Digital Twin of Built Structures assisted by Computer Vision Techniques: Overview and Preliminary Results

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Abstract

Digital Twin is an effective platform for analyzing, visualizing, and interpreting the condition of as-built structures based on sensor measurement data. Based on the data inflow from the as-built structures, the associated models (typically finite element models) are updated, and/or the full behaviors of the structures are replicated in the virtual space. Despite its potential, field implementation of digital twin concepts often faces challenge, because the specific forms of digital twin, such as sensor types/locations, structural model development, and data fusion algorithms, depend strongly on the case-specific objectives. Focusing on the digital twin concepts assisted by computer vision techniques, this research aims at facilitating the implementation of those concepts by presenting the definition, setting, and preliminary results of digital twin in different application contexts, including post-earthquake structural assessment and long-term structural health monitoring based on multiple types of measurements. This research is expected to contribute to the broader impact of digital twin concepts in the structural engineering community.

1. Introduction

Built structures, such as buildings and bridges, are critical components of people's lives, and their effective management through their lifetime is required. From structural engineering standpoint, such management relies on the understanding of the current structural conditions at the sufficient detail, as well as the predictions of the structural behavior under various excitations that might be encountered in the future. Platforms for tracking structural conditions, performing predictive analyses, and presenting the conditions in the form that can be understood easily by the stakeholders are desired in the broad range of construction industry.

Digital twin has been recognized widely as an approach to fulfill the need by combining all the available information in (near) real-time (Jiang et al., 2021). Early work about digital twin for structural health monitoring can be found in the aerospace engineering field (Glaessgen & Stargel, 2012; Tuegel et al., 2011), followed by the numerous research and implementations in many engineering fields, including civil/structural engineering field (Wagg et al., 2020). Digital twins are characterized by the physical (as-built) structures and the associated "twin" model in the virtual environment. Compared to conventional models (e.g., Building Information Models - BIMs) or physics-based simulations, the concept of digital twin puts emphasis on the continuous data inflow from the as-built structures, so that the virtual twin can always represent the current structural conditions and the structure's behaviors (Jiang et al., 2021). Digital twin is a broad concept that can take many forms, depending on the types of information and the level of details that need to be represented, as well as the format of the virtual twin (e.g., BIM, finite element (FE) models, computer aided design (CAD) models) and measurement data (e.g., point cloud, acceleration, deflection) (Sacks et al., 2020).

Computer vision techniques have been advancing rapidly, transforming many industrial processes in the level of automation and sophistication, including civil and structural engineering field (Dong & Catbas, 2020; Spencer et al., 2019). Some of the relevant applications include; pixel-level structural damage recognition in images (Hoskere et al., 2020, 2022; Narazaki et al., 2021; Zhai et al., 2022), dense three-dimensional (3D) structural displacement and strain measurement (Narazaki et al., 2019; Narazaki, Gomez, et al., 2020), autonomous unmanned aerial vehicle (UAV) navigation planning based on the 3D perception of bridge inspection scenes (Narazaki et al., 2022). The promising results from those methodological investigations push the need for their effective integration into the digital twin frameworks, so that the value of the information is maximized.

This research aims at presenting definitions, settings, and preliminary results of digital twin concepts in structural engineering applications that integrate computer vision techniques. Frameworks and prototype implementations of such digital twin concepts are discussed with examples, including those for post-earthquake building assessment and structural health monitoring. Emphasis is placed on different approaches to interface computer vision-based measurement to computer-based models in the digital twin frameworks, such as BIMs and FE models. This research is expected to contribute to the broader impact of digital twin concepts by facilitating the integration of emerging computer vision-based techniques.

2. Digital Twins Aided By Computer Vision-Based Displacement Measurement

Images and videos can capture motion (displacement) of objects by tracking pixels of interest (Szeliski, 2011). For small motions that are typically encountered in the structural engineering domain, techniques such as Kanade-Lucas-Tomasi (KLT) method (Lucas & Kanade, 1981; Tomasi, 1991), combined local-global method for dense optical flow estimation (Bruhn et al., 2005; Liu, 2009), and (near) real-time patch tracking method (Pan et al., 2016), can be readily applied to measure dense 2D pixel motion field. However, linking such data to computer models is not straightforward, because (1) pixel motion should be converted to 3D structural displacement, which is an ill-defined problem (every point on a ray originating from the camera center is projected to the same point in an image), and (2) dense measurement locations in images should be registered to the appropriate parts of the model. Approaches that performs such conversion and registration manually are inherently limited to the use of one or a few measurement points, losing much of the information contained in the original image (video) data (Feng & Feng, 2016; Yoon et al., 2017).

To address the challenge, the author has developed an approach, termed model-informed approach, that links image (video) data to the structural model during the measurement stage, systematically extracting 3D structural displacement at all visible nodes of the model (Narazaki, Gomez, et al., 2020). The overview of the approach is shown in Figure 1. First, camera intrinsic and extrinsic parameters are calibrated by specifying a few corresponding points in the 2D images and the structural model. This process leads to the alignment of the model to the image frames, based on which any 3D points on the model can be projected to/back-projected from 2D image points. Moreover, using the model geometry and the identified camera pose, visibility of each node of the model can be assessed, resulting in the automated selection of visible points in images. Then, important visible points on the model can be tracked in image frames and projected back to the 3D model coordinate system (with camera motion compensation). This approach establishes an interface between dense (2D) computer vision-based measurements

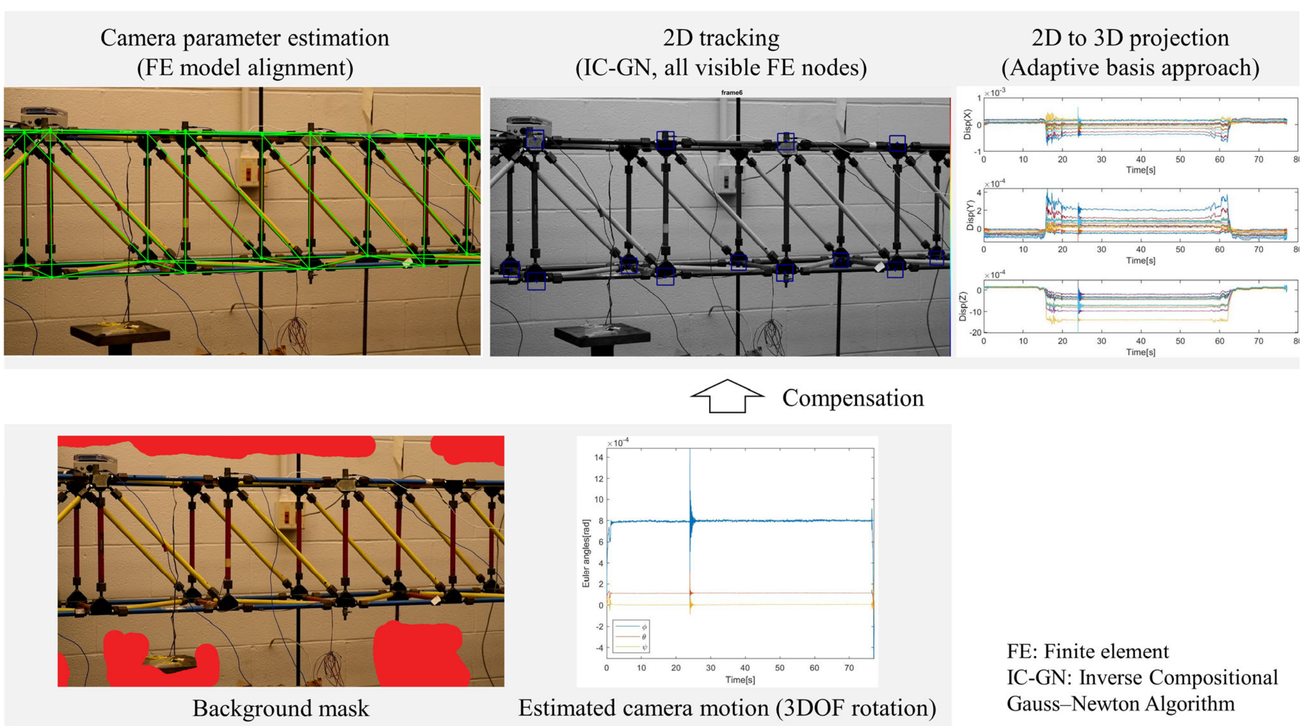

Figure 1 Overview of model-informed approach for linking computer vision-based structural displacement measurements to digital twin models (Gomez et al., 2022).

and digital twin models typically used in structural health monitoring applications.

A prototype implementation of digital twin concepts based on the model-informed approach is presented in (Gomez et al., 2022). Using the laboratory specimen of a truss bridge as a benchmark structure, this research performs 3D structural displacement measurement at the visible nodes of an FE model, and then performs model-based Bayesian inference to replicate the full structural behaviors, including displacement at the unmeasured nodes, acceleration, and strain. The estimated quantities match with measurement by an additional camera, accelerometers, and strain gages installed for the validation purpose. Related preliminary results for prototyping dense computer vision-based displacement measurement to more complex inland navigation structure in the field can be found in (S. Wang et al., 2023).

3. Digital Twins Aided By Computer Vision-Based Geometry Measurement

Computer vision techniques, together with image surveys, can reconstruct 3D shapes of the photographed objects, providing geometric information relevant to the structural conditions. Some researchers have investigated approaches for converting the reconstructed shapes into structural mesh models directly, e.g., (Zhang & Lin, 2021). While such purely data driven approaches demonstrate promising results, their integration into existing digital twin frameworks is not necessarily straightforward. One of the reasons is that FE models used by typical digital twin applications put modeling assumptions and simplifications, e.g., using beam models, not 3D solid models that replicate the target structural geometry exactly. Those modeling assumptions are the consequence of engineering decisions related to the purpose of the model and the expected levels of detail. An approach to updating digital twin models systematically in a manner consistent with those modeling assumptions is a key to integrating 3D geometric measurement into existing digital twin frameworks.

A framework for incorporating computer vision-based 3D reconstruction and geometry measurement into digital twin models for structural dynamics applications has been proposed by the author's group, which is shown in Figure 2 (Lai et al., 2022). Starting from a simplified initial FE model (beam elements are considered therein), the framework performs a sequence of vibration measurement and image surveys to update model material and geometric properties, respectively. The vibration-based model updating is performed by the measurement by accelerometers and/or computer vision techniques, followed by the application of Bayesian model updating techniques, e.g., (Yuen et al., 2006). The geometry update is performed in the following steps: (1) image survey and 3D reconstruction by Structure from Motion (SfM) method, (2) alignment of digital twin model to the reconstructed mesh

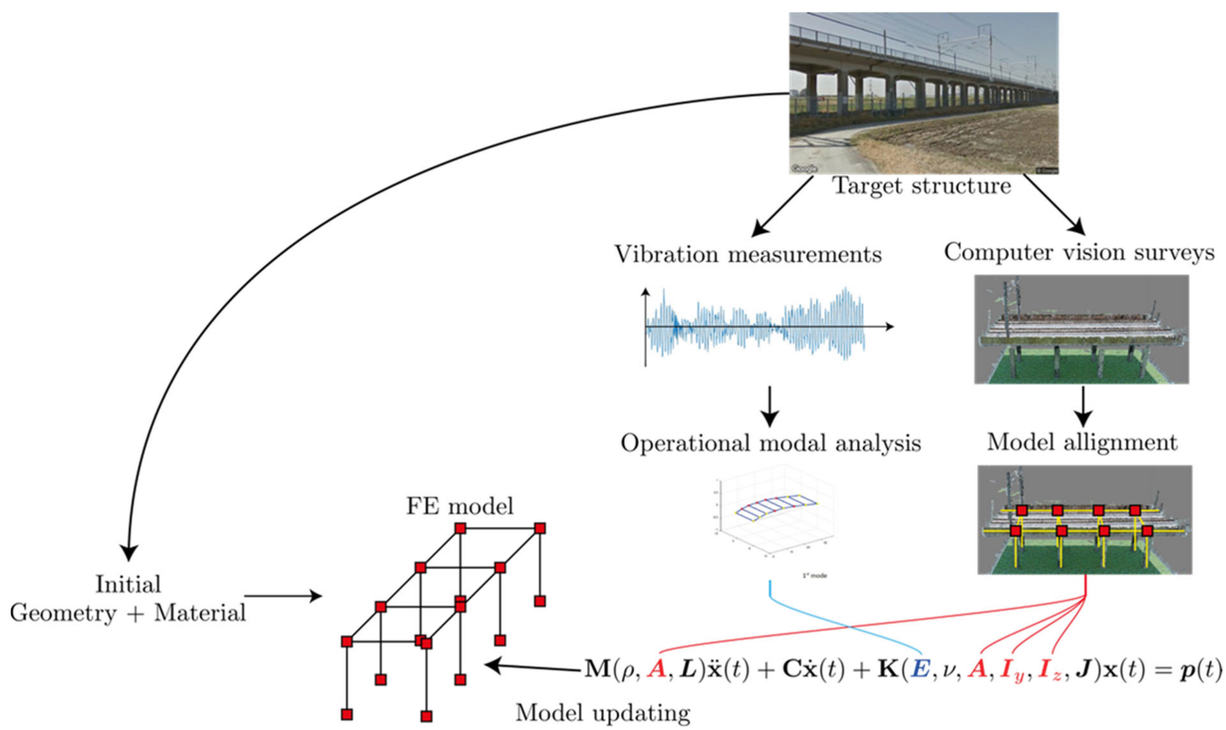

Figure 2 Framework for digital twin model updating based on vibration measurement and computer vision-based 3D reconstruction (Lai et al., 2022).

model, (3) slicing the reconstructed mesh model along the aligned beam elements of the digital twin model, (4) evaluating and updating cross-sectional geometric properties, such as areas and second moments of area. This research demonstrates the use of the same simple structural model consistently for different types of model updating, showing promising preliminary results for the detection and quantification of damage in the context of long-term structural health monitoring. Related application of computer vision-based geometry measurements for structural analysis (seismic reliability analysis) of a reinforced concrete (RC) bridge in the field can be found in (X. Wang et al., 2023).

4. Digital Twins Aided By Visual Recognition of Structural Components and Damage

Recent advances in visual recognition algorithms have brought in the significant impact on the research and development of structural inspection tasks, including the automated recognition of structural components and damage, e.g., (Hoskere et al., 2020, 2022; Narazaki et al., 2021; Narazaki, Hoskere, et al., 2020; Spencer et al., 2019; Zhai et al., 2022). Based on the promising results in the structural engineering applications of visual recognition algorithms, their integration into digital twin frameworks has drawn significant attention.

An early research attempt to create a model that contains damage information obtained by semantic segmentation algorithms can be found in (Hoskere et al., 2018). The research performs semantic segmentation of seismic structural damage, and then projects the recognition results to 3D reconstruction model (the resulting model is termed "condition-aware model" therein). (Narazaki et al., 2022) performs visual recognition of bridge structural components on an image stream assuming UAV imaging scenario, based on which the target structures and their critical structural components are identified in the 3D space. The results are used for the planning of UAV navigation path to collect images suitable for structural inspection. The collected images are further post-processed to identify structural damage.

Further integration of visual recognition methods into digital twin frameworks have been achieved by a series of research in the context of post-earthquake structural inspection (Levine et al., 2022, 2023; Levine & Spencer, 2022). In particular, (Levine et al., 2022) proposes an approach that performs visual recognition of post-earthquake structural damage from building exterior façade (the parts easily observed by UAV survey), followed by the registration of the damage to the appropriate components in the digital twin model (nonlinear FE model and the neural network-based surrogate model). The registration process starts with the 3D alignment of the reconstructed point cloud model, followed by the automated selection of images suitable for evaluating each component and damage segmentation in those images. By performing further structural and statistical analysis based on the registered damage information, structural safety of the building is derived in a format consistent with the current post-earthquake inspection practice. The prototype implementation of this digital twin framework has been tested in computer graphics-based synthetic environments, showing promising results.

5. Discussions

In this paper, several approaches for integrating computer vision-based measurements into digital twin frameworks in structural inspection and health monitoring have been presented with examples. The focus of the discussion has been put on the way to interface computer vision-based measurement data with existing digital twin framework in a systematic manner. While promising results are presented in the work discussed in this article, those results are mainly preliminary, e.g., validated for simple laboratory structures or in synthetic environments. Further research is needed to demonstrate the feasibility of presented approaches for large and complex built structures in the field. Some of the technical challenges that need to be addressed are listed in the following:

- Evaluation and optimization of the accuracy: computer vision-based measurements are categorized into non-contact measurement. While this approach enables easy implementation, the accuracy of the measurement depends not only on the target phenomena (e.g., amount of structural displacement, size of the cracks) and measurement equipment (e.g., cameras and lens), but on the camera placement. Because cameras cannot always be placed in ideal locations in the field environment, getting accurate measurement data for digital twin applications is often not straightforward. Identifying the right combinations and settings of different types of sensors and models, including computer vision-based ones, is important. Preliminary attempts to provide platforms for assessing expected accuracy of computer vision-based measurements under various implementation scenarios can be found in (Narazaki, Gomez, et al., 2020; S. Wang et al., 2022). Further investigation of such platforms is required to improve their reliability and usability.
- Improving the robustness: incorporation of computer vision-based measurements into digital twin framework is based on the establishment of the links between the digital twin model and the as-built structures photographed in image frames. However, the model always contains simplifications of the as-built structures. For example, many nonstructural components are not modeled in the digital twin models for structural engineering applications, causing

difference in the shapes and appearance between the model and the as-built structure. The robustness of the data registration and geometry assessment process should be improved in the future to accommodate such complexities. Preliminary research in this direction is ongoing in the author's research group.

6. CONCLUSION

This research provided an overview of the definitions, settings, and preliminary results of digital twin concepts in structural engineering applications that integrate computer vision techniques. Approaches for interfacing computer vision-based displacement measurement, geometry measurement, and structural component/damage recognition with digital twin frameworks are discussed with examples, including those for post-earthquake building assessment and structural health monitoring. The research efforts discussed in this article show promising results by leveraging computer vision-based data and other types of data typically used in existing digital twin applications (e.g., vibration measurement data) simultaneously. On the other hand, those approaches are mainly at the conceptualization and preliminary testing stages: main open issues include (1) how to guarantee the complete computer vision-based observations of the important parts of the large civil structures, (2) how to treat the hidden but important structural parts, and (3) how to guarantee the accuracy needed for the targeted applications. Further investigation is needed to address those issues, so that the digital twins discussed in this paper can be readily incorporated into the industrial applications.

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