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Project Report

Digital-Twin-Based Management of Sewer Systems: Research Strategy for the KaSyTwin Project

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Abstract: Sewer infrastructure is vital for flood prevention, environmental protection, and public health. As part of sewer infrastructure, sewer systems are prone to degradation. Traditional maintenance methods for sewer systems are largely manual and reactive and rely on inconsistent data, leading to inefficient maintenance. The KaSyTwin research project addresses the urgent need for efficient and resilient sewer system management methods in Germany, aiming to develop a methodology for the semi-automated development and utilization of digital twins of sewer systems to enhance data availability and operational resilience. Using advanced multi-sensor robotic platforms equipped with scanning and imaging systems, i.e., laser scanners and cameras, as well as artificial intelligence (AI), the KaSyTwin research project focuses on generating digital twin-enabled representations of sewer systems in real time. As a project report, this work outlines the research framework and proposed methodologies in the KaSyTwin research project. Digital twins of sewer systems integrated with AI technologies are expected to facilitate proactive maintenance, resilience forecasting against extreme weather events, and real-time damage detection. Furthermore, the KaSyTwin research project aspires to advance the digital management of sewer systems, ensuring long-term functionality and public welfare via on-demand structural health monitoring and non-destructive testing.

Keywords: sewer infrastructure; sewer systems; proactive maintenance; resilience forecasting; damage detection; linked data; digital twin; digital model; building information modeling (BIM); multi-sensor platforms

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1. Introduction

Sewer infrastructure has been a trailblazer for modern civilizations. Sewer infrastructure was constructed in ancient Mesopotamia between approximately 4000 BCE and

2500 BCE, and similar systems have been discovered in Scotland and Greece dating back 5200 years [1]. The term “sewer infrastructure” encompasses all infrastructure assets devised for collecting and transporting sewage (“sewer systems”), which includes pipes, lines, manholes, and pumping stations, as well as systems for treating and disposing of sewage (“wastewater treatment plants”) [2]. Currently, sewer systems are an integral part of global infrastructure closely connected to other types of infrastructure, such as road networks. Consequently, damage to sewer systems may negatively affect different types of infrastructure, resulting, e.g., in road closures and traffic jams [3], or may cause environmental pollution [4]. Sewer systems have been facing significant challenges due to aging and overstressing because of urbanization and a growing population, as well as heavy precipitation events caused by climate change.

In Germany, for example, sewage infrastructure spans nearly 600,000 km and has an average age of 37 years [5]. In large German cities, around 15% of the sewer system is over 100 years old. Furthermore, significant soil subsidence has occurred in areas of disused mines [6]—particularly in former lignite mining regions—negatively impacting sewer systems and increasing the risk of damage [7]. It is therefore clear that reliable and proactive monitoring approaches towards mitigating the risk of sewer system damage are necessary.

In response to the challenges described above, and as part of the German government’s goals to completely phase out lignite by 2038 [8], the KaSyTwin research project, hereinafter referred to as “KaSyTwin”, was launched in November 2023. The word KaSyTwin combines the German term KanalSystem (“sewer system”) with the concept of digital twins. Funded by the mFUND program of the German Federal Ministry for Digital and Transport (BMDV), the KaSyTwin project aims to increase the resilience of sewer systems by using digital technologies in maintenance. This paper introduces the conceptualization of the research framework and methodology of KaSyTwin. The primary objective of the KaSyTwin is to develop a methodology for the semi-automated development and utilization of digital twins, capable of offering real-time representations of physical sewer systems. By integrating different tools such as multi-sensor robotic platforms equipped with laser scanners and cameras, as well as artificial intelligence (AI) algorithms, KaSyTwin aims to improve data availability, enhance proactive maintenance strategies, and advance the structural health monitoring of sewer systems following a linked data approach. To meet the primary objective, the following aspects are investigated:

- Enhanced data availability and integration: KaSyTwin seeks to integrate heterogeneous and decentralized data into a cohesive digital twin that is easy to access by authorized users. The integration process involves combining laser scanning data, existing documentation (such as sewer system assessment data and structural condition reports), and sensor data recorded from sewer systems in operation.
- Proactive maintenance and resilience: By using digital twins, KaSyTwin aims to shift from reactive to proactive maintenance strategies. Digital models may enable real-time monitoring and early damage detection, facilitating timely interventions. Additionally, KaSyTwin emphasizes resilience forecasting, allowing for better preparation and response to extreme weather events and other disruptions.
- The development of a multi-sensor robotic platform: To achieve accurate and comprehensive data collection under a variety of operational conditions, a prototype of a multi-sensor robotic platform will be developed in the KaSyTwin project.
- AI-driven data processing: AI algorithms will be employed in the KaSyTwin project for advanced data analysis to enable real-time damage detection as part of structural health monitoring strategies for sewer systems.

To validate the KaSyTwin concept, a real-world test case is devised to ensure the practicality and effectiveness of the methodology. The outcomes of KaSyTwin are tailored to German sewer systems and based on the international state of the art in science and technology. While primarily applicable to Germany, the findings may also be transferable to other countries, assisting in enhancing the resilience and management of sewer systems worldwide.

The remainder of this project report is organized as follows: The research background is elaborated upon in Section 2, presenting the state of the art of the KaSyTwin topic. Next, the objectives and research questions for KaSyTwin are defined in Section 3, followed by the description of the proposed approaches and methods. In Section 4, the initial results of the project are presented, followed by the summary and conclusions and an outlook on future research.

2. Background and Research Questions

In this section, first, current maintenance and inspection processes for sewer systems in Germany are described. Thereupon, the concepts of building information modeling (BIM) and digital twins are explained, providing a foundation for understanding the role of these concepts in infrastructure management. Furthermore, methods utilizing AI algorithms for data analysis within the context of BIM and resilience analysis are discussed and classified. Next, research projects in related fields are presented, highlighting potential synergies, as well as the delimitation of KaSyTwin. Finally, the research questions of the project are proposed.

In Germany, operators of sewer systems are obliged to inspect and service sewer systems at regular intervals, mandated by the regulations for the inspection of wastewater treatment plants set by each German federal state. In North Rhine-Westphalia, for example, sewer systems must be visually inspected every 15 years [9], while in Baden-Württemberg, the interval is 10 to 20 years depending on the type, condition, and location of the system [10]. Moreover, in Hamburg, inspections must be conducted every 5 to 25 years depending on the type, condition, and location of the system [11]. Using tethered inspection vehicles equipped with cameras, sections of up to 500 m in length are covered. The data collected by the tethered inspection vehicles is then transferred for analysis to information systems, designed to manage sewer inventory and condition. In Germany, managing the inventory and condition of sewer systems is usually performed in a so-called “sewer cadaster”. These systems sometimes incorporate 3D representations of sewer networks. However, these models are predominantly geometric in nature, lacking object-oriented structures and providing only sparse information. Although such models provide a promising basis for the adoption of BIM methodologies in sewer infrastructure management, their practical application has so far been limited [12].

In [13], BIM is defined as a model-based and lifecycle-oriented digital methodology which is based on building models of three to *n* dimensions. In general, BIM models act as central data hubs, enabling collaboration among stakeholders and serving as a foundation for the digital management of information. Furthermore, BIM models may be used to implement digital shadows or digital twins. According to [14], the distinction between digital shadows and digital twins lies in the data flow between physical objects and their virtual counterparts. In digital shadows, data flow automatically from the physical to the virtual object, but the reverse flow is performed manually. In digital twins, real-time synchronization allows for automated, bidirectional data flow between physical and virtual systems. Digital twins are defined differently across diverse sectors. For example, in [15], digital twins in the water sector are described as dynamic systems in which static and real-time data are integrated to enable insights into physical systems and to optimize outcomes.

Other approaches classify digital twins into levels of maturity, such as informational, operational, and connected systems [15]. As a result, digital twins provide a dynamic, real-time reflection of physical objects, supporting decision making in maintenance, logistics, design, and process optimization [16]. Several approaches to enhance the resilience of energy systems [17], rail and road infrastructure [18,19], ports [20], and airports [21] have been introduced. Furthermore, AI has increasingly been used in the construction industry and is employed in various application fields throughout the lifecycle of structures [22]. For example, artificial intelligence is used for detecting structural damage [23] or for identifying hazardous scenarios during construction processes [24]. Further growing areas of research are the use of AI for analyzing documents and plans in building construction [25], bridge construction [26], and waterways [27], resulting in faster data processing [12]. However, AI has been scarcely used for evaluating plans of sewer systems in the current body of research. Relevant research approaches of utilizing AI to enhance data quality and of optimizing system performance can be drawn from [28], which discusses the application of AI in drinking water systems, particularly for leak detection. The findings in [28] align with the objectives of KaSyTwin, which aims to leverage AI for advanced damage detection and real-time monitoring. The maintenance of sewer systems stands to benefit from AI-based damage detection, employing state-of-the-art data analysis tools, such as image-based recognition, laser scanning, and object-oriented BIM models with embedded georeferencing, realized as digital twins [29].

Digital twins have been the focus of several studies and research projects, primarily focusing on enhancing infrastructure resilience in above-ground infrastructure systems [30]. For example, the mdfBIM+ research project introduced a partially automated creation of digital twins of existing infrastructure [31]. In the mdfBIM+ research project, a digital twin was created by merging survey data, recorded using photogrammetry or light detection and ranging (LiDAR) point clouds, with existing structural documentation. The result was an as-built BIM model for maintenance management. However, the project focused only on bridges and did not include underground infrastructure. Furthermore, the IDA-KI (infrastructure data assessment using artificial intelligence and Internet of Things technologies) research project focused on developing methods for the automated evaluation and assessment of civil infrastructure within the context of structural health monitoring (SHM) [32]. In the IDA-KI project, a 45 m long prestressed concrete bridge was built and equipped with several SHM systems, such as distributed fiber optic sensors and accelerometers. The aim of the IDA-KI project was to build a comprehensive database of monitoring data under real-world damage scenarios, contributing to the validation of structural evaluation methods and sensor fault diagnosis for reliable anomaly detection in civil infrastructure [33].

In addition to the aforementioned projects, several research projects have focused on underground infrastructure systems with the goal of contributing to proactive maintenance using intelligent and digital methods. In the DIANE (drone use for the inspection of sewer networks) project, a miniaturized and (semi-)autonomous drone for inspecting sewer infrastructure, compatible with an existing inspection software, is being developed [34]. In the context of municipal data usage, the KomIT project is focusing on consolidating municipal asset data, such as supply and disposal lines, roads, and street furniture, in a central platform and a shared data space [35]. Other research projects have been focusing on using sensors for water management and analytics. For example, the CoMoTH project monitors SARS-CoV-2 in wastewater, using AI methods and digital-twin-enabled software architectures [36]. Furthermore, in [37], a linked data approach was developed for automated failure detection in pressure sewer systems using real-time sensor data. The D4RUNOFF project is focusing on the data-driven implementation of hybrid nature-based solutions for preventing and managing diffuse pollution from urban water runoff [38]. Specifically, the D4RUNOFF project is developing novel detection methods for characterizing runoff pollutants and novel sensors for identifying and monitoring new pollutants. Furthermore, an AI-based management platform is foreseen to be developed for supporting water management stakeholders (i.e., water utilities and public authorities) in the planning, operation, and risk monitoring of urban infrastructures. Moreover, open-data approaches towards simulating and managing sewer networks have been reported. Examples include the QKan, which is a tool-based quantum geographic information system (QGIS) for simulating sewer systems, used for data preparation and post-processing and for storing sewer system data in table format within an SQLite database. In addition, the QKan approach supports importing sewer system data from spreadsheets, converting the data in a variety of data formats for file exchange, displaying the data in QGIS, processing the data with standard QGIS tools in tables or forms, and preparing the data for use in simulation programs [39]. However, the QKan tool allows neither bidirectional data flow between physical and virtual systems nor data processing.

From the previous discussion, it can be seen that only isolated approaches exist for maintaining sewer systems, including detecting damage, manually creating BIM models, or forecasting the resilience of critical infrastructure systems. In this direction, a method based on digital twins of sewer systems and open-data exchange formats for predictive maintenance management serves to address the gaps in underground infrastructure and is considered in KaSyTwin.

To meet the objectives, KaSyTwin addresses the following research questions:

- Q1: How can proactive maintenance management for sewer systems be designed using digital twins?
- Q2: How can AI methods be employed for the automated generation and verification of digital 3D sewer models in real time?
- Q3: What predictions can be made to enhance the resilience of existing sewer systems using AI?
- Q4: How can diverse data from various sources be integrated with a digital twin?
- Q5: How can different sensor technologies for the 3D visualization of sewer structures be optimally fused on an autonomous robotic system?
- Q6: How can AI be used to detect damage in sewer systems in real time?

Answering these questions is expected to significantly advance the field of sewer infrastructure management and provide a scalable solution that enhances the reliability and sustainability of critical urban systems.

3. The KaSyTwin Project: Approaches and Methodological Concepts

KaSyTwin covers seven interrelated research areas, which are developed in successive, overlapping phases over the duration of the project. An overview of the interdependencies of the research areas is presented in Figure 1. Due to the different sub-objectives of each research area, a multi-method approach is adopted in each project phase. Initially, potential BIM use cases and requirements, which digital twins designed for maintenance purposes should meet, are identified. Next, the hardware of two cooperative multi-sensor robotic platforms for scanning sewer infrastructure is developed. The geometrical information collected by the platforms is used to create a 3D model, which serves as a graphical representation of the digital twin. Further steps aim at processing and integrating semantic data into the digital twin, including the existing inventory data (as-built documentation, cadastral information, and damage documentation) as well as the SHM data collected by the platforms. The final stage of the project covers the development of a resilience analysis and proactive maintenance model, including merging of final components and validation tests. The approaches and methodologies used in the project are described in more detail in the subsections below. Two research fields are described in one subsection if there is a strong connection and dependency between the research fields.

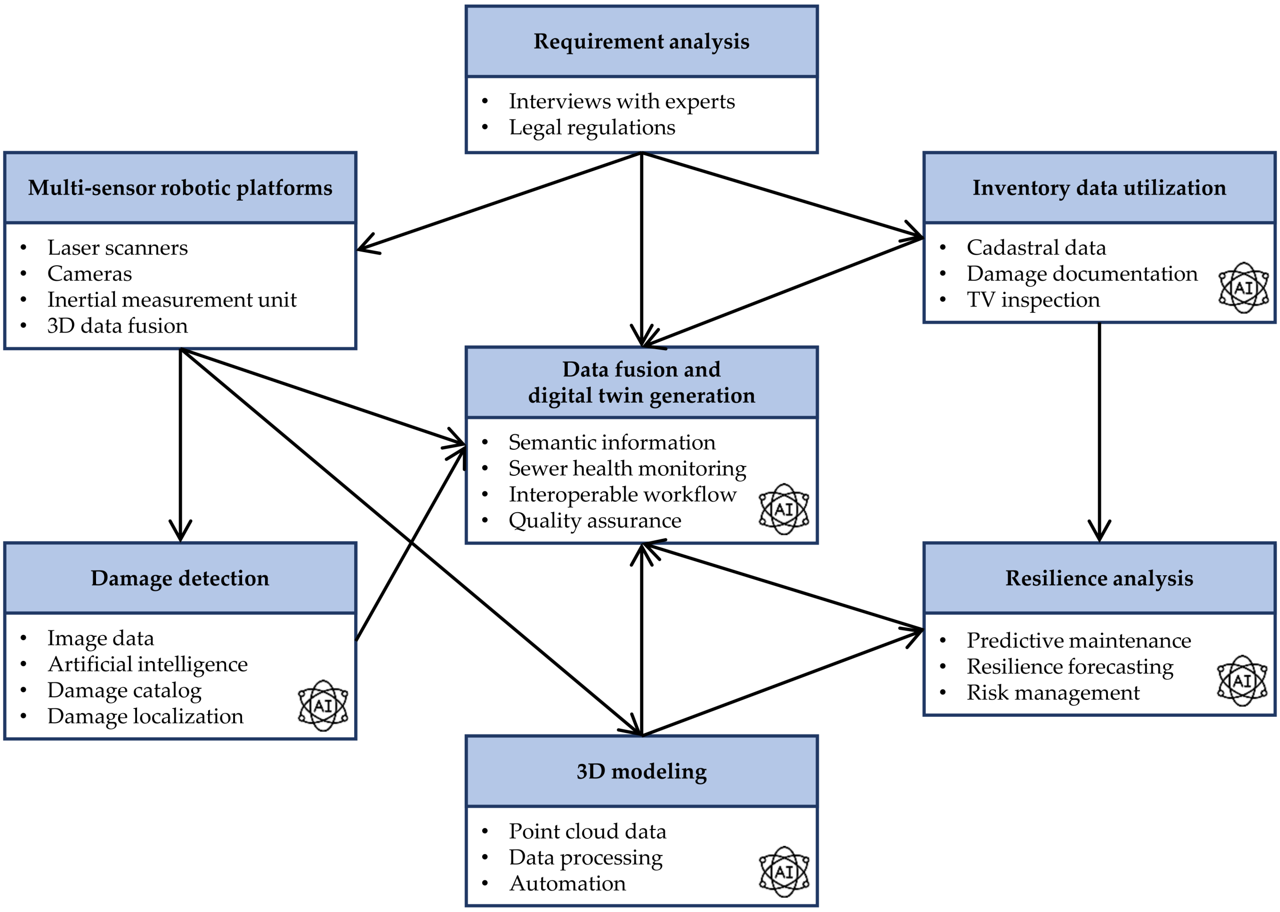

Figure 1. Research fields and connections.

3.1. Requirements Analysis

To define the requirements of digital twins in sewer systems and identify potential opportunities for digitalization and automation, the operational status of sewer systems is analyzed. In the analysis, both state-of-the-art research approaches, as well as the current state of practice, are examined. First, state-of-the-art research approaches introducing digital twins for sewer system maintenance are analyzed via a systematic literature review (SLR). Next, the current state of practice is derived from interviews with experts and stakeholders in an attempt to gather insights into challenges, potential opportunities from digitalization and automation, and the current processes used in sewer system maintenance. Based on the analysis, the data and information required by digital twins for sewer system maintenance are identified. Finally, the results of the requirements analysis are used to derive potential use cases for digital twins in sewer system maintenance.

3.2. Multi-Sensor Robotic Platforms and 3D Modeling

Two multi-sensor robotic platforms are developed to ensure reliable, efficient, and precise 3D modeling of sewer systems. The multi-sensor robotic platforms are designed with different sizes and specifications to be used in various types of sewer systems. Additionally, the two platforms will be able to cooperate, i.e., one platform functions as a communication hub. Based on the results of the requirement analysis discussed previously, the multi-sensor robotic platforms are equipped with various navigation, sensing, and processing components, i.e., laser scanners, camera systems, inertial measurement units, odometers, as well as computing, storage, and communication units. Point cloud data recorded by the laser scanners are used to capture geometry and generate 3D models of sewer systems in which the 3D models form the geometric representation of the digital twin. Another aspect of developing the multi-sensor robotic platforms involves hardware-oriented programming, which is used to optimize the platforms' performance via real-time data fusion, resulting in low data volumes and computing power requirements while simplifying data handling. The multi-sensor robotic platforms and algorithms developed undergo "staged" testing in a controlled environment in a laboratory. Upon successful completion of the tests, the multi-sensor robotic platforms are tested under real-world conditions in sewer systems.

3.3. Damage Detection

The main objectives of sewer system inspection are damage detection and localization. Currently, damage detection and localization are performed by an operator who monitors a video stream while a camera system traverses the sewer system. To address the shortage of specially trained operators and reduce the risk of errors, such as false positives/negatives on the existence of damage, damage detection and localization are automated using AI. The first step in this direction is to analyze the existing damage catalog, as outlined in [40]. Then, based on the types of damage defined in the damage catalog, sensor types on multi-sensor robotic platforms that are suitable for detecting damage in sewer systems are selected. For example, cracks, material degradation, and corrosion may typically be detected via images captured by camera systems. By contrast, other types of damage, such as deformations, holes, misaligned joints, and ingrowth, may require laser scanning. Finally, damage localization is achieved by tracking the positions of the multi-sensor robotic platforms.

3.4. Inventory Data Utilization

To enrich the geometric 3D models of sewer systems generated by the multi-sensor robotic platforms with semantic information, inventory data from sewer system operators are used. The inventory data encompass information that includes (i) as-built documentation, e.g., grid plans, connection information and other utilities details; (ii) geodata and geometrical information—e.g., background or property maps; (iii) functional data, e.g., installation dates, material types, pipe dimensions, inspection results, and maintenance history; (iv) structural data, e.g., structural condition and damage assessments; (v) operational data, e.g., flow calculations, pollutant load calculations, and inflow and infiltration data; and (vi) asset value estimations. The inventory data may be stored and exchanged either digitally using a sewer information system or, in most cases, unstructured in an analog and decentralized manner, resulting in data loss. To assess the semantic quality of the existing inventory data and further prepare them for integration into the geometric model, the data are classified using AI. Two sets of AI models are iteratively trained in a supervised learning process until satisfactory performance and classification accuracy are achieved. The first set of the AI models is trained to classify the analog inventory data (in paper or PDF form) into different document types, such as plans, technical reports, and damage reports. Next, the second set of AI models, specifically convolutional neural networks, capable of recognizing text, images, and features, is trained to analyze and extract semantic information from the previously classified documents. Finally, the semantic information extracted from the inventory data is used to enrich the 3D geometric models, constituting part of the digital twin of the sewer systems.

3.5. Data Fusion and Digital Twin Generation

Data fusion entails automating the integration of semantic information from the inventory data into the 3D geometric models by combining the training and application of the AI models previously described into an interoperable workflow with optimized interfaces, linked to a common data environment. As a result, a semantically refined digital twin of sewer systems is created. The digital twin is created as a multi-layer model, incorporating the geometric data from sewer information systems on a larger scale (2D GIS data) and 3D BIM models to visualize and manage structural data, such as blockages and damage locations. The possibility of integrating hydraulic models into the digital twin has yet to be tested. Alternatively, a platform for the data exchange between the digital twin and conventional software for hydraulic calculations will be created. Additionally, a strategy is designed and implemented to ensure continuous quality assurance, consistency, and accuracy of the digital twin, as well as to maintain traceability of data changes. Once semantically refined, the digital twin is linked to static and dynamic data platforms and systems to ensure bidirectional data flow between each physical sewer system and its virtual counterpart in the digital twin, enabling real-time status updates. Data such as structural attributes, pipe dimensions, material specifications, and sewer dynamic parameters (i.e., flow rates, pressure levels, and water quality) are included in the bidirectional data flow. As a result, a comprehensive and up-to-date representation of the sewer system is generated, supporting real-time decision making and proactive maintenance strategies. For example, data recorded by sensors in the physical system about flow changes are automatically transmitted to the digital twin and may be used to remotely control elements of the sewer system, such as discharge throttles.

3.6. Resilience Analysis

The resilience prediction approach, proposed in KasyTwin, focuses on applying digital twins at both the micro level, i.e., individual sewer structures, and macro level, i.e., entire sewer systems interacting with external environments. Separate AI models are developed for each level to optimize sewer maintenance and resilience. At the micro level, the sewer network at its current state, i.e., including potentially existing damage, is treated as a "closed system". Predicting potential damage and recommending retrofitting action are achieved via predictive maintenance using a knowledge-based system (KBS) that integrates tacit knowledge, e.g., standards and explicit knowledge (expert knowledge). The KBS is tested with real datasets and optimized to improve prediction accuracy. At the macro level, the focus is placed on the interaction of sewer systems with external facilities, such as wastewater treatment plants, weather services, and buildings. In this case, resilience prediction is performed using a data-driven risk management approach, which employs advanced AI; in particular, machine learning techniques, such as supervised and reinforcement learning, are used to model various scenarios—from overload situations to damage progression—thus enabling proactive maintenance. The overall outcome of the resilience prediction approach includes a knowledge-based system for proactive maintenance at the micro level and an AI-based resilience forecasting system at the macro level. It is expected that both systems will enable predictions and recommendations for specific maintenance measures to be carried out, enhancing the resilience and efficient operation of sewer infrastructure.

4. Initial Results

4.1. Requirements Analysis

The SLR in [41] highlights the potential of digital twins for sewer system maintenance, particularly in enabling proactive maintenance. Moreover, the SLR outlines challenges relevant to KaSyTwin. One major challenge is data collection and data quality. For example, ref. [42] emphasizes that the complexity and scale of sewer systems, combined with insufficient instrumentation and poor data quality, pose severe obstacles in implementing proactive maintenance strategies. Furthermore, in the SLR, technological challenges are emphasized, specifically when developing AI applications for predictive maintenance, which are still in early stages and often depend on synthetic data [43]. In addition, the SLR raises conceptual challenges, particularly the misuse of the term "digital twin". Many systems described in the literature are incorrectly labeled as digital twins when they are actually digital models or digital shadows. Digital twins, as opposed to digital models or digital shadows, require an automated bidirectional flow of data between the physical system and the virtual counterpart. The review also reveals that ontologies for information management in sewer systems already exist and are considered in the development process within KasyTwin to enhance data integration and management.

4.2. Multi-Sensor Robotic Platforms

Since robotic systems for sewer inspections have been used for years, a literature review is conducted to assess robotic systems for sewer system maintenance, focusing on systems employing advanced technologies [44]. The review focuses on developing project-specific multi-sensor robotic platforms to enable determining specifications for multi-sensor robotic platforms, i.e., navigation, sensing, and processing components, based on the characteristics of the sewer systems and the types of damage typically encountered, as described in Section 3.2.

Two multi-sensor robotic platforms are developed for the project: a large "master" platform for inspecting main sewer systems and a small platform designed for auxiliary or branch sewer systems. The master platform can carry more equipment, i.e., laser scanners, camera systems, inertial measurement units, or odometers, and is well suited for extensive sewer inspections, while the small platform is optimized for operating in narrow and confined spaces. The selection of the platforms is driven by the previously mentioned challenges, unveiled by the SLR.

4.3. Damage Detection

The results of a further literature search to analyze existing approaches to damage detection in wastewater systems are provided in [45]. Existing challenges and open questions regarding damage detection as well as a requirement specification for damage detection are defined. For this purpose, the review contains analyses of common standards, such as DIN EN 13508 [40], and classifications of the damages described. The classification is based on the frequency of occurrence and the type of damage, as well as the material of the sewer system. The occurrence frequency is important to train artificial intelligence for damage detection, and a sufficiently large training dataset is required. Therefore, rarely occurring damage may not be recognized automatically during the project. The classification of damage types is necessary because some damage types are visually indistinguishable or hardly distinguishable from each other, so indistinguishable damage types are grouped into one class. The first analysis shows that some damages, such as deformations or shifted connections, are more detectable in 3D data than in images, while cracks, for example, are easier to detect in images. In the context of class definition, existing training datasets, such as those in [46], are used to test initial training approaches.

5. Conclusions and Outlook

Sewer systems are critical infrastructure assets holding an essential role in flood prevention, environmental protection, and public health. Traditional methods of sewer system maintenance are largely manual, reactive, and dependent on inconsistent data, which may lead to operational inefficiency. The aforementioned issues, which are discussed in the relevant literature, highlight the need for proactive maintenance, employing state-of-the-art methods and digital tools, such structural health monitoring and digital twinning.

This paper presented an approach employing digital twins for sewer system maintenance. The proposed approach, which is the centerpiece of the KaSyTwin project, covers the whole maintenance process, ranging from data acquisition to resilience analysis and proactive maintenance. The initial results of the literature review have shown the increasing importance of digital twins in the maintenance of sewer systems, particularly in proactive maintenance and damage detection via structural health monitoring. However, the literature review also revealed a lack of consensus on the definition of a digital twin, with approaches essentially proposing digital shadows and digital models being erroneously described using the term "digital twin".

In the KaSyTwin project, the digital twin of each sewer system will be built upon data obtained using multi-sensor robotic platforms. The platforms are developed specifically for capturing data in the harsh environment of sewer systems. The concept for the first prototype has been described in this paper, and the next steps involve building and testing prototypes under laboratory and real-world conditions. As part of future work, the multi-sensor robotic platforms will be adjusted for the humid and moist conditions of sewer systems, e.g., by installing a LiDAR sensor suitable for underwater application, such as the ULi [47]. First, training data for the design of the automated modeling of the sewer system will be recorded using commercial sensors, and the resulting 3D geometric model will form the basis for the digital twin. By obtaining inventory data on the sewer systems, semantic information for each sewer system will be extracted using AI models and assigned to the respective 3D geometric model. Damage detection through the digital twin will be based on data provided by the operators of sewer systems, which, in future work, will be used to train the AI models and will be deployed in multi-sensor robotic systems for real-time damage detection.

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References

1. De Feo, G.; Antoniou, G.; Fardin, H.; El-Gohary, F.; Zheng, X.; Reklaityte, I.; Butler, D.; Yannopoulos, S.; Angelakis, A. The Historical Development of Sewers Worldwide. *Sustainability* **2014**, *6*, 3936–3974. [CrossRef]
2. Davis, M.L.; Cornwell, D.A. *Introduction to Environmental Engineering*, 5th ed.; McGraw-Hill: New York, NY, USA, 2013; ISBN 978-0-07-340114-0.
3. General-Anzeiger. Wie es um die Sanierung der Bonner Kanalisation steht. Drohender Straßeneinbruch auf Adenauerallee. Available online: https://ga.de/bonn/stadt-bonn/bonn-wie-es-um-die-sanierung-der-kanalisation-steht_aid-116708905 (accessed on 27 July 2024).
4. WTVR. Broken Pipe Leaking Sewage into James River Is Being Repaired; Why Permanent Solutions Could Be a 'Challenge'. Available online: https://www.wtvr.com/news/local-news/broken-pipe-leaking-sewage-into-james-river-is-being-repaired-july-18-2024 (accessed on 18 July 2024).
5. Berger, C.; Falk, C.; Hetzel, F.; Pinnekamp, J.; Ruppelt, J.; Schleiffer, P.; Schmitt, J. Zustand der Kanalisation in Deutschland: Ergebnisse der DWA-Umfrage 2020. *KA Korresp. Abwasser Abfall* **2020**, *67*, 939–953. [CrossRef]
6. Ito, T.; Aydan, Ö. Abandoned lignite mines in Mitake, Japan, and some issues. *Environ. Geotech.* **2020**, *9*, 463–474. [CrossRef]
7. Chai, J.C.; Shen, S.-L.; Zhu, H.-H.; Zhang, X.-L. Land subsidence due to groundwater drawdown in Shanghai. *Geotechnique* **2004**, *54*, 143–147. [CrossRef]
8. Bundesregierung Deutschland. Von der Kohle zur Zukunft. Available online: https://www.bundesregierung.de/breg-de/schwerpunkte/klimaschutz/kohleausstieg-1664496 (accessed on 16 October 2024).
9. Abw, S.A.S. Verordnung zur Selbstüberwachung von Abwasseranlagen-Selbstüberwachungsverordnung Abwasser-SüwVO Abw. *Gesetz-und Verordnungsblatt (GV. NRW.)* **2013**, *Nr. 33*, 601–612.
10. Landesanstalt für Umweltschutz Baden-Württemberg (Siedlungswasserwirtschaft). Die neue Eigenkontroll—Verordnung (EKVO)—Hinweise für Betreiber kommunaler Abwasseranlagen. 2001. Available online: https://www.dwa-bw.de/files/_media/content/PDFs/LV_Baden-Wuerttemberg/Homepage/BW-Dokumente/Homepage%202013/Nachbarschaften/73263-Hinweise_f%C3%BCr_Betreiber_kommunaler_Abwasseranlagen.pdf (accessed on 12 October 2024).
11. Hamburgisches Abwassergesetz—Technische Betriebsbestimmungen—Entwässerungsanlagen (HmbAbwG). Grundstücksentwässerungsanlagen. 2014. Available online: https://www.hamburg.de/resource/blob/160214/cfd5fb34c42601bb28769049a2cab6bb/techn-betriebsbest-grunstuecksentw-data.pdf (accessed on 6 October 2024).
12. Zhang, Y.; Yuen, K.-V. Review of artificial intelligence-based bridge damage detection. *Adv. Mech. Eng.* **2022**, *14*, 16878132221122770. [CrossRef]
13. Borrmann, A.; König, M.; Koch, C.; Beetz, J. (Eds.) *Building Information Modeling*; Springer: Wiesbaden, Germany, 2021; ISBN 978-3-658-33360-7.
14. Errandonea, I.; Beltrán, S.; Arrizabalaga, S. Digital Twin for Maintenance: A Literature Review. *Comput. Ind.* **2020**, *123*, 103316. [CrossRef]
15. Karmous-Edwards, G.; Tomić, S.; Cooper, J.P. Developing a unified definition of digital twins. *J. Am. Water Work. Assoc.* **2020**, *114*, 76–78. Available online: https://awwa.onlinelibrary.wiley.com/doi/10.1002/awwa.1946 (accessed on 16 October 2024). [CrossRef]
16. Smarsly, K.; Peralta Abadía, P.; Dragos, K.; Ahmad, M.; Al-Zuriqat, T.; Chillón Geck, C.; Al-Nasser, H. A Multivocal Literature Review of Digital Twins, Architectures, and Elements in Civil Engineering. In Proceedings of the 11th European Workshop on Structural Health Monitoring (EWSHM 2024), Potsdam, Germany, 10 June 2024.
17. Alsaleh, A.; Sattler, M. Comprehensive life cycle assessment of large wind turbines in the US. *Clean Technol. Environ. Policy* **2019**, *21*, 887–903. [CrossRef]
18. Vieira, J.; Poças Martins, J.; Marques de Almeida, N.; Patrício, H.; Gomes Morgado, J. Towards Resilient and Sustainable Rail and Road Networks: A Systematic Literature Review on Digital Twins. *Sustainability* **2022**, *14*, 7060. [CrossRef]
19. Kaewunruen, S.; AbdelHadi, M.; Kongpuang, M.; Pansuk, W.; Remennikov, A.M. Digital Twins for Managing Railway Bridge Maintenance, Resilience, and Climate Change Adaptation. *Sensors* **2022**, *23*, 252. [CrossRef] [PubMed]
20. Zhou, C.; Xu, J.; Miller-Hooks, E.; Zhou, W.; Chen, C.-H.; Lee, L.H.; Chew, E.P.; Li, H. Analytics with Digital-Twinning: A Decision Support System for Maintaining a Resilient Port. *Decis. Support Syst.* **2021**, *143*, 113496. [CrossRef]
21. Agapaki, E. Airport Digital Twins for Resilient Disaster Management Response. In *Learning and Intelligent Optimization*; Lecture Notes in Computer Science; Simos, D.E., Rasskazova, V.A., Archetti, F., Kotsireas, I.S., Pardalos, P.M., Eds.; Springer: Cham, Switzerland, 2022; Volume 13621, pp. 467–486. [CrossRef]
22. Abioye, S.O.; Oyedele, L.O.; Akanbi, L.; Ajayi, A.; Davila Delgado, J.M.; Bilal, M.; Akinade, O.O.; Ahmed, A. Artificial Intelligence in the Construction Industry: A Review of Present Status, Opportunities and Future Challenges. *J. Build. Eng.* **2021**, *44*, 103299. [CrossRef]

23. Dadoulis, G.; Manolis, G.D.; Katakalos, K.; Al-Zuriqat, T.; Dragos, K.; Smarsly, K. Towards Detecting Damage in Lightweight Bridges with Traveling Masses Using Machine Learning. In Proceedings of the 2024 European Conference on Computing in Construction (EC3), Chania, Crete, Greece, 14 July 2024. [CrossRef]
24. Ng, G.; Cheuk, H.; Cheung Chun, L.; Singh, S.; Sharma, B. Deep Learning-Based Collision Detection System for Construction Sites: System Architecture and Working of viAct's Smart Module. *Int. J. Eng. Invent.* **2021**, *10*, 24–29, e-ISSN: 2278-7461, p-ISSN: 2319-6491.
25. Çelik, F.; Faltin, B.; König, M. Improving 2D Construction Plans with Cycle-Consistent Generative Adversarial Networks. In Proceedings of the Computing in Civil Engineering 2021, Orlando, FL, USA, 12 September 2021.
26. Poku-Agyemang, K.N.; Reiterer, A. 3D Reconstruction from 2D Plans Exemplified by Bridge Structures. *Remote Sens.* **2023**, *15*, 677. [CrossRef]
27. Weber, L.A.; Schenk, D. Automatische Zusammenführung zertrennter Konstruktionspläne von Wasserbauwerken. *Bautechnik* **2022**, *99*, 330–340. [CrossRef]
28. Rapp, A.H.; Capener, A.M.; Sowby, R.B. Adoption of artificial intelligence in drinking water operations: A survey of progress in the United States. *J. Water Resour. Plan. Manag.* **2023**, *149*, 06023002. [CrossRef]
29. Li, D.; Cong, A.; Guo, S. Sewer Damage Detection from Imbalanced CCTV Inspection Data Using Deep Convolutional Neural Networks with Hierarchical Classification. *Autom. Constr.* **2019**, *101*, 199–208. [CrossRef]
30. Smarsly, K.; Ahmad, M.E.; Peralta, P.; Al-Zuriqat, T.; Al-Nasser, H.; Dragos, K.; Chillón Geck, C. Digital Twins, Architectures, and Elements in Civil Engineering—A Multivocal Literature Review. In Proceedings of the 20th International Conference on Computing in Civil and Building Engineering (ICCCBE), Montréal, Canada, 25 August 2024.
31. mFUND mdfBIM+. Teilautomatisierte Erstellung Objektbasierter Bestandsmodelle Mittels Multi-Daten-Fusion—mdfBIM+. Available online: https://bmdv.bund.de/SharedDocs/DE/Artikel/DG/mfund-projekte/mdfbim-plus.html (accessed on 18 October 2024).
32. Herbers, M.; Bartels, J.-H.; Richter, B.; Collin, F.; Ulbrich, L.; Al-Zuriqat, T.; Chillón Geck, C.; Naraniecki, H.; Hahn, O.; Jesse, F.; et al. openLAB—Eine Forschungsbrücke zur Entwicklung eines digitalen Brückenzwillings. *Beton und Stahlbetonbau* **2024**, *119*, 169–180. [CrossRef]
33. Al-Zuriqat, T.; Chillón Geck, C.; Dragos, K.; Smarsly, K. Adaptive Fault Diagnosis for Simultaneous Sensor Faults in Structural Health Monitoring Systems. *Infrastructures* **2023**, *8*, 39. [CrossRef]
34. mFUND DIANE. Drohneneinsatz zur Inspektion von Abwassernetzen—DIANE. Available online: https://bmdv.bund.de/SharedDocs/DE/Artikel/DG/mfund-projekte/diane.html (accessed on 18 October 2024).
35. mFUND KomIT. Harmonisierung von Asset-Daten in einem Kommunalen Infrastruktur-Zwilling zur Effizienten Gestaltung von Planungs- und Baumaßnahmen—KomIT. Available online: https://bmdv.bund.de/SharedDocs/DE/Artikel/DG/mfund-projekte/komit.html (accessed on 18 October 2024).
36. Smarsly, K.; Al-Hakim, Y.; Peralta, P.; Beier, S.; Klümper, C. A Systematic Review and Recommendation of Software Architectures for SARS-CoV-2 Monitoring. In Proceedings of the 16th International Conference on Health Informatics, Lisbon, Portugal, 18 February 2023.
37. Yu, J.; Davis, P.; Taylor, K.; Gould, S. Linked Data Approach for Automated Failure Detection in Pressure Sewers Using Real-Time Sensor Data. In Proceedings of the International Conference on Hydroinformatics, New York, NY, USA, 8 January 2014.
38. Preventing and Managing Pollution from Urban Water Runoff (D4RUNOFF). Available online: https://d4runoff.eu/ (accessed on 18 October 2024).
39. Höttges, J. QKan—Management of drainage system data with QGIS. In Proceedings of the Free and Open Source Software for Geospatial (FOSS4G), Boston, MA, USA, 14 August 2017.
40. *DIN EN 13508-2:2011-08*; Untersuchung und Beurteilung von Entwässerungssystemen außerhalb von Gebäuden—Teil 2: Kodiersystem für die Optische Inspektion; Deutsche Fassung EN 13508-2:2003+A1:2011. DIN Media GmbH: Berlin, Germany, 2011. [CrossRef]
41. Hartmann, S.; Al-Zuriqat, T.; Peralta, P.; Valles Gomez, R.; Gölzhäuser, P.; Al-Hakim, Y.; Mackenbach, S.; Klemt-Albert, K.; Smarsly, K. Digital twins for sewer systems maintenance: A systematic literature review. In Proceedings of the 24th International Conference on Construction Applications of Virtual Reality (CONVR), Sydney, Australia, 4 November 2024.
42. Liu, Y.; Ramin, P.; Flores-Alsina, X.; Gernaey, K.V. Transforming data into actionable knowledge for fault detection, diagnosis and prognosis in urban wastewater systems with AI techniques: A mini-review. *Process Saf. Environ. Prot.* **2023**, *172*, 501–512. [CrossRef]
43. Fu, G.; Jin, Y.; Sun, S.; Yuan, Z.; Butler, D. The role of deep learning in urban water management: A critical re-view. *Water Res.* **2022**, *223*, 118973. [CrossRef] [PubMed]
44. Villinger, G.; Reiterer, A. Robotic Systems for Sewer Inspection and Monitoring Tasks: Applications and Advanced Technologies. *IEEE Sens. J.* **2025**. [CrossRef]

45. Jung, J.T.; Reiterer, A. Improving Sewer Damage Inspection: Development of a Deep Learning Integration Concept for a Multi-Sensor System. *Sensors* **2024**, *24*, 7786. [CrossRef] [PubMed]
46. Haurum, J.B.; Moeslund, T.B. Sewer-ML: A multi-label sewer defect classification dataset and benchmark. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition 2021, Virtual Event, 19–25 June 2021; pp. 13456–13467.
47. Gangelhoff, J.; Werner, C.S.; Reiterer, A. Lightweight dual-wavelength bathymetric LiDAR for accurate seabed mapping. In Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE) Optical Metrology 2023, Munich, Germany, 26 June 2023.