Methodical Data Collection for Light Electric Vehicles to validate Simulation Models and fit AI-based Driver Assistance Systems

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Abstract

Electric bicycles and cargo bikes have become an indispensable part of today's road traffic. This is caused by the high diversity of applications and available products. Due to the growing interest, the demand of driver assistance systems (DAS) and safety concepts for light electric vehicles is increasing.
This paper presents an approach to collect vehicle dynamic parameters for the validation of simulation models. For this purpose, a measurement system is developed to capture and monitor driving dynamic information of the device under test (DUT) in real time. This data is used to fit pre-developed simulation models and DAS applications.
To investigate the vehicle dynamic behavior in critical driving situations, an extensive test study is executed. Therefore, different ordinary driving situations in urban traffic scenarios are analyzed. Finally, the collected measured data is compared with the simulation results of a multi-body model for a multi-lane cargo vehicle.

Keywords
Vehicle dynamics – Light electric vehicle – Tricycle – Data logger system – Data collection – Driver assistance systems

1. Introduction

Currently, a large amount of research is being done in the field of DAS for micromobility concepts [1][2]. Since the beginning of the pandemic, the vehicle industry has started to develop prototypes due to newly gained target groups.[3] Another reason might be the accident statistics in German road traffic. A reversal in the use of means of transport can be seen in the accident rates of car and bicycle or pedelec riders. While the participation of cars in accidents is decreasing, the participation among bicycle riders is steadily increasing. [4][5]
In contrast to the statistics, which on the one hand distinguish bicycles and pedelecs, but on the other hand do not separate cargo bicycles from bicycles, potentials of micromobility approaches are hardly considered [6]. Within the field of micromobility there also exists a large discrepancy between DAS and developed functionalities regarding mobility and driving safety [7]. Early concepts of DAS for cyclists contain common automotive functionalities like ESP and ABS, which is why this need will be addressed in the future [8]. Therefore, the development of motor-assisted DAS for cargo bicycles is in progress.
At this point, in the 4C laboratory of the Cologne University of Applied Sciences, research is being conducted on the development of a motor-assisted DAS for cargo bicycles, which aims to improve driving safety and comfort. The whole

research process and its several intermediate stages are divided to smaller projects: At first, a simulation model was created to investigate the driving dynamics of cargo bicycles. Different models were combined to increase the amount of possible driving scenarios with different conditions. The next logical step is to conduct real test drives of similar scenarios to generate measurement data for a validation of the virtual models. After the measurement data has been generated, saved and processed, it will be compared to the simulation results and evaluated. This paper deals with the creation of a data logger system which is used to log all necessary quantities during test runs. Subsequently, in upcoming project works based on the validation results, the realization of the DAS can be started. Its functionality will be carried out via two DC motors as physical actors, which are also used as traction drives.

2. Data Logger

The previously mentioned data logger system must be set up cost-efficiently. Furthermore, the system must be flexible concerning internal and external communication, because a wide range of sensor-types are used and the measurement data should easily be transferred to computers for further processing.
To explain the hardware structure, the stand-alone measurement system is created according to the given peripheral overview and concept shown in figure 1.

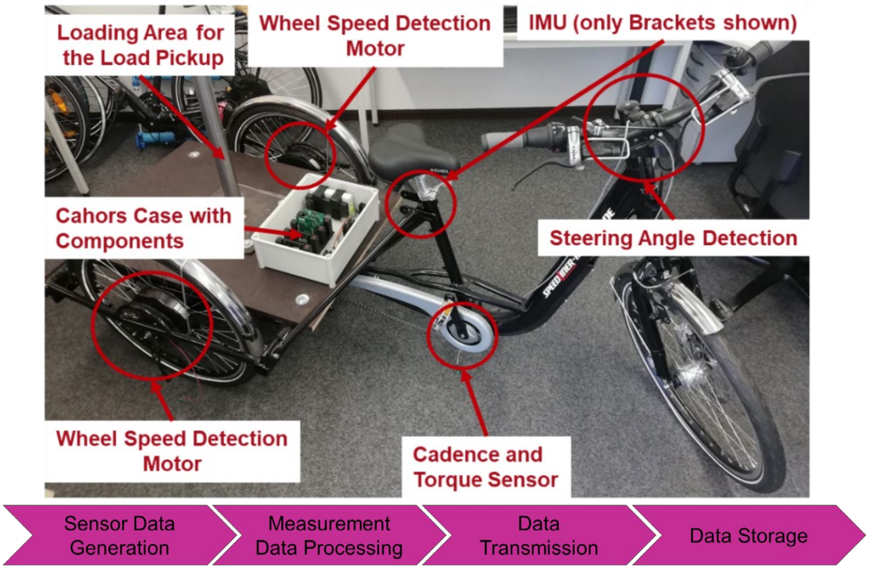

Figure 1: Peripheral overview and data-processing concept

In a first step, the measurement data generation must be processed after the sensor validation is realized. Here, it is necessary to record different comparison parameters and input signals for the simulation model, so that finally the selection of the sensors is made. After the peripheries for the generation and processing with the interface consideration were selected, the data structure is to be specified. To complete the data logger functionality, the data transfer, the communication system and the backup within the system must be realized. The measurement data is initialized using parameters determined by design and model-based conditions. During the simulation, the input parameters "steering angle" and "wheel torque" stimulate the model. The design parameters and main characteristic values of the cargo bike are used to parametrize the simulation model.
To define the requirements for the behavior of the bicycle, the data creation with sensor selection and the software-side data backup and processing must be determined. The data backup is done internally in the later developed data logger system, while the final processing is done on MATLAB/Simulink. After that, the data generation is done synchronously with a discrete-time sampling behavior. To counteract a storage error due to data loss or a delayed processing of a message, the sequence number and a timestamp are part of each bus message which transfer the measurement data via CAN.
The minimum system components required must be defined to meet the specification. There were requirements such as existing peripheral devices or system architectures. Figure 2 shows the hardware structure of the data logger.

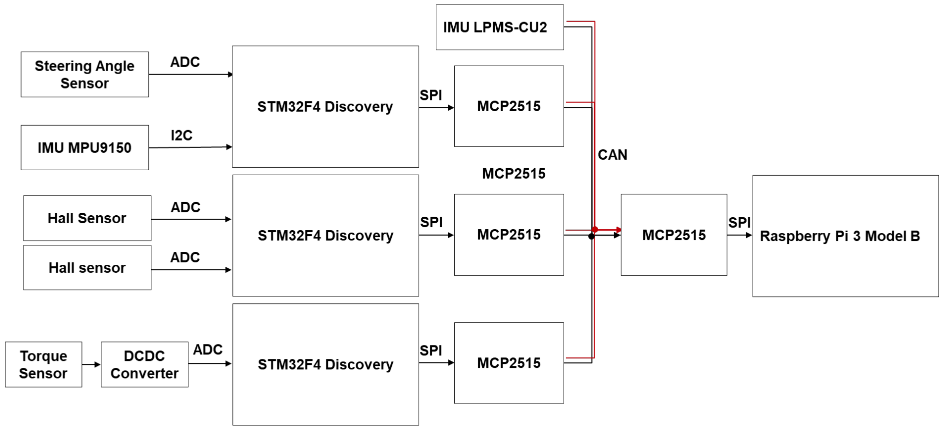

Figure 2: Sketch of the hardware structure

According to figure 2, the following peripherals are required:

- two hall sensors for the velocity and driving dynamics,
- two different types of IMUs,
- pedal torque sensor,
- steering angle sensor,
- three STM32F4 discovery boards for measurement data generation,
- several MCP2515 shields as communication interfaces
- Raspberry Pi for data logging

The communication between the peripheral devices takes place via the CAN interfaces of the MCP2515 shields. The evaluations of the sensor data are distributed to three STM32F4 Discovery Boards. Furthermore, the acceleration sensor LPMS-CU2 is integrated in the CAN communication network. This IMU has an integrated data processing, which works with the help of a Kalman filter and transfers the processed data directly into the communication network via the CAN interface. [9]

To select the routes in a meaningful way, it is necessary to determine the correct sample rate for each type of measurement data. The route is specified but not measured, because the simulation reproduces the route by means of certain input parameters. The lateral acceleration of the measurement and the simulation is compared, so that the parameters according to table 1 are measured.

Data	**Sample Rate [Samples/s]**
lateral acceleration	100 Samples/s
z-orientation	100 Samples/s
angular wheel velocity	10 Samples/s
steering angle	100 Samples/s
torque on pedal	100 Samples/s
pedal rotation	100 Samples/s

Table 1: Overview of the measured parameters

To develop systems like motorized DAS, various parameters from the measurements are needed. Especially, the acceleration values and the pedal velocity are essential, since such a DAS is supposed to act in a comfortable, driver-assisting and stabilizing way.

Finally, a cost-benefit efficient data logger system is developed, which generates and saves measurement data for the cargo bike. The collected data will be used for the validation of the simulation model to progress a development for a motor-assisted DAS. Another requirement for the system was a split of the hardware architectures, so that the sensors, the measurement data creation, the measurement data transfer and the measurement data processing is divided into different sections. The hardware interfaces are given by the individual sensors and can thus be integrated into the conceptual design.

A Raspberry Pi was chosen for the data logger system, since this is an independent computer with a user interface which still ensures access to various analog and digital interfaces, e.g. via GPIO. The realization of the data logger functionality is shown in the upcoming state diagram.

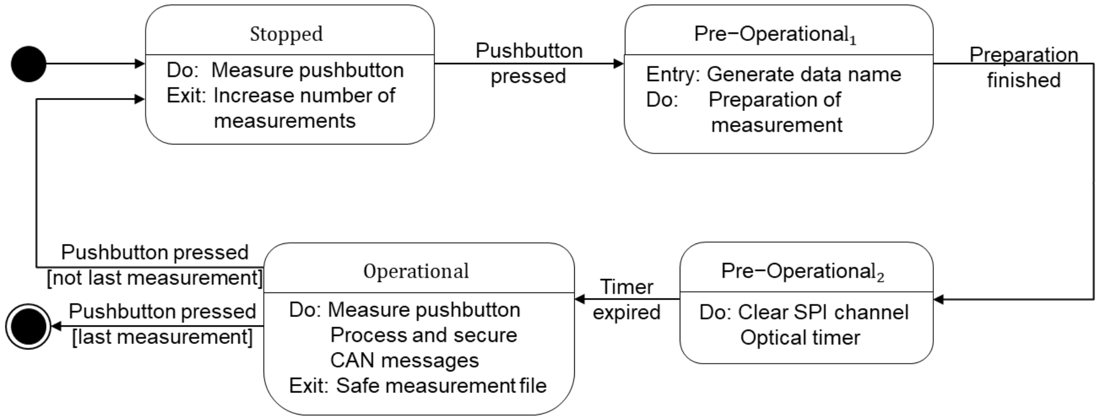

Figure 3: State diagram of the data logger

The Raspberry Pi interacts with the user, so that after activation the processes measurement preparations and SPI channel clearings are executed. The measurement data is then stored in the operational state. After the measurement is finished, the state is changed depending on the measurement count.

Due to the high number of messages, the channel capacity must be considered. Here, the samples per second are offset against the data volumes so that the sample rate is known. Then the results are compared with the capacity of the SPI channel of the Raspberry Pi. The calculated load over the sample rate is about 12%, so that the Raspberry Pi can process all incoming messages within the measurement period.

3. Measurement Setup / Verification Study

3.1 Description of Measurement Setup

To generate measurement data, it is necessary to create a structure in which the data can be generated and thus used for comparison. For this purpose, dedicated driving scenarios must be driven, which contribute to the parameterization of the driving capabilities of the real prototype but can also be simulated in the virtual environment to fulfill the project's goals of a verification of the simulation model. Three different routes are driven in our test environment:

1. Roll out: The rider first accelerates the cargo bike in a 20-meter section, after which the bike rolls out to a stop. This considers the driving resistances so that an overall judgment can be made about them.

Figure 4: Test scenario “roll out”

2. Circle driving: A maneuver is performed on a circular path at constant speed. Several trips are made for each driving direction by driving three laps. The markers are placed in a radius of about ten meters, so that the driving radius is about twelve meters.

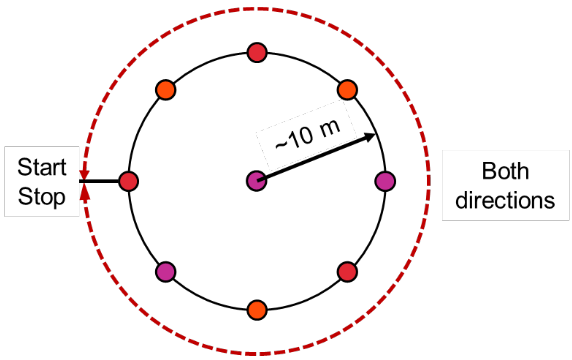

Figure 5: Test scenario “circle driving”

3. Slalom track: At the beginning, the rider accelerates to a speed of approximately 15 km/h in the first 15-meter section, which should then be maintained as far as possible throughout the entire run. Subsequently, a slalom maneuver is made around five markers, where this course is then driven back after the turn. The turn itself is made around another obstacle. This maneuver ends at the start/end line.

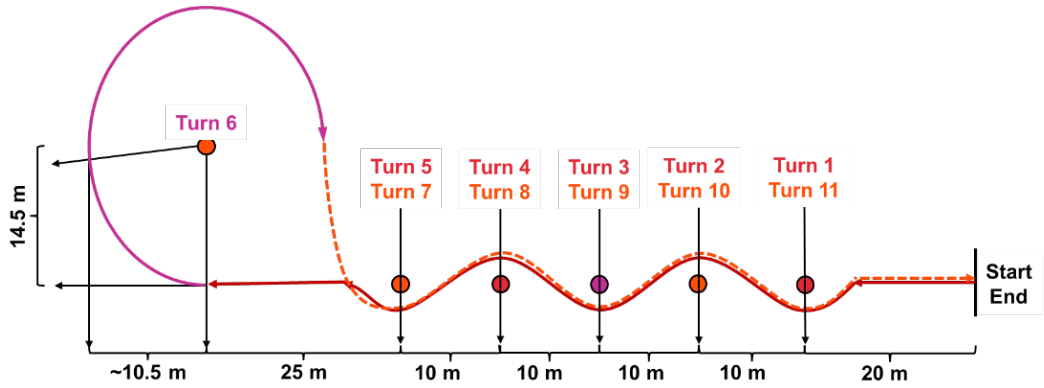

Figure 6: Test scenario "slalom track"

In addition to these measurements, further measurements are performed, which are used for later data analysis to filter out measurement noise.

3.2 Description of Execution

As mentioned in the previous subsection, the various test drives were performed with a total of 28 measurements. After the test drives and control routines were completed, seven roll out tests and twelve slalom track tests were initially performed so that an equal number of roll out tests and slalom track tests were available to be evaluated. Completing the series of measurements, three clockwise and two counterclockwise circle driving tests were made, each with three laps. The measurement series were concluded with four idle measurements to analyze the measurement noise for later project continuations.

3.3 Simulation Model

To develop a motorized DAS, various intermediate steps are needed until the final functionality can be created. The data logger system is used to generate measurement data validating a simulation model and to determine its limits. The simulation model is set up based on the physical substitute model in figure 7.

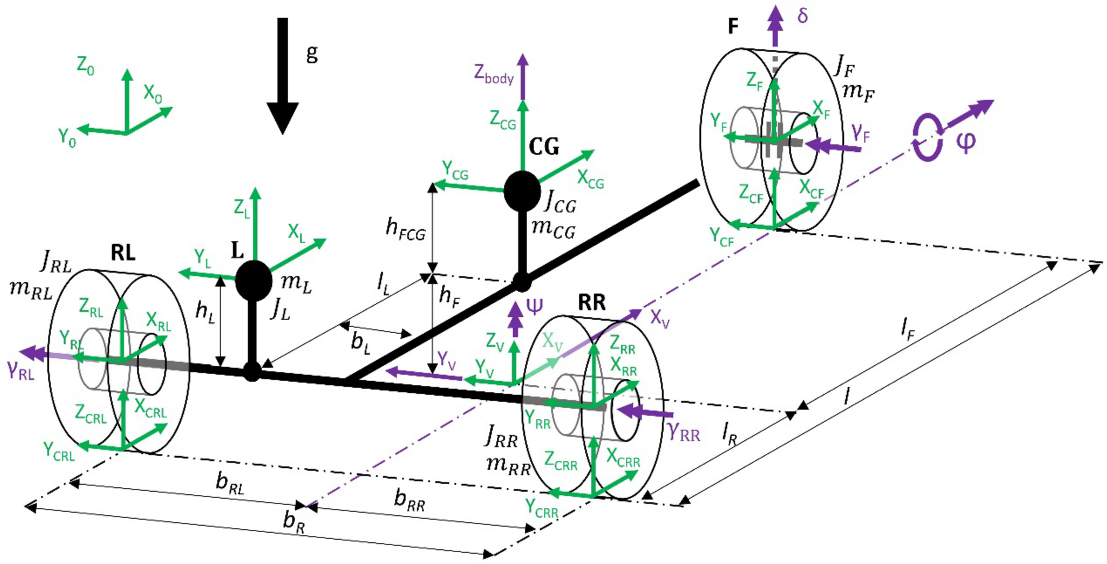

Figure 7: Integrated vehicle and calculation models in the simulation model [2]

The steering angle and the wheel torque are specified as input values in the simulation model, so that the behavior of the cargo bike represents the route travelled with the use of the measurement data. The shown nonlinear three-track model is

used to describe the longitudinal and lateral dynamics. Its modules consist of various components representing different functionalities within the simulation. These include the determination of the air resistance, the calculation for vertical forces and a linear tire model. Thus, tire dynamics are considered using a simplified tire model based on the slip angle.
In addition, an elastic contact between tire and road is considered, so that the body with rigid connections additionally assumes a tilting axis from the bicycle.
Finally, additional loads (L) can be considered apart from the center of gravity (CG) so that the virtual cargo bike can be simulated with different load states.
With the help of the described multi-body model, different vertical forces and motions can thus be represented. Further information can be found in [2].

4. Results

Several aspects stood out during the evaluation of the data. Starting with the acceleration and orientation values, a strong noise can be observed, which is due to strong vibrations caused by the ground excitation of the test tracks paving stones. The comparison of both IMUs will be captured in the upcoming figure, where the red trace is the MPU-9150 and the blue trace is the LPMS-CU2.

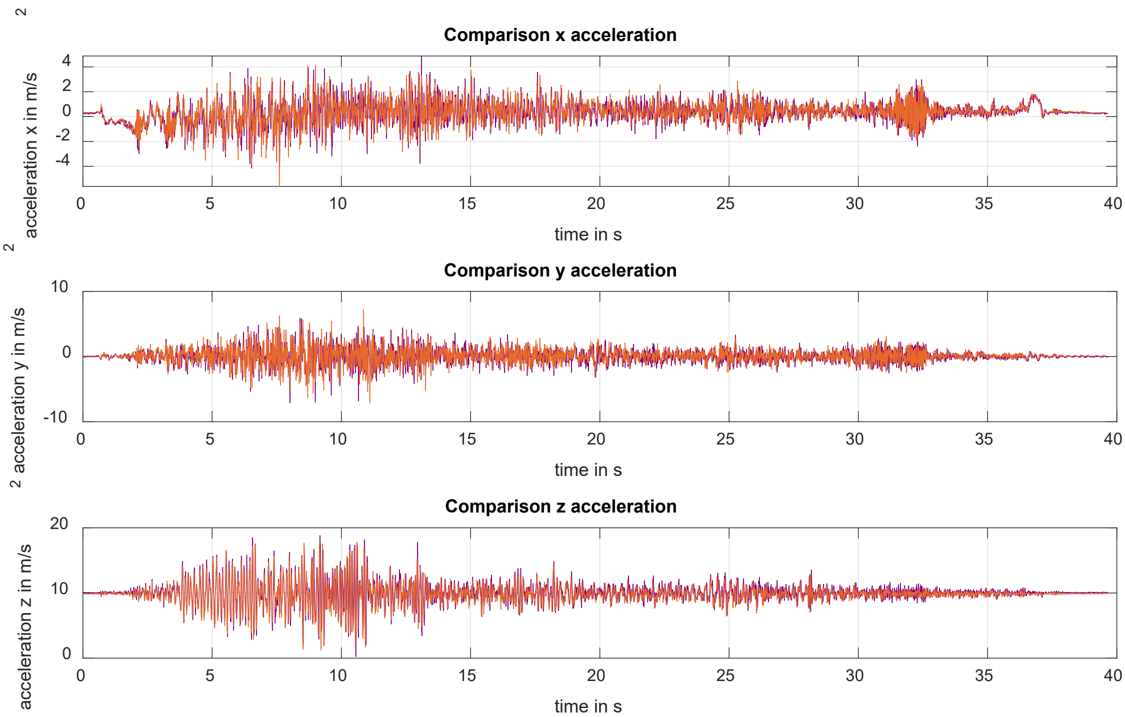

Figure 8: Comparison of all acceleration data of test run 03_Rollout_01 (purple: MPU-9150; orange: LPMS-CU2)

Since no strong lifting movements were made and no slopes were driven on, this must be considered in the data processing. This is shown well by each measurement, as exemplified by the first slalom track test.
The resulting offset of $0.0254\ \mathrm{m/s^2}$ can be justified by a relative rotation of the position of the IMUs and the mounting. Despite the two different data processing mechanisms implemented in the IMU LPMS-CU2 using a Kalman filter and in the IMU MPU-9150 using a Fast Fourier Transform, the curves of the measurements show almost identical behavior.
Further results for driving dynamic quantities can be observed about the z-orientation, the steering angle and the wheel speed. In the slalom track test, the data must reproduce a similar curve to the driven path as shown in figure 9.

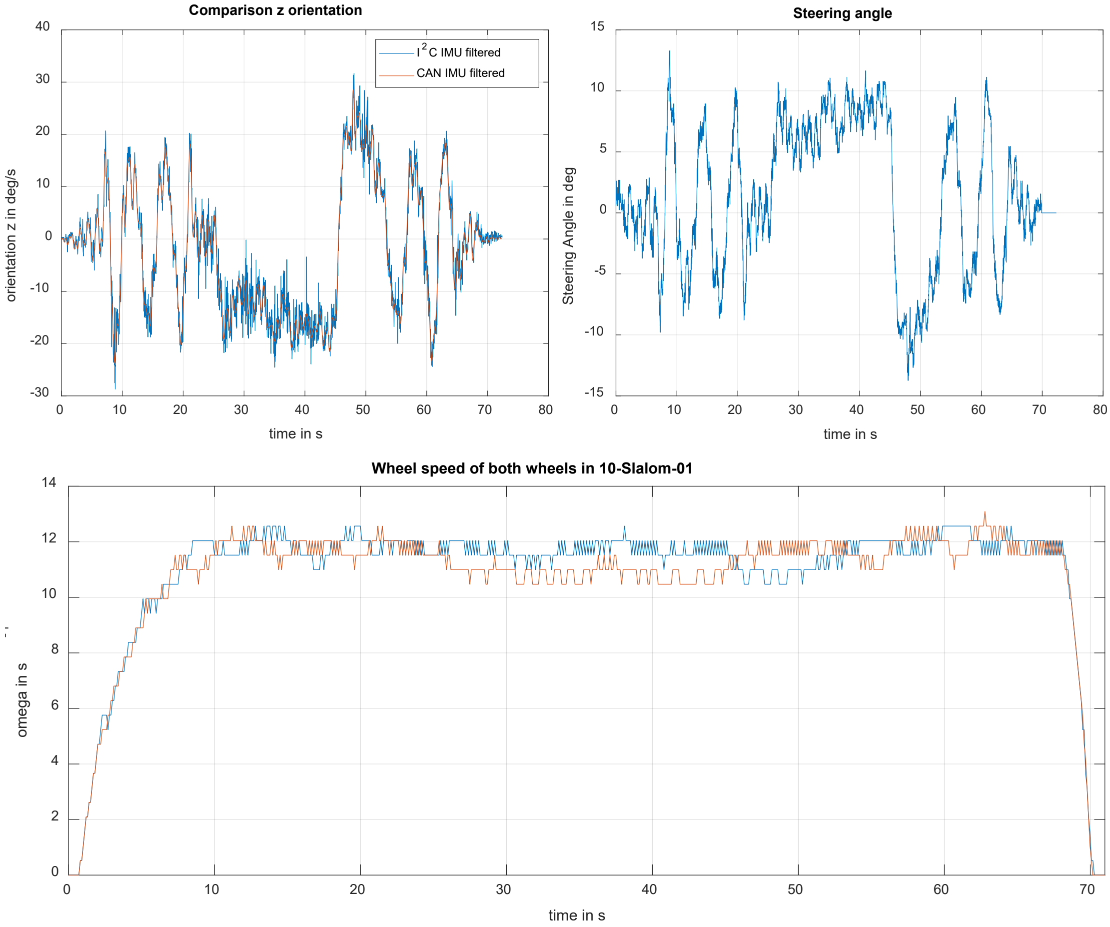

Figure 9: Overview of the slalom track test: comparison of the IMUs z orientation (Left top), measurement results of the steering angle (Right top), measurement results of both wheel frequencies (Bottom)

The steering angle behavior is shown based on the slalom track test. An offset can be compensated by subtracting the mean value of all data up to the first steering movement. The accuracy of the wheel speed detection can be varied. For this purpose, the determined speed must be transformed back to the interrupt number. Then, the interrupts must be redistributed with a new sampling rate. This rate can now be selected so that the sampling frequency is smaller than the present measuring frequency (10 Hz). In this example, the sampling frequency is adjusted to 2 Hz.
The measurement overview is completed with the torque measurement in figure 10 for the first slalom track test.

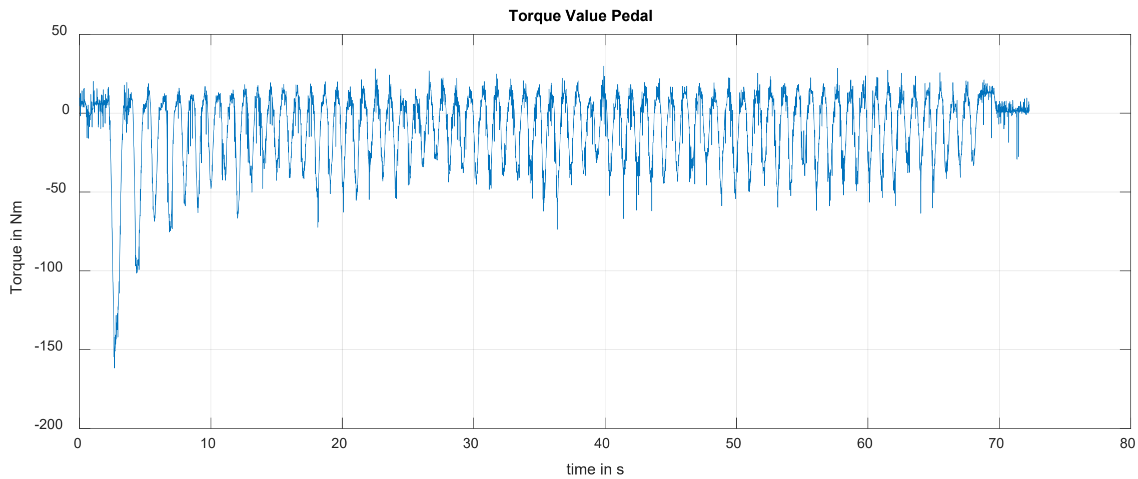

Figure 10: Measurement of the pedal torque

At the beginning of the torque measurement, a strong noise is visible. In addition, the measurement of the torque value is one-sided, so that one of the two pedaling movements is recorded as a negative value. This can be corrected by certain filter mechanisms and an extension of the torque evaluation.
To validate the simulation model, the steering angle and torque values are required. These are integrated into the system so that the following results can be displayed:

Identifier of test run	Real distance in [m]	Simulated distance in [m]	Difference in [m]
Rollout_01	68.4	78.54	10.14
Rollout_02	72.6	77.75	5.15
Rollout_03	88.1	91.08	2.98
Rollout_04	39.75	49.61	9.86
Rollout_05	64.8	76.27	11.47
Rollout_06	57.08	72.59	15.51
Rollout_07	57.25	62.97	5.72

Table 2: Measurement comparison of the roll out test results

As shown in table 2, deviations between simulation and reality are given with approximately 15%. Furthermore, two aspects must be considered for the result of the simulation: Firstly, the measured maximum speed is not reached and secondly, a residual speed is displayed at the end of the simulation. The results of the simulated slalom track test and circle driving test are shown in figure 11.

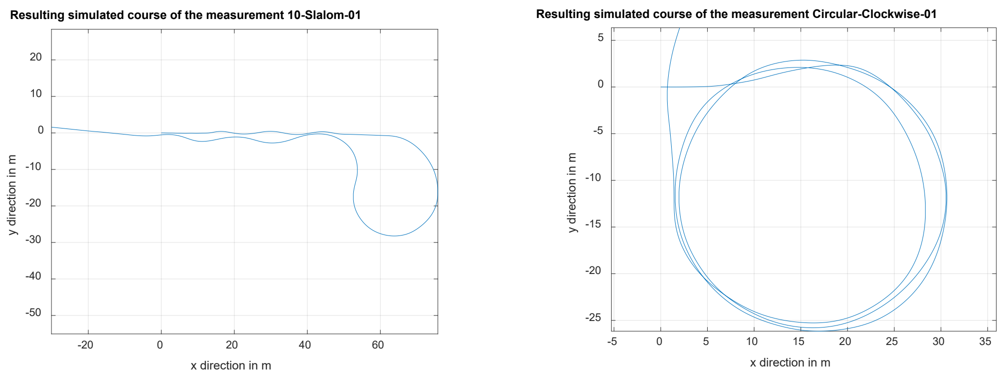

Figure 11: Resulting simulated course of the measurement Slalom_01 and Circular-Clockwise_01

An initial speed must be set in such a way that the maximum measured driving speed can be reproduced by the simulation. Thus, an initial speed of $v_{\text{init,slalom}} = 1.45\,\frac{\text{m}}{\text{s}}$ was selected for the slalom track test and $v_{\text{init,circular}} = 3\,\frac{\text{m}}{\text{s}}$ for the circle driving test. In addition, residual velocities are visible in both simulations. As shown in figure 12, the lateral acceleration and the yaw movement of the first slalom track test are comparable to the results of the simulation.
The course of the lateral accelerations is almost identical. The noise of the measured values around the turning ellipse can be removed using the Fourier transformation. It is important to mention that the amplitudes of the acceleration values of the different measured data differ by up to $0.75\,\frac{\text{m}}{\text{s}^2}$ at the beginning and by up to $0.322\,\frac{\text{m}}{\text{s}^2}$ at the end. The results of the z-orientation have an identical progression, while the measured data shows a greater oscillating behavior. The difference between the two measurement series is a maximum of approximately $0.2\,\frac{\text{rad}}{\text{s}}$.

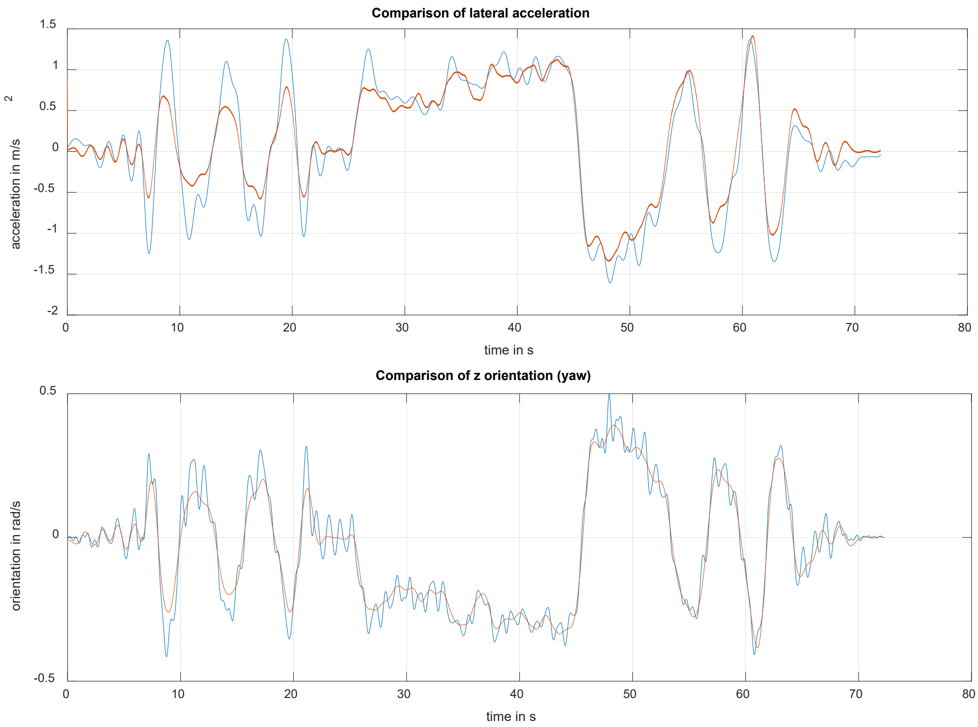

Figure 12: Comparison of lateral acceleration and z-orientation in measurement 10_Slalom_01 (blue: measurement; orange: simulation)

2. Conclusion

The developed data measurement system is powerful enough for this measurement series to pass all requirements. Through a systematic development and the simultaneous construction, the systematic adaptation capabilities have been optimized, but also further optimizable potentials have been discovered.
The large amplitudes of the z acceleration data can be related to two sources of stimulation: First, the ground excitation and thus the excitation of the bicycle construct is responsible for this noise. Second, the mounting of the IMUs is fixed by plastic screws, so that a vibration of the peripheries cannot be excluded. This results in fast strong positive and negative movements, which lead to noisy values. Therefore, the developed data processing functionality should be optimized with further adjustments for measurement noise suppression.
As shown in the comparison of the roll out tests, deviations between simulation and real measurements are given with approximately 15%. This behavior has many reasons; the influencing factors in the simulation are highly simplified and some parameters such as the skew stiffness have been estimated. In addition, a final velocity is preserved in the simulation parameters. This is to be justified with the conditions concerning the counterforces.
As can be seen in the comparison of the driven and simulated courses in the slalom track tests and circle driving tests, the measurement turns out to be identical. It can also be seen that the interaction between steering angle and torque leads to a good result if the initial speed is suitably integrated into the simulation model.
The dynamic behavior of the lateral acceleration and z-orientation of the simulation model deviate from the real measurement for distinct reasons despite identical curves. Since neither an exact position determination in the measurement system nor a velocity input is integrated within the simulation model, the simulation values depend on two input parameters. Thus, various reasons can cause the simulation to only approximate reality. However, since the simulation model is highly simplified, the results show a good result.
In summary, the developed data logger system with the added data post-processing and adjustments to the simulation model can be applied to data collection and validation tasks. The simulated results show identical driving behavior of the cargo bike, whereas the speed component does not handle braking maneuvers. A corresponding extension of the simulation model regarding the input parameters or the hardware structure with the help of additional sensor technology can optimize the tasks described here to advance the development of a motorized DAS. A continuing project might also deal with the data analysis, so that the noise effects are reduced using a Fourier transformation and thus the comparability of the data is improved. Furthermore, the syntax of the input parameters of the simulation model can be adapted so that an additional control and the measured velocity can be integrated.

Acknowledgement

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List of References

[1] **Görges**, Daniel; **Weißmann**, Andreas; **Manz**, Wilko; **Mellinger**, Nicolas: *Sicherheitsorientierte Fahrerassistenzsysteme für Elektrofahrräder (SIFAFE)*. Deutsches Institut für Urbanistik gGmbH. April 30, 2020. Available at https://nationaler-radverkehrsplan.de/de/praxis/sicherheitsorientierte-fahrerassistenzsysteme-fuer.
[2] **Ruschitzka**, Prof. Dr. Margot; **Leijon**, Mats; **Degen**, René; **Ott**, Harry: *Model-Based Approach to Investigate the Influences of Different Load States to the Vehicle Dynamics of Light Electric Vehicles*. April 2021. Vol. 11. Available at https://www.scirp.org/journal/paperinformation.aspx?paperid=108246.
[3] **Springer Fachmedien Wiesbaden GmbH**: *BMW zeigt elektrisches Lastenfahrrad und einen E-Scooter.* July 2021. Available at https://www.springerprofessional.de/mobilitaetskonzepte/elektromobilitaet/bmw-zeigt-elektrisches-lastenrad-und-einen-e-scooter/19390944
[4] **Statistisches Bundesamt** (Destatis): *Persons involved in accidents causing personal injury by type of traffic participation*. July 2021. Available at https://www.destatis.de/EN/Themes/Society-Environment/Traffic-Accidents/Tables/drivers-pedestrians.html
[5] **Sinus Markt- und Sozialforschung GmbH**: *Fahrrad-Monitor Deutschland 2019*. September 2019. Available at https://www.adfc.de/fileadmin/user_upload/Presse/Dateien_fuer_die_Pressearbeit/fahrradmonitor-2019-ausgewaehlte-ergebnisse.pdf
[6] **Maier**, Oliver; **Pfeiffer**, Prof. Dr.-Ing. Martin; **Wrede**, Prof. Dipl.-Ing. Jürgen: *Braking Dynamics Assistance System for Electrified Bicycles: Development and Validation of an Environment Model as Basis for the Model-Based Design*. March 2015. Available at https://www.researchgate.net/publication/273500201_Bremsdynamisches_Assistenzsystem_fur_elektrifizierte_Fahrrader_Aufbau_und_Validierung_eines_Umgebungsmodells_als_Grundlage_der_modellbasierten_Entwicklung
[7] **Jess**, Dennis; **Stebner**, Dr.-Ing. Gerhard; **Strube**, Prof. Dr.-Ing. Martin: *IoT-based driver assistance systems for ultra-light vehicles*. February 2021. Available at https://duepublico2.uni-due.de/rsc/viewer/duepublico_derivate_00073820/IFToMM_DACH_2021_paper_6.pdf?page=1
[8] **Burkert**, Andreas: *Forscher arbeiten an Fahrerassistenzsystem für Elektrofahrräder*. Springer Nature. July 2016. Available at https://www.springerprofessional.de/mikromobilitaet/fahrerassistenz/forscher-arbeiten-an-fahrerassistenzsytem-fuer-elektrofahraeder/10535930
[9] **LP-Research:** *LPMS Operator's Manual*. Vers. 2.0. 2019. Available at https://lp-research.com/wp-content/uploads/2019/08/LpmsOperatorsManual20190809-1.pdf.