System Identification of an Omnidirectional Test Vehicle for Model-Based Function Design

Björn Carstens*, Marian Göllner, Taihao Li, Xiaobo Liu-Henke

Control Engineering and Vehicle Mechatronics Group, Ostfalia University of Applied Sciences, Salzdahlumer Str. 46/48, 38302 Wolfenbüttel, Germany; *bj.carstens@ostfalia.de

SNE 35(4), 2025, 187-193, DOI: 10.11128/sne.35.tn.10753
Selected ASIM SST 2024 Postconf. Publication: 2024-12-10
Ext. English version: 2025-08-01; Accepted: 2025-08-15 SNE - Simulation Notes Europe, ARGESIM Publisher Vienna ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. System identification is an essential method in control engineering that enables the creation and validation of mathematical models of dynamic systems. This paper provides a detailed overview of the principles and methods of system identification, with a particular focus on validating the transfer function of an omnidirectional test vehicle with a Killough chassis. Of particular interest is the identification of the coupling structures of the overactuated system. The identified model forms the basis for model-based function design.

Introduction

The multidisciplinary field of system identification, which deals with the development of mathematical models for dynamic systems based on experimentally obtained data, plays a central role in engineering science. This process is used in many application areas, such as control engineering, signal processing, and mechanical engineering [1]. The ability to develop precise models enables engineers and scientists to understand, analyze, and control the behavior of complex systems.

The fundamental idea of system identification is to find a model that describes the behavior of a system based on input and output data. A dynamic system can be represented by various mathematical models, including differential equations, transfer functions, and state-space representations.

These mathematical models enable the description of the temporal or frequency-dependent behavior of a system and the making of predictions about its future states.

The acquisition of relevant data is the first and one of the most important steps in the system identification process. Data can be collected through experimental procedures, which include targeted experiments to generate meaningful datasets, or through passive observation, where existing data from the operation of the system is utilized. The aim of this work is to present the fundamentals of system identification and to develop a methodology for validating models based on experimental data.

Here, a methodology presented below is used and successively applied to a test vehicle described in Chapter 4.1 in order to perform the verification and validation of the results on a real system in combination with an iteratively built model.

1 Methodology

The consistently model-based and verification-oriented function design and verification of networked mechatronic systems according to [2] has proven to be time and cost-efficient in numerous applications in research and industry. Figure 1 shows the model-based mechatronic development cycle, which includes Model-in-the-Loop (MiL), Software-in-the-Loop (SiL), and Hardware-in-the-Loop (HiL) simulations as well as real-time realization through prototypes for verification.

The design process begins with modeling based on the real system, which is reduced or simplified according to requirements, initially resulting in a physical model. This is converted into a mathematical model using physical laws, which in turn can be represented in the computer, for example in the form of signal flow diagrams, and simulated using CAE tools and appropriate numerics. The modeling process includes measurements on the real system. The parameters of the mathematical model are identified and the simulation is validated.

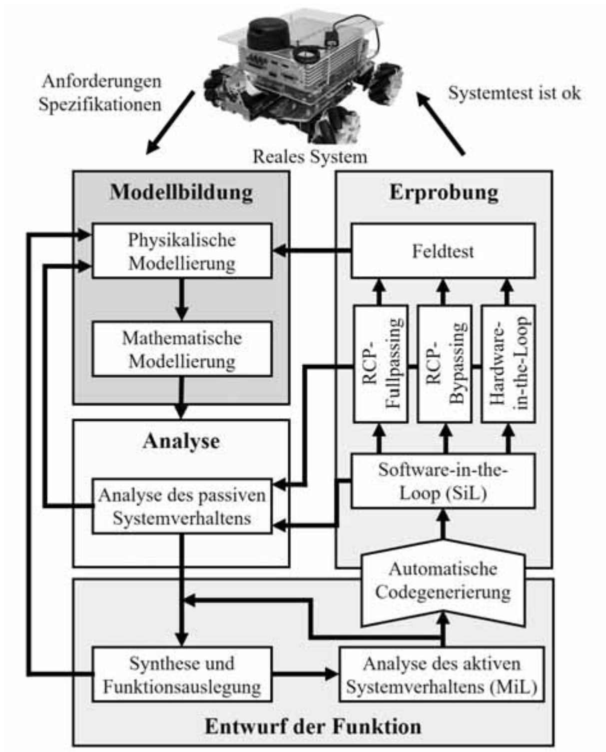

Figure 1: Mechatronic development cycle.

A subsequent analysis of the simulation results allows conclusions about the fundamental static and dynamic properties of the real system, on the basis of which the conception of functions takes place.

Both the function architecture and approaches for its design and optimization are determined. Complex functions are also broken down into hierarchical subfunctions according to the generalized cascade principle to reduce function complexity and thus make the design process manageable.

For this purpose, hardware and software requirements are considered at an early stage of development and interfaces for cross-functional communication are defined.

The testing process is carried out in parallel with development. When a subfunction has been developed, it is tested and analyzed.

In this work, requirements are first determined using this method. Through the analysis of the physical model as well as the mathematics, the function is modeled. Each part of the function is tested accordingly.

2 State of Knowledge

System identification refers to the creation of a model for a dynamic system that describes the relationship between input and output data. This paper covers the theoretical fundamentals of system identification, with particular focus on identification using linear models. Methods for determining non-parametric models are presented, such as the determination of transfer functions from step responses and the determination of the frequency response. For parametric models, parameter estimation is an essential component of system identification.

The theoretical fundamentals of parameter estimation are explained in detail in [3, 4]. Excitation signals play a central role here, as they reveal the behavior of the system to be controlled. In control engineering, it is particularly important that the excitation signal covers the relevant frequency spectrum in order to develop accurate models and ensure effective control. Various types of excitation signals, such as impulses, steps, sinusoidal oscillations, and pseudo-random binary signals (PRBS), are used to comprehensively characterize system behavior. Precise model building based on these signals enables engineers to optimize the control behavior of systems and improve the stability and performance of control loops. [4]

Frequency response analysis is a central method for the identification and validation of models in control engineering. It includes the analysis of the system response to sinusoidal input signals at different frequencies. This method describes how the system responds to different harmonic input variables, whereby amplitude and phase shifts are measured and analyzed. A Bode diagram graphically represents the results of frequency response analysis. It displays the logarithmic amplitude and phase shift as functions of frequency. This not only allows the stability and dynamics of a system to be assessed, but also weaknesses in the model to be identified. The practical steps of a frequency response analysis include:

1. Applying input signals to the system.
2. Measuring the respective output signals.
3. Calculating amplitude ratios and phase shifts between input and output signals.
4. Presenting the results in Bode diagrams.
5. Comparing experimental frequency responses with theoretical models.

Through the systematic comparison of experimental and theoretical data sets, the accuracy of the models can be validated and possible modeling errors can be identified. [5, 6, 7]

3 Conception

The process of system identification begins with modeling, in which the behavior of the system is described by physical laws and equations [8]. Subsequently, input and output signals of the system are measured, which can be generated by suitable excitation signals, see Chapter 2. Signals with a broad frequency spectrum are particularly suitable for vehicle systems [9]. Based on the measured data, a mathematical model is chosen, often in the form of AR (Autoregressive), MA (Moving Average), or ARMA (Autoregressive Moving Average) models.

The parameters of the model are optimized using methods such as the least squares method, the recursive least squares method, or the prediction error method. Validation is performed by comparing model predictions with independent data sets to ensure that the model adequately represents system behavior.

Challenges such as measurement errors, nonlinearities, and temporal variations of the system require a balanced relationship between model complexity and manageability. Experimental methods are based on measuring system responses to defined test signals, while theoretical approaches are based on modeling using physical laws.

An important step in system identification is frequency response measurement, which allows precise validation of the transfer function.

In our case, the transfer function $G(s)$, which describes the ratio of the Laplace transforms of the output to input signals, was established as follows:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{b_0 + b_1 s + \cdots + b_m s^m}{a_0 + a_1 s + \cdots + a_n s^n}$$

To verify the transfer function, the system was exposed to harmonic input signals of different frequencies, and the respective output signals were measured. The frequency response measurement was performed with an Abacus 901, which precisely analyzes amplitude and phase changes.

Validation consists of comparing the experimental frequency response with the model prediction. If the measured behavior matches the modeled behavior, the model is considered confirmed. Deviations may indicate nonlinear effects, measurement errors, or insufficient model assumptions.

3.1 Kinematics

The Mecanum wheel shown in Figure 2 displays the quantities necessary for describing the kinematics. The angular velocity ω is shown, which is often also represented by the rotational speed n in the further course. In addition, the speed of the wheel in the locking direction is at the inclination angle α of the rolling element. The vehicle velocity V can be calculated via the wheel radius r and the angular velocity ω.

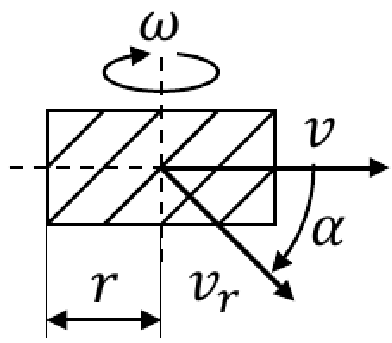

Figure 2: Kinematics of a Mecanum wheel [10].

The goal is to establish the kinematics matrix shown in Equation (1). This describes the wheel speeds n as a function of the total velocity of the test vehicle in its three degrees of freedom v_{fx}, v_{fy}, and $\dot{\omega}_f$.

$$\begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{bmatrix} = \underline{\underline{K}} \cdot \begin{bmatrix} v_{fx} \\ v_{fy} \\ \dot{\omega}_f \end{bmatrix} \tag{1}$$

3.2 Decoupling

The decoupling of mechatronic systems is a central concept in control engineering, which aims to minimize or eliminate the interactions between different components of a system.

This enables independent control of the individual components and improves the overall performance and efficiency of the system.

In mechatronic systems, which often consist of mechanical, electrical, and software-controlled components, decoupling can be particularly challenging since these components are closely interconnected. [11]

The decoupling is performed using the kinematics matrix $\underline{\underline{K}}$. For a vehicle with four Mecanum wheels, the result according to [12] is:

$$\underline{\underline{K}} = \begin{bmatrix} \frac{\cos(\delta_1)}{\sin(\alpha_1)} & \frac{-\sin(\delta_1)}{\sin(\alpha_1)} & \frac{-\sin(\varepsilon_1)}{\sin(\alpha_1)} \cdot r_1 \\ \frac{\cos(\delta_2)}{\sin(\alpha_2)} & \frac{-\sin(\delta_2)}{\sin(\alpha_2)} & \frac{-\sin(\varepsilon_2)}{\sin(\alpha_2)} \cdot r_2 \\ \frac{\cos(\delta_3)}{\sin(\alpha_3)} & \frac{-\sin(\delta_3)}{\sin(\alpha_3)} & \frac{-\sin(\varepsilon_3)}{\sin(\alpha_3)} \cdot r_3 \\ \frac{\cos(\delta_4)}{\sin(\alpha_4)} & \frac{-\sin(\delta_4)}{\sin(\alpha_4)} & \frac{-\sin(\varepsilon_4)}{\sin(\alpha_4)} \cdot r_4 \end{bmatrix} \tag{2}$$

With the barrel angle of the Mecanum wheel α_i, the position angle of the wheel axis β_i to the vehicle's coordinate system, and the orientation angle γ_i.

Together with the absolute distance of the origin coordinate system of the Mecanum wheel to the origin coordinate system of the vehicle r_i, the polar coordinates result starting from the coordinate origin.

$$\alpha_i = (-1)^i \cdot 45^\circ \tag{3}$$

$$\beta_i = \arcsin\left(\frac{b_i}{r_i}\right) - (i-1) \cdot 90^\circ \tag{4}$$

$$\gamma_i = \arcsin\left(\frac{b_i}{r_i}\right) + (i-1) \cdot 90^\circ \tag{5}$$

$$r_1 = \sqrt{{b_i^2}^2 + {b_n}^2}, r_{i>1} = \sqrt{b_{i-1}^2 + b_i^2} \tag{6}$$

The construction angles $\delta_i = \alpha_i - \beta_i - \gamma_i$ and $\varepsilon_i = \alpha_i - \beta_i$ result from these. For the test vehicle used, the kinematics matrix $\underline{\underline{K}}$ is thus:

$$\underline{\underline{K}} = \begin{bmatrix} 1 & -1 & -\frac{l_x+l_y}{2} \\ 1 & 1 & -\frac{l_x+l_y}{2} \\ 1 & -1 & \frac{l_x+l_y}{2} \\ 1 & 1 & \frac{l_x+l_y}{2} \end{bmatrix} \cdot \frac{1}{2 \cdot \pi \cdot r} \tag{7}$$

4 Test Setup Infrastructure

The identification of a simulation model requires, as already mentioned, additional hardware and software as well as corresponding adaptations in the test vehicle. All necessary interventions are presented below. The transfer function of the test vehicle's velocity is to be determined.

4.1 Test Vehicle Setup

The test vehicle offers numerous functions, whereby only the systems relevant to this work are described here. Further details can be found in [12].

One relevant system is the microcontroller. The test vehicle used is equipped with an STM32H743 board, which has a dual-core architecture. The microcontroller can receive instructions and transmit status information via a LAN interface. The drive system of the test vehicle can consist of swerve, holonomic, or Mecanum systems.

Mecanum wheels, developed by Bengt Ilon, enable omnidirectional movement through special rollers on the circumference of the wheel, which allow independent control of the direction of movement in all axes. Swerve wheels combine rotational movements and lateral displacements, allowing the vehicle to also be steered in all directions, while holonomic wheels offer similar freedom of movement, but in a completely different way. Mecanum, swerve, and holonomic wheels offer advantages such as space savings, lower construction and maintenance costs, high precision, and easy replacement of rollers.

Mecanum wheels consist of obliquely mounted rollers that allow the vehicle to move without directional restrictions. Swerve wheels are special steering and chassis combinations that enable complete freedom of movement in all directions by independently controlling the steering and speed of each wheel. Holonomic wheels refer to systems that enable a vehicle to move in all directions without restrictions on the direction of movement. They are ideal for intralogistics, automated guided vehicle systems, and mobile robotics [13]. The test vehicle is scaled down; the scaling law will be taken into account during evaluation and adaptation.

In a next step, a distance controller is to be implemented on the test vehicle's Raspberry Pi. This controller continuously records the distance to a preceding object and calculates an appropriate target velocity based on this.

The calculated velocity values are then transmitted to the vehicle's microcontroller, which takes over the control of the drive unit.

4.2 Measurement Test System

Figure 3 shows the measurement test system. A host PC with DP900 software from Data Physics is connected to the Abacus 901 via an Ethernet connection. The excitation signal as output, as well as the two inputs, are connected to the test vehicle.

The Abacus 901 generates analog excitation signals, which are converted into digital signals by the AD converters of the dSPACE real-time hardware. This digital excitation signal is immediately fed back through a DA converter to the Abacus. This signal later serves as a reference signal.

This makes it possible to compensate for the possible interfering influences resulting from the AD and DA conversion. The chosen signal path was deliberately designed so that the dead times that occur due to signal and information conversions can be recorded.

The digital excitation signal is received via the Ethernet interface of the microcontroller as a target velocity signal [12].

The microcontroller now regulates the target velocity using a velocity controller implemented on the microcontroller. The drive motors are equipped with rotary encoders.

With the help of these encoders, the microcontroller can determine the current wheel speed and, using the inverse kinematics from Eq. (7), the velocity. The velocity is then sent back via the Ethernet interface of the microcontroller to the dSPACE real-time hardware, which transmits this velocity as an analog signal to the Abacus 901.

This signal path is to be identified, since later the Raspberry Pi will also send the target velocity to the microcontroller via the Ethernet interface.

The setup shown in Figure 3 represents the transmission of measurements in the software. When forming the transfer function, the excitation signal of the Abacus is not used as the system input, but rather the signal influenced by the real-time hardware.

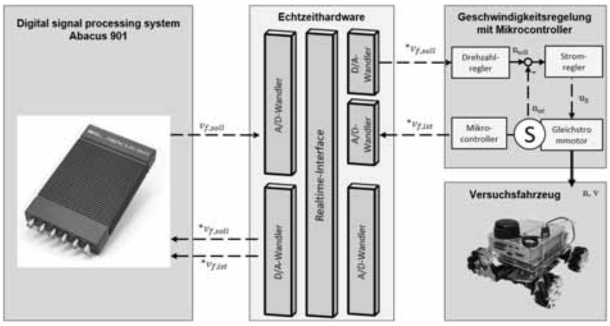

Figure 3: Transmission of excitation in the software.

5 Results

The results of the frequency response measurements were analyzed and compared with the mathematical model. Through parameter adaptation, the parameters of the model were modified and optimized with respect to the deviation from the measurements.

Thus, the transfer matrix $\underline{\underline{G}}$ of the system could be found.

$$\underline{\underline{G}} = \begin{bmatrix} G_{v;x,x} & G_{v;x,y} & G_{v;x,\psi} \\ G_{v;y,x} & G_{v;v;y,y} & G_{v;y,\psi} \\ G_{v;\psi,x} & G_{v;\psi,y} & G_{v;\psi,\psi,} \end{bmatrix} \tag{8}$$

The main diagonal describes the direct effect of the excitation signal set for the respective degree of freedom via the kinematics. The transfer functions of the main diagonal were excited with the help of the transformation matrix shown in Eq. (7) via the velocity controller and related to the degree of freedom to be investigated by direct backward transformation of the measurement signals.

The Bode diagram shown in Figure 4 represents the transfer function of velocity in the x-direction with excitation in the x-direction. The diagram shows the characteristic of a PT1 system.

The transfer function $G_{v;x,x}$ thus results as a first-order time delay element with a time constant of $\omega = 1.93 \cdot 10^1 \rightarrow T = \frac{1}{19.3} \approx 0.05$ and a gain factor $K = 1$.

The off-diagonal elements of the transfer matrix represent the coupling of the system and would be disruptive to the desired system dynamics with a relatively high gain factor.

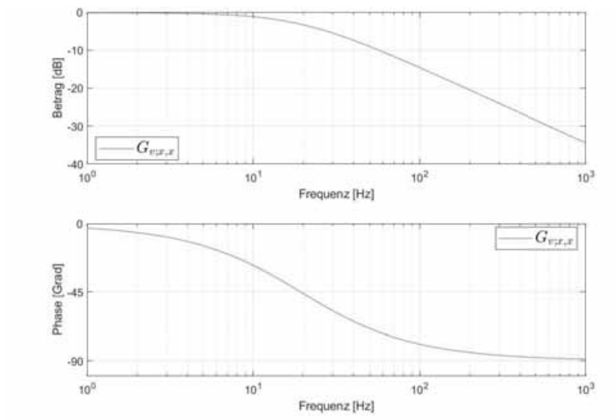

Figure 4: Transfer function of velocity from MATLAB/Simulink.

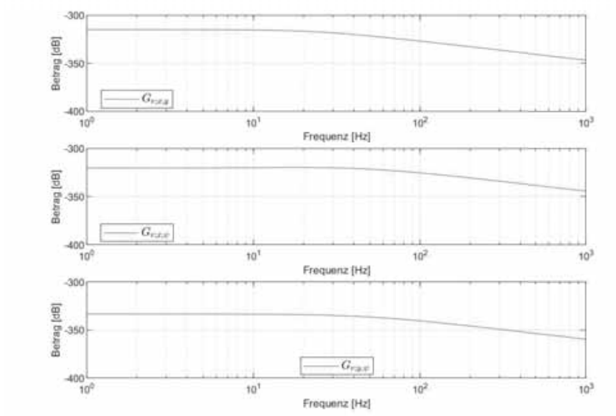

Figure 5: Transfer functions of some off-diagonal elements of velocity from MATLAB/Simulink.

The Bode diagrams shown in Figure 5 represent the transfer functions of the off-diagonal elements. The upper Bode diagram is the transfer function for velocity in the y-direction with excitation in the x-direction. The middle diagram shows excitation in the x-direction and the system response in ψ, the vertical axis of the vehicle. The last diagram shows excitation in the y-direction and again the system response in ψ around the vertical axis of the vehicle.

What all responses have in common is that the gain factor of the identified PT1 systems is at -320 dB $= 20\log_{10}(K) \to K \approx 10^{-16}$ and thus the influence of the coupling in relation to the desired system dynamics of the main diagonal is very low.

Based on this modified model, the controller synthesis and optimization can now be carried out using the mechatronic development process.

For this purpose, a reference model of the same order and structure with free parameters is built. The identification of the optimal parameters is performed by minimizing the squared error between an assumed transfer element of the reference model as the feed-forward transfer function of the separated transfer path within the transfer matrix and the measured frequency response.

The entirety of the transfer elements is thus optimally fitted to the measured frequency response in their course.

6 Summary and Outlook

To derive a model of the dynamic behavior of an omnidirectional intralogistics vehicle on a reduced scale, the presented methods of system identification were applied. The omnidirectionality of the vehicle is realized here through the use of a Killough chassis with four Mecanum wheels.

In the field of kinematics, the Mecanum wheel describes the movement of a vehicle based on angular velocity and vehicle velocity. Decoupling is a central concept for minimizing interactions between system components.

The test vehicle is also equipped with a microcontroller which is responsible for the local control of the chassis. The hardware additionally required for measurement includes a connection to the host PC and the Abacus 901 signal analyzer; necessary additions in the vehicle's software include the processing and retransmission of setpoint and actual values to these. The results include the representation of transfer functions for various degrees of freedom and show the system responses to different excitations.

In the further course, the same method for identifying the transfer function will be carried out on a larger test vehicle. The test platform AURONA serves as a platform for current research projects, therefore it is necessary to identify basic driving dynamics models for this vehicle and, based on this, to further develop various autonomous driving functions that were first implemented with the help of the small test vehicles.

Acknowledgement

Funded by the Lower Saxony Ministry of Science and Culture under funding number ZN4068 in the Niedersächsisches Vorab of the VolkswagenStiftung.

Publication Remark

This contribution is an extended English version of the workshop publication published in
ASIM Conference SST 2024 Langbeiträge
ARGESIM Report AR 47, p. 175-83
DOI DOI 10.11128/arep.47.a4723
ISBN ebook: 978-3-903347-65-6
Volume DOI 10.11128/arep.47

References

[1] Balakrishnan V. System identification: theory for the user (second edition). *Automatica*. 2002;38(2):375–378.

[2] Liu-Henke X. *Mechatronische Entwicklung der aktiven Feder-/Neigetechnik für das Schienenfahrzeug RailCab: Zugl.: Paderborn, Univ., Diss., 2005*, vol. 589 of *Fortschritt-Berichte VDI Reihe 12, Verkehrstechnik/Fahrzeugtechnik*. Düsseldorf: VDI-Verl., als ms. gedr ed. 2005.

[3] Bohn C. Systemidentifikation. In: *HÜTTE – Das Ingenieurwissen*, edited by Hennecke M, Skrotzki B, pp. 1–54. Berlin, Heidelberg: Springer Berlin Heidelberg. 2020;.

[4] Unbehauen H, ed. *Identifikation, Adaption, Optimierung: Mit 11 Tabellen*, vol. 3 of *Studium Technik*. Braunschweig: Vieweg, 6th ed. 2000.

[5] BLASS tH. Anwendung der Frequenzganganalyse beim praktischen Betrieb von Regelungseinrichtungen. *at - Automatisierungstechnik*. 1954;2(1-12):137–143.

[6] Pestel E, Kollmann E. Die Frequenzgangmethode. In: *Grundlagen der Regelungstechnik*, edited by Pestel E, Kollmann E, Regelungstechnik in Einzeldarstellungen, pp. 148–246. Wiesbaden and s.l.: Vieweg+Teubner Verlag. 1961;.

[7] Iyer SV. Frequenzganganalyse. In: *Digitales Filterdesign mit Python für Anwendungen in der Energietechnik*, edited by Iyer SV, pp. 125–161. Cham: Springer Vieweg. 2024;.

[8] Isermann R. *Identifikation dynamischer Systeme 1*. Berlin, Heidelberg: Springer Berlin Heidelberg. 1992.

[9] Isermann R. *Automotive Control*. Berlin, Heidelberg: Springer Berlin Heidelberg. 2022.

[10] Dr-Ing X Liu-Henke, Sören Scherler, Marian Göllner, Johannes Maisik, Matthias Fritsch. Simulationsgestützte Konzeption der Antriebstopologie eines fahrerlosen Transportfahrzeugs. In: *Tagungsband ASIM Workshop STS/GMMS 2018*. ARGESIM. 2018; .

[11] Labisch D, Konigorski U. Verkopplungsbasierte Methode zur Entkopplung nichtlinearer Deskriptorsysteme. *at - Automatisierungstechnik*. 2014; 62(7):475–486.

[12] Jacobitz S, Göllner M, Zhang J, Liu-Henke X. Modellbasierte Entwicklung des Antriebsmoduls für vernetzte fahrerlose Transportfahrzeuge in einem cyber-physischen Labortestfeld;.

[13] Aktuelle Meldungen der Nabtesco Precision Europe GmbH.
URL `https://j2n.eu/r/wfeEa`

[14] Max van Haren, Lennart Blanken, Tom Oomen. Frequency Domain Identification of Multirate Systems: A Lifted Local Polynomial Modeling Approach. *2022 IEEE 61st Conference on Decision and Control (CDC)*. 2022;pp. 2795–2800.

[15] Tang W, Shi Z. Robust system identification of continuous-time model from frequency response function data. In: *2011 9th World Congress on Intelligent Control and Automation*. IEEE. 2011; pp. 661–665.

[16] Göllner M, Jacobitz S, Ferrara R, Liu-Henke X. Identifikation instabiler, unteraktuierter Systeme mit nicht-linearem dynamischen Verhalten. In: *ASIM SST 2024 Tagungsband Langbeiträge*, edited by Rose O, Uhlig T. ARGESIM Publisher Vienna. 4.– 6. September 2024; pp. 175–183.