Improvement of Virtual Tour Depiction Potential Utilizing Active and Passive Sensing Data Fusion

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Abstract: *The generation of geospatial information about objects has become a well-established field of study, facilitated by the advent of diverse techniques and technologies. Furthermore, the demand for more realistic and detailed three-dimensional (3D) models and precise digital twins has led to a surge in interest in 3D modeling. The integration of high-quality 3D models and high-resolution textures in virtual reality (VR) has constituted a well-established field of study within this context. The unmanned aerial vehicle (UAV) is a highly sought-after technology due to its ability to facilitate high-resolution aerial photo acquisition in a relatively short period of time, at a relatively low cost, and with minimal labor. In addition, terrestrial laser scanning (TLS) is a widely utilized technology due to its competence in delivering high accuracy and precise 3D point clouds. Nevertheless, both technologies are subject to inherent limitations in 3D reconstruction. The UAV technique is based on the passive remote sensing principle, which presents certain challenges when attempting to view objects in areas that are partially or fully occluded, including the forest understory and roofed structures. Furthermore, the TLS technique, which is based on active remote sensing, encounters challenges in capturing the upper parts of objects, limited mobility, and high operational costs. In this study, a virtual tour of the Gebze Technical University (GTU) campus was created by using UAV and TLS data. Subsequently, the virtual tour depiction potential was improved through active and passive sensing data fusion and 3D models generated from UAV data were evaluated in comparison with 3D models produced through data fusion. In conclusion, the limitations of the applied techniques in enhancing the potential of the virtual tour to represent objects were examined in terms of their advantages and the impact of object geometry on their effectiveness.*

Keywords: digital twin, terrestrial laser scanning, three-dimensional modeling, unmanned aerial vehicle, virtual reality

Introduction

Since the advent of computer graphics, the depiction of physical reality in a virtual environment has been the subject of considerable interest and study. Technological advancements gave rise to the development of advanced surveying methods and sophisticated three-dimensional (3D) modeling algorithms over time. Furthermore, the embrace of Industry 4.0 by industries and countries provides an opportunity to integrate digital twin and virtual reality (VR) concepts into existing business models, thereby offering the potential for enhanced flexibility, speed, productivity, and product quality (Rüßmann et al., 2015). The concept of a digital twin was first introduced at the University of Michigan by Grieves in 2003, at a time when digital representations of physical products were still in their infancy (Grieves, 2014). The concept of utilizing a digital twin of an individual aircraft as a tool for reengineering the estimation of aircraft structural life was first proposed in 2011 (Tuegel et al., 2011). The aim was to develop a method for predicting the remaining lifespan of an aircraft and for conserving its structural integrity, utilizing an ultrahigh fidelity model. The concept of the digital twin was later defined as an integrated multiphysics, multiscale, probabilistic simulation of an existing system that employs the most physically realistic models and sensor data to represent the corresponding physical twin, thereby mirroring its life (Glaessgen & Stargel, 2012). The demands of the Industry 4.0 revolution can be met through the implementation of novel architectural frameworks that facilitate a collaborative simulation environment between the digital twin and VR technologies, thereby enabling interaction with cyber-physical production systems in a digital environment (Havard et al., 2019). VR technology has been adopted in a number of fields, both for commercial purposes and for research purposes. Some of these include the documentation and preservation of cultural heritage sites (Cantatore et al., 2020), the training of professional staff (Mantovani et al., 2003), simulation modeling of a product line (Kibira and McLean, 2002), engineering and construction applications (Hilfert & König, 2016), architectural design (Abdelhameed, 2013), a supplementary educational tool (Izard et al., 2017) and virtual tour generation (Kyrlitsias et al., 2020).

Virtual tours allow users to engage with digital twins in an immersive manner. The generation of digital twins is achieved through the utilization of a range of methods, including the use of unmanned aerial vehicles (UAV) and terrestrial laser scanning (TLS). UAV systems can rapidly collect photos of investigated objects, providing 3D point clouds that are employed in the generation of digital twins (Levine & Spencer, 2022). TLS systems are employed for the collection of precise and dense 3D point clouds of the object, which in turn enables the generation of realistic digital twins (Grau et al., 2021). Nevertheless, in instances where non-flat or tall objects are present, the necessity for capturing convergent photos in addition to nadir ones may emerge, which could potentially complicate the flight planning process (Remondino et al., 2011). Furthermore, passive sensing sensor UAV systems with digital RGB cameras may prove inadequate for the acquisition of information from objects with roofs or from objects that are partially or fully obscured. While TLS systems are capable of providing highly precise information regarding building facades, their capacity for doing so is significantly diminished when applied to roofs or upper portions of non-flat objects (Arayici, 2007). Furthermore, the TLS method may be appropriate for smaller-scale projects, but due to the associated costs, it is not a viable option for larger-scale projects. In a comparative study by Mohammadi et al. (2021), the quality of digital twins of a bridge generated from UAV and TLS point clouds was evaluated, with the findings indicating that the TLS-based point clouds exhibited a higher point density and a better agreement with the as-is measurements. The fusion of TLS and UAV point clouds can be employed for the generation of digital twins. In a study by Van (2023), 3D CityGML models of mining structures were generated at different levels of detail (LoD) based on the UAV and TLS point cloud datasets, with UAV point clouds used to generate LoD 2 models and the fusion of UAV and TLS point clouds with greater detail and accuracy used to generate LoD 3 models. To generate a digital twin of Xuanluo Hall, Sichuan, China for Xiegong's architectural archaeological research Tan et al. (2022) employed a methodology that incorporated the UAV and TLS point clouds and Building Information Modelling (BIM) to apply a scan-to-BIM modeling approach.

The main objective of this study is to improve the depiction potential of the virtual tour created for the Gebze Technical University (GTU) campus using the fusion of active and passive sensing data namely UAV and TLS datasets. Furthermore, a comparison was made between 3D digital twins generated from UAV data and those generated from the fusion of UAV and TLS data. Finally, an evaluation of the advantages and limitations of UAV and TLS methods in improving the visualization potential of the virtual tour is carried out, taking into account the effect of object geometry.

Materials and Methods

The study area is the GTU campus, situated in Gebze, Kocaeli, Turkey. The campus is situated in close proximity to the borders of the Kocaeli and Istanbul provinces, and the topography is relatively flat. The GTU campus is situated in the environs of the Marmara Sea, with an approximate orthometric height of 10 m. UAV flights were conducted over the entire campus, which encompasses an area of approximately 2.5 km^2 and includes a range of land cover classes. In order to enhance the potential of virtual tour depiction within the GTU campus area, it is necessary to address the limitations of the UAV method, particularly in areas where the collection of information from lower parts of non-flat, tall objects, and forest understory is not possible. In light of the circumstances outlined above, TLS surveys were conducted with a particular focus on the aforementioned areas. The location of the GTU campus is illustrated in Figure 1.

Figure 1: Location of the GTU campus area.

UAV flights were conducted using a DJI Phantom 4 Pro V2.0 UAV, which was equipped with a RGB digital camera. TLS surveys were conducted utilizing a Leica RTC360 TLS system, which incorporates an integrated high dynamic range (HDR) spherical imaging system and a Visual Inertial System (VIS) for the real-time registration of point clouds. In order to meet the requirements for the generation of a digital twin, the scanning resolution was selected as 12 mm. Table 1 provides an overview of the features of the UAV and TLS equipment that were employed in this study. The methodology encompasses the acquisition of UAV and TLS data, geometric correction, point cloud generation, the data fusion process, the generation of a 3D digital twin, and the creation of a virtual tour. The generation of a digital twin utilizing UAV data entails the capture of aerial photos, the implementation of geometric correction, the generation of point clouds, and the generation of digital twins. The aerial photos were captured using Pix4Dcapture flight planning software in a variety of flight modes, including polygonal, double-grid, and circular. The undertaking of land reconnaissance in the study area proved beneficial in the planning stage of the UAV flight. In areas of dense vegetation, polygonal flights were employed, while in urban settings, double-grid and circular flights were conducted in accordance with the objective of ensuring optimal 3D modeling performance. The flights were conducted with a total battery flight time of 27 minutes, with a maximum of 18 minutes under safety precautions. In the case of polygonal flights, the camera angle was set to 90°. In contrast, for bundle-grid and circular flights, the camera angle was set to 70° in order to enhance the performance of 3D modeling in areas characterized by a high density of buildings. In order to generate a model of the buildings in the area, 36 photographs were captured in a circular flight pattern, with each photograph taken at a 10° interval. A total of 32 flights were conducted, resulting in the capture of 8333 aerial photos. In order to meet the necessary 3D modeling performance requirements, the front and side overlap ratios were selected as 80% and 60%, respectively. The features of the utilized UAV and TLS equipment are presented in Table 1.

Table 1: Features of the utilized UAV and TLS equipment.

DJI Phantom 4 Pro V2.0 UAV		**Leica RTC360 3D Laser Scanner**	
Weight	1375 g	Type	High-speed, pulse-based, high dynamic time of flight, Laser class 1
Max speed	S-mode: 20 m/s A-mode: 16 m/s P-mode: 14 m/s	Weight	5350 g
Max battery time	Nearly 30 min	Speed	Up to 2,000,000 points/s
Satellite positioning systems	GPS/GLONASS	Resolution	Selectable by user 3/6/12 mm @ 10 m
Camera sensor	1-inch CMOS 20-megapixel	Camera system	36-megapixel 3-camera system capturing 432-megapixel raw data for calibrated 360° x 300° spherical image
Image size	5472×3648 (3:2)	Field of view	360° (horizontal)/300° (vertical)
Gimbal angle range	-90° to +30° (Pitch)	Range	0.5 m-130 m
Hover accuracy range	Vertical: ±0.1 m (with vision positioning) ±0.5 m (with GPS positioning) Horizontal: ±0.3 m (with vision positioning) ±1.5 m (with GPS positioning)	Accuracy	Angular accuracy 18” Range accuracy 1.0 mm + 10 ppm 3D point accuracy 1.9 mm @ 10 m 2.9 mm @ 20 m 5.3 mm @ 40 m

The flight altitude was selected as 80 m, with a differentiating ground sampling distance (GSD) of ≤2.2 cm for the aerial photos, in accordance with the 8.6 mm focal length and 2.345 µm sensor pixel size. The geometric correction was performed using the Agisoft Metashape Professional software. During the geometric orientation process, the relative orientation of the aerial photographs was determined. The relative orientation process yielded a sparse point cloud comprising 73 million points. This sparse point cloud represents the initial product of the aforementioned process and serves as a preliminary model for the generation of a dense point cloud. A total of 86 ground control points (GCPs) were established, distributed in a homogeneous manner, and capable of representing the topography with high fidelity, for utilization in the absolute orientation process. The GCPs were constructed as polycarbonate mobile points, which can be installed and dismantled with minimal effort. In accordance with Equation 1, the absolute orientation was conducted with 86 GCPs and geometric accuracy, as indicated by the average root mean square error (RMSE), of ±2 cm (~0.9 pixels). In the equation, the calculated values are represented by $\hat{X}_i, \hat{Y}_i, \hat{Z}_i$, whereas the actual values are represented by X_i, Y_i, Z_i.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{X}_i - X_i\right)^2 + \left(\hat{Y}_i - Y_i\right)^2 + \left(\hat{Z}_i - Z_i\right)^2}{n}} \tag{1}$$

A dense point cloud was generated through the utilization of depth maps, which were obtained through the extraction of depth information from aerial photographs. The dense point cloud comprised approximately 1.5 billion points, which were filtered manually and automatically using the Terrasolid module of Microstation software to remove noisy points. Utilizing the dense point cloud, 3D mesh models were generated and the number of mesh faces or triangles was reduced to 430 million due to the considerable volume of polygonal data. In conclusion, high-resolution textures were generated from aerial photos and applied to 3D mesh models. The TLS method has the potential to generate high-quality digital twins of objects of any size, including those as small as a few centimeters, by employing close-range scans. This study demonstrates that TLS plays an instrumental role in the generation of accurate digital twins through the process of data fusion. The following sections present a detailed examination of the methodologies employed at each stage of the TLS methodology, namely data acquisition, geometric correction, the generation of dense point clouds, and the generation of digital twins. In the data collection phase, the objective is to obtain dense point clouds by scanning areas that are not discernible by optical UAV technology and encompass approximately 5000 m^2 of the GTU campus. Given the intention to integrate the TLS data collected in the study area with the dense point cloud generated by the UAV technique, the objective is to produce colored point clouds. To ensure the integrity and consistency of the data obtained from the fusion of the two sources and to mitigate potential resolution-dependent inconsistencies in the point cloud-mesh conversion, the scanning resolution was set at a minimum of 12 mm. In light of the necessary specifications, the selected study area, and the estimated length of the fieldwork, the Leica RTC360 terrestrial laser scanner was determined to be the most suitable device for the acquisition of TLS data. With a capacity of 2 million dots per second at the maximum resolution, the device is capable of rapid and precise data acquisition through the cloud-to-cloud method, utilizing three high dynamic range (HDR) cameras and an integrated inertial measurement unit (IMU) with embedded imaging systems. The 12 mm resolution, color mode, and Visual Inertial System (VIS) were employed with great efficacy throughout the course of the surveys. The TLS surveys were commenced from the locations of the initial station points, which had been determined through preliminary land reconnaissance. The scanning duration at each station was approximately one minute and twenty seconds, contingent upon the 12 mm spatial resolution and color scanning parameters. The TLS raw data acquired as a product of the surveys was stored on the portable memory device, which had a storage capacity of 256 GB. The project file, which also recorded the relative positions and orientations of the stations, was imported into the data processing software in a pre-merged format. The data acquired through the utilization of the terrestrial laser scanner were subjected to processing in the Leica Cyclone Core 2021.1.0 software, which offers a high degree of compatibility with the device and a high data processing capacity, thus providing a foundation for extensive point cloud evaluation studies. All procedures associated with the combination, filtering, and transformation of the point cloud were conducted within the same software environment, after which the data was exported for subsequent analysis. As previously outlined, the raw laser scanning data obtained from the field surveys underwent a process of consolidation and transfer into a database constructed in Cyclone. In the pre-merging phase, the point clouds derived from TLS measurements are automatically aligned through the utilization of a video-enhanced inertial unit. This unit employs real-time tracking of the scanner's movement between station installations, based on the VIS. The neighboring stations in the database, created in accordance with the cloud-to-cloud merging approach, were analyzed in pairs using the Visual Alignment tool. This facilitated the identification of the necessary translation and rotation updates, which were then implemented manually. Subsequently, each corrected scan pair was subjected to iterative cloud-to-cloud merging with the automatic alignment tool. Upon completion of the process, each pair of neighboring stations was merged with a high degree of precision. Once all adjacent station pairs had been merged with one another, an additional iterative merging process was commenced, covering the entirety of the project. The aim of this process was to improve the precision by aligning stations that were not adjacent and had not been subjected to manual alignment. The cloud-to-cloud merging method may potentially lead to the inadvertent omission of breaks and folds that may arise between stations, as such occurrences are not identified in the merging reports. As the approach is an unsupervised merging method when employed in a standalone capacity, it is of the utmost importance that all data are subjected to visual geometric quality control checks. In order to accurately assess the geometric characteristics of the data set, a series of sections were extracted along the various axes, with the objective of identifying instances of misalignment. Once the misalignments had been identified, they were corrected through the application of manual merging techniques in conjunction with iterative automatic alignment procedures. As a result, the point clouds derived from the TLS stations were orientated through the application of the cloud-to-cloud method, with an average root mean square error (RMSE) of 6 mm.

The device is capable of recording any object within its designated scanning area, irrespective of its size or speed. These include moving vehicles and even living creatures. The presence of these objects results in the generation of noise within the resulting point cloud. The aforementioned superfluous data were subsequently removed from the point cloud through the implementation of automated and manual filtering techniques. In some instances, the Leica Cyclone is capable of detecting these objects through the utilization of automated methodologies. However, as the automatic filtering methods were found to be inadequate, manual filtering was employed to remove the remaining unwanted data. All extraneous noise was transferred to a new layer within the Cyclone, where it was then subjected to further examination, verification, and deletion from the project. Upon completion of the data processing stage, the final TLS dense point clouds were exported in the E57 file format. The colored, dense point clouds derived from optical UAV and TLS data, which underwent geometric correction and filtering, were subjected to fusion following verification of their coordinate systems and datums. The process is based on an affine transformation and four tie points were utilized. The average RMSE of the tie points was obtained as ±3.8 cm. A further visual examination was carried out on the newly generated point cloud, resulting from the preceding fusion process, and any residual noise was then removed. The resulting cloud exhibits a markedly increased density and a substantially enhanced capacity for depiction when compared to the independently obtained clouds generated through the utilization of UAV and TLS methods. The RMSE of the tie points in the X, Y, and Z directions and the total RMSE of the tie points are given in Table 2.

Table 2: The RMSE of the tie points in the X, Y, and Z directions and the total RMSE of the tie points

Tie Point Number	**X RMSE (m)**	**Y RMSE (m)**	**Z RMSE (m)**	**Total RMSE (m)**
1	0.016	-0.010	0.006	0.019
2	-0.014	-0.016	-0.010	0.023
3	0.001	-0.041	0.012	0.043
4	-0.003	0.067	-0.008	0.068

The oriented fusion cloud, obtained as a result of the preceding process, was used as the source for the generation of 3D textured mesh models in Agisoft Metashape, thus facilitating the generation of digital twins. A digital twin was generated through the fusion of optical UAV and TLS dense point clouds, which was then employed to develop a 3D virtual tour of the study area. The virtual tour was created using the Unity game engine, a proprietary software platform for the development of video games. The process of creating a virtual tour comprises several stages. Initially, the digital twin must be transferred to the Unity environment. This is followed by the implementation of environmental adjustments and the application of rendering optimization algorithms. Subsequently, the initial player application is configured, and the executable game file is prepared for use. The precise digital twin, generated using Agisoft Metashape, was subsequently exported to the Wavefront OBJ data format, which is compatible with the Unity game engine. This format is the generally preferred option for 3D model exporting due to its capacity for the inclusion of both point coordinates and polygonal data.

Additionally, these characteristics render the format compatible with a multitude of 3D computer-aided design (CAD) software applications (Kato & Ohno, 2009). In the Unity game engine, a crucial aspect is the creation of a material that incorporates the lighting texture and properties inherent to the shader object, as this enables the display of imported textures in conjunction with 3D digital twin models. In order to modify the materials that had been created, the inspector window properties were employed. To attain a realistic and higher-resolution representation of the digital twin, it was necessary to select the shader type as unlit/texture. Furthermore, the maximum size of the textures was set to 16384 x 16384 in order to achieve optimal visual fidelity. In order to enhance the realism of the virtual tour, several three-dimensional objects were incorporated into the environment, including lighting poles, trees, benches, gazebos, and tables. The considerable data volume of the high-resolution digital twin necessitated the incorporation of rendering optimization algorithms, such as occlusion culling, within the Unity game engine. This process permitted the virtual tour to identify and acknowledge solely the visible regions, thereby avoiding any potential overloads, freezes, and slowdowns on the computer during the tour that might have resulted from the processing of data from the invisible areas (Coorg & Teller, 1997). Thereafter, a Windows-compatible executable file was generated for the 3D virtual tour application developed in Unity (Sefercik et al., 2022). During the generation of the executable, the optimal quality settings for the graphical options were selected to optimize the rendering of the generated application.

Results and Discussion

Instances of the UAV and TLS point clouds of the study area are illustrated in Figure 2. UAV point cloud, generated from aerial photos taken at an average GSD of ≤2.2 cm from an altitude of 80 m can represent the top surfaces of objects and, thanks to the oblique camera view, the side surfaces of objects with a high accuracy.

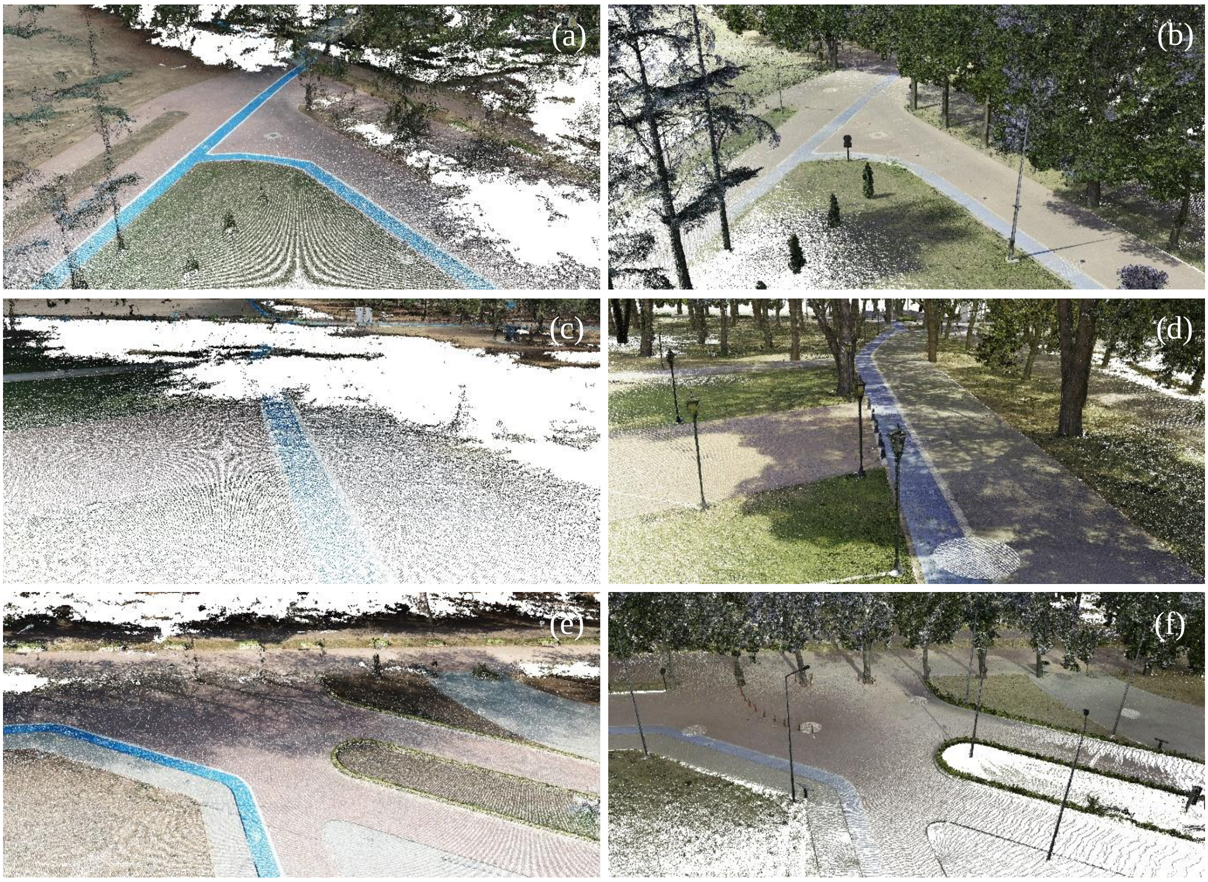

Figure 2: Instances of the UAV (a) (c) (e) and TLS (b) (d) (f) point clouds of the study area.

However, it should be noted that this does not apply to vegetation penetration capabilities. Such obstacles include dense forest cover and non-flat objects that are not discernible from an aerial perspective. This serves to illustrate the constraints of optical UAV technology. It is clear that the mobile TLS technique represents an invaluable tool in surmounting the inherent constraints of optical UAV technology. The integration of data from disparate sources can facilitate the acquisition of comprehensive, detailed information in areas where conventional optical UAV technology is limited. Conversely, optical UAV technology provides the advantage of delivering high-resolution data on elements that are essential for digital twins, such as tree crowns, where TLS is limited and can only be acquired through a top-down perspective. As a result, in the context of the fusion application, the strengths of both techniques serve to reinforce one another, thereby producing a digital twin of considerable quality and realism. The lack of data obtained from under-tree areas using the UAV method leads to a deficiency in points that can be used to accurately represent objects in the UAV dense point cloud. Nevertheless, in TLS dense point cloud areas beneath tree canopies, effective scanning can be conducted, thereby enabling the collection of relevant data and facilitating the production of precise digital twins. Digital twins generated from the UAV point cloud and digital twins generated from the fusion of the UAV and TLS point clouds are shown in Figure 3.

Figure 3: Digital twins generated from the UAV point cloud (a) (b) (c) and digital twins generated from the fusion of the UAV and TLS point clouds (b) (d) (f)

The digital twin generated from the UAV dense point cloud showed significant inaccuracy in areas under the canopy that were obstructed from the view of the digital camera during the flight. The digital twin obtained by fusing UAV and TLS dense point clouds represented the same area with higher accuracy and fewer discrepancies than the UAV digital twin, making it highly suitable for use in VR.

Conclusion and Recommendation

The generation of digital twins can be achieved through the utilization of a range of methods, including UAV and TLS. Each of these approaches possesses distinctive advantages and disadvantages. The advent of Industry 4.0 has led to a surge in interest in concepts such as VR and digital twins across a range of industries. The combination of VR technology and digital twins can be harnessed to create applications such as virtual tours. The generation of digital twins employs a variety of methods, including UAV and TLS. In this study, a virtual tour of the GTU campus was created utilizing the UAV and TLS methods. This study sought to improve the virtual tour depiction potential of the GTU campus by fusion of active and passive sensing data. A comparative analysis was conducted between digital twins generated from UAV point clouds and those generated from the fusion of UAV and TLS point clouds. The findings revealed that the UAV and TLS fusion digital twins depicted objects with correct geometry and greater detail. The virtual tour can be utilized to disseminate information to students and visitors regarding the campus environment and buildings. Moreover, the generated virtual tour and digital twins can be employed for a variety of purposes, including the accurate calculation of metrics, the development of intelligent campus applications, BIM studies, and the establishment of information systems.

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