inductances within the system. This angle is used as feedback to the first PID controller, for error calculation and correction, and as input to the front axle system. Before going into the corresponding sub-systems of the left and right wheel, the angle of the wheel in the inner curve is adjusted by a specific function in order to obtain two ideal steering angles and eliminate the error introduced by the traditional Ackermann steering system. The output from the two front wheel systems is the effective value of the wheel angle. These are used by the respective PID controllers and only the angle of the wheel on the outer corner becomes an input parameter for the steering ratio algorithm, which is sufficient given the direct relationship between the two. Since a great advantage of steer-by-wire is to allow a variable steering ratio, the resulting output is then corrected by a feedforward control, according to vehicle dynamics, specifically speed, and road conditions. After all these adjustments the proper steering ratio for the current driving conditions can be obtained.

However, as mentioned earlier, the suggested method should be revised as more promising and suitable alternatives for the present case study may emerge following the growing rate of work and research in this field. Nevertheless, the insights offered here are intended to be a valuable reference point for the forthcoming work.

5.2 CANopen as suitable communication protocol

In Chapter 2, several communication systems, which generally cooperate within the vehicle's broad EE-architecture, were discussed. Each of them suits specific vehicle subsystem, and it is therefore necessary to identify the one that displays the most suitable features for the SBW system under study and at the same time, guarantees freedom of access and use.

The communication protocol that appears to best meet the application requirements, as mentioned previously, is the CANopen. The reasons behind this preference are many and have been partially justified in the paragraph dedicated to this communication system (see section 2.2.2). Nevertheless, it may be beneficial to take up some aspects by applying them directly to the case under examination.

Firstly, CANopen is an open communication protocol, which results in a high degree of flexibility and many resources and tools made available to the developer for configuring and managing the networks. It is based on international standards, such as CiA (CAN in Automation) standards, ensuring a well-defined and widely recognized communication protocol in the automotive and industrial sectors. CANopen is designed for real-time communication, making it suitable for applications where precise timing and low-latency data exchange are critical such as SBW. CANopen offers deterministic communication, meaning that messages are sent and received with predictable timing. This is crucial in SBW applications as they require consistent and reliable data exchange. CANopen provides a robust and in real-time error handling. SBW systems require continuous monitoring and diagnostics. CANopen's comprehensive diagnostic capabilities, along with the Master/Slave model, enable efficient system monitoring and troubleshooting.

Based on the reasons underlying the decision to use CANopen as the communication framework for the SBW system's integrated network, it is now possible to proceed with its application.

5.3 SBW embedded networking with CANopen

The purpose of this paragraph is to present a conceptual layout of the network's structure, including the nodes that compose it, their connections and the information that should be exchanged. Furthermore, based on the notions provided in section 2.2.2 on the operation of a CANopen network, some guidelines are provided on how to properly address the many unknows arising from the wide flexibility left in the configuration phase by this communication protocol. In the following discussion, the block diagram shown in Figure 42 is used extensively as a valuable illustrative reference. Please note that the yellow sections show the name of the node, the blue sections the parameters measured and made available by the node (output) and the light blue sections the parameters requested by the node (input).

5.3.1 Approach to network setting

CANopen communication protocol provides a hierarchical structure called Master/Slave model (see Figure 41). In the SBW system analysed there are nine nodes or devices, where the central one is the Master node while the remaining eight are slave nodes, all connected to the Master. As is well known, the Master node is in charge of configuring the ODs of each slave node, managing the initialisation and change-of-state phase of the nodes, receiving and sending requests in the network, scanning the timing and defining a priority scale for messages. It also handles error messages by applying node correction and/or reset operations. Lastly, it is able to process calculations and return results by exploiting the mathematical models implemented within it.

In this specific case, it is advisable to configure all nodes according to the "Preconfigured Devices or Store Configuration Parameter" methodology, whereby parameters are permanently stored in non-volatile memory. This strategy provides a high degree of stability and reliability that are paramount in a safety-critical systems like SBW. Moreover, preconfigured devices that start with well-defined parameters can contribute to predictable and consistent operation. In addition, storing configurations in non-volatile memory reduces the likelihood of configuration errors or unauthorized changes. Indeed, configuration changes in SBW systems should be carefully managed to mitigate the risk of unintended consequences. Finally, using preconfigured devices with stored parameters can simplify certification efforts and ensure compliance with safety standards.

As a general consideration regarding the transmission trigger methods supported by CANopen for PDO communication, the combination of event driven and time driven is recommended. This combination of triggers helps ensure the system's safety, reliability, and real-time performance. Event-triggered communication allows system to respond promptly to dynamic, unpredictable situations such as a driver's steering input or a sensor detecting a quick change. Event-triggered communication optimizes the use of network bandwidth by sending data only when needed and minimizes latency in responding to critical events. On the other hand, time-triggered communication provides predictability in message transmission times and ensures a high level of determinism. In safety-critical systems is essential guarantees that messages are sent and received at known and consistent intervals. In addition, having both event-triggered and time-triggered mechanisms provides redundancy, feature always appreciated by safety-critical systems. Finally, safety standards, such as ISO 26262 for automotive systems, often recommend a mix of triggers for comprehensive safety assurance.

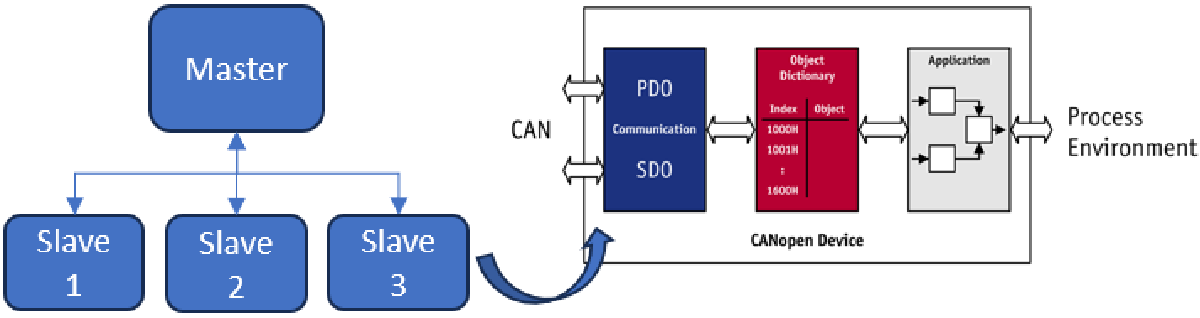


Figure 41: CANopen network [70].

5.3.2 AFIS with SBW technology flow chart

To explain the operation of the individual nodes in detail, it may be useful to follow the flow of information as a guideline.

The main command on which the steering system relies on is the steering wheel angle. It reflects the will of the driver and thus the ultimate goal that the entire system strives for. This input is detected by measuring three parameters: angle, torque, and speed of the steering wheel. The information is transmitted in real time via a TPDO to the Master node, which receives the message in the form of an RPDO and proceeds with processing. The Master node contains within it a mathematical model of both the steering wheel system and the front wheel system. A formulation of such a model for a classical SBW system is proposed in [71]. Through this model, the main ECU converts the input steering wheel angle into two output angles of different values. The angles that will be imposed on the two wheels will therefore be equal to the ideal angles calculated using the equations (2) and (3). By doing so, the goal of eliminating the Ackermann error can be achieved. Besides, the SBW system allows for a variable steering ratio as a function of steering angle, vehicle speed and driving style, which are input to the Master node as "vehicle dynamics parameters". Additional adjustment of the output angles is then required in accordance with the actual steering ratio. Finally, since the devices to which the steering angles are sent are electric motors, it is mandatory to transmit the angle by which the rotor must rotate in order to ensure that the spindle moves enough to adjust the wheels to the desired angle.

Once the motors have driven the spindle, the latter is connected to the slides on which the linear position sensor is placed. The only task of the sensor is to send the position of the slide to the Master node so that it can compare it with the input steering wheel angle and check that the manoeuvre was successful. A further information that the Master node must provide to the motors is the torque to apply and the rotational speed. These parameters are a function of the load acting on the wheel and the coefficient of friction between the tyre and the road. They are evaluated by the "Steering Arm and Suspension" node and are sent in real time to the main ECU. Other useful information for assessing the working condition of the tyre comes from input parameters to the Master node related to vehicle dynamics, such as lateral acceleration, yaw rate and wheel speed. A smart expedient when setting the type of transmission to the drive signals of the two motors is to implement the SYNC function in order to synchronise wheel rotation.

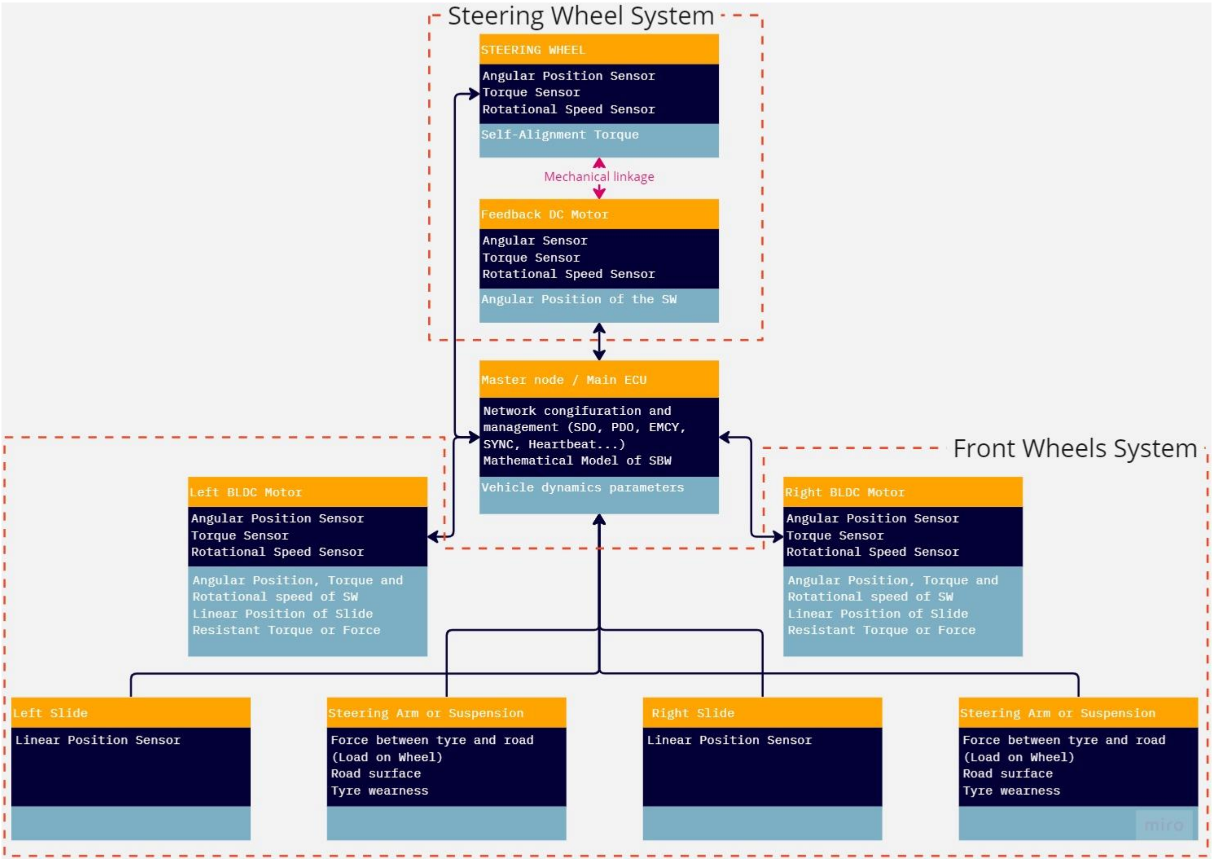


Figure 42: SBW flow chart.

The last node that needs to be discussed is the 'Feedback DC Motor'. Its task is to recreate the driving sensations experienced by a driver of a vehicle with a conventional steering system. To do this, it must provide the steering wheel with a resistant torque as a function of the steering wheel angle, contact conditions and forces exchanged between the tyres and the road. This data is provided by the 'Steering Arm and Suspension' node and converted into torque via the Master node. Another task of the feedback motor is to provide the steering wheel with self-aligning torque. This input is provided by the main ECU when the torque applied to the steering wheel is zero, but the steering wheel angle is non-zero. Through the steering wheel's self-alignment, the drive motors of the front wheel system are also instructed to gradually turn the wheels back to the straight-ahead position.

5.3.3 Parameters setting

As mentioned before, CiA (CAN in Automation) provide several CANopen device profiles that are standardized descriptions of specific device types and their communication characteristics. These profiles define how devices of a particular type should behave on a

CANopen network, specifying their Object Dictionary structure, communication parameters, and more. This means that the developers do not need to manually define the Object Dictionaries and communication parameters saving time and effort during network setup. On top of that, device profiles ensure that apparatus from different manufacturers conform to a common standard making it easier to integrate equipment from multiple sources into a CANopen network.

Many of the devices used in the SBW system can comply with these standards. These are mainly electric motors and sensors as encoders. By purchasing CANopen equipment that adhere to a specific device profile, it is possible to expect that they come with a well-structured Object Dictionary and default parameters that align with the device's intended functionality. Indeed, the device manufacturer typically provides an Electronic Data Sheet (EDS) file that can be import in a CANopen configuration tools or software allowing conveniently accessing and configuring device parameters.

A widely used programming language for network management and configuration is Python. It offers several advantages, such as flexibility, open-source libraries and packages available for CANopen communication, Cross-Platform Compatibility and many others. To manage a CANopen network or devices using Python scripts, the following components are needed:

- CAN Hardware Interface (such as a USB-to-CAN adapter).
- CANopen Stack (some popular options include python-canopen, python-can, and CANopenSocket).
- CANopen controller.
- CANopen Device (the CANopen devices you want to manage).

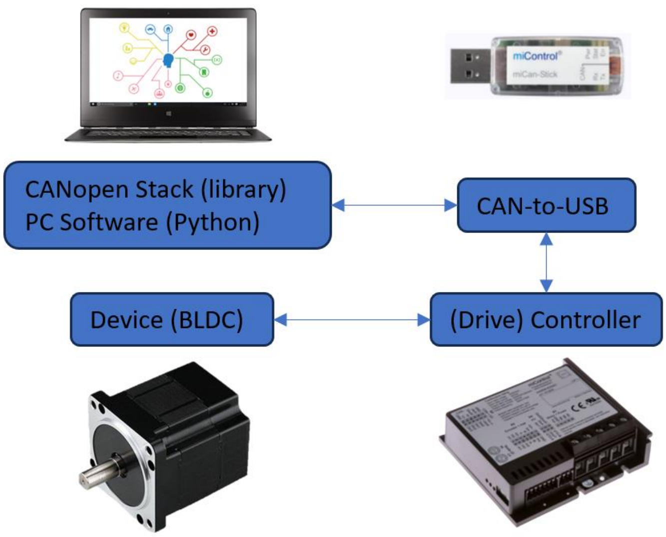


Figure 43: Hardware components for CANopen device interface [72].

Once all these components are in place, it is possible to proceed with writing Python codes for configuring individual devices by reading and writing EDS files. This may involve setting parameters, defining communication profiles, and configuring node IDs. Then it is possible to test the script and to debug any issues before integrating it into the broader application or system to automate and manage the CANopen network. The entire setup process is summarized in Figure 44.

The coding and implementation of the network is out of the scope of this thesis, but will be one of the early steps in the upcoming phases of the project.

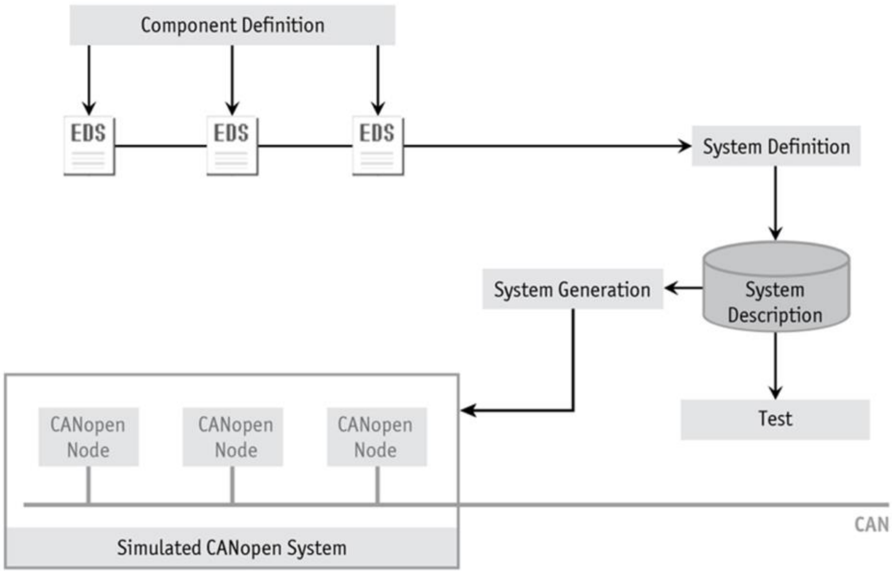


Figure 44: CANopen network design procedure [70].

6 Summary and Outlook

This chapter provides an overview of the progress made up to this point, offering a summary of the processes and steps taken to reach to the final outcomes. It also acknowledges the challenges faced and overcame during the research journey. Furthermore, the chapter emphasizes potential future enhancements and advancements that could be considered in relation to this project.

6.1 Achievements

In the not-so-distant future, a revolution is unfolding on our roads, one that promises to reshape our daily lives and the very fabric of our cities. As autonomous driving and state-of-the-art x-by-wire systems emerge, our vehicles are transcending their traditional role as mere modes of transportation. They're evolving into sophisticated technological marvels. Imagine a world where accidents and traffic jams are relics of the past. Autonomous vehicles communicate effortlessly, navigating our urban landscapes with unparalleled precision, reducing the stress of our daily commutes. The benefits are profound, from safer streets and reduced congestion to enhanced accessibility and environmental consciousness. These innovations are ushering in a new era of mobility, promising not only to change how we move from place to place, but also how we interact with our vehicles. The journey has begun, and the road ahead holds the promise of convenience, sustainability, and boundless opportunity, transforming both our society and the automotive field.

Within the scope of this Master’s Thesis work, the steering system for a test vehicle built by KIT University to demonstrate and validate new technologies was designed. It proposes the employment of steer-by-wire technology applied to an active front independent steering system to enhance its potential. In order to explore and compare different configurations, and the potential benefits they could bring to the driving experience, a mechanical sizing process was performed, and in-depth studies were made on the architecture and operation of a CANopen communication network.

First, in the early stages of the project, a strong effort was made to consolidate knowledge in the field of vehicle electronics. For this purpose, the concept of E/E architecture was defined, and its historical evolution was studied until the current concept of 'zone-based architecture' was reached. Keeping in mind the motivations that guided the development of such architecture, such as safety, cost reduction, flexibility, low communication latency, and so on, the focus was placed on which communication protocols are most frequently used in the automotive field to enable the connection between the various systems of the in-vehicle network, and how the requirements that these protocols must fulfil are evolving. In particular, the volume of information that must be able to be transmitted is increasing and traditional bandwidth is becoming a limitation. As the network becomes more complicated, and the need for real-time communication more and more stringent, latency and determinism have become key factors in the design and development of communication systems. Finally, flexibility and adaptability are essential features for upgrading and improving software throughout the whole lifetime of the vehicle.

In order to enable a comparison of the most common communication protocols, what their characteristics are and for which subsystems of the in-vehicle network they are most suitable, a brief description of CAN, LIN, FlexRay, MOST and Automotive Ethernet is provided. Special emphasis is placed on the high-level CANopen protocol, which lays its foundation on the CAN network and greatly extends its properties and fields of application. The basic concepts of CANopen are described in order to understand its structure and operating principle, which is useful information for the development of the second part of this project.

Subsequently, from a global visualisation of the vehicle system, the study moved on to the investigation of the steering system. In this phase, the novel steer-by-wire technology was introduced, the improvements it brings to traditional steering systems were highlighted, and the challenges that still have to be met in order to achieve the ultimate ascendancy of this technology in everyday vehicles were outlined. On top of that, it is provided with a description of both the hardware and software components underlying a generic SBW system. Specifically, a study on torque and angle sensors allowed a comparison of the various technologies available on the market with the aim of highlighting the types that best meet the safety, reliability, accuracy and response time requirements of SBW systems. This analysis revealed the strain gauge torque sensor, in particular for measuring the torque imposed by the driver on the steering wheel. As a steering angle sensor, a very attractive technology is spin-valve GMR sensor, but well-established optical and/or magnetic sensors such as encoders remain an excellent option. Finally, a discussion of the main control methods that an SBW system can use to monitor its proper functioning is included. The distinction is made according to the input parameters required by the control methods, which are mainly steering wheel torque and steering angle.

The analysis moves then to the core of the project. A conceptual proposal to combine front wheel independent steering with steer-by-wire technology is discussed. The steering system thus becomes 'active', which means extremely flexible and able to adapt to any driving situation required by the driver or imposed by the road. This type of configuration makes it possible both to exploit the countless advantages of SBW, but also to overcome the limitations imposed by the Ackermann geometry of traditional steering systems. Indeed, the ability to manoeuvre the front wheels independently allows to set different camber angles between the inner and outer wheels, thus avoiding the lateral sliding of the tyres known as Ackermann error.

Based on the theoretical notions acquired in the first part of the work, and taking advantage of the knowledge established and made available by KIT University, the next step is the design and sizing of an active front independent steering equipped with steer-by-wire technology. The system presented is designed and modelled for future integration and testing on the demonstration vehicle. It involves the installation of two symmetrical units based on a parallel-axis configuration, driven by an electric motor and connected via a gear. The front axle uses a ball screw to drive the wheel turning. The idea of exploiting this concept, different from the classic rack and pinion, stems from the desire to advance an innovative proposal able to maximise the performance and comfort provided by the steering system. It translates into greater accuracy, smoothness, quick response, and reliability.

The study involves a complete analysis of the system, starting with the operational logic, moving on to the sizing of the components and their fastening systems, and finally to the type of sensors employed and their place of installation.

In conclusion, a control system is proposed to manage the steer-by-wire system via a communication network based on the CANopen protocol. In this chapter, the parameters and functionalities to be monitored and guaranteed by the control system were identified. Furthermore, control methods used by SBW systems and available in the literature, such as PID controller, Fuzzy Logic controller and many others, were reported. The final step was the determination of the CANopen protocol as a communication system able to fully meet the requirements imposed by this application. Based on the standard specifications provided by CiA, the approaches and fundamental steps to be followed for the construction of the embedded network were outlined. Lastly, by means of a flowchart, the flow of information exchanged between the various nodes of the network was highlighted so that all the necessary conditions were in place for the future implementation of the system software.

6.2 Future work

KIT University has long term plans to continue to research and develop breakthrough technologies for innovative vehicle drives, such as x-by-wire technologies. The proof of its interest in developing technologies and new approaches can be found in its collaboration with the ICM platform and the many projects it has undertaken in the automotive field and beyond. On the ICM webpage [9], further details on the projects already started and the community's future plans are available.

The work carried out so far on the steering system represents only a first step towards this new way of understanding the vehicle concept. In fact, being able to proceed with the study of "by wire" technology applied to other systems, such as the braking system, the author identified and recommends different areas for further research and advancements. Specifically:

- Build a solid and reliable software component.
- Physical model of the designed active front independent steering system.
- Test bench implementation.
- Vehicle integration.

Considering this, future studies must aim to optimise the configuration by developing more information on modelling and increase the confidence in the design by iteratively testing it and tuning the models accordingly with the experimental behaviour observed. An assessment of the risks and benefits coming from the integration of these systems on board should also be conducted.

6.2.1 Build a solid and reliable software component

Although the author has laid the foundation for the construction of the control system and communication network, much progress and advancement are expected in this area. At the moment, the approach offered is still at a conceptual level. The steering system's underlying logic is understood, the role of each device belonging to the network is known and, therefore, also the parameters they must contain, the connections between the various nodes, which communication protocols to apply and what information must circulate. Besides, considerations were made regarding the trigger times and closed-loop control systems that can be implemented. Moreover, section 5.3.3 also introduced the hardware and software components required for the implementation of such an architecture.

The task at hand will be to work on the interface between the CANopen network and the programming terminal. As mentioned before, a potential programming language is Python, as it already offers some libraries for interaction with CANopen networks and signals. It is necessary to proceed with the drafting of codes for setting parameters within the Object Dictionary of each node. Finally, at a later stage, the operation of the entire SBW system must be integrated and coordinated within a program executable by the Master node.

Alongside this, a mathematical model of the system and its implementation in a virtual simulation environment such as MATLAB/Simulink or CarSim should be created. Subsequently, realistic scenarios for running iterative tests should be defined in order to validate the developed control system.

6.2.2 Physical model of the designed AFIS

The work developed in this thesis was did not progress on the purchase and manufacturing of the system, but did supported this following phase by providing a mechanical design process, CAD model and in-depth study on the software tools. Hence, starting from the assembled design of the components and the list potential suppliers and suitable equipment presented, further practical verification and testing should be performed on the challenges of integrating the steering wheel system with the front wheel system proposed and their compatibility with the vehicle chassis constraints before proceeding with the construction.

Nonetheless, as far as the steering wheel block is concerned, a FANATEC CSL DD 5 Nm [73] racing wheel has already been selected and purchased. It includes the angular and torque sensors as well as the feedback motor within it, thus completing the input device of the entire system. For the front wheel system, instead, it would be possible to proceed with the manufacture and/or purchase of the components in light of the almost definitive state of the system design. Some parts of this, such as the input shaft and gears, can be made in-house at the university, others such as tie rods and tie rod ends, as they are the same as those already implemented on the current vehicle set-up, are already available. On the contrary, bearings, sealing and connection system, couplings, slides, rails and supports require purchasing from specialised suppliers.

6.2.3 Test bench experiments

As soon as the construction of the model is done and the software component of each element has been implemented, it will be necessary to proceed with the execution of several tests to verify the operation and the consistent response of the hardware part with respect to the commands from the software. The driving situations described in section 3.3 may be simulated, so that each device is tested under different working conditions and with a consistent variation of input and/or output parameters.

Once all devices meet the system requirements, the next step will be to integrate the three main blocks of the SBW system into the global communication network. Only at this point will it be possible to carry out simulations to test the actual performance of the steering system under study.

6.2.4 Vehicle integration

The end goal of this steer-by-wire system research must be the integration of the concept into the demonstrator vehicle being developed at KIT. The purpose would be to test the steering architecture in a real-world scenario and collect useful test data along the driving tests. It must be noticed that there are several major differences between the laboratory test conditions of the steering system designed and the actual driving condition once it is integrated into the frame, such as higher external loads, vibrations, dust, temperature variations and intensive cooperation with auxiliary components.

Despite being the road to performing driving tests for the validation of the device designed in this work is still long and articulated, it does not detract from the importance of the work carried out so far. The contribution provided to this novel area of research, spanning across various areas of engineering, lays the foundation and consequent roadmap outlining the steps to follow in order to aspire to the final goal. This broad and in-depth analysis may shed light on a technology as fascinating as it is intricate, such as steer-by-wire.

7 Nomenclature

Symbol	Unit	Description
δ	rad	Ackermann or single-track angle
$\delta_{i,ideal}$	rad	Ideal steering angle of the inner wheel
$\delta_{i,ideal}$	rad	Ideal steering angle of the outer wheel
R	m	Radius of curvature
L	m	Wheelbase
F	N	Force
M	Nm	Torque

Abbreviation	Description
AD	Autonomous Driving
ADAS	Advanced Driver Assistance Systems
AFIS	Active Front Indipendent Steering
CAN	Controller Area Network
CiA	CAN in Automation
DBW	Drive-by-Wire
ECU	Electric Control Unit
EEA	Electric/Electronic Architecture
FAST	Institut für Fahrzeugsystem-technik
FWIS	Front Wheel Independent Steering
KIT	Karlsruhe Institute of Technology
OTA	Over-the-Air
SBW	Steer-by-Wire

8 Bibliography

[1] ‘SAE Levels of Driving Automation™ Refined for Clarity and International Audience’. Accessed: Oct. 05, 2023. [Online]. Available: https://www.sae.org/blog/sae-j3016-update

[2] ‘The future of mobility is at our doorstep’.

[3] M.-M. Kauhanen, ‘Master’s Programme in Automation and Electrical Engineering Drive-by-wire control for the longitudinal motion of an autonomous electric vehicle Simulation model-> Simulink Sensible 4 Oy-> Company specilized in Drive-by-Wire’.

[4] A. Huang Pei-Shih and Pruckner, ‘Steer by Wire’, in *Steering Handbook*, P. Harrer Manfred and Pfeffer, Ed., Cham: Springer International Publishing, 2017, pp. 513–526. doi: 10.1007/978-3-319-05449-0_18.

[5] S. A. Mortazavizadeh, A. Ghaderi, M. Ebrahimi, and M. Hajian, ‘Recent Developments in the Vehicle Steer-by-Wire System’, *IEEE Transactions on Transportation Electrification*, vol. 6, no. 3, pp. 1226–1235, Sep. 2020, doi: 10.1109/TTE.2020.3004694.

[6] A. Weber, ‘Wire Processing: Drive-by-Wire’, *Assembly Magazine*, Mar. 2010, Accessed: Oct. 05, 2023. [Online]. Available: https://www.assemblymag.com/articles/87508-wire-processing-drive-by-wire

[7] H. Naunheimer, Peter. Fietkau, and G. (Gisbert). Lechner, ‘Automotive transmissions : fundamentals, selection, design and application’, p. 715, 2011.

[8] A. Sampath, ‘Toward functional safety in drive by wire vehicles’, *Mobility Engineering*, no. December 2020, Accessed: Oct. 05, 2023. [Online]. Available: https://saeindia.org/jbframework/uploads/2020/12/Tech-Trends-Towards-Functional-Safety-in-Drive-By-Wire-Vehicles-compressed.pdf

[9] ‘InnovationCampus Future Mobility (ICM) | ICM’. Accessed: Oct. 05, 2023. [Online]. Available: https://www.icm-bw.de/en/

[10] ‘BUP24 - E/EeVee | ICM’. Accessed: Oct. 05, 2023. [Online]. Available: https://www.icm-bw.de/en/projects/project-overview/details/bup24-eeevee

[11] F. Häfele, ‘Bachelorarbeit Analyse, Auslegung und Konzeption eines Lenksystems für ein Versuchsfahrzeug’.

[12] H. Zhu, W. Zhou, Z. Li, L. Li, and T. Huang, ‘Requirements-Driven Automotive Electrical/Electronic Architecture: A Survey and Prospective Trends’, *IEEE Access*, vol. 9. Institute of Electrical and Electronics Engineers Inc., pp. 100096–100112, 2021. doi: 10.1109/ACCESS.2021.3093077.

[13] ‘Was ist die Norm ISO 26262 zur funktionalen Sicherheit von Fahrzeugen? - NI’. Accessed: Oct. 08, 2023. [Online]. Available: https://www.ni.com/de/solutions/transportation/what-is-the-iso-26262-functional-safety-standard-.html

[14] S. Apostu, O. Burkacky, J. Deichmann, and G. Doll, ‘Automotive software and electrical/electronic architecture: Implications for OEMs’, 2019.

[15] ‘How SOME/IP Enables Service Oriented Architecture in ECU Network’. Accessed: Sep. 01, 2023. [Online]. Available: https://www.embitel.com/blog/embedded-blog/how-some-ip-enables-service-oriented-architecture-in-ecu-network

[16] M. Rumez, D. Grimm, R. Kriesten, and E. Sax, ‘An Overview of Automotive Service-Oriented Architectures and Implications for Security Countermeasures’, *IEEE Access*, vol. 8, 2020, doi: 10.1109/ACCESS.2020.3043070.

[17] M. Schindewolf, H. Guissouma, and E. Sax, ‘Analysis and Modeling of Future Electric/Electronic Architectures for Modular Vehicles Concepts’, 2021, pp. 32–46. doi: 10.1007/978-3-658-33521-2_3.

[18] J. Huang, M. Zhao, Y. Zhou, and C. C. Xing, ‘In-Vehicle Networking: Protocols, Challenges, and Solutions’, *IEEE Netw*, vol. 33, no. 1, pp. 92–98, Jan. 2019, doi: 10.1109/MNET.2018.1700448.

[19] V. Informatik GmbH, ‘High-Performance Computing Platforms in the Automobile’.

[20] B. A. Rahim and S. Krishnaveni, ‘Comparison of CAN, TTP and Flexray Communication Protocols’, *International Journal of Innovative Research in Computer and Communication Engineering (An ISO*, vol. 3297, no. 4, 2007, [Online]. Available: www.ijircce.com

[21] W. Zeng, M. A. S. Khalid, and S. Chowdhury, ‘In-vehicle networks outlook: Achievements and challenges’, *IEEE Communications Surveys and Tutorials*, vol. 18, no. 3, pp. 1552–1571, Jul. 2016, doi: 10.1109/COMST.2016.2521642.

[22] T. Führer, B. Müller, W. Dieterle, F. Hartwich, R. Hugel, and M. Walther, ‘Time Triggered Communication on CAN (Time Triggered CAN-TTCAN)’.

[23] O. Pfeiffer, A. Ayre, and C. Keydel, ‘Embedded Networking with CAN and CANopen’. [Online]. Available: http://www.copperhillmedia.com

[24] ‘SDO services’. Accessed: Oct. 23, 2023. [Online]. Available: https://www.canopensolutions.com/english/about_canopen/SDO-services.shtml

[25] ‘PDO services’. Accessed: Oct. 23, 2023. [Online]. Available: https://www.canopensolutions.com/english/about_canopen/PDO-services.shtml

[26] ‘Network management (NMT)’. Accessed: Oct. 23, 2023. [Online]. Available: https://www.canopensolutions.com/english/about_canopen/Network-management.shtml

[27] ‘MostCorp’. Accessed: Oct. 24, 2023. [Online]. Available: https://mostcorp.com/

[28] Andreas. Grzemba, *MOST : the automotive multimedia network*. Francis Verlag, 2011.

[29] ‘ISO 26262-1:2011 - Road vehicles — Functional safety — Part 1: Vocabulary’. Accessed: Oct. 24, 2023. [Online]. Available: https://www.iso.org/standard/43464.html

[30] ‘Top_10_tech_cars_slenderized’.

[31] M. B. Nor Shah, A. R. Husain, and A. S. A. Dahalan, ‘An analysis of CAN-based steer-by-wire system performance in vehicle’, in *Proceedings - 2013 IEEE International Conference on Control System, Computing and Engineering, ICCSCE 2013*, 2013, pp. 350–355. doi: 10.1109/ICCSCE.2013.6719988.

[32] C. Christiansen and V. Alkelin, ‘Alternative Input Devices for Steer-by-Wire Systems’, 2020.

[33] A. Kader, ‘Steer-by-Wire Control System’, 2006.

[34] K. Chaaban, P. Leserf, and S. Saudrais, ‘Steer-by-wire system development using AUTOSAR methodology’, in *ETFA 2009 - 2009 IEEE Conference on Emerging Technologies and Factory Automation*, 2009. doi: 10.1109/ETFA.2009.5347123.

[35] ‘Torque Gauge | How it Works | FUTEK’. Accessed: Oct. 24, 2023. [Online]. Available: https://www.futek.com/torque-gauge

[36] J. C. S. Borges, D. B. B. De Deus, A. C. Lima Filho, and F. A. Belo, ‘New Contactless Torque Sensor Based on the Hall Effect’, *IEEE Sens J*, vol. 17, no. 16, pp. 5060–5067, Aug. 2017, doi: 10.1109/JSEN.2017.2723041.

[37] ‘What are magnetoelastic sensors for torque measurement?’ Accessed: Oct. 24, 2023. [Online]. Available: https://www.motioncontroltips.com/what-are-magnetoelastic-sensors-for-torque-measurement/

[38] R. J. Hazelden, ‘Optical torque sensor for automotive steering systems’, 1993.

[39] ‘Steer by Wire | Steering Torque Sensor | FUTEK’. Accessed: Oct. 29, 2023. [Online]. Available: https://www.futek.com/applications/Steer-By-Wire-Sensor

[40] W. Granig, S. Hartmann, and B. Köppl, ‘Performance and technology comparison of GMR versus commonly used angle sensor principles for automotive applications’, in *SAE Technical Papers*, SAE International, 2007. doi: 10.4271/2007-01-0397.

[41] ‘Resolvers - What Are They and How Do They Work? | Dynapar’. Accessed: Oct. 24, 2023. [Online]. Available: https://www.dynapar.com/Technology/Encoder_Basics/Resolvers/

[42] J. Ackermann *et al.*, ‘Four-Wheel-Steering Control Strategy and its Integration with Vehicle Dynamics Control and Active Roll Control’. [Online]. Available: http://www.zf-lenksysteme.com/en/products/car-

[43] ‘Book : The Contact Patch’. Accessed: Sep. 28, 2023. [Online]. Available: https://the-contact-patch.com/book/road/c0505-steering

[44] ‘Book : The Contact Patch’. Accessed: Sep. 28, 2023. [Online]. Available: https://the-contact-patch.com/book/road/c0504-ackermann-geometry

[45] ‘CSL DD 5 Nm | Fanatec’. Accessed: Oct. 29, 2023. [Online]. Available: https://fanatec.com/us-en/racing-wheels-direct-drive-bases/direct-drive-bases/csl-dd-5-nm

[46] ‘Brushless DC Motor Design | Portescap’. Accessed: Sep. 19, 2023. [Online]. Available: https://www.portescap.com/en/products/brushless-dc-motors/bldc-motor-design

[47] ‘L-Category Vehicles (Powered Light Vehicles-PLVs) Examples & Definitions’, 2019.

[48] ‘Baldwin Street: Die steilste Straße Neuseelands’. Accessed: Oct. 11, 2023. [Online]. Available: https://www.travelbook.de/ziele/baldwin-street-in-neuseeland-wird-zum-netz-hit

[49] ‘(Kraftfahrzeugtechnik) Peter Pfeffer, Manfred Harrer - Lenksystemhandbuch_ Lenksysteme, Lenkgefühl, Fahrdynamik von Kraftfahrzeugen -Vieweg+Teubner (2011)’.

[50] ‘48V 200W Brushless DC Motor, 0.64 Nm, 3000 rpm, 5.21A | Brushless.com’. Accessed: Sep. 19, 2023. [Online]. Available: https://www.brushless.com/48v-200w-brushless-dc-motor

[51] ‘GN 2244 Metallbalgkupplungen mit Klemmnabe | Ganter Normelemente’. Accessed: Sep. 19, 2023. [Online]. Available: https://www.ganternorm.com/de/produkte/3.6-Bewegen-Uebertragen-mit-Wellen-und-Gelenken/Wellenkupplungen/GN-2244-Metallbalgkupplungen-mit-Klemmnabe

[52] ‘Homepage der SKF Gruppe | SKF’. Accessed: Oct. 12, 2023. [Online]. Available: https://www.skf.com/de

[53] ‘Rolling bearings’, 2018.

[54] ‘Lead Screws vs Ball Screws: It’s All about the Application’. Accessed: Sep. 19, 2023. [Online]. Available: https://blog.helixlinear.com/lead-screws-vs-ball-screws-its-all-about-the-application

[55] ‘Products’. Accessed: Sep. 20, 2023. [Online]. Available: https://www.ganternorm.com/en/products/3.6-Moving-transferring-connecting-with-shafts-and-joints/Ball-joints/GN-782-Ball-joints-Steel#d1%3Du(68c877b0-62fe-49c2-a21a-f5a963ade360)%3BForm%3Du(20db18b2-3e57-4959-b6cc-5983723bdde1)%3BKennziffer%3Du(b48274dd-19a4-40da-aaaa-0c629ba97a7f)

[56] ‘EGW15SCZAH | EGW/QEW | Baureihe EG/QE | Laufwagen | Profilschienenführungen | Produkte | HIWIN’. Accessed: Oct. 29, 2023. [Online]. Available:

https://www.hiwin.de/de/Produkte/Profilschienenf%C3%BChrungen/Laufwagen/Baureihe-EG-QE/EGW-QEW/EGW15SCZAH/p/5-001418

[57] ‘Absolute position sensing: the key to better brushless DC motor control - Electronic Products’. Accessed: Oct. 03, 2023. [Online]. Available: https://www.electronicproducts.com/absolute-position-sensing-the-key-to-better-brushless-dc-motor-control/

[58] ‘Resolver (electrical) - Wikipedia’. Accessed: Oct. 03, 2023. [Online]. Available: https://en.wikipedia.org/wiki/Resolver_(electrical)

[59] ‘Incremental vs Absolute encoder - What is absolute and incremental encoder’. Accessed: Oct. 03, 2023. [Online]. Available: https://911electronic.com/incremental-vs-absolute-encoder/

[60] ‘Capacitive, Magnetic, and Optical Encoders – Comparing the Technologies | CUI Devices’. Accessed: Oct. 03, 2023. [Online]. Available: https://www.cuidevices.com/blog/capacitive-magnetic-and-optical-encoders-comparing-the-technologies

[61] R. plc, ‘RESOLUTE absolute optical linear encoder Data Sheet’.

[62] ‘Absolute linear magnetic encoder | LA11- www.rls.si’. Accessed: Oct. 03, 2023. [Online]. Available: https://www.rls.si/eng/la11-linear-absolute-encoder

[63] ‘Linear Variable Differential Transformer (LVDT) Basics | TE Connectivity’. Accessed: Oct. 03, 2023. [Online]. Available: https://www.te.com/usa-en/products/sensors/position-sensors/resources/lvdt-tutorial.html

[64] ‘Absolute linear magnetic encoder | LA11- www.rls.si’. Accessed: Oct. 29, 2023. [Online]. Available: https://www.rls.si/eng/la11-linear-absolute-encoder

[65] Institute of Electrical and Electronics Engineers., *SHUSER 2012 : 2012 IEEE Symposium on Humanities, Science and Engineering Research : Renaissance Hotel, Kuala Lumpur, Malaysia, 24 to 27 June 2012.* IEEE, 2012.

[66] M. Zaidi Mohd Tumari *et al.*, ‘The Control Schemes of Vehicle Steer by Wire System by using Fuzzy Logic and PID Controller’.

[67] S. M. H. Fahami, H. Zamzuri, and S. A. Mazlan, ‘Development of estimation force feedback torque control algorithm for driver steering feel in vehicle steer by wire System: Hardware in the loop’, *International Journal of Vehicular Technology*, vol. 2015, 2015, doi: 10.1155/2015/314597.

[68] C. Huang, F. Naghdy, and H. Du, ‘Sliding mode predictive tracking control for uncertain Steer-by-Wire system’, *Control Eng Pract*, vol. 85, pp. 194–205, Apr. 2019, doi: 10.1016/j.conengprac.2018.12.010.

[69] M. T. Do, Z. Man, C. Zhang, H. Wang, and F. S. Tay, ‘Robust Sliding Mode-Based Learning Control for Steer-by-Wire Systems in Modern Vehicles’, *IEEE Trans Veh Technol*, vol. 63, no. 2, pp. 580–590, 2014, doi: 10.1109/TVT.2013.2280459.

[70] ‘CANopen Know-how | Vector’. Accessed: Oct. 29, 2023. [Online]. Available: https://www.vector.com/int/en/know-how/protocols/canopen/#

[71] K. Al-Badri and H. Basargan, ‘Al-Badrı, Kerem & Basargan, Hakan; Design and Implementation of a Steer-by-Wire Control System for Autonomous Vehicles Design and Implementation of a Steer-by-Wire Control System for Autonomous Vehicles’.

[72] ‘Welcome to miControl — English’. Accessed: Oct. 29, 2023. [Online]. Available: https://www.micontrol.de/en

[73] ‘CSL DD 5 Nm | Fanatec’. Accessed: Oct. 25, 2023. [Online]. Available: https://fanatec.com/eu-de/racing-wheels-direct-drive-bases/direct-drive-bases/csl-dd-5-nm

9 Annex

SBW sensors

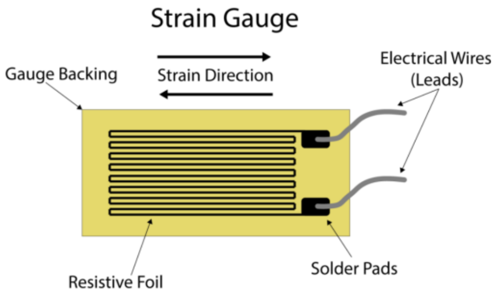


Figure 45: Strain Gauge Torque Sensors [15].

Block diagram of Torque Sensor-Based Control [5]

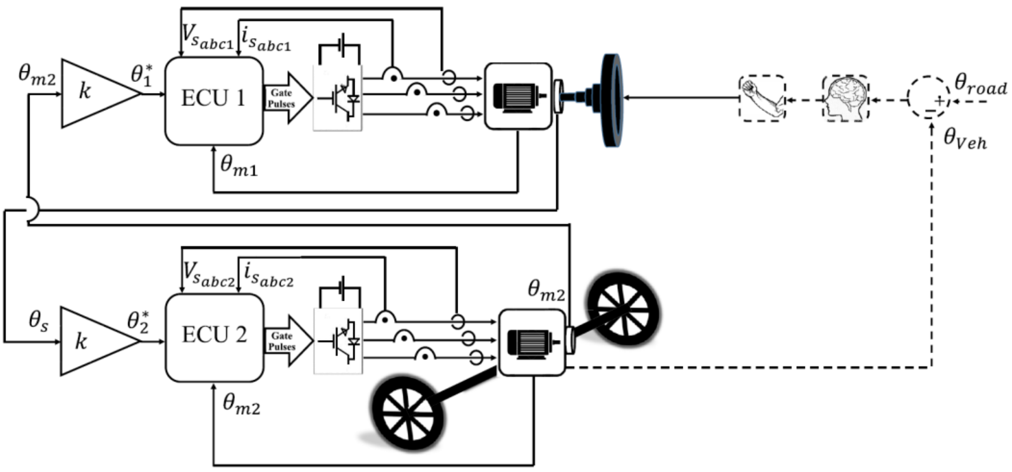


Figure 46: Angle sensor on both steering wheel and road wheel.

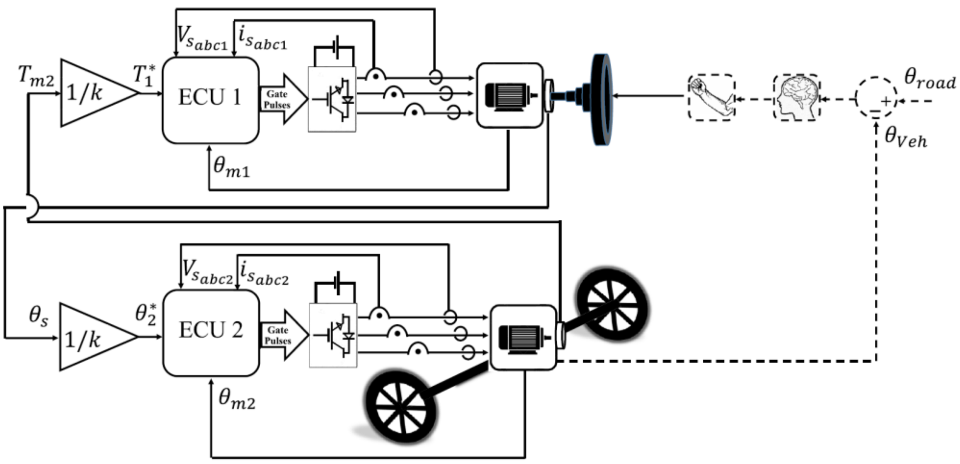


Figure 47: Angle sensor on steering wheel and torque sensor on road wheel.

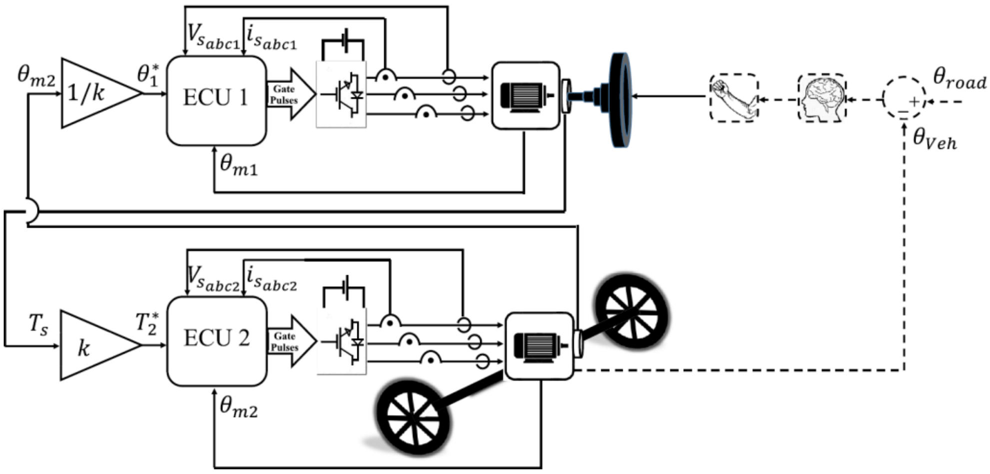
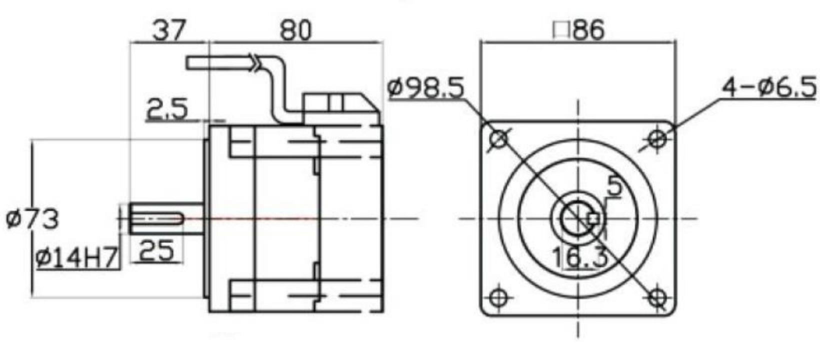


Figure 48: Torque sensor on steering wheel and angle sensor on road wheel.

Brushless direct current motor [50]

Dimension (Unit: mm)



Basic Specifications

Model: BLDC-D2BLD200-48A-30S
Matched Controller Model: BLD-300B
Rated Power: 200W
Rated Voltage: 48V
Rated Current: 5.21A
Phase: 3 phase

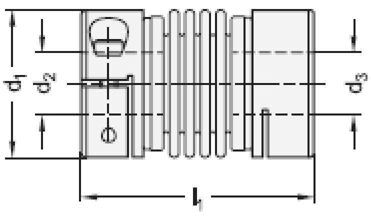
Rated Torque: 0.64 Nm
Max Torque: 1.91 Nm
Rated Speed: 3000 rpm
No-load Current: < 1.61A
Square Flange Size: 86 mm
Insulation Grade: F

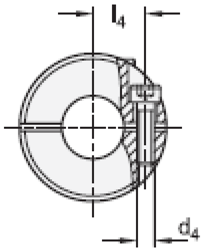
Working Efficiency: 85%
Protection Grade: IP54
Motor Lead Length: 1 meter
Certificate: CE, RoHS, ISO
Weight: 3 kg

GN 2244 Metal bellow joint [51]

GN 2244 | Metallbalgkupplungen

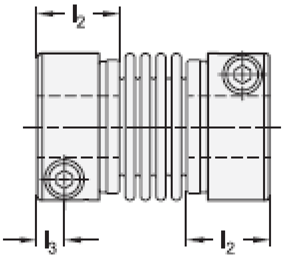
mit Klemmnabe

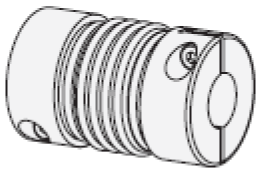




2 **Bohrungskennzeichnung**

B ohne Passfedernut





1 d_1	3 d_2 - d_3 H8 empfohlene Wellentoleranz h7					
19	5-5	5-6	5-8	6-6	6-8	8-8
27	6-6	6-8	6-10	8-8	8-10	10-10
32	10-10	10-12	10-14	12-12	12-14	14-14
40	12-12	12-15	12-19	15-15	15-19	19-19

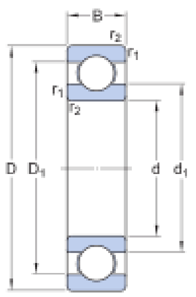
d_1	d_4	l_1	l_2 empfohlene Welleneinstecktiefe	l_3	l_4	Anzugsdrehmoment der Schraube in Nm ≈
19	M 2	30	10,5	3	6,8	0,5
27	M 2,5	35	12,5	3,5	10,3	0,9
32	M 3	46	15,5	4,3	12	1,5
40	M 4	51	16	5	15	3,5

d_1	Nenndrehmoment in Nm	Max. Drehzahl (min^{-1})	Trägheitsmoment in kgm^2	Statische Torsionssteife in Nm/rad	Max. Wellenversatz		
					radial in mm	axial in mm	winklig in °
19	1,5	33.000	$8{,}6 \times 10^{-7}$	170	0,15	± 0,5	1,5
27	2,3	23.000	$3{,}6 \times 10^{-6}$	800	0,15	± 0,5	1,5
32	4,5	19.000	$1{,}1 \times 10^{-5}$	1600	0,2	± 0,7	1,5
40	10	15.000	$2{,}8 \times 10^{-5}$	2700	0,2	± 1	1,5

Bearings [53]

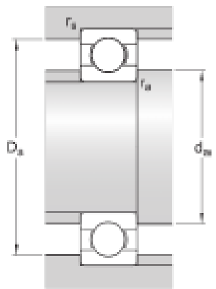
Single row deep groove ball bearing “61802”:

Technical Specification



Dimensions

d	15 mm	Bore diameter
D	24 mm	Outside diameter
B	5 mm	Width
d_1	≈ 17.8 mm	Shoulder diameter
D_1	≈ 21.3 mm	Shoulder diameter
$r_{1,2}$	min. 0.3 mm	Chamfer dimension



Abutment dimensions

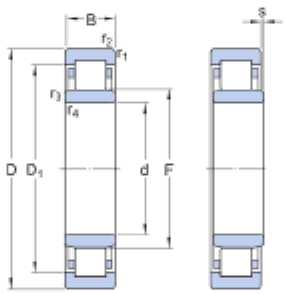
d_a	min. 17 mm	Diameter of shaft abutment
D_a	max. 22 mm	Diameter of housing abutment
r_a	max. 0.3 mm	Radius of shaft or housing fillet

Calculation data

Basic dynamic load rating	C	1.9 kN
Basic static load rating	C_0	1.1 kN
Fatigue load limit	P_u	0.048 kN
Reference speed		60 000 r/min
Limiting speed		38 000 r/min
Minimum load factor	k_r	0.015
Calculation factor	f_0	13.8

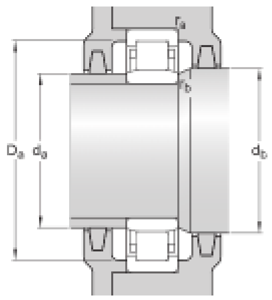
Single row cylindrical roller bearing “NU 202 ECP”:

Technical Specification



Dimensions

d	15 mm	Bore diameter
D	35 mm	Outside diameter
B	11 mm	Width
D_1	≈ 27.7 mm	Shoulder diameter of outer ring
F	19.3 mm	Raceway diameter of inner ring
$r_{1,2}$	min. 0.6 mm	Chamfer dimension
$r_{3,4}$	min. 0.3 mm	Chamfer dimension
s	max. 1 mm	Permissible axial displacement



Abutment dimensions

d_a	min. 17.4 mm	Diameter of spacer sleeve
d_a	max. 18.4 mm	Diameter of spacer sleeve
d_b	min. 21 mm	Diameter of shaft abutment
D_a	max. 31.3 mm	Diameter of housing abutment
r_a	max. 0.6 mm	Radius of fillet
r_b	max. 0.3 mm	Radius of fillet

Calculation data

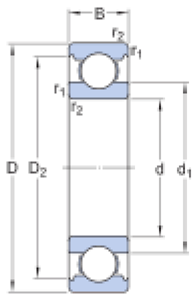
Basic dynamic load rating	C	12.5 kN
Basic static load rating	C_0	10.2 kN
Fatigue load limit	P_u	1.22 kN
Reference speed		22 000 r/min
Limiting speed		26 000 r/min
Minimum load factor	k_r	0.15
Limiting value	e	0.2

Single row deep groove ball bearing “6007”:

Technical Specification

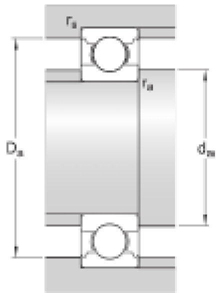
SKF performance class	SKF Explorer

Dimensions



d	35 mm	Bore diameter
D	62 mm	Outside diameter
B	14 mm	Width
d_1	≈ 43.75 mm	Shoulder diameter
D_2	≈ 55.61 mm	Recess diameter
$r_{1,2}$	min. 1 mm	Chamfer dimension

Abutment dimensions



d_a	min. 39.6 mm	Diameter of shaft abutment
D_a	max. 57.4 mm	Diameter of housing abutment
r_a	max. 1 mm	Radius of shaft or housing fillet

Calculation data

Basic dynamic load rating	C	16.8 kN
Basic static load rating	C_0	10.2 kN
Fatigue load limit	P_u	0.44 kN
Reference speed		24 000 r/min

Linear Sensors

Table 8: Motor Angular Sensor.

Parameters	Absolute Optical Linear Encoder [61]	Absolute Magnetic Linear Encoder [62]	LVDT [63]
Accuracy	±1 to ±10 µm/m	±5 to ±50 µm/m	±1 to ±10 µm/m
Precision	±0.1 to ±5 µm	±1 to ±10 µm	±0.1 to ±5 µm
Resolution	±1 nm to ±10 µm	±10 nm to ±100 µm	±1 nm to ±1 µm
Durability	Sealing and protective measures	Robust	Robust and durable
Working Conditions	Clean and stable	Harsh condition	Harsh condition
Cost	Expensive (40€ to more than 400€)	Cost-effective (15€ to more than 200€)	Expensive (100€ to 1000€ or more)
Installation and Set-up	Careful installation to ensure the alignment of scale and sensor	Easier to install and align. Less sensitive.	Proper mounting and alignment. Require signal conditioning electronics and calibration
Proximity Sensing	Yes	No	No
Weight	Light	Light	Havier
Electric Supply	DC	DC	AC
Output Signal	Digital	Analog or Digital	AC Voltage
Range	Up to several meters	Up to several meters	Less than a meter (±0.762 meter)
Speed measurement	>10 m/s	~7 to 10 m/s	<7 m/s

SBW control methods

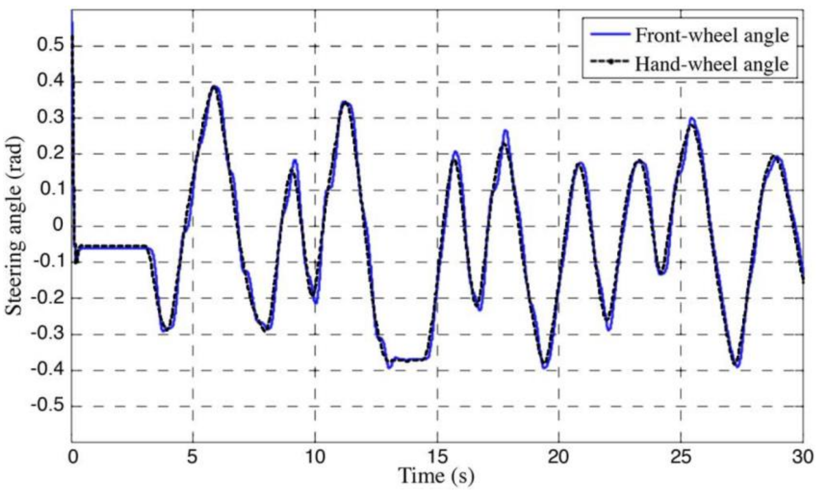


Figure 49: Steering performance after SMLC scheme implemenentation [69].

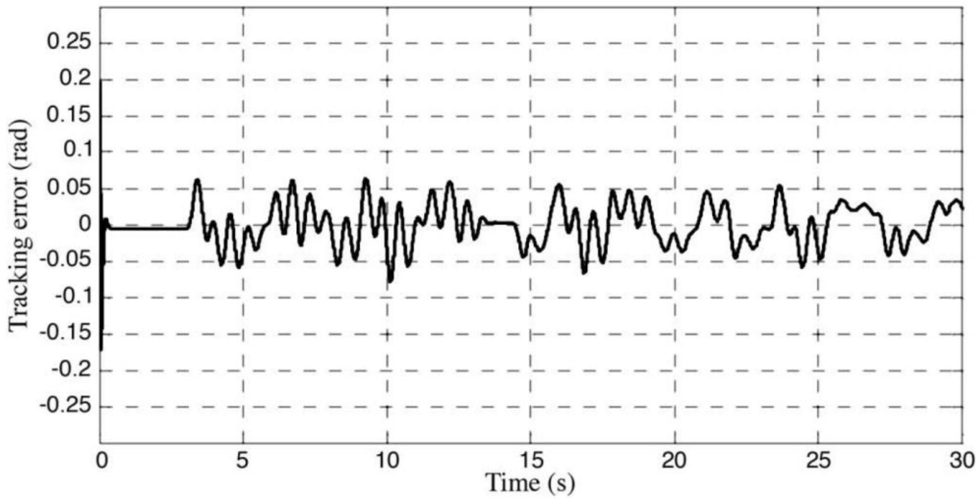


Figure 50: Tracking error (SMLC) [69].

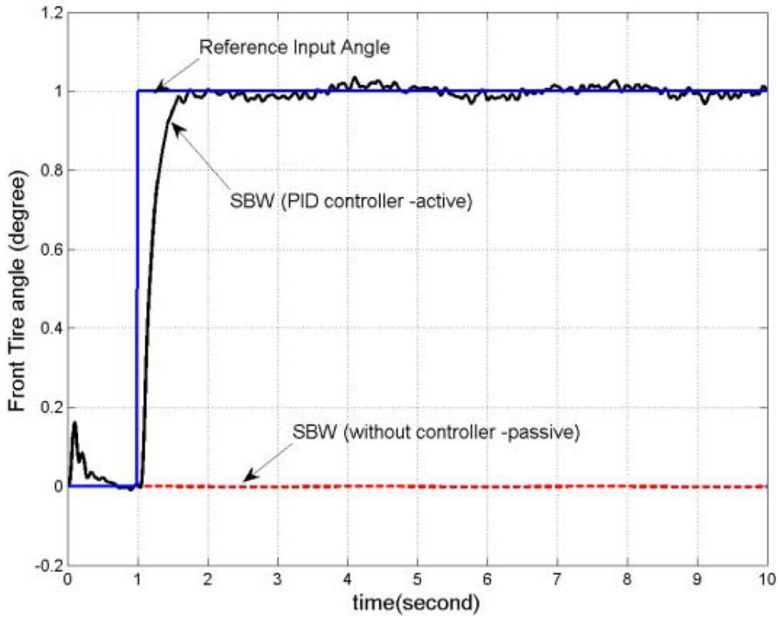


Figure 51: PID controller for wheel synchronization [65].