Digital Twin Development for Feed Drive Systems Condition Monitoring and Maintenance Planning

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Abstract

Current Prognosis and health management (PHM) technology suffers from challenges such as data availability, system interoperability, scalability, and transferability. In previous years, the PHM field has advanced a lot, but very few studies have been presented in which these challenges are addressed, and hence, PHM solutions are still confined to the lab environment. Digital Twin technology has the potential to address these challenges altogether and can add significant value to the PHM field. This thesis aims to develop an implementable Digital Twin framework for feed drive systems' condition monitoring and maintenance optimization, targeting these prevalent PHM challenges. The proposed framework will employ multiple physics-based models to generate synthetic data for different system states, configurations, and applications, and utilize this data with the help of machine learning to overcome the PHM challenges. The successful address of these challenges will pave the foundation in the direction of generalization of PHM solutions and also enhance the trustworthiness and reliability of PHM solutions.

Keywords-Digital Twin; Feed drive; Artificial intelligence

1. Motivation

The feed drive systems primarily ball screw systems are used to convert rotary motion to linear motion and are employed in the field of manufacturing, machine tools, and robotics due to its high precision, and are used as electromechanical actuators for the aerospace and aviation components such as landing gear systems, flight control, engine actuation systems, etc.,(Qiao et al. 2018) where seamless and reliable operation is required. These systems have been employed due to high positioning accuracy and rigidity, which has been achieved by introducing preload between the screw and nut. Due to continuous operation, fatigue, and wear, these systems accumulate defects and lose preload over time, which leads to a loss in required precision and creates a backlash. Along with preload loss, the common fault modes for these systems are jam, spall, binding, and shaft bent (Yin et al. 2023). The mechanism failure of the feed drive is responsible for 18.72% of downtime in machine tools (Jia, Rong, and Huang 2019). As per the ASM handbook (Anon 1989) feed drive condition monitoring can decrease the production cost by up to 40% and increase the total productivity by 140% for machine tools.

For PHM of the feed drive, primarily physics-based or data-centric approaches are used (Butler et al. 2022). The physics-based approaches provide enhanced interpretability, but they are very sensitive to system parameters and fail to accommodate the uncertainties involved in the system. Data-centric approaches utilize the potential of machine learning. These approaches tend to be more accurate, but their accuracy depends on the amount of available historical data of the asset, which is not readily available in the field, making these approaches difficult to implement. Additionally, issues such as model interpretability may arise, hindering the understanding of how the model arrives at its conclusions.

Alternatively, digital twin (DT) technology offers a promising solution, which utilizes the concept of both physics-based and data-centric modeling strategies in synchronization and mitigates the shortcomings of both (K. Liu et al. 2022). Advancements in developing Digital Twins for feed drive systems have been relatively limited. W. Zhang et al. (2022) developed a DT framework for identifying rolling joints' dynamic parameters (stiffness and damping) for an FEA model. This involved conducting model tests on hardware and utilizing a DNN model in conjunction with the PSO algorithm to ascertain the parameter value. (D. Liu et al. 2022) developed a Digital Twin lumped mass dynamic model of a feed drive servo actuator system that maps the command and load information of the actuator to identify its vibration mode for the purpose of its health monitoring. (K. Liu et al. 2022) presented a multi-layer DT framework to predict and compensate for time-varying positioning errors for a CNC machine. These existing DT frameworks focus on only one aspect of DT, i.e., developing virtual models, and fail to provide an implementable DT for a complete PHM solution with the capability of anomaly detection, diagnosis, and prognosis of the asset.

Additionally, existing PHM solutions face challenges like transferability, scalability, interoperability, and historical data availability. Transferability refers to the capability of employing a single PHM solution across various designs, materials, and configurations of the same asset. Scalability involves the adaptability of the PHM solution to the system used in diverse applications. Interoperability denotes the ability to apply the same PHM solution across different operating conditions of the asset. Lastly, historical data availability pertains to the accessibility and adequacy of data related to different fault severities and failures.

There have been progress in DT development for other applications which tries to tackle these challenges, such as (Feng et al. 2023) developed a DT framework for gear surface degradation monitoring. They utilized physics-based models to virtually represent the gear dynamics and employed optimization algorithms to fine-tune their dynamic parameters. These models were used to generate a data library for various degradation states, enabling transfer learning models to provide meaningful predictions by utilizing the vibration signal from the target asset. The framework is capable of adapting to uncertainties and demonstrates interoperability for different operating conditions. However, it focuses solely on monitoring specific defects, lacking a complete comprehensive solution. (Qi et al. 2024) Developed a DT-based monitoring system for the machining process of complex workpieces. The framework contains multiple layers and digital representation includes multiple models such as geometric, physics, behavior, and rule models. Real-time dynamic data is used for interaction mapping between the virtual models and the physical process. These tuned virtual models provide the state of the process. The framework applies to different operating conditions but fails to adapt to different applications and configurations.

This thesis aims to provide an approach for the development and implementation of a DT framework aimed at PHM of a feed drive system. The proposed framework aims to tackle the above defined PHM challenges.

2. PROPOSED METHODOLOGY

Figure 1. shows the proposed conceptual DT framework for condition monitoring and maintenance optimization, which has four distinct layers.

- Physical layer

The physical layer includes the monitored asset, with sensors for acquiring dynamic signals and necessary data acquisition devices. The layer provides the DT framework with the essential data for tuning the virtual model and for continuous monitoring of the asset.

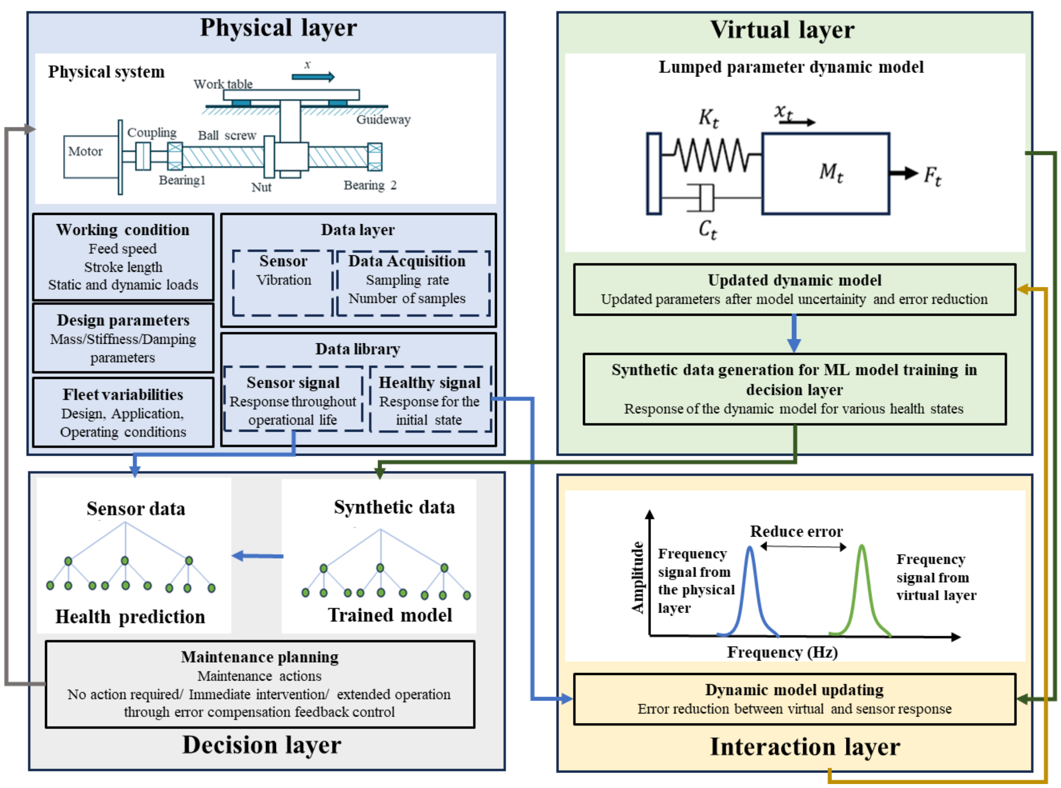

Figure 1. Proposed Digital Twin framework

- Virtual layer

The virtual layer mirrors the physical layer and simulates the dynamic behavior of the asset through either a lumped parameter dynamic model or an FEA model. The model employed is developed with adjustable parameters, which are adjusted as per the design configuration of the asset with the help of the interaction layer. This adaptability ensures that the virtual model correctly represents the physical asset.

- Interaction layer

This layer plays a crucial role in maintaining the virtual model's precise correspondence with the physical system. It accomplishes this by observing and modifying the virtual model's parameters to reduce any differences noted during comparisons of the model's behavior with the real-world responses of the physical system. The parameters will be tuned only once with the help of data for the healthy condition of the asset when the condition of the asset is known with relative certainty. This will help in overcoming the need for historical failure data.

- Decision layer

The tuned virtual model is utilized to create data repositories for various operational scenarios and fault severity stages of the physical asset. The decision layer utilizes this compiled data to train the machine learning (ML) models. After its training phase, the ML models employ the physical asset's responses as inputs to monitor the condition of the asset in real time. Further, the output from this health prediction model will be used for maintenance planning of the feed drive.

3. Objectives and Research Plan

The DT framework will be developed by focusing on each layer discussed in the previous section as a full objective. The proposed thesis has four objectives:

1. Configure a test rig with sensors and data acquisition hardware to gather data essential for the development and validation of the proposed framework.
2. Develop lumped parameter models for the test rig, enabling simulation of various faults, operating conditions, and applications of the feed drive. Additionally, create parametric and ML models to assess discrepancies between physical and virtual responses, facilitating adjustments to model parameters.
3. Develop ML models with the help of data from models created in objective 2 for health predictions.
4. Based on the output of the models from objective 3, develop maintenance planning strategies for the asset.

These objectives will be achieved by the following plan:

In objective 1, a test rig for the feed drive system will be configured. This rig would be used for multiple experiments related to different operating conditions and faults to closely emulate the environmental and operational variables encountered in an industrial setting. A triaxial accelerometer along with required data acquisition hardware will be used to gather vibration data from the rig. The vibration data will be further processed using advanced signal processing techniques such as wavelet transform and empirical mode decomposition to remove random noise components and extract the signal relevant to feed drive system dynamics only. The rig would be used to gather vibration data for three different nuts with different preloads to understand the effect of preload loss on the system's dynamics. The rig would later be used to collect data for the insinuated faults such as wear, nut and screw spalling, and backlash creating at least three datasets related to each fault. At last two run-to-failure experiments will be performed on the rig to understand the natural degradation of the feed drive. Based on the collected data health indicators will be selected for anomaly detection and diagnosis.

In objective 2, based on the configured test rig a lumped parameter model will be developed for the multiple rotational and translational degrees of freedom (DOF) of the feed drive. The model will incorporate the Hertzian contact theory to simulate the rolling elements and the Archard wear theory to simulate defects like wear. The model will be capable of simulating the experiment conditions planned with the rig. The models representing the interaction layer will be developed by using lumped models related to specific DOF and by using ML models that can provide a nonlinear mapping between the response of the physical asset and virtual model parameters such as stiffness and damping parameters. These parameters will be updated by comparing the difference in various features between the collected signal from the test rig and the synthetic signal generated through the virtual layer.

In objective 3, using the data gathered from objective 2 different explainable regression and classification ML models such as random forest, linear regression and decision tree models (Kundu, Darpe, and Kulkarni 2020) will be used for health assessment and damage quantification of the asset under the natural fault progression. These models will utilize the real-time vibration signal from the physical asset to predict its health state using features like natural frequency and ball pass frequency extracted from the signal. The predicted health state will further be utilized to estimate the stochastic positioning error. The initial concept of the proposed DT framework based on a single DOF model was developed and demonstrated in (Gupta and Kundu 2024).

In objective 4, the results obtained from objective 3 will serve as the basis for devising maintenance planning strategies for the asset based on the life cycle cost analysis. Further, the error compensation feedback control strategy will be formulated by utilizing an ML model to estimate required compensation based on location-specific positioning errors estimated in objective 3. This is very important to utilize the maximum life of the feed drive.

Once all the objectives are fulfilled the DT framework will be ready to implement on any feed drive system. The framework designed will possess the flexibility to adjust parameters based on the specific asset and application, thus ensuring high transferability and scalability. Also, DT will be trained for different operating conditions and fault severities addressing interoperability and data availability issues. The current objectives of this thesis will focus on detection, diagnosis, and health management aspects.

Future work for this thesis could involve integrating the prognosis module and exploring the implementation of the framework on edge devices. Additionally, investigating order reduction techniques for both machine learning and physics-based models could help alleviate computing load and further improve the implementability of the framework.

4. Conclusion

This thesis aims to develop a digital twin framework for PHM applications that can provide better accuracy and versatility than physics-based and data-centric approaches. The proposed framework would be adaptable to different design configurations and also compensate for any system variations such as changes in operating conditions and applications. The research will contribute to tackling key PHM challenges such as transferability, scalability, interoperability, and historical data availability.

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