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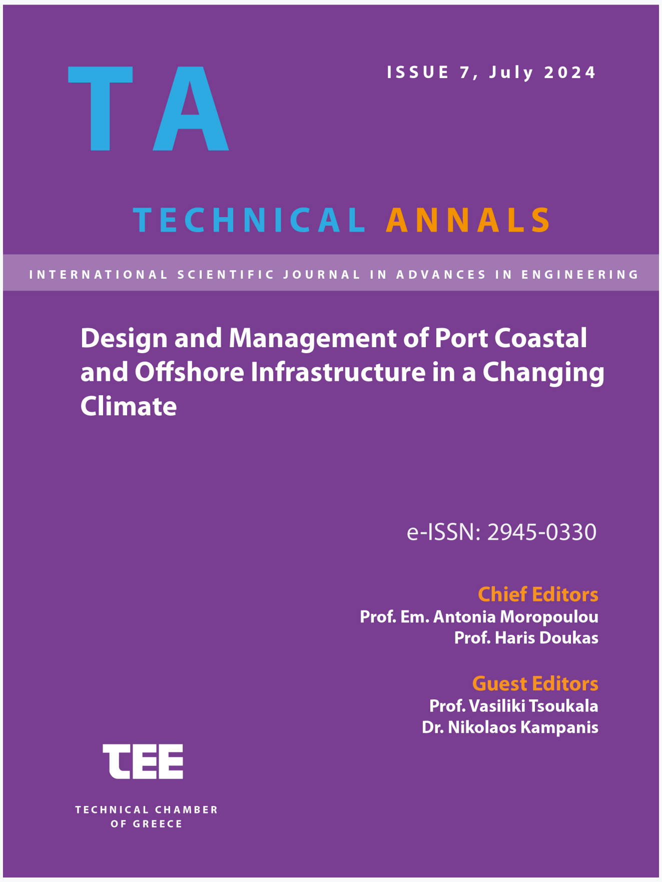

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Spatial Digital Twins for Port Concrete Pavements: A Theoretical Framework and Practical Insights

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Abstract. Ports are critical infrastructure assets that play a key role in the functional and spatial activities related to maritime transportation. In today's digital age, the creation of Digital Twins (DTs) of port systems has become increasingly important in order to proactively address maritime issues. While port DTs are primarily used for logistics and operations, DT technologies can also aid in managing the performance of port infrastructure over its lifespan. This study presents a conceptual framework for developing Spatial Digital Twins (SDTs) of port concrete pavements at mooring facilities using Structural Health Monitoring (SHM) data. The framework incorporates Non-Destructive Testing (NDT) techniques including Ground Penetrating Radar (GPR), Falling Weight Deflectometer (FWD), and Unmanned Aerial Vehicle (UAV) camera-based methods. Moreover, Geographic Information Systems (GIS) tools are also employed to facilitate the creation of digital replicas using geospatial information. A contextualization of a UAV-driven application is presented for the concrete pavements of a Greek port, specifically Lavrio port with a focus on twinning structural surface defects, particularly cracking, with computer vision-based techniques. The results indicate that the UAV-based geospatial crack detection methodology effectively tracks crack patterns over time, despite variations in surface conditions and noise interference. By showcasing how SDTs enable real-time representations of port concrete pavements, this study is valuable for understanding maintenance needs and offers practical insights for DT applications in port infrastructure management.

Keywords: Port Concrete Pavements, Spatial Digital Twins, Non-Destructive Testing (NDT); Unmanned Aerial Vehicles (UAVs), Geographic Information Systems (GIS); Surface Cracking.

1 Introduction

Ports are essential hubs that facilitate the transportation of passengers and goods, create job opportunities, and drive economic development in port regions through value-added services and logistics activities [1]. As sustainability becomes a top priority and the global economy relies heavily on maritime transportation, ports face challenges in improving operational efficiency and addressing environmental, energy, safety, and security concerns [2].

The competitive nature of maritime transportation motivates ports to adopt innovative technologies to enhance their performance, service quality, and productivity [3]. In recent years, digital transformation in ports has expanded to include 5G networks, radio frequency identification (RFID), blockchain, and artificial intelligence-driven automation, forming the foundation of port digitization [4]. Moreover, the Internet of Things (IoT) including sensors and embedded systems enables the seamless interconnection of devices, allowing for real-time monitoring and control of port operations [5]. These advancements support digital platforms, cargo forecasting, and automated management, enabling ports to operate more efficiently, optimize assets, lower costs, and boost revenue and sustainability [4].

The infrastructure digitization includes smart sensors, artificial intelligence, and IoT which play a crucial role in the evolution of Digital Twin (DT) technology [6,7]. DT create virtual representations of physical assets, utilizing real-time data to simulate, analyze, and optimize system behavior [8,9]. The concept of DTs first emerged in the early 2000s with Grieves introducing twinning for Product Lifecycle Management (PLM) purposes [8,9]. Since then, DTs have expanded beyond PLM and are now being utilized in the port industry [8]. European marine networks are incorporating DTs for port systems, with the port of Rotterdam in the Netherlands developing a DT version that includes infrastructure data, shipping movements, and environmental conditions to optimize mooring, loading, and departing processes [10]. The Digital Port Twin project in Hamburg, Germany aims to enhance control centers by digitizing infrastructure and analyzing sensor data [11]. Moreover, the Hamburg Port Authority is working on a DT for a bridge based on structural condition data from monitoring sensors [12]. The port of Livorno in Italy is using a DT engine with a pilot 5G network for virtual navigation through a digital replica [13]. The port of Gothenburg in Sweden is also embracing digitalization [14]. Except for Europe, ports worldwide, including Shanghai and Dalian in China, are also adopting DTs for container terminals [9].

Digital twinning is a rapidly evolving trend in which digital models serve a variety of functions, making it challenging to establish a unified definition [8,9]. In the port industry, this challenge is further complicated by the complexity of port systems affected by the interaction of various actors in operations and processes. As a result, digital twinning for port systems is still in its early stages, requiring decentralized policies to manage specific parts of port facilities and operations before implementing a systematic approach to port DTs. Hence, port DTs encompass various aspects, including integrated port energy systems that support low-carbon development through comprehensive data coverage, minimal delays, reliable transmission, and real-time system mapping [15]. Additionally, they enhance port logistics by enabling accurate predictions, autonomous distribution, and optimized container deployment through digital replicas fed with operational and warehousing data [7]. Furthermore, virtual sensing technologies assist in addressing safety control challenges during construction [16].

While Digital Twins in ports have primarily been developed to optimize logistics, operations, and energy management, their application in Lifecycle Management and

Maintenance of port infrastructure remains underdeveloped. Most initiatives focus on enhancing efficiency in cargo handling and supply chain coordination, whereas the use of DTs for monitoring structural integrity and supporting long-term maintenance strategies has received comparatively less attention. This gap can be attributed to challenges in real-time data integration, as running high-fidelity models and managing large datasets for real-time structural analysis introduce significant computational demands and costs [17]. Additionally, adapting DTs to heterogeneous port infrastructures further complicates their implementation.

Ports are complex engineering systems with various constructed facilities [18]. These facilities are vulnerable to climate change [19], natural hazards [20], marine conditions, and human-induced factors [21], affecting their structural integrity. To tackle issues related to structural degradation and implement smart maintenance strategies, creating a digital replica of a port structure with data from Structural Health Monitoring (SHM) applications can be beneficial [22]. SHM information provides valuable insights into the structural behavior of a structure through intelligent inspections and structural condition assessments [23]. Hence, utilizing SHM-driven digital twins for scenario planning, risk assessment, and decision-making optimizes maintenance costs and enhances the overall resilience of port infrastructure.

In light of the above, the present work presents a conceptual framework for modeling digital replicas of port infrastructure with a special focus on the concrete pavements of mooring facilities. Its main contribution is to demonstrate the process of creating a Spatial Digital Twin (SDT) that focuses on the geospatial aspects of the port pavement (i.e., location and dimensions) [24] using SHM data. The innovative aspects of the framework lie in the synergistic combination of multiple Non-Destructive Testing (NDT) techniques, enabling a comprehensive assessment of both surface and subsurface structural conditions. Specifically, Ground Penetrating Radar (GPR) allows for subsurface defect detection, Falling Weight Deflectometer (FWD) provides structural performance evaluation through deflection measurements, and UAV-based imaging enables real-time, large-scale surface condition monitoring. By integrating these methods, the framework can screen the entire structure, offering a complete evaluation of its surface and subsurface integrity. This approach enhances accuracy, spatial coverage, and real-time data acquisition, making it a powerful and efficient tool for digital modeling.

The study contextualizes the results of UAV-driven applications conducted at the concrete pavements of a Greek port, namely Lavrio port, located in the southeastern tip of Attica, aiming to provide practical insights for shifting from theory to practice. The digital modeling process concludes with analyzing geospatial metadata collected by UAVs using programming modules and GIS tools. The investigation initiates the creation of a database that will be regularly updated with structural information required to simulate structural response. The research findings indicate the potential for developing real-time replicas that, with additional research, can help in testing structural behavior, assessing remaining lifespan, and examining maintenance scenarios.

2 Methods

2.1 Building an SHM-driven DT framework

A Digital Twin (DT) is a digital representation of a physical system, developed based on three key aspects [8,25]:

a. Physical integration: identifying the components of the physical structure that are incorporated into the digital model.
b. Lifecycle consideration: analyzing the temporal evolution of the structure, including lifecycle stages, changing requirements, and long-term value.
c. Functional capabilities: ensuring the DT can support modeling, visualization, interaction, and synchronization.

An SDT is an extended DT, mirroring a real-world object with precise geospatial accuracy in terms of location and dimensions [24]. For port concrete pavements, the extended SDT principles are applied in three main areas:

a. Structural identification and defect mapping: locating the pavement within the port system, determining cross-section properties (e.g., materials and layer thicknesses), and mapping surface defects.
b. Service life estimation: predicting the remaining lifespan using pavement design principles and updated traffic data.
c. Geospatial data management and scenario analysis: utilizing tools to update structural information while evaluating various traffic and maintenance scenarios, such as increased heavy-truck traffic or milling and replacing concrete layers, respectively.

To streamline these processes, it is essential to adopt a smart infrastructure management mindset. Effective infrastructure asset management relies on Structural Health Monitoring (SHM) to maintain functionality and serviceability over time and aid in maintenance and repair decisions [23]. By integrating SHM data, port SDTs can enhance modeling and analysis for improved decision-making (Figure 1). SHM involves the use of NDT techniques to acquire data on a structure’s condition and assess its structural performance throughout its lifespan [23].

Commonly used NDT measuring processes for concrete pavements in highways, airports, or ports include the GPR and FWD [26-28]. The GPR technique is based on the transmission of electromagnetic pulses through the structure. These waves partially return to the receiver depending on the electric properties of the encountered layer materials [29]. GPR data are used to estimate layer thicknesses.

The FWD technique is a reliable method for estimating the modulus of the pavement layers. Its basic principle involves creating a load impulse by a dropping known mass from a specified height onto a loading plate which transmits the load to the pavement [28]. The typical deflection response is measured and used for backcalculation to estimate pavement moduli.

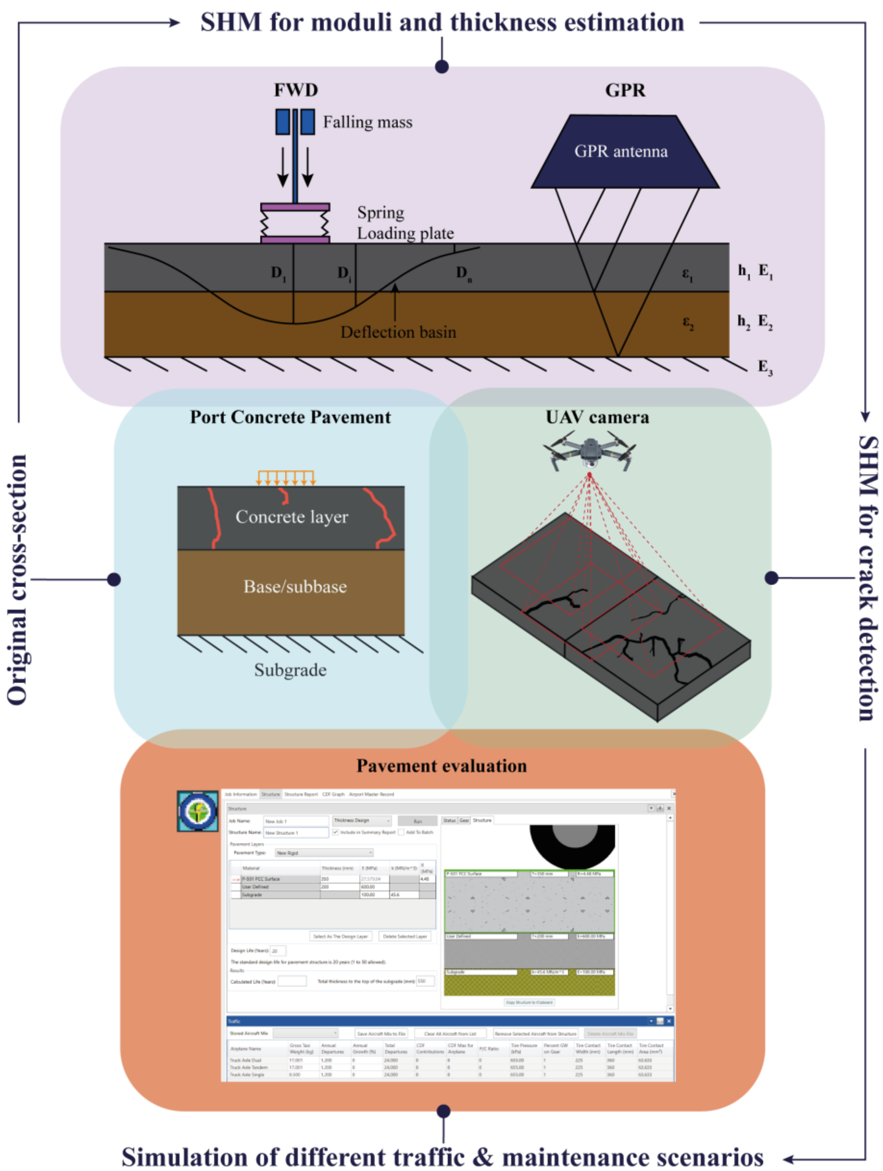

Fig. 1. The SHM-based SDT framework for port concrete pavements

Considering the above, the estimated moduli obtained from FWD, combined with the GPR thickness data, can create a digital pavement cross-section. By simulating various traffic scenarios within this digital representation, it is possible to estimate the remaining pavement life. While established methodologies and software are available for analyzing rigid (concrete) airport pavements such as aprons [30-31], similar tools for port pavements are currently lacking. In the absence of dedicated methodologies, the FAARFIELD software, originally developed for airport pavement design and evaluation, can be adapted by customizing the integrated non-aircraft vehicle loads to reflect port-specific loading conditions.

Except for the GPR and FWD techniques, current trends in SHM of port infrastructure include the employment of cameras mounted on UAVs [32]. Remote sensing with UAVs has been acknowledged for delivering SDTs by utilizing the geospatial metadata acquired through photogrammetry applications [24]. UAV-captured images with integrated geospatial information can be analyzed with the Close Range Photogrammetry (CRP) method to generate georeferenced maps with a 2D illustration of the considered structure. This allows for identifying surface defects such as cracking, spalling, scaling, and others [33]. The acquired information is useful for calibrating FWD moduli based on the actual condition of the concrete layer. Moreover, guidelines for NDT testing with FWD on rigid (concrete) pavements outline the recommended test locations and spacing for the FWD equipment [31]. UAV cameras can complement FWD measurements by offering a comprehensive overview of the entire structure and digitally examining all concrete slabs [32].

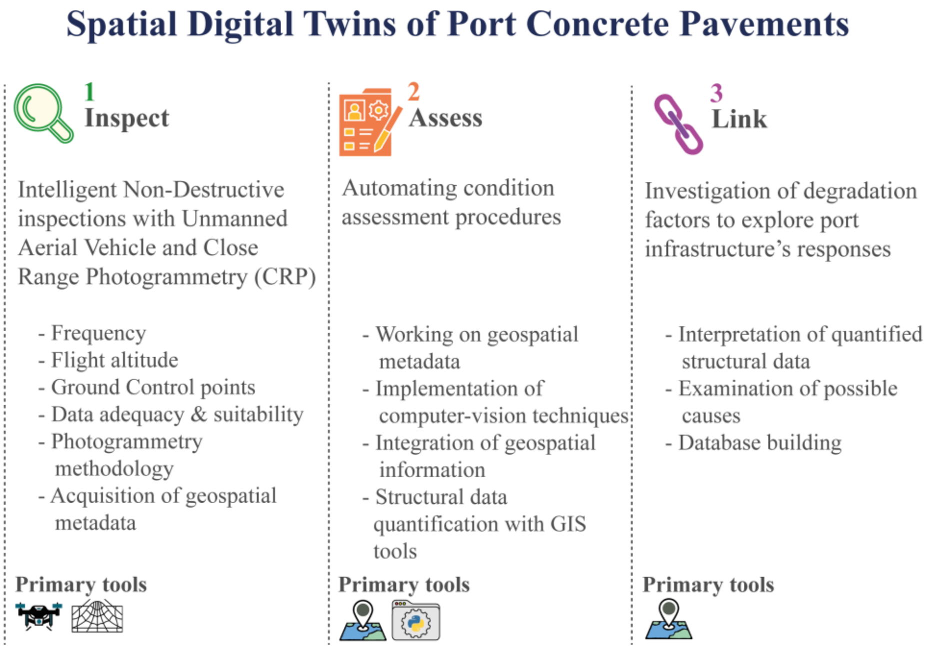

Fig. 2. The steps of building a UAV-based SDT of port concrete pavements

2.2 The UAV Spatial Digital Twinning

This study explores the use of UAV technology to initiate spatial digital twinning of concrete pavements at mooring facilities, with a specific focus on crack detection – a prevalent defect in port concrete pavements [34]. Identifying and accurately locating cracks is crucial for assessing the structural condition of the pavement. Digital Image

Processing (DIP) is increasingly being used to automate crack detection procedures [35]. However, current methodologies often do not provide the necessary geospatial information to pinpoint the exact crack location. To address this issue, a three-step UAV-based approach is presented for working on geospatial metadata during the construction of an SDT (Figure 2):

- Step 1: Implementation of periodic intelligent NDT inspections with UAVs equipped with high-resolution cameras and in-situ data analysis with CRP for generating geospatial metadata (i.e., orthophotos and Digital Elevation Models, DEMs).
- Step 2: Automation in the structural condition assessment of in-service port concrete pavements. Computer vision techniques are employed to work with the geospatial data from Step 1 (i.e., CRP output) for crack detection with: a) modules imported in programming languages for managing georeferenced images and b) GIS applications for analyzing geospatial metadata acquired by image analysis.
- Step 3: Change detection in structural integrity and investigation of degradation factors. The detected crack patterns are related to loading conditions from vehicles and other factors. Linking structural defects and failures to potential causes assists in planning maintenance actions to address forthcoming damage evolution.

Additional information on Steps 1 and 2 can be located in references [32] and [36], respectively. Figure 3 provides an overview of the STD architecture shifting from Step 1 to Step 2 and Step 3, respectively, illustrating the workflow for inspecting, analyzing, and evaluating when applying UAV-driven SHM programs.

3 Contextualized outcomes

The SDT approach depicted in Figure 2 was applied to the concrete pavements of the mooring facilities of the domestic ferry and cruise domain of Lavrio port, a Greek port located at the southeastern tip of Attica (Figure 4). The specific port serves a wide variety of operations including domestic ferry, yacht, and cruise shipping, as well as commercial activities. The intelligent UAV in-situ inspections (ISIs) were conducted on four discrete dates with different UAV flight altitudes (Table 1). Four orthophotos were generated with the Agisoft Metashape Professional software (Figure 5). The total duration of data collection and data analysis are included in Table 1.

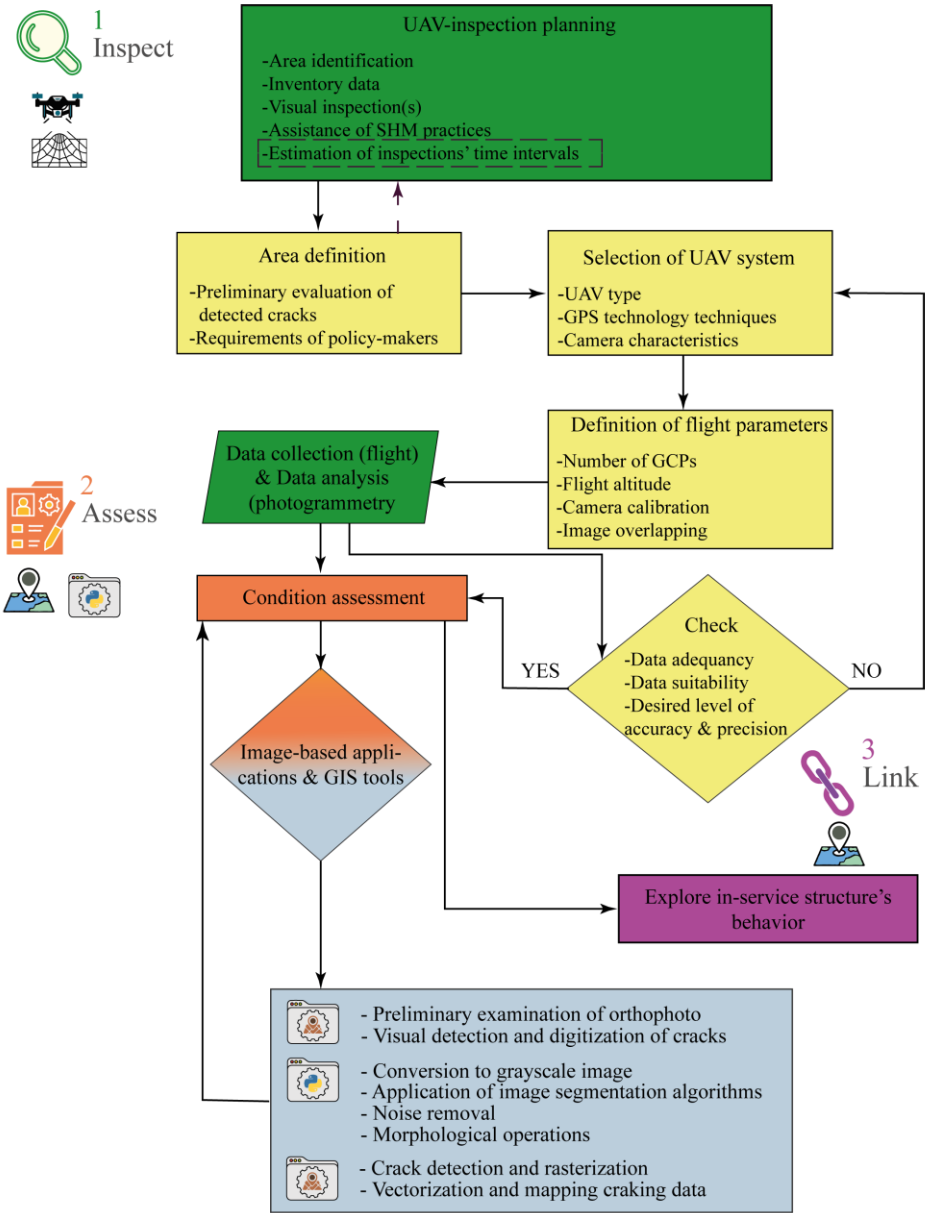

Fig. 3. The UAV-based SDT architecture for port concrete pavements

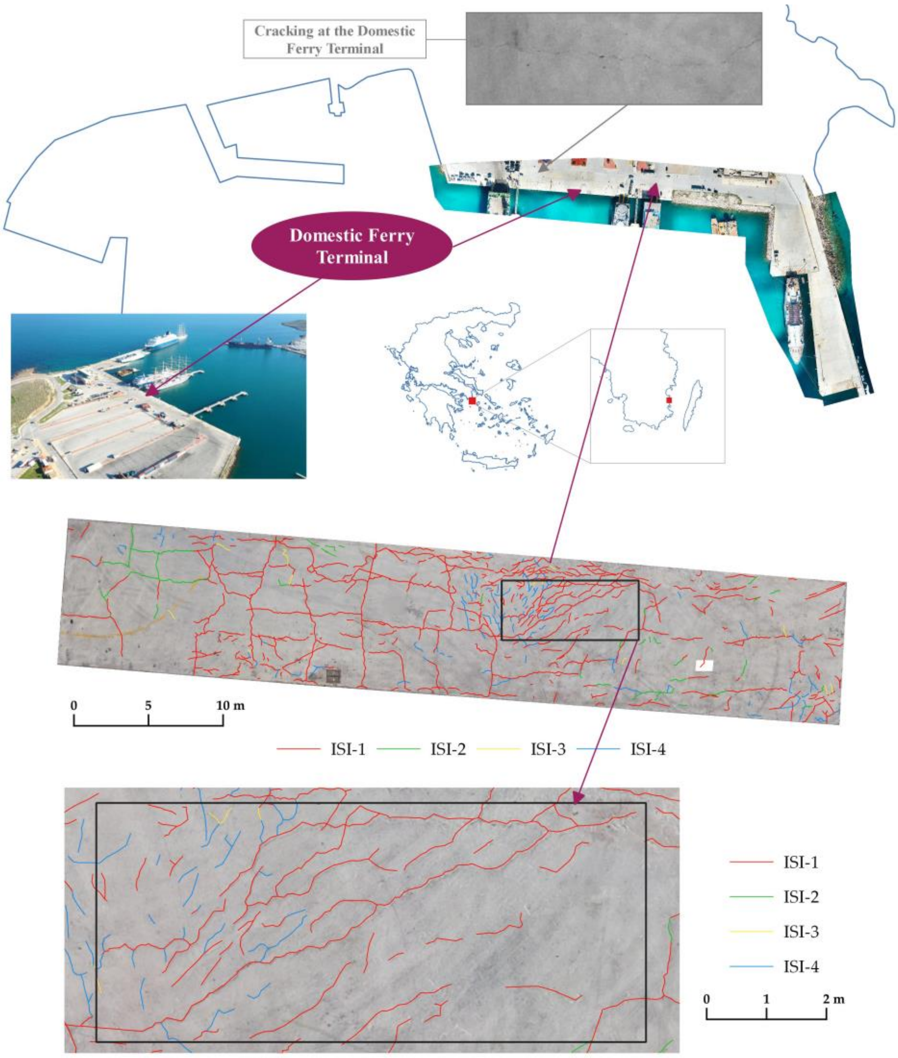

Fig. 4. The Lavrio Port, Attica, Greece - Definition of the study area for further investigation [36]

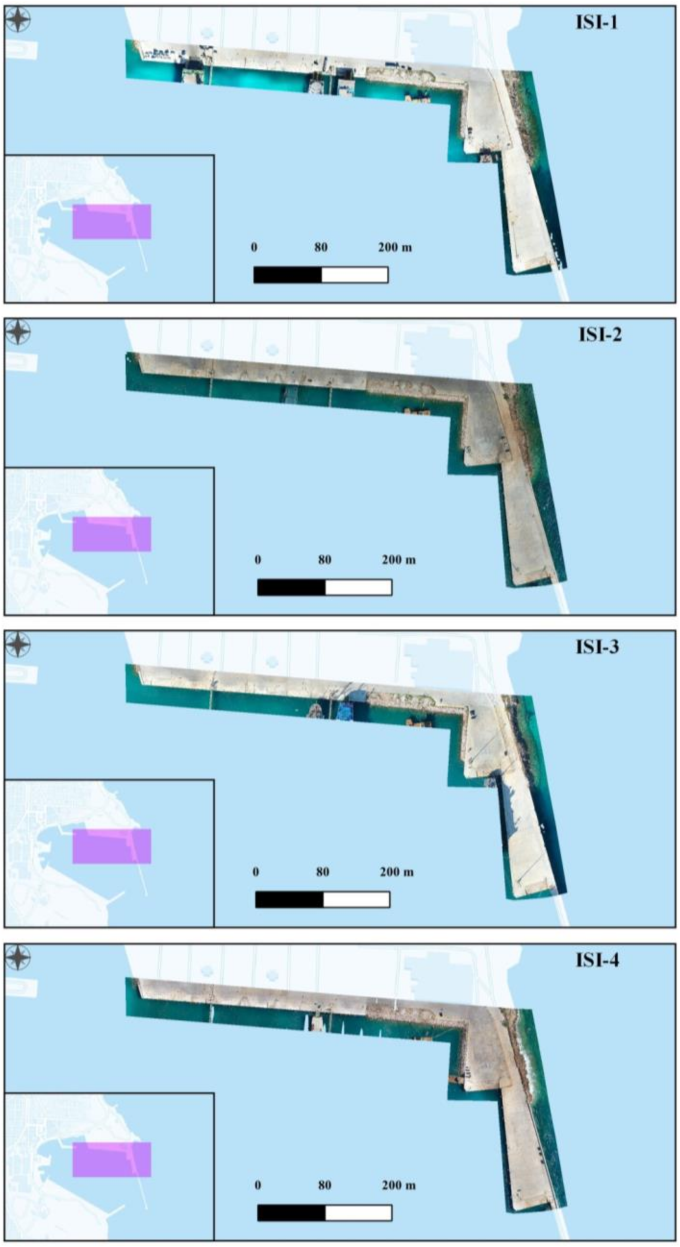

Fig. 5. The four orthophotos illustrating the concrete pavements of the mooring facilities of the domestic ferry and the cruise domain of the Lavrio port for the four (4) in-situ inspections: ISI-1 (2020-02-10), ISI-2 (2020-09-04), ISI-3 (2021-02-10), and ISI-4 (2021-07-09) [32]-Step 1 of Figure 2

Table 1. Summary table regarding the application of Step 1 of the port DT (Figure 2) [32]

In-situ inspection No.	Date	Flight altitude (m)	Flight duration (min)	Duration of UAV data analysis (min)	Ground resolution (cm/pixel)
ISI-1	2020-02-10	48	20	48	1.06
ISI-2	2020-09-04	56	33	56	1.21
ISI-3	2021-02-10	76	13	76	1.66
ISI-4	2021-07-09	56	12	56	1.17

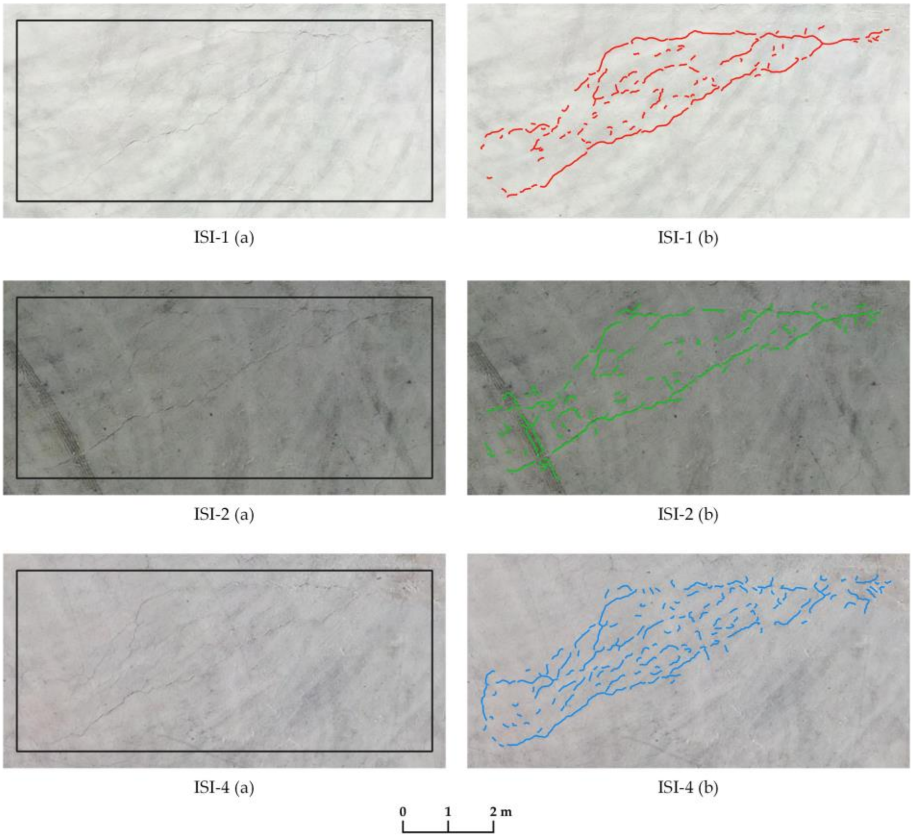

Fig. 6. Geospatial crack detection at the concrete area under investigation (Figure 4) for the three in-situ inspections: ISI-1 (2020-02-10), ISI-2 (2020-09-04), and ISI-4 (2021-07-09) [36] - Step 2 of Figure 2

As shown in Figure 4, the study area enclosed in the black box refers to a cracked concrete slab. The cracks highlighted in red, green, yellow, and blue were manually detected. The increasing number of manually digitized cracks observed between the

ISIs indicates that crack propagation was occurring at frequent intervals, approximately every six months. Hence, crack detection needed to be performed regularly to examine structural degradation and identify potential causes. Although crack screening in the study area was time-consuming, it provided valuable insights for evaluating the results of the image processing-based methodology outlined in Step 2 of Figure 2.

The geospatial crack detection approach was applied for the orthophotos of ISI-1, ISI-2, and ISI-3. The flight altitude and the ground resolution of ISI-3, along with the presence of a large shadow from the berthed vessel within the study area resulted in the exclusion of the georeferenced image of ISI-3 from the crack detection process (Step 2 of Figure 2). Figure 6 shows the results of the crack detection process by analyzing the geospatial metadata of the photogrammetry applications. The illustrations of Figure 6 are limited to the primary cracking pattern of the study area. By comparing the manually digitized cracks in Figure 4 with the results of the geospatial crack detection methodology (Figure 6), it is evident that the proposed approach effectively identifies cracking patterns, demonstrating its reliability for structural condition assessment of port concrete pavements. Further details regarding the performance metrics of the crack detection analysis can be found in the study of [36].

The use of GIS tools allowed for mapping cracks' location with precise coordinates, quantifying their features (such as length and width), and tracking variations over the time intervals by building a database (Step 3 of Figure 2). Indicatively, Table 2 presents the changes in length and width characteristics for ISI-1 and ISI-2, which were recognized as the most accurate inspections [36]. The results suggest that crack propagation could be an ongoing process, influenced by factors such as aging infrastructure, lack of maintenance treatments, and continuous operation of Lavrio Port. However, due to surface noise and variations in pavement conditions, the outcome primarily can serve as a trend indicator rather than precise growth measurement. In older concrete pavements, direct numerical comparisons are limited due to dirt accumulation, scratches from dragging loads, and other irregularities that can interfere with image-based measurements. Despite these challenges, the UAV-based geospatial crack detection methodology effectively tracks crack patterns over time, demonstrating its usefulness for maintenance planning and decision-making.

Table 2. GIS-based measurements of crack features [36]

In-situ inspection No.	Total Length (m)	Maximum width (mm)
ISI-1	23.65	82.0
ISI-4	27.88	89.0

The above results and observations that occurred from the application of Steps 1, 2, and 3 of Figure 2 are essential for the spatial digital twinning of the concrete pavements at the mooring facilities of Lavrio port. To assist with maintenance planning, GPR thicknesses are required to examine the depth of intervention and FWD moduli are significant to determine the extent of the structural degradation of the slab. If cracking is limited to the surface, local treatments may be considered adequate. However, significantly low values of concrete moduli may indicate the need for total slab replacement.

4 Conclusions and Discussion

Digital Twinning of port systems can take many forms. Logistics, shipping operations, and security are among the most popular aspects of port DT. Within the context of Lifecycle Management and Maintenance of port infrastructure, the present paper seeks to feed a DT engine for port concrete pavements with SHM information. The contextualization of state-of-the-art remote sensing inspections, condition assessment methodologies, and GIS-based management of geospatial metadata supported the building of SDTs. The periodic implementation of the UAV-based SHM program complied with the twinning aspect of temporal span by providing useful information for temporal structural changes and damage evolution. Therefore, decision-making on applying smart maintenance practices can be supported.

The present work indicated that port SHM-based SDTs using UAV approaches allow for detecting and mapping structural defects of port concrete pavements by visualizing and digitally transforming the structural condition to geospatial output. Information regarding the length, width, and location of the detected cracks is acquired. The DIP-based approach can reduce the need for manually digitizing cracks, significantly saving time. However, engineering judgment remains crucial to filter out noise and exclude irrelevant surface features (e.g., dirt, tire marks, or scratches) that may interfere with crack detection. Crack evolution patterns are tracked and rapid quantification for building a database is achieved. Major crack expansion is reliably captured while subtle changes in smaller cracks may not always be conclusive. Nevertheless, this approach provides a valuable tool for identifying significant cracks that require monitoring over time, supporting data-driven maintenance strategies.

The study provides a foundation for future advancements in the integration of SDT frameworks for port infrastructure monitoring, opening new research avenues in automated structural assessment and predictive maintenance. Although the camera-based UAV technique used for the SHM applications proved efficient for condition assessment, the SDT simulation for predicting and managing the pavement structure's remaining lifetime could be enhanced with additional structural data, as shown in Figure 1. Further research could explore automated thresholding for crack severity classification and crack progression models to strengthen predictive maintenance strategies within port concrete pavement DTs. Additionally, integrating machine learning models, such as convolutional neural networks (CNNs) for crack detection and anomaly detection algorithms for sensor networks, could enhance real-time monitoring and predictive analytics. The combination of real-time sensor data with artificial intelligence-driven analysis could improve damage progression modeling, enabling more effective automated decision-making in DT systems.

Furthermore, the scalability of the UAV-based SDT framework can be expanded to other port infrastructures by adapting the methodology to different structural materials and environmental conditions. For instance, breakwaters experience wave-induced loading and require stability assessments [37], while steel port structures such as jetty conveyors involve nodal displacements [17]. Future research could tailor UAV-SHM workflows, data fusion techniques, and predictive modeling approaches to address the unique structural health challenges of diverse port assets.

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References

1. Mehmood, B.; Khan, S.A.; Raza, M.: Econometric evidence of catalytic effect of seaport Activity in OECD countries: Getting it right. Maritime Transport Research 4, 100090 (2023)
2. Molavi, A.; Lim, G.J.; Race, B.: A framework for building a smart port and smart port index. International Journal of Sustainable Transportation 14(9), 686-700 (2020.
3. Mudronja, G.; Jugović, A.; Škalamera-Alilović, D.: Seaports and economic growth: Panel data analysis of EU port regions. Journal of Marine Science and Engineering 8(12), (2020)
4. Yang, Y.-C.; Hsieh, Y.-H.: The critical success factors of smart port digitalization development in the post-COVID-19 era. Case Studies on Transport Policy 17, 101231 (2024).
5. Yang, Y.; Zhong, M.; Yao, H.; Yu, F.; Fu, X.; Postolache, O.: Internet of things for smart ports: Technologies and challenges. IEEE Instrumentation & Measurement Magazine 21(1), 34-43 (2018)
6. Broo, D.G.; Schooling, J.: Digital twins in infrastructure: definitions, current practices, challenges and strategies. International Journal of Construction Management 23(7), 1254-1263 (2023)
7. Yao, H.; Wang, D.; Su, M.; Qi, Y.: Application of Digital Twins in port system. Journal of Physics: Conference Series 1846(1), 012008 (2021)
8. Klar, R.; Fredriksson, A.; Angelakis, V.: Digital Twins for ports: Derived from smart city and supply chain twinning experience. IEEE Access 11, 71777-71799 (2023)
9. Neugebauer, J.; Heilig, L.; Voß, S.: Digital Twins in the context of seaports and terminal facilities. Flexible Services and Manufacturing Journal, (2024)
10. Port of Rotterdam. Available online: https://www.portofrotterdam.com/en/to-do-port/futureland/smart-shipping-process (accessed on 21/11/2024)
11. Hamburg Port Authority. Available online: https://www.hamburg-port-authority.de/en/themenseiten/digital-testing-ground (accessed on 21/11/2024)
12. Wenner, M.; Meyer-Westphal, M.; Herbrand, M.; Ullerich, C.; Poliotti, M.: The concept of Digital Twin to revolutionise infrastructure maintenance: the pilot project smartBRIDGE Hamburg. (2021)
13. Cavalli, L.; Lizzi, G.; Guerrieri, L.; Querci, A.; De Bari, F.; Barbieri, G.; Ferrini, S.; Di Meglio, R.; Cardone, R.; Tardo, A.; et al.: Addressing efficiency and sustainability in the port of the future with 5G: The experience of the Livorno Port. A methodological insight to measure innovation technologies' benefits on port operations. Sustainability 13(21), (2021)
14. Dimitrios, D.; Christodoulou, A.; Ölçer, A.; Ballini, F.; Dalaklis, A.; Lagdami, K.: The port of Gothenburg under the influence of the fourth stage of the industrial revolution: Implementing a wide portfolio of digital tools to optimize the conduct of operations. Maritime Technology and Research 4, 253844 (2022)

15. Yu, P.; Zhaoyu, W.; Yifen, G.; Nengling, T.; Jun, W.: Application prospect and key technologies of digital twin technology in the integrated port energy system. Frontiers in Energy Research 10, (2023)
16. Li, M.; Lu, Q.; Bai, S.; Zhang, M.; Tian, H.; Qin, L.: Digital twin-driven virtual sensor approach for safe construction operations of trailing suction hopper dredger. Automation in Construction 132, 103961 (2021)
17. Jayasinghe, S.C.; Mahmoodian, M.; Sidiq, A.; Nanayakkara, T.M.; Alavi, A.; Mazaheri, S.; Shahrivar, F.; Sun, Z.; Setunge, S.: Innovative digital twin with artificial neural networks for real-time monitoring of structural response: A port structure case study. Ocean Engineering 312, 119187 (2024)
18. Smith, P.E.: 2 - Types of marine concrete structures. In Marine Concrete Structures, Alexander, M.G., Ed.; Woodhead Publishing: 2016; pp. 17-64
19. León-Mateos, F.; Sartal, A.; López-Manuel, L.; Quintás, M.A.: Adapting our sea ports to the challenges of climate change: Development and validation of a Port Resilience Index. Marine Policy 130, 104573 (2021)
20. Cho, H.; Park, H.: Constructing resilience model of port infrastructure based on system dynamics. International Journal of Safety and Security Engineering 7, 352-360 (2017).
21. Hake, F.; Göttert, L.; Neumann, I.; Alkhatib, H.: Using machine-learning for the damage detection of harbour structures. Remote Sensing 14(11), (2022)
22. Chiachío, M.; Megía, M.; Chiachío, J.; Fernandez, J.; Jalón, M.L.: Structural digital twin framework: Formulation and technology integration. Automation in Construction 140, 104333 (2022)
23. AlHamaydeh, M.; Ghazal Aswad, N.: Structural Health Monitoring techniques and technologies for large-scale structures: Challenges, limitations, and recommendations. Practice Periodical on Structural Design and Construction 27(3), 03122004 (2022)
24. Ali, M.E.; Cheema, M.A.; Hashem, T.; Ulhaq, A.; Babar, M.A.: Enabling Spatial Digital Twins: Technologies, challenges, and future research directions. PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science 92(6), 761-778 (2024)
25. Jiang, Y.; Yin, S.; Li, K.; Luo, H.; Kaynak, O.: Industrial applications of digital twins. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379, 20200360 (2021)
26. Alsharqawi, M.; Dawood, T.; Abdelkhalek, S.; Abouhamad, M.; Zayed, T.: Condition assessment of concrete-made structures using ground penetrating radar. Automation in Construction 144, 104627 (2022).
27. Joshaghani, A.; Shokrabadi, M.: Ground penetrating radar (GPR) applications in concrete pavements. International Journal of Pavement Engineering 23(13), 4504-4531 (2022)
28. Gkyrtis, K.; Armeni, A.; Plati, C.; Loizos, A.: Structural performance assessment of airfield concrete pavements based on field and laboratory data. Infrastructures 6(12), (2021)
29. Plati, C.; Loizos, A.: Using ground-penetrating radar for assessing the structural needs of asphalt pavements. Nondestructive Testing and Evaluation 27(3), 273-284 (2012).
30. Federal Aviation Administration: Airport Pavement Design and Evaluation - AC 150/5320-6G; U.S. Department of Transportation: 2021
31. Federal Aviation Administration: Use of Nondestructive Testing in the Evaluation of Airport Pavements - AC 150/5370-11B; U.S. Department of Transportation: 2011
32. Tsaimou, C.N.; Sartampakos, P.; Tsoukala, V.K.: UAV-driven approach for assisting structural health monitoring of port infrastructure. Structure and Infrastructure Engineering, 1-20 (2024)

33. Harris, D.K.; Brooks, C.N.; Ahlborn, T.M.: Synthesis of field performance of remote sensing strategies for condition assessment of in-service bridges in Michigan. Journal of Performance of Constructed Facilities 30(5), (2016)
34. Heffron, R.E.: Waterfront facilities inspection and assessment: Waterfront facility inspection committee. pp. 1-392 (2015)
35. Gupta, P.; Dixit, M.: Image-based crack detection approaches: a comprehensive survey. Multimedia Tools and Applications 81(28), 40181-40229 (2022)
36. Tsaimou, C.N.; Kagkelis, G.; Sartampakos, P.; Karantzalos, K.; Tsoukala, V.K.: Mapping cracks on port concrete pavements by analyzing structural health monitoring metadata with computer vision-based techniques. Complex Engineering Systems 4(4), 21 (2024)
37. Tsaimou, C.; Kagkelis, G.; Karantzalos, K.; Sartabakos, P.; Tsoukala, V.: Remote sensing synergies for port infrastructure monitoring and condition assessment. Journal of Engineering Project and Production Management 14(3), 0027 (2024)