IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 12 September 2022, accepted 25 September 2022, date of publication 4 October 2022, date of current version 11 October 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3211942

RESEARCH ARTICLE

Influence of the Accuracy and CAN Frame Period of the Steering Wheel Angle Sensor (SAS) on the Trajectory of a Steer-by-Wire-Equipped Car

MICHAŁ PIETRUCH[1], **ANDRZEJ WETULA**[2], **(Member, IEEE), AND ANDRZEJ MŁYNIEC**[1]
[1]Department of Robotics and Mechatronics, AGH University of Science and Technology, 30-059 Kraków, Poland
[2]Department of Measurement and Electronics, AGH University of Science and Technology, 30-059 Kraków, Poland

Corresponding author: Michał Pietruch (mpiet@agh.edu.pl)

ABSTRACT With the popularization of active safety systems, autonomous driving, and Steer-by-Wire (SBW) technology, steering wheel angle sensors (SAS) have begun to play a key role in these systems. It is responsible for measuring the angle and angular velocity of the steering wheel and sending these data via a bus to the cooperating devices. For this reason, automakers are making increasingly demanding requirements that are difficult for sensor suppliers to meet. These requirements describe the metrological properties of the sensor, but their influence on the quality of car control is not clear. It is impossible to directly determine whether systems that use these sensors work properly and efficiently. Therefore, the question that needs to be asked is whether and to what extent sensor parameters such as accuracy and data transmission period affect the Steer-by-Wire car's trajectory and behavior during actual driving? For this purpose, a test bench was built based on the CarMaker and CANoe software using virtual test drives. It was used to perform a series of tests for different combinations of sensor accuracies and CAN frame periods, based on which errors were determined, and their influence on the number of knocked down cones during slalom performance.

INDEX TERMS Steering wheel angle sensor, virtual test drives, steer-by-wire, CAN frame period, SAS accuracy.

I. INTRODUCTION

Steer-by-Wire (SBW) technology was first commercially used in automotive applications in 2013 in Infinity Q50 and Q60 [1]. Only nine years later, in 2022, there was a premiere of another car equipped with this technology - the Lexus RZ 450e [2]. Other automakers such as Tesla [3] and steering suppliers [4], [5] are also actively working on developing this technology, which makes it possible to predict that this technology will be increasingly used in the future.

In a classic steering system, the steering column has a fixed, mechanical connection to the steering gear, as shown in Fig. 1 [6].

In SBW technology, on the other hand, the steering column has been completely separated from the other components of the steering system, losing the direct mechanical connection to the wheels, as shown in Fig. 2. Steering is performed using an electric motor based on the measured steering angle. A standalone electronic control unit (ECU), which is most often called the steering wheel angle sensor or steering angle sensor (SAS), is responsible for measuring the angle and angular velocity of the steering wheel. The measured angle is sent on a communication bus, which is then received by the device that implements the wheel turn - the road-wheel motor (RWM). In addition to the wheel-turn realizing motor, there is an additional motor in the steering column - the hand-wheel motor (HWM). It is responsible for generating forces for the steering wheel such that the driver has the impression of classic steering.

SBW technology has many advantages, such as the ability to change the steering ratio at will, depending on the speed of the car or driving mode. This allows the use of a steering yoke instead of the classic round steering wheel, because there is no need to cross the hands when turning. An example of a

The associate editor coordinating the review of this manuscript and approving it for publication was Chao Yang.

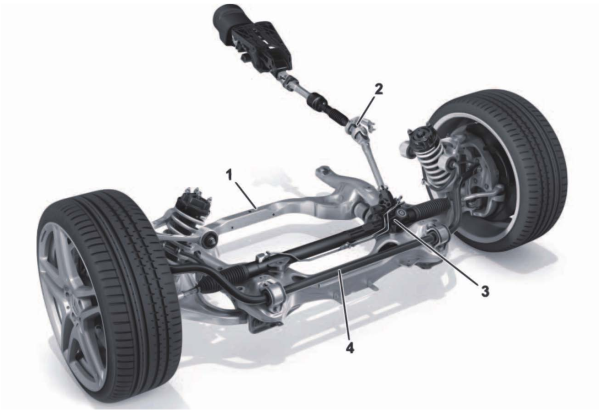

FIGURE 1. Construction of a classic mechanical steering system of the Mercedes–Benz SLS AMG, where the steering column is mechanically connected to the steering rack. 1 – Frame-type integral support, 2- Constant velocity joint, 3 – Steering gear, 4 - Stabilizer bar [6].

FIGURE 2. Steering system of the Lexus RZ 450e car designed with Steer-by-Wire technology with visible separation of steering column and actuators [2].

steering yoke from Lexus RZ 450e is shown in Fig. 3. Another advantage is the improved driving comfort, as vibrations are not transmitted from the ground to the steering wheel [7], although this feature can also be considered a disadvantage. Because the steering column is separated from the steering rack, it is possible to make the wheel turn without this being reflected in the steering wheel's turn. It can also be hidden in the dashboard when using the autopilot function. This provides the driver more space in the cabin of the car. The disadvantage of SBW systems is their high complexity, as such a system has many sensors, actuators, and complex control methods, which can contribute to a reduced overall reliability [1].

SAS data are also used in the operation of many other systems such as electric power steering (EPS), electronic stability program (ESP), active steering, lane-keeping assistance (LKA), four-wheel steering, active suspension [8], adaptive headlights [9], and driver drowsiness detection [10], [11]. An example of a sensor is shown in Fig. 4.

FIGURE 3. Steering yoke of the Lexus RZ 450e [2].

FIGURE 4. Example of steering wheel angle sensor [12].

In the technical documentation of steering angle sensors, there are parameters such as the measurement range and accuracy of angle and angular velocity, nonlinearity, hysteresis, or period of sending data to the bus [12]. These parameters describe the metrological properties of the sensor, however their influence on the quality of car control is not clear. It is impossible to directly determine whether systems that use these sensors work properly and efficiently. Car manufacturers, knowing that the steering system has a huge impact on the health and lives of the driver and passengers, have automatically put forward increasingly stringent accuracy requirements for the steering sensor. These requirements are becoming increasingly difficult for sensor suppliers to meet, so it is worth asking whether and to what extent sensor parameters such as accuracy and data transmission period affect a car's trajectory and behavior during actual driving? For this purpose, a test bench was built based on the CarMaker and CANoe software using virtual test drives. It was used to perform a series of tests, based on which the errors were determined depending on the period of data sending, the accuracy of the sensor, and the influence of these errors on the number of knocked down cones during slalom execution. The direct influence of parameters such as nonlinearity and hysteresis is not the subject of this study, whereas sensor range is a property related to mechanical design and does not affect control quality.

II. CURRENT STATE OF KNOWLEDGE

Reviewing the publications available in the field of steering angle sensors, one can find a lot of articles demonstrating the implementation of sensors based on various technologies such as magnetoresistance GMR [13] or AMR [14], Hall effect [15], magnetic induction [16] or optical [17]. These technologies are widely compared with each other in terms of the obtained accuracy, nonlinearity, etc. [18], however there is still no translation of their impact on the actual driving and trajectory of the car. In a publication [19] carrying out a series of simulations and tests, an attempt was made to create a coefficient that determined the driver's satisfaction with the SBW depending on the speed of communication. The successful creation of such a coefficient would allow the actual translation of sensor parameters into the driving quality of the car. Another frequently studied element is the effect of communication network quality on SBW. Influence of network speed, vehicle speed [20], jitter, frame period, and network failure [21]. In addition, various communication protocols and their impact on SBW such as controller area network (CAN) or time triggered protocol (TTP/C), have been studied [22], as well as the sum effect of delays introduced by communication along the entire steering-wheel chain [23]. Among the studies analyzed, there was no presenting effect of the data-sending period and total sensor accuracy on the car's trajectory and translation into the number of knocked down cones during slalom execution.

III. TEST SYSTEM DESCRIPTION

CANoe software from Vector and CarMaker from IPG were used to perform the measurements. CarMaker is an advanced software program in which virtual test drives represented in a graphical environment can be performed. The software allows the creation of roads, specifies the number of lanes, slope level, insert trees and buildings, and other traffic participants, such as cars or pedestrians [24]. Specific car maneuvers encountered in real driving and less likely also can be defined. The software has built-in car models whose kinematics and other characteristics correspond to those of real cars. Also, the algorithm of a driver behavior is defined by CarMaker. It means when the driver sees that for example the car does not follow the requested trajectory, the driver tries to make the correction of steering wheel angle.

A virtual test drive was set up in CarMaker to perform a slalom between 10 cones spaced every 18 m, for a total distance of 230 m, as shown in Fig. 5. Of the various test maneuvers available, the slalom was chosen because when performing it, the steering wheel is turned at a wide range of angles, in both directions and at different angular speeds. In this case the steering wheel was turned form −150° to +150°. Regarding the slalom parameters such as cone spacing there are neither European nor USA standards, which define it. There are only standards for double lane change [25] and obstacle avoidance (moose test) [26]. There is only one available standard for slalom prepared by General Motors, which defines distance between cones to 23 m, but it is not an international standard. Reviewing the publications, which use slalom maneuver, the distance between cones varies from 17 m [27], through 18 m [28] and 23 m [29] to 30 m [30], [31]. The distance of 18 m was chosen, because such small distance is more demanding for steering wheel angle sensor. The car that performed the run was a model Volkswagen Beetle with the default parameters set in CarMaker. The car started the slalom at an initial speed of 55 km/h and attempted to maintain this speed throughout the slalom execution. The speed of 55 km/h was set experimentally because at this speed, the car was able to complete the slalom in the shortest time without knocking down any cones.

FIGURE 5. Visualization of the test car while performing slalom.

A simulation based on a high-speed CAN bus operating at 500 kbit/s was created in the CANoe. The SAS responsible for measuring the angle and angular velocity of the steering wheel was simulated, and it cyclically sent a frame with these data to the bus.

The functional mock-up interface (FMI) [32] was used for communication between CANoe and CarMaker. This is an open standard that is used for exchanging models between different engineering applications and for co-simulation, which is the simultaneous execution of simulations by two different applications exchanging data in real time [33]. The general principle of communication between CarMaker and CANoe using the FMU is shown in Fig. 6.

The rate of data exchange between CarMaker and CANoe is configurable, and in this case, it was set to a period of 1 ms, meaning that data are exchanged between these applications every 1 ms. Such a time allows, on the one hand, to reliably transfer data between the applications without putting too much strain on the CPU and, on the other hand, provides sufficient accuracy required for testing.

It is worth mentioning here that the exchanged variables are of the double 64-bit floating-point type. This allows for the exchange of data with very high accuracy and avoids rounding or truncation errors. The flow and mapping of the variables are illustrated in Fig. 7.

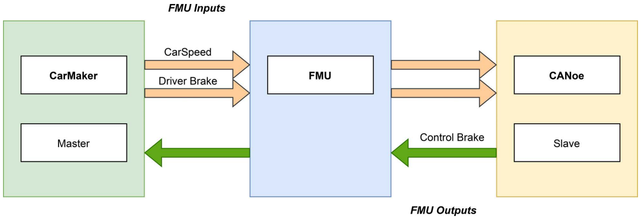

FIGURE 6. **Example of communication scheme between CarMaker and CANoe using FMU in the master-slave architecture.**

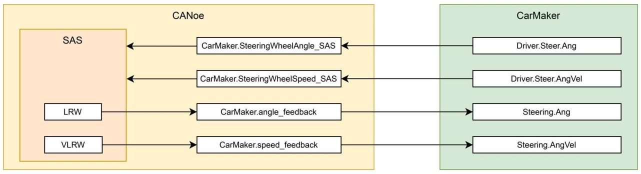

FIGURE 7. **Variables exchanged between CANoe and CarMaker and their mapping.**

IV. RESEARCH

Tests were performed for different angle accuracies and frame periods. The frame period was varied from 5 ms to 150 ms, while the angle accuracy was varied from 0.1° to 2.0°.

The minimum frame period was chosen as 5 ms for two reasons. First, in real devices equipped with a CAN bus, frame periods vary widely from several hundred milliseconds for less important data to approximately 10 ms for important data such as steering angle measurements. It is worth noting here that frame duration is not a limitation, since a frame at 500 kbit/s lasts about 0.25 ms, so it is much shorter than a 5 ms period.

The second reason is that data between applications are exchanged for a period of 1 ms, therefore the period of sending a frame must be larger so that no measured angle is missed. A period of 5 ms meets this requirement and allows the applications to work together reliably.

The maximum period was set by trial and error to a value of 150 ms. This is the maximum period of frame transmission at which the virtual car, in most cases, is able to complete the slalom without falling off the road. Such an event causes the test to be aborted and is considered to be incomplete.

The sensor accuracies chosen for testing were determined based on the market knowledge. The most common accuracy is 0.5°, whereas the latest cars already have an accuracy of 0.1°. A maximum value of 2.0° was chosen because of the potential decrease in device accuracy caused by component wear.

The tests were performed with all possible combinations of the following parameter values:

1. Angle accuracy: 0.1°, 0.5°, 1.0°, 2.0°
2. Frame period: 5 ms, 10 ms, 20 ms, 50 ms, 100 ms, 150 ms

Each combination was performed 4 times to be sure that the environment is reliable and always gives the stable, similar results. Nevertheless, the consecutives measurements varied slightly, because of the start-up delay between CANoe and CarMaker applications. Therefore, each four measurements was averaged to be sure that the comparison is done between the same type of error. For example, if the measurement had been performed only once, there would have been a risk that comparison would be between minimum error for 0.1° accuracy with maximum error for 0.2° accuracy.

TEST PROCEDURE

1. Set the accuracy of the angle sensor and the period of the frame sent by the SAS.
2. Start the virtual test drive.
3. Collect the waveforms:
   a. the steering angle requested by the driver and
   b. the steering angle applied by the car
4. Note down how many cones the car knocked down and what was the time of slalom execution
5. Process the data and determine the root mean square error (RMSE) (1) and the maximum absolute error (MAE) (2) The root mean square error was determined by comparing it with the trajectory of a car moving at the same speed and along the same simulated track, but stripped of errors and delays due to the sensor. Such a trajectory was obtained by omitting the CarMaker-CANoe connection from the simulation and transferring the data internally using CarMaker software. The root mean square error is defined as

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i,j=1}^{n}(X_i - X_j)^2} \tag{1}$$

$$\mathrm{MAE} = \max(\Delta x_1, \Delta x_2, \ldots, \Delta x_n) \tag{2}$$

where:

$$\Delta x_n = |X_{in} - X_{jn}| \tag{3}$$

n is the number of samples, X_i the requested value, and X_j the measured value

V. RESULTS

The results are surprising and unexpected because the accuracy of the angle measurement in the range of 0.1° to 2.0° has no effect on the trajectory of the car, as shown in Fig. 8 and the number of knocked down cones during slalom performance, when the CAN frame period is equal or lower than 50 ms. On the other hand, the period of the frame has a very large effect on the trajectory, as shown in Fig. 9 and number of cones knocked down.

A. INFLUENCE OF SENSOR ACCURACY

Regardless of whether the sensor accuracy was 0.1° or 2.0°, the trajectory and errors were essentially identical, when the CAN frame period is equal or lower than 50 ms. All waveforms practically overlapped, as shown in Fig. 8, 10, and 11. The car trajectory is not disturbed. The car follows the requested trajectory by the driver and driver does not have to make any corrections of steering wheel, as shown in Fig. 8.

For a frame period of 5 ms and an accuracy of 0.1°, the RMSE was 0.9° and the MAE was 3.3°, and for an accuracy

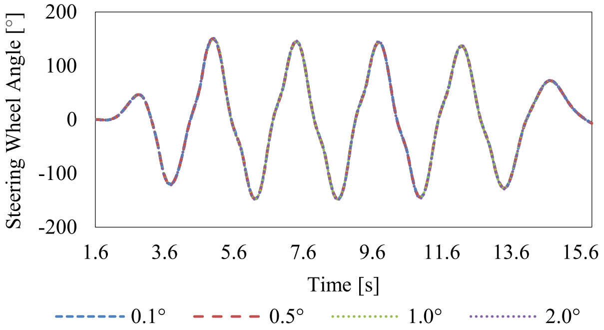

FIGURE 8. Influence of SAS accuracy on steering angle.

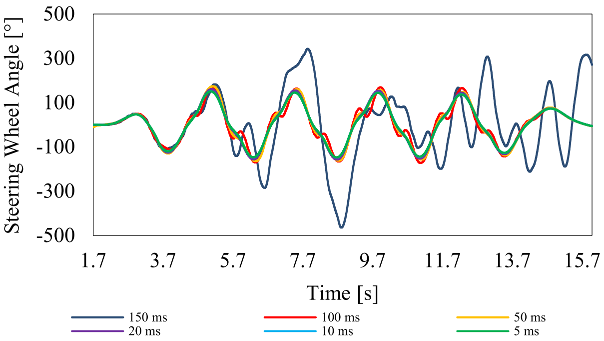

FIGURE 9. Influence of CAN frame sending period on steering angle.

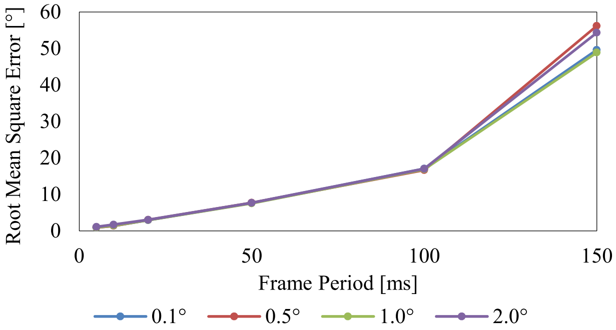

FIGURE 10. Influence of CAN frame sending period and angle accuracy on the root mean square error.

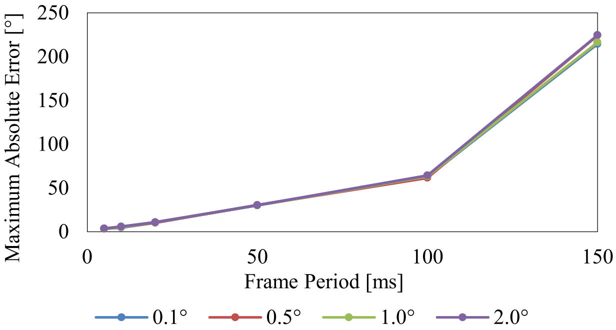

FIGURE 11. Influence of CAN frame period and angle accuracy on the maximum absolute error.

20 times smaller, that is, for 2.0°, the RMSE was 1.1° (an increase only of 0.2°) and the MAE was 3.7° (an increase only of 0.4°). These data clearly indicate that the angle accuracy within the tested limits had almost no effect on MAE and RMSE.

Only for a period of 150 ms do small discrepancies begin to appear, where it can be seen that the angle accuracy has little significance on MAE and RMSE. For 150 ms and 0.1° accuracy, the RMSE was 49.6° and the MAE was 214°, and for 2.0° accuracy, the RMSE was 54.3° (an increase of 4.7°) and the MAE was 224° (an increase of 10.0°).

In terms of the number of cones knocked down, up to a frame period of 50 ms, the accuracy of the sensor did not matter at all. Regardless of whether the sensor had an accuracy of 0.1° or 2.0°, the car perfectly performed slalom in the shortest possible time of 15.1 s without knocking down a single cone. For a period of more than 50 ms, the cars started knocking down the cones, as shown in Fig. 12.

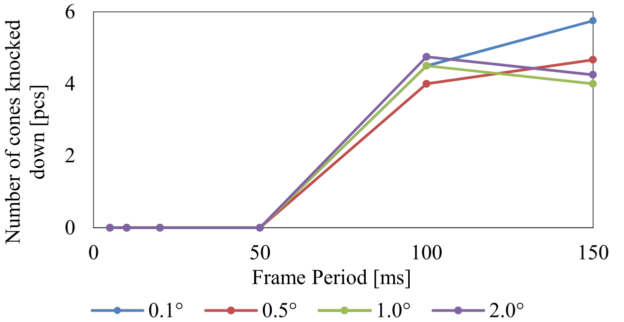

FIGURE 12. Influence of CAN frame period and sensor accuracy on the number of cones knocked down during slalom execution.

At 150 ms, cars with a more accurate sensor paradoxically started knocking down more cones than cars with a less accurate sensor. This is because with a high frame period, a higher accuracy results in smoother maneuvers of the car. Worse accuracy results in sharper maneuvers, which results in the car driving in a wider arc, hitting between the cones more easily. As the car takes a wider arc, the travel time increases, as shown in Fig. 13.

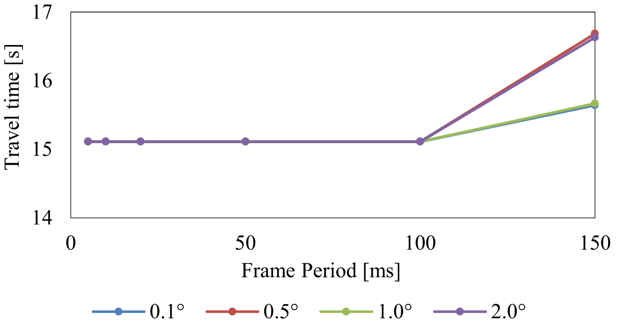

FIGURE 13. Influence of CAN frame period and sensor accuracy on slalom time.

Regardless of the accuracy, with a period of 150 ms, the car performs slalom chaotically. Often, it is unable to complete it, falling off the road, so the number of knocked down cones in this case can be falsified and should not be considered.

B. INFLUENCE OF THE FRAME PERIOD

In terms of frame period, the errors were an order of magnitude larger. As shown in Fig. 10 and 11, the frame period significantly affects the RMSE and MAE. Also, the car trajectory is disturbed, as shown in Fig. 9. The waveform differs significantly from sine-type optimal waveform – 5 ms green waveform. This is because when the car does not follow the requested path, the driver makes the correction of steering wheel angle.

In the range from 5 ms to 100 ms, this relationship is linear, that is, each doubling of the frame period results in doubling of errors. For an accuracy of 0.1° and a period of 5 ms, the RMSE was 0.9° and the MAE was 3.3°, and for a period of 20 times larger, that is 100 ms, the RMSE was 17.0° (a 19-fold increase) and the MAE was 62.5° (also a 19-fold increase).

In contrast, there was a significant increase in errors between 100 and 150 ms. For an accuracy of 0.1° and a period of 100 ms, the RMSE was 17.0° and the MAE was 62.5°, and for a period of 1.5 times as long, that is 150 ms, the RMSE was 50.0° (three times greater) and the MAE was 214.4° (more than three times greater).

As for the number of cones knocked down, this was also the case. Up to a frame period of 50 ms regardless of angle accuracy, the car perfectly performed the slalom in the shortest possible time of 15.1 s without knocking down any cones. Only for times above 50 ms regardless of the angle accuracy, did the cars start knocking down cones.

VI. CONCLUSION

The study concluded that the accuracy of the steering angle measurements in the range of 0.1° to 2.0° had no effect on the steering angle and trajectory of the car, when the CAN frame period is equal or lower than 50 ms. Both the root mean square error and the maximum absolute error of the trajectory are very small for values in this range, on the order of single degrees and very close to each other. The no effect of accuracy was confirmed during slalom performance. Regardless of the accuracy of the sensor, the car smoothly performed the entire slalom in the shortest possible time without knocking down a single cone. In contrast, the period of sending a frame, ranging from 5 ms to 150 ms, had a significant impact. Errors are an order of magnitude larger than those caused by sensor accuracy and have a key impact on the trajectory of the car. In the range from 5 ms to 100 ms, this relationship is linear, that is, each doubling of the frame period results in doubling of the errors. When running up to a period of 50 ms, the car, regardless of accuracy, completed the slalom without knocking down any cones. Only above 100 ms did the car start knocking down the cones.

Because the very small impact of errors due to sensor accuracy compared to those due to the data transmission period, automakers should place emphasis on the speed and reliability of data exchange first and second on the accuracy of the steering angle sensor. This approach significantly reduces production costs while maintaining the high performance and safety of the Steer-by-Wire system.

REFERENCES

[1] S. A. Mortazavizadeh, A. Ghaderi, M. Ebrahimi, and M. Hajian, "Recent developments in the vehicle steer-by-wire system," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 3, pp. 1226–1235, Sep. 2020, doi: 10.1109/TTE.2020.3004694.

[2] Lexus Europe Newsroom. (Dec. 8, 2022). *World Premiere of the All-New Lexus RZ.* [Online]. Available: https://newsroom.lexus.eu/world-premiere-of-the-all-new-lexus-rz/

[3] F. Lambert. (Dec. 8, 2022). *Tesla is Looking to Move to Steer-by-Wire With New Motor and Geartrain Team in Austin*. [Online]. Available: https://electrek.co/2020/10/12/tesla-steer-by-wire-motor-geartrain-team-austin/

[4] Nexteer Automotive. *ADAS & Automated Driving Steer-by-Wire*. (Dec. 8, 2022). [Online]. Available: https://www.nexteer.com/a-d-a-s-automated-driving/steer-by-wire/

[5] A. Neuwirth. (Dec. 8, 2022). *The Networked Steer-by-Wire Steering System is Available Now*. [Online]. Available: https://www.zf.com/mobile/en/technologies/domains/vehicle_motion_control/stories/sbw.html

[6] D. Ag, "Introduction of the new SLS AMG. Introduction into service manual for model series 197," Technical Information and Workshop Equipment (GSP/OI), Stuttgart, Tech. Rep. D-70546, Dec. 2022. [Online]. Available: https://manualzz.com/doc/24843277/introduction-of-the-new-sls-amg

[7] S. E. Mohamed and A. S. Albatlan, "Modeling and experimental design approach for integration of conventional power steering and a steer-by-wire system based on active steering angle control," *Amer. J. Vehicle Des.*, vol. 2, no. 1, pp. 32–42, 2014.

[8] S. Zacharia, T. George, E. Rufus, and Z. C. Alex, "Implementation of steering wheel angle sensor system with controlled area network," in *Proc. Int. Conf. Intell. Comput., Instrum. Control Technol. (ICICICT)*, Jul. 2017, pp. 54–60, doi: 10.1109/ICICICT1.2017.8342534.

[9] J. Youn, J. An, M. D. Yin, J. Cho, and D. Park, "Safe adaptive headlight controller with symmetric angle sensor compensator using steering-swivel angle lookup table," *Trans. Korean Soc. Automot. Eng.*, vol. 24, no. 1, pp. 112–121, Jan. 2016, doi: 10.7467/ksae.2016.24.1.112.

[10] B. J. Moon, K. B. Yeon, S. G. Lee, S. P. Hong, S. Y. Nam, and D. H. Kim, "Drowsy driving detection algorithm using a steering angle sensor and state of the vehicle," *Inst. Electron. Inf. Eng.*, vol. 49, no. 2, pp. 30–39, 2012. [Online]. Available: https://www.koreascience.or.kr/article/JAKO201223052005905.pdf

[11] L. Li, K. Werber, C. F. Calvillo, K. D. Dinh, A. Guarde, and A. König, "Multi-sensor soft-computing system for driver drowsiness detection," in *Advances in Intelligent Systems and Computing*, vol. 223. Cham, Switzerland: Springer, 2014, pp. 129–140, doi: 10.1007/978-3-319-00930-8_12.

[12] Bosch Motorsport. *Steering Wheel Angle Sensor LWS*. Dec. 8, 2022. [Online]. Available: https://www.bosch-motorsport.com/content/downloads/Raceparts/Resources/pdf/Data%20Sheet_191153675_Steering_Wheel_Angle_Sensor_LWS.pdf

[13] M. Xiao, "A high-accuracy steering wheel angle sensor based on GMR," in *Proc. 6th Int. Conf. Instrum. Meas., Comput., Commun. Control (IMCCC)*, Jul. 2016, pp. 1–4, doi: 10.1109/IMCCC.2016.115.

[14] E. Dilge, M. Gulbins, T. Ohnesorge, and B. Straube, "On a redundant diversified steering angle sensor," in *Proc. 9th IEEE On-Line Test. Symp. (IOLTS)*, 2003, pp. 191–196, doi: 10.1109/OLT.2003.1214397.

[15] J. Liu, S.-J. Qin, H.-S. Zhou, and L.-X. Jia, "Steering wheel angle sensor in vehicle steer-by-wire (SBW) system," *J. Chongqing Univ. Technol. Natural Sci.*, vol. 28, no. 7, pp. 1–4, 2014, doi: 10.3969/j.issn.1674-8425(z).2014.07.001.

[16] K. Byeongwoo, "A study on the characteristics of steering angle sensor using magnetic induction," *Trans. Korean Soc. Automot. Eng.*, vol. 18, no. 2, pp. 48–55, 2010. [Online]. Available: https://koreascience.kr/article/JAKO201020733096844.pdf

[17] H. M′uller, H. Franz, T. Sauerwein, and M. Stollberg, "Optical steering angle sensor for determining the absolute value of the steering angle," U.S. Patent 201 000 232 19A, Jan. 28, 2010.

[18] W. Granig, S. Hartmann, and B. Köppl, "Performance and technology comparison of GMR versus commonly used angle sensor principles for automotive applications," SAE Tech. Papers 2007-01-0397, 2007, doi: 10.4271/2007-01-0397.

[19] C. Wilwert, Y. Q. Song, F. Simonot-Lion, Loria-Trio, and T. Clément, "Evaluating quality of service and behavioral reliability of steer-by-wire systems," in *Proc. IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, vol. 1, Jan. 2003, pp. 193–200, doi: 10.1109/ETFA.2003.1247706.

[20] 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 *Proc. IEEE Int. Conf. Control Syst., Comput. Eng.*, Nov. 2013, pp. 350–355, doi: 10.1109/ICCSCE.2013.6719988.

[21] F. Li, L. Wang, and C. Liao, "Evaluating the communication impact on quality of service in steer-by-wire systems," in *Proc. IEEE Vehicle Power Propuls. Conf.*, Sep. 2008, pp. 1–4, doi: 10.1109/VPPC.2008.4677541.

[22] F. Ataide, M. M. Santos, and F. Vasques, "A comparison of the communication impact in CAN and TTP/C networks when supporting steer-by-wire systems," in *Proc. IEEE Int. Conf. Ind. Technol.*, vol. 2, Dec. 2004, pp. 1078–1083, doi: 10.1109/icit.2004.1490227.

[23] K. Klobedanz, C. Kuznik, A. Elfeky, and W. Müller, "Development of automotive communication based real-time systems—A steer-by-wire case study," in *Proc. Int. Embedded Syst. Symp.*, in IFIP Advances in Information and Communication Technology, vol. 310, 2009, pp. 218–225, doi: 10.1007/978-3-642-04284-3_20.

[24] M. Pietruch, A. Młyniec, and A. Wetula, "An overview and review of testing methods for the verification and validation of ADAS, active safety systems, and autonomous driving," *Mining Inform., Automat. Elect. Eng.*, vol. 1, no. 1, pp. 19–27, 2020, doi: 10.7494/miag.2020.1.541.19.

[25] *Passenger Cars—Test Track for a Severe Lane-Change Manoeuvre—Part 1: Double Lane-change*, document ISO 3888-1:2018, 2018.

[26] *Passenger Cars—Test Track for a Severe Lane-Change Manoeuvre—Part 2: Obstacle Avoidance*, document ISO 3888-2:2011, 2011.

[27] K. Lundahl, J. Aslund, and L. Nielsen, "Vehicle dynamics platform, experiments, and modeling aiming at critical maneuver handling," Division Veh. Syst., Dept. Elect. Eng., Linkoping Univ., Linkoping, Sweden, Tech. Rep., SE-581 33, 2013. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:630272/FULLTEXT01.pdf

[28] J. P. Pauwelussen, "Vehicle handling performance," in *Essentials of Vehicle Dynamics*, 1st ed. Amsterdam, The Netherlands: Elsevier, 2014, pp. 123–125.

[29] C. Chucholowski, M. Vögel, O. von Stryk, and T.-M. Wolter, "Real time simulation and online control for virtual test drives of cars," in *High Performance Scientific and Engineering Computing* (Lecture Notes in Computational Science and Engineering), vol 8, H. J. Bungartz, F. Durst, and C. Zenger, Eds. Berlin, Germany: Springer, doi: 10.1007/978-3-642-60155-2_13.

[30] R. Zheng, K. Nakano, Y. Okamoto, M. Ohori, S. Hori, and Y. Suda, "Evaluation of sternocleidomastoid muscle activity of a passenger in response to a car's lateral acceleration while slalom driving," *IEEE Trans. Hum.-Mach. Syst.*, vol. 43, no. 4, pp. 405–415, Jul. 2013, doi: 10.1109/tsmc.2013.2258908.

[31] L. Wang, "Vehicle dynamics development process with offline and driver-in-the-loop (DIL) simulation," M.S. thesis, Dept. Mecha. Marit. Scie., Chalmers Univ. Techno., Gothenburg, Sweden, 2021. [Online]. Available: https://odr.chalmers.se/bitstream/20.500.12380/304136/1/2021-59%20Lidong%20Wang.pdf

[32] IPG Automotive GmbH. (2019). *CarMaker Tips & Tricks no. 6–005. Connecting CarMaker With CANoe Through FMU.* [Online]. Available: https://ipg-automotive.com/uploads/tx_pbfaqtickets/files/86/CarMaker_CANoe_FMU_connect.pdf

[33] Modelica Association. (2020). *Functional Mock-Up Interface for Model Exchange and Co-Simulation. Document Version: 2.0.2.* [Online]. Available: https://fmi-standard.org/downloads/

MICHAŁ PIETRUCH received the B.Sc. degree in mechatronics and the M.Sc. degree in electrical engineering from the AGH University of Science and Technology in Cracow, Poland, in 2014 and 2016, respectively, where he is currently pursuing the Ph.D. degree in automatics and robotics. Since 2015, he has been working in the automotive industry and currently holds a position of a Software & System Tests Engineering Group Manager. His research interests include testing and verification of advanced driver assistant systems, drive-by-wire systems, and autonomous driving.

ANDRZEJ WETULA (Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from the AGH University of Science and Technology in Cracow, Poland. He is currently employed as an Assistant Professor at the Department of Measurement and Electronics, Faculty of Electrical Engineering, Automatics, Computer Science, and Biomedical Engineering, AGH University of Science and Technology in Cracow. He is the author or coauthor of 73 articles and patents.

ANDRZEJ MŁYNIEC received the Ph.D. degree from the AGH University of Science and Technology, Cracow, Poland, in 2011, and the D.Sc. (Habilitation) degree from the Warsaw University of Technology, in 2016. He has been involved in research and development in the automotive industry for over ten years. He is currently employed as a Professor at the AGH University of Science and Technology. His research interest includes application of modern modeling methods, including machine learning in scientific research and industrial applications.

• • •