Digital Development of a Robust Steer-by-Wire System

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Abstract. This paper presents ZF's digital development approach for the Steer-by-Wire (SbW) system. The introduction of SbW technology in the automotive industry creates a new architecture of steering systems that poses a unique set of challenges, particularly in the design of proper steering feel, and functionalities beyond those of conventional Electric Power Steering (EPS) systems due to the missing mechanical connection between the steering wheel and rack. Virtual product development and digital twins are essential from the initial development to optimize the system design before physical prototypes are built. This paper presents three exemplary use cases that demonstrate how ZF uses virtual development methods and digital twins in the development of SbW systems.

The paper explains how ZF uses digital twins to optimize the design of the Torque Feedback Unit (TFU) for robust steering feel, the dynamic performance of the Front Axle Actuator (FAA) and the functional safety at the vehicle level. The results show that by leveraging digital twins, ZF has been able to accelerate the development process and ensure a high-quality product that meets the demands of the automotive industry.

Keywords: Steer-by-Wire, Model-based Development, Digital Twin.

1 Introduction

ZF is currently at the forefront of the development of Steer-by-Wire (SbW) systems, seen as a significant contribution to the vision of a software-defined vehicle. The introduction of SbW technology in the automotive industry creates a completely new architecture of steering systems (Fig. 1). SbW poses a unique set of challenges, particularly in achieving excellent steering feel, and functionalities beyond those of conventional Electric Power Steering (EPS) systems due to the missing mechanical connection between steering wheel and rack.

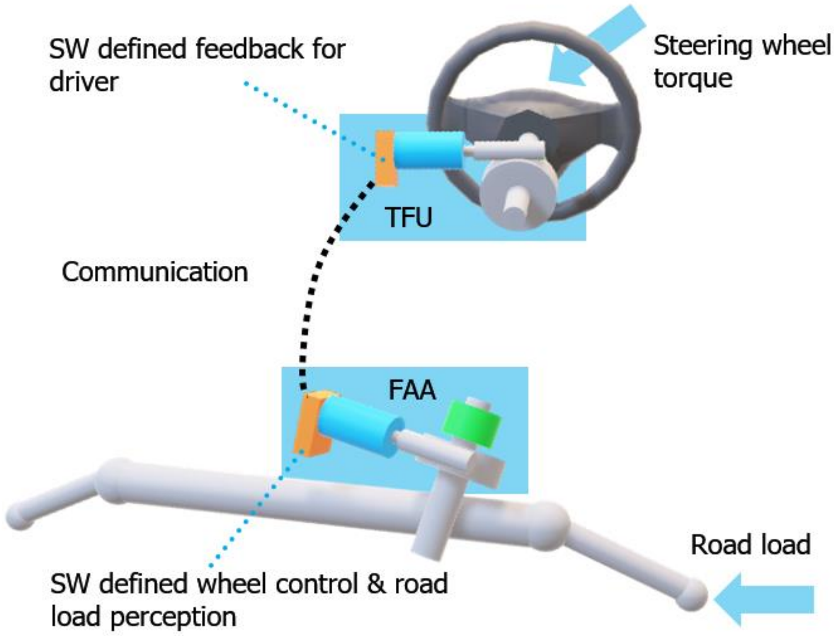

Fig. 1. Architecture of a SbW system containing of torque feedback unit (TFU) and front axle actuator (FAA) as separate actuators connected by (CAN) communication link

Therefore, SbW systems require certain features that are specific to this technology to overcome these challenges, such as closed-loop road wheel angle control and haptic feedback to the driver that is both comfortable and safe. Additionally, the system must follow the "fail operational" approach, having sufficient redundancies to continue operating if a failure occurs.

SbW offers several advantages over conventional EPS. The steering ratio can for example vary with vehicle states or be adjusted with driving modes. The steering wheel could fold into the dash while the vehicle drives autonomously, enabling a more immersive infotainment system. SbW is also safer in the event of a vehicle crash as there is no collapsible steering column and it is easier to accommodate left and right-hand drive variants.

Given the complexity of the mechatronic system and sometimes conflicting requirements for its optimization, virtual development methods are needed from the start of development. Digital twins enable engineers to optimize the system design before physical prototypes are built. In this paper, three use cases are presented to demonstrate the virtual development of SbW systems at ZF: Ensuring robustness of steering feel, dynamic performance of the front axle actuator and functional safety at the vehicle level. By leveraging digital twins, ZF has been able to accelerate the development process and ensure a high-quality product that meets the demands of the automotive industry.

2 Virtual Steering-Feel Development for Torque Feedback Unit

The steering system must fulfill two functions. It must translate the driver's steering request into a corresponding road wheel angle. Additionally, it provides haptic feedback to the driver of the state of the road and tires, often referred to as steering feel.

Steering feel is tuned by software but is influenced both by the closed-loop performance of mechatronic systems and noise factors like production tolerances and environmental conditions. All components of the SbW system must be robust against those disturbances.

To enable an objective judgement of the steering feel performance with quantitative numbers, KPIs have been developed. Any torque disturbances at steering wheel can be evaluated as KPIs containing - for instance - torque oscillation amplitude, frequencies, and energies. A TFU Digital Twin was used to understand the effect of external noise factors on these measures.

A robustness and sensitivity study was then conducted on the TFU Digital Twin to understand how the objective measures are influenced by external noise factors and controller parameters. A representative result of a robustness and sensitivity study is shown in Fig. 2.

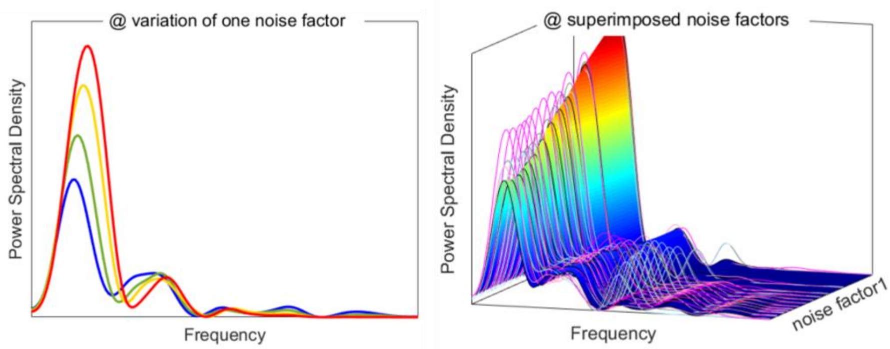

Fig. 2. Analysis of steering feel sensitivity regarding a single noise factor (left) and combined noise factors (right).

Fig. 2 shows the influence on the power spectral density of the steering wheel torque oscillation by external noise factors. The oscillation amplitude should be small enough that it is imperceptible to a driver. An objective evaluation becomes more complex due to the interaction between parameters and the non-linearity of the system. The use of digital twins enables an efficient determination of the optimal design, that is robust against those influences.

For evaluating whether simulated KPIs match system requirements for good steering feel, tests in a Driver-in-the-Loop simulator have been conducted with generic torque disturbances (Fig. **3**).

Fig. 3. Driving simulator tests with generic disturbances and objective KPIs by digital twin

A study with several drivers was performed to derive limits for the objective steering feel measures. A correlation analysis was performed to determine the relationship between the subjective evaluations and the objective steering feel measures derived from the digital twin. The result is an objective target for steering feel robustness. With the use of a digital twin, ZF can take the system level targets and derive component level requirements to ensure robust steering feel.

3 Digital Development of the Front Axle Actuator

The Front Axle Actuator (FAA) is a major contributor to steering feel, vehicle performance and Noise Vibration and Harshness (NVH). Although there is no physical connection to the steering wheel, the FAA must precisely control the front axle steering and provide a road feedback signal to the TFU.

ZF is developing different FAA drive mechanisms for different vehicle classes. Front axle kinematics, flexibility and inertia all have an influence on the system dynamics. The FAA interacts with the entire front axle and cannot be considered as an isolated system.

ZF is combining digital twins of the FAA with a virtual representation of the front axle as a development platform to achieve performance targets. This allows for a comprehensive understanding of how the FAA interacts with the remaining parts of the front axle (Fig. 4).

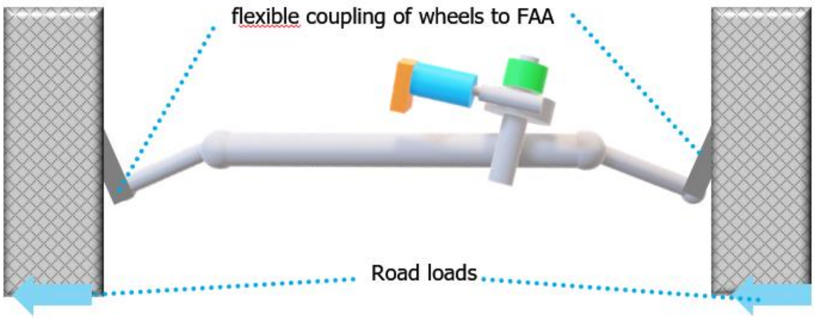

Fig. 4. FAA integrated in model of entire front axle as entire dynamic system modelled by digital twin

Validation of the FAA Digital Twin is therefore done in vehicle or using a front axle rig, where the front axle, including the FAA, can be tested under dedicated conditions. As the model of the FAA needs to be valid under excitations from the road (e.g., by cobblestones), the frequency range of model validation is significantly higher than for the TFU.

Figure 5 shows the dynamic response to a step input of demanded rack position of the Digital Twin compared to a vehicle test result. The very good correlation of the response variable (rack position) and the input variable of the mechanical system (motor torque demand) reflects the interaction of controller and mechanical system that is modelled with high accuracy.

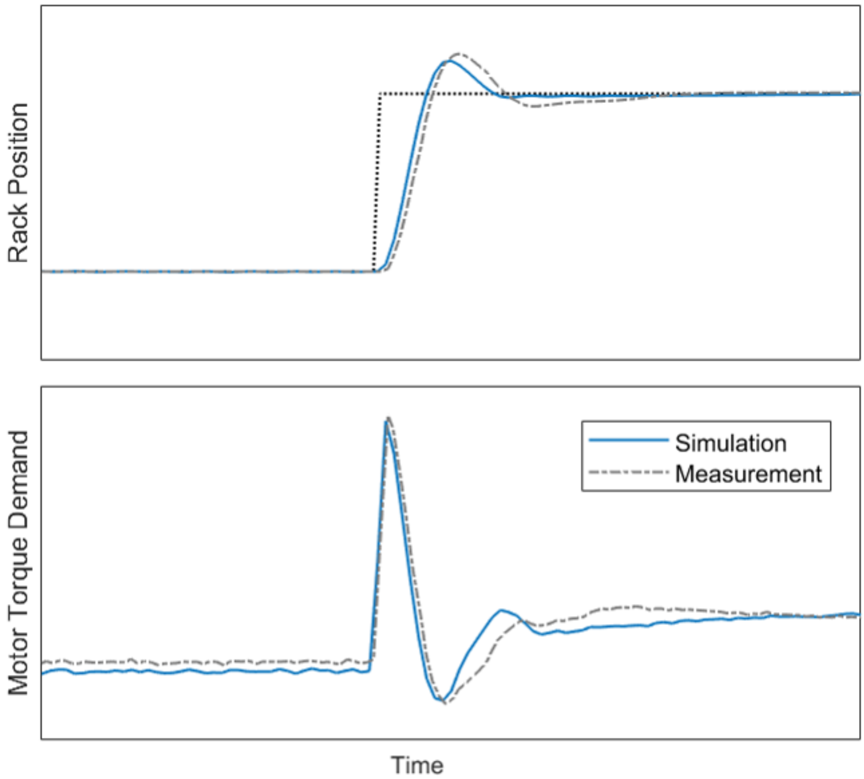

Fig. 5. Response on a step input of demanded rack position. Digital twin compared to vehicle test result.

Within ZF's SbW development, digital twins of the FAA are used for robustness analysis, covering different system frictions and environmental conditions, virtual tuning activities, and integration into the complete SbW system model for system validation purposes. This approach streamlines the development process, reducing the number of physical prototypes needed and shortening the development time.

4 Virtual Vehicle Testing of Fail Operational Functionalities & Hazard Testing

Besides all necessary development activities for the TFU and FAA subsystems, the integrated SbW system must pass numerous requirements for performance, NVH and systems safety as well. As a result, functional safety is an integral part of the SbW development process. In contrast to EPS, where the system must be 'fail safe', a SbW system needs to be 'fail operational' as the driver has no physical connection to the front wheels. This means the SbW system has sufficient redundancies to continue operating if a failure occurs.

ZF participates in a working group with other automotive partners to define basic safety guidelines for SbW systems in a new DIN standard. In this standard, the safety goals as well as the fundamental behavior of a SbW system in case of a first fault will be regulated to ensure controllability of the vehicle. Additionally, the required driver action and operating behavior is defined after the first fault, ranging from “Drive to Service” up to “Stop in Lane”. [1]

In vehicle fault testing of SbW systems is complex and potentially dangerous, so a comprehensive simulation environment is used in addition. Based on the vehicle-dependent parameters in the assessment process [1], this tool must cover all the physical parts for testing SbW systems. In addition to models of the TFU and FAA, models are needed for the driver, road and vehicle (Fig. 6.).

The integration of the software features and their corresponding parameterization into the simulation environment is mandatory to cover the intended behavior of the torque feedback at the TFU and the position control of the FAA resulting in a realistic overall system behavior. In the ZF model, the software features can be implemented in a prototype variant (MiL) or as part of a virtual ECU (vECU). This approach enables the direct exchange of software parameter sets between the digital twin and real vehicle.

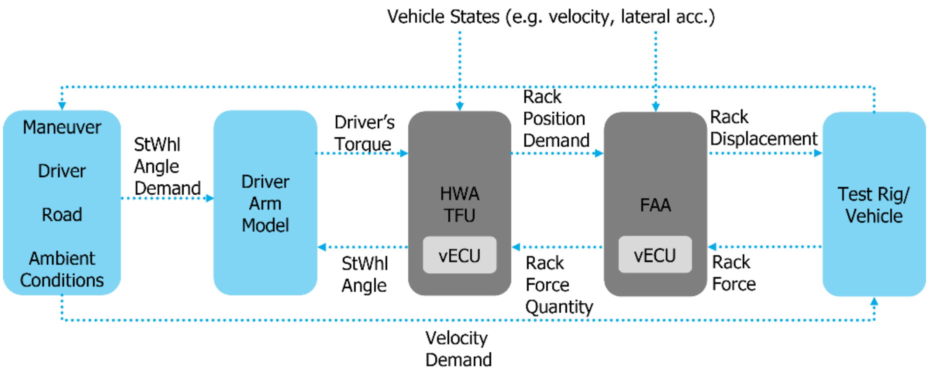

Fig. 6. Overall Model Structure

The ZF simulation environment also supports customers’ requirements for integrated simulation models as well as in-house validation with various virtual vehicle simulation tools. ZF has developed processes to deliver compiled models of the SbW system or it’s subsystems in state-of-the-art Functional Mockup Units (FMUs). These FMUs can be used in numerous simulation environments while protecting ZF’s intellectual property.

Beside the validation of the actuator assemblies (FAA, TFU) and the software features on subsystem level, the complete vehicle model must be validated against driving maneuvers like steady-state circular driving (ISO 4138), sine steer (ISO 13674-1), step steer and/or sine sweeps (ISO 7401) at different vehicle speeds to cover the whole range of intended use cases.

A typical validation can be seen in Fig. 7. For clarity only critical signals are shown related to the vehicle's lateral dynamics and it's interface to the steering system. Comparing the measured data and the corresponding output of the vehicle dynamics simulation tool, certain performance measures for a single test drive could be calculated. By considering many test drives covering the intended operating range of the vehicle model, a confidence level for a dedicated test case could be derived.

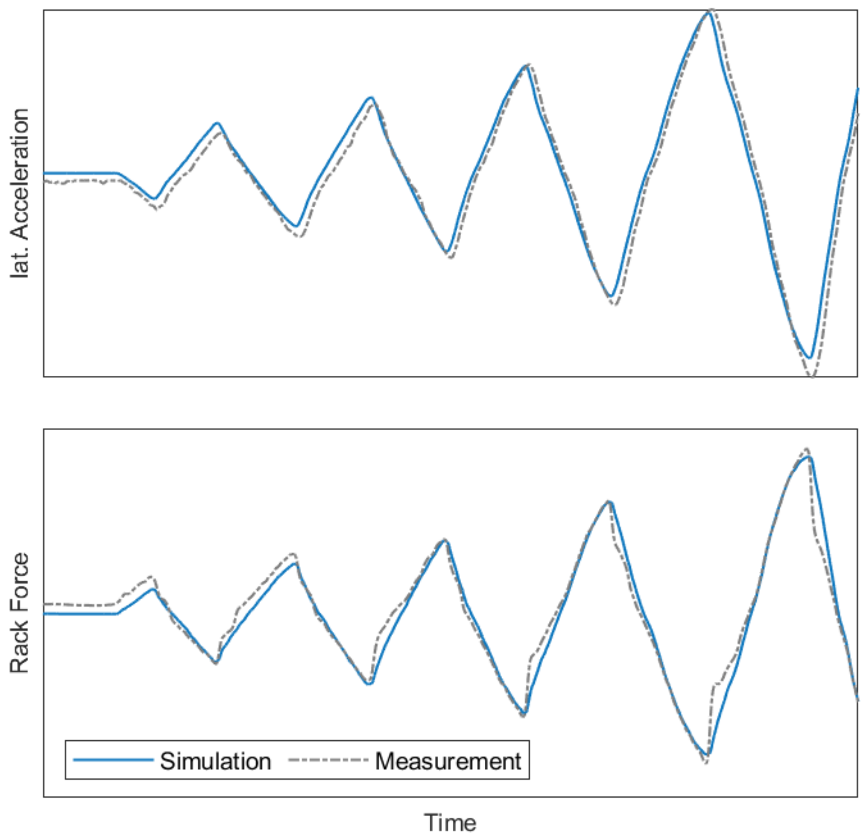

Fig. 7. Vehicle Model Validation in Sine Steer Maneuver

A simulation environment consisting of a virtual vehicle and the SbW system allows the simulation of hazardous maneuvers and system failures on a vehicle level.

The driver’s reaction to the fault, which is difficult to simulate, is neglected by trimming the simulation data to an appropriate time range without driver’s reaction (<< 1 seconds), see Fig. .

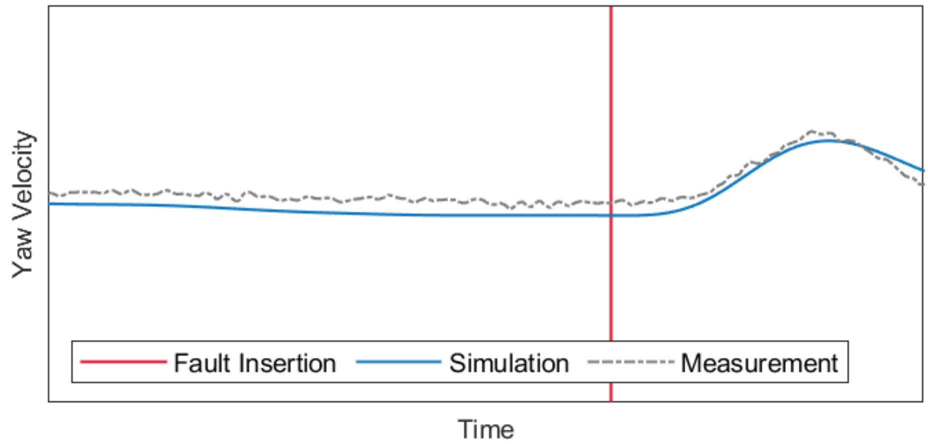

Fig. 8. Hazard test comparison of measured data and simulation output

After the fault insertion in the steering system, the simulated vehicle’s reaction matches the measured data well. Afterwards the driver’s reaction might lead to higher differences due to different behavior of the simulated driver and the real test driver.

5 Summary & Outlook

In this paper, ZF's approach was presented to develop a robust SbW system using virtual development methods and digital twins. It was shown how digital twins allow a system optimization before physical prototypes are built, accelerating the development process. Three exemplary use cases were shown covering different aspects that are important for a complex mechatronic system like SbW.

The first use case was the virtual development of the torque feedback unit where robustness against noise factors like tolerances and environmental conditions play an important role. It has been shown that digital twins can be used to optimize the design of hardware and controller to be robust against these factors.

In the second example, the digital development of the front axle actuator was presented where the interaction with the entire front axle is of special importance. By developing digital twins of this subsystem, an environment for the optimization of this performance now allows faster development with lower number of iterations.

The third example covered functional safety which is the highest priority in a SbW system. It was shown, how the integration of SbW actuators in a virtual vehicle environment allows the simulation and evaluation of failures of the steering system and their influence on vehicle controllability. That not only speeds up safety validation but also allows the simulation of failures that might be too dangerous to test in real life in early development phases.

Looking forward virtual development methods will play an increasing role in SbW development. On the one hand the maturity of the models will increase step by step by involving more test data of different development stages into the validation process. That leads to an increasing acceptance of virtual development methods in the engineering community. On the other hand, the demand for Digital Twins will rise due to the complex interactions of different subsystems within future vehicle motion control applications.

6 References

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