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Zaid Khaddour
1st Year PhD Student
Scientific Supervisor:
Alexey A. Vedyakov
PhD, Associate Professor
ITMO University
St. Petersburg

DIGITAL TWIN–BASED DECISION SUPPORT SYSTEM FOR PIPELINE CONDITION MONITORING AND REMAINING LIFE ASSESSMENT

Abstract: *Oil and gas pipelines operate under severe environmental and operational conditions that lead to progressive degradation of structural integrity. Corrosion, cyclic loading, material aging, and operational uncertainties significantly increase the probability of failures and create substantial economic and environmental risks. Traditional integrity management approaches are primarily based on periodic inspections and expert assessment, which often provide only fragmented information about the actual condition of pipeline assets. This study proposes a digital twin–based decision support system (DSS) for continuous pipeline condition monitoring and remaining life assessment. The proposed framework integrates heterogeneous inspection data, operational measurements, structural integrity models, and artificial intelligence methods within a unified digital environment. A deterministic digital twin core based on the Modified B31G methodology is employed to evaluate corrosion defects and estimate structural adequacy. The architecture supports continuous updating of the asset state, defect assessment, maintenance planning, and future implementation of probabilistic remaining useful life prediction. The proposed approach represents a step toward predictive integrity management and risk-informed maintenance optimization in the oil and gas industry.*

Keywords: *digital twin, decision support system, pipeline integrity, corrosion assessment, remaining useful life, predictive maintenance.*

Хаддур Зейд,
аспирант 1 курса
Научный руководитель:
Алексей Алексеевич Ведяков
Кандидат технических наук,
доцент Университет ИТМО,
г. Санкт-Петербург

ЦИФРОВАЯ ДВОЙНАЯ СИСТЕМА ПОДДЕРЖКИ ПРИНЯТИЯ РЕШЕНИЙ ДЛЯ МОНИТОРИНГА СОСТОЯНИЯ ТРУБОПРОВОДОВ И ОЦЕНКИ ОСТАВШЕГОСЯ СРОКА СЛУЖБЫ

Аннотация: *Нефте- и газопроводы работают в суровых экологических и эксплуатационных условиях, которые приводят к постепенному ухудшению целостности конструкции. Коррозия, циклические нагрузки, старение материалов и эксплуатационные неопределенности значительно повышают вероятность отказов и создают существенные экономические и экологические риски. Традиционные подходы к управлению надежностью в основном основаны на периодических проверках и экспертной оценке, которые часто предоставляют лишь фрагментарную информацию о фактическом состоянии трубопроводных активов. В этом исследовании предлагается цифровая система поддержки принятия решений на основе двойников (DSS) для непрерывного мониторинга состояния трубопровода и оценки оставшегося срока службы. Предлагаемая платформа объединяет разнородные данные контроля, эксплуатационные измерения, модели целостности конструкций и методы искусственного интеллекта в единой цифровой среде. Для оценки коррозионных дефектов и соответствия* *конструкции используется детерминированное цифровое двойное ядро, основанное на модифицированной методологии B31G. Архитектура поддерживает непрерывное обновление состояния активов, оценку дефектов, планирование технического обслуживания и будущую реализацию вероятностного прогнозирования оставшегося срока полезного использования. Предлагаемый подход представляет собой шаг на пути к прогнозируемому управлению целостностью и оптимизации технического обслуживания с учетом рисков в нефтегазовой отрасли.*

Ключевые слова: *цифровой двойник, система поддержки принятия решений, целостность трубопровода, оценка коррозии, оставшийся срок службы, профилактическое техническое обслуживание.*

1. Introduction

Pipeline transport systems represent one of the most critical elements of oil and gas infrastructure. Their reliable operation directly affects industrial productivity, environmental safety, and economic performance. However, pipeline assets are continuously exposed to degradation mechanisms including corrosion, fatigue, mechanical loading, and environmental influences. Over time, these mechanisms reduce structural reliability and increase the probability of failure.

The consequences of pipeline failures include production interruptions, environmental contamination, safety hazards, and significant financial losses. Therefore, the development of advanced integrity management technologies remains an important research and industrial objective.

Current monitoring practices largely rely on periodic inspections, threshold-based evaluation procedures, and expert interpretation of collected data. Although these methods remain widely used, they suffer from several limitations. Inspection data are typically collected at discrete intervals, condition assessment is often fragmented across multiple information sources, and maintenance decisions frequently depend on expert judgment rather than quantitative predictive models. As a result, degradation processes may remain insufficiently monitored between inspection campaigns.

The emergence of digital twin technology creates new opportunities for addressing these challenges. A digital twin can be defined as a dynamically updated digital representation of a physical asset that continuously integrates operational and inspection information with predictive analytical models [1]. Combined with artificial intelligence and decision support methodologies, digital twins provide a foundation for continuous condition monitoring, structural assessment, and remaining life estimation.

The objective of this research is to develop a digital twin–based decision support system capable of integrating heterogeneous monitoring information, evaluating technical condition, and supporting future maintenance decisions for pipeline infrastructure.

2. Analysis of Existing Approaches

Recent years have witnessed substantial growth in the application of decision support systems within the oil and gas sector. Existing studies demonstrate the effectiveness of DSS technologies in emergency management, project evaluation, predictive maintenance, and risk assessment.

Li et al. proposed an integrated decision support system for offshore oil spill management combining simulation models, risk assessment procedures, and optimization algorithms [2]. The proposed architecture demonstrates the advantages of integrating multiple analytical modules within a unified decision-making environment. However, the system is primarily focused on emergency response scenarios and does not address long-term degradation monitoring.

Zemenkova et al. investigated neural-network-based monitoring methods for hydrocarbon transportation facilities [3]. Their research demonstrated the feasibility of artificial intelligence applications for technical condition assessment and safety evaluation. Nevertheless, the presented framework does not include a digital twin representation or remaining life prediction mechanisms.

Rajakannu et al. analyzed the application of artificial intelligence methods for condition monitoring in the oil and gas industry [4]. Their work highlights the importance of feature extraction, machine learning classification, and predictive maintenance strategies. However, most existing AI approaches remain focused on specific equipment types rather than integrated infrastructure-level decision support systems.

The performed analysis indicates that current solutions often address isolated monitoring, diagnostics, or optimization tasks. A unified framework capable of integrating monitoring data, structural assessment, degradation prediction, and maintenance planning remains insufficiently developed.

3. Problem Statement

The operation of modern pipeline systems generates large volumes of heterogeneous information originating from inspection campaigns, operational measurements, maintenance records, and expert evaluations. Despite the availability of these data, their practical utilization is frequently limited by the absence of a unified analytical environment.

Several critical limitations can be identified in current integrity management practices. First, inspections are often fragmented and performed at discrete intervals. Second, monitoring results obtained from different sources remain poorly integrated. Third, existing assessment procedures typically provide information about current condition but offer limited predictive capabilities. Finally, maintenance decisions frequently depend on subjective expert interpretation.

To address these challenges, it is necessary to develop an integrated decision support system that combines heterogeneous information sources into a single digital representation of the pipeline. Such a system must continuously estimate technical condition, evaluate structural integrity, support degradation analysis, and provide a foundation for remaining life assessment.

4. Digital Twin Architecture

The proposed digital twin architecture consists of several interconnected functional layers.

The first layer is responsible for data acquisition. Information is collected from inline inspections, non-destructive testing procedures, operational monitoring systems, and historical maintenance databases.

The second layer performs data validation and preprocessing. Inspection parameters are standardized, missing values are handled, and defect characteristics are transformed into engineering features suitable for analysis.

The third layer represents the digital twin core. This module maintains a continuously updated representation of the pipeline state including geometric parameters, material characteristics, defect information, operational conditions, and degradation history.

The fourth layer contains analytical models responsible for diagnostics and prognostics. Structural integrity assessment is performed using engineering models, while future development includes integration of machine learning algorithms for degradation forecasting.

The final layer represents the decision support subsystem. Based on the evaluated condition and predicted degradation trends, the system generates maintenance recommendations and supports risk-informed decision making.

5. Dataset and Structural Assessment

A real industrial dataset containing information about 1388 detected pipeline defects was analyzed during the research. Preliminary investigation revealed that corrosion defects constitute the dominant degradation mechanism within the dataset. Defect depths reach values up to 31 mm, while critical defects represent only a relatively small portion of the population. Furthermore, defects are unevenly distributed along the pipeline network, indicating localized degradation patterns.

The identified characteristics confirm the necessity of implementing a continuous monitoring framework capable of integrating heterogeneous inspection information into a unified condition assessment model.

For structural evaluation, the digital twin employs the Modified B31G methodology. This approach is widely used for assessing corrosion-related metal loss defects and estimating allowable operating pressure. The method utilizes geometric defect parameters together with pipe dimensions and material properties to determine structural adequacy indicators.

The use of Modified B31G provides an interpretable engineering basis for digital twin implementation. Unlike purely data-driven approaches, the methodology preserves physical meaning and facilitates practical decision-making by maintenance engineers.

6. Remaining Life Assessment Perspective

Although the current implementation focuses primarily on structural integrity assessment, the developed architecture establishes a foundation for future remaining useful life prediction.

The next stage of research involves extending the deterministic digital twin toward a probabilistic framework capable of modeling degradation evolution and uncertainty propagation. Such an extension will allow estimation of failure probability, confidence intervals for predicted condition trajectories, and quantitative remaining life indicators.

Artificial intelligence techniques are expected to play an important role in this process. By integrating historical degradation patterns, operational parameters, and inspection results, machine learning algorithms can improve prediction accuracy and support proactive maintenance planning.

The combination of physics-based integrity assessment and data-driven prognostic models represents one of the most promising directions for future pipeline integrity management systems.

7. Conclusion

This paper presented a digital twin–based decision support system for pipeline condition monitoring and remaining life assessment. The proposed framework integrates inspection information, operational data, structural assessment procedures, and decision support functionality within a unified architecture.

The digital twin maintains a continuously updated representation of pipeline condition and employs the Modified B31G methodology as a deterministic structural integrity core. Analysis of a real dataset containing 1388 defects confirmed the necessity of integrated monitoring and assessment tools capable of supporting predictive maintenance strategies.

Future research will focus on the development of probabilistic degradation models, uncertainty quantification, and machine-learning-based remaining useful life prediction. The proposed approach provides a practical foundation for intelligent pipeline integrity management and supports the transition from periodic inspection strategies toward predictive and risk-informed maintenance.

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