Development Methodology for Creating the Digital Twin for Propulsion Drive of an Electric Vehicle

Viktor Rjabtšikov

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

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signature

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Elektrisõiduki veoajami digitaalse kaksiku arendusmetoodika

VIKTOR RJABTŠIKOV

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List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I **V. Rjabtšikov**, A. Rassõlkin, K. Kudelina, A. Kallaste, and T. Vaimann, "Review of Electric Vehicle Testing Procedures for Digital Twin Development: A Comprehensive Analysis," Energies, vol. 16, no. 19. Multidisciplinary Digital Publishing Institute (MDPI), Oct. 01, 2023. doi: 10.3390/en16196952.

II A. Rassõlkin, **V. Rjabtšikov**, T. Vaimann, A. Kallaste, and V. Kuts, "Concept of the Test Bench for Electrical Vehicle Propulsion Drive Data Acquisition," *2020 XI International Conference on Electrical Power Drive Systems (ICEPDS)*, Oct. 2020.

III **V. Rjabtšikov**, M. Ibrahim, A. Rassõlkin, T. Vaimann, and A. Kallaste, "EV-Powertrain Test Bench for Digital Twin Development," in *2022 IEEE 20th International Power Electronics and Motion Control Conference, PEMC 2022*, Institute of Electrical and Electronics Engineers Inc., 2022, pp. 559–563. doi: 10.1109/PEMC51159.2022.9962879.

IV A. Rassõlkin, **V. Rjabtšikov**, T. Vaimann, A. Kallaste, V. Kuts, and A. Partyshev, "Digital Twin of an Electrical Motor Based on Empirical Performance Model," *2020 XI International Conference on Electrical Power Drive Systems (ICEPDS)*, Oct. 2020.

V **V. Rjabtšikov**, A. Rassõlkin, V. Kuts, K. Kudelina, T. Vaimann, A. Kallaste, A. Partyshev, "Parametric digital twin of autonomous electric vehicle transmission," *Journal of Machine Engineering*, vol. 21, no. 2, pp. 131–140, 2021, doi: 10.36897/jme/134435.

VI V. Kuts, A. Rassõlkin, A. Partyshev, S. Jegorov, and **V. Rjabtšikov**, "ROS middle-layer integration to Unity3D as an interface option for propulsion drive simulations of autonomous vehicles," in *Proceedings of the International Conference of DAAAM Baltic,* DAAAM International Vienna, 2021. doi: 10.1088/1757-899X/1140/1/012008.

VII **V. Rjabtšikov**, M. Ibrahim, B. Asad, A. Rassõlkin, T. Vaimann, A. Kallaste, V. Kuts, M. Stepien, M. Krawczyk, "Digital Twin Service Unit Development for an EV Induction Motor Fault Detection," in *2023 IEEE International Electric Machines and Drives Conference, IEMDC 2023*, Institute of Electrical and Electronics Engineers Inc., 2023. doi: 10.1109/IEMDC55163.2023.10239085.

Author's Contribution to the Publications

Contribution to the papers in this thesis are:

I Viktor Rjabtšikov is the primary author of this article. He conducted an extensive literature review of existing electric vehicle testing procedures relevant to Digital Twin development. He also took the lead in structuring the review, compiling the data into coherent sections, and writing the initial draft of the manuscript.

II Viktor Rjabtšikov is the secondary author of this article. He was instrumental in identifying key technical requirements for the data acquisition system and suggesting innovative solutions to integrate software with the hardware components of the test bench. He also assisted in revising the manuscript and preparing it for publication.

III Viktor Rjabtšikov is the primary author of this article. He is responsible for designing the EV-powertrain test bench aimed at Digital Twin development and writing the initial draft of the paper.

IV Viktor Rjabtšikov is the secondary author of this article. He contributed to the development of the Digital Twin for an electrical motor by refining the empirical performance model and integrating real-world test data. He also assists in drafting and revising the manuscript.

V Viktor Rjabtšikov is the primary author of this article. He conceptualized and developed a parametric Digital Twin for an autonomous electric vehicle transmission. His work involved designing the framework and implementing simulation models based on varying parameters. He also assists in drafting and revising the manuscript.

VI Viktor Rjabtšikov is the last author of this article. His expertise in both autonomous vehicle systems and simulation technologies provided the project with strategic direction and ensured the technical accuracy of the final manuscript. He also reviewed and refined for publication.

VII Viktor Rjabtšikov is the primary author of this article. He led the creation of a Digital Twin service unit for detecting faults in EV induction motors, from design to validation. Also, he wrote the initial draft of the paper.

1 Introduction

The automotive industry is currently experiencing a major paradigm shift, led by the urgent demand for environmentally friendly modes of transportation and advancements in technology. Europe is at the cutting edge of this transition, transitioning from internal combustion engine (ICE)-powered vehicles to electric vehicles (EVs). Environmental concerns, regulatory requirements, and technological advancement all contribute to this modification. It represents an overall progression towards a transportation system that is more environmentally sustainable, highly technologically advanced, and efficient. [1]

Priority is given to the adoption of EV primarily due to the critical need to reduce greenhouse gas emissions and reduce carbon footprint. ICE vehicles, which are powered by fossil fuels, make a significant contribution to carbon emissions and air pollution. In contrast, EVs offer a more environmentally friendly alternative, surpassing substantial emission reductions when utilized in tandem with renewable energy sources. The European Union (EU) has pushed for this transition in pursuit of its environmental objectives. Therefore, transitioning to EVs is not only a strategic priority but also an environmental requirement to adhere to stringent emission regulations and accomplish enduring sustainability goals. [2]

The directive from the EU to discontinue the sale of new ICE vehicles by 2035. This legislation serves to underscore the EU’s commitment to environmental sustainability while also fostering innovation in the automotive industry. Encouraged manufacturer emphasis on EV technology has resulted in rapid advancements in charging infrastructure, battery technology, and vehicle efficiency. In addition to encouraging the development of EVs, the ban facilitates the adoption of electric mobility by consumers, thereby causing a market transition toward cleaner transportation alternatives. [3]

Moreover, the introduction of autonomous vehicles represents the integration of cutting-edge technologies within the realm of transportation. EVs primarily integrate automation and electrification using sensors, cameras, and sophisticated algorithms that enable autonomous navigation through complex traffic scenarios. Electric propulsion systems provide the precision required for autonomous operation as well as environmental benefits. [4]

Digital technologies, and Digital Twins (DT) in particular, are important for the development and improvement of autonomous vehicles. DTs, which are virtual representations of real systems, empower engineers to replicate and evaluate the real-time performance of vehicles. DTs can process vast amounts of sensor data for autonomous vehicles, thereby facilitating algorithm optimization and improving the safety and efficiency of the vehicles. By assuring high standards of safety, performance, and dependability, digital technology advances autonomous vehicle capabilities, as evidenced by the development process's utilization of DTs. [5]

1.1 EV Propulsion Drive System Components

EVs sustainability, performance, and efficiency are primarily determined by their electric motor (EM) propulsion system, a vital part of the vehicle’s architecture. Unlike vehicles powered by ICEs that rely on fossil fuels, EVs utilize actuators powered by electricity stored in batteries. The following sub-chapter examines the components comprising an EVs propulsion system and clarifies how these components function in concert to propel the vehicle.

1.1.1 Battery Pack

EVs rely heavily on the battery cell, which supplies the propulsion system with its primary energy source. A variety of battery technologies are utilized in EVs, each having a unique combination of properties. Presently the standard for EVs, lithium-ion (Li-ion) batteries, provide an optimal blend of energy density, cycle life, and safety. [6] Constant advancements are being made to decrease expenses and improve performance. Battery packs mentioned are for propulsion drives and not standby power batteries, which are present in all vehicles. Hybrid vehicles utilized Nickel-Metal Hydride (NiMH) batteries, which were once prevalent. Despite their reputation for affordability and safety, NiMH batteries have a lower energy density than Li-ion batteries. [7] The potential of lithium-sulfur (Li-S) batteries in EVs is considerable, due to their increased energy density and the accessible availability of sulfur. Nevertheless, there are safety and cycle life concerns associated with the sulfur cathode that require attention. [8] Solid-state batteries are at the forefront of EV battery technology, offering the possibility of an unmatched amount of energy density and safety. With the advancement of technology, it is anticipated that the steep technical obstacles and high current costs of mass production will decrease. [9]

Table 1 compares the most common types: Li-ion, NiMH, Li-S, and Solid-State batteries used in modern EVs.

Table 1. Comparison of battery technologies used in EVs. [6][7][8][9]

Feature	Li-ion	NiMH	Li-S	Solid-State
Energy Density	High, enables longer driving ranges.	Moderate, lower than Li-ion.	Very high, potentially longer ranges than Li-ion.	Extremely high, offering the longest ranges.
Cycle Life	High, around 1,000 to 2,000 cycles.	Moderate, typically less than Li-ion.	Lower, due to degradation issues with sulfur.	Expected to be very high, surpassing Li-ion.
Safety	Good with proper management, though risks of thermal runaway exist.	Safer, less prone to thermal runaway.	Moderate, with challenges related to polysulfides leakage.	Superior, due to solid electrolytes minimizing leakage and fire risks.
Charge/Discharge Efficiency	High, typically 80-90%.	Moderate, slightly lower than Li-ion.	Moderate to high, but with current challenges in maintaining capacity.	Potentially very high, with low internal resistance.
Temperature Performance	Performs well in moderate temperatures, efficiency drops in extreme cold.	Good, better than Li-ion in cold temperatures.	Moderate, with performance affected by low temperatures.	Expected to perform well across a broad temperature range.
Maintenance	Low, requires minimal maintenance.	Low, like Li-ion.	Moderate, due to challenges with sulfur cathode.	Very low, expected to require minimal maintenance.
Application Suitability	Widely used in consumer electronics and EVs for its balance of energy density and cycle life.	Used in hybrid vehicles and some older EV models for its safety and cost-effectiveness.	Emerging technology with potential for high energy density applications.	Promising for future EV applications, offering high energy density and improved safety.

The high energy density and cycle life of Li-ion batteries make them well-suited for consumer devices and EVs. Both Li-S and Solid-State batteries exhibit potential for future applications due to their ability to provide energy densities ranging from very high to extremely high, as well as enhanced safety characteristics. However, the widespread commercial use of Li-S and Solid-State batteries is currently hindered by several challenges. Li-S batteries struggle with short cycle lives and capacity fading, while Solid-State batteries face manufacturing complexities, material compatibility issues, and increased costs.

1.1.2 Power Electronics Controllers and Semiconductors used in EVs

In EVs, Power Electronics Controllers (PECs) regulate the electrical power transfer between the EM and the battery. Charge regulators facilitate energy recovery during deceleration and convert DC from the battery to AC or change DC power for the motor. Main PEC topologies in EV divide into two types: DC-AC inverters and Multilevel inverters. DC-AC inverters, particularly Voltage Source Inverters (VSIs), are of utmost importance in the realm of EV technology as they enable the transformation of DC derived from the vehicle's battery into alternating current AC to power the motor. These inverters provide accurate regulation of motor speed and torque, hence ensuring optimal performance, by utilizing Pulse Width Modulation (PWM) and Field-Oriented Control (FOC). [10] The introduction of multilevel inverters represents a notable progress, providing decreased harmonic distortion and increased efficiency, which is especially advantageous for high-power EV applications. This progress not only improves the performance of vehicles but also leads to a longer lifespan of the motor and less maintenance requirements. Each of the technologies utilized in these controllers possesses unique features. A comparison of various PEC semiconductors varieties presented in Table 2.

Table 2. Comparison of power electronics controllers for EVs' based on semiconductors. [10][11][12]

Feature	Si-based	SiC-based	GaN-based
Efficiency	High, but less efficient at higher frequencies.	Higher efficiency, especially at high frequencies and temperatures.	Highest efficiency, outperforming Si and SiC at high frequencies.
Thermal Performance	Good, requires cooling at high power levels.	Superior, operates at higher temperatures with less cooling required.	Excellent, operates efficiently at high temperatures with minimal cooling.
Switching Speed	Moderate, limited by higher losses at high switching frequencies.	Fast, enables higher switching frequencies with lower losses.	Fastest, with very low switching losses even at high frequencies.
Durability and Reliability	Good, well-understood and widely used.	Better, due to high temperature and high-power handling capabilities.	Emerging, with promising potential but less historical data.
Size and Weight	Larger and heavier, due to larger heat sinks and cooling systems.	Smaller and lighter, as less cooling is required due to higher efficiency.	Smallest and lightest, benefiting from high efficiency and thermal performance.
Application Suitability	Widely used in current EVs for its reliability and lower cost.	Preferred in high-performance EVs where efficiency and high temperature performance are critical.	Emerging as a choice for next-generation EVs, offering superior efficiency and thermal management.

Silicon (Si)-based controllers have long been favored for power electronics in EVs due to their cost-effectiveness and commendable efficiency and dependability. Although these devices find extensive application, they encounter constraints when it comes to high power and high frequency usage because of difficulties in thermal management. Silicon Carbide (SiC)-based controllers exhibit enhanced thermal performance and efficiency in comparison to silicon-based controllers, rendering them well-suited for applications involving high temperatures and performance. Despite the increased expense, their capability to function at higher frequencies while experiencing reduced losses enables the development of power electronics that are more compact, lightweight, and efficient. [11] Gallium Nitride (GaN)-based controllers epitomize the highest level of power electronics technology, showcasing unmatched thermal performance and efficiency. They enable the operation of systems that are compact and lightweight by supporting highly fast switching rates. Although presently more costly, their implementation in EVs is anticipated to increase as the technology advances and costs decline. [12]

1.1.3 Electric Propulsion Motor

The EM used in EVs consists of a variety of technologies designed to suit specific needs related to efficiency, cost, maintenance, and performance. Each type of motor has distinct advantages that impact the decision-making process, considering elements such as upfront expenses, effectiveness, upkeep needs, and vehicle performance standards. Ongoing development and optimization of EMs are crucial for advancing performance, efficiency, and sustainability in the automobile sector as the EV market progresses. The advantages and disadvantages of the most widely used EMs for EV are presented in Table 3.

Table 3. Main types of EMs used in electrical vehicles. [13][14][15][16]

Feature	BLDC	PMSM	AC Induction Motor	SRM
Principle	Operates with electronic control to rotate the motor without brushes.	Utilizes permanent magnets on the rotor.	Operates on electromagnetic induction without permanent magnets.	Operates by magnetic reluctance, without permanent magnets or brushes.
Efficiency	High efficiency, especially at high speeds.	Very high across a wide range of speeds.	Generally high, slightly lower than PMSM at certain speeds.	High, particularly in specific speed ranges with controlled operation.
Maintenance	Low, as there are no brushes for wear and tear.	Low, due to the absence of brushes.	Low, due to the lack of permanent magnets and simple construction.	Low, as it lacks brushes and commutators.
Torque & Speed	High torque over a wide range of speeds.	High torque across a broad range of speeds.	High torque at low speeds, decreases at high speeds.	High torque at low speeds, with specific torque-speed characteristics.
Thermal Management	Efficient, due to absence of brushes and precision electronic control.	Efficient, with careful management needed.	Less efficient due to rotor design.	Moderate, with design challenges in heat dissipation.
Durability	High, as electronic controls and absence of brushes reduce wear.	Sensitive to high temperatures.	High, robust design suitable for harsh conditions.	High, due to the robust and simple design.
Application Suitability	Preferred for applications needing precise speed and torque control.	Ideal for passenger vehicles and applications demanding high efficiency.	Suitable for heavy-duty and industrial applications.	Favored in applications where cost and simplicity are prioritized, with specific performance requirements.

DC series motors are ideal for applications with frequent starts and stops because to their high starting torque, but they require regular maintenance due to brush wear. [13] Brushless DC Motors (BLDC) are known for their great efficiency and precise control at various speeds. They require minimum maintenance because they do not have brushes, making them well-suited for precise EV applications. [14] Permanent Magnet Synchronous Motors (PMSM) are highly efficient and high-performing motors that utilize permanent magnets. They are commonly used in passenger automobiles due to their outstanding features. [15] Three-phase AC Induction Motors (IM) provide a well-rounded solution, offering strong performance and longevity at a reduced price, making them ideal for a range of EV applications, particularly where simplicity and cost-efficiency are important. Switched Reluctance Motors (SRM) are known for being simple and solid, providing a cost-efficient choice for situations where performance is needed, with the advantage of requiring minimal maintenance. [16]

1.1.4 Mechanical Transmission

As EV technology advances, there is potential for a variety of transmission systems to be developed to meet the specific performance and efficiency needs of various EV models. Comparison is shown in Table 4.

Table 4. Types of transmission. [17][18][19]

Feature	Single-Speed Transmission	Multi-Speed Transmission	CVT
Complexity	Lowest, simplest design with fewer moving parts.	Higher, more complex design with multiple gears.	Moderate, complex design but no actual gears.
Efficiency	High, minimal mechanical losses due to simplicity.	Variable, can be optimized for specific speeds.	High, but can vary due to pulley system losses.
Performance	Good, optimized for a balance of acceleration and top speed.	Better, allows for optimization across a wider range of speeds.	Good, allows for seamless acceleration without gear shifts.
Cost	Lower, due to simplicity and fewer components.	Higher, due to more components and complexity.	Moderate to high, depending on the CVT design.
Maintenance	Lowest, fewer parts mean less wear and maintenance.	Higher, more parts and complexity mean more potential for wear.	Moderate, less than multi-speed but more complex than single speed.
Driver Experience	Smooth, no gear shifts.	Engaging, allows for manual control over gears.	Smooth, continuous acceleration without noticeable gear changes.
Application Suitability	Suitable for most passenger EVs, where simplicity and efficiency are key.	Used in performance or heavy-duty EVs where driving conditions vary widely.	Suitable for EVs where smooth driving and efficiency are prioritized over outright performance.

EVs mainly use single-speed transmissions since the EM can function effectively at various speeds. The system's simplicity ensures dependability, decreases weight, and lowers costs while delivering smooth, linear acceleration. [17] Manufacturers are exploring multi-speed transmissions and continuously variable transmissions (CVT) for certain uses. Multi-speed transmissions, while not as prevalent in EVs, can provide advantages for high-performance EVs by enhancing power distribution at high speeds and increasing efficiency across different driving scenarios. [18] CVTs offer the potential for endless gear ratios, allowing the EM to function at its most efficient level, which could increase the vehicle's range and improve performance. [19] The single-speed Transmission is the favored option for most EVs because of its ability to balance efficiency, simplicity, and performance requirements.

1.2 Integrating DT Technology with EV Propulsion System Components

Advanced techniques enable a seamless blend of real and virtual environments, fostering an innovative approach to engineering that transcends traditional methodologies.

Applying DT technology into EV represents a significant advancement in optimizing and developing electric propulsion systems. This advanced simulation tool creates a connection between the physical and digital realms, enabling a thorough and dynamic investigation of EV components such battery packs, EMs, power electronics controllers, and transmission systems. Engineers and designers can use DT technology to analyze and improve the performance, efficiency, and reliability of components in ways that were previously considered impossible in traditional development procedures.

DTs are being applied to the battery pack at the forefront of the technological revolution. [13] Developing a digital model of the battery pack allows for a comprehensive simulation of its performance under various conditions and usage situations. Virtual modeling is crucial for analyzing the complex dynamics of battery chemistry, design, and management systems. [14] Utilizing this capability can drive progress in energy density, operational efficiency, and the overall longevity of the battery. This raises the battery's performance and improves the vehicle's range and durability. [15] DT's predictive powers are transforming the development of maintenance strategies. DT technology enables preventive maintenance and timely replacement plans by accurately predicting battery degradation and probable failures. Anticipating potential issues not only extends the battery's lifespan but also enhances vehicle dependability and safety, reducing the chances of unforeseen battery malfunctions.

The PEC, which regulates the electrical energy flow between the battery and the motor, also gains advantages from using DT technology. DTs enable the smooth integration of the PEC with the battery and EM, ensuring an efficient flow and conversion of electrical energy. Precise coordination is crucial for optimizing the vehicle's performance and range by achieving a harmonious balance between power output and energy efficiency. DTs help improve the durability and efficiency of power management systems by simulating thermal behavior and stress factors on power electronics. This not only decreases the likelihood of overheating but also greatly prolongs the lifespan of these essential components.

The EM benefits significantly from DT technology. Virtual replication of the EM enables a detailed investigation of its thermal management, efficiency, and performance under numerous operating circumstances. [16] Exploring various materials, winding arrangements, and cooling methods digitally offers new opportunities to enhance motor design. The aim is to reach exceptional levels of performance and efficiency to improve the motor’s response to different driving patterns and maximize energy usage. Adjusting control algorithms based on dynamic response analysis enhances the motor’s acceleration, torque delivery, and energy efficiency.

DT technology provides a distinct advantage in maximizing transmission efficiency for EVs equipped with multi-speed transmissions or CVTs. DTs improve transmission efficiency by studying and optimizing gear ratios and shifting algorithms, leading to increased vehicle acceleration and performance. Moreover, the ability to replicate the mechanical loads of the gearbox during operation helps estimate wear and tear of single-speed transmission. Having this predictive information allows for the use of preventative maintenance procedures, which helps save expensive repairs and downtime, preserving the longevity and reliability of the transmission system.

The use of DT technology holds significant promise. However, there is still a gap in practical research. While some studies explore theoretical benefits like predictive maintenance, few delve into actual implementation in EVs. Key areas lacking detailed investigation include how DTs can optimize battery systems, enhance component reliability, and improve overall vehicle efficiency. More research in these areas could help fully realize the potential of DTs in advancing EV technology.

1.3 Hypotheses

DT technology is being integrated into EV propulsion systems to change their development, optimization, and maintenance in the fast-changing EV industry. This integration is crucial for dealing with the existing obstacles in simulating and monitoring EV components in real-time, such as data accuracy, operational efficiency, and system flexibility. This chapter suggests a series of hypotheses to use DT technology to overcome obstacles and improve the effectiveness and reliability of EV propulsion systems.

- Specialized scaled demonstrators are projected to improve data collecting for EV propulsion systems due to the limitations of current data acquisition methods. This method is anticipated to improve the accuracy and comprehensiveness of the data, enhancing the reliability of DTs and their predictive abilities, and therefore supporting more efficient and effective propulsion system advancement.
- Utilizing DTs for Component-Specific Analysis. Because of the intricate nature of EV propulsion systems and the necessity for a comprehensive comprehension of individual component behavior, recommend creating DTs for specific components to gain deep understanding into their operational dynamics in different scenarios. This method is expected to greatly enhance the operational efficiency of the components, thus leading to the optimization of the entire propulsion system.
- Integrating real-time data acquisition into the development and testing framework will expand the scope of component simulation due to the dynamic nature of EV operations and evolving driving conditions. The connection will improve simulation accuracy and enable the addition of new features, enhancing the versatility and performance of EV propulsion systems.
- Based on the need of early fault detection for the reliability and upkeep of EV propulsion systems, we propose that utilizing DT technology can facilitate the immediate forecasting and identification of possible defects. This method is anticipated to greatly save downtime and maintenance expenses while improving vehicle safety and dependability.

1.4 Objectives of the Thesis

This thesis intends to investigate the latest advancements in EV propulsion system development using DT technology. This aims to connect theoretical modelling with practical application to enhance the efficiency, dependability, and performance of EVs through an extensive and systematic methodology. The following aims are intended to direct the thesis toward achieving its goals:

- The main goal is to create a scaled demonstrators that has the key components of an EV propulsion drive system. This scaled demonstrator will be a crucial tool for simulating EV performance, allowing for the analysis of component interactions and system dynamics in different operational conditions. Creating a scaled demonstrators is crucial for simulating real-world conditions and gaining significant insights into optimizing the performance of EV propulsion systems.
- Researching and building DTs for individual components inside the EV propulsion system. This involves thoroughly examining the details of each part, comprehending how it functions and performs in various situations, and generating precise digital duplicates. The DTs will enable accurate analysis and optimization, leading to progress in component design and system integration.
- Exploring the possibility of using real-time data collecting in the construction of DTs. This will investigate the integration of real-time data, such as operational and environmental variables, into DTs to improve their accuracy and usefulness. Emphasis will be placed on the visualization aspects to ensure that the DTs accurately reproduce the functional features of their physical counterparts and offer a complete visual representation.
- Create and execute a DT service designed to provide detailed information on the maintenance needs of EV propulsion drive components. This service will provide proactive maintenance methods and defect detection by utilizing the predictive capabilities of DT. The objective is to improve the dependability and durability of EV propulsion systems, minimizing downtime and maintenance expenses while enhancing the overall performance of the vehicle.

1.5 Scientific Contributions

1.5.1 Scientific Novelty

- Development of a theoretical framework for the physical representation of DT.
- Creating a DT of an EM, utilizing an empirical model to simulate its performance. It investigates the data essential for the DTs development. Additionally, a comprehensive structural analysis of the virtual model, crafted within the Unity3D engine.
- Development of a robust physical model that effectively includes the performance characteristics of autonomous electric car transmissions. The examination and improvement of the performance of contemporary autonomous EVs can be facilitated by the utilization of the produced DT.

1.5.2 Practical Novelty

- The creation of a scaled-down demonstrator for evaluating the electric propulsion drive system.
- The proposed framework and tools include a middle-layer ROS interface that integrates with both the physical propulsion drive system and its DT. This interface enables visualization in different simulation engines.
- Developed a diagnostic service unit for the EM in propulsion drive systems, utilizing ROS communication for fault detection.

2 Scaled Demonstrators Development

The EV propulsion drivetrain is a complex structure that requires precise mathematical modelling, monitoring, and validation. The complexity of the system is due to its combination of many electrical and mechanical components. These components are unique in their functionality and must operate and interact seamlessly with one another. Complete EV powertrain modelling is crucial for optimizing motor control across various driving scenarios and ensuring effective interaction among all powertrain components. Torque vectoring is a system that distributes power from the EM to the wheels to avoid bends in all possible situations. These issues require the ongoing development of suitable measurement technology. A comprehensive test bench of the EV powertrain is the most suitable representation of the physical model, which is a crucial aspect of the DT.

The ISEAUTO, a self-driving vehicle from Estonia [17], was created through collaboration between Tallinn University of Technology (TalTech) and various industrial partners. The ISEAUTO project has many objectives and achievements. The ISEAUTO project began in June 2017, following an agreement between TalTech and Silberauto AS Estonia to collaborate on the development of a self-driving vehicle. The company aimed to engage in self-driving technology to anticipate the future of the automobile industry and gain expertise in production. The project was simultaneously utilized for scientific research.

2.1 DT Concept and Requirements

The DT is typically viewed as a digital model that engages with the physical object during its entire lifespan, offering insights for assessment, enhancement, forecasting, and other functions. [18]. Figure 1 shows the interaction of the DT components. All components are interdependent from each other. The physical entity provides the basis for the virtual entity development; the virtual entity is responsible for the simulations, control of the physical part, and optimization strategies for the service system. The service system represents an integrated service platform responding to the demands of both physical and virtual entities. DT data is the combined data from physical, virtual, and service entities; methods for modelling, optimizing, and predicting. Data acts as a driver for all entities and involved in the creation of the DT itself, more comprehensive and consistent data is formed.

Figure 2 depicts each dimension of the DT for the propulsion motor drive of the self-driving shuttle. A real physical entity comprises multiple subsystems and sensory devices. The self-driving shuttle includes the following subsystems: electric propulsion drive system, control system, safety system, and auxiliary systems (door controller, lights, etc.). The sensors collect the present state of the subsystems. There are two primary types of sensors utilized in self-driving vehicles: dead reckoning sensors (encoders, inertial sensors, GPS, etc.) and sensors for vehicle perception (cameras, radars, lidars, ultrasonic, etc.). The primary use of the sensors is to achieve autonomy. Additionally, they can be utilized to change control algorithms for propulsion electrical drives and assist in selecting cruising mode. The test bench, which merges the benefits of real-time software models and actual equipment, helps decrease the amount of test iterations and ensures safe maintenance. The virtual entity comprises the geometric model, physical model, behaviour model, and rule model. The components of the self-driving shuttle in the geometric model, such as the EM, gearbox, and transmission, are created as computer-aided geometric models for assembly in the virtual engine. Datasets consist of diverse collections of data. IoT sensors and platforms can be used to collect, sort, convert, and send large amounts of data from physical entities. The data includes information on working and environmental circumstances, as well as operating statuses. Virtual entity data comprises the parameters of models and simulation data. The services entity provides information about algorithms used for data collection, processing, and utilization. Furthermore, service entity data delineates the interaction algorithms among entities.

The service entity includes rules for both virtual and physical entities and may consist of several sub-services, such as maintenance and diagnostic, energy optimization, path planning, etc.

The connection entity describes the link between other entities.

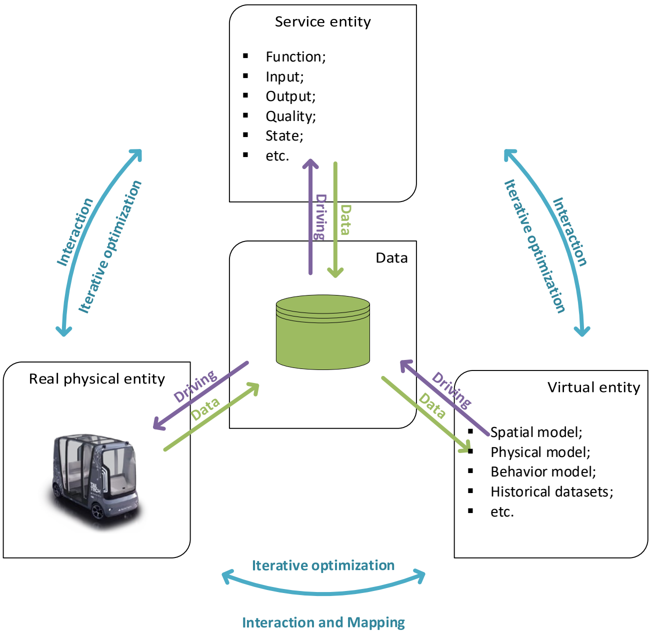

Figure 1. Five-dimensional DT model. [19]

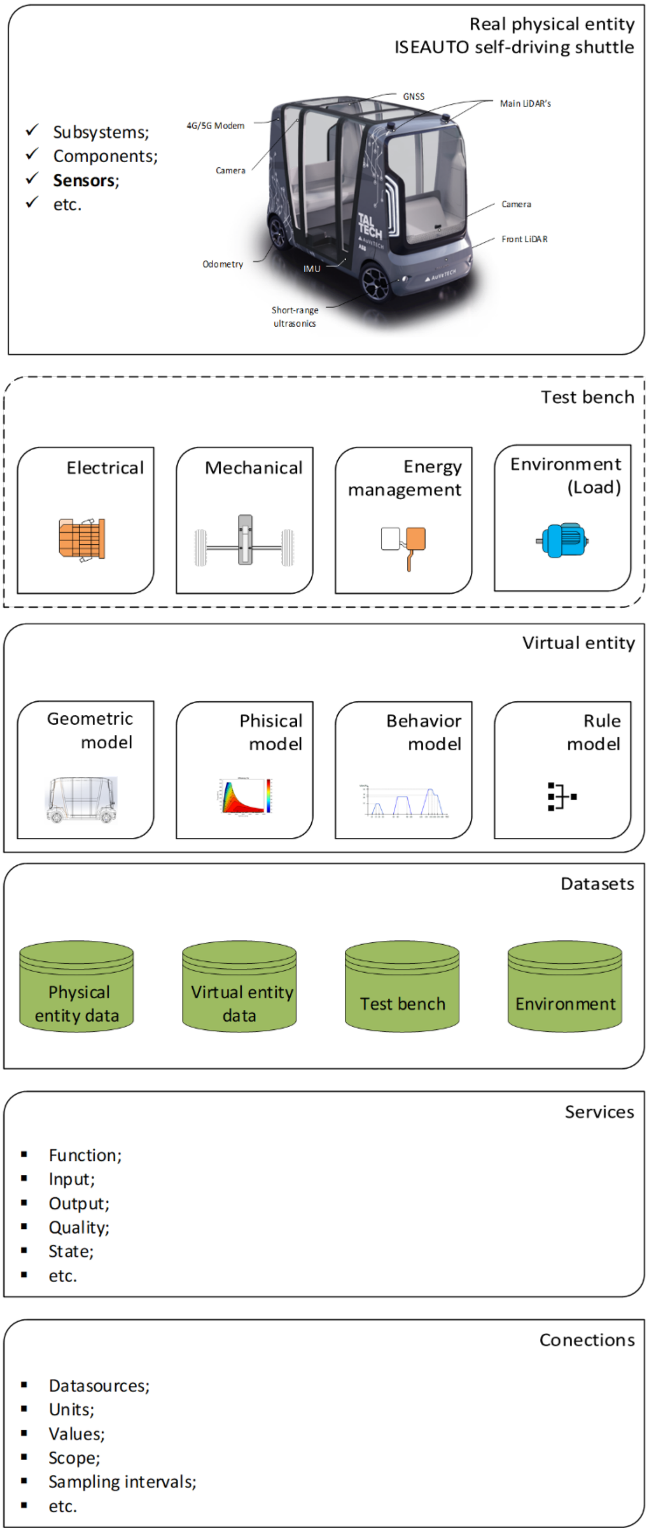

Figure 2. DT components for the ISEAUTO self-driving shuttle. [19]

2.2 ISEAUTO Powertrain Scaled Demonstrators and Components

The propulsion drive system of ISEAUTO was developed using the Mitsubishi i-MiEV trolley as a basis, including the Y4F1 PMSM. [20] ISEAUTO is a last-mile vehicle with limited speed that utilizes the transmission to operate within the most efficient range of the propulsion motor. The transmission in the self-driving vehicle F1E1A (without shifting function) consists of two pairs of gears meshing together and a dependable differential, resulting in an overall reduction ratio of 6.066.

2.2.1 Battery Emulator

The CINERGIA B2C+ battery emulator unit comes with a regenerative AC to DC converter to imitate the behaviour of actual batteries. The unit's DC output can be varied from 20 to 750 V. By serializing or parallelizing outputs, it is possible to change power and current. The system is operated by a PC that is connected to sophisticated software. The device can send and receive data through the interface module using CAN bus, Modbus, or Ethernet Open protocol.

2.2.2 Traction Drive

The traction drive system utilizes a 55 kW heavy-duty water-cooled electric drive manufactured by ABB (model HES880). The system is operated by PC software and can exchange data using CAN bus or Ethernet. It can be utilized in both inverter and generating modes. It is designed using the direct torque control (DTC) technique. When operating in inverter mode, the drive regulates both the torque and speed of the motor. The generator mode is utilized to regulate the DC-link voltage during regenerative braking. The open-loop control algorithm decreases the need on external encoders, leading to lower maintenance and risk expenses.

2.2.3 Electric Motor

The electric traction motor utilized in ISEAUTO is a 25 kW Mitsubishi Y4F1 water-cooled PMSM. The device is fitted with a resolver unit on its internal shaft to monitor speed and position. Table 5 outlines the motor parameters.

Table 5. Specifications of motor for i-MiEV. [Paper III]

Type	Water-cooled permanent magnet type synchronous motor
Max. output	47 kW (3000 - 6000 RPM)
Rated output	25 kW
Max. torque	180 Nm (0 - 2000 RPM)
Battery voltage	330 V

2.2.4 Transmission

F1E1A is a four-gear double-stage transmission unit. The first gear is the pinion gear on the input shaft, coupled to the rotor of the vehicle's traction motor. The second and third pinion gears share a same shaft. The fourth gear is linked to both the output shaft and the differential unit. Table 6 displays the parameters of the gears.

Table 6. Transmission gears. [Paper III]

Gear	Diameter, mm	Width, mm	Teeth number
1st	58,9	27	25
2nd	93,9	251	42
3rd	56,1	32,2	18
4th	179	27,6	65

2.2.5 Loading Motors

Two 7.5 kW IMs are installed on either side of the differential unit to mimic the movement of the vehicle wheels. Two ABB frequency converters power the motors.

2.2.6 Data Acquisition System

A Dewesoft data gathering device was set up on the scaled demonstrator to gather essential data from its components. The measurement device must meet the following criteria:

- Take measurements of the direct current voltage and current of CINERGIA.
- Measure the PMSM three-phase power, resolver speed, and winding temperature.
- Measure the loading speed of motors 1 and 2.
- Measure the torque data from the analog output of the inverters of the loading motors and HES880.

Figure 3 displays the full list of necessary channels. At least 3 high voltage channels and 3 low voltage channels were needed for current transducers to evaluate the electrical properties of the main propulsion motor. 5 low voltage channels were required to measure the resolver speed, winding temperature, and analog output from the inverters. 2 counter channels were crucial for the encoders. The SIRIUSi-HS-4xHV-4xLV and DEWE-43-A devices were used to record the required parameters. Dewesoft's product line provides the benefit of utilizing their software for data analysis and recording. The devices can measure at a wide range of sample rates and export data in multiple file formats.

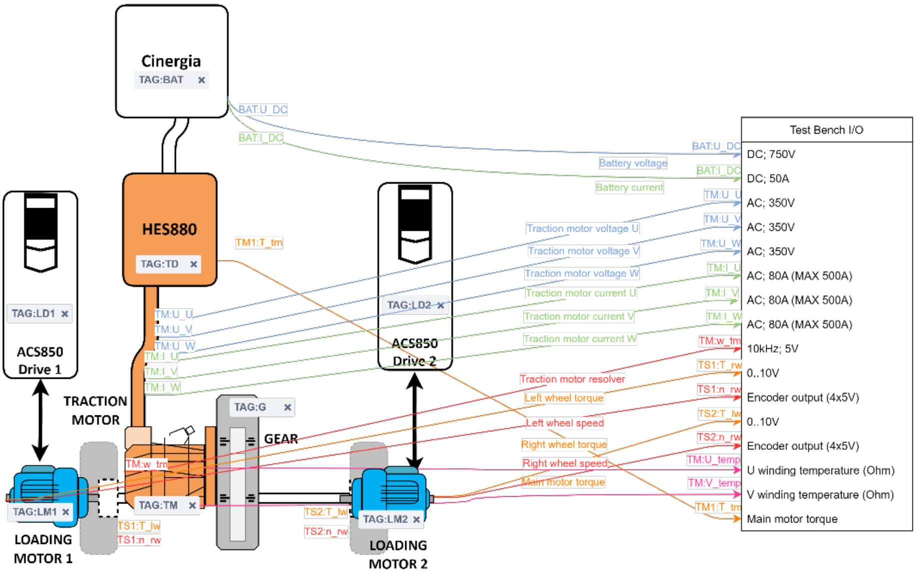

Figure 3. Scaled demonstrator I/O.

2.3 Scaled Demonstrator Development

A Computer-aided design (CAD) model was produced for each component based on the actual dimensions of the object. For accuracy, complex geometric models such as a motor and gearbox were scanned using a 3D scanner. Areas where a 3D scanner's laser line cannot capture 3D geometry will be identified as "Through-holes" and removed during the model post-processing. Figure 4 displays the chronology of creating a digital model of a motor and a gearbox.

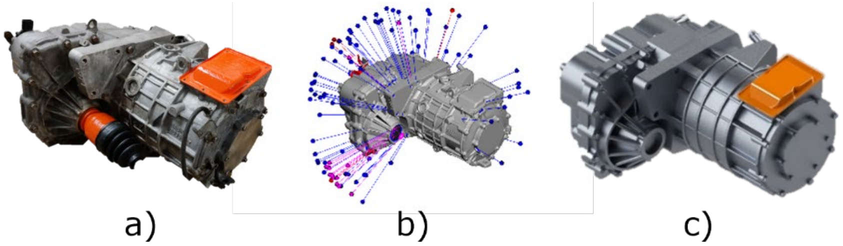

Figure 4. A chronology depicting the process of creating a digital model: a) an actual motor with a gearbox, b) a scanned model with imperfections, and c) the refined final form of the digital model produced by SolidWorks.

The electric car's whole electric propulsion system was designed in SolidWorks following the same method illustrated in Figure 4. An extra frame was designed in SolidWorks for the laboratory scaled demonstrator. The primary functions of the frame were to support the entire electric drive system and allow for the addition of loading motors on both sides of the transmission to replicate the real operating conditions of an electric car, as depicted in Figure 5. Figure 6 displays the assembled ISEAUTO powertrain scaled demonstrator.

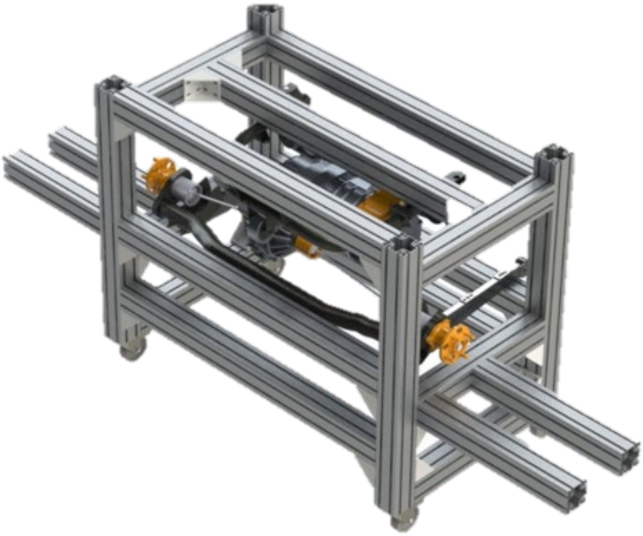

Figure 5. Rendered image of a scaled demonstrator frame setup.

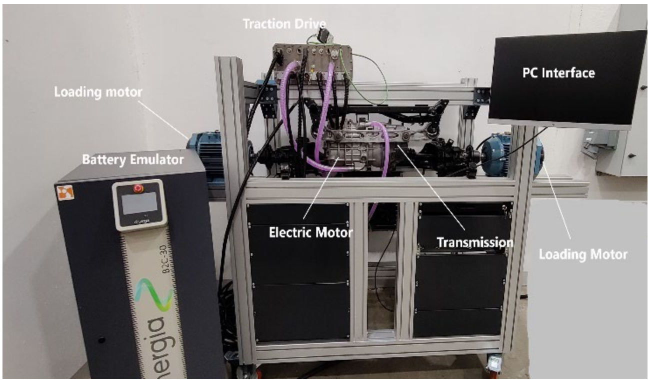

Figure 6. ISEAUTO powertrain scaled demonstrator.

More information on the testbench concept and construction can be found in [Paper I] and [Paper II].

2.4 Performance Tests and Results

2.4.1 Tests Procedures

The test bench plays a significant role in validating results with a physical object, specifically ISEAUTO in this instance. Data collection is required to validate the parameters of the test bench under the operational conditions of a self-driving bus. These tests are crucial for reducing errors during test bench operation and replicating real ISEAUTO circumstances accurately for propulsion drive operation simulations. The experiments were carried out on the premises of TalTech University. Three primary routes were utilized for testing:

- Driving on a flat surface. The test area was selected to be 100 meters in distance and have a minimal slope suitable for the bus. Six tests were conducted at this distance along the same path.
- Driving over an inclined surface. A test site was selected with a 50-meter distance and the steepest slope possible to assess the EM's load capacity for the bus. Three tests were conducted at this distance along the same path.
- Driving regularly in a TalTech smart city between passenger stops. The site features a smart city area designed for testing self-driving buses, including intelligent bus stops, smart pedestrian crosswalks, smart traffic lights, automatic bollards, self-driving autonomous vehicle shuttles, and remote-control stations. Two tests were conducted following the same circular path as shown in Figure 7.

Figure 7. TalTech campus smart city round trajectory. [Paper III]

Below are the primary measurement parts, sensors, and parameters:

- Battery pack of the ISEAUTO – for DC voltage device was connected directly to the battery and for DC current were using a current clamp.
- The propulsion system of the ISEAUTO includes a three-phase voltage supply to a permanent magnet synchronous motor which connected directly with the device and a three-phase current supply to the same motor using a current clamps.
- GPS module provides data about speed, altitude, and distance.

The measurements aim to understand the electrical properties of the ISEAUTO and then verify the test bench using this data. Figure 8 displays an example of the received data.

Due to the country's restrictions limiting the speed of self-propelled vehicles to 20 km/h, ISEAUTO does not utilize the full capacity of the EM, resulting in the voltage remaining significantly lower during operation. The ISEAUTO inverter was found to load the phases asymmetrically at the starting moment, with one phase having an amplitude value that is half of the other two phases. Once the initial phase is over, the currents return to being symmetrical. Altitude data obtained from GPS is seen in Figure 8. Altitude data can be used to determine the motor load during actual ISEAUTO operation. GPS data was acquired, although it was rather noisy. The GPS signal was unstable because of tall structures. Future efforts will focus on enhancing signal reception and integrating the Inertial measurement unit (IMU) sensor into the existing measuring setup alongside the GPS.

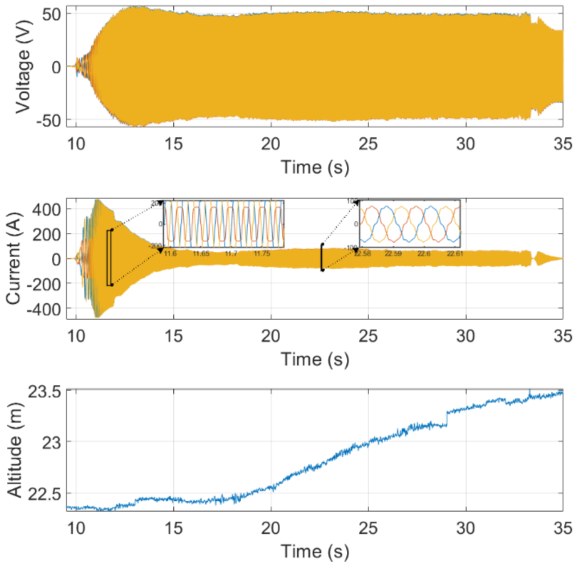

Figure 8. Measurement of an ISEAUTO motor voltage, current, and altitude while driving no slope. [21]

2.5 Chapter Summary

This research study detailed the steps for developing a complete PC-controlled test bench for an autonomous EV propulsion drive system. A detailed description of the primary test bench components was provided. Performance tests were conducted on ISEAUTO under various operating conditions: six tests without slop driving mode, three tests with slop driving mode, and two regular driving modes. The performance test data will be utilized for validating the test bench. The initial findings from the scaled demonstrator show promise for the powertrain DT development.

3 Digital Twin of an Electrical Motor

3.1 Empirical Performance Model

A potential application of DT is for control and monitoring. A physical entity often contains many subsystems and sensory equipment, while a virtual entity can be created using existing data. The virtual entity consists of one or more models depending on the DT application, such as behaviour, thermal, rule, or other models. The DT data consist of multiple datasets obtained from the actual physical object, gathered through numerous sensors and data collecting devices. The service entity primarily includes regulations for virtual and physical entities and may offer other sub-services, such as maintenance and diagnostics, energy optimization, and path planning. The connection entity often specifies the interaction among other entities. Unity3D is utilized in the study for conducting physics simulations and visualizing the DT. The paper reveals a component of a project focused on creating a specialized unsupervised prognosis and control platform to estimate the performance of electric propulsion drive systems in an autonomous self-driving electric car. This goal involves creating various subtasks and objectives, one of which is to create physical models of different energy system components such as motors, gearboxes, and power converters, along with their corresponding simplified models (testbeds) to build the system's DT. [22]

An Induction motor was utilized in this example as one of the potential configurations to develop a model based on an efficiency map. A study was conducted on an ABB 3GAA132214-ADE induction motor to develop a practical empirical performance model. The electrical motor under examination is powered by an industrial frequency converter, specifically the ABB ACS880, utilizing the DTC algorithm. An extra frequency converter (ABB ACS800) was utilized as a load during the setup. An efficiency map is generated by gradually increasing the load torque from zero to the rated load torque determined during the design phase in a stepwise manner. An efficiency map was obtained from research comparing the efficiency of induction and synchronous reluctance motors [23]. Motor efficiency is calculated as the ratio of the motor shaft power ($P_{\text{mech\_motor}}$) to the total electrical input power ($P_{\text{in\_total}}$).

$$\eta_{\text{motor}} = P_{mech\_motor}/P_{in\_total} \tag{1}$$

In [Paper IV] the graphical depiction of an empirical performance model of IM, while Table 7 provides the rated data of the motor.

Table 7. Rated Data of Induction Motor. [Paper IV]

Parameter	**Unit**	**Value**
Motor frame size		132 MA
Rated Power	kW	10.5
Rated Current	A	22
Rated Speed	rpm	1460
cosφ		0.6
Moment of inertia	kgm^2	0.048

The empirical performance model describes the loss distribution of IMs on speed-torque characteristics. Copper losses are the primary power losses in all EMs. The torque of an IM is directly proportional to both the electrical loading and the magnetic loading. [23] To boost the torque generated by the motor, both electrical and magnetic loads need to be amplified. To improve motor torque in high magnetic flux density, the only effective method is to increase the electrical loading due to the saturation of the stator iron core. Increasing the current density in motor windings can lead to higher copper losses and decreased efficiency. A numerical representation of an empirical performance model for an IM is utilized as an input for constructing a DT to assess the IM across a specified speed-torque range.

3.2 DT based on Empirical Model

The setup for the DT of the IM is as follows: The Unity 3D physics engine simulates basic physics in connection with the Robot Operation System (ROS) bridge. Linux ROS nodes simulate more complex electrical machine behaviours, such as motor efficiency based on the efficiency map and motor controller. As seen in Figure 9. Unity 3D’s main advantage is its appealing framework for handling 3D objects and simulating virtual physical forces. The advantages of Unity3D were a key factor in selecting it over the more frequently utilized MATLAB or Matplotlib in research, or at the current project level.

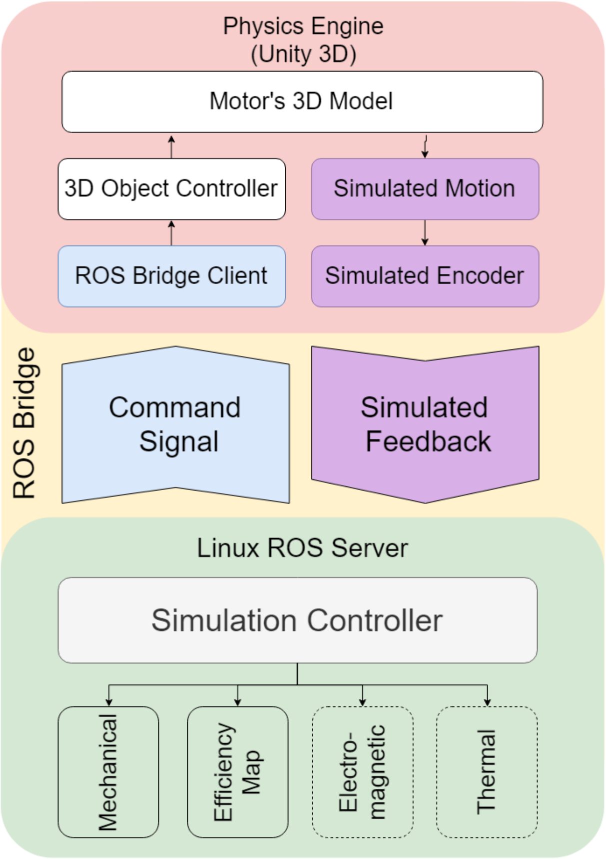

Figure 9. The operational architecture of DT. [Paper IV]

The Linux ROS Server transmits a User Datagram Protocol (UDP) command packet to the Unity 3D Visualizer over the ROS Bridge standard. The primary function is to receive a control message from a defined IP address in a standardized ROS Bridge message format published by the Linux ROS Server. It controls the 3D models to demonstrate the motor's behaviour as it would occur. It is responsible for providing feedback to the Linux ROS Server for processing, similar to how an encoder sends updates on the motor rotation rate to a motor controller.

The Linux ROS Server consists of multiple nodes that replicate different facets (such as mechanical, thermal, electrical, diagnostic, etc.) of the motor. It includes a single motor controller simulator node and a simulation controller node that integrates data from all other aspect simulation nodes and Unity 3D feedback, processes it, and transmits the information to a visualization client in Unity 3D.

The detailed physics engine of the DT is depicted in [Paper IV]. The Unity 3D Visualizer message is received as a UDP packet in a proprietary ROS Bridge format by the ROS Bridge Client. It is then deserialized into input variables (empirically estimated velocity and torque) for the motor and forwarded to the 3D object controller as variables. The object controller transforms data from the empirical performance model into the velocity of the motor shaft in the DT model. This data is utilized for the motor's 3D visualization. A virtual sensor, known as a simulated encoder, measures the motor shaft's angular velocity, translates it to feedback data, and transmits it to the Linux ROS Server.

There are currently two active nodes in the simulation: a motor controller simulator node and a mechanical simulation node. The motor controller features a proportional–integral–derivative (PID) controller that supplies a control signal to the motor. The mechanical simulation node utilizes an efficiency map obtained from an actual motor to simulate accurate torques and power output at specific angular velocities, ensuring that the DT behaves like the real motor.

3.3 Graphical representation

Utilizing a virtual visual model can help avoid numerous mistakes and errors without incurring any negative impact on performance or costs. Additionally, this model can serve as a great tool for training technical personnel and in academic institutions. In a physical model, the various parts of an actual object (such as windings, rotor, shaft, encoder, etc.) are created as CAD geometric models and then put together to form the virtual object. Figure 10 displays the graphical model utilized for DT visualization.

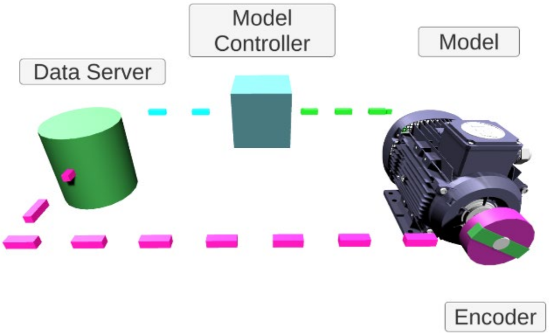

Figure 10. Graphical representation of induction motor in Unity 3D. [Paper IV]

The Physics engine has a ROS Bridge client that receives a data package from the ROS Server. The ROS Bridge client extracts data from the package and transmits it to the 3D object controller, which then recalculates new positions and orientations for the simulated motor components. The 3D model is then updated with new states. This stage verifies that a 3D model accurately simulates the behaviour of a genuine motor visually. The model considers additional physical forces acting on the motor, such as friction losses and moment of inertia, which are simulated using the angular drag feature in Unity 3D's Rigidbody. The simulation updates encoder values, which are then transmitted to the ROS Server to provide feedback for the speed controller. The simulated encoder is interchangeable and can be used with any required feedback simulation. A PID controller is currently utilized for its simplicity and user-friendly nature.

3.4 Chapter Summary

[Paper IV] describes the development process of DT for an EM using an empirical performance model. The study examines the facts necessary for developing the DT. An in-depth structural analysis of the virtual entity created using the Unity3D engine is provided. The current DT is mostly used as a loading motor drive system on a test bench to evaluate the performance of the electric propulsion drive system in an autonomous electric car. Developing and implementing the concept of DT will offer a new method for measuring and estimating the performance of motor-drive systems.

4 DT of An EV Transmission

The mechanical component of the electrical drive system is responsible for a significant share of the total issues, which are degenerative and tend to worsen over time. [24] Regularly maintaining mechanical components, inspecting device operations, ensuring adequate lubrication, and operating devices that are rarely used are essential practices for any electrical drive system. [25] The DT solution encompasses several services, including enhancing efficiency, reducing failure rates, accelerating development cycles, and creating new business prospects. [26] DT, being a virtual entity, needs to accurately replicate operations happening in a physical entity through digital means. In reality, various physical processes have influence on an object at the same time, making it unfeasible to see the electrical drive system purely as an electrical device. [27] It is important to take into account other phenomena, such as heat effects or mechanical vibrations. This ideal may need to be evaluated. DT should represent impacts across several physical realms such as electrical, mechanical, and thermal. The current study aims to provide a customized unsupervised prognosis and control platform for the propulsion drive of an autonomous EV. This platform may be utilized for performance estimation, control system tuning, maintenance, diagnostics, and various other services. The study aims to outline the development process of a parametric design table for an autonomous electric car gearbox.

The transmission in the self-driving vehicle F1E1A is a straightforward meshing of two pairs of gears with a dependable differential, resulting in an overall reduction ratio of 6.066.

4.1 3D Scanning of Transmission

The initial stage of transmission parametrization involved creating a geometric model with the 3D scanner ATOS II 400. This inspection device utilizes structured light technology and has a measuring frequency of 1.4 million points every 7 seconds. The resolution is 0.177 millimetres. To digitize larger objects, markers should be employed. These markers are placed on the object being scanned to combine different scanning images during post-processing. [28] This scanning method offers excellent precision in a short time frame and is safe for the eyes. Drawbacks include sensitivity of system setup to ambient light, inability to 3D scan glossy surfaces, and insufficient precision for intricate pieces with diverse surface characteristics like ribs and sharp edges. The ATOS 3D scanner was utilized for digitizing transmission due to its excellent precision in huge item examination. The autonomous electric car transmission depicted in [Paper V] is considered a geometric component of the DT.

F1E1A is a dual-stage transmission with four speeds, depicted in [Paper V]. The initial gear is the pinion gear on the input shaft, linked to the rotor of the vehicle's traction motor. The second and third pinion gears share a same shaft. The fourth gear is linked to both the output shaft and the vehicle's differential. Table 6 displays the specifications of the gears, with all shafts having a uniform diameter of 22 mm.

The transmission's gear ratio (n) can be determined using the following equation:

$$n = \frac{n_4}{n_3} \cdot \frac{n_2}{n_1}, \tag{2}$$

where n (1...4) is the number of teeth of gears 1 through 4, respectively. The gear ratio has an impact on maximum speed, wheel radius, and traction between the road and tires. A slower motor speed compared to the vehicle speed results in a reduced gear ratio, smaller dimensions, and less expenses. [29] The powertrain features an extra regenerative brake mode for increased deceleration by boosting regenerative brake effort, as well as a comfort mode for suburban driving by reducing regenerative brake intensity.

4.2 The Efficiency of the Transmission

Power losses in transmission occur in gears, bearings, and seals. Additionally, supplementary losses should be taken into account. Gear and bearing losses are categorized as load and no-load dependant losses, while transmission losses (Δp_{meh}) are classified in [Paper V]. It is important to note that for nominal power transmission, the load losses of the gear are typically dominant, and in the case of part load and high speed, no-load losses dominate the total losses. [30][31][32]

$$\Delta p_{meh} = \Delta p_{G0} + \Delta p_{GL} + \Delta p_{B0} + \Delta p_{BL} + \Delta p_{s} + \Delta p_{aux} \tag{3}$$

No-load gear losses are not affected by the amount of torque applied to the gear. The no-load losses can be attributed to the lubrication losses caused by the viscosity and density of the lubricant, internal design of the transmission, and bearings, which become apparent as the mechanism rotates. No-load gear losses are dependent on the configuration, dimensions, category, viscosity of lubricant, and level of submersion.

Load-dependent gear losses happen at the contact point of the power-transmitting components. Load dependent gear losses are determined by the friction force ($F_{R(X)}$) and relative velocity $V_{rel\ (X)}$, following the fundamental Coulomb law:

$$\Delta p_{GL} = F_{R(X)} \cdot V_{rel\ (X)} \tag{4}$$

Load-dependent gear losses are often stated as a function of the gear loss factor:

$$\Delta p_{GL} = P_{IN} \cdot H_{V} \cdot \mu_{mZ}\ , \tag{5}$$

P_{IN} is the transmission input power; H_V is the gear loss factor and μ_{mZ} is the coefficient of friction. Gear loss factor (H_V) is a fixed value determined by the base helix angle, load distribution, path of contact, and other gear characteristics. C. Fernandes et al. present three equations and propose a calculating method that excludes the elastic effects of the gears in their investigation. The forecast of power loss is influenced by the calculation of the gear loss factor, which depends on the gear's geometry. The average coefficient of friction (μ_{mZ}) between gear teeth for various gear geometries is a complex factor derived from empirical data, and it naturally varies under the same operating conditions. No-load bearing losses are primarily influenced by the type and size of the bearing (such as cylindrical roller bearings having the lowest losses), bearing configuration, lubricant viscosity, and supply. Load dependent bearing losses are influenced by factors such as the size, type, rolling and sliding conditions, and type of lubricant used.

Shaft sealing losses result from the friction between the shaft and its seal. Shaft sealing losses (Δp_s) are determined by the shaft diameter (D) and rotational speed (n). According to C. Changenet et al., these losses can be estimated using the following formula [33]:

$$\Delta p_s = 7{,}69 \cdot 10^{-6} \cdot D^2 \cdot n \tag{6}$$

Auxiliary losses refer to losses that are difficult to quantify, such as lubricant losses. Transmission relies on lubrication to prevent friction and deformations in the gear teeth connection. Losses occur when the lubricant splashes over the pinion, causing a drag torque. Lubricant losses are influenced by the pinion's rotational speed, the surface area of contact between the pinion and the lubricant, the pitch diameter of the pinion, and the density of the lubricant. C. Changenet et al. provide an equation to calculate the drag torque operating on a pinion as an extra load.

Various computational tools are utilized to calculate power losses and create an efficiency map of the mechanical transmission. The WTplus software, created at TU Munich, is utilized for determining the efficiency and heat dissipation of manual, automatic, and industrial gearboxes. KISSsoft is another software that includes a specialized template in KISSsys to automate the efficiency calculation and thermal rating of an entire gearbox, encompassing gears, shafts, bearings, seals, discs, synchronizers, and other machine components. A 3D model of the F1E1A gearbox was created by measuring all its gears, as shown in [Paper V]. by utilizing the KISSsoft software to import a 3D model for the purpose of calculating the efficiency of a gearbox. An efficiency map of a gearbox was generated by analyzing materials, bearings, grease, and other factors, as depicted in [Paper V]. The electric drive's capabilities are limited to 180 Nm of torque and 2000 rpm of speed.

4.3 DT of a Transmission

The DT simulation of the transmission consists of two main components, illustrated in Figure 11. A primary simulator, functioning as a ROS Node, receives torque (τ_{in}) and angular velocity (ω_{in}) inputs using the ROS Bridge protocol. Any ROS-based motor controller with an encoder, including a virtual one, can provide this input. The main simulator computes an anticipated result using the subsequent equations.

$$\tau_{out} = \frac{\tau_{in}}{n}, \tag{7}$$

$$\omega_{out} = \omega_{in} \cdot n, \tag{8}$$

The primary simulator's main duty is to simulate the efficiency of the transmission using formula (1) to compute n. Efficiency of the transmission is determined by interpolating data from an empirically constructed efficiency map at a certain torque and rotational velocity. The torque (τ_{out}), angular velocity (ω_{out}), and efficiency are published as a ROS subject for use by the DT's 3D Visualizer.

Both simulating and visualizing the transmission rely on the framework established for the dynamic testing of the load motor. They function and interact similarly through the ROS Bridge. However, the display of the data transmission does not offer feedback to the simulation because to the absence of a closed-loop speed controller that necessitates feedback. The transmission is not self-propelled. It just transforms the inputs provided by the rest of the system.

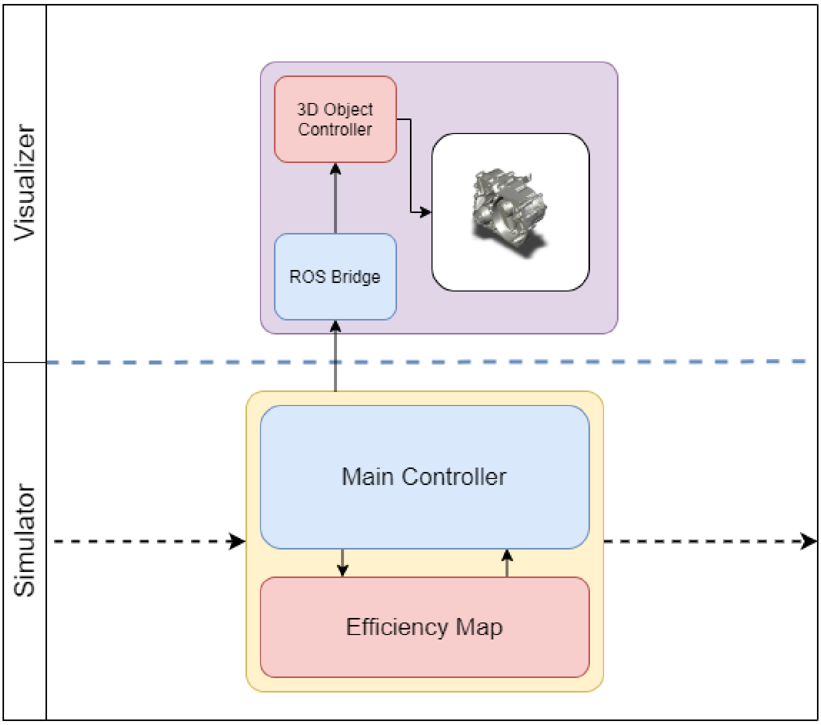

Figure 11. The operational architecture of the transmission DT. [Paper V]

The visualizer is responsible for creating a 3D depiction of the DT's behavior, capturing the transmission in Unity 3D as depicted in Figure 12. The process involves utilizing data from the primary simulator to update the states of each 3D object in the 3D model controller, resulting in the CAD model of the transmission being displayed on the screen realistically under various scenarios.

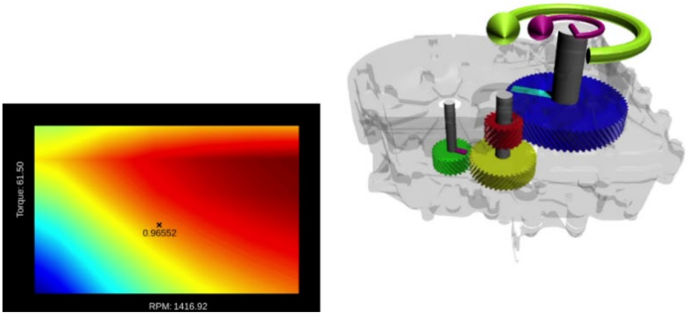

Figure 12. Unity 3D live visualization of transmission. [Paper V]

Figure 13 displays the architecture of the creation process for the DT of the gearbox. A 3D scan of the gearbox is needed to ascertain its mechanical and material properties. The acquired data is utilized to construct a geometrical model of the gearbox, which can subsequently be employed in the simulator. The simulator comprises a middle-layer, specifically ROS, which retrieves data from the cloud server. The 3D visualizer block utilizes a Unity 3D engine to showcase the functionality of the gearbox.

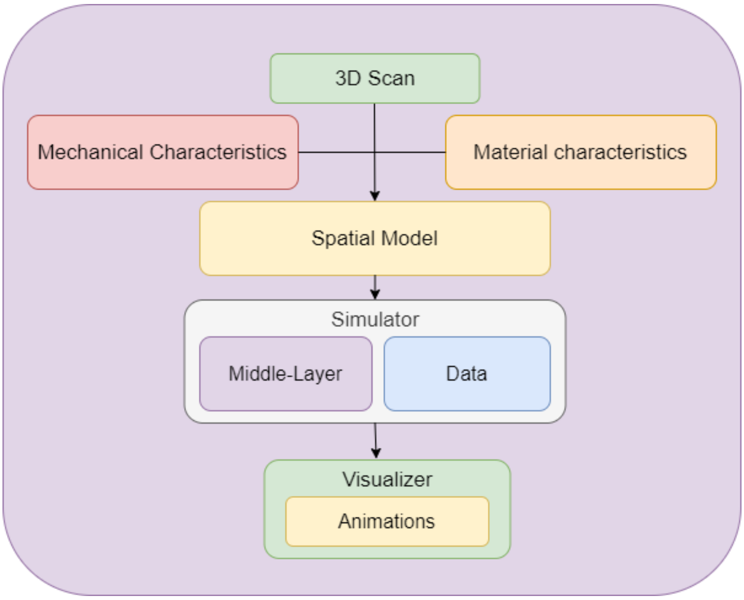

Figure 13. Process architecture. [Paper V]

4.4 Chapter Summary

The transmission parametrization method commences with 3D scanning of the object under study, then proceeds to gear selection and efficiency computation. The Unity 3D real-time development platform's geometrical model is equipped with appropriate inputs and outputs for connecting to the physical model. An efficient physical model that considers the performance of autonomous EV transmission is a valuable tool for developing the design and technology for the mechanical component of the entire propulsion motor-drive system. Virtual Sensors based on the created DT may be introduced. The performance of the existing autonomous EV can be analysed and enhanced using the built DT.

5 Unity3d As an Interface Option for Propulsion Drive Simulations

The primary goal of the study is to create a framework and tools that consist of a middle-layer ROS interface linked to the physical propulsion drive workbench and its DT, which can be displayed in different simulation engines. The project intends to create a system for linking the interface with Unity3D for visualization, focusing on data exchange and feedback.

5.1 Working Principle of a Test Bench on a DT

The DT is applied to simulated data created from genuine data collected from IM for the current case study. The information was collected utilizing the data acquisition system (DAS) Dewetron Dewe 2 and stored in files with various extensions (*.mat, *.xlsx, *.csv, *.txt). The measured data can include information on the motor's operation such as input currents, voltages, consumption and shaft powers, torque, angular velocity during data gathering, and other derived data. The parameters in DAS tuning (16Hz – 100kHz) can be tested at various frequencies, and the data collected is time-dependent. This capability allows for the accurate replication of the motor's behavior exactly as it occurred in a real-life setting with the assistance of the ROS Server. An instance of this may be shown in [Paper VI], where the input current from the frequency converter to the IM was measured and can now be replicated in ROS. The graph from the ROS package *rqt plot* was not included in the paper as it was unable to plot messages at such a high frequency.

The ROS Server functions as both a data server and a physics simulator in the proposed DT system. The server is an independent part of a TB DT system that processes actual motor data, computes additional motor parameters from the data, and sends the information to ROS topics for models to access.

Figure 14 displays the architectural design of the DT setup for TB. The actual data is retrieved by certain ROS Nodes on the server, where it is analysed, converted into ROS messages, and then transmitted to the DT model over the ROS Bridge. The authentic data may derive from the empirical model or map of the motor or its components, or from the actual raw data.

The model can replicate mechanical, electrical, and thermal behavior by processing ROS messages. Models can exist in any simulation setting. They subscribe to ROS Server's topics via API or ROS Bridge and are set up to execute required activities according to the subscribed ROS topic, such as rotating based on received angular speed. Moreover, the module can include simulated 'measurement' devices or sensors that are capable of transmitting data across the ROS bridge. The ROS Nodes can compute and derive additional necessary values, mirroring the behavior of a tangible TB.

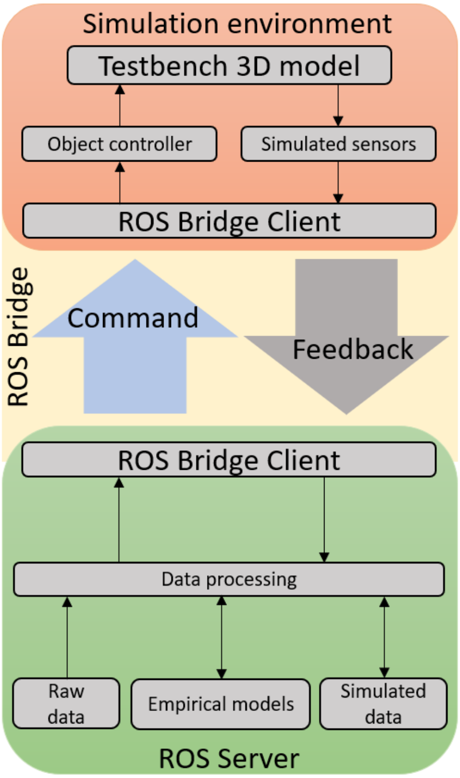

Figure 14. The generic architecture of TB DT. [Paper VI]

5.2 ROS Interfacing

To facilitate the integration of ROS with other systems, a ROS Bridge node must be utilized. The tool transforms ROS messages into JSON format and transmits them beyond the ROS environment. JSON is utilized due to its universal format and the availability of tools that facilitate its serialization and deserialization in nearly all contemporary programming languages. ROS Bridge can facilitate the transfer of certain ROS topics to and from the Message Queuing Telemetry Transport (MQTT) protocol, enabling the system to operate on numerous machines globally. The MQTT Bridge transmits serialized messages from a designated ROS topic to a defined MQTT topic on a remote server. MQTT Bridge can also reverse this process by receiving a JSON-serialized message and trying to convert it back into a defined ROS topic using a specific message type. These solutions work together to simplify the development of connecting ROS with any visualization solution. Classes matching ROS message types were developed in C# for the Unity3D implementation of the ROS interface to streamline the deserialization process. This method is highly efficient since a ROS message sent in serialized form through MQTT may be deserialized immediately into an object of the corresponding type. This method may be applied in a similar manner across most computer languages, making it the most direct and adaptable choice.

The visualization is conducted in Unity3D engine (Figure 15), connected to the physics simulator through the ROS Interface. It represents a 1:1 scale propulsion drive model including the transmission, wheel parts, and non-visible gears. The model is being constructed to mimic the physical one, with each component being managed by an associated script that receives data from the intermediate layer.

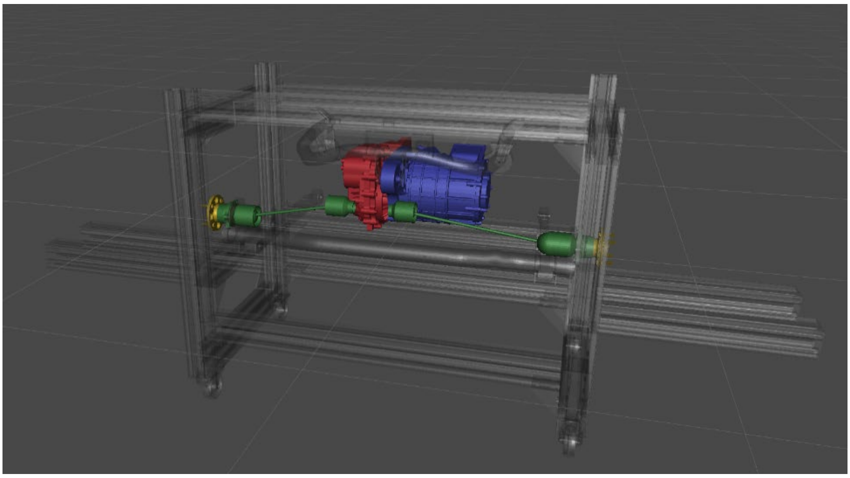

Figure 15. Visualization of propulsion drive test bench done in Unity3D. [Paper VI]

The main result of the specific section of the broader research on creating the completely synchronized DT of the propulsion drive is the development of the ROS interface. It is possible to input physical data into a visual simulation, particularly in the context of using Unity3D. The data simulation provides feedback on physical interactions to the ROS intermediate layer, which refines the model and updates the visual representation in each data movement cycle. Limitations were encountered during the approach creation, and further advancements are necessary to achieve the final goal of the research (Refer to Table 8).

Table 8. Limitations and further steps. [Paper VI]

Limitations	Future steps
The model was tested using a single kind of visual simulation tool. Additional integrations may need to be implemented in the middle layer to be compatible with extra software tool packages.	To determine accurate torque calculations using genuine data obtained from the physical torque TB.
	To implement a two-way connection between physical TB and its DT.
If DT and TB work simultaneously over the internet, the frequency of data acquisition may be too high to send on time, the possibility of lags	The injection process flow of new components of TB into the DT.
	To create unpredicted behaviours in the system, trigger points, and try to make the system respond to the unpredicted change making it more adaptive to changes

5.3 Chapter Summary

[Paper VI] presented the integration of the ROS interface with the DT of the propulsion drive workbench, which was visualized in Unity3D. Raw and simulated data, along with empirical models, are post-processed and inputted into the visual simulation. Additional data is logged and provided as feedback to the middleware to enhance the model and physical simulation. The next important stage involves providing the physical simulation with data straight from the physical drive to achieve synchronization between the actual and virtual worlds via the defined interface.

6 DT Service Unit for Fault Detection

The DT service units that are suitable, dependable, precise, and effective in detecting faults can be a significant asset during the whole lifespan of an electrical motor-drive. A review of the literature reveals that implementing preventative maintenance programs leads to a decrease in the overall number of electrical motor rewinds from 85% to 20% of all motor repairs. [34] The failures observed in rotating electrical machines can be attributed to a confluence of factors stemming from various aspects, including design, manufacturing tolerance, assembly, installation, operating environment, load characteristics, and maintenance timelines. The inter-turn defect of the AC machine stator is regarded as one of the four most common potential failures in electrical motors, alongside air gap eccentricity, broken rotor bar/end-rings, and bearing issues. [35] Typically, the occurrence of an inter-turn short circuit is initiated by the failure of insulation, which is accompanied by a significant increase in current flow. This is attributed to the substantial voltage potential disparities between neighbouring coils.

This work focuses on the detection of inter-turn short circuit faults in the stator (IM) of an induction machine. Nevertheless, the stator architecture of IM is identical to that of other AC machines, and designated DT service units can be employed to identify faults in other types of AC electrical machines.

6.1 Fault Diagnostics and Detection

Unlike preventive and reactive maintenance, predictive maintenance is gaining heightened popularity [7]. The fault detection of electrical machines at the incipient stage for predictive maintenance is essential for a safe and reliable industrial operation. This is also vital for machine life estimation as the faults are degenerative. Any machine under ideal conditions should be perfectly symmetrical for all its phases. But practically, the asymmetry is investable. The main contributors to those asymmetries are the electrical and mechanical faults. Nearly all faults can be divided into two classes: electrical and mechanical. The most common of them are rotor faults [9], such as bad bearings, broken bars, eccentricity, and winding short circuits. These fault's leading causes may include thermal degradation, hazardous industrial environment, bad foundation, and magnetic stress and vibrations. The winding insulation degradation is slow but a continuous process that can lead to a catastrophic situation. This can lead to the faults such as inter-turn short circuit, phase to phase short circuit, or phase to ground short circuit. Moreover, the increased asymmetry among phase impedances can increase the speed and torque ripples, which can cause other mechanical faults. Almost all faults modulate the supply current with a specific bandwidth of frequencies. Being present in the current, they influence the other parameters such as speed, torque, flux, and voltage, etc.

The detection of those frequency components at the early stage of the fault can avoid significant damage. [10] In induction machines, all fault dependent harmonics are the function of slip. This divides the signal under observation into two categories: the transient and the steady state. In a steady-state regime, the signal is stationary, and the standard signal processing techniques can be used for fault detection. Among several signal processing techniques, the discrete-time Fourier transform (DTFT) is being used successfully. This is because it can be used on a piece of equipment with low computation power and can give a good insight into the harmonics. Since the fault-based harmonics are dependent on the slip, DTFT fails to provide any meaningful information under no and low load conditions. Another problem of DTFT is the spectral leakage, which can hide all small-amplitude faulty harmonics. In the transient regime, the signal is non-stationary due to varying slip. Hence the time-frequency analysis becomes essential. It may lead to a specific frequency pattern as, during the transient period, the slip changes its value from one to nominal. The signal analysis in the transient interval reduces the problems related to the load dependency of faulty frequency components. The most common time-frequency techniques include short-time Fourier transform (STFT), wavelet transform (WT), and multiple signal classification (MUSIC), etc.

The electrical motors should have minimal speed and torque ripples. In induction machines, the most prominent causes of those ripples are because of the current harmonics. The primary sources of currents harmonics in induction machines are the supply-based, inherit eccentricity, bad bearings, bad foundation, and the presence of any fault. Moreover, the thermal, skinning, and proximity effect also reduces the symmetry of winding electrical parameters such as resistance. The non-symmetrical three-phase impedances produce negative sequence currents in the motor, increasing the speed and torque ripples. These ripples can become a cause for more mechanical faults due to the increase in vibration. The problem becomes worst with the degrading winding insulation resulting in short circuit failures. Various techniques can be used to detect the short circuit early, such as Park and Clark's vector, extended Park's vector, Park's vector modulus, symmetrical components, pattern recognition-based advanced techniques, etc.

Finding faults in the early stages of the machine work is advantageous when planning and maintaining the machine. Confirmation of a DT fault can be carried out by verifying the mathematical model in which the real physical model's accurate data is continually being sent. A massive amount of data is needed to properly train the mathematical model, so the fault detection's result will be more accurate.

An imbalance occurs in the stator windings with an inter-turn short circuit, where the resistance decreases in the winding with a turn-to-turn short circuit. For experiments with a smooth decrease in the first phase of the winding resistance, an adjustable resistor was used, connected in parallel to the winding's first phase. By adjusting the parallel-connected resistor, the total resistance of the first phase winding changes and, at the same time decreasing current passing by winding by directing some of the phase current to the resistor. Suppose the resistance of the regulated resistor is equal to the winding resistance of the first phase. In that case, the current passing through the first phase will be divided exactly in half, which gives 50% of the fault, or in other words, an inter-turn short circuit between half of the winding. The illustrative figure is shown in [Paper VII].

The stator inter-turn short circuit introduces asymmetry in phase currents and voltages. This asymmetry can be detected either by the Park's vector approach or by detecting negative sequence currents. In case of Park's vector, the circle made by id and iq currents will change its shape with increasing fault which can be depicted in [Paper VII].

6.2 TB for Fault Emulation

The test bench contained two IMs, where one was used as a driving motor and the other as the loading motor. The driving motor was connected directly to the grid to eliminate harmonics that can be carried out by a frequency converter.

There are several advantages to connecting a resistor in parallel. The first is the possibility of testing the motor without harming it and without changing the winding side of the stator.

The second is the ability to measure an error of one percent where the change in current will be minimal, but at the same time, it is essential for the rapid response of the fault detection system. And the third is the ability to adjust the fault percent over a very large interval. This resistance interval depends only on the number of resistors in parallel, where it is possible to achieve any winding resistance. The test bench, on which the experiment was carried out, is shown in [Paper VII].

First, the tests were carried out with an intact and faulty motor where the results could be compared. The points of reference for us were faults of 1%, 2%, and 5%; for each fault point, there were four stages of load: no load, 25%, 50%, and 75%. Lastly, two different scenarios were carried out where the neutral point was connected and disconnected from the motor.

Comparing the graphs of the current of different percentages of failure, then a dependence appears that the greater the percentage of failure, the greater the currents' asymmetry. It is notable that as the failure percent is increasing phase shift of currents are not equal.

Also, the more load on the motor, the less harmonics in the current are visible, and there is less curvature of the current. And lastly, a disconnected neutral point not only increases the current asymmetry but also affects the voltage shape and amplitude.

Data collected during the experiment were transferred to a ROS-based server, where the studied motor's DT is located. The next section describes the structure of the DT service and presents an example of data processing. To test different file formats performance with ROS in the current setup, measurement data from the real induction motor were saved into files with various extensions (*.mat, *.xlsx, *.csv, *.txt). This data is further fetched into the ROS, transformed to ROS messaged, and is advertised on the topics.

6.3 DT Service Unit Description

The developed DT's virtual entity consists of models' set, spatial model, physical model, behavior model, rule model, etc. In the spatial model, the studied electrical motor parts are constructed as a computer-aided geometric model to be assembled in ROS's virtual engine. In the physical model, the performance of separate parts of the physical entity is simulated using numerical computing environments, like MATLAB, FEMM, Agros2D, etc. The behaviour model is the main focus of the current research paper; it is responsible for transfer data from the real physical entity, calculating motor parameters, and stream to the ROS topics available for models. Rule model covering constraints for road load can be simulated through behaviour analysis and data associations that can be observed using virtual sensors.

ROS acts as a physics engine for the current setup of the DT. It simulates the real induction motor's behaviour and features and acts as a publisher of data to be used by virtual models. ROS has a publisher/subscriber architecture, it allows models from different environments to publish or subscribe to the ROS topics and interact with them. The communication between various platforms is handled using ROS bridge – a node that converts ROS messages into JavaScript Object Notation (JSON) or MQTT formatted data. Subscription or publishing to ROS bridge's port allows direct communication with ROS nodes themselves. Due to the JSON standard format, any model in a virtual environment can be programmed to receive or publish messages to ROS topics.

The process of input signal tracking involves comparing measurement data from the motor windings as an input current to the ROS. If the received measurement on any of the windings exceeds the margins determined by the admitted error, a fault notification is generated. The collected data is aggregated and compared over a designated duration required to compute an optimal error, hence enabling the system to effectively detect any potential faults in the motor windings. Once the designated time has passed, the total value and error are updated.

Figure 16 displays the implemented fault detection technique for DT. ROS is linked to the actual motor (in this study, recorded motor data was utilized to replicate the motor's true input). The data obtained from motors is presently undergoing processing, wherein it is transformed into ROS messages and subsequently disseminated within the ROS environment, as demonstrated in [Paper VII].

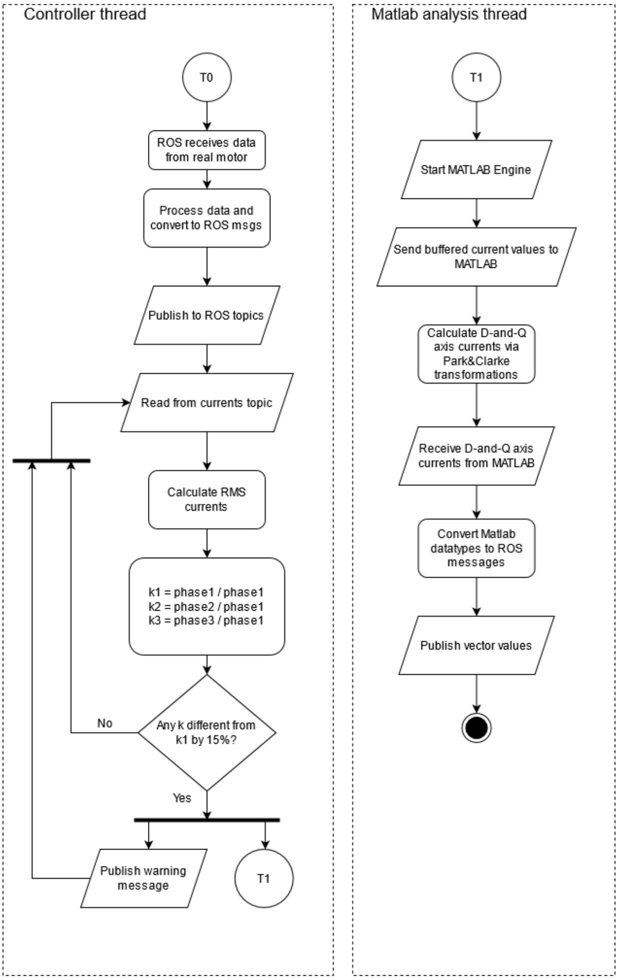

Figure 16. Inter-turn short circuit fault detection algorithm realized for DT. [Paper VII]

The collected data consists of the unprocessed measurements for each phase of the three-phase electric current. Simultaneously, the node that is now listening to the subject begins to receive messages. The received values from these messages are processed in the following manner: The present data are saved within a buffer of predetermined dimensions. Once the buffer reaches its maximum capacity, the root mean square (RMS) value of the three-phase current is computed. Once the RMS values have been calculated, a motor phase is selected as the base phase. In comparison to this stage, we transform currents in other phases into imaginary units. The utilization of these hypothetical units enables the representation of the proportion of load exerted on the motor. Typically, these values should be near one other, specifically within the permissible tolerances (as a result of sounds and flaws). If any of the imaginary units surpasses the predetermined margins, ROS will generate a warning message to inform the model, which will be shown in the interface. ROS invokes a MATLAB function through the MATLAB Engine API to examine the buffer of recorded phase currents, including the record of malfunction, using Park and Clarke vectors. This analysis aims to determine the magnitude of the divergence from the norm and the specific phase experiencing the malfunction. Once the analysis is completed by MATLAB, the resulting Q-and-D axis currents are transformed into ROS messages and subsequently published. In the context of the DT spatial model or real test bench, the published message can serve as an indicator of a potential defect within the system.

6.4 Further Implementation

The current state of technological advancement enables the utilization of smartphones and other portable recording devices for the purpose of condition monitoring. Furthermore, the provision of a service dataset for the purpose of condition monitoring and fault diagnostics in DT can significantly enhance the efficiency of electrical energy conversion systems. DT assets allow system users to see the real-time behavior of a plant system and use practical knowledge acquired. The application of DT enables the utilization of hybrid analytical approaches to enhance computational modelling and simulation of complex problems that occur in various multidisciplinary applications. The main principles of the DT have a direct and significant relevance to identifying faults in energy conversion systems, particularly in electric drives. Nevertheless, it is important to acknowledge the risks that are associated with the complexity and utility of potential DT services. For certain applications, DT may be too complex, costly, or technologically demanding.

The comparative analysis may rely on several signal processing methodologies, dependent upon the kind and magnitude of the problem. One potential method for detecting stator inter-turn short circuit failures is through the utilization of negative sequence currents using Park’s vector. Figure 17 illustrates the upward trajectory of negative sequence currents, accompanied with fault severity levels that can reach up to 5%. The negative sequence currents do not exhibit absolute zero at 0% fault due to the inherent impossibility of achieving symmetry in a practical machine, even when operating under optimal conditions. The observed asymmetry can be attributed to various factors, including the asymmetrical supply voltage, small variations in winding characteristics, and inherent eccentricity, among others. Figure 18 illustrates the transformation of Park’s vector locus from a circular shape in the healthy case to an oval shape in the erroneous instance. It is important to note that all of these measurements were conducted under conditions of no load. The previously mentioned phenomena become further clarified when subjected to loaded situations.

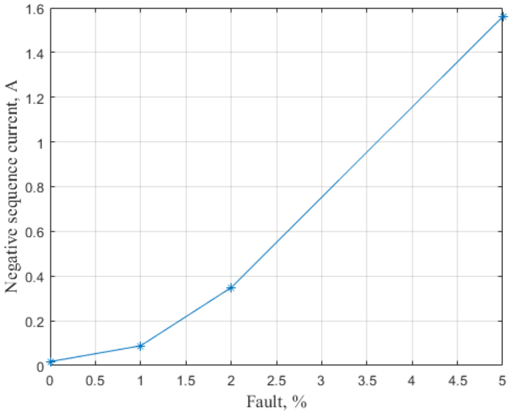

Figure 17. The increase in negative sequence currents as a function of fault severity. [Paper VII]

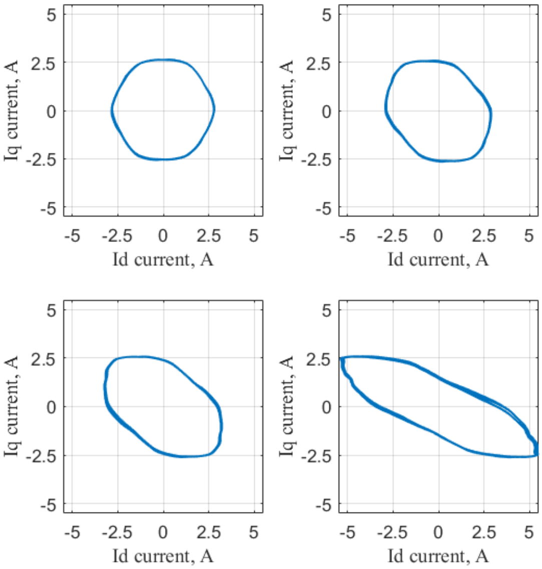

Figure 18. The Park's vector shape deformation from circular to elliptical. [Paper VII]

6.5 Chapter Summary

As a modern trend in the industry, DT is used for many different applications to connect real physical entities with a corresponding virtual entity established by generating real-time data using sensors. The DT of any device or system is a "living model" that represents real physical entity operation throughout its life cycle. In this research work, a methodology for developing a DT service unit for AC motor stator inter-turn short circuit fault detection is presented. DT is based on real-time measurements send data to ROS-based representation of the motor to simulate its specific behaviour in case of unbalanced stator currents and notify about possible fault appearance and propagation. The ROS-based DT is extended with an external MATLAB analysis block that provides a more precise analysis of Park vectors' fault. The link for video representation that demonstrates the operation of the DT is presented in the Appendix, as well as the source code.

AC machine stator fault as inter-turn is considered one of the most prevalent possible electrical motor failures. However, the presented methodology of DT development allows adding additional services that consider another filature', and as a result, improve physical entity reliability.

7 Conclusion and Future Work

The primary aim of this study was to investigate the possibilities of DT technology in augmenting comprehension and management of electric propulsion drive systems in EV. This work aimed to utilize scaled demonstrations to capture real-time data, which was subsequently included into a model for improved control and predictive maintenance. This methodology not only enhanced the understanding of the propulsion system of an EV but also created opportunities for enhancing its reliability and efficiency.

The research yielded significant insights on the constituents of EVs by means of a series of individual case studies, thereby emphasizing the crucial areas for data measurement and gathering. The presented case studies provided a pragmatic framework for determining the fundamental factors that impact the performance and efficiency of EVs. The study made a substantial contribution to the field of EV diagnostics and maintenance plans by accurately identifying the specific locations and methods for measuring these characteristics.

The research made a significant accomplishment by creating a real-time communication system utilizing the ROS and ROS2. This technological advancement allowed the development of a comprehensive communication protocol customized to meet the unique requirements of the project. The successful integration of DT technology in EV achieved an important stage by enabling smooth data transfer and communication between the DT and the TB.

Nevertheless, the study also revealed specific constraints, specifically pertaining to the magnitude of data and the speed of data transfer. The insufficiency of the data exchange rate provided by ROS2 to enable the advanced functionalities required became apparent as the complexity of DT models increased. The previously mentioned constraint has underscored the necessity of investigating alternate communication technologies that possess the capability to manage larger datasets and ensure accelerated data transfer rates. The solution of this challenge holds significant importance for helping the progress and flexibility of DT applications within the realm of EVs.

This study showcases the utility and advantages of utilizing DTs to track and control EV propulsion systems in real-time. It sets an example for the development of advanced and efficient vehicle management strategies. The findings obtained from this study are anticipated to make a valuable contribution towards the advancement of EVs that are characterized by improved reliability, efficiency, and user-friendliness.

Furthermore, the constraints highlighted in this work offer prospects for future investigation. It is crucial to investigate novel communication technologies that can accommodate larger amounts of data and enable faster transfer speeds to progress DT technology. Furthermore, it is recommended that future studies prioritize the optimization of data collecting and processing techniques to improve the precision and efficacy of predictive maintenance programs.

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Abstract

Development Methodology for creating the Digital Twin for Propulsion Drive of an Electric Vehicle

The automotive industry is currently undergoing a significant shift, emphasizing environmentally friendly transportation options and leveraging technological advancements. The focus on electric vehicles (EVs) stems primarily from the need to lower greenhouse gas emissions and reduce the overall carbon footprint. Unlike internal combustion engine (ICE) vehicles that contribute significantly to carbon emissions and air pollution, EVs represent a cleaner alternative, especially effective in reducing emissions when used with renewable energy sources. The performance and efficiency of EVs depend heavily on their electric motor (EM) propulsion systems, a crucial component of their design.

Introducing DT technology into EV development represents a significant leap in optimizing and advancing electric propulsion systems. This technology creates a link between the physical and digital worlds, enabling detailed and dynamic evaluations of EV components like battery packs, EMs, power electronics controllers, and transmission systems. This study aims to examine the latest developments in EV propulsion systems using DT technology, connecting theoretical models with practical applications to improve the efficiency, reliability, and performance of EVs through a thorough and systematic approach.

A scaled demonstrator consisting of key components of an EV propulsion system was developed to simulate its performance and analyze the interactions of its components and system dynamics under various conditions.

Concurrently, DTs for each component within the system were researched and constructed. This provided a understanding of how each component functions and performs in different situations, allowing for the creation of accurate digital replicas. Such DTs enabled precise analysis and optimization, leading to improvements in component design and system integration.

Furthermore, the incorporation of real-time data collection into DTs was explored to assess how operational and environmental data could enhance their accuracy and practicality. Special attention was given to the visualization processes to ensure that DTs provided a true-to-life representation of the physical components' functionalities.

Additionally, a DT service that delivers comprehensive insights into the maintenance requirements of EV propulsion components was developed and implemented. Leveraging the predictive capabilities of DTs, this service offered proactive maintenance strategies and fault detection, which were aimed at boosting the reliability and longevity of EV propulsion systems, reducing downtime and maintenance costs, and ultimately improving overall vehicle performance.

Based on the findings, further research is needed to explore advanced communication technologies that can handle larger data volumes and facilitate faster transfer speeds to advance DT technology. Additionally, it is advisable for future studies to focus on refining data collection and processing methods to enhance the accuracy and effectiveness of predictive maintenance programs.

Lühikokkuvõte

Elektrisõiduki veoajami digitaalse kaksiku arendusmetoodika

Autotööstus läbib praegu olulist muutust, rõhutades keskkonnasõbralikke transpordivõimalusi ja kasutades ära tehnoloogilisi edusamme. Elektrisõidukitele keskendumine tuleneb peamiselt vajadusest vähendada kasvuhoonegaaside heitkoguseid ja vähendada üldist süsinikujalajälge. Erinevalt sisepõlemismootoriga sõidukitest, mis annavad olulise panuse süsinikdioksiidi heitkogustesse ja õhusaastele, pakuvad elektrisõidukid puhtamat alternatiivi, mis on eriti tõhus heitkoguste vähendamisel, kui neid kasutatakse koos taastuvenergia allikatega. Elektrisõidukite jõudlus ja tõhusus sõltuvad suuresti nende elektrimootori jõuülekandesüsteemidest, mis on nende disaini oluline komponent.

Digitaalse kaksiku tehnoloogia tutvustamine elektrisõidukite arendusse teeb olulist arengut elektriliste jõuülekandesüsteemide optimeerimisel ja edasiarendamisel. See tehnoloogia loob sideme füüsilise ja digitaalse maailma vahel, võimaldades üksikasjalikku ja dünaamilist hinnangut elektrisõidukite komponentidele, nagu aku, elektri mootorid, kontrollerid ja ülekandesüsteemid. Uuringu eesmärk on uurida uusi arenguid elektrisõidukite jõuülekandesüsteemides, kasutades digitaalse kaksiku tehnoloogiat, ühendades teoreetilised mudelid praktiliste rakendustega, et parandada elektrisõidukite tõhusust, usaldusväärsust ja jõudlust põhjaliku ja süstemaatilise lähenemisviisi kaudu.

Uuringus simuleeriti ja analüüsiti komponente, kasutades elektrisõiduki jõuülekandesüsteemi võtmekomponentidega skaleeritud demonstraatorit, et hinnata komponentide ja süsteemi dünaamika koostoimeid erinevates tingimustes.

Samal ajal uuriti ja loodi iga süsteemikomponendi jaoks digitaalne kaksik. See võimaldas mõista, kuidas iga komponent erinevates olukordades toimib ja töötab, võimaldades luua täpseid digitaalseid koopiaid. Sellised digitaalsed kaksikud võimaldasid täpset analüüsi ja optimeerimist, mis viis komponentide disaini ja süsteemi integratsiooni täiustamiseni.

Lisaks uuriti reaalajas andmekogumise lisamist digitaal kaksikutesse, et hinnata, kuidas operatiiv- ja keskkonnaandmed võivad nende täpsust ja praktilisust suurendada. Eritähelepanu pöörati visualiseerimisprotsessidele, et tagada digitaalse kaksiku usaldusväärne esitus füüsiliste komponentide funktsionaalsusest.

Lisaks arendati ja rakendati digitaal kaksiku teenust, mis pakub põhjalikku ülevaadet EV jõuülekandesüsteemi komponentide hooldusnõuetest. Digitaal kaksikute ennustusvõimeid ära kasutades pakkus see teenus proaktiivseid hooldusstrateegiaid ja vea tuvastamist, mis olid suunatud elektrisõidukite jõuülekandesüsteemide usaldusväärsuse ja eluea suurendamisele, vähendades seisuaega ja hoolduskulusid ning parandades lõppkokkuvõttes kogu sõiduki jõudlust.

Leidude põhjal on vajalik täiendav uurimine, et uurida täiustatud suhtlustehnoloogiaid, mis suudaksid käidelda suuremaid andmemahte ja võimaldada kiiremaid andmeedastuskiirusi digitaal kaksiku tehnoloogia arendamiseks. Lisaks on soovitatav, et tulevased uuringud keskenduksid andmekogumise ja -töötluse meetodite täiustamisele, et suurendada ennustava hooldusprogrammi täpsust ja tõhusust.

Appendix 1

Publication I

V. Rjabtšikov, A. Rassõlkin, K. Kudelina, A. Kallaste, and T. Vaimann, “Review of Electric Vehicle Testing Procedures for Digital Twin Development: A Comprehensive Analysis,” Energies, vol. 16, no. 19. Multidisciplinary Digital Publishing Institute (MDPI), Oct. 01, 2023. doi: 10.3390/en16196952.

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Review

Review of Electric Vehicle Testing Procedures for Digital Twin Development: A Comprehensive Analysis

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Abstract: This article explores the transformative potential of digital twin (DT) technology in the automotive sector, focusing on its applications in enhancing propulsion drive systems. DT technology, a virtual representation of physical objects, has gained momentum due to its real-time monitoring and analysis capabilities. Within the automotive industry, where propulsion systems dictate vehicle performance, DTs offer a game-changing approach. Propulsion drive systems encompass electric motors, transmissions, and related components, significantly impacting efficiency and power delivery. Traditional design and testing methods need help addressing these systems' intricate interactions. This article aims to investigate how DTs can revolutionize propulsion systems. The study examines various applications of DTs, ranging from predictive maintenance to performance optimization and energy efficiency enhancement. The article underscores the technology's potential by reviewing case studies and real-world implementations. It also outlines challenges tied to integration and validation. In unveiling the capabilities of DT technology for propulsion systems, this article contributes to a comprehensive understanding of its role in shaping a more data-driven and efficient automotive industry.

Keywords: digital twin; propulsion drive system; automotive; vehicle propulsion; powertrain; virtual modeling; simulation; performance optimization; real-time monitoring; vehicle modeling

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1. Introduction

The automotive industry has undergone a transformative shift in recent years driven by technological advancements. One of the most promising innovations to emerge is the concept of DT technology [1]. A DT is a virtual representation of a physical object, system, or process created and maintained in real time [2]. It enables a bidirectional flow of information between the physical entity and its digital counterpart, allowing for continuous monitoring, analysis, and optimization. The application of DT technology can potentially revolutionize various sectors, including the automotive industry [3].

The concept of DTs draws inspiration from aerospace, manufacturing, and simulation, where they have already demonstrated remarkable benefits [4]. DTs have gained traction in the automotive sector due to their ability to address complex challenges associated with vehicle design [5], production [6], operation [7], and maintenance [8]. Manufacturers can gain insights into real-time performance, anticipate issues, and make informed decisions by creating a digital replica of an entire vehicle or its components.

At the heart of every electric vehicle's performance lies its propulsion drive system, which encompasses the electric motor, transmission, and related components [9]. Propulsion systems determine a vehicle's efficiency, power delivery, and overall driving experience [10]. The battery powers a control unit that oversees the electric motor. At the same time, the transmission facilitates the transfer of this power to the wheels, allowing the vehicle to accelerate, decelerate, and maintain different speeds.

Optimizing propulsion drive systems is essential for achieving various performance objectives, including efficiency and enhanced drivability. However, the complexity of these systems, with numerous interconnected components and intricate interactions, presents significant challenges for manufacturers and engineers [11]. Traditional design, testing, and analysis approaches may need to address these challenges comprehensively.

This research aims to delve into the applications of DT technology for enhancing propulsion drive systems within the automotive sector. The objective is to explore how DT technology can address the challenges and complexities associated with propulsion systems, ultimately leading to improved vehicle performance, efficiency, and reliability. Specifically, in this study, an exploration is conducted into the diverse applications of DT technology within propulsion drive systems, encompassing its potential for predictive maintenance, performance optimization, and energy efficiency augmentation. The investigation encompasses a comprehensive overview of case studies and instances wherein DTs have notably propelled advancements in propulsion systems. Furthermore, this research delves into the recognition of prospective hurdles and constraints that may arise during the practical integration of DT technology into real-world scenarios for propulsion drive systems.

By shedding light on the capabilities and potential of DT technology in the context of propulsion systems, this research aims to contribute to a deeper understanding of how the automotive industry can leverage this innovative approach to drive performance improvements, streamline development processes, and embrace a more data-driven and efficient future.

The manuscript is organized as follows. In the subsequent sections of this article, we will delve into the fundamental principles of DT technology and its historical evolution and explore the various facets of propulsion drive systems and the complexities they entail. By systematically examining relevant literature and case studies, we will illuminate how DTs are already making a difference in enhancing propulsion systems' design, operation, and maintenance.

2. DT Technology: Fundamentals and Evolution

A DT represents a virtual counterpart of a physical object, system, or process. It is a dynamic and interactive digital model replicating real-world entities' behavior, characteristics, and interactions [12]. Not only does this technology enable a bidirectional flow of information, exchanging data between the physical entity and its digital counterpart in real time, but also new ideas might be introduced. A DT goes beyond mere simulation; it continuously captures and updates data from the physical world, providing insights into its performance, status, and behavior [13]. The DT evolves alongside its physical counterpart, reflecting changes and responding to inputs like a real-world object.

As presented in Figure 1, the core components of a DT include the following [14]:

1. The DT represents the physical object, system, or process. In the automotive context, this could be a vehicle, its propulsion drive system, or specific components like the engine and transmission.
2. The virtual model is the digital representation of the physical entity. It includes geometry, attributes, behavior, and interactions. The accuracy and fidelity of the virtual model are critical for achieving meaningful insights.
3. DTs rely on data collected from sensors embedded within the physical entity. These sensors monitor temperature, pressure, vibration, and performance metrics.
4. The DT and the physical entity are connected through data networks, enabling real-time data exchange and communication.
5. Advanced analytics, machine learning algorithms, and simulations process sensor data and model interactions within the virtual counterpart.
6. Visualization tools visually represent the DT's behavior, making complex data understandable to users.

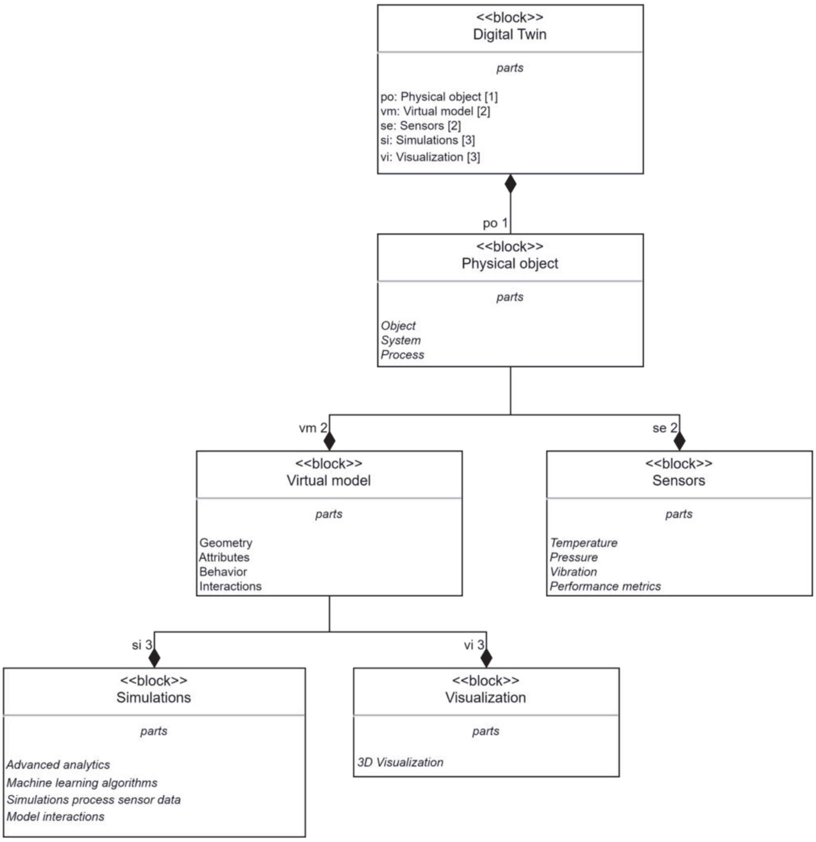

Figure 1. Core components of the DT.

The concept of DTs has its roots in aerospace and manufacturing. NASA pioneered DTs for spacecraft design and operation while manufacturing industries used them to optimize production processes [15]. Recent computing power, data analytics, and connectivity advances have propelled DT technology into new domains.

For instance, the authors in [16] present the design methodology, mathematical analysis, simulation study, and experimental validation of a DT approach for fault diagnosis distributed photovoltaic systems. In [17], the authors introduce a technique where the online diagnostic analysis of power electronic converters utilizing real-time, probabilistic DT technology is proposed. The authors in [18] offer an approach based on the Internet of Things and the DT of the cyber-physical system that interacts with the control system to ensure its proper operation. In [19], the authors propose a novel methodology for predicting the remaining useful life of an offshore wind turbine power converter in a DT framework as a strategy for predictive maintenance. The authors in [20] present a new architecture and its associated supporting implementation technologies in the DT framework and its application of online analysis of power grids. In [21], the authors introduce a DT of distribution power transformers for real-time monitoring of medium voltage from low voltage measurements.

Nonetheless, the DT has attracted particular attention in the automotive industry [22,23], which is shown in Figure 2.

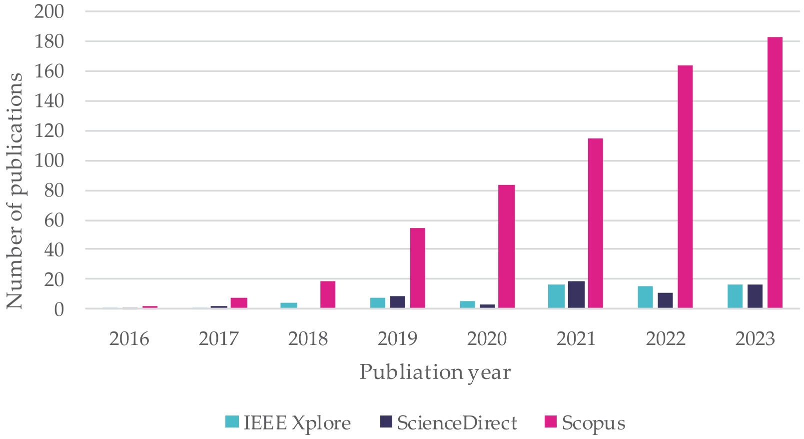

Figure 2. Search results for publications related to DT in automotive applications during the period 2011–2023 in IEEE Xplore, Scopus, and ScienceDirect.

DTs are becoming increasingly relevant in the automotive sector due to their potential to address challenges at various stages of a vehicle's lifecycle. In the design phase, virtual prototyping and testing via DTs enable engineers to identify issues before physical prototypes are built [24]. During manufacturing, DTs optimize production processes, predict equipment failures, and reduce downtime [25]. In the operational phase, DTs provide real-time insights into a vehicle's performance, enabling predictive maintenance, optimizing fuel efficiency, and enhancing safety [26].

In general, there can be highlighted numerous benefits of the usage of DTs in domestic and industrial applications:

- Predictive maintenance [27];
- Performance optimization [28];
- Efficient design and development [29];
- Data-driven decisions [30,31];
- Improved safety [32].

DTs allow rapid prototyping, testing, and iteration, reducing design time and cost. Real-time insights enable engineers to fine-tune propulsion systems for optimal efficiency and power delivery. DTs can predict and prevent breakdowns by monitoring components' health, reducing maintenance costs and vehicle downtime. Real-time data from DTs empower manufacturers to make informed decisions, from production to operations. Monitoring and analyzing real-time data can enhance vehicle safety, prevent accidents, and aid in designing safer vehicles.

At the same time, there are several practical challenges:

- Computational demands [33];
- Data integration [34];
- Accuracy and fidelity [35];
- Privacy and security [36];
- Validation and calibration [37].

It can be complex to gather and integrate data from various sources and sensors and to integrate them into a coherent DT. The accuracy of the virtual model is crucial; any discrepancies between the DT and the physical entity can lead to misleading insights [38]. Handling sensitive vehicle data raises concerns about privacy and cybersecurity. Running real-time simulations and analytics requires significant computational resources. Ensuring that the DT accurately reflects real-world behavior can be challenging. Table 1 shows the strengths, weaknesses, opportunities, and threats of using DT in the automotive industry.

Table 1. SWOT analysis about using DT technology in the automotive industry.

	Description
Strengths	Efficient Design and Development: DTs allow for rapid prototyping, testing, and iteration, reducing design time and cost. Performance Optimization: Real-time insights from DTs enable engineers to fine-tune propulsion systems for optimal efficiency and power delivery. Predictive Maintenance: DTs can predict and prevent breakdowns by monitoring components' health, reducing maintenance costs and vehicle downtime. Data-Driven Decisions: Real-time data from DTs empower manufacturers to make informed decisions, from production to operations. Improved Safety: Monitoring and analyzing real-time data can enhance vehicle safety, prevent accidents, and aid in designing safer vehicles.
Weaknesses	Data Integration: Gathering and integrating data from various sources and sensors into a coherent DT can be complex. Accuracy and Fidelity: The accuracy of the virtual model is crucial; any discrepancies between the DT and the physical entity can lead to misleading insights. Privacy and Security: Handling sensitive vehicle data raises concerns about privacy and cybersecurity. Computational Demands: Running real-time simulations and analytics within DTs requires significant computational resources. Validation and Calibration: Ensuring that the DT accurately reflects real-world behavior can be challenging.
Opportunities	Broader Industry Application: The concept of DTs originated in aerospace and manufacturing, indicating potential applications beyond the automotive sector. Technological Advancements: Ongoing advances in computing power, data analytics, and connectivity can expand the capabilities of DT technology. Innovation in Fault Diagnosis: Opportunities exist for developing advanced fault diagnosis techniques using DTs, enhancing system reliability and maintenance efficiency.
Threats	Complex Implementation: The complexities of integrating DTs into existing automotive processes and systems could slow down widespread adoption. Lack of Standardization: A lack of standardized approaches and frameworks for DT implementation could lead to compatibility issues and hinder collaboration. Competitive Landscape: As DT adoption grows, competition among automotive companies and technology providers in implementing effective DT strategies could intensify.

Furthermore, Table 2 shows the pros and cons of different DT development methods.

In conclusion, DT technology represents a groundbreaking approach with the potential to revolutionize the automotive industry. By creating a dynamic virtual counterpart of physical entities, DTs offer real-time insights, enabling efficient design, performance optimization, predictive maintenance, and more. While benefits are promising, data integration, accuracy, security, and validation challenges must be addressed for the technology's successful implementation. As the automotive sector continues to evolve, DTs stand poised to play a pivotal role in shaping their future.

Table 2. Subdivision of DT methods.

DT Method	Advantages	Shortcomings
Data-Driven DTs	- Utilizes real-world data for accurate modeling. - Suitable for predictive maintenance applications. - Incorporates machine learning for pattern recognition. - Enables anomaly detection and predictive analytics.	- Highly dependent on data availability and quality. - May struggle to capture complex physical behaviors. - Lack of interpretability in black-box models. - Requires extensive computational resources.
Physics-Based DTs	- Offers a deep understanding of system dynamics. - Suitable for complex simulations and virtual testing. - Provides transparency in modeling physical phenomena. - Supports optimization of system performance.	- Relies on comprehensive and accurate physics models. - Development and validation can be time-consuming. - Complexity can limit real-time capabilities. - May require specialized expertise for modeling.
Hybrid DTs	- Combines the strengths of data-driven and physics-based models. - Offers versatility and adaptability to different scenarios. - Enables accurate modeling using limited data. - Suitable for complex systems with uncertain dynamics.	- Integration can be complex and challenging. - Balancing model components may require effort. - Development and maintenance can be resource-intensive. - Proper validation of hybrid models can be tricky.

3. Propulsion Drive Systems in the Automotive Sector

The automotive sector is undergoing a seismic shift, marked by the rapid advancement of propulsion drive systems [39]. At the heart of every vehicle's performance lies its propulsion system, a complex assemblage of components working harmoniously to convert energy into motion [40]. This article delves into the intricacies of propulsion drive systems, highlighting their features, complexities, interactions, and challenges in optimizing their performance.

Propulsion drive systems encompass the mechanisms that generate and transmit power to propel a vehicle [41]. Traditionally, internal combustion engines (ICE) have been the mainstay of propulsion. However, the surge towards sustainability and energy efficiency has led to the proliferation of electric propulsion systems, particularly electric motors [42].

Figure 3 presents a view of the main components of the electric vehicle propulsion drive system. Electric motors are at the forefront of the electric vehicle revolution, functioning as the primary source of propulsion. These motors convert electrical energy from the battery into mechanical energy, propelling the vehicle [43]. Electric motors boast simplicity, compactness, and instantaneous torque delivery, unlike their ICE counterparts, enhancing driving dynamics and efficiency [44]. Complementing the electric motor or internal combustion engine are transmissions, responsible for transmitting power to the wheels and optimizing performance across various driving conditions. Transmissions enable the vehicle to transition through gears smoothly, adjusting torque and speed for optimal efficiency and power delivery [45].

Within propulsion systems, an array of components, such as power inverters, differentials, and clutch systems (in the case of conventional transmissions), further contribute to the system's functionality. These components ensure torque distribution, manage power flow, and facilitate smooth transitions between different modes of operation. The complexity of propulsion systems arises from the intricate interactions among their components.

Electric propulsion systems, for instance, require sophisticated power electronics to manage the energy flow between the battery and the electric motor [46]. Thermal management systems are critical to prevent overheating, optimize efficiency, and prolong the lifespan of components.

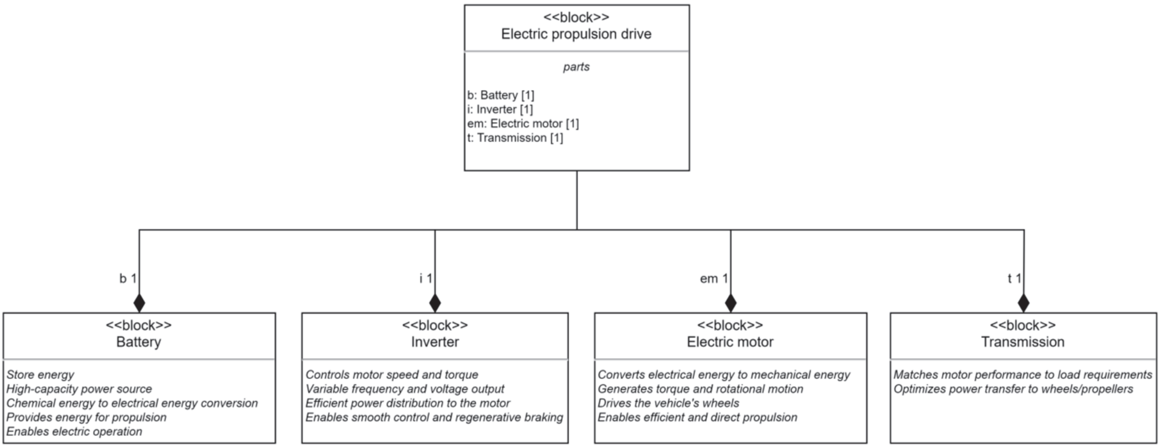

Figure 3. Main components of electric propulsion drive system.

Conventional powertrains' interactions between engines and transmissions are intricate, affecting power distribution, fuel efficiency, and vehicle responsiveness [47]. Achieving seamless transitions between gears necessitates meticulous engineering to avoid power loss and improve overall driving comfort.

Optimizing propulsion drive systems hinges on key performance metrics, each influencing the vehicle's overall efficiency, power delivery, and environmental impact. Some of the critical metrics include:

1. Efficiency [48,49]: The efficiency of propulsion systems determines how effectively they convert energy into motion. Electric propulsion systems, particularly electric motors, often exhibit higher efficiency than traditional internal combustion engines due to fewer energy conversion steps.
2. Power-to-Weight Ratio [50,51]: This metric reflects the power generated by the propulsion system relative to the vehicle's weight. Higher power-to-weight ratios lead to better acceleration and overall performance.
3. Energy Consumption [52]: Energy consumption of propulsion systems directly impacts the vehicle's range and operational costs. Electric propulsion systems tend to be more energy-efficient, contributing to longer electric vehicle ranges.
4. Emissions [53]: For internal combustion engines, emissions play a crucial role in environmental impact. Efforts to reduce emissions while maintaining performance are central to propulsion system optimization.
5. Reliability and Durability [54]: Propulsion systems must be reliable and durable, minimizing maintenance requirements and enhancing the vehicle's lifespan.

While DT has the potential to be utilized across various electric propulsion drive elements, it is evident from Figure 4 that transmission and battery are the most widely adopted ones. Figure 4 presents search results for publications related to DT components in automotive applications.

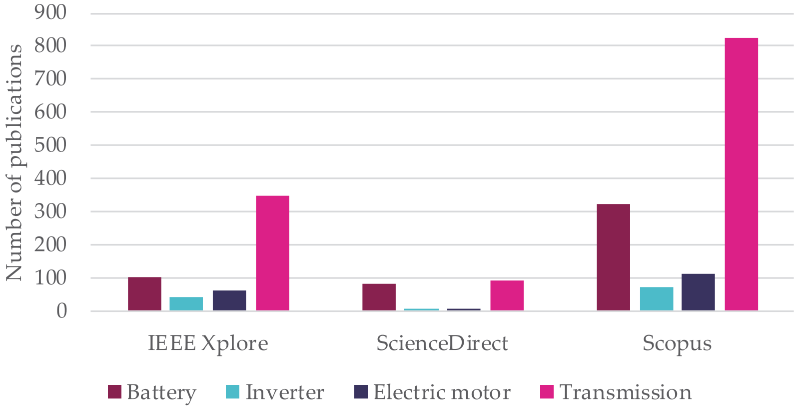

Figure 4. Search results for publications related to DT components in automotive applications during the period 2000–2023 in IEEE Xplore, Scopus, and ScienceDirect.

Challenges in optimizing propulsion drive systems are multifaceted. Integrating components within the system, balancing performance with efficiency, and addressing thermal management and energy storage pose significant hurdles. Battery technology advancements and infrastructure development are vital for electric propulsion systems to address range anxiety and charging concerns [55].

In conclusion, propulsion drive systems are the beating heart of modern vehicles, evolving to meet the demands of efficiency, performance, and sustainability. Electric propulsion systems are gaining prominence for their simplicity and eco-friendliness, while conventional powertrains continue to improve through meticulous engineering and innovation. The intricate web of components, interactions, and metrics defines the landscape of propulsion systems, and navigating this complexity is essential for unlocking their full potential in shaping the future of transportation.

4. Applications of DTs for Electric Propulsion Drive Systems: Pioneering Efficiency and Sustainability

The automotive landscape is profoundly transforming, with electric propulsion systems taking center stage in the quest for cleaner, more efficient transportation [56]. At the forefront of this transformation is integrating DT technology into electric propulsion drive systems, heralding a new era of performance optimization, predictive maintenance, and sustainable energy consumption. This section delves into the multifaceted applications of DTs within electric propulsion drive systems, spotlighting their role in predictive maintenance, performance optimization, energy efficiency enhancement, and emissions reduction.

4.1. Predictive Maintenance and Condition Monitoring

DTs revolutionize maintenance strategies by offering real-time insights into the condition of components within electric propulsion systems. Through embedded sensors and continuous data collection, DTs create a dynamic virtual representation that mirrors the behavior of their physical counterparts [57]. This real-time monitoring equips manufacturers and operators to detect anomalies, irregularities, and potential failures before they escalate into costly breakdowns [58].

Many cases highlight instances where DTs have prevented breakdowns and optimized maintenance schedules. In [59], there is a case study where DT was combined with deep transfer learning to detect faults in a car body-side production line. Authors in [60] address a verified DT model of life-cycle rolling bearing for fault diagnosis. In [61], a data-driven DT model is proposed for preventing incipient inter-turn short-circuit faults in permanent magnet synchronous motors. In [62], the authors outline a methodology for monitoring and diagnosing the degradation of power electronic converters based on DTs. In [63], an approach for the early-stage degradation of fuel cells and its prediction is addressed using DT, which is tolerant to different degradation patterns and can achieve real-time degradation prediction. The authors in [64] propose a novel wind speed-sensing methodology for wind turbines based on DT technology.

Case studies serve as compelling testaments to the efficacy of DTs in predicting and preventing failures. For instance, a DT of an electric motor can monitor variables such as temperature, vibration, and power consumption. Anomalies detected in these parameters trigger alerts, allowing maintenance teams to intervene proactively, preventing motor failure and minimizing downtime [65]. Such interventions can also lead to optimized maintenance schedules, reducing operational disruptions and costs [66].

4.2. Performance Optimization and Virtual Testing

DTs offer a virtual laboratory for engineers to explore design variations, simulate scenarios, and predict performance outcomes. In electric propulsion drive systems, virtual prototyping using DTs expedites the iterative design process. Engineers can explore diverse configurations and evaluate their impact on performance metrics, narrowing down the most promising design iterations for physical implementation.

There are numerous illustrative examples of using DTs to optimize engine efficiency, transmission responsiveness, and overall drivability. For instance, in [67], a DT-based optimization procedure is presented for an ultraprecision motion system, subject to backlash and friction. The authors in [68] present a development case study of a DT for an electric motor based on an empirical performance model. In [69], the DT concept is applied to electric motors. It is used to solve general problems related to the application of electric motors in the automotive industry, such as estimating the driving torque or the rotor temperature to improve cooling control. The authors in [70] introduce how motor dielectric aging can be prevented. In [71], the authors present a DT-based optimization for optimally adjusting parameters in ultraprecision motion systems.

DTs open avenues for optimizing propulsion systems' efficiency and responsiveness. Consider an electric propulsion system's motor controller. Engineers can fine-tune control algorithms to maximize efficiency, torque delivery, and response to driver inputs via simulating various control strategies and motor performance scenarios using a DT. Moreover, DTs optimize transmission gearing ratios for optimal power delivery across different driving conditions, contributing to enhanced drivability and energy consumption.

4.3. Energy Efficiency Enhancement and Emissions Reduction

DTs are potent tools for energy efficiency and emission reduction. For electric propulsion systems, accurate modeling of battery behavior within DTs aids in optimizing energy usage. This includes predicting the battery state of charge, discharge rates, and overall performance under varying conditions. Accurate simulations help engineers design battery management systems that enhance efficiency, extend battery life, and minimize energy waste.

Numerous case studies showcase DTs' role in achieving regulatory compliance and sustainability goals. For example, DTs are widely used in the oil and gas industry to enhance their operations' productivity, efficiency, and safety while minimizing operating costs, health, and environmental risks [72]. In autonomous transportation, a DT is a promising tool as the safety and security of vehicles have obvious advantages of reducing accidents and maintaining a cautious environment for drivers and pedestrians [73]. In [74], the authors explore a potential approach based on DT that aims to achieve optimization and automation systems for energy management meeting the near zero energy buildings through the Internet of Things and machine learning. The authors in [75] demonstrated the applications based on DTs for sustainability and vulnerability assessments that enable the next-generation risk-based inspection and maintenance framework. Smart manufacturing is also addressed in many cases [76–78].

DTs also play a pivotal role in aligning propulsion systems with regulatory and sustainability objectives. Consider the challenge of reducing emissions in internal combustion engines. Engineers can virtually explore combustion strategies, timing adjustments, and exhaust after-treatment systems by creating a DT that models combustion dynamics and emissions generation. This proactive approach enables the development of strategies to meet stringent emission standards while optimizing engine performance.

In conclusion, integrating DT technology into electric propulsion drive systems is poised to redefine automotive engineering and propel the industry toward unprecedented efficiency and sustainability. DTs provide a multifaceted toolkit for engineers to design, test, and operate propulsion systems with unmatched precision, from predictive maintenance and performance optimization to energy efficiency enhancement and emissions reduction. As the automotive sector embraces this digital transformation, the possibilities for innovation and progress are boundless, promising a future of greener, more innovative, and more efficient transportation.

5. Practical Implications of DTs for Automotive Advancement

Integrating DT technology into the automotive sector heralds a new era of possibilities, reshaping how vehicles are designed, developed, and operated. This section explores the practical implications of DTs for automotive manufacturers, designers, and engineers. It delves into how DTs expedite design iterations, reduce development time, and enhance product quality. Moreover, it identifies areas where DTs can stimulate innovation and drive transformative changes within the automotive landscape.

Numerous practical implications for automotive manufacturers, designers, and engineers can be found in the literature. The authors in [79] present a new embedded system that provides a complete set of self-driving modules, including localization, detection, prediction, planning, and control. In [80], an overview of existing inverter designs from several production vehicles across multiple manufacturers is presented from the perspective of industrial demands and future trends. An overview of additive manufacturing for automotive branches is presented in [81] to make production more sustainable and reliable. In [82], the author discusses a DT demonstrator for privacy enhancement in the automotive industry.

DTs serve as a common ground for collaboration among multidisciplinary teams. Designers, engineers, and manufacturers can collectively visualize, simulate, and assess vehicle components and systems. This collaboration fosters a shared understanding, expedites decision making, and enhances communication throughout development. DTs provide real-time insights into the behavior and performance of components and systems. This enables manufacturers and engineers to make informed decisions and identify design flaws, optimization opportunities, and potential failures early in the development cycle [83]. Traditional design cycles involve multiple iterations and physical prototypes. DTs streamline this process by enabling virtual prototyping, assessment, and refinement. Designers can explore various configurations, simulate performance outcomes, and optimize designs without the need for costly physical prototypes. Engineers can leverage DTs to develop predictive maintenance strategies. Monitoring real-time data from the DT can anticipate potential maintenance issues, allowing for timely interventions and minimizing vehicle downtime.

DTs dramatically accelerate the design iteration process. Engineers can swiftly modify and test design parameters in the virtual environment, assessing their impact on performance metrics [84]. This agility allows for rapid adaptation and refinement, reducing the time required to iterate through design alternatives. Integrating DTs shortens the development lifecycle by reducing the need for physical prototyping and testing. Simulating performance outcomes and conducting virtual tests eliminates time-consuming phases, leading to faster time-to-market for new vehicle models and innovations. DTs contribute to higher product quality by facilitating thorough testing and optimization before physical manufacturing [85]. Design flaws, inconsistencies, or inefficiencies are identified early in development, minimizing the risk of costly recalls or post-launch modifications.

DTs facilitate the design of integrated vehicular systems. Rather than treating components in isolation, engineers can optimize the interactions between propulsion, chassis, and connectivity systems, leading to holistic vehicle performance and efficiency improvements [86]. With DTs, engineers can explore the effects of different materials on performance, durability, and weight. This encourages innovation in materials selection, enabling the development of lighter, more efficient, and sustainable vehicle components. DTs would allow manufacturers to create tailored vehicle configurations based on customer preferences and needs. Manufacturers can refine designs by analyzing real-world data collected from vehicles in operation to align with customer expectations and usage patterns [87]. As DTs collect data from connected vehicles, machine-learning algorithms can identify patterns, anomalies, and optimization opportunities [88]. Manufacturers can then apply these insights to drive continuous innovation, resulting in evolving and improving vehicles over time.

In conclusion, the practical implications of DTs for the automotive industry are profound and far-reaching. From streamlining design iterations and reducing development time to enhancing product quality and fostering innovation, DTs offer a paradigm shift in how vehicles are conceived, developed, and operated. As manufacturers, designers, and engineers embrace this transformative technology, the automotive landscape stands poised for unprecedented advancements, efficiency gains, and a future where innovation flourishes like never before.

6. Challenges and Future Directions

As DT technology continues to reshape EV industries, its integration into propulsion drive systems within the automotive sector is poised to unlock transformative potential [89,90]. However, this journey has its share of challenges [91–95]. This section delves into the intricacies of implementing DTs for propulsion systems, discussing hurdles such as data integration, accuracy, computational demands, and real-world validation. Looking forward, it also speculates on the future of DT technology in the automotive industry and the potential advancements that lie on the horizon.

6.1. Exploration of Challenges in Implementing DTs for Propulsion Drive Systems

One of the primary challenges in implementing DTs for propulsion systems is the seamless integration of data from various sources [96]. Propulsion systems are comprised of many components, each generating a data stream. Ensuring these data streams converge into a coherent and meaningful DT can be complex. In addition, the effectiveness of a DT hinges on the accuracy of its virtual representation. Achieving accuracy requires careful consideration of material properties, real-world behavior, and environmental conditions. Deviations between the DT and the physical system can lead to inaccurate predictions and insights. At the same time, creating and operating a DT entails substantial computational demands [97]. Real-time monitoring, data processing, simulation, and analysis necessitate robust computing infrastructure [98]. This can pose challenges regarding resource allocation, scalability, and managing computational costs. The success of a DT is contingent on its ability to replicate real-world behavior faithfully. Validating a DT's accuracy against the physical system involves extensive testing and validation. Ensuring that predictions generated by the DT align with real-world outcomes requires meticulous verification.

6.2. Discussion of Data Integration, Accuracy, Computational Demands, and Real-World Validation

Successful data integration requires a standardized data collection, storage, and transmission approach. Ensuring compatibility among different data sources and formats is essential for creating a holistic DT that accurately represents the propulsion system. Achieving accuracy entails a comprehensive understanding of the physical system's behavior.

Accurate modeling of components' characteristics, interactions, and responses to various inputs is crucial for generating reliable insights [99]. Also, meeting the computational demands of DTs involves a trade-off between processing power, scalability, and resource allocation. Cloud computing, edge computing, and distributed computing models are potential solutions to manage computational requirements effectively [100]. Rigorous real-world validation involves subjecting the DT to various operating conditions and scenarios that mirror real-world situations. This process verifies the accuracy of the DT's predictions and its ability to respond accurately to changes in the physical system.

6.3. Speculation on the Future of DT Technology in the Automotive Industry and Potential Advancements

The potential of DT technology in the automotive industry is vast, promising a future characterized by innovation and efficiency. As technology evolves, several potential advancements could shape the trajectory of DT integration:

1. Advanced Machine Learning [101]: Integrating advanced machine learning algorithms within DTs can enhance their predictive capabilities. Real-time anomaly detection, fault prediction, and prescriptive maintenance recommendations can empower manufacturers to optimize vehicle performance.
2. Holistic Ecosystem Integration [102]: Future DTs may encompass the entire vehicular ecosystem, extending beyond propulsion systems to include chassis, sensors, communication networks, and road infrastructure. This holistic approach could comprehensively understand vehicle behavior in diverse contexts.
3. DT Interoperability [103]: The development of standards for DT interoperability could facilitate seamless collaboration and information exchange across various stakeholders in the automotive value chain. This could lead to improved decision-making, faster innovation cycles, and enhanced operational efficiency.
4. Autonomous System Collaboration [104,105]: DTs could play a pivotal role in developing and testing autonomous driving systems. They could serve as a safe and controlled environment for simulating complex scenarios and validating the behavior of autonomous vehicles.

In conclusion, integrating DT technology into propulsion drive systems promises to reshape the automotive industry. However, data integration, accuracy, computational demands, and real-world validation must be navigated thoughtfully. The future of DT technology in the automotive industry holds immense potential for transformation, with advancements in machine learning, ecosystem integration, interoperability, and collaboration with autonomous systems offering a glimpse into an exciting era of innovation and progress.

7. Conclusions and Discussion

In conclusion, the integration of Digital Twin (DT) technology into the automotive industry represents a major shift in how vehicles are conceptualized, manufactured, and operated. This revolutionary approach provides real-time insights, and it changes various aspects of propulsion drive systems. DTs hold the promise of forecast refinement, better performance, increased energy efficiency, and reduced air pollution, all while fostering innovation and cross-sector collaboration.

The practical implications of DT are profound. Automakers, manufacturers, and engineers are empowered to optimize rework, reduce production time, improve product quality, and drive innovation. Virtual prototyping enabled by DT accelerates the process, allowing rapid optimization and optimization without the need for expensive physical prototypes, providing real-time insights that facilitate informed decision-making from system improvements to maintenance options. DTs encourage integrated vehicle design and innovation, resulting in lighter, more efficient, and sustainable products.

But the journey to full DT integration is not without challenges. Ensuring seamless integration of data from multiple sources, maintaining accuracy in virtual representations, managing computational requirements, and verifying DT predictions against real-world results are necessarily obstacles that need to be addressed.

The potential advancements of DT technology are exciting. Advanced machine learning algorithms, holistic ecosystem integration, DT interoperability standards, and collaboration with autonomous systems are all areas that could shape the future of DT technology in the automotive industry. As the automotive sector continues to evolve, DTs stand at the forefront of innovation, poised to drive efficiency, sustainability, and a new era of automotive excellence.

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Appendix 2

Publication II

A. Rassõlkin, V. Rjabtšikov, T. Vaimann, A. Kallaste, and V. Kuts, “Concept of the Test Bench for Electrical Vehicle Propulsion Drive Data Acquisition,” 2020 XI International Conference on Electrical Power Drive Systems (ICEPDS), Oct. 2020.

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Concept of the Test Bench for Electrical Vehicle Propulsion Drive Data Acquisition

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Abstract— **The goal of the proposed concept is to develop a specialized unsupervised prognosis and control platform for electrical vehicle propulsion drive performance estimation. This goal requires the development of several subtasks and related objectives, therefore the state-of-the-art analysis of the current development in electric vehicle propulsion drives is presented in the paper. Digital Twin as modern technology trend covers a wide range of services, such as efficiency improving, minimizing failure rates, shorten development cycles, and provides new opportunities for remote control and maintenance of the device. In this paper, the general description of requirements for creating a Digital Twin is discussed. The construction of electric vehicle propulsion drive, as physical devices models of Digital Twin, can be carried out using the well-established modeling techniques, the possible solutions are also presented. Different physical models of separate parts of electric vehicle components (power controller, motor(s), gearbox(es), etc.), and the related reduced models of these components (test benches) are proposed.**

Keywords— Autonomous vehicles; Vehicles; Intelligent vehicles

I. INTRODUCTION

The world population is already approaching eight billion people and the number of vehicles in operation has surpassed one billion units. According to OICA (International Organization of Motor Vehicle Manufacturers) statistics, almost 96 million vehicles were produced in 2018, and the number is increasing each year. With further globalization, industrialization, and urbanization, the trend of the fast growth of the number of vehicles worldwide is inevitable. The main issues due to increasing vehicle numbers are the limited volume of oil and the emissions from burning oil products. Reducing fossil fuel usage and as a result, reducing carbon emissions are the main goals of humanity nowadays. Hybrid Electric Vehicles (HEVs) in use instead of Internal Combusting Engine (ICE) Vehicles could notably decrease the atmospheric pollution. The effect of using an Electric Vehicle (EV) could be still better. According to Statista [1] here was just under 3.3 million battery EVs in use globally in 2018 and almost 1.5 million battery EVs were sold worldwide in 2018.

The EV (as well as HEV) is a rather complex system for accurate mathematical description, monitoring, and validation. However, today much attention is paid to the studies of different parts of vehicles. The laboratory studies with test benches, combining advantages of software models and real equipment, contribute to the reduction of the number of vehicle test runs and safe maintenance. By using a variety of different test benches, separate parts of a vehicle could be studied and improved.

Nowadays, along with the developments of new-generation information technologies, such as cloud computing, the Internet of Things (IoT), big data, and artificial intelligence (AI), the roles of the virtual space are becoming increasingly important and interactions between the physical and virtual worlds are more active than ever before [2]. Such a massive change of paradigm in scientific research and industry brings changes into general concepts of design and testing. Sometimes it is impractical to emulate all possible loadings in laboratory conditions and component scaling is not always achievable. At this rate, identification and assessment of the separate parts or states via computational simulation are required. Electrical, mechanical, thermal, and acoustic stresses may be reproduced separately and combined in the proper digital replica or Digital Twin (DT).

The major objective of the studies is to develop and implement the DT based framework for exploring, modeling, identification, and assessment of self-driving shuttle (or any other EV) propulsion drive configurations aiming to provide fast and concise information about most important indicators. The goal is to propose a methodology for adjusting the propulsion electric drive under the testing conditions different from standard ones (incl. unique testing cycles). This goal requires developing the physical models that will serve to construct the DT of the system. Reduced models (test bench) of these propulsion electrical drive components (e.g. motor, gearbox, transmission, etc.) will be used for the development and implementation of the concept of virtual sensors. Virtual sensors of a DT are the observed outputs of a physical entity. These observations [3] can be either raw data that will be processed by the cloud-based functional units of a virtual entity to detect events or the events themselves.

II. STATE OF THE ART AND LITERATURE REVIEW

Many reports and publications delivered by different research centers are covering various areas of EV and HEV development. According to searches in Scopus and IEEE Xplore databases keyword “Electrical Vehicle” gives 24 109 (83% of publications was published in the last 20 years) and 65 799 (92% in last 20 years) results respectively. The growth of published documents in the Scopus database in the recent 20 years is shown in Fig. 1.

This chapter includes an overview of electric propulsion drive testing facilities for EVs and HEVs.

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A. *Testing of Electric Propulsion Drive Components*

The energy-efficiency of EV (incl. HEV) is one of the main component of many research works [4]–[13], in [8]–[12], [14] the evaluation is based on chassis dynamometer testing, researchers in [4]–[7] investigate dynamic efficiency based on software and standard test cycles [15], [16], at the same time as in [13], [17]–[19] efficiency is evaluated based on statistic and performance field tests of EV. Some of the model-based design and testing methods are focused on the EV drivability aspect as shown in [20]. Variable and dynamic loads [21]–[23] are required to satisfying variable working conditions in the EV experiments of the traffic [24]. An alternative to the installation of the propulsion drive on the real vehicle, it is represented by the emulation of performances with a real-time controlled test bench [25].

Optimal power distribution among multiple sub-systems for electric propulsion drive of EV and HEV could offer a lower energy consumption, optimization methodologies is another topic of interest [21], [26], [27]. To achieve optimal power delivered to the different power-consuming components and delivering the optimal required power to the electric motor and thereby increasing the driving range of the electric vehicle, deep learning methods [28] and neural networks [29] are used.

Energy management systems are the key technologies of EV and HEV, they have functions of managing, monitoring, and recovering the energy of the vehicle propulsion system which used in a release, storage, distribution, and braking time. Energy management systems are widely discussed in [4], [11], [24], [30], [31]. According to the energy requirements of the EVs, the control strategies of the energy management system are studied considering the combination of different energy sources: battery and super-capacitor [21], [31], [32], battery and fuel cell [9], [24], [33] and combinations with ICE [25], [34], [35]. The energy storage system of EV and HEV is a rather complex system, it's internal module usually includes battery monitoring and control, dc-dc convertor(s), an internal battery charger and internal battery cooling control [36].

Test benches for EV and HEV help to provide a comparative lifecycle analysis of separate parts of the vehicle, as motors [37], insulation [32], etc., and especially batteries [6], [33], [38], [39]. As more EVs and HEVs appear on road, the disposal of the batteries has become a concern, [33] estimates that there will be nearly one million retired EV battery packs in the US alone by 2020. The lifecycle assessment implies important procedures that can help to reduce the impact of a component on the environment, being, therefore, an instrument for the assessment of the influence exerted by particular products on the environment – from cradle to grave – beginning with the acquisition of the materials, followed by manufacturing, transporting, marketing, usage, and recycling [40]. The ability to run an accelerated life test [41], [42] through a limitless number of cycles is one of the important features of any test bench.

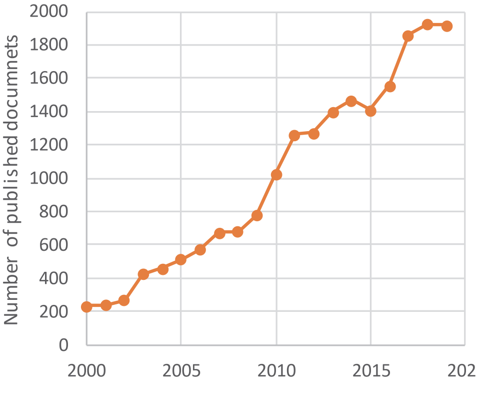

Fig. 1. A number of documents on "Electrical Vehicle" published in Scopus in recent 20 years.

As is presented in literature, different parts of the vehicles, like motors [10], [17], [43], [44], power electronics [35], [41], [45], mechanical transmission [10], [21], [41] (incl. shafts, gears), braking system [13], [46] incl. ABS [47], [48], for electric propulsion systems has their own requirements and need additional studies [32], [49]. It should be mentioned, that for self-driving vehicles special attention should be paid to estimation of load coefficients. Because the friction coefficient of the road is the primary factor of the traction control system [48], [50] and correct determination of the road conditions can significantly improve such systems as brakes, steering, active suspension, etc.

In the case of EV and plug-in HEV special attention is focused on charging system testing [51]–[54] and problems of integration of the vehicle with electric propulsion drive into distribution system [55]–[57] like unregulated charging and current harmonics effect. Comprehensive electromagnetic compatibility (EMC) testing of EV and HEV energy storage system requires a paradigm shift from module or component level testing to complete EMC system-level testing [36], proper EMC standards must be applied [58], [59]. Recent studies show that the position of the charging inlet affects the measured level of radiated disturbances [60]. There are mainly three organizations that are involved in writing and maintaining automotive EMC regulations: CISPR, ISO, and SAE. However, every vehicle manufacturer has developed its internal standards specific to the test levels and testing approaches to ensure EMC integrity for its components and systems [58].

Low-level emission, such as acoustical noise and vibration, may cause discomfort for vehicle users. Experimental studies show that not only electric propulsion drive system [61], but any other energy conversion module in EV or HEV may be a source of acoustic or vibration noise: electric motor [42], [62], gearbox [42], power electronics converters and control system [63], and even battery [64]. Such operational conditions require proper diagnostic and condition monitoring methods [65]. Existing techniques are mostly based on physical sensors. Nonetheless, diagnostics and prognostics of electrical energy conversion systems are moving forward with the rapid development of IoT and AI possibilities, this also broadens the horizons for classical and advanced condition and operation monitoring techniques, resulting in more accurate fault detection, degradation prognosis and calculation of remaining life of energy conversion systems, utilized in every aspect and field of the industry today [66].

B. *Cyber-physical System for Electric Propulsion Drive Testing*

Sometimes, physical test benches are expensive to build and maintain so Virtual Testbeds (VT) are used as a cost-effective alternative [67]. VT has been used in networking and communications for a long time, however, nowadays they are also widely used in robotics, where complex technical systems and their interaction with prospective working environments [68], [69] and humans [70] are designed, programmed, controlled and optimized in simulation before commissioning the real system, at the same time. For such VT, DT is promoted as virtual substitutes of real-world objects consisting of virtual representations and communication capabilities, making up smart objects acting as intelligent nodes inside the IoT and services. The combination of these two approaches (VT and DT) leads to a new kind of experimental DT breaking new ground in the simulation-based development and operation of complex technical systems [71]. Some of the works are focused on a goal to provide a comprehensive simulation tool for various mobile robotics applications [72], [73] based on VT.

The cyber-physical system engaged a lot of attention from research and industry, it provides the framework and mechanism for the integration between physical and virtual fields. Nowadays, the cyber-physical system is a mainly conceptual methodology aimed to inspire new technologies and foundations, rather than a practical tool that is able to guide the development. DT is a focused application of the cyber-physical system that provides more practical values and implementation details, it is introduced as a pragmatic way for seamless integration and fusion [2].

DT models are gaining more and more interest in their potentials and strong impact in such fields as manufacturing, aerospace, healthcare, and medicine [74]. Possible application of DT for vehicles (incl. EVs) certifications is discussed in [75], the DT paradigm is presented as a long-term vision aimed to address these and other shortcomings of current practices for certification, fleet management, and sustainment. In [76] a possible application of DT to track data of failures throughout the logistic process and to the prediction of failures of each particular vehicle by the example of the KAMAZ trucks was analyzed, the comparison of the predicted number of failures, obtained from the proposed DT, with the real values confirmed the adequacy of the forecasts at the level of 10%, which is a very significant improvement.

III. DIGITAL TWIN CONCEPT AND REQUIREMENTS

In most definitions, the DT is considered as a virtual representation that interacts with the physical object throughout its lifecycle and provides intelligence for evaluation, optimization, prediction, etc. [2] When DT concept was presented by M. Grieves [77], [78], the DT was composed of three main components – the physical entities in the real world, their virtual models (or virtual entity), and the data. However, without the usage of additional components, DT is mainly limited only by simulations usage in the virtual environment [79]. In [80], DT technology is already presented as a five-dimension system, where services and connections are presented as separate entities. More studies are needed on design methods for DT, which allows full synchronization and connectivity between virtual and real environments [81].

Fig. 2 shows the interaction of the DT components. All components are interdependent from each other. The physical entity provides the basis for the virtual entity development; the virtual entity is responsible for the simulations, control of the physical part, and optimization strategies for the service system. The service system represents an integrated service platform responding to the demands of both physical and virtual entities. DT data is the combined data from physical, virtual, and service entities; methods for modeling, optimizing and predicting. Data acts as a driver for all entities and involved in the creation of the DT itself, more comprehensive and consistent data is formed.

Shown in Fig. 2, the DT model of EV can help with its optimization by the usage of deep learning tools before implementation in the real physical system.

A. Requirements for DT

Each dimension of DT for propulsion motor drive of self-driving shuttle is illustrated in Fig.3.

A real physical entity consists of various subsystems and sensory devices. In the case of the studied system, a self-driving shuttle includes the next subsystems - electric propulsion drive system, control system, safety system, supplementary systems (door controller, lights, etc.). The sensors gather real-time states of the subsystems, there is two main type of sensors used for self-driving vehicles – dead reckoning sensors (encoders, inertial sensors, GPS, etc.) and sensors for vehicle perception (cameras, radars, lidars, ultrasonic, etc.). The main task of the sensors is to achieve autonomy, however, they can be used also for adjusting the control algorithms for propulsion electrical drives and supports the selection of cruising mode.

The test bench, combining advantages of real-time software models and real equipment, contributes to the reduction of the number of test runs and safe maintenance. The virtual entity consists of the spatial model, physical model, behavior model, and rule model. In the spatial model, the components of self-driving shuttle (e.g., electric motor, gearbox, transmission) are constructed as computer-aided geometric models to be assembled in the virtual engine – either in commercial simulation software, which is agnostic to a brand like Visual Components, Tecnomatix Plant

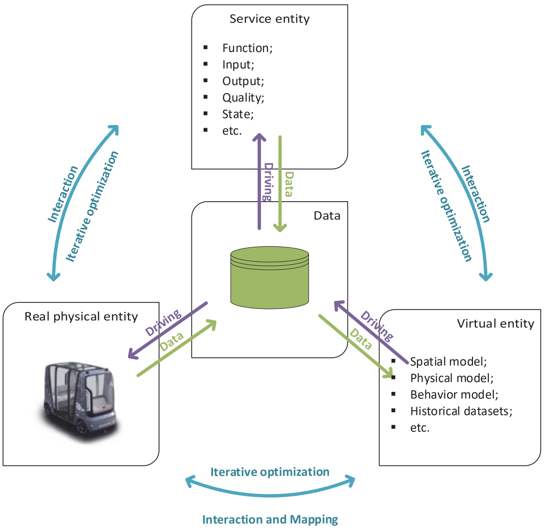

Fig. 2. Five-dimensional Digital Twin model.

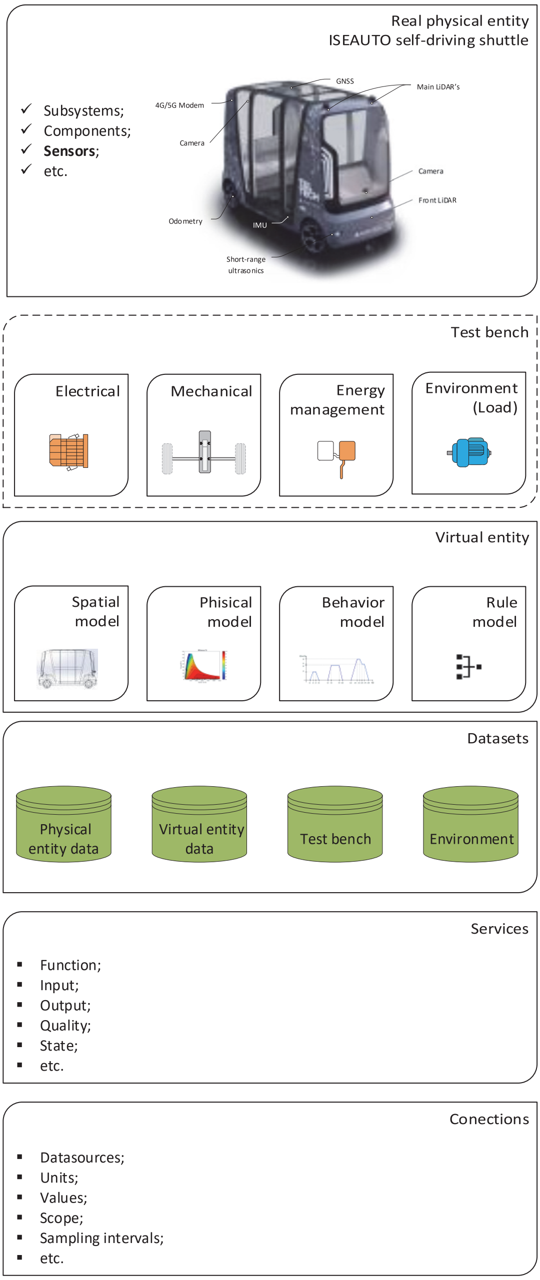

Fig. 3. Digital Twin components for the ISEAUTO self-driving shuttle.

Simulation, etc., or free to use or open-source software as Autoware, Unity3D, UnrealEngine4, Gazebo/RVIZ, Carla or others dedicated to simulation of physics and other aspects software packages. In the physical model, the performance of separate parts can be simulated using numerical computing environments (e.g. MATLAB, Agros2D, etc.). The behavior model includes traction effort generation, the reaction on load changing, and features related to dynamic forces simulation. For example, tractive effort of self-driving shuttle [82] has to overcome the rolling resistance, the aerodynamic drag, the climbing resistance force, and if the velocity is not constant, the accelerating force of the vehicle, which in turn determinate propulsion force for the vehicle to move forwards. Rule model covering constraints for road load can be simulated through behavior analysis and associations of data that can be observed using virtual sensors.

Datasets contain various sets of data. The data from the real physical entity can be obtained by the implementation of IoT sensors and platforms that allows automatic collection, sort, conversion, and transfer of the big amount of data. That data consists of the working and environment conditions, as well as operational states. Virtual entity data includes models' parameters and simulation data. Data from the services entity describes algorithms for data collection, processing, and usage. Moreover, services entity data describes interaction algorithms between entities.

Service entity includes regulation for both virtual and physical entities and may include several sub-services, such as maintenance and diagnostic, energy optimization, path planning, etc.

The connection entity characterizes the interaction between other entities.

B. *Application Examples of DT for EV*

In [83], DT is presented as a promising technology for condition monitoring, operation optimization, and fault prediction in the automotive industry. More and more companies, such as Bsquare, PACCAR, ANSYS, GE, etc. are making efforts on DT applications in this field.

In [84], the authors are discussing a possible application of DT in the automotive industry. Although, the product life cycle of a vehicle involves various stages (e.g. conceptualization, design, procure, build, stock, sell, maintenance and service, recycle, etc.) and the huge amount of data that stays isolated on different stages and is hardly integrated with the following stages. As it is stated in the paper, DT has the potential to address multiple challenges that exist in the automotive industry today.

Application of VT for assessing probe vehicle data generation within a microscopic traffic-simulation environment is shown in [85], the proposed application includes the use of vehicles as traffic probes, systems warning drivers of traffic slowdowns, systems warning about cross-street vehicles that may potentially run through a red light, and systems notifying drivers of roadway features, such as sharp curves. The ambition of [86] research is an adaptable, modular simulation framework to analyze complex questions of autonomous driving for improving safety performance in complex urban traffic scenarios. Such a simulation framework will take into account unanticipated safety impacts of mixed traffic, which would otherwise be difficult or impossible to quantify and to address and assess potential solutions, such as improved prediction algorithms for road users.

IV. TEST PLATFORM FOR DT

A. *ISEAUTO*

The ISEAUTO self-driving shuttle project is a cooperation project between industry and university [87], which has a range of objectives from both sides, as well as a very practical outcome. The purpose of the company side was to get involved with self-driving technology as the future of the automotive industry and to get experience in

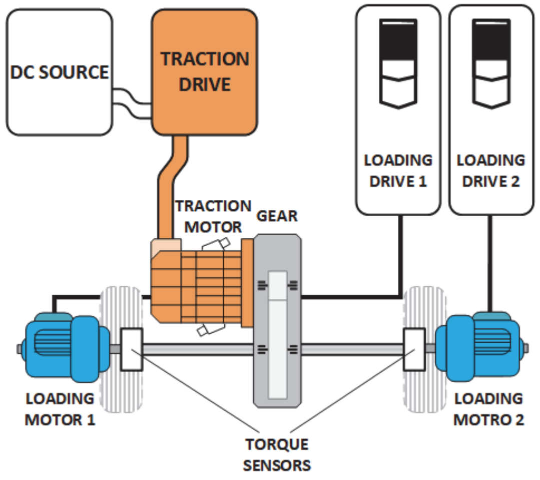

Fig. 4. Test bench concept.

manufacturing a special purpose car body, as it is one of the interests of the company. Carrying out a hands-on project helps to structure the know-how about autonomous vehicles and self-driving algorithms at the university, while providing valuable practical experience for future engineers. The main goals of the ISEAUTO self-driving shuttle project, together with research and implementation results of simulations, software development, and mechanical design, are presented in previous research works [87], [88].

ISEAUTO self-driving shuttle is based on a Mitsubishi i-MiEV trolley that uses Y4F1 [89] permanent magnet synchronous motor (PMSM). The maximum speed of Mitsubishi i-MiEV is limited to 130 km/h and Y4F1 to 9900 rpm. Transmission, used in the self-driving car, is a parallel shaft type two-step reduction F1E1A (without shifting function) with an overall reduction ratio of 6.066 [90]. A traction drive controller is used to control 3-phase battery-powered traction PMSM. The controller adapts its output current to suit the loading conditions and the ambient in which it is operating.

The car autonomy is archived running Autoware, Robot Operating System (ROS) based open-source software, which includes self-driving mobility to be deployed in open city areas, in a PC that communicates with the controllers over dedicated Ethernet to minimize delays.

Additionally, to existing sensors, which is already installed to the ISEAUTO self-driving shuttle [87], a set of IoT based devices is required to obtain supplementary information on operation conditions. Most of IoT sensors are hardware-independent, have a small footprint, and may be used independently from the main routines.

B. *Test Bench*

The electrical energy conversion system driven by controlled electrical drives can be analyzed without actual mechanics by using virtual testing. The testing can use a multi-body dynamic modeling approach. The multi-body system is a structure constructed with flexible or rigid objects that are connected by couplings or force elements. The couplings can be modeled using combinations of different basic constraints that define the allowable movement between objects connected to these. The force elements consist of springs, dampers, or more complicated actuators, in this case, electric motors and other components, such as gears and brakes. The multi-body simulators are often interacting with a virtual landscape and a user-to-machine interface of actual machinery. When considering modeling techniques for such an electrical energy conversion system it is clear, that such a test bench needs specific tools and models of electric propulsion drives, independent of the multi-body system. The electromechanical framework of the test platform provides controller software communication with a propulsion motor drive system that has three main tasks: braking, steering, acceleration.

The general concept of the test bench for propulsion drive data acquisition is shown in Fig. 4. The main parts of the test bench are propulsion drive system similar to the one used in ISEAUTO and additional data acquisition system that allows to simultaneously measure, save and analyze data from electrical, mechanical, thermal, and other sensors, as well as a set of loading drives that enable an examination of the system beyond standard modes of operation, identical to one described in [91]–[93].

V. CONCLUSION AND DISCUSSION

As can be seen from the literature review, there is a high interest in the topics related to EV in recent years. The fast development of computer engineering and IoT affects all scientific research fields and industries. What is more important this development brings changes into general concepts of design and testing of single parts. Identification and assessment of the separate parts of EV propulsion drive using the DT paradigm opening a new trend of research and development in that area. Depending on the DT development phase, multiple tests can be performed on the conceptual test bench. The main focus of the functional tests lay in the measurements of power and energy efficiency and investigations in driving simulation mode, which are used for self-driving vehicle application purposes.

To enable an examination of the drive trains beyond standard modes of operation, different parameters like wheel slip (variable friction coefficient and adjustable rotational inertia of the simulated vehicle wheels), multiple wheel speed left/right, front/rear, and uphill/downhill grades may be assumed.

The main objectives of the conceptual setup development may be summarized as follows:

- proposed to provide the research environment for analysis, investigation, and simulation of the ISEAUTO propulsion drive system;
- enable the investigation of the ISEAUTO propulsion drive system beyond standard modes of operation, different parameters like wheel-slip, multiple wheel speed, left/right, front/rear, and uphill/downhill grades can be imitated;
- to establish the assessment and verification procedures for different components of DT motor, gear, and power converter, etc.;
- ISEAUTO self-driving shuttle path planning and verification based on energy requirements of propulsion drives;

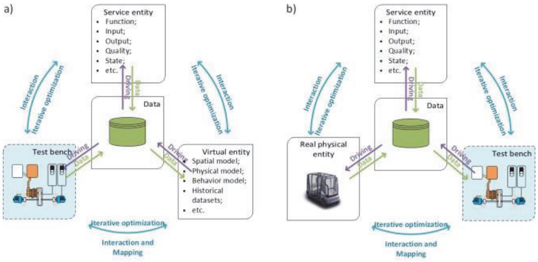

Fig. 5. A possible implementation of test bench into five-dimensional Digital Twin, in scenario (a) test bench substitutes the physical entity of Digital Twin, and in scenario (b) test bench substitutes virtual entity and used as a simulation environment.

- studying the energy recovery processes and efficiency during the ISEAUTO braking processes;
- determination of the behavior model of the propulsion drive system and simulating the functionality consisting of different combinations of energy sources and mechanical loads, to establish the optimal configurations for the system.

VI. FUTURE WORKS

Conceptual test bench that allows evaluating energy management, optimal control configuration, the combination of different energy sources, etc. would be an added value to ISEAUTO propulsion drive DT concept and can be implemented in different ways.

Development and implementation of the concept of DT and virtual sensors will help to provide a brand-new approach for measurement and estimation of the steady-state and transient of the ISEAUTO propulsion drive system. Fig. 5 presents two possible scenarios of test bench integration into a five-dimensional DT concept. In the first scenario (Fig 5.a), the test bench substitutes the physical entity of DT and is used as the main component for DT development and virtual sensors tuning. In the second scenario (Fig.5.b), the test bench substitutes a virtual entity and is used as a simulation environment to analyze the performance of the ISEAUTO propulsion drive system in operation modes that are different from the standard ones.

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Appendix 3

Publication III

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EV-Powertrain Test Bench for Digital Twin Development

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***Abstract*— The paper is devoted to the development of a PC-controlled experimental bench dedicated to the testing of an electric vehicle (EV) powertrain. The test bench was built with the goal of facilitating the creation of digital twin (DT) that simulate the real EV propulsion drive system. Different components of the test bench were described in detail. The potentialities of the developed bench are highlighted through the emulation of different automotive cycles including acceleration and braking.**

Keywords— Powertrain, System validation, Digital twin

I. INTRODUCTION

Environmental and economic factors have played a prominent role in the global shift towards the production of vehicles with lower carbon emissions. Electric and hybrid vehicles offer an effective solution to reducing environmental pollution and carbon emissions. In addition, those types of vehicles are characterized by their high efficiency and wider range compared to their counterparts of conventional internal combustion engine (ICE) vehicles. The efficiency of the propulsion drive system in an electric vehicle ranges from 77 to 84%, while the maximum efficiency of the propulsion system in conventional ICE vehicles does not exceed 30% [1]. The EV propulsion drivetrain is a rather complex system for accurate mathematical modeling, monitoring, and validation. Its complexity relies on the fact that it comprises a mixture of different electrical and mechanical parts. Not only because these components are completely different in the way they work, but also because they need to work and communicate with each other in harmony [2].

Full EV powertrain simulation is essential to optimize motor control for different driving profiles and to allow all the powertrain components to interact efficiently. Torque vectoring, for instance, is a technology that distributes the power from the electric drive to the wheels so that bends can be negotiated safely in all conceivable scenarios [3]. These challenges make it essential to continue developing appropriate measurement technologies.

Studies on EV powertrains testing platforms are gaining much attention nowadays. Test benches play a key part in research and development, during production, and also in final acceptance inspections. Many test benches were developed in different research centers to cover energy management [4] optimal configuration [5] and a combination of different energy sources for EVs, like batteries, supercapacitor packs, flywheels, and fuel cells [6]. A versatile laboratory test bench for experimental tests on hybrid propulsion powertrains was presented. It was designed as a combination of a low-power engine and electric motor to emulate the hybrid architectures [7]. Another testbench was developed to emulate the dynamic loading of an EV propulsion motor by coupling two induction motors mechanically on a common shaft. A powertrain test bench system was developed to emulate the vehicle dynamics under different test cycles [8]. In the same context, a test bench was designed and implemented to replica a measured cyclic current of any electrical vehicle's powertrain [9].

In another context, a Digital Twin (DT), one of the main features of the 4th industry, is a virtual/digital replica of physical entities such as devices, assets, processes, or systems that help to make model-driven decisions. The purpose of a digital twin is to run cost-effective simulations [10]. Digital Twin in the automotive industry can be a replica of an entire vehicle, software, mechanics, electrical system, and physical behavior of a vehicle. The digital twin holds all real-time performance, sensor, and inspection data, as well as service history, configuration changes, parts replacement, and warranty data. General DT architecture consists of at least three main components – the physical entity in the real world (physical model), its virtual entity (or virtual model/models), and the data exchange set (communication model) [11]. Since the physical model is a fundamental pillar of the DT, a complete test bench of the EV powertrain is the most suitable representative of it.

This research paper presents a detailed testbench of an EV powertrain built to emulate the physical model of the system's DT. The paper is organized as the following; A deductive introduction about the main article idea is presented in section I. Section II provides the detailed EV powertrain test bench configuration. Static and dynamic tests performed on the powertrain testbench were discussed in section III. Section IV. Provides the main paper outcomes and prospective future work.

II. TEST BENCH CONFIGURATION

ISEAUTO (Estonian self-driving vehicle) was developed in cooperation between Tallinn University of Technology (TalTech) and several industrial partners. The ISEAUTO project has a range of objectives as well as practical outcomes. In June 2017 ISEAUTO project started, when TalTech and (Silberauto Estonia) agreed to jointly develop a self-driving vehicle. The purpose from the company's side was to get involved with self-driving technology to be aware of the future of the automotive industry and also get experience in manufacturing. At the same time, the project was used for scientific research purposes[12][13].

A. *ISEAUTO Powertrain Components*

ISEAUTO's propulsion drive system was designed on the basis of Mitsubishi i-MiEV trolley based on Y4F1 permanent magnet synchronous motor (PMSM) [12]. While ISEAUTO is a last-mile vehicle and its speed is limited, the transmission is used to cover the best efficiency region of the propulsion motor. The transmission used in the self-driving vehicle F1E1A (without shifting function) comprises a simple meshing of two pairs of gears as well as a highly reliable differential at an overall reduction ratio of 6.066.

B. *ISEAUTO Powertrain Testbench*

The test bench was created to replicate the ISEAUTO's powertrain as shown in Fig. 1.

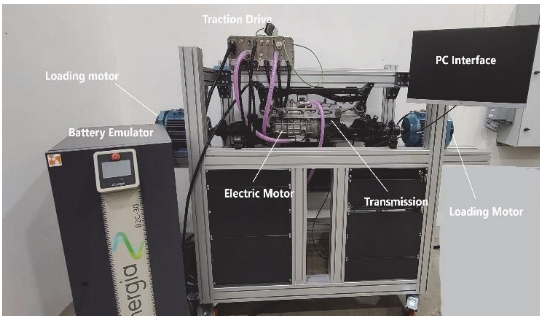

Fig. 1. ISEAUTO powertrain testbench.

In the following context, The components of ISEAUTO's powertrain testbench are described in detail.

1) *Battery Emulator*

(CINERGIA B2C+) battery emulator unit combined with a regenerative AC to DC converter designed to behave like real batteries. The DC output, of the unit can be adjusted from 20 to 750 V (800 V with the HV option). It is also possible to serialize the unit to reach up to 1500 V or to parallelize units to increase the power and current. It is controlled by a PC integrated with advanced software. It also has the possibility to send and receive data with the interface module via CAN bus, Modbus, or Ethernet Open protocol. Fig. 2 shows the Cinergia battery emulator unit.

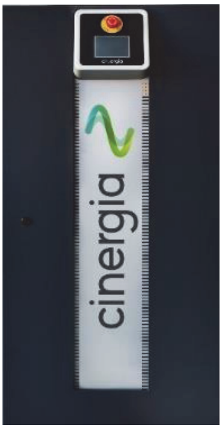

Fig. 2. CINERGIA B2C+ unit

2) *Traction Drive*

A 55 kW (ABB-HES880) heavy-duty water-cooled electric drive is used as a traction drive system. It's driven by PC software with the ability of data exchange via CAN bus or Ethernet. It can be used in both inverter and generation modes. It's designed based on the direct torque control (DTC) strategy. In the case of inverter mode, the drive controls the torque and speed of the motor. Generator mode is used to control the DC-link voltage for regenerative braking. The open-loop control algorithm reduces the need for external encoders which reduces maintenance and risk costs. Fig. 3 shows the traction drive unit of the test bench.

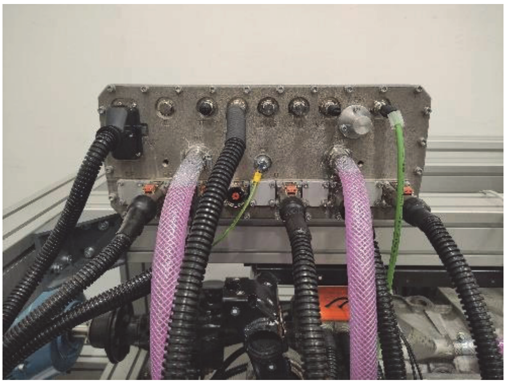

Fig. 3. ABB-HES880 traction drive unit.

3) *Electric motor*

The electric traction motor used in ISEAUTO is a 25 kW Mitsubishi Y4F1 water-cooled Interior permanent magnet synchronous motor (IPMSM) as shown in Fig. 4. It's equipped with a resolver decoder unit on its inner shaft for speed and position control. Table 1. describes the motor parameters.

TABLE I. MOTOR PARAMETERS

Parameter	Value	Unit
Nominal power	25	kW
Maximum power	40	kW
Rated Torque	150	Nm

The research has been supported by the Estonian Research Council under grant PSG453 "Digital twin for propulsion drive of an autonomous electric vehicle".

Maximum Torque	180	Nm
Rated Speed	3000	rpm

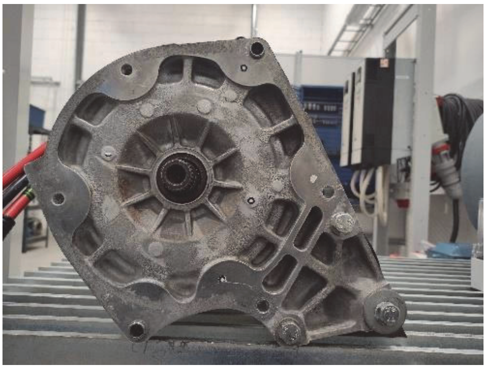

Fig. 4. ISEAUTO IPMSM

4) *Transmission*

F1E1A is a four-gear double-stage type transmission unit, as shown in Fig. 5. The first gear is the pinion gear of the input shaft, which is connected to the rotor of the vehicle traction motor. The second and third pinion gears have a common shaft. The fourth gear is connected to both the output shaft and the differential unit. The gears parameters are presented in Table 2.

TABLE II. TRANSMISSION GEARS

Gear	Diameter, mm	Width, mm	Teeth number
1st	58,9	27	25
2nd	93,9	251	42
3rd	56,1	32,2	18
4th	179	27,6	65

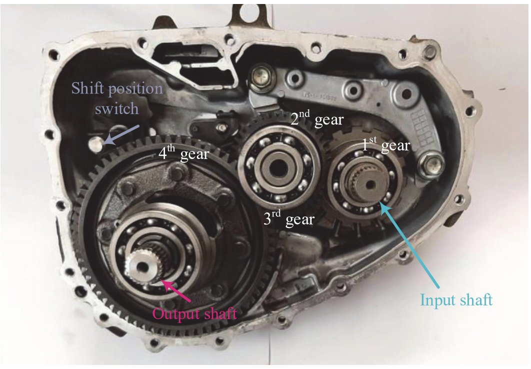

Fig. 5. F1E1A transmission unit construction.

5) *Loading Motors*

Two 7.5 kW loading induction motors IMs are mounted on both sides of the differential unit to simulate the vehicle wheels. The motors are driven by two ABB frequency converters.

III. PERFORMANCE TESTS AND RESULTS

A. *Tests procedures*

A large role of the test bench is the validation of the results with a real object, which in our case is IseAuto. To validate the parameters of the test bench, data collection is needed in the conditions of operation of a self-driving bus. These tests are essential to minimize the error during the operation of the test bench and to get closer to the real conditions of IseAuto, which can be used in simulations of propulsion drive operation.

The tests were conducted on the campus of TalTech University. Three main routes were taken for testing:

1) *Driving on a surface without a slope.* A test area was chosen with a distance of 100 meters and with a minimum slope for the bus. At this distance, a total of 6 tests were carried out along the same trajectory.

2) *Driving on a surface with a slope.* A test area was chosen with a distance of 50 meters and with a maximum slope that could find to load the electric motor for the bus. At this distance, a total of 3 tests were carried out along the same trajectory.

3) *Normal driving in a TalTech smart city between passenger stops*. The campus has a smart city where there are various components built for testing the self-driving bus like intelligent bus stops, smart pedestrian crosswalks, smart traffic lights, automatic bollards, self-driving av shuttles, and remote control stations [14]. A total of 2 tests were carried out along the same round trajectory which can be seen in Fig. 6.

For the measurement, a DEWETRON data acquisition system was used. DEWETRON allows the recording of several data channels simultaneously with a high frequency (up to 200 kHz). The advantage of this system is the possibility to connect not only sensors but also separate modules for additional needs. One of these models is the GPS module, which made it possible to record the location, speed, and altitude of the road along which the bus was moving. In Fig. 7 the measurement setup can be observed.

Fig. 6. TalTech campus smart city round trajectory

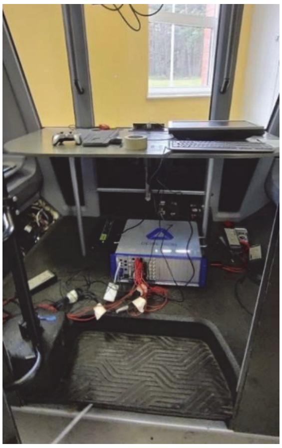

Fig. 7. Measuring setup with DEWETRON data acquisition system

The main measurement components, sensors, and parameters are listed below:

1) *Battery of the IseAuto.*
   a) *DC voltage, directly to the battery*
   b) *DC current, current clamp*
2) *Propulsion system of the IseAuto*
   a) *Three-phase voltage of a permanent magnet synchronous motor, directly to the motor*
   b) *Three-phase current of a permanent magnet synchronous motor, current clamp*
3) *Speed, altitude, and distance, GPS module*

B. *Results*

The purpose of these measurements is to become familiar with the electrical parameters of the IseAuto and subsequently use them to validate the test bench. In Fig. 8 an example of the received data is exposed.

Since the country's regulations prohibit the movement of self-propelled vehicles above 20 km/h, IseAuto does not use the full potential of the electric motor, and during operation, the voltage remains nominally 10 times lower. Also turned out that the IseAuto inverter, at the starting moment, loads the phases asymmetrically, where the amplitude value of one phase is 2 times less than the other two. But as soon as the starting phase passes, the currents become symmetrical again. This will need to be indicated when setting up the test bench in particular the motor behavior model.

Received altitude data from GPS is also shown in Fig. 8. Based on data from altitude, it is possible to calculate the load on the motor in real conditions of IseAuto operation. Although GPS data was being recorded, very noisy data was received. The GPS signal was not very stable due to high buildings. Further work will be to improve the receiving signals and implement the IMU sensor into the measuring environment in place with the GPS.

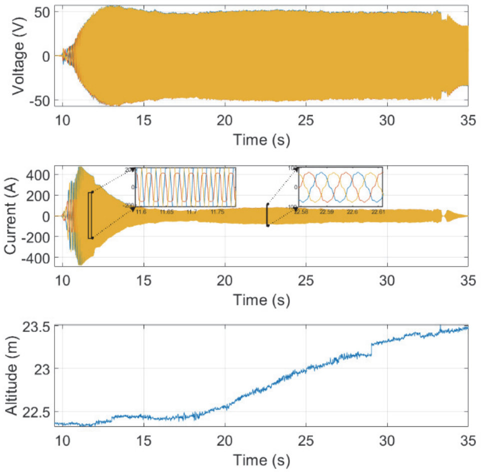

Fig. 8. Measurement of an IseAuto motor voltage, current, and altitude while driving no slope

IV. CONCLUSION

In this research paper, the procedures for creating a full PC-controlled test bench of an autonomous EV propulsion drive system were presented. The main test bench components were described in detail. Performance tests were done on ISEAUTO under different operating conditions as follows; six tests without slop driving mode, three tests with slop driving mode, and, two normal driving modes. The acquired data of the performance tests are going to be used for the test bench validation. The obtained preliminary results from the testbench are a promising aspect of the powertrain DT development.

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Appendix 4

Publication IV

A. Rassõlkin, V. Rjabtšikov, T. Vaimann, A. Kallaste, V. Kuts, and A. Partyshev, “Digital Twin of an Electrical Motor Based on Empirical Performance Model,” 2020 XI International Conference on Electrical Power Drive Systems (ICEPDS), Oct. 2020.

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Digital Twin of an Electrical Motor Based on Empirical Performance Model

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***Abstract*— The concept of Digital Twin is creating and maintaining a digital representation of the real physical entity and supporting its performance utilizing simulation and optimization tools, which are fed with real data. Development and implementation of Digital Twin technology is a hot topic in many industry-oriented research projects. However, more detailed studies are needed on design methods for Digital Twins, which allows full synchronization and connectivity between virtual and real environments. This paper presents a development case study of Digital Twin for an electric motor based on an empirical performance model. The paper discusses the way how the data required for the Digital Twin were obtained and present a detailed structural description of the virtual entity. Unity3D is used for physics simulations and visualization of the Digital Twin, because of simple accessible and meticulously detailed documentation highly useful for rapid prototyping in early stages.**

***Keywords*— Motor drives, Model-driven development, Industry applications**

I. INTRODUCTION

The concept of Digital Twin (DT) is creating and maintaining a digital representation of the real physical entity and supporting its performance through simulation and optimization tools, which are fed with real and updated data. DT is a part of the digitalization and simulation pillar of Industry 4.0 paradigm [1]. The application of Industry 4.0 technologies in many sectors has been barely examined yet since the variation of sub-processes and manufacturing technologies results in a large number of potential combinations. DT technology may present a valuable tool for the rapid integration of Industry 4.0 in today's technologies. DT covers three components: knowledge content, effect, and functionality, and application domain [2]; for utilization of a DT technology, the relations of the three components must be recognized, and the gaps remaining for exploration identified.

DT consist of three main components – the physical entity in the real world, its virtual entity (or virtual model(s)), and the data, furthermore services and connections are presented as separate entities. Generally, a real physical entity consists of assorted subsystems and sensory devices; however, for the establishment of a virtual entity, it is possible to use already collected data. The virtual entity subsists of one or several models according to the DT application; it can be the spatial, behavior, thermal, rule, or another model. The DT data contain various sets of data from the real physical entity that can be obtained by the implementation of different sensors and data acquisition platforms. The service entity mainly includes regulation for both virtual and physical entities and may carry several sub-services, such as maintenance and diagnostic, energy optimization, path planning, etc. The connection entity usually defines the interaction between other entities. More studies are needed on design methods for DT, which allows full synchronization and connectivity between virtual and real environments [3].

A. Rasheed et al. [4] give a taste of what a state-of-the-art DT of an offshore oil platform looks like. The DT at the example study is continuously updated with sensors data in near real-time and can be supported by synthetic data generated from a virtual entity. In this case, DT does not only give real physical entity real-time information for more precise control and decision making but may serve as prediction makers about how the asset will evolve or behave in the future. A perfect DT will be identical to the real physical entity in terms of appearance and behavior with the extra advantage of making future predictions. The DT presented in the study also provide the possibility for operator or scholar to interact with the physical entity using an avatar.

To create an industrial avatar in Mixed Reality (XR) application with realistic physics as a part of a DT, various software packages can be used. For it, game engines such as Unity3D, UnrealEngine, and CryEngine are popular tools used for creating industrial simulations with real-time graphics requirements. For simulations that are more precise or mathematical or realistic task, other toolkits can be used as an addition on separately, as MatLab, Visual Components Arena, Technomatrix.

There are some particular reasons for using game engines as visualization output tools:

1. The easiest way to implement graphical applications and make an animation from external commands or internal algorithms.
2. Out-of-the-box support of existing XR hardware and embedded connectivity methods for various protocols.
3. Community support and large knowledge bases both from consumers, experts in the fields, and various field researchers.
4. Flexible to work with real physical external equipment by telemetry connection means.

The research has been supported by the Estonian Research Council under grant PSG453 "Digital twin for propulsion drive of an autonomous electric vehicle."

Industrial and research applications created using those engines are called "serious games."[5] Each of those visual engines has its advantages and drawbacks – in the end, the selection is made according to specific task requirements and user competence level.

Except for game engines, there exist other software products used for industrial simulation applications:

- MATLAB – accessible simulation environment and programming language that can be used for running physical simulations connected to game engine code;
- Computer-aided design (CAD) and 3D modeling software Solidworks, ANSYS, COMSOL Multiphysics, etc. that typically used for physical design and optimization;
- Visual Components, Technomatrix – the software's for creating interactive factory layouts and plans; Processes visualizations;
- Industrial Robot offline programming software packages – latest versions of robot programming environments by ABB, Yaskawa, Kuka, and other companies have simulation support;
- Open-source software packages as a Robot Operating System (ROS) embedded with simulation and visualization tools as Gazebo, Rviz.

In the current study, Unity3D is used for physics simulations and visualization of the DT, because of previous research stuff experience and high-quality documentation provided by software producer and community.

A recent study presents a part of the project that aimed to develop a specialized unsupervised prognosis and control platform for electric propulsion drive systems performance estimation of an autonomous self-driving electric vehicle. This goal requires the development of several subtasks, and the related objectives, one of them is to develop physical models of different energy system components (motors, gearboxes, power converters, etc.) and the related reduced models of these components (testbed), which will serve to construct the DT of the system [6].

The paper is structured as follows: Section II reports how the empirical performance model was obtained. Section III presents the detailed structure description of the Digital Twin virtual entity ant its implementation framework. IN the discussion and conclusion section, the further development and application of presented DT are characterized.

II. EMPIRICAL PERFORMANCE MODEL

In order to have a reasonable empirical performance model, an induction motor (IM) ABB 3GAA132214-ADE was studied. The tested electrical motor is driven by an industrial frequency converter (ABB ACS880) with Direct Torque Control (DTC) algorithm. Additional frequency converter (ABB ACS800) IM setup was used as a load. To obtain an efficiency map, the load torque is gradually increased from zero to the calculated during the design stage rated load torque in a present ramp mode. All the experiments are performed in a real-time setup, including motors and frequency converters. The process of efficiency map obtaining is described in previous research by authors [7].

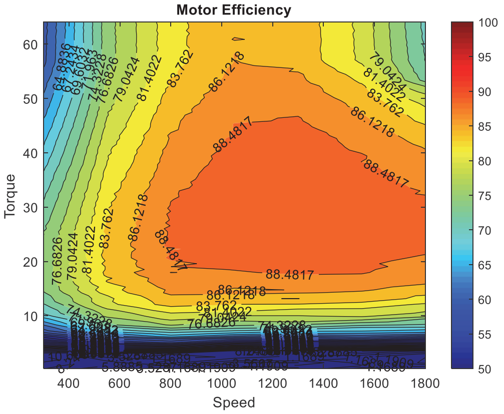

Fig. 1. The empirical performance model of induction motor used for Digital Twin.

The ratio of the motor shaft power (P_{mech_motor}) to the total electrical input power (P_{in_total}) is taken as motor efficiency:

$$\eta_{\text{motor}} = P_{mech\_motor}/P_{in\_total} \tag{1}$$

The graphical representation of an empirical performance model of IM is presented in Fig. 1 and rated data of the motor is given in Table I.

TABLE I. RATED DATA OF INDUCTION MOTOR

Parameter	**Unit**	**Value**
Motor frame size		132 MA
Rated Power	kW	7.5
Rated Current	A	22
Rated Speed	rpm	1460
cosϕ		0.6
Moment of inertia	kgm^2	0.048

The empirical performance model characterizes the loss distribution of IM on speed-torque characteristics. The copper losses are the dominant power losses in any electrical motor [7]. The torque of IM is proportional to the electrical loading and the magnetic loading. To increase the torque produced by the motor, both (electrical and magnetic) loadings must be increased. However, due to the saturation of the stator iron core in high magnetic flux density, the only constructive way to increase the motor torque is by increasing the electrical loading. That can be achieved by increasing the current density in motor windings, which in turn higher copper losses as well as lower efficiency.

Numerical representation of an IM empirical performance model may be used as one of the inputs for building DT to evaluate the IM performance over a given speed-torque region.

III. DIGITAL TWIN

A. Structure of the Digital Twin

The DT for the IM is set up in the following way: Unity 3D physics engine is used to simulate fundamental physics while connected via Robot Operation System (ROS) bridge, Linux ROS nodes simulate more advanced electrical machine-specific behaviors such as motor efficiency following the efficiency map and motor controller. As shown in Fig. 2. The primary benefit of Unity 3D, that it has a very

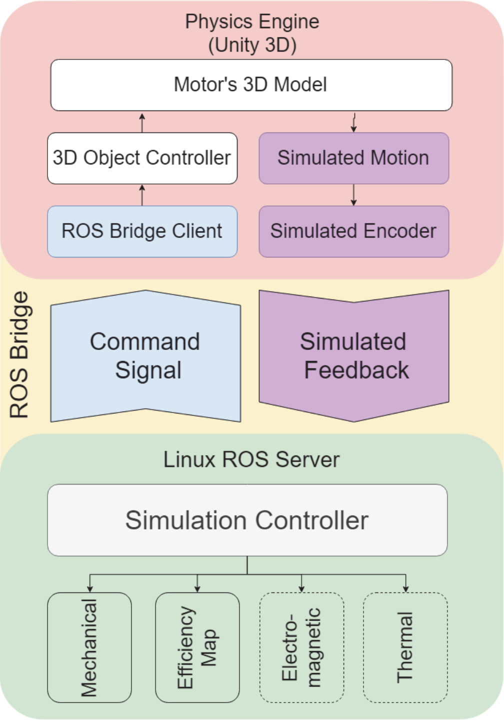

Fig. 2. The operational architecture of Digital Twin.

attractive system to work with 3D objects and simulate the effects of virtual physical forces. These upsides were a primaryreason for choosing Unity3D over more commonly used in research MATLAB, Matplotlib, or Mathworks on the recent stage of the project.

Linux ROS Server sends a User Datagram Protocol (UDP) command packet via ROS Bridge standard to the Unity 3D Visualizer. Its main task is to receive a control message from a specified IP address in a standardized ROS Bridge message format that is being published by the Linux ROS Server and control the 3D models to display the behavior of the motor as it would be in real life. It is also responsible for sending feedback to the Linux ROS Server for processing, just like a real encoder would send updates on the motor rotation rate to a motor controller.

Linux ROS Server Consists of multiple nodes that simulate various aspects (e.g., mechanical, thermal, electrical, diagnostic, etc.) of the motor, a single motor controller simulator node and a Simulation controller node that combines information coming from all other aspect simulation nodes and feedback from the Unity 3D, process it and send the data to a visualization client in Unity 3D.

More in the details physics engine of the DT is represented in Fig. 3. Unity 3D Visualizer message is received in the form of a UDP package in a custom ROS Bridge format by the ROS Bridge Client, reserialized into input variables (Empirically Estimated Velocity and Torque) of the motor and passed on to the 3D Object Controller as variables. Object Controller converts data from the empirical performance model to DT model velocity at which the shaft of the motor rotates. This data is applied to the motor's 3D visualization. Then a simulated encoder (so-called Virtual Sensor) takes the angular velocity of the motor shaft, converts it to feedback data, and sends it to the Linux ROS Server.

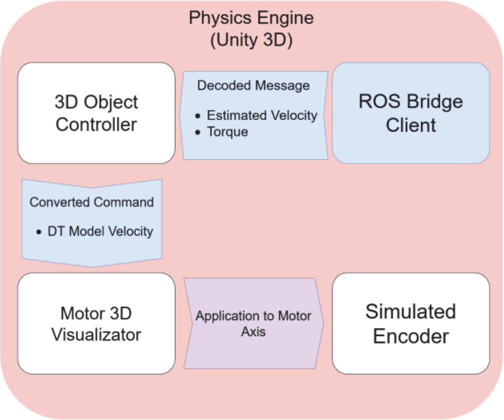

Fig. 4. Detailed representation of Digital Twin Physics Engine.

Currently, there are 2 active nodes in the simulation: a motor controller simulator node and a mechanical simulation node. The motor controller, has a proportional–integral–derivative (PID) controller that provides a control signal to the motor. Mechanical simulation node works with an efficiency map measured and recorded on a real motor and applies it to a simulation to emulate proper torques and power output at certain angular velocity to make DT act just like real entity motor.

B. Graphical representation or spatial model

The DT model does not undoubtedly mean a spatial or graphical model. The main accent should be paid to process flow and relations behind it as well as the data entity. However, the application of augmented reality (AR) and virtual reality (VR) tools for distance simulation via DT add safety layer and more possibilities for accelerated lifecycle tests, applications in hazardous environments, and remote work maintenance overall. Implementation of a virtual visual model can prevent plenty number of mistakes and errors without any performance or economic loss. Besides that, such a model can be a valuable tool for the education of technical staff and in universities. In the spatial model, the components of a real physical entity (e.g., windings, rotor, shaft, encoder, etc.) are constructed as CAD geometric models to be assembled in the virtual entity. The spatial model used for DT visualization is shown in Fig. 4.

Physics Engine has a ROS Bridge client that receives a data package from ROS Server. The data in that package is

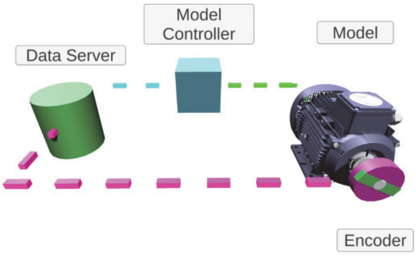

Fig. 3. The spatial model used for Digital Twin visualization.

extracted by the ROS Bridge client and sent to the 3D object controller that recalculates new positions and orientations of the simulated motor components. It then updates the 3D model with new states. This step ensures that a 3D model is acting like a real motor would from a visual standpoint. Then model takes into account any other physical forces applied to the motor, such as friction losses and moment of inertia of the motor simulated via angular drag feature in Unity 3D's Rigidbody, simulation and updates simulated encoder values which are then packed and sent to the ROS Server to act as feedback for the speed controller. The simulated encoder is modular and can be replaced by any other necessary feedback simulation. Currently a PID controller is used for its simplicity and ease of use.

IV. DISCUSSION

The term Digital Siblings (DS) is also introduced in [4] and can be considered as copy(ies) of the physical entity which need not necessarily run in real-time but can be used to test out hypothetical scenarios for maintenance, diagnostics, "what if?" analysis and risk assessment. Reduced models of the physical entities for DT and DS can be constructed using different model order reduction methods. A variety of condition monitoring techniques are available nowadays and may be combined with DT and DS approaches, e.g. electromagnetic field monitoring, noise and vibration monitoring, infrared recognition, temperature measurements, radio frequency emission monitoring, chemical analysis, acoustic noise measurement, motor current signature analysis (MCSA) and most advanced artificial intelligence-based techniques, such as fuzzy logic and neural networks etc. [8]

Very different software can be combined to achieve the proper sibling. An example of hybrid Finite Element Analysis (FEA)-Simulink modelling of permanent magnet assisted synchronous reluctance motor is presented by J. Pando-Acedo et al. in [9]. Cross-platform software that combines multiphysics graphical applications with powerful pre-processing, solvers, and post-processing capabilities will be preferable for DS and DT creation. Nowadays, some of the optimization framework as Artap [10] are linking together different software parts and interfaces for both of gradient-free and evolutionary based optimization methods, meta-modeling techniques, surrogate models and FEM solvers.

That fact that developed DT ROS nodes are modular makes it very easy to add nodes responsible for electromagnetic, thermal, diagnostic or any other simulations. Different reduced models of the devices running parallel and in real-time can be used to assemble a DT. Studies shows [11] that model order reduction is a promising tool for controlling industrial processes, where some of the parameters cannot be measured directly.

Diagnostics as a promising application will be considered as foreground implementation of the DT based on the modified winding function-based model described in [12]. However,

V. CONCLUSION

The concept of DT is gaining popularity nowdays in many different industry oriented fields. Creating and maintaining a digital representation of the real physical entity, and supporting device performance using different simulation and optimization tools are a key goal of many research works.

This paper presents a development case of DT for an electric motor based on an empirical performance model. The paper consider obtained data required for the DT development. A detailed structural description of the virtual entity based on Unity3D engine is presented.

The main application of the recent DT is a loading motor-drive system for the test bench to estimate the performance of the electric propulsion drive system of an autonomous electric vehicle. The development and implementation of the concept of DT, will help to provide a brand-new approach for measurement and estimation of the performance of motor-drive systems.

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Appendix 5

Publication V

V. Rjabtšikov, A. Rassõlkin, V. Kuts, K. Kudelina, T. Vaimann, A. Kallaste, A. Partyshev, "Parametric digital twin of autonomous electric vehicle transmission," Journal of Machine Engineering, vol. 21, no. 2, pp. 131–140, 2021, doi: 10.36897/jme/134435.

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autonomous vehicles, gears

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PARAMETRIC DIGITAL TWIN OF AUTONOMOUS ELECTRIC VEHICLE TRANSMISSION

Variable applications and methodologies are used in the Digital Twin technology. Digital Twin as a trending technology is also a general topic of many industry-oriented research projects. To develop and implement a novel technology, a detailed study of any single part of a system is required. This paper presents a development case study of the parametric Digital Twin of autonomous electric vehicle transmission. Digital Twin combines the advantages of software models and real equipment to reduce total test runs and safe maintenance. The primary duty of the Digital Twin is to allow complete synchronization and connectivity between virtual and real entities. The paper presents a detailed structural description of the virtual entity that considers the parametrization of the transmission.

1. INTRODUCTION

As traditional design methods and control approaches are often ignored, it is impossible to receive, store, and process real-time data. However, the Digital Twin (DT) concept enables use of system data in many different ways, i.e., not only for detecting anomaly or fault. The advantage of DT is an ability to simulate several modes of system behaviour, trying to reproduce the actual data from the object to predict operation modes that may contain serious failures or just improve the overall performance. The DT concept is based on the idea that a digital informational construct about a physical system could be created as an entity on its own [1].

A distinct advantage of the DT technology is the ability to review detailed data of a single system unit. As a result, DT helps to determine the components that lead to poor performance of a system and thus can be replaced to improve results. That is a merit of essential importance for such a complex system as a propulsion motor-drive system of an electric vehicle that typically includes an electrical machine(s) (motor(s) and/or generator), transmission (reduction gear or gearbox, bearings, etc.), power electronics converter, sensors, and control units. The mechanical part of the electrical drive system causes

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a major proportion of overall faults that are degenerative, i.e., they tend to increase with time [2]. Maintenance of the mechanical part and checking the mechanical operation of devices, verifying proper lubrication, and manually or electrically operating any device that seldom operates should be standard practice [3] for any electrical drive application. DT solution covers a wide range of services, such as efficiency improvement, minimization of failure rates, shortening of development cycles, and opening up new business opportunities [4].

DT, as a virtual entity, must digitally mirror processes occurring within a physical entity. In the real world, multiple physical effects act on an object simultaneously [5], and it is impossible to consider the electrical drive system as an electrical device. There is always a need to consider other phenomena, such as thermal effects or mechanical vibrations. This optimum may need to be reconsidered. DT must reflect effects in different physical domains (electrical, mechanical, thermal). The current study is a part of the research project [6] with the final goal to develop a specialized unsupervised prognosis and control platform for the propulsion drive of an autonomous electric vehicle that may be used for performance estimation, control system tuning, maintenance and diagnostics, and many other services. The main aim of the paper is to present a development process of a parametric DT for an autonomous electric vehicle transmission.

2. TRANSMISSION PARAMETRIZATION

2.1. TEST PLATFORM (ISEAUTO)

ISEAUTO is the first Estonian self-driving vehicle developed in cooperation between Tallinn University of Technology (TalTech) and several industrial partners. ISEAUTO is a last-mile vehicle designed to operate mainly on the TalTech campus. Therefore, the speed of the car is limited up to 20 km/h. ISEAUTO self-driving vehicle is an interdisciplinary project that includes contributions from different fields [7]. The mechanical structure is an essential part of a self-driving vehicle; it is to be altered and designed to guarantee dynamical unwavering. ISEAUTO self-driving car was built on a Mitsubishi i-MiEV trolley based on Y4F1 permanent magnet synchronous motor (PMSM) [8]. Electrical motors show better performance at a precise speed and torque [9]. That performance region depends on the type of the motor and is usually chosen based on a certain application. While ISEAUTO is a last-mile vehicle and its speed is limited, the transmission is used to cover the best efficiency region of the propulsion motor. The transmission used in the self-driving vehicle F1E1A (without shifting function) comprises a simple meshing of two pairs of gears as well as a highly reliable differential at an overall reduction ratio of 6.066.

2.2. 3D. SCANNING OF TRANSMISSION

To define the domain to be simulated, specific data is required, such as mechanical and material characteristics, Poisson's ratio (i.e., the negative of the ratio of (signed) transverse strain to (signed) axial strain) and Young's modulus (i.e., a mechanical property that measures the stiffness of a solid material), which create the geometry of the component [10]. For the first step of transmission parametrization, the spatial model was created using 3D scanner ATOS II 400. This inspection hardware uses structured light technology, and the measuring frequency is 1.4 mil points per 7 seconds. The resolution is 0.177 mm. For larger object digitalization, markers should be used – those are being installed on the scanning object to merge various scanning pictures later during the post-processing process [11]. The advantages of this scanning technology are: high precision in a short amount of time and technology safe to the eyes. Disadvantages are: system setup is sensible to the ambient light; glance surfaces are impossible to 3D scan, and precision is not enough for small detailed parts with various surface features such as ribs and sharp corners. In related research, due to its high precision for large object inspection, the ATOS 3D scanner was used for digitalization of transmission. As a result, autonomous electric vehicle transmission shown in Fig. 1 is taken as a spatial entity of the DT.

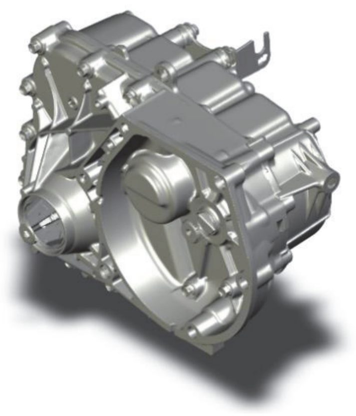

Fig. 1. The parametrization of DT spatial entity of the transmission accomplished with 3D scanner ATOS II 400

F1E1A is a double stage type transmission with four gears, as shown in Fig. 2. The first gear is the pinion gear of the input shaft, which is connected to the rotor of the vehicle traction motor. The second and third pinion gears have a common shaft. The fourth gear is connected to the output shaft and vehicle differential. The parameters of gears are presented in Table 1; all the shafts have the same diameter of 22 mm.

Table 1. Transmission gears

Gear	Diameter, mm	Width, mm	Teeth number
1st	58.9	27	25
2nd	93.9	251	42
3rd	56.1	32.2	18
4th	179	27.6	65

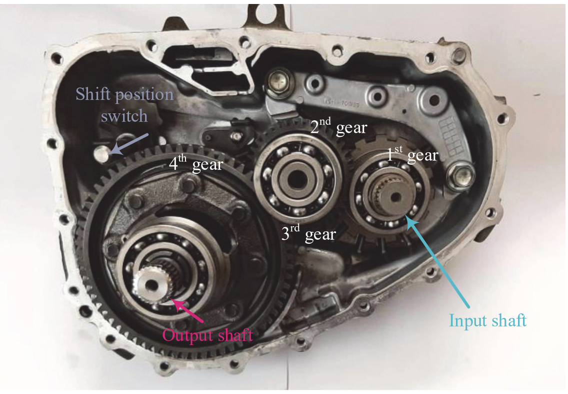

Fig. 2.F1E1A transmission levels and construction

Gear ratio (n) of the transmission can be calculated by the next equation:

$$n = \frac{n_4}{n_3} \times \frac{n_2}{n_1}, \tag{1}$$

where $n_{(1..4)}$ is the number of teeth of gear 1..4, respectively. Gear ratio depends on the maximum speed, the wheel radius, the maximum motor speed, and the traction power between the road and the tires. A smaller motor speed relative to the vehicle speed means a lower gear ratio, smaller size, and lower cost [8].

To switch the working modes, a shift position switch is used. While there is no gear shifting mechanism, no actual gear change occurs when the shift position is changed, but the shift position detected by the shift position switch is transmitted to the vehicle control unit, e.g., when the shift position switch is in reverse, the motor revolution is inverted. Regene-rative brake is in the standard model of the standard driving mode of the vehicle. However, the transmission has an additional regenerative brake mode in which a stronger deceleration effect can be obtained by enhancing the regenerative brake effort, and a so-called comfort mode, suitable for driving through the suburbs by decreasing the regenerative brake.

2.3. THE EFFICIENCY OF THE TRANSMISSION

Power losses in transmission appear in gears, bearings, and seals. Moreover, auxiliary losses should also be considered. Gear and bearing losses are separated into two different categories: load and no-load dependent losses [12, 13], the transmission losses (Δp_{meh}) are classified in Fig. 3. It is important to note that for nominal power transmission, the load losses of the gear are typically dominant, and in the case of part load and high speed, no-load losses dominate the total losses [14].

$$\Delta p_{meh} = \Delta p_{G0} + \Delta p_{GL} + \Delta p_{B0} + \Delta p_{BL} + \Delta p_s + \Delta p_{aux} \tag{2}$$

No-load gear losses are independent of the loading torque. They appear with the rotation of the mechanism since no-load losses may be counted as lubricant losses due to the viscosity and density of the lubricant, internal design of the transmission, and bearings. No-load gear losses rely on the arrangement, size, type, lubricant viscosity, and immersion depth.

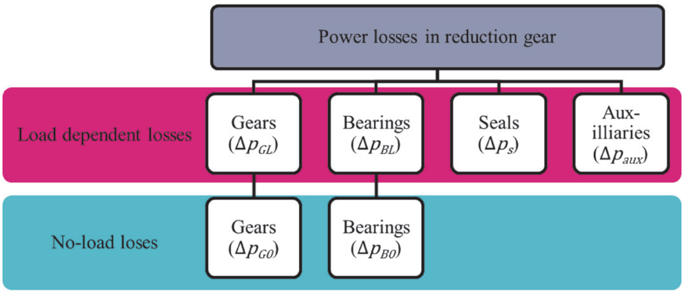

Fig. 3. Power losses in transmission

Load dependent gear losses occur in the contact point of the power transmitting elements. Load dependent gear losses rely on the friction force ($F_{R(X)}$) and relative velocity $V_{rel\,(X)}$, and follow the basic Coulomb law:

$$\Delta p_{GL} = F_{R(X)} \cdot V_{rel\,(X)} \tag{3}$$

Commonly, load dependent gear losses that take into account the gear loss factor is expressed as:

$$\Delta p_{GL} = P_{IN} \cdot H_V \cdot \mu_{mZ} \, , \tag{4}$$

where: P_{IN} is the transmission input power, H_V is the gear loss factor and μ_{mZ} is the coefficient of friction.

Gear loss factor (H_V) is a constant calculated based on the base helix angle, load distribution, the path of contact, and other gear parameters. In their study, C. Fernandes et al. [12] give three different equations for the calculation and propose the calculation method that does not consider the elastic effects of the gears. They show the influence of the calculation of the gear loss factor that is dependent on the geometry of the gear in the prediction of the power loss. The average coefficient of friction (μ_{mZ}) between the gear teeth for different gear geometries is a complex gain that is usually based on empirical results, and naturally, the results vary for the same operating conditions.

No-load bearing losses highly depend on the bearing type and size (e.g., lowest no-load losses of radial bearings are expected for cylindrical roller bearings [12]), bearing arrangement, lubricant viscosity, and supply. Load dependent bearing losses rely on the size, type, rolling (load) and sliding conditions, and lubricant type. Wimmer et al. [15] provide an analysis of the influence of different bearing types on no-load and load losses.

Shaft sealing losses are caused by the friction that occurs between the shaft, and its sealing. Shaft sealing losses (Δp_s) depend on the shaft diameter (D) and rotational speed (n), and according to C. Changenet et al. [16], these losses can be calculated by:

$$\Delta p_s = 7.69 \cdot 10^{-6} \cdot D^2 \cdot n \tag{5}$$

Auxiliary losses take into account losses that are hard to determine, e.g., lubricant losses. Transmission requires lubricant to avoid friction and deformations on the gears teeth connection where losses occur when the lubricant is splashed to the pinion, which creates a drag torque on it. Lubricant losses depend on the rotational speed of the pinion, the surface area of the pinion contacts with the lubricant, pitch diameter of the pinion, and density of the lubricant. C. Changenet et al. [16] give an equation to estimate the drag torque that is acting on a pinion as an additional load.

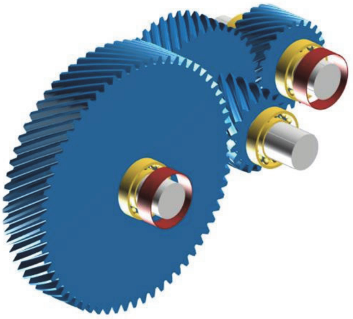

Fig. 4.3D model of a F1E1A gearbox gears

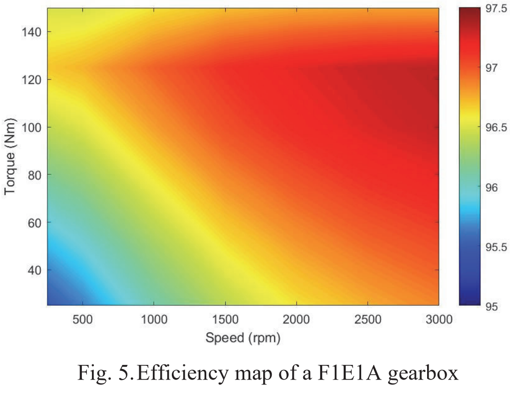

Fig. 5.Efficiency map of a F1E1A gearbox

Various computation tools are used to determine the power losses and build an efficiency map of the mechanical transmission. WTplus software [17] developed in TU Munich is used to calculate the efficiency and the heat management of any manual, automatic, and industrial gearbox. Another software is KISSsoft, with a special template implemented in KISSsys to automate the efficiency calculation and thermal rating of a whole gearbox - including gears, shafts, bearings, seals, discs, synchronizers, and other machine elements [18]. By measuring all the gears of the existing F1E1A gearbox, the 3D model was built, which can be observed in Fig. 4. Using the KISSsoft software, we imported a 3D model to the software we used to calculate a gearbox's efficiency. By considering materials, bearings, grease, etc., an efficiency map of a gearbox was calculated and shown in Fig. 5. The torque and speed upper limit is defined by an electric drive's capabilities, which is 150 Nm of torque and 3000 rpm of speed.

3. DIGITAL TWIN

DT simulation of the transmission has two key parts, as shown in Fig. 6. A primary simulator is a ROS Node that receives an input consisting of torque (τ_{in}) and angular velocity (ω_{in}) via the ROS Bridge protocol. This input can be supplied by any ROS-based motor controller with an encoder, even a simulated one. The primary simulator then calculates an expected output based on the following equations:

$$\tau_{out} = \frac{\tau_{in}}{n}, \tag{6}$$

$$\omega_{out} = \omega_{in} \cdot n, \tag{7}$$

where n is calculated using formula (1); efficiency simulation of the transmission is one of the main tasks of the primary simulator.

It is achieved by interpolating the efficiency of the transmission at a specific torque and angular velocity based on an empirically (generated, gathered, collected, created) efficiency map. Afterward, the resulting torque (τ_{out}), angular velocity (ω_{out}) and efficiency are published as a ROS topic for further use by the second part of the DT – 3D Visualizer.

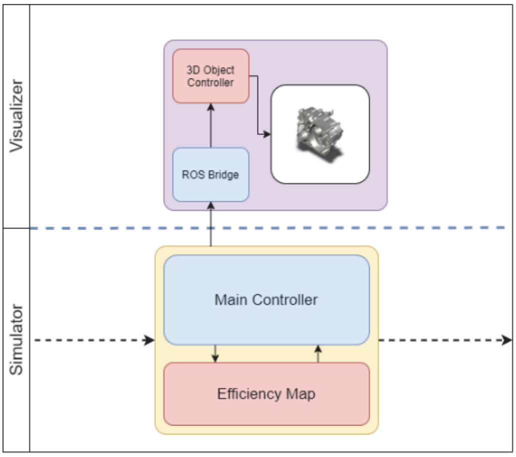

Fig. 6. The operational architecture of the transmission Digital Twin

Both simulation and visualization of the transmission are based on the framework created for the DT of the load motor [19]. They work and communicate in the same way via the ROS Bridge; however, visualization of the transmission does not provide feedback to the simulation because there is no closed-loop speed controller that requires feedback. The transmission does not drive itself. It only converts the inputs it is given by the rest of the system.

Visualizer is responsible for providing a 3D representation of the behaviour of the DT, Unity 3D capture of the transmission shown in Fig. 7. It is achieved by taking the data published by the primary simulator and feeding it to the 3D model controller that recalculates states of each 3D object and makes the transmission's CAD model appear on the screen as the real transmission would in any given conditions.

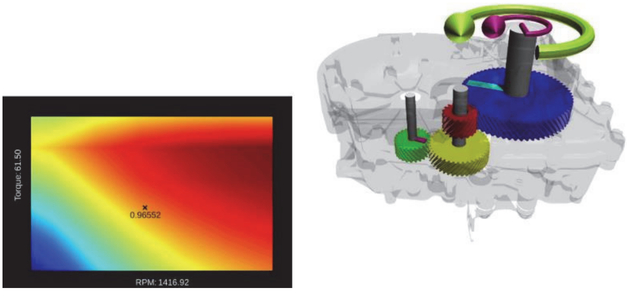

Fig. 7.Unity 3D live visualization of transmission

Digital Twin of the gearbox creation process architecture is presented in Fig. 8. 3D scan of the gearbox is required to determine mechanical and material characteristics. Obtained data is used to create a spatial model of the gearbox, which later can be used in the simulator. The simulator is consisting of a middle-layer, in our case is ROS, and data is taken from he cloud server. Finally, the 3D visualizer block uses a Unity 3D engine and demonstrates the gearbox work.

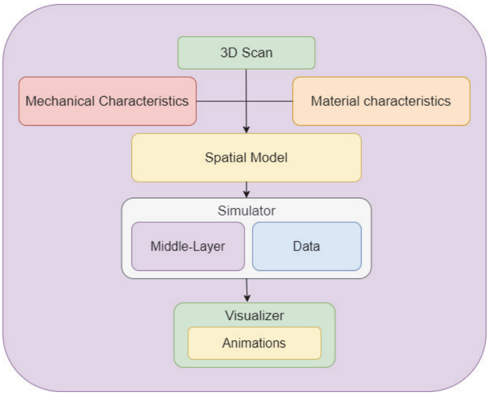

Fig. 8. Process architecture

4. CONCLUSION

The transmission parametrization process starts with 3D scanning of the studied object, followed by the prescription of gears and efficiency calculation. The spatial model created in the Unity 3D real-time development platform is supplied with proper inputs and outputs to connect the physical model. Such a physical model that takes into account the efficiency of autonomous electric vehicle transmission serves as a perfect tool to construct the DT for the mechanical part of the whole propulsion motor-drive system. The concept of Virtual Sensors based on the developed DT may be introduced. The overall performance of the current autonomous electric vehicle may be studied and improved based on the developed DT.

The future transmission DT development will include combining transmission DT with the DTs of the other parts of the propulsion drive of autonomous electric vehicles (motor, controller, etc.). Moreover, transmission DT will be synchronized with the real transmission on the developed test bench [20] and will be trained to provide a bridge between real and virtual entities of the system. Artificial Intelligence (AI)-based system will be developed to be able to diagnose and predict the condition of the device to timely provided services (incl. future services schedules), data about unusual situations and other circumstances based on the historical data of the propulsion drive system and the physical/mathematical model (DT).

ACKNOWLEDGMENTS

The visualization of real-time operation of the considered example one can see in the following URL: https://youtu.be/RggHNE3hvOo Source code of developed DT is available on: https://github.com/TalTech-PSG453/gearbox_dt.git.

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Appendix 6

Publication VI

V. Kuts, A. Rassõlkin, A. Partyshev, S. Jegorov, and V. Rjabtšikov, “ROS middle-layer integration to Unity3D as an interface option for propulsion drive simulations of autonomous vehicles,” in Proceedings of the International Conference of DAAAM Baltic, DAAAM International Vienna, 2021. doi: 10.1088/1757-899X/1140/1/012008.

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ROS middle-layer integration to Unity3D as an interface option for propulsion drive simulations of autonomous vehicles.

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Abstract. As autonomous vehicle development continues at growing speeds, so does the need for optimization, diagnosis, and testing of various autonomous systems elements, under different conditions. However, since such processes should be carried out in parallel, it may result in bottlenecks in development and increased complexity. The trend for Digital Twins brings a promising option for the diagnosis and testing to be carried out separately from the physical devices, incl. Autonomous vehicles, in the virtual world. The idea of intercommunication between virtual and physical twins provides possibilities to estimate risks, drawbacks, physical damages to the vehicle's drive systems, and the physical one's critical conditions. Although the problem of providing communications between these systems arises, at the speed that will be adequate to represent the physical vehicle in the virtual world correctly, it is still a trending topic. The paper aims to demonstrate a way to solve this problem - by using ROS as a middleware interface between two twining systems on the autonomous vehicle propulsion drive example. Data gathered from the physical and virtual world can be exchanged in the middle to allow continuous training and optimization of the propulsion drive model, leading to more efficient path planning and energy-efficient drive of the autonomous vehicle itself.

1. Introduction

Simulation is an approximate or 1-to-1 imitation of a real process, often taking part in the virtual environment, troubleshooting, researching, testing, training, monitoring, controlling, or educating. In the past decade, simulations have been vital in production and development as they are capable of preventing many problems related to planning and reducing bottlenecks at early stages, also during the real-time maintenance of the process [1]–[5] and, especially with increasing technology complexity and rise in using fully autonomous systems, enforcing and changing work-safety features. One side of the simulation aspect - the concept of Digital Twin (DT) [6], [7] is being exploited in the related research to develop a precise dual-way synchronized simulation interface for the propulsion drives [8], [9] to be ready to be integrated into the electrical vehicles [10].

Physics simulations are very common and critical nowadays. They are used enormously in such applications as MATLAB Simulink, Simscape, CAD design, SolidWorks, etc., and gaming physical processes simulations. They should be considered in the mechatronic systems' planning stage [11]. Of course, they all have approximation and simplifications, while not all possible physical laws can be yet simulated simultaneously; however, such simulations provide considerable benefit in research and testing.

In a previous study done by authors of the related paper, which was on the on electrical motors simulation under development of DT for propulsion drive of an autonomous electric vehicle [12], Unity3D was used for simulations of DT that was exchanging messages with Robot Operation System (ROS) node through a ROS bridge [13]. However, ROS is not being used only for robots but also for various drones, self-driving vehicles, and autonomous systems. ROS enables inter-process communication; it is believed to be a quality method of interconnecting a digital twin propulsion drive system with its real counterpart. ROS was used for performance calculation using an empirical performance model for induction motor (IM). As a visualization tool in the related research is being used Unity3D which is connected with ROS directly [14]. Even though Unity3D simulated most of the motor's physical behavior (torque and rotation), the response and received numerical values, unfortunately, do not suit the DT development in the long run. The reason for this is the complexity of the overall system of physics of IM. Moreover, to make the system transferable and usable with other models (not the ones present in Unity3D but also in Gazebo or elsewhere) the physics handling has to be close to standalone.

The research's main aim is to develop a framework and a toolkit, including a middle-layer ROS interface connected with the physical propulsion drive workbench and its DT, which can be visualized in various simulation engines. The related paper aims to develop a methodology to connect the interface with Unity3D for the visualization, considering data exchange and feedback.

2. Methodology

2.1. Working principle of a test bench on a digital twin

For the current case study, the DT operates on the simulated data generated based on real data measured and gathered from the 7,5 kW IM (ABB 3GAA132214-ADE). The data was gathered using the data acquisition system (DAS) Dewetron Dewe 2 and saved into files with a different extension (*.mat, *.xlsx, *.csv, *.txt). The measured data can be anything regarding the motor's operation, namely input currents and voltages, consumed and shaft powers, torque and angular velocity on data acquisition, and other side data calculated from them. According to DAS tuning (16Hz - 100kHz), the parameters can be measured with different frequencies, and received data is relative to time. This feature enables to recreate of the motor's behavior precisely as it happened in the real case scenario with the help of ROS Server. An example of such can be seen in Figure 1, where the input current from frequency converter to IM was recorded and now can be simulated in ROS (graph from ROS package *rqt plot* we were not included to the related paper because it could not handle plotting messages at such high frequency).

In the proposed DT system, ROS Server acts as a data server and physics simulator. The idea behind it is the following: the server is a standalone subsystem of a TB DT that is responsible for processing real, measured data of the motor, calculating other motor parameters based on the processed data, and streaming to the ROS topics available for models.

Figure 2 features the architecture of the DT setup for TB. The real data is fetched to appropriate ROS Nodes (components of ROS server that are performing calculations, real data processing, and streaming of data) present in the server, processed and translated into ROS messages, and finally, sent to the DT model over ROS Bridge. The real data can be based on the empirical model/map of the motor (or its part) or the actual raw data.

Upon receiving ROS messages, the model can perform the necessary actions to simulate the mechanical/electrical/thermal behavior. Models can be present in any simulation environment. They are subscribed to ROS Server's topics over API or ROS Bridge and configured to perform the necessary operations based on the subscribed ROS topic (for example, rotation based on received angular speed). Furthermore, the module can feature simulated 'measurement' devices/sensors that can send back the data over the ROS bridge. In this case, the ROS Nodes can process and calculate other required values, as it would happen in the real TB.

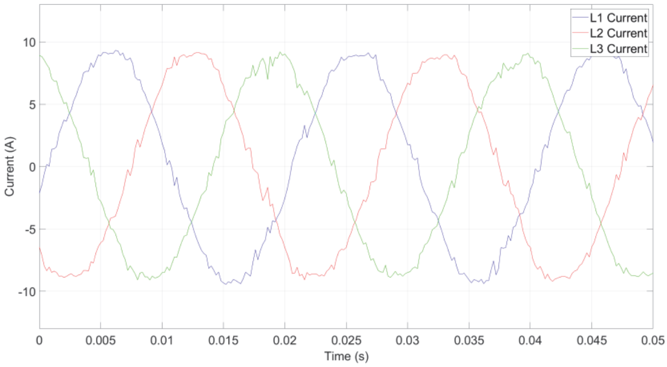

Figure 1. Input current measurements sampled at 5kHz frequency

The current DT of TB consists of the Unity 3D model and ROS Server. ROS Server streams simulated values regarding input power (3-phase current and voltages), efficiency calculated based on measured torque and angular velocity. The torque is calculated by the physics engine of the Unity3D, whereas other values are based on the real ones. This creates a problem of incorrect data calculation because Unity does not focus on calculating correct values on physics laws, as it is more for games, allowing developers to adjust the physics laws to the game setup. This is why the shift from the physics engine of the model environment to ROS was introduced. ROS server would serve physical parameters based on the real TB data and independent of the modeling environment.

Additionally, ROS can record *rosbags* – files with recorded values from topics/servers that can be played back to repeat the behavior. Such a feature would allow us additional analytical features from the DT side.

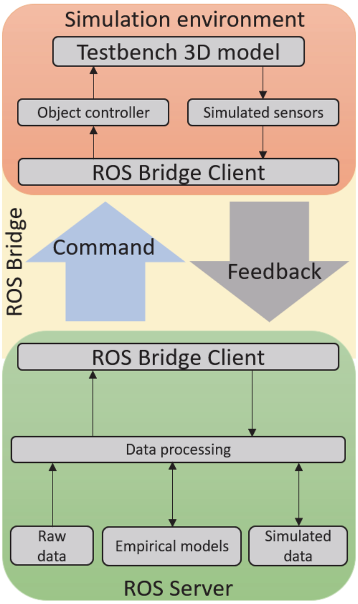

Figure 2. The generic architecture of TB DT

2.1.1. ROS Interfacing

To allow easy interfacing of ROS with other systems, a ROS Bridge node has to be used. It converts ROS communications into a JSON file format and sends them outside of the ROS ecosystem. JSON is used because of its universal format with existing libraries that support its serialization and deserialization in almost every modern programming language. Taking it one step further, ROS Bridge can be used to port specific ROS topics to and out of Message Queuing Telemetry Transport (MQTT) protocol to upscale the system and allow it to run on multiple machines around the world. This so-called MQTT Bridge sends data to the remote server by taking the serialized message on a specified ROS topic and publishes it into a specified MQTT topic. MQTT Bridge is also capable of the inverse - it receives a JSON-serialized message and attempts to deserialize it into a specified ROS topic in a specific message type. Together these systems make interfacing of ROS with any visualization solution much simpler to develop. To further simplify the deserialization process, classes that match ROS message types were created in C# for Unity3D implementation of the ROS interface. This approach can be considered the most efficient because, in this case, a ROS message delivered in the serialized form via MQTT can be directly deserialized into an object of a matching type. This approach can be implemented in similar ways on the majority of existing programming languages, making it the most straightforward and most versatile option.

Visualization is being done in Unity3D (See Fig. 3) engine connected to the physics simulator via ROS Interface, where it is a 1 to 1 scale propulsion drive model with the transmission, wheel parts, and non-visible gears. Model is being assembled as the physical one, and each part is being controlled by a related script, where data is being fed from the middle layer.

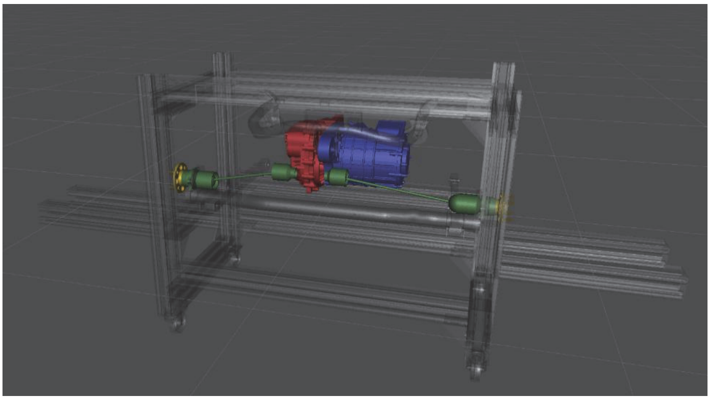

Figure 3. Visualization of propulsion drive test bench done in Unity3D

3. Discussion

The primary outcome of the related part of the more extensive research in developing the fully synchronized DT of the propulsion drive is that the ROS interface was developed. It is possible to feed it with gathered from the physical data and give to the visual simulated, which in related use-case is being Unity3D. The given data simulation runs and gives logged feedback about physical interactions back to the ROS middle layer, where the model is being improved and sent back to the visual side, improving it after each data movement loop. However, some limitations were met during the development of methodology, and more developments go to reach the final aim of the stated research aim (See Table 1).

Table 1. Limitations and further steps

Limitations	**Future steps**
The model was tested with only one type of visual simulation tool. Possible additional integrations should be done in the middle layer to be suitable for additional software tool packages.	To establish correct torque calculations based on the real values collected from the physical TB.
	To implement a two-way connection between physical TB and its DT.
If DT and TB work simultaneously over the internet, the frequency of data acquisition may be too high to send on time, the possibility of lags	The injection process flow of new components of TB into the DT.
	To create unpredicted behaviors in the system, trigger points, and try to make the system respond to the unpredicted change making it more adaptive to changes

4. Conclusions

The ROS interface connected with the Digital Twin of the propulsion drive workbench visualized in Unity3D was introduced during the related work. Raw and simulated data and empirical models can be post-processed and fed to the visual simulation, where additional data is being logged and given as feedback to the middleware to improve the model and physical simulation itself. The next crucial step is to feed physical simulation directly with data from the physical drive, enabling synchronization between the real and virtual worlds through the developed interface.

5. Acknowledgments

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Appendix 7

Publication VII

V. Rjabtšikov, M. Ibrahim, B. Asad, A. Rassõlkin, T. Vaimann, A. Kallaste, V. Kuts, M. Stepien, M. Krawczyk, “Digital Twin Service Unit Development for an EV Induction Motor Fault Detection,” in 2023 IEEE International Electric Machines and Drives Conference, IEMDC 2023, Institute of Electrical and Electronics Engineers Inc., 2023. doi: 10.1109/IEMDC55163.2023.10239085.

Digital Twin Service Unit Development for an EV Induction Motor Fault Detection

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***Abstract*—The principle of Digital Twin (DT) is to create a connection between a physical asset and its corresponding virtual twin established by generating real-time data using sensors. DT can be used for real-time condition monitoring, fault detection, optimization, prognosis, and lifetime prediction. This paper proposes the application of a DT service unit for an electric vehicle (EV) induction motor (IM) fault detection. IM stator inter-turn short circuit fault is used as a study case to highlight the DT service unit function. Such a fault is considered one of the most prevalent possible IM failures. Based on real-time measurements, Linux Robot Operation System (ROS) simulates IM's specific behavior in case of unbalanced stator currents and notifies about possible fault appearance and propagation. The obtained results from DT allow adding additional services that consider another failure, and as a result, improve physical entity reliability.**

Keywords—Digital twin, fault detection, induction motor.

I. INTRODUCTION

Digital Twin (DT) is one of the trending technologies nowadays. It is defined as a virtual representation of a physical object that collaborates throughout its lifecycle and provides services for evaluation, optimization, prediction, etc. Although both simulations and DTs simulate products and processes based on digital models, they differ in keyways [1]. As an example, a DT can be used to run several simulations, backed up with real-time data, and it can be connected to sensors that collect this data so that both parties can exchange information. Recent works [2] described DT technology as a five-dimension structure, with services and connections as separate entities. Different test benches may be added as an additional entity to the complex system's development and implementation process as simplified models of the system as presented in [3]. Fig. 1 shows the 5-dimensional DT model. The virtual entity represents the physical entity in various ways and oversees the DT system's observation, simulation, control, and optimization strategies.

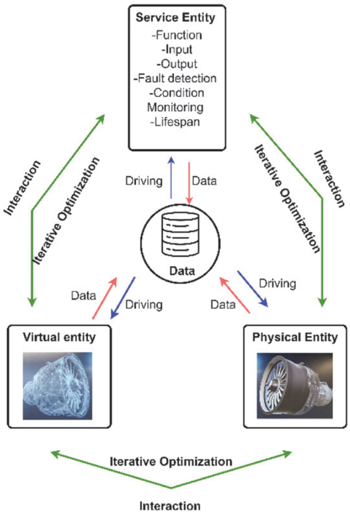

Fig.1. 5-D Digital Twin Model Components.

The data entity operates the entire system and creates the DT itself. The service entity is a platform with a set of services that responds to the needs of both physical and virtual entities. The connection that defines the interaction between other entities is the final entity that completes the five-dimensional DT model. In addition to regulations in the physical element, service entities may include sub-services, such as path planning, energy optimization, fault detection, maintenance, diagnostic, etc.

In another context, the potential of EV technology to reduce emissions and improve the environment has been receiving a great deal of attention recently. An electric motor is considered the core element of the EV powertrain. Many types of electric motors are usable in EVs such as

Induction Motors (IMs), Permanent Magnet Synchronous Motors (PMSM), and Switched Reluctance Motors. The main reasons behind using IMs are due to their simple and robust construction as well as electric drive-friendly implementation in EV powertrains [4]. One of the severe problems that could occur to the EV powertrain is the electric motor failure. The reasons behind motor failures might be a combination of one or more issues that have their origin in design, manufacturing tolerance, assembly, installation, working environment, nature of the load, and maintenance schedule. IM stator inter-turn short circuit fault is considered one of the four most prevalent possible electrical motor failures, together with air gap eccentricity, broken rotor bar/end-rings, and bearing failures [5]. Usually, the inter-turn short circuit starts with insulation failure, accompanied by extremely high current flow due to the high voltage potential differences between adjacent coils.

DTs for electric motors fault detection is a relatively new concept that has been gaining traction in recent years. It involves the use of digital models of electric motors to detect and diagnose faults in the physical motor. Research has explored the use of DTs for fault detection in electric motors. Drummond et al [6] proposed a 3D finite element model of an IM with broken rotor bars in a DT concept to verify the fault effects. While, Venkatesan et al [7] developed an intelligent DT for health monitoring and prognosis of an EV-PMSM based on an artificial neural network (ANN) and fuzzy logic algorithm. Generally, literature review has revealed that preventive maintenance programs can significantly reduce the number of electrical motor rewinds from 85% to 20% of the entire motor repairs [8].

This paper presents the development procedures of a DT service unit of an EV- IM for fault detection. It’s organized as follows. Section I highlights generally the research topic and recent works done in this regard. The procedures of fault-imitating measurements for DT development are presented in Section II. Section III is divided into two subsections. In section III.A. The specific behavior IM’s simulation model dedicated to detecting possible fault appearance and propagation. While section III.B addresses the real physical motor model (IM test bench). A detailed description of the ROS-based service unit is proposed in section IV. The main research findings are addressed in section V. The overall conclusion and future research works are proposed in section VI.

II. PROCEDURES OF FAULT DETECTION

Fault detection of electric machines at the elementary stages for predictive maintenance is essential for a safe and reliable industrial operation. This is also essential for machine life-time prediction as the faults are degenerative. Finding faults in the early stages of machine operation is advantageous when designing and maintaining the machine. A fault can be confirmed by verifying the mathematical model in which the accurate data from the real physical model is constantly sent. A massive amount of data is required to properly train the mathematical model, resulting in a more accurate fault detection result.

With an inter-turn short circuit, an imbalance occurs in the stator windings, whereas the resistance decreases in the winding with a turn-to-turn short circuit. An adjustable resistor connected in parallel to the winding's first phase was used for experiments with a smooth decrease in the first phase of the winding resistance. Adjusting the parallel connected resistor changes the total resistance of the first phase winding while also decreasing current passing through the winding by directing some of the phase current to the resistor. Assume the regulated resistor's resistance equals the first phase's winding resistance. In that case, the current passing through the first phase is divided exactly in half, resulting in 50% of the fault, or an inter-turn short circuit between half of the winding. Fig. 2 depicts an illustrative figure.

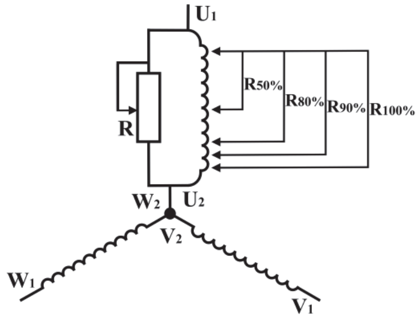

Fig. 2. Stator winding of induction machine with parallel connected regulated power resistor.

III. DT DEVELOPMENT PROCEDURES

The creation of a DT of a system is supported by three main pillars: the physical element, the virtual representation, and the means of communication (service unit) between them.

A. EV-IM Spesific Behaviour Simulation Model

The stator inter-turn short circuit introduces asymmetry in phase currents and voltages. This asymmetry can be detected either by the Park’s vector approach or by detecting negative sequence currents. In case of Park’s vector, the circuit made by id and iq currents will change its shape with increasing fault. The Park’s vector and its modulus can be defined as.

$$i_a(t) = I_m \ sin(\omega t) \quad (1)$$

$$i_b(t) = I_m \sin\left(\omega t + \frac{2\pi}{3}\right) \quad (2)$$

$$i_c(t) = I_m \sin\left(\omega t - \frac{2\pi}{3}\right) \quad (3)$$

parent $$\vec{i}_s(t) = \frac{2}{3}\left(\vec{i}_{as}(t) + a\vec{i}_{bs}(t) + a^2\vec{i}_{cs}(t)\right) \quad (4)$$

$$\vec{i}_s(t) = \frac{2}{3}\left(\vec{i}_{as}(t) + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)\vec{i}_{bs}(t) + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)\vec{i}_{cs}(t)\right) \quad (5)$$

$$\vec{i}_s(t) = \vec{i}_{ds}(t) + j\vec{i}_{qs}(t) \quad (6)$$

$$PVM_h = \sqrt{i_{ds}^2 + i_{qs}^2} = I_m \quad (7)$$

Where ia, ib and ic are the measured three phase currents, the space vector, and PVM is the Park's vector modulus. Since the asymmetrical faulty machine will lead to asymmetrical three phase currents, the negative sequence currents can never be zero. The zero, positive and negative sequence currents can be calculated as.

$$I_0 = |I_a + I_b + I_c| / 3 \tag{8}$$

$$I_n = |I_a + aI_b + a^2 I_c| / 3 \tag{9}$$

$$I_p = |I_a + a^2 I_b + aI_c| / 3 \tag{10}$$

There are many ways to detect the fault and estimate its severity available in literature. Those algorithms may depend upon the detection of specific harmonics in the current, voltage, speed, torque, or stray flux spectrum. The most common methods to detect them are FFT in stationary regime and STFT or wavelet transform in the non-stationary situation. Some other methods such as multiple signal classification (MUSIC) and estimation of signal parameters via rotational invariance (ESPIRIT) are also based on the detection of signal harmonics. The other diagnostic techniques may include techniques based on a mathematical model of the system (hardware in the loop, parameters estimation, inverse problem theory) and artificial intelligence. However, for DT to detect stator short circuits Park's vector and negative sequence currents are used as the fault indicator because these indicators are very less computationally intense and depict very strong change with a minor change in insulation. The more indicators we add to the algorithm will undoubtedly increase the accuracy but at the cost of increased complexity and computational cost.

B. IM Physical Model (Test Bench)

The test bench comprises two 7,5 kW induction motors, where one was used as a driving motor and the other as a loading motor. The motors are coupled with one another via a rigid coupling, which transfers the rotation of the drive motor to the loading motor. Current clamps and DEWETRON data acquisition systems (DAS) were used for data acquisition. The star connection was used in both induction motors. To eliminate harmonics caused by frequency converters, the driving motor was connected directly to the grid. The test bench, on which the experiment was carried out, is shown in Fig. 3.

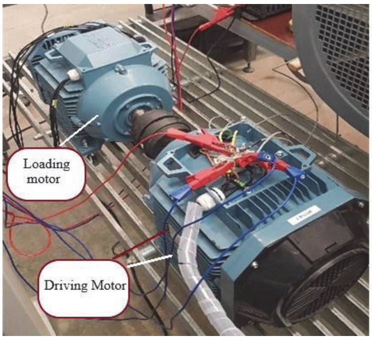

Fig. 3. Experimental testbench

First, the tests were performed with an intact and faulty motor, and the results were compared. For us, the reference points were 1%, 2%, and 5% faults; for each fault point, there were four stages of load: no load, 25%, 50%, and 75%. Finally, the neutral point was connected and disconnected from the motor in two different scenarios. When the current graphs of different percentages of failure are compared, it appears that the greater the percentage of failure, the greater the asymmetry of the currents. It is notable that as the failure percent increases phase shift of currents is not equal. Furthermore, as the load on the motor increases, the harmonics in the current become less visible, and the curvature of the current decreases. Finally, a disconnected neutral point affects not only the voltage shape and amplitude but also the current asymmetry.

IV. DT SERVICE UNIT DEVELOPMENT

The developed DT's virtual entity is made up of models such as a model set, spatial model, physical model, behavior model, rule model, and so on. The studied electrical motor parts are built as a computer-aided geometric model in the spatial model, ready to be assembled in ROS's virtual engine. The performance of individual parts of the physical entity is simulated in the physical model using numerical computing environments such as MATLAB. The current research paper focuses on the behavior model, which oversees transferring data from the real physical entity, calculating motor parameters, and streaming to the ROS topics available for models. Through behavior analysis and data associations observed with virtual sensors, a rule model covering road load constraints can be simulated. ROS serves as a physics engine for the DT's current configuration. It simulates the behavior and features of a real induction motor and serves as a publisher of data for use by virtual models. ROS employs a publisher/subscriber architecture, which enables models from various environments to publish or subscribe to ROS topics and interact with them. ROS bridge - a node that converts ROS messages into JavaScript Object Notation (JSON) or Message Queuing Telemetry Transport (MQTT) formatted data - handles communication between various platforms. Subscription or publication to the ROS bridge's port enables direct communication with ROS nodes. Any model in a virtual environment can be programmed to receive or publish messages to ROS topics based on JSON standard format. When measurement data from the motor windings is received as an input current to ROS, it is compared against the expected data, and if the received measurement on any of the windings exceeds the margins determined by the admitted error, a fault notification is filed. The measured data is summed and compared for a specific amount of time required to calculate an optimal error, allowing the system to accurately inform if there is a fault in the motor's windings. The sum value and error are refreshed after the specified time passes. Fig. 4 depicts the fault detection algorithm developed for DT. ROS is connected to a real motor (for this article, recorded data from the motor was used to simulate the motor's real input).

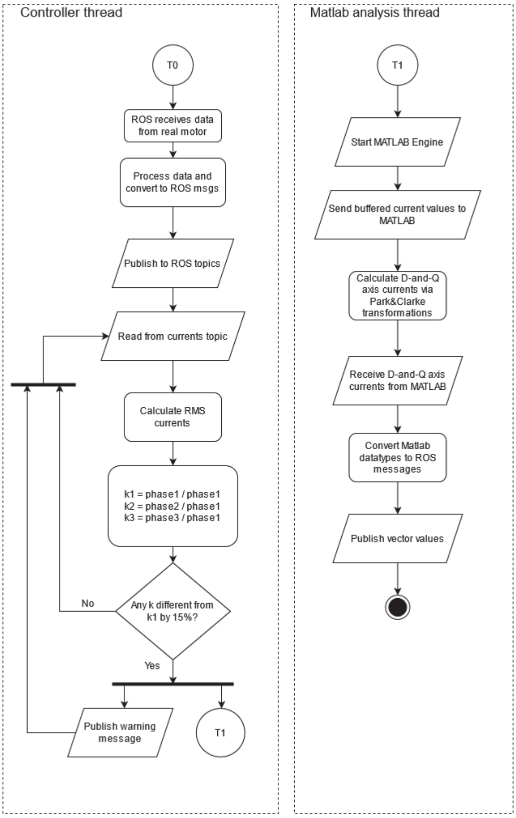

Fig. 4. DT Service unit fault detection procedures chart.

The data recorded are the raw measurements of each phase of the 3-phase current. Data is recorded several times per second. Meanwhile, the node listening to the current topic starts receiving messages. The current values retrieved from these messages are processed as follows: current measurements are stored in a buffer with a fixed size; as soon as the buffer gets full, the RMS value of the 3-phase current is calculated. After RMS values are computed, a motor phase is chosen as the base phase. Relatively to this phase, we convert other phase currents to imaginary units. These imaginary units can be used to represent the percentage of motor load. Generally, these values should be very close, i.e., within the allowed margins (due to noises and imperfections). If one of the imaginary units exceeds the set margins, then a warning message is published by ROS (used to notify the model) and is output in the terminal. To identify how big the deviation is from the norm and which phase is malfunctioning, ROS makes a call to a MATLAB function (via MATLAB Engine API) to analyze the buffer of recorded phase currents (that includes the record of malfunction) using Park and Clarke vectors. As soon as MATLAB finishes its analysis, it outputs q-and-d axis currents which are converted into ROS messages and published. The published message can be used as an indicator in the DT spatial model or real test bench of a potential fault in the system.

V. RESULTS AND DISCUSSION

The proposed work is meant to highlight the development of the DT service unit. ROS service can detect a malfunction in the motor based on sensory data of the stator current. After that, the signal is forwarded to the motor MATLAB model to process and confirm the fault. The deviation of the practical measurement from a set value will define the cause and severity of the fault. The comparison can depend upon several signal processing techniques depending upon the type and severity of the fault. For example, negative sequence currents and Park's vector can be a good choice for detecting stator inter-turn short circuit faults. Fig. 5 shows the increase of negative sequence currents with fault severity reaching up to 5%. The negative sequence currents are not absolute zero at 0% fault because the practical machine can never be symmetrical even under healthy conditions. This asymmetry is due to the asymmetrical supply voltage, slightly changed winding parameters and inherent eccentricity, etc. Similarly, the deformation of Park's vector locus from the circle in the healthy case to the elliptical in the faulty case is presented in Fig. 6. It is worth mentioning that all these measurements are at no load while the described phenomenon becomes even more clear under loaded conditions.

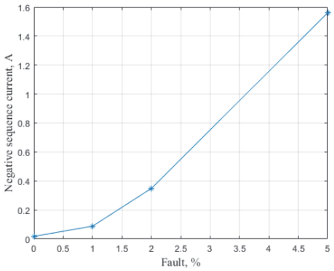

Fig. 5. Negative sequence currents as a function of fault severity

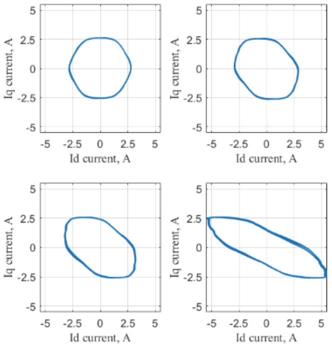

Fig. 6. Park's vector shape deformation from circular to elliptical

VI. CONCLUSION

In this research work, a methodology for developing a DT service unit for AC motor stator inter-turn short circuit fault detection is presented. The novelty of the work is application of well-known diagnostic technique for real-time operating system of possible fault diagnosis. DT is based on online measurement data, that are sent to ROS-based representation of the motor for preliminary fault detection. The model simulates the motor's specific behavior in case of unbalanced stator currents and notifies about possible fault appearance and propagation. Additional ROS node is extended with an external MATLAB analysis block that provides a more precise analysis of Park vectors' fault, for more precise inter-turn short circuit fault detection. The link for video representation that demonstrates the operation of the developed DT is presented in the Appendix, as well as the source code. IM stator fault as inter-turn is considered one of the most prevalent possible failures in electrical machines. The presented methodology of DT development allows adding additional services that consider another filature', and as a result, improve physical entity (real motor) reliability for any type of AC electrical machine (incl. induction, synchronous, reluctance)

APPENDIX

The visualization of real-time operation of the considered example one can see in the following URL:

https://youtu.be/5jGrRPq4oDY

Source code of developed DT is available on:
https://github.com/TalTech-PSG453/ros2-loading_motor_dt

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