TOWARDS A GUIDE FOR BUILDING DIGITAL TWINS OF PORT INFRASTRUCTURE

Christina N. Tsaimou, Vasiliki K. Tsoukala

Abstract: Ports are critical infrastructure assets with a pivotal role in functional and spatial activities associated with maritime transportation. In an era of intense pressures on the digitalization of every part of the economy, building Digital Twins (DTs) of port systems has become increasingly important aiming at solving problems before they occur. Although port DTs are mostly used for logistics and operational purposes, DT technologies can also support lifetime performance management of port infrastructure by investigating the in-service structures' behavior against potential degradation threats. To this end, the present work conceptualizes a guide for building DTs of port infrastructure based on Structural Health Monitoring (SHM) applications. The guide includes sensors mounted on Unmanned Aerial Vehicles, Geographic Information Systems tools, automation techniques, and structural condition assessments combined to assist in computer-aided twinning. To examine the effectiveness of the guide, a pilot DT was applied for the waterfront facilities of a Greek port, namely Lavrio port. The real-time replicas proved promising in searching for smart maintenance actions.

Keywords: Port infrastructure, Digital Twins (DTs), Structural Health Monitoring (SHM), Unmanned Aerial Vehicles (UAVs), Geographic Information Systems (GIS)

Christina N. Tsaimou, NTUA - Laboratory of Harbour Works, Greece, ctsaimou@gmail.com, 0009-0008-3401-5223
Vasiliki K. Tsoukala, NTUA - Laboratory of Harbour Works, Greece, tsoukala@mail.ntua.gr, 0000-0001-8526-6286

Referee List (DOI 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Christina N. Tsaimou, Vasiliki K. Tsoukala, *Towards a Guide for Building Digital Twins of Port Infrastructure*, pp. 1019-1029, © 2024 Author(s), CC BY-NC-SA 4.0, DOI: 10.36253/979-12-215-0556-6.89

Introduction

Ports, as complex networks that facilitate the transition of passengers and goods, hold a pivotal position in economic expansion by creating employment opportunities, providing income for workers engaged in port-related tasks, and boosting the economic prosperity of port-based areas through added value and logistics activities [13]. With the ever-increasing focus on advancing efforts toward sustainability and the high dependence of the global economy on maritime transportation, ports are challenged to enhance their performance with regard to operational, environmental, energy, safety, and security issues [14].

The competitive nature of maritime transportation forces ports to adopt innovative technologies to improve their performance, quality of services, and productivity [15]. Such innovations involve actions for conceptualizing and delivering smart ports [9, 14, 21], as well as for building Digital Twins (DTs) [10, 21]. Digital modeling of port systems assists in enhancing the asset's smartness [2] by constructing a digital replica with various technologies for visualizing and simulating the systems' behavior [10, 16]. These technologies may include state-of-the-art sensors for inspection purposes, artificial intelligence algorithms, and the Internet of Things (IoT) [2, 23].

Digital twinning is a constantly evolving trend. Digital models serve a variety of functions thus making it difficult to establish a unified definition and comprehension [10, 16]. Within the port industry, this challenge is further intensified by the complexity of port systems, the functionality of which relies upon the synergy of various actors in operations and processes. Hence, DT approaches for port systems are still in their infancy, requiring decentralized policies on managing targeted parts of port facilities and operations before proceeding with a systematic approach for port DTs. Considering this, port twinning has been expressed in terms of various aspects. Indicatively, DT technologies are applied to integrated port energy systems to achieve low-carbon development goals by combining full data coverage, low delay, reliable transmission, and real-time mapping of the physical system [24]. Advancements in port logistics include reliable predictions, autonomous distributions, and optimized container deployment by feeding digital replicas with operational and warehousing data [23]. Li et al. employed DT virtual sensing technologies to assist control issues in safety during construction [12].

Despite the ongoing research on port twinning, DT approaches for managing the lifetime performance of port infrastructure have not been yet explored. Ports are structural engineering systems with a variety of constructed structures [17] the integrity of which is affected by climate change challenges [11], exposure to natural hazards [5], adverse marine conditions, and anthropogenic actions [7]. To address such structural degradation-related issues and perform smart maintenance strategies, similar to other civil infrastructure systems, building a digital replica of a port structure can prove to be useful by forming a virtual representation continuously updated with Structural Health Monitoring (SHM) data [4]. SHM information is exceptionally useful for gaining a deep insight into the structural condition and behavior of a structure through intelligent inspections and structural state assessments [1]. Hence, SHM-based DT approaches may contribute to the optimization of maintenance costs and the on-time prediction of structural damages thus increasing the value of the infrastructure asset.

In light of the above, the present work conceptualizes a pilot guide for building DTs of port infrastructure by integrating SHM approaches with the ultimate goal of retaining functionality, ensuring sustainability, and increasing resilience. Technologies (e.g., remote sensing with Unmanned Aerial Vehicles, UAVs), tools (e.g., Geographic Information Systems, GIS), automation techniques (e.g., image processing of aerial imagery), and structural condition assessments are coupled together within the context of an SHM methodology to assist in computer-aided DT applications. To validate the robustness of the port DT guide, the structural twinning is applied at the mooring facilities and the windward breakwater of the domestic ferry and cruise domain of a Greek port. The overall investigation highlights the effectiveness of the proposed guide on modeling a DT for in-service port structures.

Materials and Methods

Digital Twins in Europe

The first appearance of DTs can be traced back to the early 00s when Grieves originated the concept within the context of Product Lifecycle Management [10, 16]. Since then DTs have gone far beyond PLM finding also applications in the port industry. DTs of port systems are popping up in European marine networks [10]. The port of Rotterdam in the Netherlands is developing a DT version that includes information about the port area such as infrastructure data, shipping movements, and environmental conditions aiming to construct a platform for optimizing mooring, loading, and departing (https://www.portofrotterdam.com/en/to-do-port/futureland/smart-shipping-process). The Digital Port Twin project related to the port of Hamburg in Germany targets to optimize control centers by digitizing infrastructure and analyzing sensor data (https://www.hamburg-port-authority.de/en/themenseiten/digital-testing-ground). Moreover, the Hamburg Port Authority initiated a project for building a DT for a bridge based on structural condition data acquired by monitoring sensors [22]. For the port of Livorno in Italy, a DT engine is fed with a pilot 5G network to navigate inside the digital replica through virtual reality applications [3]. One more port that leans to a digitalization mentality is the port of Gothenburg in Sweden [6]. Except for European ports, other ports worldwide have adopted the concept of twinning, such as the Ports of Shanghai and Dalian in China for the container terminals [16]. Despite the increasing popularity of port twinning, no attempts have been devoted to developing DT approaches for Lifecycle Management and Maintenance of port infrastructure. Therefore, in the following, a DT architecture is presented for port waterfront facilities built upon the engagement of SHM principles.

The SHM-based DT guide

The effective management of infrastructure assets recognizes the importance of SHM to ensure functionality and serviceability during their lifetime while assisting maintenance and repair decisions [1]. SHM applications are usually based on the employment of Non-Destructive Testing (NDT) sensors to acquire information about the structural condition of a structure and examine its structural behavior throughout its lifecycle. Current trends in SHM of port infrastructure include the employment of cameras mounted on UAVs [21]. The camera-based UAV applications improve the practicality of inspections and provide flexibility while reducing test duration, complexity of interpreting the results, and cost [18].

Complying with the core aspects of digital twinning included in [8] and summarized in [10] (a) identifying the *components* of the physical counterpart integrated into the twin, b) investigating the *temporal span* of the examined structures in terms of *complete lifecycle*, *changing requirements*, and *increased value over time*, and c) achieving the *functional scope* of a DT for *modeling*, *visualization*, *interaction*, and *synchronization*) the present research introduces a guide for SHM-based twinning focused on port waterfront facilities (e.g., concrete pavements of mooring facilities and rubble mound structures) by implementing the following three steps (Figure 1):

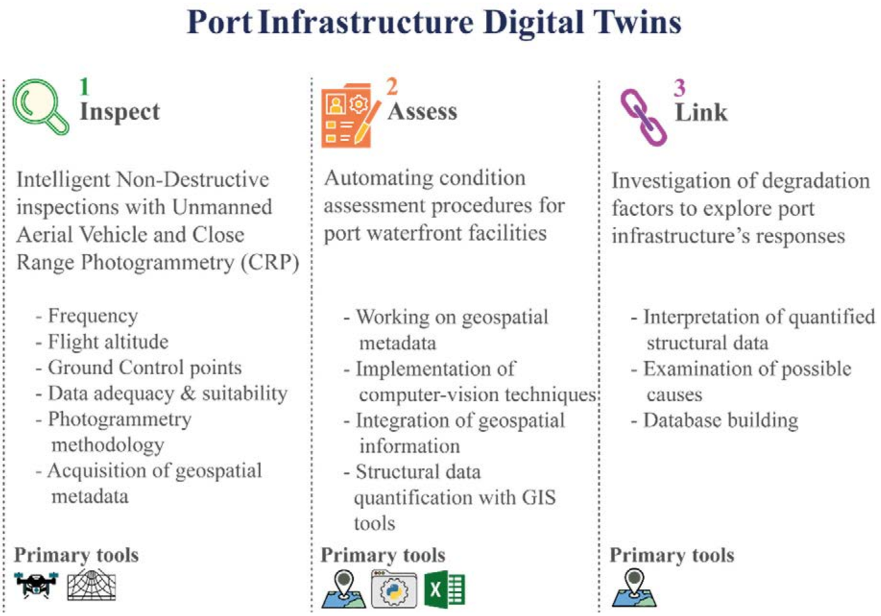

Figure 1 – The steps of a SHM-based DT guide for port waterfront facilities.

- Step 1: Implementation of periodic intelligent NDT inspections with UAVs equipped with high-resolution cameras and in-situ data analysis with Close Range Photogrammetry (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 and rubble mound structures. For the 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. Regarding the rubble mound structures SHM metadata acquired by analyzing UAV imagery (i.e., Step 1) are processed with GIS tools to investigate armor layer stability and develop an automated methodology to detect changes.

- 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, while the detected instability issues are related to wave characteristics identified in between in-situ inspections. Linking structural defects and failures to potential causes assists in planning maintenance actions to address forthcoming damage evolution.

A detailed workflow of the processes required for the above steps is depicted in Figure 2. By following the DT architecture of Figure 2, the digital replicas of port waterfront facilities can be visualized and managed with GIS technology as proposed in similar work for digitizing the supply chain network in ports [23].

Results

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

Figure 3 shows an indicative example of the results of geospatially detecting a crack at the concrete pavements of the mooring facilities of the domestic ferry domain (Step 2 of Figure 1). Further details regarding the actions required for applying crack detection techniques for port concrete pavements through coding and GIS technologies can be found in [20]. Both the length and width of the detected crack can be quantified as shown in Figure 3 (images No. 9A and 9B). In this way, the DT engine of the port concrete slabs can be fed with crack characteristics. This information can be continuously updated with periodic inspections and included in GIS-based databases.

Table 1 – Summary table regarding the application of Step 1 of the port DT (Figure 1).

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

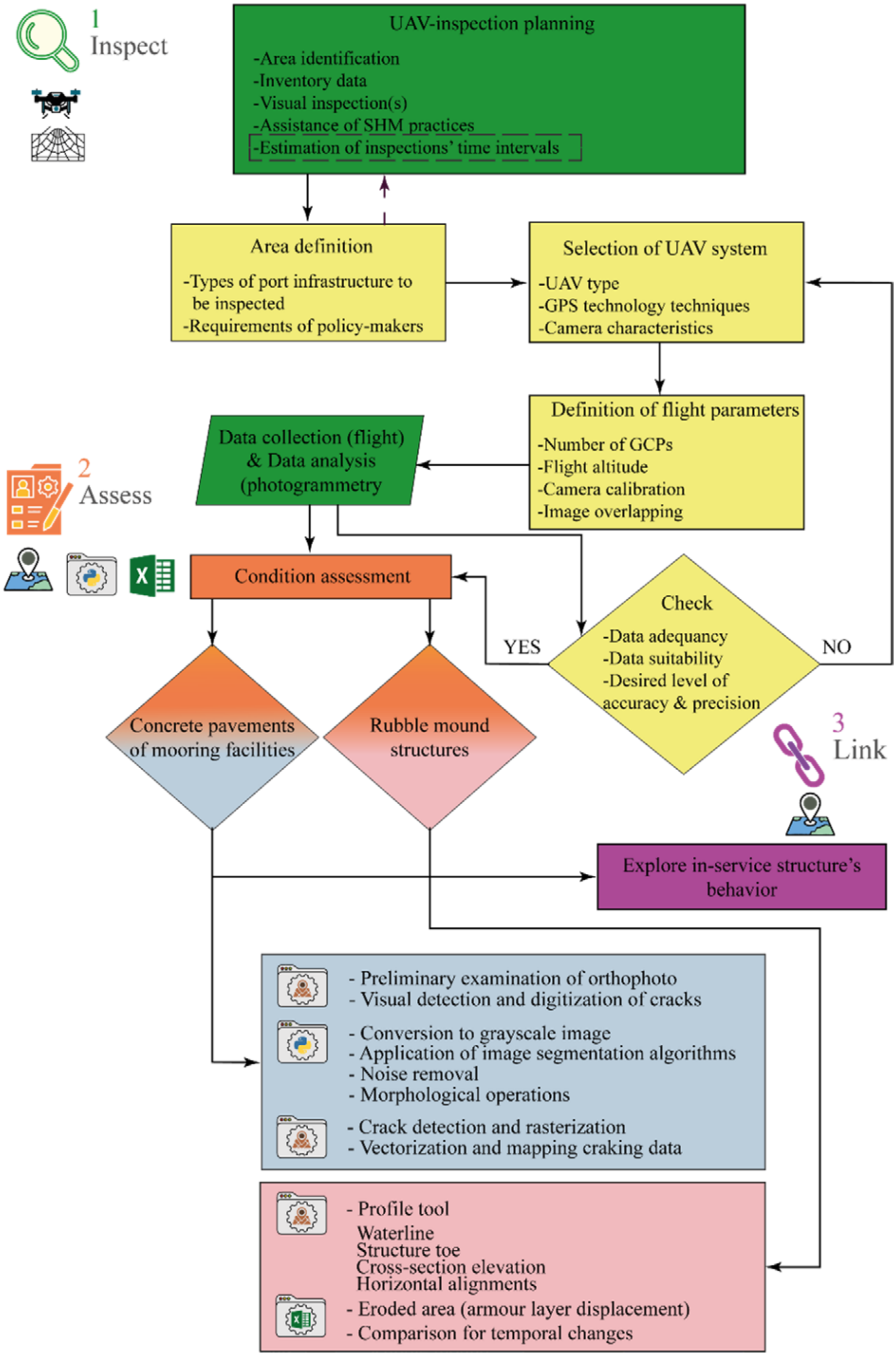

Figure 2 – The DT architecture for port waterfront facilities.

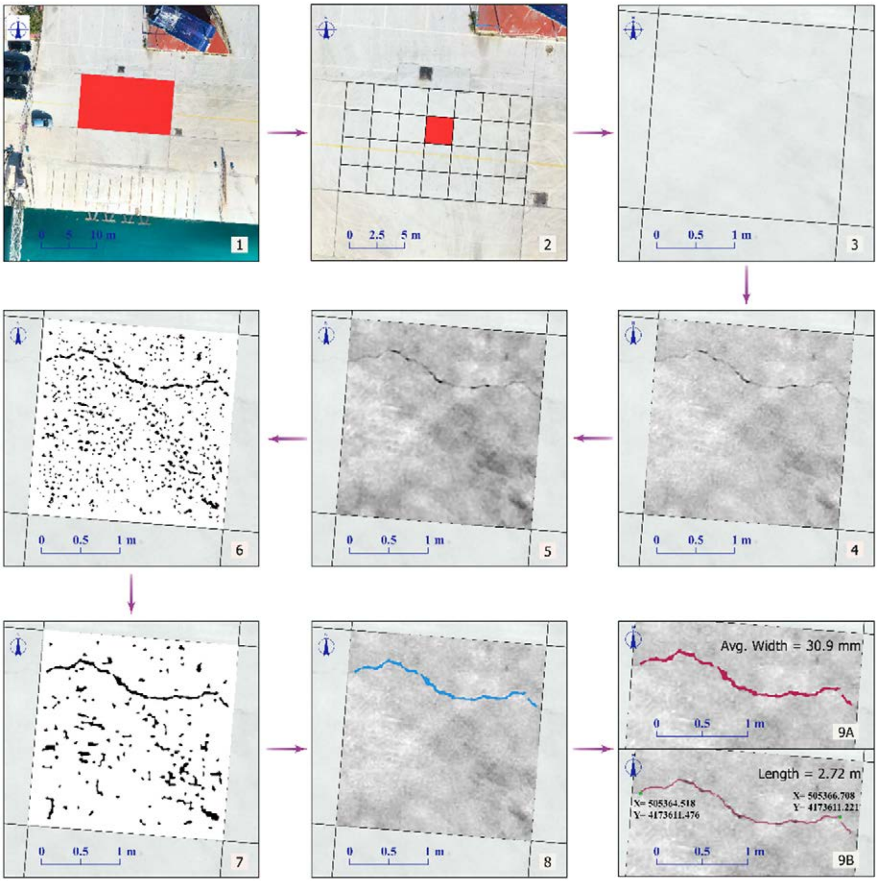

Figure 3 – Crack detection in a concrete slab of the mooring facilities of the domestic ferry domain in Lavrio port for ISI-1 [20]. Each image corresponds to the actions undertaken for automating crack detection processes including grayscale conversion of the Red Green Blue (RGB) orthophoto image (4), median filtering (5), image segmentation (6), morphological operations (7), and quantification of crack characteristics. The applied coordinate system is the Greek Geodetic Reference System 1987 (GGRS87).

Figure 4 illustrates the elevation changes in the armor layer of the considered rubble mound structure in Lavrio port. GIS techniques allowed for monitoring the displacements of the armor units and the increase in the eroded area between the time intervals of the in-situ inspections (Step 2 of Figure 1). The transverse cross-sections (profiles) were constructed along the examined structure as indicatively shown for sections 6 and 12 in Figure 4. Further details regarding the actions required to acquire this information are included in [19]. The DT engine is fed with cross-section details, thus assisting in monitoring the structural condition of the structure.

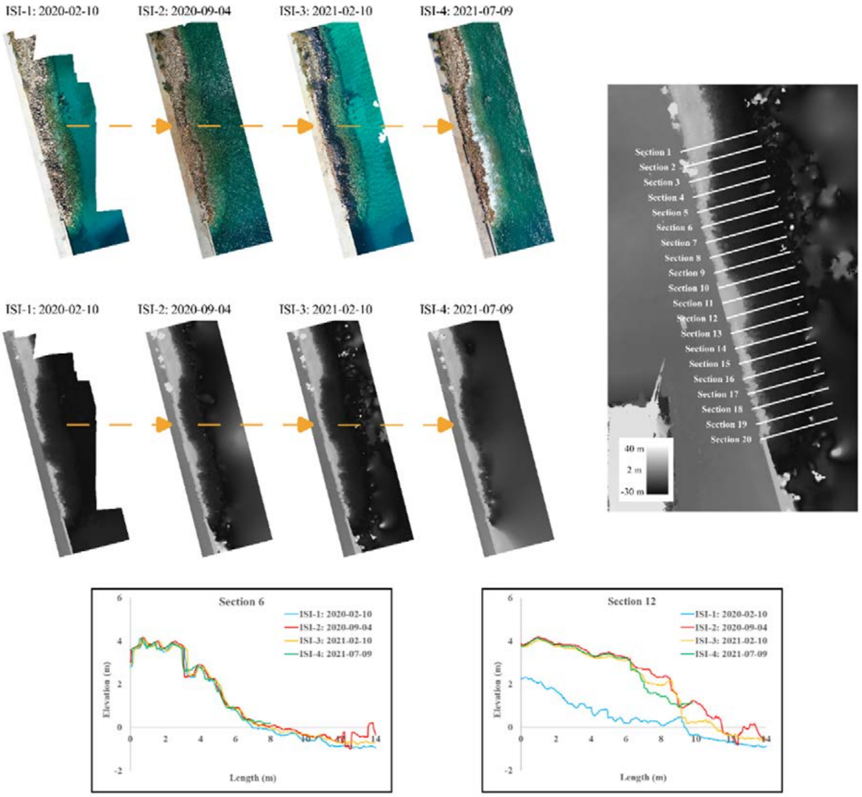

Figure 4 – Extracting information regarding armor units' displacement for the rubble mound structure of the domestic ferry and cruise domain in Lavrio port [19]. The elevation profiles were constructed based on the DEMs generated in Step 1 of Figure 1.

Discussion

Lifecycle Management and Maintenance of port infrastructure can be supported by i) comprehending the structural behavior and ii) modeling structural response against potential threats. The present work indicated that port SHM-based DTs allow for detecting and mapping structural defects of port concrete pavements and rubble mound structures by visualizing and digitally transforming the structural condition to geospatial output. Although the camera-based UAV technique employed herein for the SHM applications proved efficient in terms of condition assessment, the DT simulation for predicting and managing the structure's remaining lifetime requires further structural data. Indicatively, for the port concrete pavements of mooring facilities, the combination of UAV-acquired cracking data along with pavement thickness information from Ground Penetrating Radar (GPR) applications enables the development of simulation processes based on various loading scenarios (Figure 5a). Moreover, the integration of Remotely Operated Vehicles (ROVs) into unmanned intelligent inspections allows for constructing the entire rubble mound structure's profiles both above and under the waterline to examine the structural response against wave actions (Figure 5b).

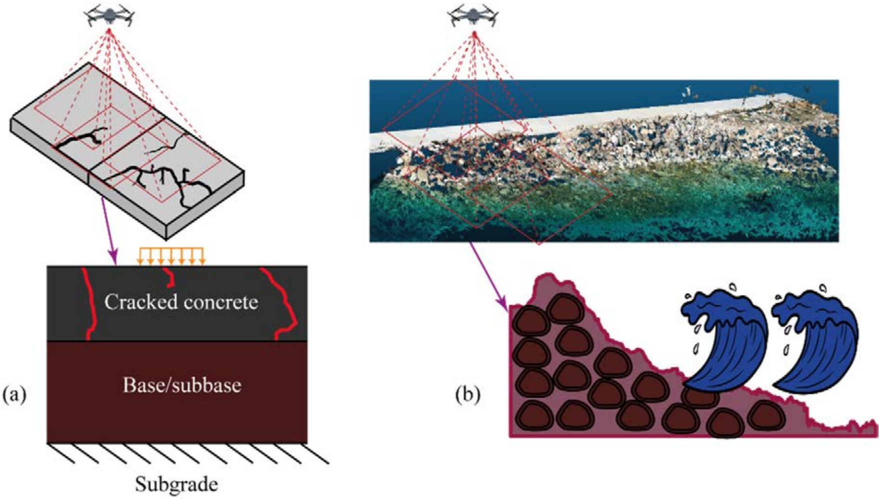

Figure 5 – Digital twinning for simulating the structural response of (a) port pavements with cracked concrete slabs against vehicle loads and (b) rubble mound structures under the influence of wave actions.

Conclusions

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 and rubble mound structures 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 DTs. 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 in terms of defects, failures, and applied maintenance actions. Therefore, decision-making on applying smart maintenance practices can be supported.

Funding

The first author was supported for this research by the Special Account for Research Funding of the National Technical University of Athens, Greece (Scholarship grant number 65/219100).

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