LOW-COST WORKFLOW FOR 3D URBAN FOREST VIRTUAL RECONSTRUCTION

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ABSTRACT:

This contribution addresses, on one hand, the increasing need and demand of 3D data (e.g., point clouds) in urban forestry – for monitoring, analysis, and visualisation purposes –, on the other, the lack of standardised procedures to manage them, also towards engaging and empowering the broader audience. Practitioners in landscape architecture – as a potential bridging field between forestry, geomatics and computer science – could 'smartly' manage dynamic ecosystems as forests, parks, and gardens in urban contexts if efficiently provided with digital tools, technologies and techniques for design-oriented information. To this end, a low-cost workflow for 3D virtual reconstruction of under-storey urban vegetation is here proposed to allow exploiting the aesthetic, analytical, and generative potential of 3D point clouds in landscape and urban design. As a proof-of-concept, a combination of a wide range of methods (e.g., spherical photogrammetry, point cloud modelling, virtual reality), tools (e.g., 360° camera, tablet with lidar sensor), and software (e.g., Agisoft Metashape, 3DF Zephyr, CloudCompare, Unity) is tested in the development of a virtual plot of the Mesiano University park in Trento (Italy). Covering all the different steps of the information management activities (namely acquisition, processing, and visualisation), the presented workflow enables a GIS-based, texturized, real-world 3D point cloud rendering of urban forests to be intuitively and interactively experienced in Virtual Reality.

1. INTRODUCTION

Urban forests, parks, and gardens are fundamental components of urban sustainability and resilience, offering several ecosystem services (i.e., provisioning, regulation and maintenance, and cultural services) to face anthropogenic climate change. Nowadays, the smart management of these inherently dynamic ecosystems in urban contexts requires a multidisciplinary approach to support forestry applications (Nitoslawski et al., 2019). The prominent fields to refer to are geomatics for data acquisition and processing and computer science for rendering/visualisation purposes. Landscape architecture can thereafter draw from these disciplines to provide the remaining lack of knowledge about digital tools, technologies and techniques to manage design-oriented information among its practitioners.

In the rather traditional field of forestry, the use of digital 3D data (i.e., point clouds, meshes) – together with the concept of 'virtual forest' – is on the rise, especially for research, training, gaming, and planning forest applications (Murtiyoso et al., 2023). However despite their aesthetic, analytical, and generative potential, 3D point cloud models have not yet been completely exploited by workflows in landscape and urban design (Urech et al., 2022), mainly because of their relatively high acquisition costs (especially when considering the use of terrestrial laser scanners, the current industry standard) and the lack of standardised procedures to process and visualise them in spatial decision-making to ultimately promote stakeholder engagement and public empowerment.

Regarding the data acquisition with reality-based methods, nowadays close-range remote sensing allows many previously impossible investigations (Liang et al., 2022) to derive information about stem (e.g., position, curvature, diameter), branches (e.g., angles, diameters, distances between branches), canopy (e.g., multispectral characteristics, size, length, area, volume distribution), neighbourhood (e.g., number of trees, size and relative position, dominance). In addition to expensive and time-consuming (even if considered as gold standard in terms of quality) tools such as Terrestrial Laser Scanners (TLS), low-cost sensors have also seen rising popularity in forest applications as solid alternatives (Mokroš et al., 2021). Regarding point cloud processing and rendering/visualisation, standard methods from other fields (such as game development, architecture, construction) might not entirely work in forestry because of its unique characteristics and dynamic nature.

Therefore, the aim of this contribution is to collect, test, and coordinate promising explorative techniques and chunks of existing procedures from different fields of research and practice towards the definition of an organic and 'agile' workflow to virtually reconstruct real-world urban forests, enabling landscape architects to effectively manage, plan and design them.

Indeed, the bigger framework of this research exploration is an ongoing research investigating the development of a Territorial Digital Twin (TDT) – of which forest digital twins (Buonocore et al., 2022) would be essential components as a multiscale 3D digital copy of fragile landscapes to increase their resilience (Chioni, 2023). Specifically, even if the modelling of the natural environment has only recently started to be developed in urban digital twins (e.g., the GreenTwins project for Helsinki and Tallinn, in Nummi et al., 2022), it seems crucial to address the rising importance of urban vegetation for the well-being of citizens.

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2. MATERIALS AND METHODS

Methodological premises and case study. The investigation of the proposed low-cost workflow can be divided into three main steps, corresponding to the main information management activities, namely (i) acquisition, (ii) processing, and (iii) visualisation. The operative implementation of each of these steps derives from recent literature and guidelines, regarding respectively: (i) rapid and low-cost sensors, using both passive sensing method, as 360° cameras for spherical photogrammetry (Murtiyoso et al., 2022) and active sensing method, as Solid-State Lidar sensors in the latest Apple products (Bobrowski et al., 2022); (ii) scanning apps (Gollob et al., 2021) and software solutions for spherical photogrammetry (e.g., Agisoft Metashape Professional, 3DF Zephyr); and (iii) 3D point cloud rendering approaches (Fraiss, 2017; Schutz et al., 2019) for setting virtual environments using game engines, such as the popular Unity engine (Fol et al., 2022; Wissen Hayek et al., 2023; Luoma et al., 2023).

The case study chosen for defining and testing the workflow is a plot of the Mesiano University park in Trento (Italy) (Figure 1) where there are eleven trees, four planes (*Platanus acerifolia*) and seven pines (*Pinus Sylvestris*), distributed in an area of about 580 m^2 (about 18x32m). A conventional survey of the area – with a calliper and a digital hypsometer – was initially conducted to gather data about species, DBH, and height for each of the eleven trees; not surprisingly, this urban green space has structurally different characteristics compared to natural forest (e.g. the development of branches and canopy) and thus it has its own specific management, planning, and design questions.

Figure 1. Case study location (red boundary) in the Mesiano University campus in Trento (Italy).

Data acquisition. The survey campaign was carried out during a single winter morning, 21 February 2023, using the Ricoh Theta V 360° camera and the Apple iPad Pro WI-FI 12.9" with lidar sensor (Figure 2). In order to then be able to scale the generated models, prior to the spherical video and scans acquisition, it was necessary to place several coded-targets in the study area, in line with common 3D registration requirements. Even if the coded-targets do not have georeferenced coordinates, the point cloud from the iPad was nevertheless roughly georeferenced thanks to the embedded GNSS receiver of the device (theoretical precision in the metric order).

The data acquisition with the Apple iPad (Figure 2a) was conducted using the 3D Scanner App (https://3dscannerapp.com/, accessed on 7 July 2023) with the 'LiDAR advanced' setting and in the 'high resolution' mode (meaning maximum depth 5 m, resolution 5 mm, confidence high and masking off). Following current best practices (Bobrowski et al., 2022) and the app's recommendations for use, the scans were acquired by slowly circling each tree in the plot, at a distance of 2-3 m from the trunk and of 1.30-1.50 m above the ground, trying not to scan the same area twice as this generates scanning errors. In addition, to avoid memory and post-processing issues, the study area was divided in four portions to be separately scanned; to then allow connecting different scans, it was important to scan again, at the beginning of a new portion, at least the last tree acquired in the previous scanning session. The entire acquisition required no more than half an hour.

With regard to the spherical video acquisition with the Ricoh Theta V 360° camera (Figure 2b), it was conducted through the RICOH THETA app, with the default settings for videos (i.e., 4k and 29.97 fps), and by walking around the study plot, circling each tree at a distance of 2-3 m from the trunk and maintaining the camera above the operator's head (to avoid recording their face). The overall acquisition required no more than five minutes.

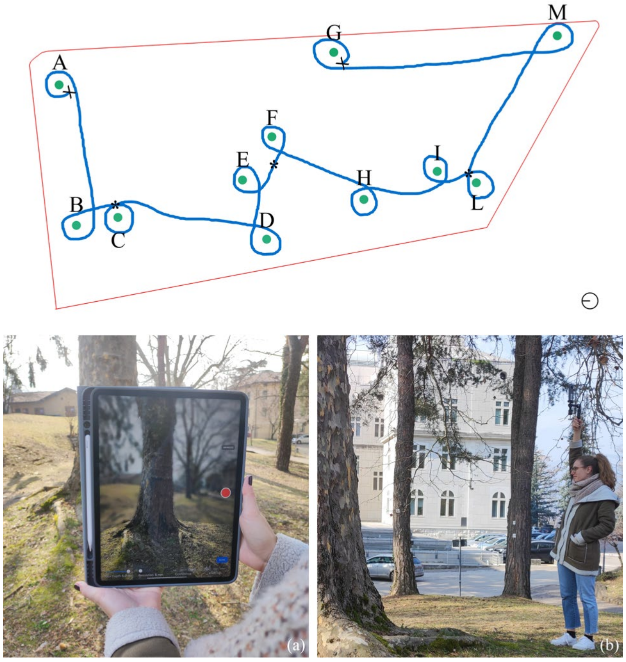

Figure 2. The data acquisition path (blue line) of both the used devices, Apple iPad (a) and Ricoh Theta V (b), on the study plot (red boundary); the green dots, named with capital letters, represent the tree positions; the asterisks (*) along the path indicate interruptions in iPad scans. Photos by Anna Maragno (2023).

Data processing. According to the different acquisition modes, the data need to be processed following a specific procedure and then converted into common formats for digital application, as 3D point clouds. For both the processing the used device was a personal laptop with NVIDIA GeForce RTX 3060 GPU, 16 GB RAM, Intel(R) Core™ i7-12700H processor.

With regards to the acquisitions from iPad, the 3D Scanner App directly generates point clouds and also allows to automatically process them, in 'HD' mode, meaning the addition of texture. The models can be then exported in several formats: the 'XYZ colour, space delimited (CloudCompare)' format was selected to optimise the compatibility with the open source software, CloudCompare (https://www.danielgm.net/cc/, accessed on 7 July 2023), used to align the different scans through the coded-targets. The result is one textured 3D mesh of trees up to a height of about 2 m and portions of the surrounding terrain (Figure 3). In principle the clouds do not need to be scaled since lidar is an active sensor computing distances with the laser beams, nor georeferenced thanks to the embedded GNSS, but the accuracy of the latter information can be very low.

Figure 3. Front e top views of the textured 3D mesh from iPad's scans.

With regards to the acquisition from the Ricoh Theta V, a proper spherical photogrammetry process was conducted in order to obtain a textured 3D point cloud. First, the spherical video needed to be stitched with the RICOH THETA app (for desktop), then it could be imported into the software Agisoft Metashape Professional (https://www.agisoft.com/, accessed on 7 July 2023). The software allows splitting the video in a number of frames per second: since the video has 4:46 min of duration, extracting 5 frames per second results in a total of 1720 frames. Then, the main steps and general recommendations for processing images from HDR panorama cameras, were followed: after setting the spherical camera model, the photo alignment first and the dense point cloud building then were performed, setting the 'high' accuracy. Finally the textured 3D model was properly scaled with the scale-bar method, using the measured linear distances between the coded-targets.

Similarly, the same procedure can be followed using another photogrammetric software that has been tested, 3DF Zephyr (https://www.3dflow.net/, accessed on 7 July 2023). The main difference with Metashape is that 3DF Zephyr cannot directly process panoramic images but need to split them into several images following the pinhole camera mathematical model (https://www.3dflow.net/case-studies/the-north-grotto-temple-360-photogrammetry-for-cultural-heritage/, accessed on 7 July 2023).

Before proceeding further, an optional step to improve the point cloud resulting from spherical photogrammetry could be to clean up the noise and polish it with CloudCompare (Figure 4), where it can be imported in several formats. A prior attempt to (partially) remove noisy points representing the sky was made . After converting the three RGB channels of the point cloud into a single channel, each point in the cloud is associated with a scalar colour value between 1 (black) and 255 (white) RGB value; it is then possible to select a range of points filtering by colour values and, since the sky tends to white, the upper limit of the range was reduced from 255 to 131. Then, the SOR (Statistical Out Removal) filter was used to remove noise (meaning 'isolated' points), on the basis of the average distance of a point from its neighbours.

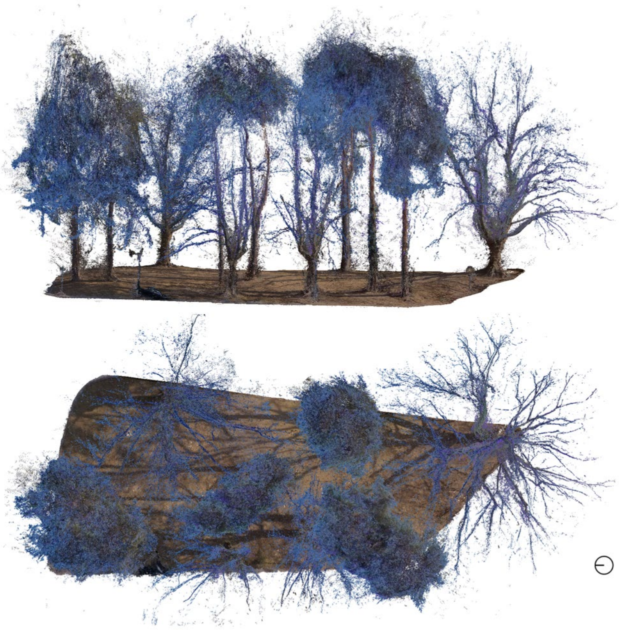

Figure 4. Front and top views of the textured 3D point cloud from spherical photogrammetry, after the cleaning.

Data visualisation. In the last step, the issue of rendering point clouds in a Virtual Reality (VR) environment was attempted to be solved using the free Unity game engine (https://unity.com/, accessed on 7 July 2023). Aware that so far Unity cannot directly support the loading of point clouds in its 'projects', different plugins can be used as Unity custom packages, according to the format and size of the input data: the LASzip plugin (https://github.com/stefanmaierhofer/LASzip, accessed on 7 July 2023), requiring a LAS/LAZ file; the Pcx plugin (https://github.com/keijiro/Pcx#readme, accessed on 7 July 2023), requiring a PLY format; and, finally, the BA Point Cloud Renderer plugin (https://github.com/SFraissTU/BA_PointCloud/releases/tag/v1.5, accessed on 7 July 2023), requiring a Potree format and more suitable for large data because of its established hierarchical rendering approach with adaptive level of detail (Fraiss, 2017; Schutz et al., 2019). All the mentioned format files are available while exporting dense point cloud from both Metashape and CloudCompare with the exception of the Potree format: this latter cannot be exported from CC, needing the open-source software PotreeConverter, version 1.7 or lower (https://github.com/potree/potree/, accessed on 7 July 2023).

After importing the data, in order to set up a proper VR environment, usable with different VR headsets, another plugin needs to be used: SteamVR Unity Plugin (https://valvesoftware.github.io/steamvr_unity_plugin/, accessed on 7 July 2023).

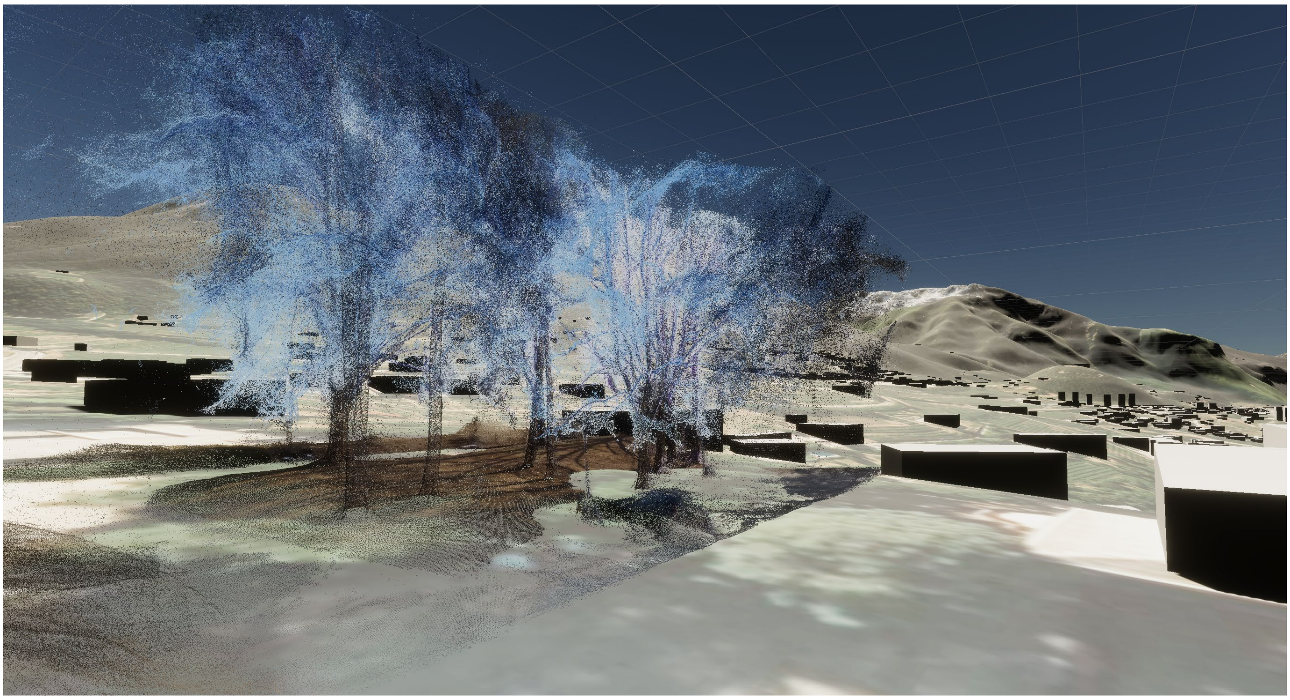

Figure 5. Screenshot of the plot's point cloud in Unity environment, with Cesium World Terrain and Cesium OSM Buildings.

Finally, since for landscape and urban design purposes 3D digital reconstructions are generally based on a Geographic Information System (GIS) approach (Wissen Hayek & Grêt-Regamey, 2021), the open source Cesium for Unity package (https://github.com/CesiumGS/cesium-unity, accessed on 7 July 2023) – with Cesium World Terrain and Cesium OSM (OpenStreetMap) Buildings – can be also loaded into the scene to provide a global reference and the scaled point cloud can consequently be oriented and geolocated (Figure 5).

3. RESULTS AND DISCUSSIONS

A novel low-cost (both in terms of economic resources and computational power) workflow for the 3D virtual reconstruction of under-storey vegetation is here proposed to support urban forest management, planning and design from the perspective of landscape architects. It connects a wide range of methods and tools (e.g., spherical photogrammetry, point cloud modelling, virtual reality) to tackle different steps of information management activities (e.g., data acquisition and transformation, data elaboration and results' visualisation); and it mostly requires software, plugins and packages which are open source or have free licensing options (excluding the photogrammetric processing for which only proprietary software were tested), thus also generating open file formats (Figure 6).

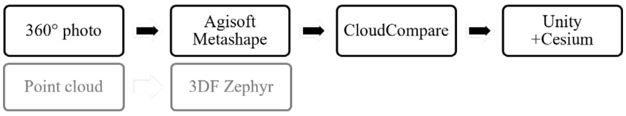

Figure 6. Summary flow chart.

With respect to our purposes, the tests involving different devices for data acquisition, different photogrammetric software for data processing, and different procedures to render point clouds in VR ultimately suggest to prefer:

- 360° cameras for data acquisition, because the iPad's output is negatively affected by its sensors' range and cannot allow a complete scan of the urban forest plot. Indeed, the iPad is severely limited by its range for this particular application, even if the time of later processing is significantly shorter using it, and the level of detail (meaning geometry and texture) of its scans is on average higher;
- Agisoft Metashape for data processing, because 3DF Zephyr does not directly process panoramic images, thus requiring an additional step in the data preparation. However, other open source solutions may exist which can further reduce the cost of this step of processing;
- BA Point Cloud Renderer plugin for large data, because it avoids needing prior sampling by adopting a hierarchical rendering approach.

Overall, the visual output of the performed 3D digital reconstruction is satisfactory for its purposes, given the limited time and expense required to generate it. Indeed, the use of low-cost sensors for 3D data generation in forestry proved to be a valid alternative to expensive gold standards, allowing to easily and quickly repeat the survey and thus to effectively monitor the dynamics of (urban) forest ecosystems. This gives the possibility not only to generate engaging visualisations dependent on the passage of seasons and years, but also to gather data that cannot be collected in a single timeframe, such as biodiversity.
However, it remains to be seen in future work if the result fills the metric requirements of specific applications, also considering that, by operating from the ground, info about the canopy (and in general the higher part of the tree) cannot be the most accurate.

4. CONCLUSIONS

At the end of the proposed workflow, merging survey and digital modelling disciplines and using point clouds data potentially coming from different sources, the output is a GIS-based, texturized, real-world 3D point cloud visualisation of an urban forest plot that can be also intuitively and interactively experienced in VR.
Encouraging findings support future outlooks as the solution for the development of digital twins of urban forests for different scales of action: from the macro scale of landscape and urban design to the micro scale of single tree management.

The potentials of texturized 3D point clouds of urban forest need to be further investigated, especially in support of qualitative operations such as biodiversity assessment, soundscape representation, etc. Furthermore, an interesting research question would be to what extent geometric precision influences the efficacy of such management systems: for example, are the resulting models sufficient to estimate the above-ground biomass and thus the carbon sequestration? Indeed, tabular mathematical models used for traditional forests cannot be used in urban contexts, as trees under human care are structurally and qualitatively different from wild trees.

Nevertheless, the proposed workflow arguably has a large potential in achieving a smart urban forest management system based on the findings of the paper. Addressing the lack of understanding about methodologies and tools on one hand, and of standardised procedures on the other hand, it potentially enables landscape architects to autonomously handle the acquisition, processing, and visualisation of data regarding urban greenery in order to ultimately support their planning and design work.

Finally, this workflow could also acquire a participatory character by considering the general audience as prosumers (both producers and consumers) of data and information about urban green infrastructure. Indeed, professionally generated 3D digital reconstructions could theoretically be fuelled and periodically updated with videos, photos, lidar scans from mobile devices, etc. collected and shared by citizens and tourists, increasingly involved in and responsible for the management of public green spaces.

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