International Journal of Scientific Multidisciplinary Research (IJSMR)
Vol. 4, No. 7, 2026: 1357 - 1374

Development of a Real-Time Sensor-Based Digital Twin for Predictive Maintenance of Vehicle Gearbox Systems

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A R T I C L E I N F O
Keywords: Digital Twin, Real-Time Sensor, Predictive Maintenance, Vehicle Gearbox, Condition Monitoring

Received : 23, May
Revised : 20, June
Accepted: 31, July

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A B S T R A C T
This study develops a real-time sensor-based digital twin for predictive maintenance of vehicle gearbox systems. The contribution lies in integrating vibration sensing, IoT-based data transmission, and machine learning to monitor gearbox health and detect anomalies early. A case study was conducted on a tactical vehicle gearbox using three ADXL345 accelerometers installed at the input shaft, gear mesh, and output shaft. Vibration data were collected in real time under three operating conditions over multiple observation days. The proposed model used Random Forest for condition classification and GRU neural network for health scoring. Results show that the system can identify gearbox conditions accurately and support earlier maintenance decisions, offering a practical basis for condition-based maintenance.

INTRODUCTION

In the context of modern defense, the operational readiness of military tactical vehicles (Tactical Vehicles) is a crucial factor in ensuring the success of combat operations and logistical mobilization. Tactical vehicles are a vital element in supporting troop maneuvers, equipment delivery, and battlefield evacuation. Failure of the propulsion system, such as the engine or gearbox in the transmission system, which contains gears, at critical times can significantly reduce combat effectiveness. Therefore, a maintenance system that is not only responsive but also proactive is required to maintain the availability and reliability of military vehicles (Sung et al., 2021; Defense Acquisition University, 2019).

To date, military maintenance systems in many countries, including Indonesia, are still dominated by reactive (corrective maintenance) and preventive approaches based on time or mileage. These methods risk over-maintenance or even under-maintenance because they don't take into account the actual condition of vehicle components. This leads to logistical inefficiencies, budget wastage, and uncertainty in operational readiness (Ghosh & Roy, 2020). Therefore, a new approach based on actual data and condition simulations is needed to build a more adaptive and efficient maintenance system.

As noted in the flagship publication of the Army Equipment Center (Bengpuspal Puspalad), there are several limitations to the ability to carry out maintenance and repairs, including limited systems in the form of encrypted digital modules. In an article entitled "Transformation of the Indonesian Army Maintenance, Repair, and Overhaul System to Support Defense Equipment Readiness: A Case Study of the Army Equipment Center Workshop/Bengpuspal," the results of the research interviews revealed that support in the form of technology transfer facilities and training for defense equipment repair technicians should always be available. Other facilities at this maintenance workshop are not significantly different from those at other workshops. No special technology is used, relying solely on existing tools and the expertise of the technicians on duty.

A digital twin is a virtual representation technology that can simulate physical conditions in real time through the integration of sensor data, physical models, and predictive algorithms. In the context of a military propulsion system, a digital twin enables technical and logistics personnel to dynamically monitor system health, predict failures before they occur, and optimize maintenance schedules and resources (Tao, Zhang, Liu, & Nee, 2019). With a digital twin, the transition from conventional maintenance to predictive maintenance can be implemented in a measurable and data-driven manner, thereby reducing downtime in maintenance and repair processes.

Although research on digital twins has developed significantly in the automotive, aviation, and manufacturing sectors (Glaessgen & Stargel, 2012; Wang et al., 2023), the application of this concept in the context of military tactical vehicle (TACTICAL) maintenance in Indonesia remains limited. A study by van Dinter et al. (2023) showed that digital twins can increase logistics fleet efficiency by up to 25%, while Qiu et al. (2025) emphasized the role of artificial intelligence

integration in improving the reliability of defense systems. However, local research in Indonesia generally still focuses on preventive and corrective maintenance systems without digitalization (Widytama, 2022). **This reliance on traditional methods creates a critical operational gap, as standard maintenance scheduling cannot predict random component failures in high-stress military environments. Therefore, a significant research gap exists in the absence of an empirical digital twin architecture specifically designed for Indonesian Army (TNI AD) tactical vehicles, which integrates multi-location vibration sensing and real-time machine learning deployment.** The transition from conventional maintenance systems to predictive maintenance can thus be implemented in a measurable and data-driven manner, thereby reducing downtime in maintenance and repair processes. For a digital twin to accurately represent a system, real-time sensor data integration is key. Sensors such as the ADXL345 accelerometer are used to detect vibrations in the gearbox gears. This data is then processed and modeled within the digital twin to generate health trends, remaining useful life (RUL) predictions, and time series anomaly detection. The challenges lie in sensor accuracy, data network stability, and algorithms capable of processing multivariate data in military field conditions (Lee et al., 2020; Liu et al., 2022).

The application of digital twin technology in combat vehicle maintenance is a strategic step for the Indonesian Army (TNI AD) in addressing the challenges of modernizing defense equipment and optimizing logistical resources. As the need for military mobility and speed of response increases, a predictive maintenance system will be crucial in ensuring the availability of combat vehicles at all times. This research is expected to provide the scientific and technical basis for developing a digital twin-based maintenance system within the TNI AD, in line with the direction of the national defense digital transformation (Puslitbang TNI AD, 2023).

This research emphasizes the importance of designing a real-time sensor-based digital twin model to detect anomalies in the gearbox gears for predictive maintenance of Indonesian Army (TNI AD) vehicles. The research statement of this thesis is that the successful development of a digital twin will not only address the gap in academic research on digital technology-based maintenance systems in the defense sector, but will also provide a practical contribution to the Indonesian Army (TNI AD) in increasing readiness rates, reducing downtime, and supporting the defense equipment modernization agenda in line with Indonesia's long-term defense policy (Ministry of Defense of the Republic of Indonesia, 2020; Ministry of Defense of the Republic of Indonesia, 2021).

Based on the urgency and complexity of the problem, the research statement of this study is: "How to develop and evaluate a digital twin model based on real-time sensor data that can support predictive maintenance of automotive gearbox systems accurately, efficiently, and effectively to improve the operational readiness of the Indonesian Army." This research is expected to produce novel results in the form of developing a digital twin architecture specifically for the vehicle's propulsion system, specifically the gearbox in the transmission system, directly integrated with sensors and field data. It also validates the model in the context of military operational readiness, a topic that

has not been widely addressed in previous studies specifically in the Indonesian defense sector. With this approach, the research contributes practically to improving advanced technology-based military maintenance systems and theoretically enriches the literature in the field of defense-oriented predictive maintenance. Research Objectives: Analyze and design a digital twin model based on sensor data for predictive maintenance of military vehicles. Analyzing the digital twin model can improve the accuracy of conventional damage predictions. Analyze the impact of digital twin implementation on downtime and readiness rates of Indonesian Army vehicles.

THEORETICAL REVIEW

Digital Twin & Predictive Maintenance

A digital twin is a virtual representation of a physical system that is synchronized in real time with sensor data and environmental information (Ghosh, Ullah, Teti, & Kubo, 2021). A digital twin creates a two-way connection between the real world and the simulated world, enabling condition monitoring, diagnosis, and failure prediction (Glaessgen & Stargel, 2012). In the context of defense equipment maintenance, a digital twin is a strategic tool for detecting anomalies, reducing downtime, and optimizing equipment lifecycles (van Dinter, Tekinerdogan, & Catal, 2023). Predictive maintenance is a maintenance strategy based on predicting the time of component failure using historical data analysis and sensors. Compared to time-based preventive maintenance, the predictive approach is more efficient because it is only performed when truly needed (Thompson, 2024).

Vehicle Gearbox Powertrain & ISO 20816-9

The tactical vehicle propulsion system consists of key components, such as the engine and transmission system components, namely the gearbox, which play a critical role in the vehicle's mobility and operational performance (Piancastelli, Toccaceli, Sali, & Leon-Cardenas, 2023). Gearbox (Transmission system component), the transmission is responsible for transferring power from the engine to the drive wheels. Modern transmission systems are equipped with sensors to monitor conditions such as temperature and pressure, enabling early detection of wear or damage. The integration of a Prognostics and Health Management (PHM) system into the transmission allows for more proactive and efficient maintenance (Narayanan & Padhy, 2023). ISO 20816-9:2020 is an international standard that establishes guidelines and procedures for measuring and evaluating mechanical vibrations in various types of machinery.

Neural Network

Using a neural network-based model, a model was developed to predict machining time. To build the model, a neural network-based model only requires input and measurements from the system as a training set. However, a disadvantage of data-driven models is the need for sufficient data. If the quality and quantity of data are low, it will be difficult to build a high-quality data-driven model. Therefore, usually, before a data-driven model starts to function properly, it is necessary to wait until the system has collected enough data,

especially when a new system or process is designed and developed and only a limited amount of data is available.

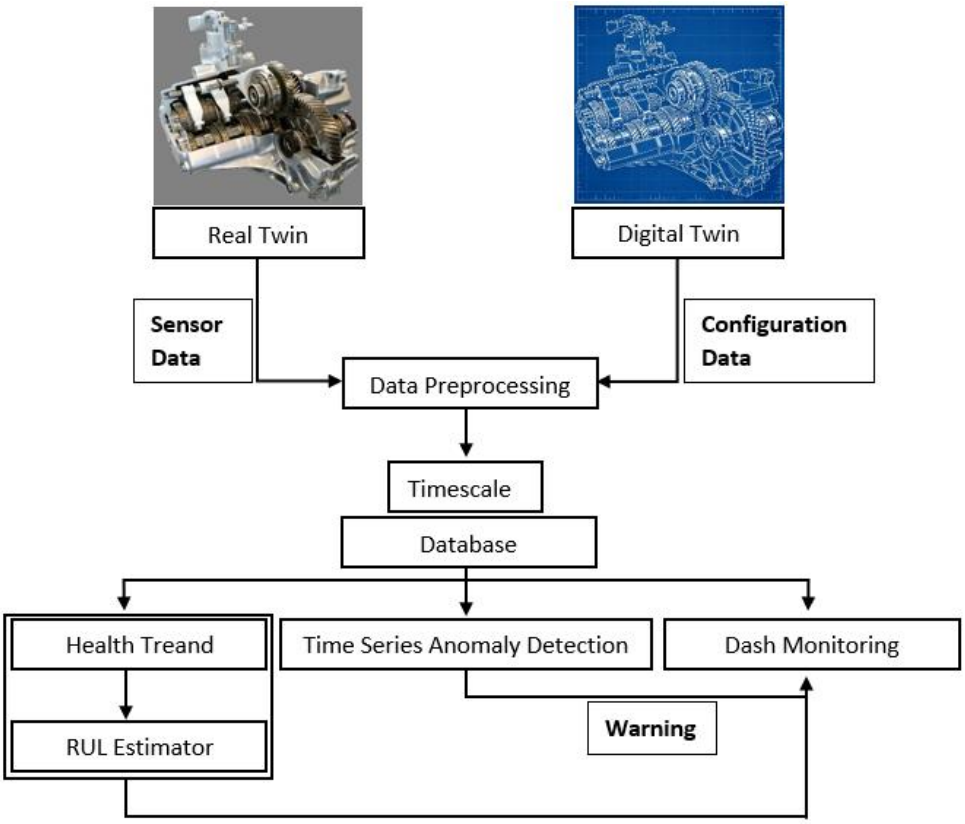

Figure 1. Conceptual Framework

METHODOLOGY

This study uses a quantitative approach with an explanatory approach, which aims to explain the relationship between the implementation of a real-time sensor-based digital twin for predictive maintenance and the improvement of transmission system maintenance performance in military vehicle gearbox components. The explanatory approach was chosen because this study not only describes the phenomenon but also empirically tests the influence of independent variables on the dependent variable based on measurable indicators.

The research method is applied in the form of a case study on a military vehicle platform, focusing on the transmission subsystem as a critical component in the vehicle's propulsion system. This subsystem was chosen due to its high wear rate, sensitivity to operating loads, and direct contribution to vehicle downtime and readiness rates. Therefore, the transmission, including its gearbox components, is treated as the primary unit of analysis in the study.

The research methodology framework is built through the integration of physical vehicle operational data obtained from ADXL345 accelerometer sensors installed at three points on the gearbox component. The data is then processed and analyzed using machine learning algorithms, namely Neural Network and Random Forest, to predict the health condition of the gearbox gears, potential failures, and estimate the Remaining Useful Life (RUL).

The prediction results generated by the model are then evaluated quantitatively using accuracy metrics, such as Mean Absolute Error (MAE) and Root Mean Square Error (RMSE), and associated with maintenance performance indicators, namely maintenance downtime and vehicle readiness rate. With this research design, the effectiveness of implementing a digital twin with Neural Network and Random Forest in supporting predictive maintenance of transmission systems on gearbox components can be analyzed objectively and measurably. This combination strengthens the validity of the study and also tests its impact on technical performance indicators (accuracy, downtime, readiness rate) in the operational context of military vehicles (Wang et al., 2023; Qiu et al., 2025).

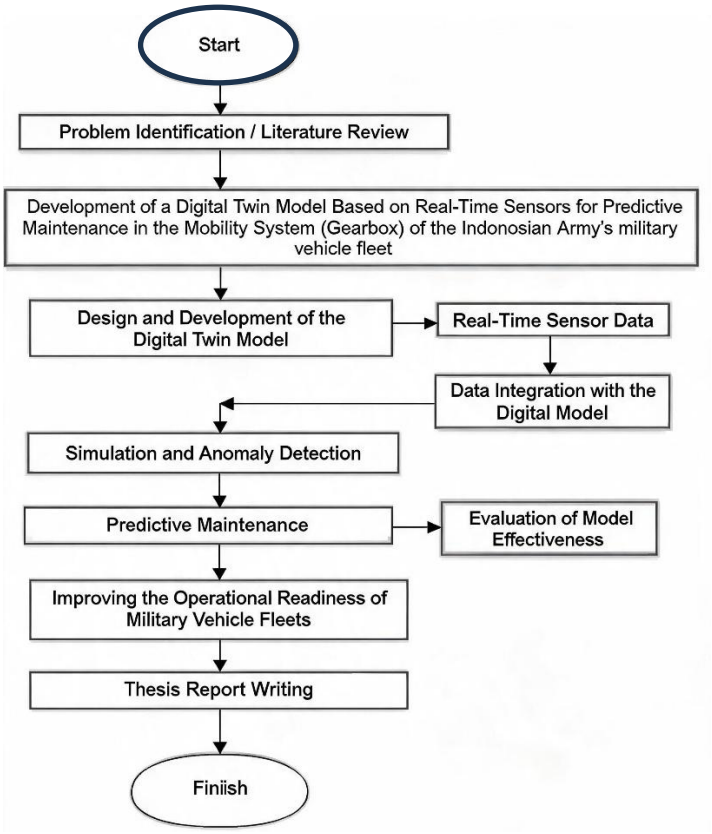

Figure 2. Research Design

The research design steps to be undertaken in this study are as follows, start the research implementation. Identify the problem through a literature review of the Indonesian Army's military vehicle maintenance system. Determine the research topic based on the identified problem: "Development of a Real-Time Sensor-Based Digital Twin Model for Predictive Maintenance of the Indonesian Army's Gearbox System." Next, design a digital twin model that will be integrated with real-time sensors. Integrate data with the digital model. The processed data, used as input variables, will be simulated and subjected to anomaly detection. The model's effectiveness in predictive maintenance will then be evaluated. The results of this research will be a real-time sensor-based digital twin architecture for the Indonesian Army's transmission system, capable of

prediction, anomaly detection, and RUL (Remaining Useful Life) estimation. This will then be presented in a thesis report.

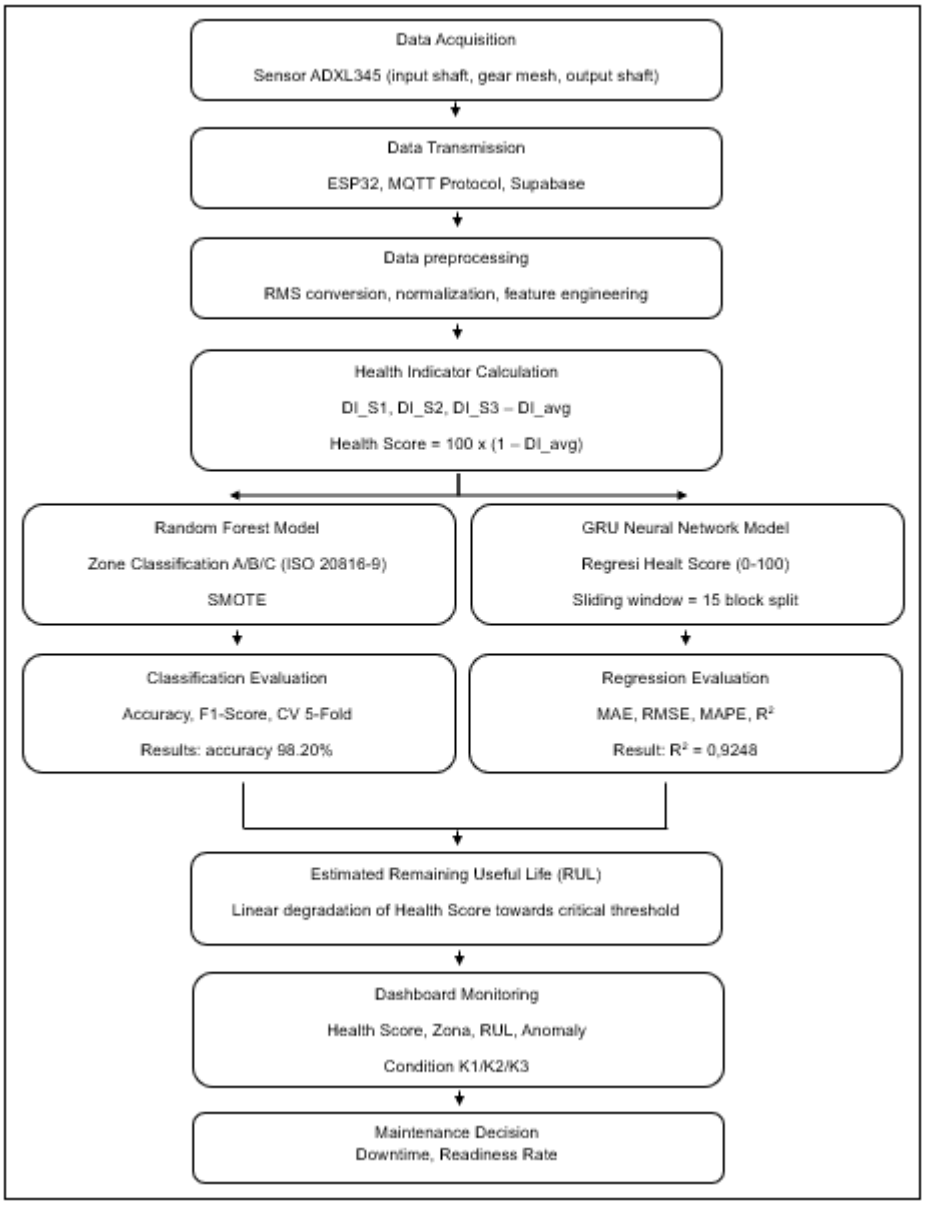

Figure 3. Data Analysis Techniques

RESULTS

This research results in the development of a real-time sensor-based digital twin model to support predictive maintenance on military vehicle gearboxes. The model consists of a vibration data acquisition subsystem, Internet of Things (IoT)-based data communications, a digital twin dashboard, and a machine learning model for diagnosing and predicting gearbox conditions.

Table 2. Data Vibration Processed – Day 1 (Condition: Not On and Silent)

Created_at	Vib_s1 (mm/s RMS)	Vib_s2 (mm/s RMS)	Vib_s3 (mm/s RMS)	Day	Operation Condition	Risk Level

2026-05-13 02:11:24.728206+00	16.1137	16.1137	16.1137	1	Not On and Silent	MODERATE
2026-05-13 02:11:41.438886+00	0.3767	0.3767	0.3767	1	Not On and Silent	LOW
2026-05-13 02:11:58.235197+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:12:42.382537+00	14.958	15.2006	15.2006	1	Not On and Silent	MODERATE
2026-05-13 02:12:59.23681+00	0.374	0.3744	0.3744	1	Not On and Silent	LOW
2026-05-13 02:13:16.041779+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:13:32.707606+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:13:49.473142+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:14:06.237004+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:14:23.138437+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:14:40.045887+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:14:56.755697+00	0.3403	0.3403	0.3403	1	Not On and Silent	LOW
2026-05-13 02:15:02.949527+00	33.5413	33.8288	30.446	1	Not On and Silent	HIGH

Table 3. Data Vibration Processed – Day 2 (Condition: On and Not Moving)

Created_at	Vib_s1 (mm/s RMS)	Vib_s2 (mm/s RMS)	Vib_s3 (mm/s RMS)	Day	Operation Condition	Risk Level

2026-05-18 04:41:01	15.9488	30.7819	17.4607	2	On and Not Moving	MODERATE
2026-05-18 04:41:03	18.7491	31.1571	17.5368	2	On and Not Moving	MODERATE
2026-05-18 04:41:05	18.1544	30.8104	17.1379	2	On and Not Moving	MODERATE
2026-05-18 04:41:07	17.599	30.6989	15.9819	2	On and Not Moving	MODERATE
2026-05-18 04:41:09	15.7083	29.3614	17.3018	2	On and Not Moving	MODERATE
2026-05-18 04:41:11	14.5446	29.2245	17.056	2	On and Not Moving	MODERATE
2026-05-18 04:41:13	14.2909	29.688	17.1758	2	On and Not Moving	MODERATE
2026-05-18 04:41:15	17.8995	28.5322	16.813	2	On and Not Moving	MODERATE
2026-05-18 04:41:17	16.1327	30.1884	17.1301	2	On and Not Moving	MODERATE
2026-05-18 04:41:18	15.3404	29.2663	16.9892	2	On and Not Moving	MODERATE
2026-05-18 04:41:20	15.5177	29.5482	16.9661	2	On and Not Moving	MODERATE
2026-05-18 04:41:22	17.2139	29.4767	16.6123	2	On and Not Moving	MODERATE
2026-05-18 04:41:24	14.5706	29.6153	17.3568	2	On and Not Moving	MODERATE

Table 4. Data Vibration Processed – Day 3 (Condition: On and Moving)

Created_at	Vib_s1 (mm/s RMS)	Vib_s2 (mm/s RMS)	Vib_s3 (mm/s RMS)	Day	Operation Condition	Risk Level
2026-05-19 03:17:47	25.1176	69.795	22.3333	3	On and Moving	CRITICAL

2026-05-19 03:17:50	21.5273	24.4997	21.9857	3	On and Moving	MODERATE
2026-05-19 03:17:52	18.1303	44.5281	13.5186	3	On and Moving	HIGH
2026-05-19 03:17:54	13.838	23.5505	14.908	3	On and Moving	MODERATE
2026-05-19 03:17:56	16.422	25.4509	11.6093	3	On and Moving	MODERATE
2026-05-19 03:17:58	27.1005	31.7745	21.5407	3	On and Moving	HIGH
2026-05-19 03:17:59	29.1215	36.7301	21.1939	3	On and Moving	HIGH
2026-05-19 03:18:01	29.4847	53.0153	23.9249	3	On and Moving	HIGH
2026-05-19 03:18:03	29.7603	62.4982	24.7589	3	On and Moving	CRITICAL
2026-05-19 03:18:05	26.9163	37.0538	21.8465	3	On and Moving	HIGH
2026-05-19 03:18:07	26.9573	25.2996	21.6042	3	On and Moving	HIGH
2026-05-19 03:18:09	24.7456	21.0836	13.6826	3	On and Moving	MODERATE
2026-05-19 03:18:11	21.4673	27.5109	13.6643	3	On and Moving	MODERATE

Vibration data was obtained in real-time under three vehicle conditions using three ADXL345 accelerometer sensors installed at three points: the input shaft, the gear mesh, and the gearbox output shaft. The sensor data was then sent via an ESP32 WiFi microcontroller using the MQTT protocol, which was then connected to a supabase cloud database for monitoring, condition analysis, failure prediction, and RUL.

The research results obtained are not only in the form of vibration measurement data, but also a digital twin system that is capable of monitoring gearbox conditions in real-time, detecting anomalies, estimating Remaining Useful Life (RUL) and presenting information on gearbox health conditions via a monitoring dashboard.

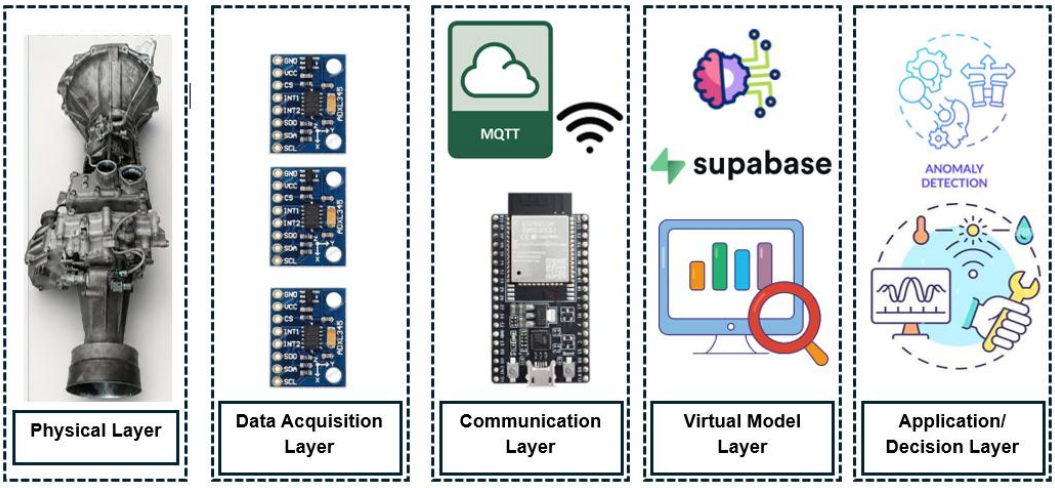

Figure 4. Digital Twin Architecture Five Layer

Physical layer: The monitored physical object consists of the Triton car gearbox of the Bengpuspal Task Force at three points: the input shaft, gear mesh, and output shaft. Data acquisition layer: Real-time vibration data collection from the physical object, namely the gearbox, is carried out through three ADXL345 accelerometer sensors connected using a PCA9548A multiplexer. Communication layer: The communication process of sending data from the sensors to a digital twin system consisting of an ESP32 microcontroller and the MQTT protocol over a Wi-Fi network. Virtual model layer: A representation of the gearbox condition, consisting of a cloud database, dashboard, health score, and machine learning models for gearbox condition diagnosis and Remaining Useful Life (RUL) prediction. Application/decision layer: This layer functions to analyze the gearbox condition, predict failures, and estimate its Remaining Useful Life (RUL), which provides information for decision-making.

Data Acquisition

Vibration data is successfully sent in real-time using the MQTT protocol and stored directly to the supabase cloud database.

	id	created_at	vib_s1	vib_s2	vib_s3	Hari	Kondisi_Operasi	Kode_Kondisi	DI_S1	DI_S2	DI_S3	DI_avg	Health_Index	Health_Score	Status_S1	Status_S2
0	2011	2026-05-13 02:11:24.728206+00	16.113700	16.113700	16.113700	Hari 1	Tidak Menyala & Diam	K1	0.372220	0.243168	0.411781	0.328511	0.6715	67.15	Fault	Fault
1	2012	2026-05-13 02:11:41.438886+00	0.376695	0.376695	0.376695	Hari 1	Tidak Menyala & Diam	K1	0.000000	0.000000	0.000000	0.000000	1.0000	100.00	Normal	Normal
2	2013	2026-05-13 02:11:58.235197+00	0.340338	0.340338	0.340338	Hari 1	Tidak Menyala & Diam	K1	0.000000	0.000000	0.000000	0.000000	1.0000	100.00	Normal	Normal
3	2016	2026-05-13 02:12:42.382537+00	14.958000	15.200600	15.200600	Hari 1	Tidak Menyala & Diam	K1	0.344264	0.228591	0.387218	0.306586	0.6934	69.34	Fault	Fault
4	2017	2026-05-13 02:12:59.23681+00	0.373976	0.374442	0.374442	Hari 1	Tidak Menyala & Diam	K1	0.000000	0.000000	0.000000	0.000000	1.0000	100.00	Normal	Normal
5	2018	2026-05-13 02:13:16.041779+00	0.340338	0.340338	0.340338	Hari 1	Tidak Menyala & Diam	K1	0.000000	0.000000	0.000000	0.000000	1.0000	100.00	Normal	Normal

Figure 5. Database – Supabase

Random Forest

The random forest model is used to classify gearbox conditions based on vibration characteristics based on ISO 20816-9:2020.

Table 5. Random Forest Model Evaluation

Accuracy	0.9820 (98.20%)
F1-Score	0.9821
CV 5-fold	0.9717 ± 0.0117

The training results show that the model is able to identify the condition of the gearbox based on the vibration patterns obtained from the gearbox with an accuracy of 98.20%.

GRU Neural Network

The GRU Neural Network model is used to predict health scores (0-100) from vibration time-series sequences.

- DI_Si = clip((VIB_Si − BL_Si) / (MAX_Si − BL_Si) , 0, 1)
- DI_avg = 0.4 × DI_S1 + 0.4 × DI_S2 + 0.2 × DI_S3
- HI = 1 − DI_avg (range 0–1, internal mathematical model)
- HS = 100 × (1 − DI_avg) (range 0–100, output dashboard)

Table 6. Random Forest Model Evaluation

MAE	4.0768
RMSE	6.1054
MAPE	8.48%
R^2	0.9248

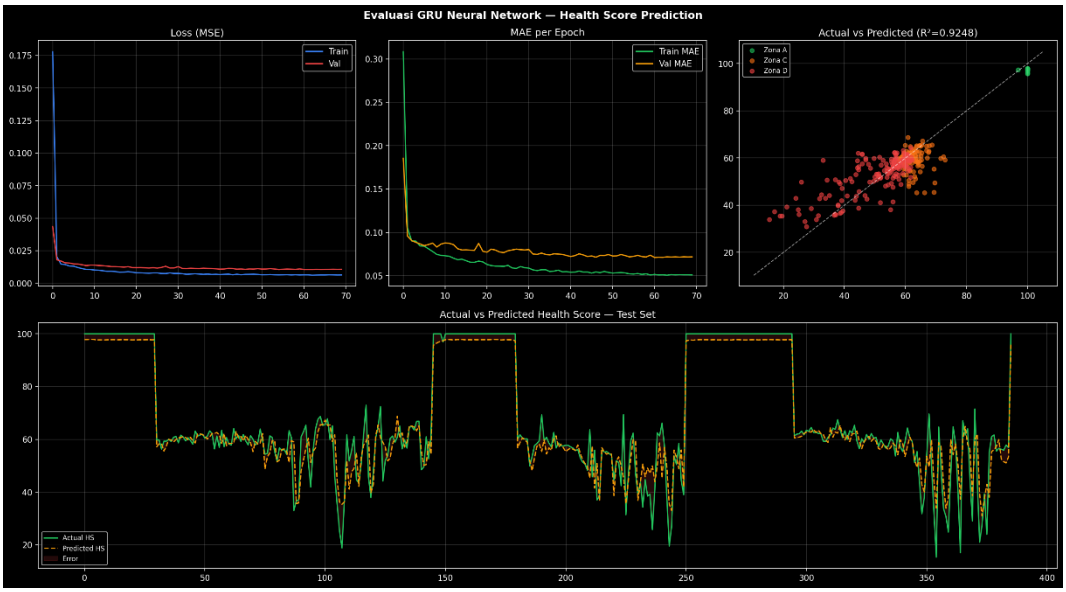

Figure 6. Evaluation of GRU Neural Network - Health Score Prediction

Dashboard Monitoring

The results of this research are a monitoring dashboard that displays the results of the analysis related to the condition of the car's gearbox, in three conditions, namely the first condition is off and stationary, the second condition is on and stationary and the third condition is on and moving.



Figure 7. First Condition Vehicle Gearbox



Figure 8. Second Condition Vehicle Gearbox



Figure 9. Third Condition Vehicle Gearbox

DISCUSSION

In this study, a real-time sensor-based Digital Twin model was successfully developed for predictive maintenance on the Indonesian Army's Rantis (gearbox) powertrain system. The developed model consists of five main layers, namely the Physical Layer, Data Acquisition Layer, Communication Layer, Virtual Model Layer, and Application Layer which are integrated with each other to produce a virtual representation of the gearbox condition in real-time. The results of this development are in line with the Digital Twin concept proposed by Michael Grieves in a UX Magazine platform entitled Digital Twins in an Agentic World, which states that Digital Twin is a virtual representation of a physical object that is continuously connected through a real-time data stream. The integration of ADXL345, ESP32, MQTT sensors, dashboard monitoring, and artificial intelligence models in this study shows that the Digital Twin concept can be applied to the transmission system on the gearbox components of tactical vehicles to support condition monitoring and predictive maintenance activities.

Test results show that three ADXL345 sensors installed at the input shaft, gear mesh, and output shaft points are capable of generating real-time vibration data and sending it to the dashboard via the MQTT protocol and storing it in a supabase database. The vibration data obtained shows differences in vibration characteristics at each measurement point. These differences indicate that each part of the gearbox has a different dynamic response to operating conditions and potential mechanical damage.

The experimental results demonstrate that the integration of Random Forest and GRU networks yields a high diagnostic capability, achieving a condition classification accuracy of 98.20% and a health score prediction R^2 of

0.9248 (Tables 5 & 6). Theoretically, this confirms the framework by Michael Grieves regarding the necessity of a continuous, bidirectional data loop within a five-layer digital twin architecture. While traditional automotive frameworks rely on standalone diagnostic systems (Rajesh et al., 2019), this research proves that deploying an IoT-edge layout using ESP32 and MQTT allows multivariate raw data to be successfully converted into standardized operational zones based on ISO 20816-9:2020 in real time.

The severe fluctuation in vibration profiles observed during the "On and Moving" condition (Table 4)—where the risk level escalated rapidly to HIGH and CRITICAL—highlights the dynamic structural stress experienced by the gearbox mesh under field environment loads. The GRU model effectively tracked these non-linear degradation trends, validating the data-driven paradigm proposed by Thompson (2024). It bypasses the limitation of classical physics-based models which often fail to adapt to unpredictable military operational dynamics.

From a research perspective, this study advances the defense-oriented literature by providing an empirical validation of a digital twin model using a specific military platform workshop (Bengpuspal Puspalad), moving beyond pure software simulations common in current literature (Daly et al., 2024).

Practically, this framework introduces a direct operational advantage for military fleet management. By utilizing the web-based monitoring dashboard (Figures 7, 8, and 9), maintenance personnel can transition from rigid, schedule-based intervals to dynamic, condition-based interventions. The capability to accurately forecast a localized health score decay (e.g., estimating an RUL of 27 days during critical zone shifts) allows logistical teams to pre-stage spare parts and schedule maintenance repairs proactively. Consequently, this minimizes sudden powertrain failures during mobilization, shortens repair workshop downtime, and significantly boosts the combat readiness rate of defense equipment.

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CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis and discussion of the research, it can be concluded that a real-time sensor-based digital twin model can be designed to represent the condition of the Indonesian Army's (TNI AD) vehicle gearboxes through the

integration of vibration data from the ADXL345 accelerometer sensor, historical maintenance data, and a machine learning model. The digital twin model can support predictive maintenance by continuously monitoring changes in gearbox vibration, allowing for earlier detection of anomalies and potential damage compared to conventional reactive or schedule-based maintenance methods. The implementation of the digital twin also demonstrates the potential for increased damage prediction accuracy because maintenance decisions are based on the actual condition of the components, not just time intervals or mileage. This reduces the risk of over- and under-maintenance.

Furthermore, the implementation of the digital twin has a positive impact on reducing downtime and increasing the readiness rate of TNI AD vehicles, as damage can be anticipated earlier, repair times can be planned more precisely, and vehicle operational readiness can be maintained optimally.

FURTHER STUDY

Future research is recommended to develop the digital twin model by adding other sensor variables, such as temperature, rotational speed, and lubrication pressure, as well as a 3D model, to provide a more comprehensive representation of gearbox conditions and improve prediction accuracy. Future research should also compare several algorithmic approaches, such as neural networks, classical machine learning, and hybrid physics-data-driven models, to determine the most appropriate method for use in military gearbox systems under operational conditions. Furthermore, further research with larger data sets and a wider variety of operating conditions is needed to ensure the digital twin model has better generalization capabilities and is more robust to changes in load and operating environment.

ACKNOWLEDGMENT

The author would like to express his gratitude to the Faculty of Defense Engineering and Technology, Indonesia Defense University, for their support in conducting this research. The author also thanks the leaders and mentors who assisted in conducting this research and for providing the opportunity to conduct research at the Bengpuspal Puspalad.

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