Sensor Redundancy Elimination in Hydrogen pipeline systems

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INTRODUCTION

Hydrogen energy is increasingly recognized as a key component in the transition to a sustainable, low-carbon future. As an abundant and clean fuel, hydrogen has the potential to replace fossil fuels in various industries, from transportation to power generation. The main reason hydrogen is considered as a clean energy carrier, because during the energy release, there is no harmful by-products, only H_2O[1]. However, its widespread adoption is hindered by challenges related to production, storage, and, most critically, **efficient transportation through pipeline systems**[2]. Ensuring the safe and cost-effective distribution of hydrogen is essential for its viability as a mainstream energy source.

This research explores how **Digital Twin Technology** [3,4] **and Graph Neural Networks** [5] **(GNNs) can enhance hydrogen pipeline management**. Digital twins create real-time, data-driven virtual models of physical pipeline systems, allowing for predictive maintenance, improved operational efficiency, and fault detection. Unlike traditional simulations, digital twins continuously update based on sensor data, providing more accurate and responsive insights. Additionally, **GNNs offer a powerful tool for analyzing complex pipeline networks**, optimizing hydrogen flow, and identifying potential failures before they occur. [7]

Integration of these cutting-edge technologies enables **bottleneck elimination** from the system while **real-time analysis** helps efficient maintenance.

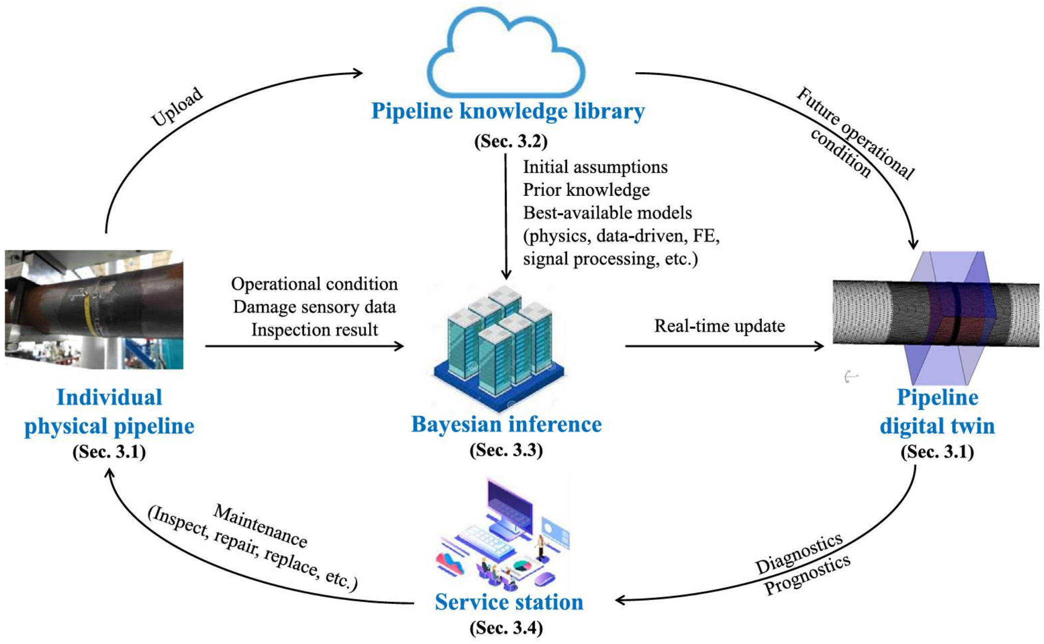

Fig 1: Digital twin system for condition monitoring of a pipeline system [4].

LITERATURE REVIEW

1. Hydrogen Energy Usage and Comparison with Classical Resources

Hydrogen has long been considered a viable alternative to conventional fossil fuels due to its **high energy density and zero-carbon emissions at the point of use**. Compared to traditional energy sources such as coal, oil, and natural gas, hydrogen offers significant environmental benefits, particularly when produced using **renewable energy sources like wind or solar (green hydrogen)**. Studies highlight that while hydrogen can be a more sustainable energy carrier, its adoption is hindered by **high production costs, storage limitations, and inefficiencies in current distribution networks**. Recent advancements in **electrolysis and fuel cell technology** have improved its feasibility, yet further optimization is required to make hydrogen a mainstream energy solution.

2 . Optimization of Pipeline Systems for Hydrogen Transport

Pipeline infrastructure plays a critical role in the large-scale deployment of hydrogen energy. While existing natural gas pipelines could be repurposed for hydrogen transport, challenges such as **hydrogen embrittlement, leakage, and pressure regulation** require new engineering solutions. Previous research has focused on improving **pipeline materials, pressure control mechanisms, and leak detection methods**. Traditional pipeline monitoring relies on **sensor-based systems and fluid dynamics modeling**, but these approaches often lack real-time adaptability. Emerging studies suggest that **digital twin technology** can significantly enhance pipeline efficiency by **providing real-time data analytics, predictive maintenance, and optimized flow control**, surpassing the limitations of conventional simulation-based models.

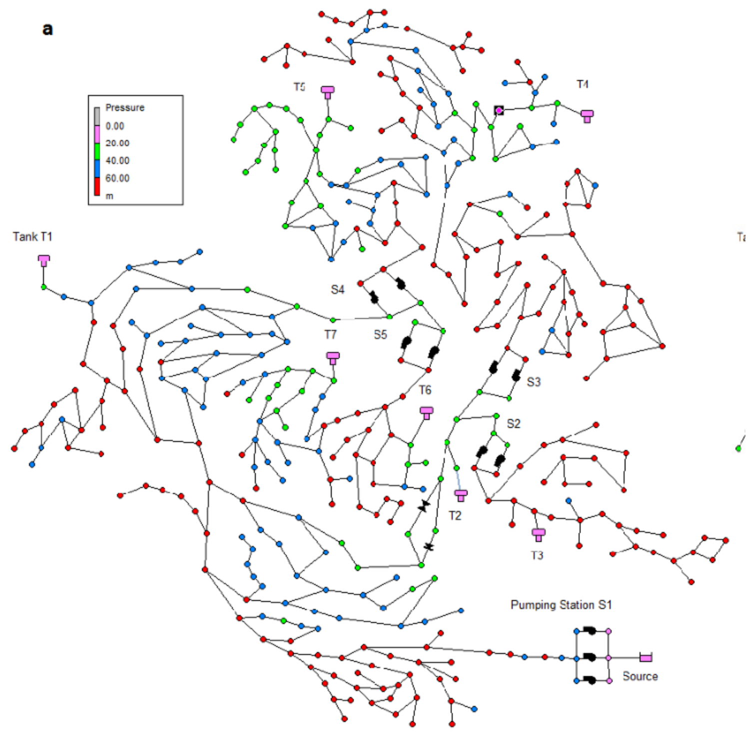

Fig 2: Example pipeline network from Sousa et al.[6], our method opt to minimize the number of sensors needed and detect anomalies.

3. The Role of Graph Neural Networks (GNNs) in Pipeline Optimization

Recent research has demonstrated the potential of **Graph Neural Networks (GNNs) in modelling complex networked systems**, including energy distribution grids and pipeline infrastructures. Unlike classical machine learning techniques, GNNs are particularly effective for **analysing interconnected pipeline structures**, detecting anomalies, and optimizing flow dynamics. Prior applications of GNNs in pipeline systems have shown improvements in **fault detection, pressure balancing, and energy efficiency**. However, studies indicate that **further integration with digital twin technology could unlock even greater predictive capabilities**, leading to a **more resilient and adaptive hydrogen transportation network**.

METHODOLOGY

The combination of the above-mentioned state-of-the-art methods has the potential for ENEA to create a pipeline system that has **high efficiency hydrogen transition** capability. The reliability is supported with real-time **maintenance** thanks to the digital twin, which holds information about the pressure sensor values while estimating the possible anomalies.

This method helps to turn away from the classical energy resources and change them to a cleaner energy while making it financially more appealing.

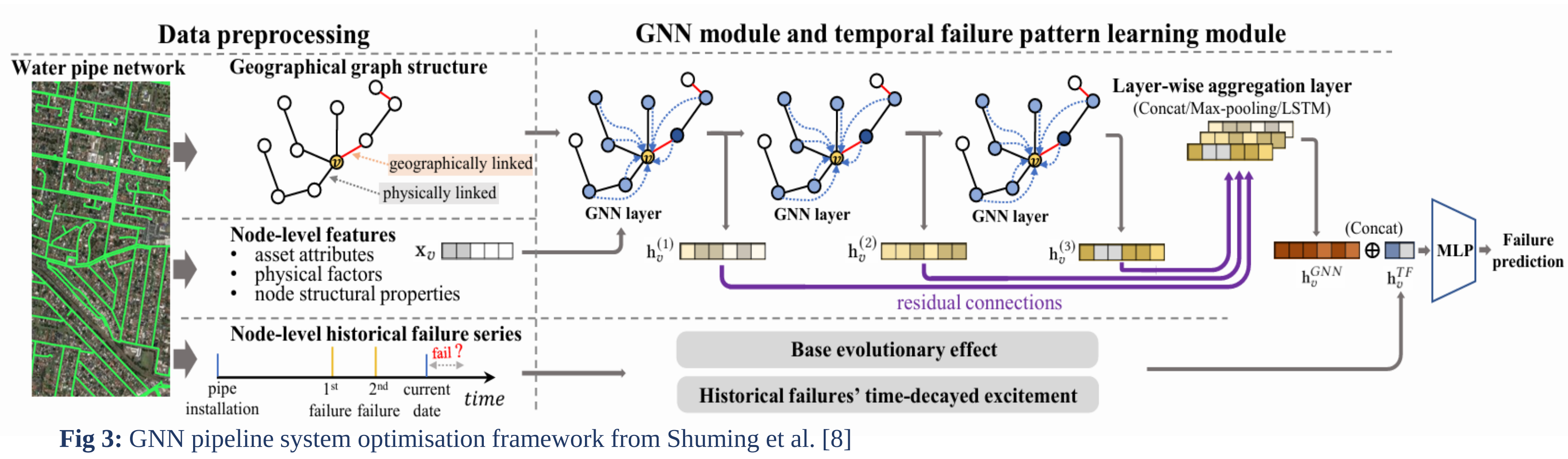

Fig 3: GNN pipeline system optimisation framework from Shuming et al. [8]

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