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A Review on Challenges and Advancements in Photorealistic 3D Modeling and Visualisation

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Abstract: *This research delves into the main challenges of generating 3D models from ground-based photographs and proposes potential solutions. Close-range photogrammetry has traditionally relied on manual or automated image measurements for accurate 3D modelling. While 3D scanners have gained popularity as a data source in various applications, image-based modelling remains the most comprehensive, cost-effective, portable, adaptable, and widely employed technique. This paper presents a comprehensive pipeline for creating 3D models using terrestrial image data, encompassing various approaches and analysing each step involved. The study explores the entire process, from data acquisition to model generation, highlighting the different techniques and methodologies employed to ensure precise and detailed 3D representations. By examining the strengths and limitations of existing approaches, this research aims to contribute to advancing 3D modelling techniques using terrestrial photographs.*

Keywords: 3D modelling, Terrestrial image, Photogrammetry

I. INTRODUCTION

The complete three-dimensional (3D) modelling process involves acquiring data and creating an interactive virtual model on a computer. While many people consider 3D modelling as converting a measured point cloud into a mesh or textured surface, it encompasses a broader object reconstruction process. The field of 3D modelling is extensively studied in the graphic, vision, and photogrammetric communities. It plays a crucial role in various applications, such as inspection, navigation, object identification, visualisation, and animation. Additionally, it has gained significant importance in cultural heritage digital archiving, serving purposes such as documentation, virtual tourism, museum preservation, education, and risk-free interaction.

Numerous requirements are specified for different applications, including digital archiving and mapping. These requirements include high geometric accuracy, realistic results, detailed modelling, automation, affordability, portability, and flexibility of the modelling technique. However, selecting the most suitable 3D modelling technique to fulfil all these requirements for a specific application is often challenging. Digital models are now ubiquitous and accessible online, even on low-cost computers. While creating a simple 3D model may seem straightforward, generating a precise and photorealistic computer model of a complex object still demands substantial effort.

The classification of 3D object measurement and reconstruction techniques can be broadly divided into contact methods (e.g., coordinate measuring machines, callipers, rulers, or bearings) and non-contact methods (such as X-ray, SAR, photogrammetry, and laser scanning). This paper will focus on modelling from reality rather than creating artificial world models using computer graphics and animation software like 3DMax, Lightwave, or Maya. These software packages, which allow subdivision and smoothing of geometric elements using splines, are primarily used in movie production, games, architecture, and object design.

Presently, the generation of 3D models primarily relies on non-contact systems based on light waves, particularly active or passive sensors. Additional information derived from CAD models, measured surveys, or GPS may also be integrated with the sensor data in some applications. Active sensors provide range data containing the necessary 3D coordinates for generating a mesh. On the other hand, passive sensors produce images that require further processing to derive 3D object coordinates. Once the measurements are obtained, the data must be organised, and a consistent polygonal surface is created to construct a realistic representation of the modelled scene. In order to enhance the visual appeal, the virtual model can be textured using image information, resulting in a photorealistic visualisation.

Considering active and passive sensors, four distinct object and scene modelling methods currently exist: (1) Image-based rendering (IBR). This technique does not involve generating a geometric 3D model but instead focuses on creating virtual views of 3D environments directly from input images. Successful implementation of IBR requires accurate knowledge of camera positions or performing automatic stereo-matching, which relies on a large number of closely spaced images in the absence of geometric data. However, object occlusions and discontinuities can affect the output, especially in large-scale and complex environments. The freedom to move within the scene and view objects from any position may be limited depending on the method used. Therefore, IBR is typically employed in applications that require limited visualisation.

II. RELATED WORKS

Li, Jia, Sheng, Yehua, Duan, Ping, Zhang, Siyang, and Lv, Haiyang (2014) proposed a cost-effective and efficient method for constructing 3D models. The process involves capturing a 360-degree scene of the object using photographs, uploading the images to a cloud-based platform, and utilising cloud computing power for registration and conversion into a 3D model. This approach eliminates the need for a complex customer modelling strategy. By taking multiple photos of the subject and performing simple settings, a realistic 3D model can be obtained.

Kim, Hyungki, and Han, Soonhung (2018) developed a 3D building modelling technique that combines geospatial data, photography, and facade components. This approach utilises ground-based images and geospatial data from aerial surveys to generate high-quality 3D models. The proposed method involves tilt adaptation, 3D model generation, geo-registration of images, and structure and shape evaluation. The study demonstrates the technique's effectiveness through quantitative evaluations and real-world modelling scenarios.

Kawai, Masahide, Iwao, Tomoyori, and Maejima et al. (2015) introduced a technique for creating highly photorealistic 3D mouth animations synchronised with speech movements. The method utilises frontal images and small-scale details to reconstruct the teeth and tongue. By combining 3D reconstruction with 2D image processing, the proposed approach achieves photorealistic internal mouth appearances using minimal input information. The technique significantly improves the realism of individualised animations.

Heindl, Christoph, Akkaladevi, Sharath, and Bauer, Harald (2016) developed a method for creating real-time 3D models of people using RGB-D sensors. The approach focuses on capturing both geometry and textures of the models efficiently. The study compares the performance and visual appeal of the proposed technique using synthetic and real-time data.

Erving, A., Rönnholm, Petri, and Nuikka, Milka (2020) explored the challenges and opportunities in creating 3D virtual models using different data sources, such as photogrammetry and laser scanning. The study utilised LandXplorer Studio Professional software for data integration and model creation. The final model included ground surfaces, roads, street structures, buildings, and vegetation. The research highlights the complexity of the 3D modelling process when integrating various datasets.

Chen, C., Bolas, M., and Rosenberg, E. S. (2017) presented a comprehensive pipeline for capturing, processing, and delivering 3D virtual models from a single RGB-D camera. The approach involves replicating mathematical models, and camera poses from RGB-D image sequences, enabling continuous model delivery based on the user's head-mounted display (HMD) position. The pipeline produces high-quality 3D models suitable for virtual reality applications, particularly when viewing objects from different perspectives.

Kheyfets, L., Vasilieva, V. N. (2017) focused on improving graphic techniques for creating and analysing photorealistic images. The paper discusses the creation of specific objects using mathematical operations and automated graphical data processing. The study demonstrates the application of the proposed techniques in engineering design and educational contexts.

Alfarhan, Mohammed, Alhumimidi, Mansour et al. (2020) highlighted the applications of 3D photorealistic digital models (3DPMs) in communicating authentic artefacts and settings to a global audience. The study emphasises the cost and time efficiency of 3DPMs for various purposes, such as oil and gas exploration, virtual field trips, and educational purposes. The research introduces techniques for creating high-resolution 3DPMs using LiDAR and photographic data, reducing the effort and resources required for on-site visits.

Nebel, Steve, Beege, Maik, Schneider, Sascha, and Rey, Günter Daniel (2020) discussed the challenges and fundamental knowledge required for creating photorealistic 3D models. The paper provides an overview of photogrammetry and its applications in generating realistic virtual content. It also explores the potential uses and challenges of photorealistic 3D models in educational contexts.

Lo Castro, Dario, Tegolo, Domenico, and Valenti, Cesare (2020) categorised the techniques for generating visually-based images into anatomical eye models and deep learning processes. The paper uses minimal morphometric data to generate high-quality fundus images for eye-related pathologies and diseases. The proposed method relies on efficient vessel placement without requiring actual morphometric data, achieving accurate and detailed representations of anatomical properties.

Chistyakov, Andrey, Shabiev, and Salavat (2018) explored using interactive perception and virtual reality systems for architectural projects. The research aimed to determine the most effective rendering techniques for continuous photorealistic images. The study focused on illumination strategies and their combination with other techniques to achieve realistic and real-scale representations of architectural environments.

III. PROBLEM STATEMENT

This study aims to address various challenges encountered in object reconstruction. Each step of the reconstruction process presents different problems that must be resolved. The first step involves acquiring images, and it is crucial to determine the most effective approach for image acquisition. Once the images are obtained, proper organisation and precise projection of the images need to be carried out. The accuracy of the image projection can be improved by testing and refining the parameters of the rotational positions with the help of pack equitable adjustments.

One of the major challenges when working with voxels is the high memory requirements, as voxels consume a significant amount of memory. Therefore, defining the voxel 3D cube to approximate the region of interest is essential while optimising memory usage. Since colour images are used instead of grayscale images, effectively leveraging the colour information is important. Existing image-matching algorithms can be evaluated for colour image matching.

The volume fusion technique results in an estimated shape of the object, but it may introduce additional voxels in the inner regions. Algorithms must be explored to accurately identify and remove these additional voxels in the critical regions. Recovery of visibility information is another crucial problem that needs to be addressed. It is essential to determine whether a specific voxel is visible from a particular viewpoint. This information is particularly important for image organisation, as voxels should only connect similar regions on the actual surface of the object. Additionally, the sensitivity of a voxel needs to be accurately calculated. Challenges arise when determining the visibility of an interested voxel and outputting a line.

Line tracing plays a significant role in several steps of the reconstruction process. However, the process of mapping a line of sight can be tedious. It is necessary to define a precise geometric containment to trace the line within the defined voxel field. Another challenge arises from the different viewpoints considered during image synchronisation. Proper consideration of the slave fix is crucial for distortion compensation, improving the reliability and robustness of image coordination. The digressive surface of a voxel also poses challenges that need to be addressed.

IV.PHOTOREALISTIC MODELS OF OBJECTS USING IMAGES

Object detection in computer vision involves identifying and measuring the 2D bounding boxes of specific objects in an image. Convolutional neural networks (CNNs) have been the standard approach for handling this task. Training CNN models requires many annotated real-life images, which can be costly and time-consuming. Computer graphics techniques have been used to synthesise images for various computer vision tasks to alleviate the need for massive amounts of real-life data. However, models trained solely on synthetic images often show a significant drop in performance when evaluated on real images.

One approach to bridge the gap between synthetic and real imaging is through domain adaptation techniques that aim to reduce the domain shift. These techniques assume that certain spatially invariant representations hold across different domains or transfer pre-trained models from one domain to another. Another line of research focuses on synthesising visually more realistic images to reduce the domain gap. It has led to the consideration of physically-based rendering techniques.

Physically-based rendering techniques, such as Arnold, accurately simulate the propagation of light energy throughout a scene, capturing complex lighting effects like diffuse and specular interreflection, dispersion, refraction, and reflection. The rendered images are highly convincing and difficult to distinguish from real images. On the other hand, rasterisation rendering techniques, such as OpenGL, can approximate complex effects using custom shaders, but these approximations can introduce artefacts that are challenging to remove. Traditionally, physically-based rendering has been slower than rasterisation, but recent advancements, such as the Nvidia RTX ray-tracing technology, have significantly improved rendering speed.

This study explores the training of Faster R-CNN, a CNN-based object detector, using exceptionally photorealistic synthetic images. We propose a technique that combines three main ingredients to synthesise these images. Firstly, we create 3D object models and simulate natural materials and illumination for six indoor scenes. Secondly, we generate a realistic geometric structure by utilising physics-based simulations of objects and the camera within the scene. Finally, we employ physically-based rendering techniques to achieve high graphic realism in the synthesised images.

CONCLUSION

In the field of close-range applications, numerous methods have been explored for capturing, processing, and visualising 3D information from photographs. Image-based modelling (IBM) offers several advantages over laser scanning, including portability and affordability of sensors and the ability to accurately recover 3D information regardless of the object's size. Although IBM can produce precise and realistic models, sometimes comparable to those obtained through laser scanning, it remains highly interactive as many automated methods have not been thoroughly tested in practical scenarios. Furthermore, automated IBM struggles to capture details on unmarked or featureless surfaces without assuming their contours. Consequently, developing geometrically accurate and comprehensive 3D models for complex objects remains a challenging and active area of research.

Full automation for generating accurate, comprehensive, and photorealistic 3D models of medium- and large-scale objects in real-world settings is still a distant goal. It is challenging to select automated procedures for practical applications due to the difficulty in properly evaluating their effectiveness. However, semi-automated techniques are recommended, where humans perform tasks that they can easily complete, such as seed point extraction and topological surface segmentation. At the same time, computers handle tasks best suited for them, such as feature extraction, point correspondence, image registration, and modelling of segmented regions.

There are still many challenges to overcome in accurately transforming a measured point cloud into a realistic 3D polygonal model that meets the requirements of advanced modelling and visualisation. Existing commercial “reverse engineering” solutions often fail to generate correct meshes without dense point clouds, leading to longer mesh creation and modification times than point measurement. In computer graphics, ongoing research addresses geometric and radiometric distortions that affect interactive visualisation, rendering speed, photorealism, and visual quality. The size and complexity of detailed models often hinder achieving photorealism and smooth navigation within current computer and graphics hardware without simplification techniques or innovative rendering approaches like level of detail (LOD) control. While hardware capabilities continue to improve, model sizes are growing rapidly to satisfy the demand for realistic visualisations.

In conclusion, the field of 3D modelling and visualisation is still evolving, and further advancements are needed to overcome the challenges in generating accurate and realistic models. Continued research and development in automated and semi-automated techniques and advancements in hardware capabilities will contribute to the progress and application of 3D modelling in various industries and fields.

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