New methodology for preventive conservation: real-time data and digital twins for shaping the museum metaverse

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Context and objectives

Wooden panel paintings (WPPs) are among the most significant and vulnerable historical artworks requiring preservation for future generations. The complexity of these artworks, which behave as nonlinear and evolving systems, is now well-recognized. Moreover, recent studies have identified the key variables that affect WPP behavior (Riparbelli et al 2023a), and advanced simulation models (Riparbelli et al 2023b) confirm that each painting must be evaluated as a unique object, defined by its specific construction, materials, and aging history. In this context, monitoring their deformation behavior plays a crucial role by enabling a detailed assessment of the wooden support's strain levels, which directly impacts the integrity of the paint layers.

However, museum monitoring nowadays is limited to environmental conditions. Although European standards provide guidelines for managing temperature and relative humidity levels to limit climate-induced physical damage to hygroscopic materials stored in museums, galleries, churches, and similar settings, assessing environmental conditions is insufficient to offer direct insights into the structural behavior of a specific artwork. Since climate information cannot currently be directly correlated with the behavior of complex systems such as WPPs, significant information regarding the conservation status of these artworks is missing.

To overcome this problem, we must take a step forward so that monitoring data – both environmental and shape-related – do not remain mere records without practical relevance. Indeed, the aim of this project is precisely to provide restorers and conservators with a new methodology to assess the conservation status of WPPs in order to support their decision making in restoration and preventive conservation. Our new approach creates a WPP metaverse, conceived as an interactive space where the physical (WPP) and digital worlds converge and communicate continuously in real time through a bidirectional dataflow (Tagliagambe 2022). This integration will not only enable the analysis and monitoring of the deformation of WPPs in real time – allowing potential damage to be addressed before it arises – but will also establish a control interface through which the physical world can be simulated, tested, and ultimately modified from the digital environment.

Material and methods

New measurement device

Various techniques are available to study the deformation of WPPs (Gagliardi et al 2025). However, none currently fully meet the requirements for continuous, long-term monitoring in museum or exhibition contexts. To fill this gap, we are developing a new measurement device designed to provide accurate and continuous monitoring of the painting's deformations. Particularly, we conceived it prioritizing conservation and display needs, including unobstructed viewing of the artwork, a minimal physical footprint, wireless data transmission capability, and sufficient operational autonomy.

As shown in Fig. 1, the measurement device consists of a crossbeam that will be attached to the back of the painting using two metal brackets: one connected to the crossbeam via a ball joint, the other via a universal joint. This configuration is not conceived as a replacement for the original wooden crossbeams; rather, it enables the WPP to move freely, allowing the crossbeam to follow deformations in some points of the wooden support without imposing significant additional stresses. The sensors include three strain gauge bridges, mounted on three flexible stainless-steel lamellae, and a potentiometric transducer. The lamellae measure out-of-plane deformations as deflections at three different points, enabling the calculation of the panel cupping. On the other hand, the potentiometric transducer records the displacement component along the axis of the crossbeam, providing information related to the shrinkage/swelling tendency of the wooden support. Moreover, a relative humidity and temperature sensor will be placed on the crossbeam and will monitor environmental variations related to the painting's deformations. Finally, an electronic board will manage data acquisition and wireless transmission to a control unit in real time, with the option of remote storage and access.

Designed to be versatile and non-invasive, this instrument bridges a technological gap by providing continuous and real-time cupping variations and environmental data, essential for assessing the painting's conservation state.

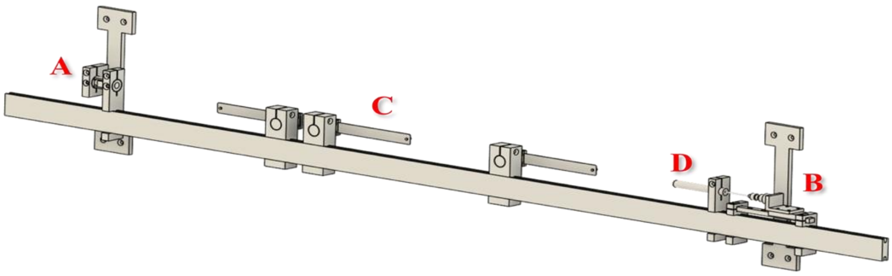

Fig. 1 : Schematic representation of the new measurement device that allows the crossbeam to follow all deformations of the wooden support thanks to a universal joint (A) and a ball joint (B). The sensors are three strain gauges mounted on lamellae (C) and a potentiometric transducer (D).

IoT technologies

The establishment of a continuous, real-time dataflow between the artwork and its digital twin requires a methodology that connects the two realities – physical and digital – via the transfer of shape-related data. Achieving this objective necessitates the use of Internet of Things (IoT) technology. IoT refers to an interconnected system of physical objects equipped with sensors and software that enable data collection, exchange, and action through the web. To date, however, its application in the conservation field has been limited to monitoring environmental parameters in museums (Manfriani et al 2021) and restoration laboratories.

Digital twins

In recent years, digital twins of WPPs have emerged as sophisticated simulation models capable of accurately replicating the hygromechanical behavior of these artworks when properly calibrated (Riparbelli et al 2024). So far, they have mainly been employed to simulate the response of individual paintings (Riparbelli et al 2023c), allowing risky scenarios to be explored without damaging the original artwork. Particularly, digital twins enable researchers to assess the effects of different environmental conditions, identify critical zones of stress concentration, and simulate potential restoration strategies. However, their application has been largely confined to providing valuable – but context-specific – insights under predefined conditions, and not yet extended to real-time monitoring.

First results

The creation of the metaverse of a WPP by establishing a continuous dataflow between the artwork and its digital twin will be made possible through the connection of the three components previously described (Fig. 2). In particular, the deformation data monitored with the new device will be transmitted through IoT structures and stored in a web service which, with appropriate security measures, will provide authorized users access to the data via web interfaces. Digital twins, integrated into the back-end of this web service, will process real-time measurements from the artwork to support analytical analyses, predict short-term behavior, and identify potential risks, acting as a simulation and evaluation tool directly connected to the artwork.

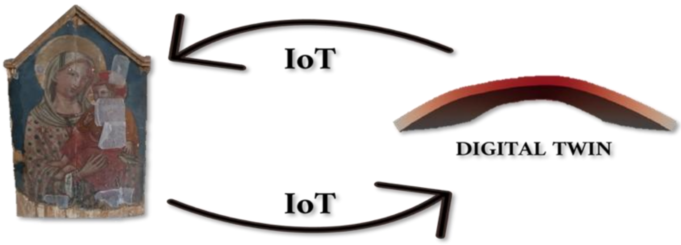

Fig. 2 : Schematic representation of the continuous dataflow between the artwork and its digital twin utilizing IoT technologies

A key aspect of this workflow was selecting the most appropriate methodological approach to derive meaningful information from raw shape-related and climatic data that restorers and conservators could easily interpret. Specifically, we defined the main modules of this pipeline:

1. calculation of the equilibrium moisture content of the wooden support based on Frandensen (2007), Merakeb et al (2009), and Rémond et al (2018);
2. data treatment to prepare data for the numerical model, maintaining the significant trends and eliminating noise on the signal;
3. calculation of stresses and strains within the wooden support and paint layers through a calibrated numerical model (digital twin).

This pipeline (shown in Fig. 3) is a crucial component of the overall process of transferring WPPs into the metaverse, as it provides restorers and conservators with a practical methodology for assessing the artwork's state of conservation and supporting appropriate conservation strategies.

Fig. 3: Methodological approach from raw shape-related and climatic data to meaningful information

Conclusion and perspectives

This research will yield significant advancements in the field of preventive conservation of WPPs by introducing a new methodology to support restorers and conservators in their decision making. Through the design of a new measurement device and, consequently, the establishment of a continuous, real-time dataflow between the artwork and its digital twin via IoT structures, we aim to achieve the successful transfer of the artwork into the metaverse. This will not only enable remote monitoring of the deformation of a WPP but also the possibility to assess the effects of different environmental conditions and identify critical zones of stress concentration in real time, allowing restorers and conservators to address potential damage.

Beyond applying this workflow to a historical artwork, a promising prospect lies in integrating artificial intelligence (AI) within the described pipeline, substituting or in synergy with the numerical model. Indeed, once neural networks have been trained with monitoring data and the predictive model has been developed, AI will be able to predict the deformation behavior of WPPs solely from environmental parameters.

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