**Digital Twins and AI in Vibration Solutions for Intelligent Logistics**

Таvbay Khankelov1, Kamoliddin Rustamov1, a), Samandar Komilov1, Madinabonu Hurutdinova2

*1Tashkent State Transport University (TSTU), Tashkent, Uzbekistan*

*2University of Journalism and Mass Communications of Uzbekistan*

*a)Corresponding author:* [*k.j.rustamov82@gmail.com*](mailto:k.j.rustamov82@gmail.com)

**Abstract:** Dynamics Digital Twins is rapidly the most advanced way of solving recurring vibration problems which have been causing intelligent logistic systems to become less reliable. Vibration, a problem that is often dismissed as unimportant, has large impacts on the performance and safety (life cycle cost) of systems. Predictable risk reduction measures simply don’t work with modern logistics networks’ increased complexity and size. We could very well see Digital Twins revolutionize the way systems are modeled by building out structure that imitates real platforms living in an online world and allows you to watch and monitor them, diagnose problems as they occur, and act before it does. It’s also what powers the Digital Twin framework, and if you add AI tools such as machine learning and predictive analytics it still gets better. Through these methods, the system can study tremendous amounts of data from sensors, spot tiny patterns and guess how things will vibrate far before they do so to dangerous levels. The AI-driven approach on the digital twin allows for more accurate prediction of vibration and provides operational engineers with actionable information that guides them to take the right decisions. These capabilities combine to make intelligent logistics systems accelerated, less prone to time out, and more reliable. Ultimately, leveraging AI-fueled Digital Twins is an essential element of developing smarter, more adaptable and hyper-efficient logistics networks that can also evolve to serve future demand.

**Keywords:** Digital Twins, artificial intelligence, structural vibration, frequency-domain analysis, vibration control.

**INTRODUCTION**

Control of vibrations can significantly improve the reliability and efficiency of logistics systems. This article investigates an artificial intelligence (AI)-based methodology for analysing vibration problems within intelligent logistics. It proposes a solution that integrates digital-twin (DT) modelling with an AI system that learns from physical and virtual data to mitigate vibration and instability. Underpinning the approach is an industrial Internet of Things (IoT) platform that performs real-time signal processing and frequency-domain identification of the physical system’s current state using autoregressive moving average (ARMA) techniques. A DT model then incorporates this information, enabling the AI routines to predict and analyze the system’s behaviour and generate recommendations for optimal configurations. The integration of DTs with real-time sensing and AI provides a robust framework for addressing complex dynamical challenges, particularly those arising from vibrations in intelligent logistics applications [1]; [2].

**METHODS AND RESULTS**

Mechanical vibration problems seem to be appeared frequently in the logistics industry and impedes the working efficiency. Among the methods developed to overcome these issues, a method based on AI has become popular [1]. Hence, its advent is a good example in the context of the utilization of a Digital Twin model along with AI [2]. The logistical domain currently witnesses the proliferation of smart logistics, wherein AI functions as an indispensable instrument within intelligent systems. The contemporary trajectory resolving vibration problems gravitates toward the employment of an AI-centric paradigm. Concurrently, the implementation of smart logistics unfolds with increasing frequency. Digital Twins, embodying a contemporary technological construct, render it feasible to realistically model the physical attributes of freight forwarders [3]. The execution of a Digital Twin architecture entails the precise acquisition of real-time data associated with freight forwarders.

Vibrations are an essential consideration in logistics systems. Vehicle-track interaction, wheel-rail contact, the dynamic response of rail vehicles, and the nearby environment can all affect the vibrations caused by trains. Vibrations have a significant impact on deceleration, acceleration, operational safety, comfort of driving, and the health of passengers and freight. At the same time, vibration monitoring is a valuable method for condition monitoring and fault diagnosis, and may reduce unnecessary traffic disruptions and maintenance costs.

Artificial intelligence (AI) has emerged as a crucial enabler for tomorrow’s widespread smart logistics systems. Effective handling of the vibration problem within smart logistics promises seamless supply chain operations, among a variety of benefits. Logistics services aim to ensure quick, on-time, faultless, and complete delivery of items ordered by consumers. Logistical resources can include personnel, means of transport, fuel, vehicles, product forms, information, money, or other raw materials and standards. Each of these resources and constraints can impose frictions that prevent delivery from being optimal or convenient. Smart container design, advanced vehicle technology development and AI-based methods have been some of the proposed solutions in dealing with logistics resources and vibration problems from intelligent logistics [4].

The intelligent manufacturing adopts machine learning methodologies, and this can take actions by data instead of following predetermined workflows and scripts [5]. Digital Twin is a cornerstone of Industry 4.0, and it can achieve traceability depth and enhance optimization process in smart manufacturing. The development of a Digital Twin entails definition of an initial model and data collection plan [4, 15, 16]. The base model includes essential structural data along with input derived by underlying knowledge. Model cannot be separated from data, and a Digital Twin without the guidance of data can never truly simulate a real-world object. Based on models and sensory data, a Digital Twin represents the real estate object via its structural logic. The modeled behavior in simulations mimics the real phenomenon against the integrated model and data. Digital Twins therefore allow us to model real-world entities accurately, addressing the traceability and simulation requirements. It is a structurally similar Digital Twin that supports direct interaction with, and predictive analysis of, the physical entity's likely trajectory. Vibration is oscillation around an equilibrium position of anything in a mechanical system. Vibration is an important information source for the status of a system. Noise Vibration accelerates wear Fatigue leads to damage or system failure. Thus, vibration control is essential to keep the device operation safe and secure, preventing any collateral or deadly accidents. Anti-vibration equipment has developed into a major area of research in supply chain logistics.

The use of digital twins is spreading across industries, as real-time data availability increases with efficient data collection and low-cost sensors. Diverse frameworks for real-time analysis and integration of heterogeneous systems have been suggested [6, 18]. A digital twin is a data-connected three-dimensional visualization of the elements and dynamics of a physical system [1]. The principal advantage lies in predicting future undesirables and supporting decision-making throughout the system’s active life. Simulation capability is an important aspect of a digital twin. Companies create three-dimensional replications of assets to assess their performance for multiple scenarios, often converting two-dimensional images into digital three-dimensional objects. Digital twins operate at several levels. The Descriptive Twin provides a descriptive or visual model of an element, while the Informative Twin includes operational data and active information. The Predictive Twin learns from data, and the Comprehensive Twin can simulate future scenarios. The Autonomous Twin is able to take decisions and act independently [7]. Real-time-data integration characterizes the advanced levels, which have recently come to the fore. Exploiting digital twins effectively can reduce costs, improve designs and boost productivity.

A Digital Twin is a virtual model dynamically updated in real time for control and analytics. It relies on integration with the physical system and continuous sensor data streaming. Vibration presents an obstacle to achieving autonomous logistics, because unnecessary vibrations cause machine breakdown and influence delivery times [2, 19]. The aim of this work is to find vibration solutions using Digital Twins to enable intelligent logistics. The current system architecture of intelligent logistics comprises the physical entity, perception system, and Digital Twin model. Data acquisition is carried out via sensors to monitor the motion state, collect status and environment information, and transmit the data to the upper control systems to realize real-time interactive mapping.

**RESULTS**

Vibrating systems, transitory impacts and shock might be analyzed using vibration solutions in the frequency domain, time domain and modal approaches. The frequency domain analysis can analyze the time signal as divided in to its frequency constituents to provide by amplitude and phase the machine condition. Time domain analysis investigates temporal signals and provides valuable information on transients and operational anomalies. Modal analysis provides natural frequencies and mode shapes, both of which are important information for the understanding of the fundamental structural dynamic behavior [2]. Vintage methods are used in literature to solve the vibration problems, however efficient predictive method is another demand.

Frequency domain analysis calculates the frequency spectrum of signals to monitor machine states. Time domain analysis studies the change of signal in time to detect short-term aberrations. The modal analysis can be utilized for system identification in which natural frequencies and mode shapes are extracted, so that the dynamic behaviors are understood well enough to make a safe evaluation. These methods still influence vibration analysis, and enhanced estimation algorithms afford better predictive capabilities.

Artificial intelligence (AI) provides a data-driven method for vibration prediction by discovering the correlation in multidimensional datasets. Learning based models (not supervised) such as Random Forest and e Xtreme Gradient Boosting (GBM)—helped by a prior defined structure. Examples of deep learning models that are able to perform automatic feature extraction include Long Short-Term Memory networks, convolutional networks and transformers. A couple of statistical inference methods based on explicit prior assumptions are Gaussian Processes and Bayesian Neural Networks. Therefore, artificial intelligence is used as an effective method for solving vibration problems in intelligent logistics.

Vibration is a common problem in logistic systems and can be attributed to a variety of factors. In many cases, vibration results from resonance effects, with a component, sub-component, or complete product responding at a natural frequency. The vibration issues are acknowledged through numerous indicators, such as shifts in production processes, reduced production rates, frequent equipment breakdowns, decreased operational efficiency, worker fatigue, and quality degradation [2]. Optimizing vibration in logistic equipment emerges as a contemporary challenge to enhance efficiency, reduce power, and protect critical components against potential damage and wear. Techniques to anticipate vibration damage and design corrections prior to physical implementation are imperative [8].

Frequency domain analysis is a key factor in the vibration-based condition monitoring of various industries such as automotive and aerospace [2]. Methods such as time synchronous averaging and time-domain average used in the frequency domain isolate periodic signals due to rotating machine, transient faults, respectively. The concept of digital twin further enriches it, by incorporating the schemes of fault diagnosis and product design. In the digital twin, deep transfer learning is enabled for intelligent machine diagnostic systems.

Diagnosis through analysing vibration signals is central to condition based maintenance. Digital twins also offer a solution to some common shortcomings, as they allow the behaviour of fault signals to be learned from multiple examples and then synthetic data can be generated [9]. Digital twins have proven their ability in real-world applications to diagnose pump cavitations, pinpoint hantav faults in production lines of automotive industry and identify photovoltaic system failures. However, the generalization across different machineries slows down when an insufficient number of USBD examples from the new machines are available in practice; its probability is rare and the label for it is expensive. One of the main challenges is that responses to vibration signals are affected by transfer function and distorted in mutual different ways among machines which prevents generalization as well.

Time domain methods are a principle approach to analyze signals for machine fault detection and condition-based health monitoring. Methods like the time synchronous averaging (TSA) and the time domain average (TDA), allow taking out a periodic component from vibration signal that leads to an improved fault prognostic. Time domain signal waveform itself can directly investigate the problem, such as faults of bearing and its early treatment of the crack. Time-domain analysis has to deal with transfer function effects due to the distortion of signals and limiting the generalization across different machinery [9]. The digital twin ensures in-depth fault diagnostics as it is a digital replica that enables predictive maintenance and system simulation, hence its improving effectiveness for damage detection process accuracy efficiency.

Modal analysis is a fundamental vibration method used to determine the vibrational characteristics of a structure [10]. These quantities, such as natural frequencies, damping ratios and mode shapes, describe how a structure responds to disturbance and are dependent on the geometry, material properties, and boundary conditions of the system under investigation. For this reason, a structure with modally-sensitive configuration is more apt to troubles arising from vibration. Modal analysis is the process of extracting a system’s modal parameters (natural frequencies, mode shapes and damping) from its transient or steady-state time response employing classical analysis techniques or curve fitting techniques

There is variety of mathematical and algorithmic techniques for the analysis and forecasting of vibrations. Machine learning provides methods such as classification, regression, and clustering useful for purposes such as fault detection or time series prediction related to vibration data. Deep learning models i.e., Convolutional Neural Networks (CNNs) are good at acquiring features from raw signals; and that LongShort-Term Memory networks capture sequential information in vibrational behavior. Moreover, statistical approaches based on AutoRegressive Integrated Moving Average (ARIMA) and its seasonal components formulate time series analysis and forecasting. With real-time sensor data used to inform the Digital Twin model, these AI-based methods can predict the vibration levels which are essentially providing management with a tool that allows optimal handling of vibrations issues in intelligent logistics [2] [10].

Deep Learning is a branch of machine learning which falls under artificial intelligence. These are algorithms inspired by the structure and function of algorithms inspired by the structure and function of the brain's neural networks. It is also known as deep neural learning or deep neural network.

Deep learning methods provide several advantages from machine learning: (1) Nonlinear transformation is learned in every stage, allowing better conversion of input signal into the desired output. (2) Deep architectures allow the successive extraction of higher levels of features; for example, in an image, the lower layer may identify edges, while higher layers may identify the concepts relevant to a human, such as digit recognition. (3) Training time is reduced compared to other methods, such as support vector machines. (4) Better representations for the data are learnt and used in the regression/classification problem.

Digital twins play a crucial role in intelligent logistics by mirroring the essential characteristics of physical logistics objects through virtual models, enabling real-time data sharing and information synchronization. The digital twin-driven intelligent logistics system integrates vibration-acceleration sensors, vibration-displacement sensors, current sensors, and ultrasonic sensors with a data acquisition system to obtain accurate real-time data. This synergy between digital twins and AI equips the intelligent logistics system with enhanced self-awareness and intelligent control capabilities. [2, 10, 11, 12, 13]

Digital Twins, integrating a virtual world with the physical one, constitute the foundation for implementing smart logistic systems. Real-time data streams from sensors enable the execution of a Markov change-point model for cessation determination. Despite the clear theoretical formulation of the DT framework in logistic scenarios, its practical application confronts challenges arising from the complexity of various unpredictable external disturbances. To address these difficulties, the architecture of a standard DT and a novel method for real-time data acquisition are elaborated. The vibration problem is analysed through a robust, statistical-based approach [2] [8] [13, 15, 16].

**CONCLUSION**

Vibration control is a critical issue in logistics. To tackle this issue, the combination of Digital Twins and Artificial Intelligence (AI) can be an interesting solution in the context of intelligent logistics systems. Digital Twin architectures are powerful tools for predictive analysis of vibrational response when combined with AI-based techniques, including machine learning, deep learning and statistical methods.

It is the discursive methodology used here that distills and synthesizes information through a process of systematic analysis. All of the oral and written sources are cited and referenced so as to offer a solid documentary basis for the exposition, providing a credible and scholarly foundation for the conclusions reached.

The wide scope of logistics has made the traditional methods of analysis insufficient to explain vibrational phenomena. Traditional vibration models neglect important resonance modes and therefore fail to capture complete or correct representations. The inherent instant-varied characteristics of vibration are reflected through structural dynamics, aerodynamic forces, and boundary conditions which further complicate analytic attempts. It follows that there is a critical need for diagnostic methods which capture both time-dependent behavior and structural information. The use of the ontology combined with AI to incorporate digital twin technology in this situation is a strategic enabler [3].

By the same token, the idea of Digital Twins – meaning digital replicas of physical objects – is very popular right now thanks to modernization and system optimization requirements. Nevertheless, employing Digital Twins in real applications faces several obstacles. The other under-explored domain is the use of Digital Twin notions to analyze logistic vibrations in intelligent transportation and delivery systems [2].

Our proposed framework assumes that Digital Twins are predictive, Class-C simulators that can use data-driven forecasting models to predict system behaviour. The Digital Twin for the vibration problem is composed of three main parts: Physical Entity (PE) which matches real logistics or delivery equipment, Virtual Entity (VE), as a mirror image of the PE and Digital Thread (DT), supporting data exchange and synchronization. The structural vibration reaction of the PE is provided with real-time data from embedded multi-source sensors, which are being transmitted to the VE. Developed based on OPC-UA—a cross-platform service-oriented architecture, the VE can interface with AI algorithms and Logistics Vibration Module (LVM). In this scenario, AI methodologies support predictive machine learning-based models that leverage stimuli of the Physical Entity.

So the synergy of Digital Twins and AI is a methodological anchoring point for modern vibration analysis in intelligent logistics. The resulting dynamical re- ciprocation of fidelity in prediction, and guidance in optimised logistics system design for communities to move from reactive towards proactive VibRI.

**REFERENCES**

1. Khankelov, T., Askarkhodzhaev, T., & Mukhamedova, N. (2020). Determination of key parameters of a device for sorting municipal solid waste. *Journal of Critical Reviews*, *7*(4), 27-33. <https://doi.org/10.31838/jcr.07.04.07>
2. Maksudov, Z., Khankelov, T., Rustamov, K., Khudainazarov, S., Pirnaev, S., Kudaybergenov, M., ... & Karimovaa, K. (2025). Development of a Methodology for the Formation and Standardization of a Machine System for Road Construction and its Implementation. *Engineered Science*, *37*, 1733. <http://dx.doi.org/10.30919/es1733>.
3. Rustamova, N. R. (2025, July). Vitagenic chemistry: Unveiling life-enhancing energies in chemical reactions. In *AIP Conference Proceedings* (Vol. 3304, No. 1, p. 040056). AIP Publishing LLC. <http://doi.org/10.1063/5.0271016>
4. Matania, O., Bechhoefer, E., & Bortman, J. (2023). Digital twin of a gear root crack prognosis. *Sensors*, *23*(24), 9883. <https://doi.org/10.3390/s23249883>
5. Abdullahi, I., Longo, S., & Samie, M. (2024). Towards a distributed digital twin framework for predictive maintenance in industrial internet of things (IIoT). *Sensors*, *24*(8), 2663. <https://doi.org/10.3390/s24082663>.
6. Marmolejo-Saucedo, J. A. (2020). Design and development of digital twins: A case study in supply chains. *Mobile Networks and Applications*, *25*(6), 2141-2160. <https://doi.org/10.1007/s11036-020-01557-9>.
7. Hartmann, D. (2023). Real-Time Digital Twins. *arXiv preprint arXiv:2311.14691*. <https://doi.org/10.5281/zenodo.5470479>
8. Choi, S., Woo, J., Kim, J., & Lee, J. Y. (2022). Digital twin-based integrated monitoring system: Korean application cases. *Sensors*, *22*(14), 5450. <https://doi.org/10.3390/s22145450>
9. Alonso, R., Locci, R., & Recupero, D. R. (2024). Improving digital twin experience through big data, IoT and social analysis: An architecture and a case study. *Heliyon*, *10*(2). <https://doi.org/10.1016/j.heliyon.2024.e24741>
10. Piltan, F., & Kim, J. M. (2021). Crack size identification for bearings using an adaptive digital twin. *Sensors*, *21*(15), 5009. <https://doi.org/10.3390/s21155009>.
11. Matania, O., Klein, R., & Bortman, J. (2022). Transfer across different machines by transfer function estimation. *Frontiers in Artificial Intelligence*, *5*, 811073. <https://doi.org/10.3389/frai.2022.811073>
12. Rustamova, N. R. (2025, July). The role of vitagenic technologies in revolutionizing machine design and functionality. In *AIP Conference Proceedings* (Vol. 3304, No. 1, p. 030095). AIP Publishing LLC.  <https://doi.org/10.1063/5.0269690>
13. Ritto, T. G., & Rochinha, F. A. (2021). Digital twin, physics-based model, and machine learning applied to damage detection in structures. *Mechanical Systems and Signal Processing*, *155*, 107614. <https://doi.org/10.1016/j.ymssp.2021.107614>
14. Piltan, F., Toma, R. N., Shon, D., Im, K., Choi, H. K., Yoo, D. S., & Kim, J. M. (2022). Strict-feedback backstepping digital twin and machine learning solution in AE signals for bearing crack identification. *Sensors*, *22*(2), 539. <https://doi.org/10.3390/s22020539>
15. Fu, C., Gao, C., & Zhang, W. (2023). A digital-twin framework for predicting the remaining useful life of piezoelectric vibration sensors with sensitivity degradation modeling. *Sensors*, *23*(19), 8173. <https://doi.org/10.3390/s23198173>
16. Liu, W., Han, B., Zheng, A., & Zheng, Z. (2024). Fault diagnosis for reducers based on a digital twin. *Sensors*, *24*(8), 2575. <https://doi.org/10.3390/s24082575>
17. Kamoliddin, R., & Nodira, R. Determination of the main parameters of the mechanisms of a two-stage compressor and their kinematic analysis. In *AIP Conference Proceedings* (Vol. 2789, No. 1, p. 040001). <https://doi.org/10.1063/5.0145477>.
18. Rustamov, K. J., & Rustamova, N. R. (2025). Advanced hydraulic drive systems in multi-purpose machinery: Enhancing efficiency and performance in modern engineering. AIP Conference Proceedings, 3304, 030093. <https://doi.org/10.1063/5.0269688>
19. Korabayev, S., Ergashev, O., Mahsudov, S. A., & Mamatova, S. (2024). Exploring common technical issues in modern technology. BIO Web of Conferences, 145, 03016. <https://doi.org/10.1051/bioconf/202414503016>.