Embodied digital twins of forest environments
– Short paper –

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Abstract

We address the concept of embodied digital twins of real-world forest environments to support research, education, communication, and decision-making. We discuss approaches to generate these kinds of immersive experiences and how to link them to ecological models. We then present the prototype of an iVR embodied digital twin intended as an interactive workbench for analyzing remotely sensed forest data. Lastly, we discuss challenges for future work in this area.

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1 Introduction

Due to advances in computing and 3D modeling, we are now able to create digital replicas, so-called *digital twins* (see discussions in [2, 18]), of physical entities and systems whose components are well understood. For natural environments, similar ideas and approaches have been discussed under the term *virtual geographic environments* [14] but the complexity of the natural world poses additional challenges [9]. Recent developments in environmental sensing and modeling have led to major improvements in visualizing environmental data [7] and, even more importantly, in making the data experiential [1], catering to important principles of human cognition. Together with the emergence of affordable immersive technologies able to provide high levels of agency and sense of embodiment when experiencing digital content, this has started a fundamental shift in how environmental phenomena, processes, and problems can be investigated by experts and communicated to decision-makers and the general public, not solely based on data and traditional media but in the form of embodied immersive experiences, which we refer to as *embodied digital twins* of real-world environments [13].

The importance of forests for the Earth's ecosystem cannot be overstate including serving as a pivotal stabilizing factor for our planet's climate [3]. Furthermore, deforestation, forest management, wildfire ecology and the need to improve forest resilience are far-reaching and extensively debated topics of our current times. Embodied digital twins of forest environments have the potential to facilitate a deeper understanding of the complex interactions involved. Hence, our focus in this article is on embodied digital twins of forest environments that can be utilized for applications in research, education, communication, and decision-making, including the analysis and communication of climate change effects. We summarize and reflect on previous work to design immersive virtual reality (iVR) experiences of forest environments and related workflows based on different approaches, media, and scientific data, as well as predictive ecological models. We then present a new prototype for an embodied digital twin of a forest environment that serves as a scientific workbench for visualizing forest data and conducting data analysis. We close the article with a discussion of challenges and future research directions pertaining to embodied digital twins of natural environments.

Figure 1 360° image (left), 3D model (middle, credit: J. Huang), and LiDAR point cloud (right).

2 Embodied forest experiences: Approaches and data

Experiential iVR applications of forest environments can be based on different media and fundamental modeling approaches coming with their individual advantages and limitations, leading to trade-offs that have to be taken into account in the context of the concrete application and target audience. At the "low-cost" end of the spectrum (in terms of involved costs, efforts, and expertise required), we find iVR experiences that predominantly use 360° photos and video. Fig. 1 (left) shows an example of an iVR tour-like experience created for educational and outreach purposes [19]. We generated this iVR environment from 360° images taken at different locations and heights including drone-based images, and then added audio narrations and complementary media. While a pure 360° based approach allows for producing a highly realistically looking digital twin quickly and cost-efficiently, the movement and interaction options are typically too limited to provoke a high sense of embodiment.

In contrast to 360° imagery, full 3D models of forest environments (see Fig. 1 (middle)) have the advantage of facilitating free movement and choice of view points, powerful interaction opportunities, and the potential to adapt the model to realize simulations or match different conditions. They also can provide a higher level of detail at a close range. The generation of realistic tree models has been actively researched in both academia and industry, while in the film and game industry, forest scenes are created through commercial 3D modelling software dedicated to vegetation modeling. The focus here typically is on creating visually appealing scenes, not so much on modeling existing forests and visualization of scientific data. Existing work on scientific visualization of forests based on data includes the work in [8]. In addition, there have been efforts to develop 3D models of forest ecosystems for simulation and decision-making that take into account the underlying biological laws (e.g., [15]).

3D models of forests can range from exact reproductions based on actual tree data to models that only simulate important characteristics such as species distribution and density. Exact reproductions are typically created from remote sensing data or detailed tree databases. Models that aim at preserving key properties can, for instance, be generated using procedural modeling approaches that place and adapt tree models based on grammatical rules and a set of input parameters. GIS (data) providers such as ESRI, SuperMap, Mapbox, and Google not only have included 3D modeling and VR capabilities into their products but now also provide extensions for common 3D engines that, for instance, allow for creating textured models of the underlying terrain. Nevertheless, the creation of a 3D model based digital twin still tends to be much more costly and complex compared to the 360° image based approach.

360° imagery and 3D models are two main approaches for achieving visual realism but the increased availability of remotely sensed and terrestrial geospatial data sets provides further options when this is not a key requirement. LiDAR data is one main source of information, resulting in a point cloud model that can be used directly (Fig. 1 (right)) or processed to, for instance, derive individual tree models. In addition to using the three main approaches

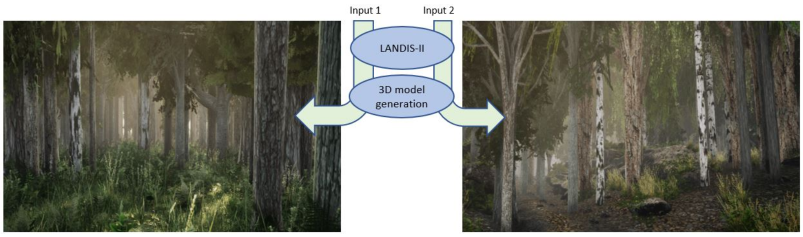

Figure 2 Highly realistic 3D forest models produced for different climate predictions [11].

we discussed (360°, 3D, sensed environmental data) on their own, hybrid approaches allow for solutions in which shortcomings of one approach are compensated by another one. For instance, a LiDAR-based point cloud model can be complemented by 360° imagery to add a photorealistic impression for particular points of interest (see overlay in Fig. 1 (right)).

3 Simulation and prediction: Visualizing environmental change

One focus of embodied digital twins of natural environments is to let us experience and interact with the current state of an environment in a highly immersive and experiential fashion. However, an embodied digital twin further opens up the potential to, in the same way, experience past or future states, which makes it ideal to investigate temporal processes and developments, and study the impacts of different conditions.

One such example is the task of understanding and communicating environmental changes that result from climate change, which can be challenging based on traditional representation media such as graphs, maps or photos. To study the application of embodied digital twins to communicate the effects of climate change on forest environments to decision-makers and the public using intuitive and visceral immersive visualizations rather than abstract concepts, we created a data-driven workflow to produce a comprehensive iVR forest ecosystem [11] (see Fig. 2) that accounts for topography, species composition and density, coarse woody debris, and understory conditions based on the LANDIS-II forest landscape ecosystem model [17]. Using data on tree species composition stemming from the Forest Inventory and Analysis (FIA) as a starting point, the LANDIS-II model is used to generate two scenarios for the forest 50 years into the future under different climate conditions. The model outputs are used in combination with procedural modeling to create the tree overstory, and additional vegetation found in the region is added to produce the final iVR experience. In the experience, users can then interact with the environment to explore the two different climate scenarios. While the workflow to create this temporally-enabled embodied digital twin involved manual data analysis and modeling in different software applications before creating the final applications in the Unreal 3D engine, it demonstrates the potential of linking scientific simulation and prediction models with (semi)automatic 3D modeling approaches. The iVR experience has been evaluated in a heuristic evaluation focusing on system usability and graphical quality, resulting in a highly positive overall rating of 6.25 on a 7-level Likert scale [11].

4 Interactions: Embodied workbenches for researchers

Agency and embodied interactions are key building blocks to go beyond visualizations to experiences of environmental data that cater to human cognitive principles. Embodied digital twins have the potential to enable both, high interaction fidelity and interaction opportunities that go far beyond what would be possible in the real world. We recently implemented this

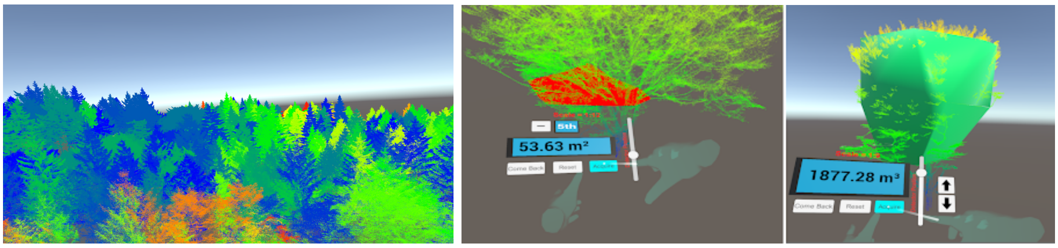

Figure 3 iVR workbench application: Overview on LiDAR data and performing measurements.

concept of embodied interactions with an environmental digital twin in a project that has the goal of creating an iVR workbench for researchers to analyze forest data, using the example of the Speulderbos forest in the Netherlands. The current prototype of the iVR workbench enables interactive visualization and quantitative measurements based on Earth science data (mainly LiDAR) through an embodied interface. The data was collected in 2017 [5] with a RIEGL RiCopter with VUX-1UAV, a high-end UAV-LiDAR system, and covers ~ 2 ha of forest with stands of a variety of different tree species. The openly available dataset [6] is one of the first UAV-LiDAR datasets collected with high-end commercially available systems and has been explored to derive forest inventory metrics like diameter at breast height (DBH) and canopy height [5], as well as explicit geometric tree modelling [4].

In the workbench prototype, which is illustrated in Fig. 3, researchers can navigate the environment consisting mainly of a LiDAR based point cloud model with the help of the controller touchpad, adjusting the movement speed to fit their needs (Fig. 3 (left)). They can rotate, vertically translate, and resize the forest model using hand gestures, as well as isolate individual trees. This then allows for performing measurements of distance and tree characteristics (height, DBH, basal area, volume) by placing measurement points via the hand controllers (Fig. 3 (right)). For linear measurements, users add intermediate measurement points that will be snapped to points in the LiDAR point cloud. For area and volume measurements, users define a 2D detector plane or 3D detector volume. These shapes can then be adjusted to measure a specific part or portion of the tree. These operations are enabled by a k-d tree representation of the LiDAR point cloud and by triangulated mesh construction [20]. The measurement functionalities are implemented as different VR tools that are attached to the hand controllers. The general idea behind the immersive workbench application is to allow scientists to visit forest sites of interest virtually as often and as long as they like to immerse themselves in the data and conduct both qualitative and quantitative observations using intuitive tools and interactions, some of them similar to what they would use during actual field work. In addition, the implementation allows for interactions not possible in the real world, including switching between and combining different data sets, performing measurements that would be difficult to perform in-situ, and the ability to freely move through and scale the environment, which can accelerate the research and lead to new discoveries. Our current work is focused on adding further data and visualizations (e.g., hyperspectral data), implementing additional measurement and analysis tools, and conducting an empirical evaluation of the workbench with multiple domain experts.

5 Challenges for future research

The comprehensive modeling of forest environments requires coordinated multi-disciplinary efforts and the fusion of different research directions including work on biological modeling and environmental visualization [9]. Such developments have the potential to take embodied digital twins of forests and other natural environments to new levels in terms of accuracy, simulation power, and cost-effectiveness. While we may see some shifts, we still expect that the different fundamental approaches we discussed in Section 2 with their trade-offs and orthogonal strengths will remain relevant, and the choice will continue to depend on the concrete application. We conclude this article with brief discussions of five topics that we believe will be of particular importance for future research in this area:

- **Fully automatic workflows:** Even though it is easier than ever before to import geospatial data into a 3D/iVR project, we are still some steps away from automatically creating realistic digital twins of existing environments on-the-fly, with or without predictive capabilities. AI-based landscape/tree classifiers can be expected to play a key role in future workflows, potentially serving as an input to procedural modeling techniques.
- **Empirical evaluations:** The excitement about embodied digital twins stands in contrast to the lack of empirical research with, in particular, the effects of levels of embodiment on environmental decision-making still largely unexplored. Systematic empirical evaluations of benefits and user experience (e.g., [11, 19]) are challenging and have led to contradicting results in other areas of iVR research. However, they are crucial to fully comprehend and unfold the potential of embodied digital twins and guide their future design.
- **Realism & fidelity:** While the general idea of a digital twin is that of a digital version of a system that looks and behaves exactly like the real system, it is a valid question how much realism and fidelity are actually required in a given scenario, for instance to optimally support learning or communicate impacts of environmental change to decision makers or the public. In addition to visual realism and interaction fidelity, work on incorporating other modalities is gaining traction but the degree to which such additions can make embodied digital twins more effective in practice still needs empirical investigation.
- **Dynamics:** In this article, we mainly focused on static models of forests or long-term change of conditions, rather than dynamic models including growing trees or moving tree objects under different weather or seasonal conditions. The goal of instead creating dynamic models (potentially based on real-world sensor data) limits the choices in suitable modeling approaches but progress in this direction (e.g., [16]) has the potential to strongly benefit scientific applications and domains where high realism is considered crucial.
- **Communicating uncertainty:** Lastly, the concept of uncertainty is a difficult concept to grasp for humans and a challenge in many areas of GIScience and geospatial visualization [10, 12] but the difficulties are amplified when projecting into the future or past as in the climate effect project from Section 3. Even if the outputs of a predictive model include uncertainties, how can these be communicated to the user efficiently and intuitively in the context of a discrete 3D forest model? We believe that this is an area in need of novel ideas and approaches but also again empirical research to assess how different alternatives affect user experience and gaining an understanding of the communicated phenomena.

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