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Advancing Forest Monitoring and Assessment Through Immersive Virtual Reality

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Abstract. The recent influx of remote and proximal sensing data provides new opportunities to understand environmental processes. A potential application of these datasets is to facilitate forestry operations. However, forest management decision-making through sensing techniques faces many challenges, partly due to the involvement of stakeholders with different knowledge levels and objectives. We present a virtual reality application developed for forest monitoring and assessment to address some of these challenges. First, a workflow for visualizing different sources of environmental sensing data is introduced to reconstruct digitally forest and terrain characteristics. Then, the VR experience is introduced in which users can observe, manipulate, and measure LiDAR-derived forest and tree models in immersive virtual environments. Finally, a heuristic expert evaluation to assess the overall user experience and the usability of individual application features is reported. We also gathered open-ended responses from domain experts to reflect on the potential and actual uses of the application in forest-related practices.

Keywords. immersive media, environmental data visualization, LiDAR, workflow, user evaluation

1 Introduction

Forests are an integral part of the world's ecosystems and can be found in nearly all climate zones from the tropics to the sub-Arctic regions (Martell et al., 1998; FAO and UNEP, 2020). About 30% of the ice-free land surface of the Earth is covered by forests or woodlands, and this value is 43% for the European Union (European Commission, 2021). Forests serve as crucial habitats to more than 80% of all Earth's species and offer natural resources such as soils, timber, and coal that benefit people and industry (Ansari et al., 2021). Furthermore, forests are a prime factor in the oxygen and carbon dioxide balance in the Earth's atmosphere. According to the Intergovernmental Panel on Climate Change report, afforestation and deforestation are the main drivers of global climate change and, therefore, have a long-term impact on economics, sustainability, and human well-being (Arias et al., 2021; IPCC, 2021). Despite their importance, forests are disappearing worldwide at a rate of seven million hectares per year for example, from poor management practices with fragmentation, consequently leading to loss of habitats and threats to environmental sustainability (Huete, 2012).

Forest monitoring and management have been a major focus of ecologists and conservation scientists for decades. Forest monitoring involves data collected in a specific forest site for assessing stand dynamics and formulating management policies (Vries et al., 2003). In practice, large-scale geocoded data such as multispectral satellite images are incorporated with finer resolution laser scanning information (such as the Light Detection and Ranging scans, also known as LiDAR) towards a multi-modal/multi-resolution and multi-temporal data set for analysis (Hilker et al., 2008). Recently, more and more foresters have begun using UAV (unmanned aerial vehicle) and ground-based LiDAR to monitor and assess key parameters of forest structure and biomass (van Leeuwen and Nieuwenhuis, 2010; Thiel and Schmullius, 2017). In a traditional workflow for data analysis, information derived from these datasets is often interpreted visually on a desktop screen and communicated with diverse groups using paper reports and charts intended for professionals (Perez-Huet, 2020). Stakeholders with little domain expertise may experience difficulties in distilling key points from the analysis, thus not gaining much intuition or insight about a forest ecosystem.

With the recent advance in display technology, combined with the rapid progress in environmental sensing techniques, we can now bring the data to life by allowing users to immerse themselves in a digital simulation of real-world systems. In this article, we use the term immersive media to refer to the content, software, and device that mimic unmediated sensory experiences (Sobel, 2019). Examples are 360° videos or images and 3D digital models and simulations experienced through a head-mounted display (HMD). In the forestry domain, existing research on immersive media mainly focuses on their psychological effects on rehabilitation (Tabrizian et al., 2018; Mostajeran et al., 2021; Leung et al., 2022; Breves and Schramm, 2021) and training (Fabrika et al., 2018). These studies point out the benefits of using immersive nature experiences to improve mood states (Mostajeran et al., 2021), reduce the psychological distance to environmental challenges such as climate change (Breves and Schramm, 2021), and facilitate the communication between stakeholders (Tabrizian et al., 2018).

Immersive media allow the interactive inspection of a place through embodied interfaces at any time and from any location in the actual world. Users can do prospective planning and retrospective learning of complex natural phenomena that are difficult or even impossible to grasp in physical reality (Greengard, 2019). With the HMD and motion-tracking sensors, users become part of the virtual space, wherein environmental sensing and simulation data together with abstract information (e.g., concepts and relations) become experiential while still being analytical in nature (Bailenson, 2019). For example, Huang et al. (2021) report a successful integration of a variety of model-derived data into an immersive experience to demonstrate the influence of climate change on forest stands.

Despite the opportunities and proven benefits that immersive media offer (Bailenson, 2019), their potential is not yet fully realized, probably due to the high development cost and practitioners' preference for conventional screen-based analysis (Zhao et al., 2019; Müller et al., 2019). It is unclear whether and to what extent immersive applications can be used to facilitate forestry decision-making. Research in environmental science education shows that immersive media provide effective results in terms of learners' enjoyment (Zhao et al., 2020), task performance (Dalto et al., 2010), and understanding of spatial-temporal concepts through hands-on experience (Markowitz and Bailenson, 2021). Considering the complexity of forest structure and its *spatial* nature, immersive media would appear to have great potential in understanding the properties and relationships of data obtained from a forest environment.

There are three gaps in previous research on designing immersive media for forestry. First, procedural modeling has been the preferred method of reconstructing real-world forests in VR. This method takes a set of rules and parameters to generate content (Favorskaya et al., 2011); however, to what extent the virtual replica mirrors its physical counterpart depends on the collection of ground truth data from the field, which is a time-consuming and costly undertaking. Second, and inherently related to the first identified gap, the use of environmental sensing data has largely been ignored in VR forest applications. In this regard, new sensing techniques such as UAV-based LiDAR allow the quick acquisition of dense positions from 3D surfaces, making the accurate yet efficient modeling of spatially complex objects realizable. Third, most previous studies focus only on the development of virtual forests, without accounting for user experiences and outcomes. Since immersive media are still new to most people, it is critical to empirically validate their effectiveness as a visualization and analysis tool and to provide evidence-based suggestions on the future design of forest XR applications.

In the current study, we aim to explore the potential of using immersive technologies together with environmental sensing data to support forest monitoring, assessment, and management. To address the aforementioned research gaps, this paper presents an immersive workbench with which users can virtually observe, manipulate, and analyze data collected from a real-world forest. We first developed a reproducible workflow for forest reconstruction in VR using various sensing techniques such as LiDAR imagery and 360° photo/videography. We then implemented a suite of measurement tools in the virtual environment for users to capture the structure and geometric features of individual trees. Finally, a heuristic evaluation was conducted with a small group of forest experts to answer the following research questions:

1) What is the user experience gained with our virtual forest application in general in the context of forest monitoring?
2) Are different components of the virtual forest application perceived to be easy to use and useful by domain experts?
3) What is the measurement accuracy of LiDAR-derived tree models in VR?

2 Related Work

2.1 Challenges in Forest Management

Contemporary forest management presents significant challenges due to stakeholders' competing interests and often conflicting perspectives (Bruin et al., 2015). Timber production companies and forest owners, for example, aim to increase profits from wood and paper products. In contrast, local residents, educational institutes, and other non-profit organizations might be more interested in the recreational and ecological values of the forests (FAO and UNEP, 2020). While public sectors such as the government have been attempting to reconcile the conflicting demands of those parties, forestry continues to be the source of controversial discussions, probably because environmental concerns have outweighed the exploitation of natural resources in many forest areas (Heinimann, 2007).

Sustaining forest development is a complex process that requires broad ecological knowledge and the use of qualitative and quantitative data for characterizing environmental features. For example, Barmpoutis et al. (2019) used multispectral images of the forest canopy acquired from a UAV to assess tree health. Trotsiuk et al. (2020) assimilated data from hundreds of forest monitoring sites to simulate the climate sensitivity of dominant tree species across Switzerland. In these cases, foresters have to incorporate information from multiple sources, such as understory composition and canopy structure, into a coherent whole, which is often beyond their capabilities (Wallgrün et al., 2021a; Favorskaya and Jain, 2017). With more partners participating in the management process and their competing pressures exerted on forest resources, there is a growing demand for efficient information visualization towards the creation and exchange of knowledge (Hasan et al., 2019; Müller et al., 2019). Following this rationale, in the present study we propose to use immersive media as a visualization and analysis tool to assist stakeholders with diverse backgrounds in understanding and interpreting forest monitoring data.

2.2 Immersive Media as a Tool for Forestry

Immersive media, including Virtual Reality (VR) and Augmented Reality (AR), are an umbrella term often used interchangeably with eXtended Realities (XR; Sherman and Craig, 2018). VR places users in a computer-generated environment rendered with 3D graphics and supporting real-time interaction, while AR superimposes virtual objects onto users' perceptions of the real-world space so that both can be experienced simultaneously (Kee and Zhang, 2022). According to Milgram and Kishino (1994), immersive media span a variety of technologies along a continuum with the physical world at one end and a completely digital environment, i.e. VR, at the other. Within this continuum, AR together with other technologies that mix real with virtual contents sits in a range between physical and virtual realities.

Immersive media have a long history of development, with the first HMD dating back to the 1960s; however, their growth as an industry had been in its infancy until 2016 (Greengard, 2019; Sherman and Craig, 2018). The year 2016 was called by many "the year of VR" because major tech firms began investing heavily in the hardware and software of immersive media. Since then the evolution of a range of key technologies has reached an exciting stage that allows vivid, sensory, and interactive experiences to be delivered to users (Woods et al., 2019). As the cost has declined and ease of use has improved, immersive technologies, particularly portable and untethered HMDs have become increasingly popular and widely available to mainstream consumers. Following this trend, in recent years, we have been witnessing a paradigm shift of XR applications from pure entertainment to more serious education and science-oriented activities (Greengard, 2019).

What are the advantages of immersive media in visualizing and analyzing forest data? In many forest applications, LiDAR information is captured as 3D point clouds which are typically viewed on a desktop screen. Simpson (2020) coined the term 3D-on-2D to refer to representations of 3D information on standard 2D displays that afford only limited visual depth cues. The lack of binocular depth cues on traditional desktop screens may explain the failure of laypersons to grasp the key features of some complex 3D objects such as tree canopies (Ellefsen, 2022). In contrast, 3D-in-3D refers to applications that use stereoscopic HMDs with head tracking. By incorporating 3D models into real 3D space, 3D-in-3D overcomes the perceptual limitations of 3D-on-2D by providing an additional spatial dimension to represent LiDAR point clouds or other 3D types of data for forest mapping. Another major benefit of immersive media, according to Zhao et al. (2020), is the capability to mimic direct experiences in the field. Leveraging the motion capture system of VR, the users' body and head movements are mapped into the virtual space in real-time, which provides a more natural way of interaction compared to the keyboard and monitor interface. Such embodied, egocentric experiences can evoke visceral feelings within the user to facilitate an intuitive understanding of physical measurements (Lee et al., 2021); therefore, immersive media may be particularly useful for studying natural entities and phenomena. For instance, observing and interacting with a tree model on a one-to-one scale while being immersed in a virtual forest can provide foresters with a powerful way to essentially work in situ.

Over the past few years, several studies explored the use of immersive environments to advance forestry sciences and practices. Fabrika et al. (2018) developed a thinning simulator in the Cave Automatic Virtual Environment as a practical solution for the remote training of forest managers and workers.[1] The training system connected a forest-growth model with the 3D visualization of forest stands through individual tree parameters, allowing trainees to obtain a tangible experience of the actual consequences of their thinning operations. Wallgrün et al. (2021b) created a virtual tour for teaching natural resource management in fire-prone forests. The authors used 360° images along with audio commentary realizing low-cost and realistic forest environments. However, the virtual tour application was delivered to students as a browser-based experience due to the lockdowns of the COVID-19 pandemic. Huang et al. (2021) visualized forest dynamics under different climate change scenarios. In their work, historical meteorological data were combined with species distribution maps as input for LANDIS-II, a process-based ecological model, to predict changes in forest biomass as well as other ecosystem characteristics at a decadal time scale. The simulation results were visualized as an immersive virtual experience via an HMD. A preliminary user evaluation showed positive feedback on using data-driven visualization methods to improve public awareness of climate change impacts.

3 Methods

3.1 Immersive Forest Application

We selected the Eifel National Park in Western Germany as the target area of our immersive forest application (Figure 1). The park had been a productive forest with many human disturbances before its founding in 2004. The dominant tree species of the forest are beech, Norway spruce, and oak. The data obtained for this study was derived from a large-scale biomass monitoring project coordinated by the European Space Agency and the German Forestry Service. As part of this effort, in September 2021 a research team including the first author went to the Eifel National Park and collected various sensing data of the forest, including terrestrial, mobile, and UAV laser scanning (TLS, MLS, and UAV-LS) and 360° images and videos, from 11 pre-defined 50 by 50 meter plots.

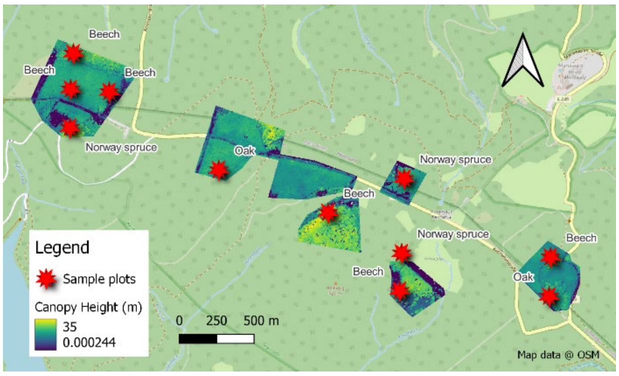

Figure 1. Overview map of the Eifel National Park, Western Germany. Eleven areas selected for visualization are denoted as red stars (50x50m).

We created a Digital Terrain Model (DTM) of the Eifel National Park using the World Composer[2] package from the Unity Asset Store. This package enables the automatic reconstruction of any terrain surface on Earth by obtaining topographic and textural data available on Microsoft Bing maps. In the initial phase of the VR experience, users can slide their fingers on the touchpad to fly through a large-scale terrain to explore its topographic features such as slope and aspect (Figure 2a). Two levels of raster resolution, including 3 and 24 meters per pixel, were extracted for the DTM of an area of 50 km^2 to ensure a smooth transition between holistic and close-up views. For each scanned plot, a cm-accuracy DTM was obtained from TLS data by using the LAStools las2dem tool[3] which allows a 3D map with height information to be created from LiDAR point clouds.

For the visualization of forest and individual trees, we first used the software Riscan Pro[4] to generate a single point cloud containing LiDAR data from all scanned plots. This merged point cloud was then passed to MatLab[5] for segmenting trees as well as separating wood from leaves using the method described in the paper of Wang et al. (2020). An attempt was also made to improve the data quality by removing noise and alignment errors in CloudCompare[6]. Once the LiDAR data sets had been processed, they were loaded into the Cloud Viewer & Tools[7] to produce a meshed dense point cloud for their representations in the Unity game engine (Figure 2b), and

[1] Thinning involves the selective removal of trees to increase the growing space of remaining standing individuals (Bravo-Oviedo et al., 2017).
[2] https://assetstore.unity.com/packages/tools/terrain/world-composer-13238
[3] https://lastools.github.io/
[4] http://www.riegl.com/products/software-packages/riscan-pro/
[5] https://nl.mathworks.com/products/matlab.html
[6] https://www.danielgm.net/cc/
[7] https://assetstore.unity.com/packages/tools/utilities/point-cloud-viewer-and-tools-16019

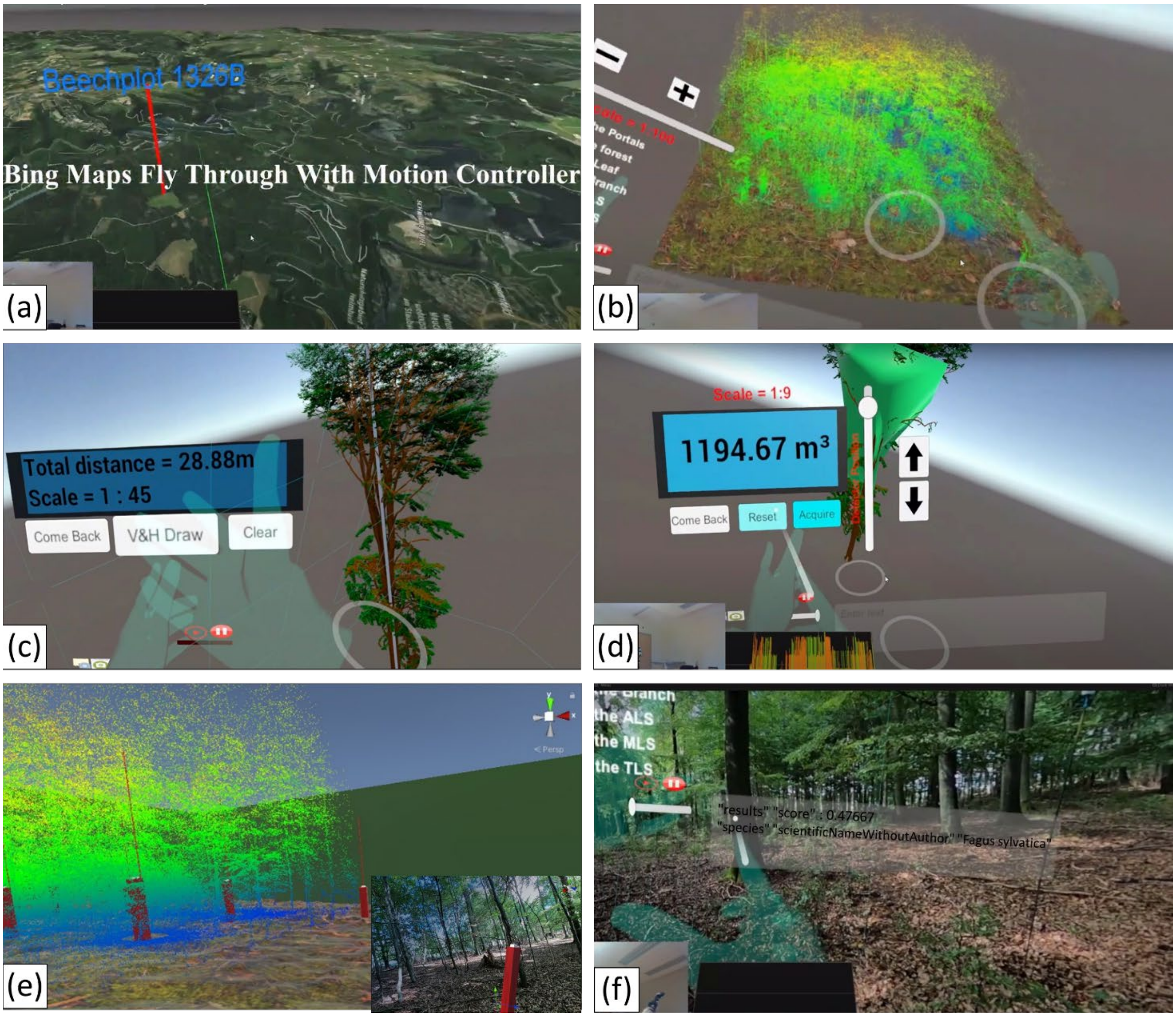

Figure 2. Screenshots from the virtual forest application. (a) Flying through the Digital Terrain Model of the Eifel National Park; (b) forest LiDAR point cloud; (c) vertical & horizontal draw mode in distance measurement; (d) volume measurement; (e) Button on a pillar for switching between the forest point cloud and 360° image; (f) species identification using the Pl@ntNet API.

at this stage, down-sampling might be performed if a lower resolution was needed. Figure 3 shows the workflow of processing forest point cloud data for immersive experiences.

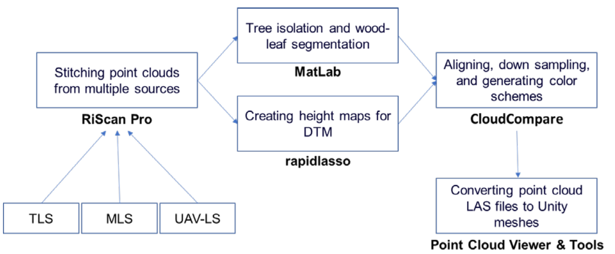

Figure 3. Procedure of visualizing forest LiDAR data sets in VR environments. TLS, MLS, and UAV-LS stand for terrestrial, mobile, and UAV laser scanning, respectively. DTM represents the Digital Terrain Model.

We built on the work of Zhao et al. (2019) and developed an immersive workbench for the direct observation and quantitative analysis of individual trees in the forest areas studied. The k-dimensional tree algorithm, which enables an efficient search of the nearest neighbors in a large data set (Bentley, 1975), was used to extract LiDAR-derived geometric features. Our workbench has three types of length measurement including free draw, vertical & horizontal (V&H) draw, and curve draw. The free draw option allows users to place reference points in a 3D space without any restrictions; the adjacent pairs of points are then connected by line segments for cumulative length calculation. In the V&H draw (Figure 2c), one end of each line segment is snapped to the closest point on the tree point cloud, while the other end is snapped to the horizontally or vertically nearest point, depending on the orientation of the line to be constructed. The curve draw also snaps user points to the point cloud and further inserts multiple auto-snapped nodes in between to capture an irregular surface (e.g., tree stem). In terms of area and volume measurement, users first move vertically a 2D plane or 3D box that acts as a proxy for their region of interest in a tree structure. Once they make a choice, reference nodes in the plane or box will be snapped to the point cloud surface for triangulated mesh construction. The resultant meshes will then be combined to calculate the area or volume of the user-defined region in a tree (Figure 2d). While performing measurements, users can walk around and operate a single tree model through hand gestures, such as rotating, scaling, and position adjusting to find a suitable perspective for viewing and obtaining measurements of the model.

Additionally, sixteen 360° images and two 360° videos were acquired for two in-depth scanned plots (as shown in Figure 1) and mapped on an inverted sphere surrounding the user. These supplementary media provide visually correct representations of the forest environment. Their locations were georeferenced and matched with the corresponding locations on the forest point cloud. At each location, a pillar with a button was presented for users to switch between the forest point cloud model and its real-world counterpart captured using a panoramic camera (Figure 2e). Within a 360° image, users can recognize tree species through the Pl@ntNet [8] API (Application Programming Interface). After the user takes a screenshot of a tree of interest, the picture is sent to the Pl@ntNet deep learning model via an HTTP request for processing and identification of plant categories. The output (the species scientific name along with a confidence score) is displayed to the user on a real-time basis (Figure 2f).

3.2 Apparatus and Participants

Seven participants (two females) were recruited from the Forest Ecology and Forest Management Group and the Forest and Nature Conservation Policy Group at Wageningen University & Research. They were domain experts working on research or consultancy in forest modeling, management, or education fields. Participants were between 24 and 59 years old (average age 36 years), with education levels ranging from a bachelor to PhD. Among them only two had prior experience with VR. Despite a relatively small number of participants in this study, the number was larger than Nielsen's recommendation of 3-5 expert evaluators for heuristic evaluation (Nielsen, 1994). During the experiment, participants stood in the center of a 2.5m x 3.5m tracking area and held two Vive controllers. A tethered HTC Vive Pro 2 HMD was used to display the virtual content. The headset has a resolution of 4896 x 2448 pixels (2448 × 2448 per eye), a refresh rate of 90 Hz, and a 120° field of view. Rendering was performed by a gaming computer with a 3.50 GHz Intel i9-11900KF processor, 32 GB RAM, and an NVIDIA GeForce RTX 3080 graphics card.

3.3 Procedure and Measures

All participants gave their informed consent by ticking a box in the questionnaire after being informed about the purpose of the study, the potential risks of VR activities, and the voluntary and anonymous nature of the evaluation. After providing demographic information, participants wore the HMD and held the controllers; they had sufficient time to familiarize themselves with the interface and interactions required by the target application. Participants were introduced to the virtual forest environment to perform a series of tasks, including 1) navigation and manipulation of forest models, 2) switch between point cloud visualization and 360° images/videos, 3) identification of tree species from 360° imagery, and 4) measurement of the total height and the diameter at breast height (DBH) of two individual trees.

The VR experience was followed by a heuristic evaluation, which relies on a small number of domain experts to evaluate to what extent the application complies with a set of user experience principles or heuristics (Huang et al., 2021; Sutcliffe and Gault, 2004). The heuristics used in this study, as chosen and adapted from the questionnaires developed by Davis (1989) and Tcha-Tokey et al. (2019), were:

1) *Technology adoption*: users' intention for future use of the application (e.g., "if I use again the same virtual environment, my interaction with the environment would be clear and understandable for me").
2) *Engagement*: the extent to which users feel engaged in the virtual environment (e.g., "I was involved in the virtual environment experience").
3) *Flow*: the degree to which users are absorbed by their tasks (e.g., "I was losing the sense of time").
4) *Presence*: the sense of being in virtual space (e.g., "I could examine objects from multiple viewpoints").
5) *Immersion*: the illusion that the VR technology replaces the user's sensory stimuli with the virtual sensory stimuli (Tcha-Tokey et al., 2019; e.g., "I felt physically fit in the virtual environment").
6) *Experience consequence*: the sickness users may experience during VR exposure (e.g., "I suffered from nausea during my interaction with the virtual environment").

[8] https://my.plantnet.org/

7) *Usability*: measured with two variables: *ease of use*, defined as the extent to which system use is perceived to be free from additional effort, and *usefulness*, defined as the extent to which system use is perceived to be beneficial (Davis, 1989).

Each heuristic principle was composed of three or four Likert scale statements ranging from 1 (strongly disagree) to 5 (strongly agree). Heuristics 1-6 (Tcha-Tokey et al., 2019) assessed participants' feelings about the VR experience as a whole, while Heuristic 7 (Davis, 1989) assessed the usability of different components of the virtual forest application, including LiDAR representations, 360° images & videos, measurement tools, and species recognition. In addition to the Likert scale questionnaire, we also asked open-ended questions to encourage participants to consider the potential of the VR experience for forest monitoring, elaborate on the benefits and limitations of each application component, and give suggestions about possible improvements.

3.4 Data and Software Availability

The materials that enable the development of the application and the datasets that support the findings of this study are openly available at https://doi.org/10.5281/zenodo.7661268. A video demonstrating the virtual forest application can be found on YouTube (https://youtu.be/I0oAZmCybHU). The workflow underlying this paper was partially reproduced by an independent reviewer during the AGILE reproducibility review and a reproducibility report was published at https://doi.org/10.17605/osf.io/27wzp.

4. Results

To examine the user experience of the virtual forest application, we calculated the mean (*M*) and median (*Mdn*) of participants' ratings on each of the first six heuristics: technology adoption (M = 3.7, Mdn = 4), engagement (M = 4.0, Mdn = 4), flow (M = 3.9, Mdn = 4), presence (M = 4.0, Mdn = 5), immersion (M = 3.6, Mdn = 4), and experience consequence (M = 1.7, Mdn = 1). The overall user experience score is 3.8 (Mdn = 4), resulting in a rounded "agree" on the 5-point Likert scale.[9] Regarding the usability of individual application components, the mean and median of the usability heuristic, from high to low, were: 360° images & videos (M = 3.8, Mdn = 4), LiDAR representations (M = 3.8, Mdn = 4), measurement tools (M = 3.3, Mdn = 3), and species recognition (M = 3.0, Mdn = 3). The overall usability score is 3.5, resulting in a rounded "agree" on the 5-point Likert scale.

To evaluate the accuracy of the LiDAR measurement tools, the height and the diameter at breast height (DBH) of two individual trees measured by participants were compared with the corresponding actual values as extracted from the raw LiDAR data using RStudio. The tree heights were measured by participants in VR as 26.7m and 28.7m on average, which deviated -3.3% and -2.9% from the actual tree heights. The DBHs were measured by participants in VR as 64.4cm and 67.1cm on average, which deviated 0.7% and 0.2% from the actual DBH values.

Participants' responses to open-ended questions were generally positive and complemented their ratings on Likert scale statements. In terms of the potential for forest monitoring, participants commented on the application being promising for remote collaboration, communication, training, and gaining new insights. For example, "People could share forest data with others around the world to showcase their forest research or get second opinions.", "It could be very useful to recreate imagery for forest owners like municipalities to use in communication with citizens.", "It could be a great training tool for students and professionals in the context of marteloscopes [note: a marteloscope is defined as an area of forest where all the trees are mapped, numbered, measured, and classified].", "It is a great opportunity to see the forest from angles that you normally do not see (from above, inside the canopy, etc.)." Although some participants mentioned that "I do not see the system as it is now to contribute to forest inventory." and made a note of "missing the connection with the forest."

Assessing different components of the virtual forest application, participants perceived the 360° images & videos and the LiDAR representations to be realistic and useful for validating data gathered in the field: "[The LiDAR data] provide realistic representations of tree shape, size, and relations to neighbors.", "The [360°] images give a very clear way for observing the structure of a forest and to assess what species grow there, how much light can come into the forest, and the amount of undergrowth present on the forest floor. This can make validating field measurements much simpler, as you have a way of 'revisiting' the forest from a distance." In contrast, the participants considered themselves less likely to use the measurement and species recognition tools for regular inventory work, but rather for training

[9] When calculating the overall score of the user experience, the items for the heuristic *experience consequence* were reversely coded to be interpreted as higher scores meaning better outcomes.

and data exploration: “It [species recognition] is a nice additional function, but with the current scan [referring to 360° imagery] quality, you might miss certain plants.”, “I think it [the measurement tool] works fine for understanding concepts. It is very nice and impressive and very useful for data exploration. [But] in a finished app, I would not need most of the measurements as they could be precalculated per tree.”, “Bigger buttons would help a lot with the [measurement] interface, as well as being able to enter a numerical height for the basal area/volumes tool, rather than relying on a slider.”, and “I would not use the tools for performing actual measurements; that should still be done in the forest itself.”

In respect of future development, participants suggested the following functions or features: 1) forest thinning and growth simulation, 2) a cylinder-fitting algorithm for volume calculation, 3) zooming in and out of 360° images, 4) crown projection measurement, 5) light rendering, and 6) a virtual tablet for data overview. We plan to review and incorporate these suggestions in the next phase of the application development.

5. Discussion and Conclusions

In this paper, we present a VR experience of the Eifel National Park as the first step toward the integration of immersive media in forest monitoring and management. A digital reconstruction of the forest and terrain characteristics was created in virtual space using LiDAR in combination with other sources of environmental sensing data. The VR experience allows users to view and manipulate LiDAR-derived forest models from an egocentric, embodied perspective. Users can also utilize a set of interactive tools to investigate the qualitative and quantitative features of tree point cloud models. The results of the heuristic evaluation showed an overall good rating on the user experience of the virtual forest application. Concerning the usability of individual application components, participants rated positively on the visualization features—LiDAR representations and 360° images & videos. This result agrees with Wallgrün et al. (2021b) and Huang et al. (2021) who emphasize the beneficial effect of visual quality on the effectiveness of ecological visualization. These days, computer graphics have reached a level of quality almost comparable to real-life views. The ever-increasing graphical performance over the past few years has made it possible to describe a rather complex virtual world containing all sorts of details. Our findings suggest that both LiDAR representations and 360° images and videos can be part of the continued evolution toward higher fidelity virtual forest environments.

Participants perceived the measurement and species recognition tools to be less useful and more difficult to use than the visualization components of our application. Using these tools requires intensive interactions with the input controllers, such as pressing buttons and sliding a finger across a touch, while most participants had little or did not have prior experience with VR devices. As can be observed from open-ended comments, the novelty brought by immersive user interfaces might have increased the learning curve for participants to become proficient with the technology. Still, participants showed relatively high accuracy when measuring tree height and DBH with the LiDAR measurement tools. This suggests that despite the possibly increased mental workload of interacting with a novel interface, participants can learn how to use the tools with a few minutes of exploration to achieve positive outcomes. A future study with repeated exposure to VR is recommended to mitigate the novelty effect on product evaluation (e.g., Zhao et al., 2021). Expert evaluators who are familiar with the VR interface may better reflect on the contextualized nature of those immersive tools and thus consider them more useful for a variety of forestry activities.

Despite the potential of the virtual forest application, participants commented in the open-ended questions that they would prefer using this application for training and outreach over actual forestry operations. On the one hand, immersive media provide an embodied, intuitive user interface that can bridge the knowledge gap between expert and novice stakeholders to promote the communication of forest information and scientific results (Tabrizian et al., 2018). On the other hand, forest experts appreciate the hands-on aspect of actual fieldwork and, consequently, regard the VR experience as an addition or supplement to traditional methods. This is not surprising given that most of the application components presented to participants are still in their prototype stages. We can, of course, continue refining the application to iteratively improve its usability, but more importantly we should incorporate opinions and knowledge of domain experts throughout the development lifecycle. For example, a joint interview between forest practitioners and VR developers can act as a starting point to identify real-world forestry problems where immersive media may come into play. Another possible future research direction is to evaluate the effectiveness and efficiency of our virtual forest application in comparison to traditional workflows for forest monitoring and management (in the real world or using desktop applications).

The presented workflow of importing environmental sensing datasets into the Unity game engine requires data pre-processing through various third-party software (see Figure 3). We are in the midst of developing a LiDAR visualization toolkit to streamline this process. Compared to existing Unity asset packages, such as Point Cloud Viewer & Tools (used in the current study), our proposed toolkit has the advantage of employing a highly optimized graphics rendering pipeline and supporting different levels of detail for visualizing large data sets. Furthermore, our approach provides fast operations over point cloud data including segmentation, selection/deselection of points, and labeling and classification of selected points. This is achieved by creating a modularized framework for direct data operations in immersive environments using the HMD and hand controllers which serve as a base to implement manipulation tools. Our work-in-progress toolkit is already improving the efficiency of existing workflows for LiDAR visualization, and the next step is to enable multi-user collaboration in VR to construct a further integrated platform for point cloud data processing and presentation. All the source code along with documentation will be shared as a Unity project in GitHub once it is completed. As a future research direction, we will build on the implementation of immersive LiDAR visualization to investigate how user input such as point cloud annotation in VR can aid in the efficiency of training data generation for AI-based segmentation of wood and leaves.

The virtual forest application employs the Pl@ntNet API to identify tree species, but it is important to realize the existence of other off-the-shelf or open-source APIs for this purpose, such as iNaturalist[10] and Plant.id[11], with strengths and weaknesses for various plant species in different environments. Future research may be conducted to compare the accuracy of those plant identification APIs based on screenshots of panoramic views in VR.

Our work does not address ethical concerns that may be raised during the experience of virtual forests, which in the future researchers and practitioners should consider when developing this kind of application. Some issues reflect the use of immersive media in general, such as its long-term effect on the mental and physical well-being of users (Lavoie et al., 2021) and the privacy of behavior data gathered by technologies (Roth et al., 2019). Other ethical concerns are relevant to the forestry domain, including stakeholders' trust in the digital representations of forest data, access for local communities to immersive technologies, and the communication of uncertainty in forest simulations (Huang et al., 2019).

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