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ARAŞTIRMA MAKALESİ/RESEARCH ARTICLE

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From photogrammetric modeling to augmented application of a quarry

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Abstract

The study presents a methodological approach for a pipeline from three-dimensional photogrammetry model generation by an Unmanned Aerial Vehicle (UAV) to an Augmented Reality (AR) application development in a quarry. Initially, a high precision 3D model of a real quarry pit was generated using the imagery of a non-RTK UAV. After scanning the area, the successive photographs taken by the drone were processed by using a photogrammetry software application to build a mesh that was optimized to 50,000 polygons. It was later developed into an interactive holographic application with the Unity engine and Vuforia platform. Two AR tracking paradigms, namely Image Target and Ground Plane were generated and tested on both mobile platforms and Microsoft HoloLens 2 device. In a system evaluation conducted by a group of 17 students and 12 academics who tested the application, a minimum average score of 85 and 90 relatively, out of 100 were given in terms of spatial understanding. This perspective was framed within the context of increased memorability, positive contribution to learning, more enjoyable learning, improved educational quality, and the widespread adoption of such applications. Academicians' outcomes related to the practices included in the study were found to be more positive and this qualitatively supports the educational effectiveness of the system. Additionally, it is observed that there is a trade-off between geometric accuracy and real-time rendering execution on mobile platforms. It was concluded that the Ground Plane method provides a workable material for a high-fidelity digital shadow, which can be applied to remote inspection. Additionally, it is foreseen that AR applications executed on smartphone/tablet and HoloLens 2 have infrastructurally potential to enhance the level of engineering, planning and control process and support mine-safety.

Keywords: AR; photogrammetry; 3D model; quarry

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Bir Taş Ocağının Fotogrametrik Modellemesinden Artırılmış Gerçeklik Uygulamasına

Öz

Bu çalışma, bir taş ocağında İnsansız Hava Aracı (İHA) tarafından üç boyutlu fotogrametri modeli oluşturulmasından Artırılmış Gerçeklik (AR) uygulaması geliştirilmesine kadar uzanan bir süreç için metodolojik bir yaklaşım sunmaktadır. Başlangıçta, gerçek bir taş ocağı çukurunun yüksek hassasiyetli 3D modeli, RTK olmayan bir İHA'nın görüntüleri kullanılarak oluşturulmuştur. Alan tarandıktan sonra, dron tarafından çekilen ardışık fotoğraflar, 50.000 poligona optimize edilmiş bir ağ oluşturmak için bir fotogrametri yazılım uygulaması kullanılarak işlenmiştir. Daha sonra, Unity motoru ve Vuforia platformu ile etkileşimli bir holografik uygulamaya dönüştürülmüştür. Görüntü Hedefi ve Zemin Düzlemi olmak üzere iki AR izleme paradigması oluşturulmuş ve hem mobil platformlarda hem de Microsoft HoloLens 2 cihazında test edilmiştir. Uygulamayı test eden 17 öğrenci ve 12 akademisyenden oluşan bir grup tarafından yapılan sistem değerlendirmesinde, mekansal anlama açısından 100 üzerinden sırasıyla en az 85 ve 90 ortalama puan verilmiştir. Bu bakış açısı, artan akılda kalıcılık, öğrenmeye olumlu katkı, daha keyifli öğrenme, iyileştirilmiş eğitim kalitesi ve bu tür uygulamaların yaygın olarak benimsenmesi bağlamında çerçevelenmiştir. Çalışmaya dahil edilen uygulamalarla ilgili akademisyenlerin sonuçlarının daha olumlu olduğu ve bunun sistemin eğitimsel etkinliğini niteliksel olarak desteklediği bulunmuştur. Ek olarak, mobil platformlarda geometrik doğruluk ve gerçek zamanlı işleme arasında bir denge olduğu gözlemlenmiştir. Zemin

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Düzlemi yönteminin, uzaktan denetim için uygulanabilecek yüksek doğruluklu dijital gölge için işlevsel bir malzeme sağladığı sonucuna varılmıştır. Ayrıca, akıllı telefon/tablet ve HoloLens 2'de yürütülen AR uygulamalarının, mühendislik, planlama ve kontrol süreçlerinin seviyesini yükseltme ve maden güvenliğini destekleme potansiyeline sahip olduğu öngörülmektedir.

Anahtar kelimeler AR, Fotogrametri, 3B Model, Taş Ocağı

1.Introduction

The mining sector faces significant challenges in its operation such as inadequate facilities to protect the safety of the workers, poor working performance measures, and the limited ability to conduct remote surveillance in dangerous settings [1]. Virtual Reality (VR) and Augmented Reality (AR) technologies are revolutionary solutions to these issues as they can be used to simulate, monitor, train, and manage mining operations remotely, as well as in safe places, exchange information on hazardous activities without placing humans in dangerous conditions [2].

AR and VR have become invaluable resources to create safe training conditions and enhance awareness of the situation during the active mining activities. The combination of the technologies makes use of real-time data, the three-dimensional maps, and the cloud computing platforms to assist with mine planning, equipment tracking, and remote operation of the machinery [2]. They are usually used together with drones' platforms, LiDAR technology, and AI-based computer vision to streamline the workflow of surface mining and control such operations as dragline excavation [2].

With the digital transformation of the mining sector, the use of immersive technologies becomes one of the elements of this change [3]. AR and VR enable operators to be trained in simulated hazardous conditions that do not pose physical danger, and predictive maintenance is possible due to information-based choices that eliminate system failures [4]. Similar to the modern world, technology is an integral component of the mining industry, since it requires regular machines to perform their tasks. Therefore, AR and VR have already become an inseparable part of typical workflows and offer considerable convenience and efficiency [4].

These technologies allow the development of a high-fidelity digital shadow, a dynamic virtual reflection that enables field workers to intuitively understand complex site conditions [33]. They are used as very important tools to prevent accidents and to reduce the operational time in areas which are at high risk like those which are vulnerable to gas leak or unstable ground. Additionally, VR and AR platforms can allow users to perform complex operations with a lot of accuracy, such as geological modelling, optimization of blast patterns, and maintenance of equipment. These improvements lead to better recovery of resources as well as the minimization of waste.

The mining sector is currently transitioning from Mining 4.0 to a more human-centric Mining 5.0 paradigm, where virtual technologies are leveraged to enhance safety and sustainability [48]. Recent research highlights the transformative potential of Digital Twins in managing complex quarry operations through real-time data integration [49,50]. Furthermore, immersive technologies like the HoloLens 2 have emerged as critical tools for vocational training; specifically, augmented reality systems now provide interactive 3D guidance for heavy equipment operators (e.g., bulldozers and excavators), significantly reducing operational risks and improving training efficiency in surface mining [51, 52]. This shift toward a 'Mining Industrial Metaverse' allows for precise object detection and positioning within a georeferenced virtual environment [53].

In this regard, the current research suggests the integrated workflow that will fill the gap between the raw field data and the immersive visualization. This research approach will imply the creation of a high-precision photogrammetric 3-D model of a quarry using UAV and the conversion of the model in an interactive experience of a holograph using the Unity game engine with the Vuforia AR platform [31]. Two different AR solutions, Image Target and Ground Plane were assembled and deployed to the mobile devices and the Microsoft HoloLens 2. The relevance of the study is that it establishes a cost-efficient pipeline of creating interactive three-dimensional models and digital shadows of mining sites. This method will provide significant technological benefits in remote location evaluation, improve safety training through immersion learning, and promote better decision making in mine-planning activities since it allows engineers and trainees to see and engage with the quarry model in real world conditions.

The rest of the present paper is organized in the following way: Section 2 provides a targeted review of the AR and VR technologies in mining. Section 3 outlines the methodology, including photogrammetric modelling and development of AR applications. Section 4 demonstrates the results of user evaluation and comparative analysis of the devices. Lastly, the conclusions and recommendations are provided in Section 5.

2. Theoretical background

2.1. Ar and vr technologies

AR and VR have evolved much beyond their initial purposes as means of entertainment and become key elements of the Industry 4.0 paradigm. They continue to remain the leading industrial trends driving the digital revolution in various areas [6,20,21]. Unlike VR, which completes the user into an artificial world, AR incorporates digital superimposition on the real-life view of the user, thus creating a smooth unity between the physical production space and the virtual content, which does not replace the real world, but only enhances the perceptual experience of the user [7].

It can be summarized that the interdependence between AR and VR is summarized in the Reality-Virtuality Continuum proposed by Milgram and Kishino [14] (Fig. 1). It is a continuum that defines a transition between completely real worlds to completely

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simulated worlds and highlights the unique but complementary roles of AR and VR [15]. In the context of Industry 4.0, digital representations are classified by their data integration levels: Digital Model (no automated data flow), Digital Shadow (one-way automated flow from physical to digital), and Digital Twin (bidirectional automated flow) [33, 34]. Since the current study uses photogrammetric data for visualization without real-time bidirectional IoT communication, the system is considered a high-fidelity digital shadow or an interactive 3D model [35, 36].

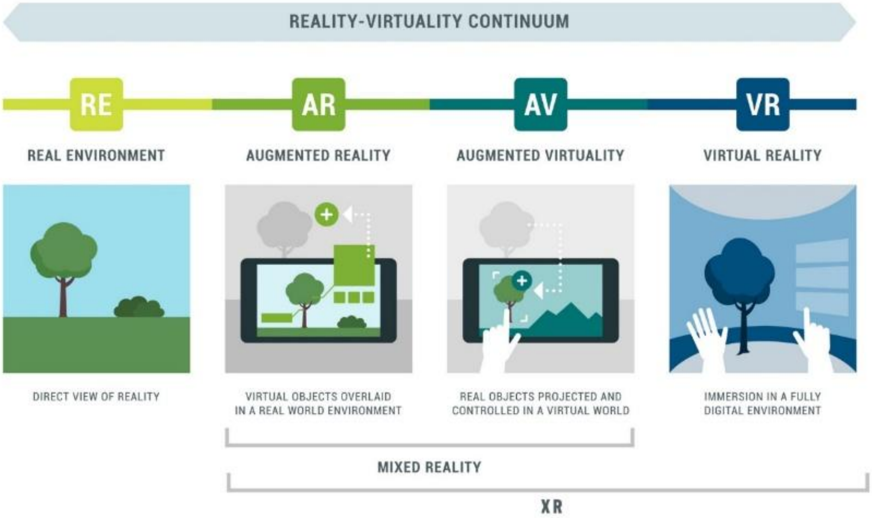

Fig. 1. Example of the augmented reality-virtuality continuum [15].

In the modern social and business environment, AR and VR serve a variety of purposes, providing strong convenience and performance [4]. Particularly in the learning context, AR has spawned novel ways of pedagogy whereby learners can experience the physical artefacts, in a manner that directly and tangibly leads to higher motivation, fun and self-directed learning abilities [5,25].

2.2. Applications in the mining industry

Immersive technologies are increasingly becoming part of the mining industry and forming the foundation of the digital transformation agenda. This development helps alleviate acute problems such as poor safety of workers, unsafe working environments, and complex servicing of advanced machinery [3,28]. AR and VR provide radical solutions, creating safe, simulated training parameters and training the staff to retrieve vital information through wearable devices, even in situations of negative exposure, including power outage or emergency situations [8].

The main use of AR in the mining industry is in safety training and hazard reduction. Operational hazards including possible cave-ins, contact with poisonous vapor or equipment malfunctions, are often too dangerous or complex to be faithfully reproduced in the standard classrooms [17]. The efficacy of AR and VR instruments in promoting the efficacy of safety training is proven by empirical research by Lampropoulos et al. [3,27] and Singh et al. [2], which indicates that they have a significant positive impact on such training compared to the traditional methods. The technologies allow the operators to practice the control and maintenance of the heavy machinery in a virtual setting, which eliminates the risk of equipment destruction and physical injuries when acquiring skills [18].

Recent advancements in UAV photogrammetry between 2024 and 2026 emphasize the importance of Real-Time Kinematic measurements for direct georeferencing. Studies have shown that RTK-equipped UAVs can achieve centimeter-level accuracy, with flight altitude and the strategic distribution of Ground Control Points playing a decisive role in final photogrammetric precision [54, 55]. Comparative evaluations of RTK-GNSS and multispectral UAV surveys confirm that these high-fidelity topographic mappings are essential for the construction of accurate digital twins in quarrying and extractive industries [56].

In addition to training applications, unmanned aerial vehicles converging with LiDAR and AR allow building so-called high-fidelity digital shadows in the form of dynamic and high-resolution three-dimensional reconstructions of sites [19,26]. These digital twins are the pillars of key processes, such as mine planning, dragline excavation surveillance, and waste disposal management by providing real-time data visualisation [2,29,31-32]. For example, 3D computer-vision algorithms powered by artificial intelligence can handle LiDAR point clouds obtained from drone surveys to perform automated terrain measurements and, therefore, optimise dump-disposal operations and increase the efficiency of the operational process through digitised workflows [22-24].

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3. Methodology

The pipeline followed in the study consists of the following stages: field scanning with a UAV, photogrammetric modeling, importing into a Unity project, deploying Image Targets and Ground Plane applications in Android format (APK) using the Vuforia engine for augmented reality, and deployment to the MS Hololens 2 device using Unity Universal Window Platform + Visual Studio C# (Fig. 2).

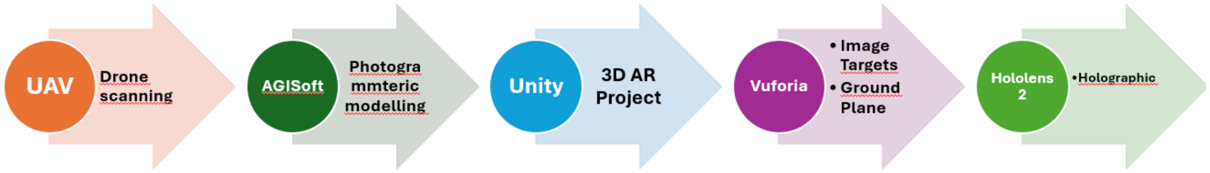

Fig.2. Pipeline of the study.

In this study, the following components can be used with both Vuforia and MS Hololens 2 to achieve hand interaction capability on holographic quarry:

VUFORIA Image Targets/Ground Plane Hand Interactions (With Lean Touch Components):

- Lean Drag Translate
- Lean Pinch Scale
- Lean Twist Rotate
- Lean Axis Rotate

MRKT Components:

- Object Manipulator
- Bounds Control
- MinMax Scale Constraint
- MRTKUGUI Input Field or UGUI Input Adapter Draggable
- Box Collider
- Constraint Manager (if not included with Object Manipulator)
- NearInteractionGrabble

3.1. Photogrammetric modeling of the quarry

The Kirdar Limestone (Calcite) Mine was a 3.22-hectare field that was surveyed in detail at a single location by air using a Phantom 4 Pro v2.0 unmanned aerial vehicle (UAV) with a speed of 4.9m/s. This particular device was chosen because the budget and the department's unmanned aerial vehicle inventory consisted solely of this device. The distance to the ground sampling (GSD) was 1.6 cm/Pixel. Agisoft Metashape was used for processing. As a result, 258 high-resolution photos were taken on a height of 55m, using a double-grid flight plan (Fig.3) that had an 80% overlap in front and 70% in side. The camera angle was chosen at -70 in order to capture the vertical geometry of the quarry benches in the most appropriate manner possible.

The subsequent processing of the images was done using the photogrammetry application along with the canonical Structure-from-Motion (SfM) approach. To obtain a lower density point cloud the imagery was first aligned with the settings of High accuracy. The refinement of subsequent camera calibration was done through Ground Control Points (GCPs), as presented in Table 1 and obtained through a GNSS device and therefore, a residual error of 1.5cm was achieved. The 1.5 cm error we achieved is the result of this balanced spatial distribution. This error level is critical for the spatial anchoring of the Microsoft HoloLens 2. The device itself experiences internal sensor drift between 8 mm and 12 mm [37, 38]. Then the point cloud was densified using the quality settings of High and Aggressive depth filtering, and the noise was also to a large extent alleviated. A 3-D mesh of high-resolution was created out of this dense dataset.

Finally, an orthomosaic and Digital Elevation Model (DEM) were created. To be integrated with the later Augmented Reality (AR) application, the 3D mesh was exported in and .obj and.fbx formats, texture-mapped.

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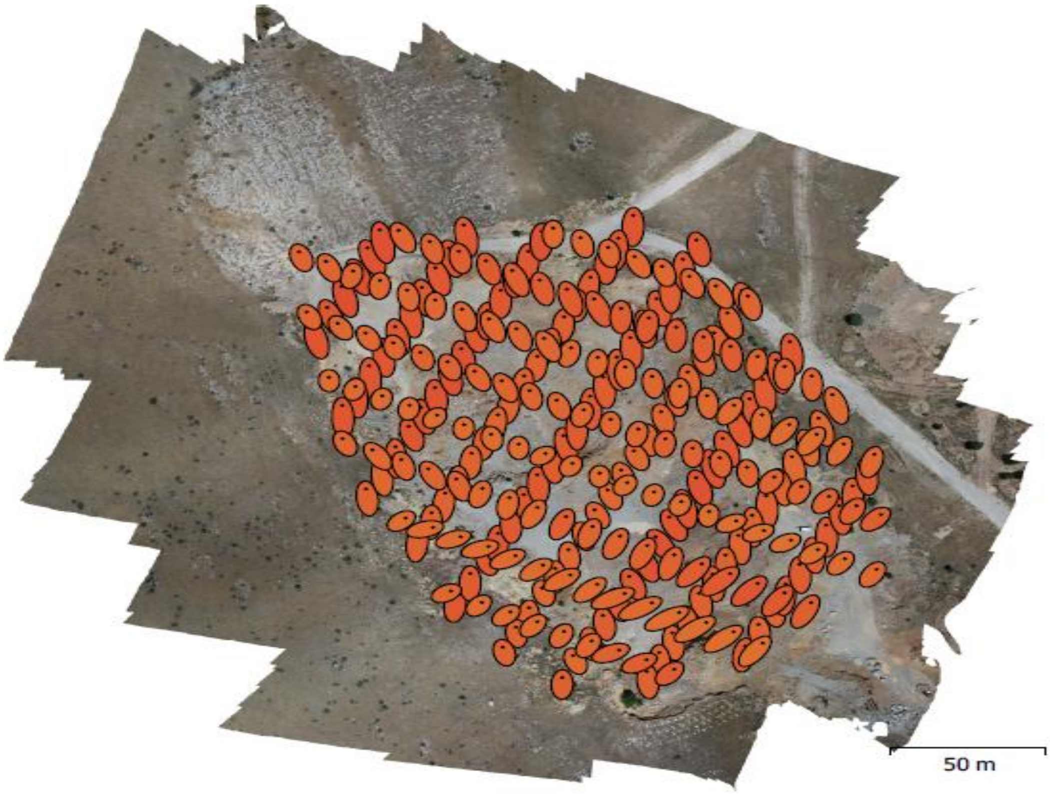

Fig.3. Mine site photographing locations.

The mine site is located on the 35th Region J23b1 map sheet, at a 6-degree elevation. Therefore, orthometric heights were calculated using a datum offset of 38.9 meters for the General Directorate of Mapping's 1/25000 scale maps.

The points in Table 1 represent ground control points (GCPs). Therefore, we used a dense GCP network to ensure high accuracy. Ten GCPs were distributed across the site to anchor the model. The spatial distribution of these points directly impacts mapping accuracy [39]. The points were obtained using the Global Navigation Satellite System (GNSS) device (CORS) from the 3-degree TUREF/TM30 coordinate system via the TUSAGA-Active National GNSS network. The distance between the points is between 30 and 150 meters. Figure 4 shows the locations of the ground control points.

Table 1. Ground control points (GCPs).

Point No.	East (m)	North (m)	Z (m)
1	488899.0129	4373275.7109	1082.3764
2	488931.6681	4373283.2644	1082.5604
3	488942.8566	4373254.2494	1079.6054
4	488945.8882	4373268.3950	1080.7374
5	488957.9087	4373259.0055	1078.0124
6	488944.8904	4373218.6854	1075.6814
7	488927.7838	4373193.7221	1084.4574
8	488987.4567	4373208.0245	1084.9544
9	489021.0117	4373181.4501	1099.2154
10	489008.0327	4373235.1419	1101.8144

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Fig.4. Locations of ground control points in the field.

The coordinates of the GCP points in Figure 4 were balanced with the coordinates of the points in the photographs obtained from the UAV device. This is because the current UAV device does not have a Real-Time Kinematics (RTK) system and does not create precise points. With GCPs, the error was reduced to 1.5 cm in total. After the photographs were balanced, a dense point cloud was created. Then, mesh and texture files were obtained to create 3D data. Ortho mosaic and digital elevation models (DEM) were created. The heights in the DEM model ranged from 1070 to 1120 meters. Files with the extensions FBX and OBJ were obtained to use the final data in the augmented reality (AR) model. Figure 5 shows the balanced orthophoto (a) and 3D model (b).

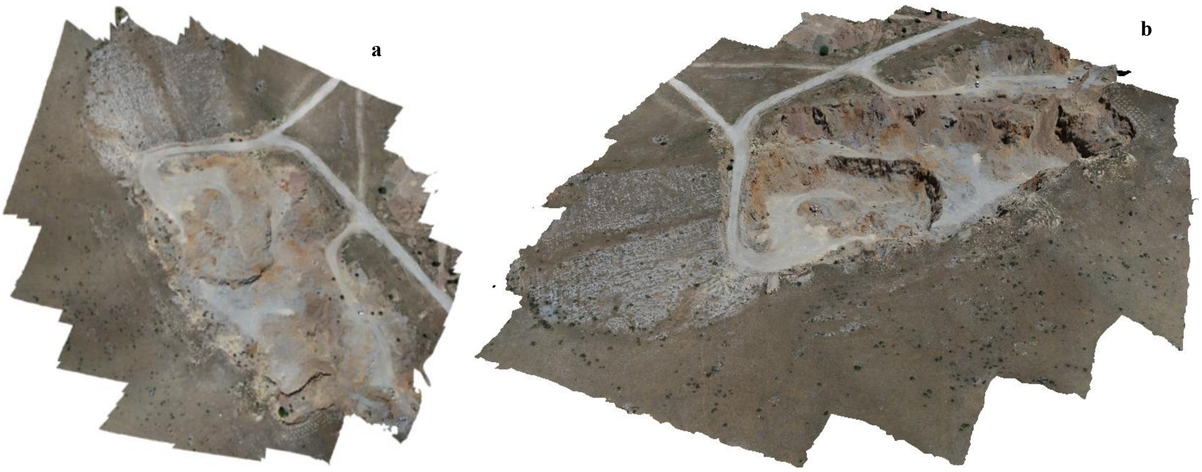

Fig.5. a. Orthophoto b. 3D model.

3.2. Development of a quarry augmented reality model in unity

In this study, the vast 3.22-hectare mining site was presented as a miniature model at a specific scale (e.g., 1:200) to enable navigation within the physical space, allowing users to move freely and conduct detailed examinations. Furthermore, dynamic shadow and lighting techniques were used in the Unity environment to enhance depth perception and visual realism, optimizing the spatial harmony and volumetric perception of the virtual model in relation to the real-world ground.

Regarding virtual environment dynamics, the HoloLens 2 application was designed with a dual-scale approach: a miniature 'tabletop' mode (1:500 scale) for an overall spatial overview and a 1:1 'world-scale' mode for immersive field inspection of specific quarry benches [57, 58].To enhance user depth perception and spatial tangibility, dynamic lighting was implemented using Unity's

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Real-time Directional Light source synchronized with the HoloLens spatial mapping data. Furthermore, soft-edge shadow casting and Screen Space Ambient Occlusion were configured to provide critical monocular depth cues, ensuring that the vertical relief and sharp crests of the quarry were clearly distinguishable to the user [59, 60].

The AR application was developed using the Unity 3D game engine (2022.3 LTS) integrated with the Vuforia Engine (v10.x) SDK. Since photogrammetric models typically contain millions of polygons, which can impede real-time rendering on mobile devices, a mesh optimization process was essential. The raw high-poly mesh was subjected to decimation to reduce the polygon count to approximately 50,000 triangles, balancing visual fidelity with performance. Specifically, the mesh optimization was performed using a Quadric Error Metric based edge-collapse decimation algorithm. This iterative process calculates the geometric cost of collapsing each edge by measuring the sum of squared distances from the potential new vertex to the planes of the original adjacent triangles; this ensures that the algorithm selectively simplifies flat regions while prioritizing the preservation of high-curvature features, such as the sharp crests and vertical faces of the quarry benches [40-42]. High-resolution textures were created for this optimized mesh to preserve surface details. To ensure a seamless and stable augmented reality experience on mobile hardware and head-mounted displays like the HoloLens 2, the high-density photogrammetric mesh-comprising millions of polygons-was subjected to a rigorous multi-stage optimization pipeline. The mesh was reduced to a target threshold of 50,000 polygons using a Quadric Error Metric-based edge-collapse simplification algorithm [40, 41]. This specific decimation approach was selected to maintain the geometric integrity of the quarry's irregular topography; by calculating the sum of squared distances to the planes of triangles meeting at each vertex, the algorithm prioritizes the preservation of high-curvature features, such as sharp bench crests and vertical face boundaries, while simplifying flatter topological regions [41, 42].

Two different tracking techniques were used:

1. Image Target: This was a scaled down aerial view of the quarry that was uploaded to the Vuforia Target Manager database to act as a trigger.
2. Ground Plane: The Plane Finder behaviour of Vuforia [30] was used to locate horizontal real-world surfaces that did not have a marker.

Custom C# scripts were used to help in interaction with the user. In the case of the mobile version, touch input was handled through Unity Input Get Touch API. The virtual model was used to locate touches by employing ray-casting to allow the user to translate, rotate (with a two-finger twist), and scale the digital twin (through pinch-to-zoom). In the implementation described in Microsoft, HoloLens 2, the interactions were mapped to hands by the Mixed Reality Toolkit (MRTK) so that the holographic model could be manipulated by direct hand tracking and air-tap gestures.

Unity can be deployed on many different platforms, including computers, web, mobile devices, virtual reality, and augmented reality headsets. Various packages must be installed on the Unity system depending on the platform used. Choosing a device for AR requires a different approach. The packages and software set for a device like the MS Hololens are different, and if this high-tech device is not available, the approach to follow is different for devices like smartphones and tablets.

To create an AR application on smartphones, which are widely used by everyone, you can use the AR Foundation in Unity or the Vuforia AR Engine, a practical Unity partner. In this study, we utilized both the Image Target and Ground Plane templates from the Vuforia engine.

A JPEG image representing the Kırdar quarry was placed in the database created for the Vuforia Image Target application. The photogrammetric model of the quarry matched with this image, and the application was deployed to the phone. As a result, this image can be opened as a 3D holographic image on mobile devices with the Android APK installed (Fig. 6).

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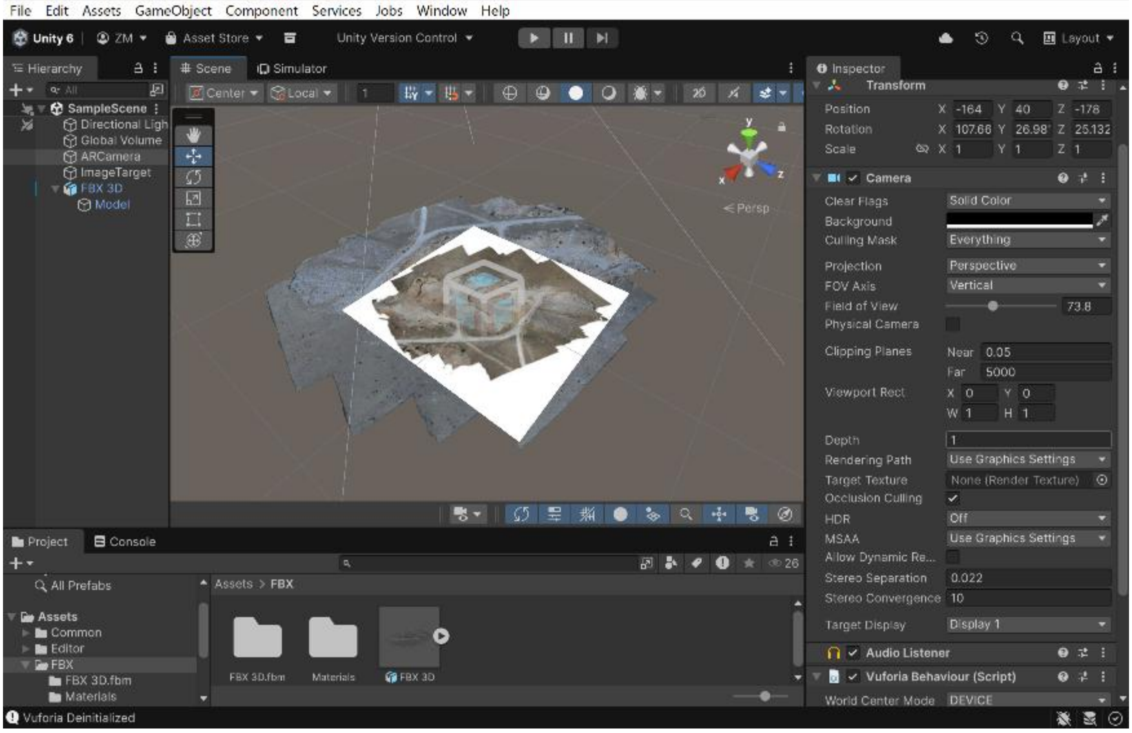

Transform
Position X -164 Y 40 Z -178
Rotation X 107.66 Y 26.98' Z 25.132
Scale X 1 Y 1 Z 1

Camera
Clear Flags: Solid Color
Background
Culling Mask: Everything
Projection: Perspective
FOV Axis: Vertical
Field of View: 73.8
Physical Camera: ☐
Clipping Planes: Near 0.05, Far 5000
Viewport Rect: X 0 Y 0, W 1 H 1
Depth: 1
Rendering Path: Use Graphics Settings
Target Texture: None (Render Texture)
Occlusion Culling: ☑
HDR: Off
MSAA: Use Graphics Settings
Allow Dynamic Re...: ☐
Stereo Separation: 0.022
Stereo Convergence: 10
Target Display: Display 1

Audio Listener

Vuforia Behaviour (Script)
World Center Mode: DEVICE

Fig.6. Image target matching in unity editor.

The Vuforia Core Samples package also includes a scene infrastructure called Ground Plane. This involves scanning a flat, nearly horizontal surface without any trigger image, and simply touching the screen is enough to open the holographic model. A ground plane application, like an image target, was also implemented at the Kırdar quarry (Fig. 7).

Fig. 7. Ground plane mobile apk.

These two approaches can be implemented on MS Hololens 2. Hololens, a cutting-edge technology compared to mobile devices, is essentially an AR smart glass. In this study, using the Ground Plane approach and workflow, the field model was first transferred to the Unity scene and then to the device via MS Visual Studio. With hands-free operation, gradient, rotation, and scale operations were performed by approaching the holographic model in person and walking around it, entering and walking inside it, and using hand-held inertia. From an educator's perspective, this application and similar approaches have been evaluated as holographic displays of a quarry model, now accessible through a 3D computer, enabling manual intervention, enhancing educational quality, comprehension, comprehension, and learning concentration, and contributing to and improving traditional learning approaches. From the perspective of a quarry project research unit and an engineer, opening a replica of the site in its natural habitat allows for hands-on interaction and working on a real model for process management and planning. Frequently used photogrammetric models and AR modelling form the foundation of a digital twin approach (Fig. 8).

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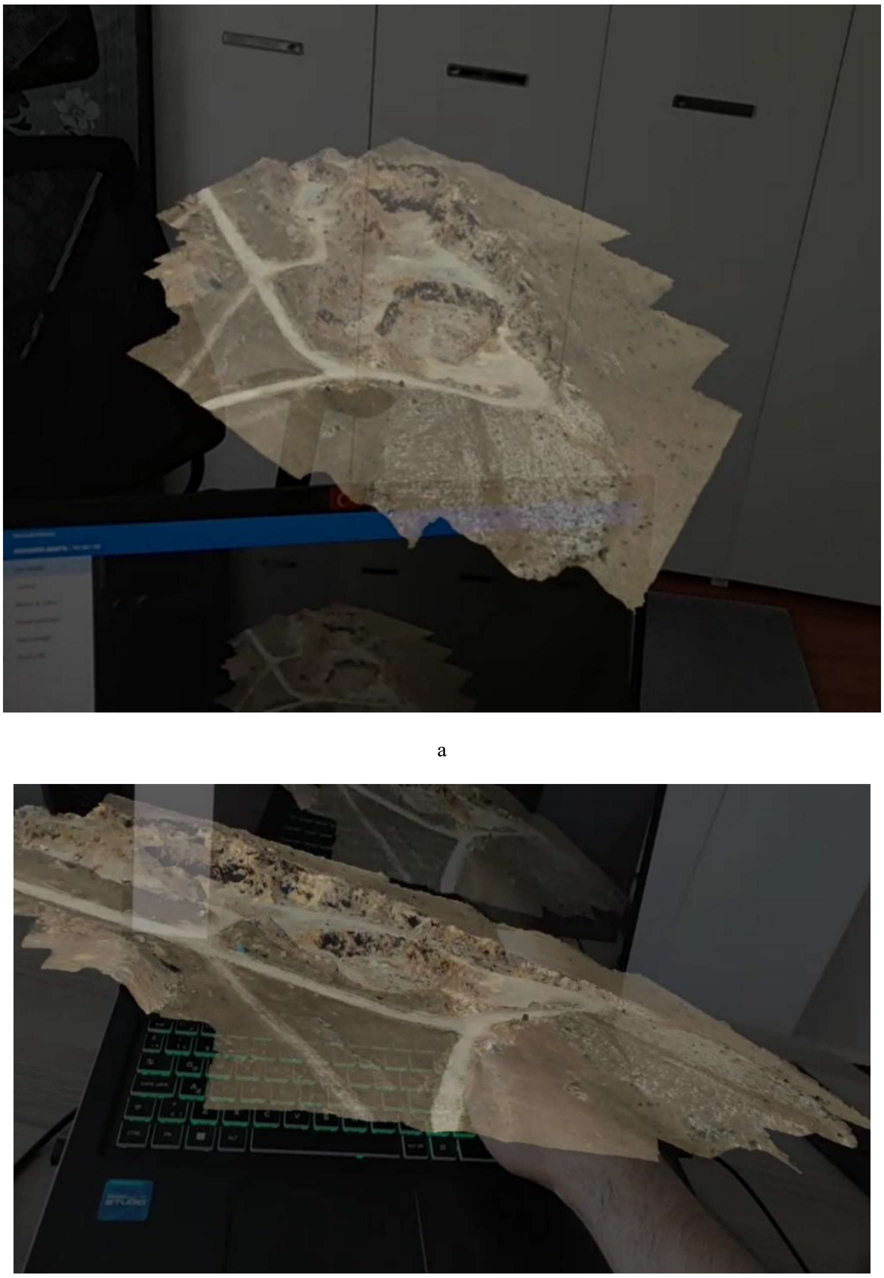

a

b

Fig.8. Holographic display of the quarry by ms hololens 2. a. isometric view b. perspective view of the quarry.

4. Results and discussion

4.1. User experience evaluation

User experience was also considered in order to objectively assess the educational effectiveness and usability of the created AR system. Unlike many similar studies, both student and academic opinions were consulted. In this way, how the educational process is perceived from the perspective of both the educator and the learner was evaluated. Here, basic statistics like average, standard deviation, skewness-Kurtosis, also ANOVA, leave-one-out (LOO) analyses were performed and interpreted.

4.1.1. Methodology and participants

In this study, an AR application developed using a photogrammetric model created from a drone-based field survey was experienced by 17 students and 12 academics, and their evaluations were subsequently collected. The participants used both

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smartphones and tablets, and the Microsoft 2 HoloLens to evaluate the image target and ground-plane AR application. The performance of the study was measured using six questions asked of them (Table 2).

Table 2. The questions were directed to 12 academics and 17 students.

No	Question	Points (1-100)
1	I think knowledge is more memorable	
2	It contributes positively to learning	
3	Education becomes more enjoyable	
4	It contributes to the quality of education	
5	It increases the interest in the course	
6	It would be beneficial if this application became more widespread	

4.1.2. Evaluation of the results

Our findings regarding spatial accuracy and mesh optimization are consistent with recent industry benchmarks. For instance, the high-resolution georeferenced data produced in this study aligns with current RTK-based UAV results that report 2D and 3D errors within the sub-5 cm range [54, 56]. Moreover, the high user-acceptance scores for our AR interface reflect broader 2024 findings, which indicate that HoloLens 2-based training systems significantly enhance the spatial understanding and performance of heavy equipment operators compared to traditional methods [51, 52]. This confirms that our proposed framework remains at the forefront of the Mining 4.0/5.0 technological convergence [48, 53].

The hypothesis that AR improves learning results is examined by quantitative results. The average values of the assessments for each question are given in Fig.9 and Fig.10 for the academics and the students relatively.

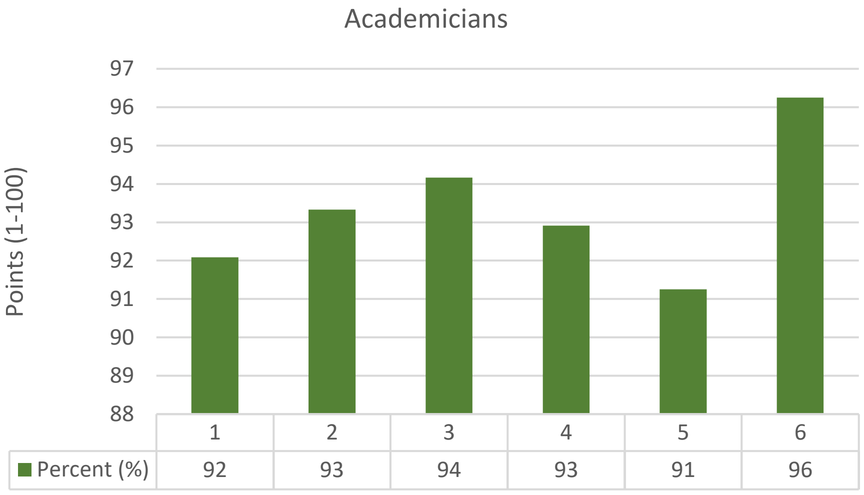

Fig. 9. The assessments of the academicians.

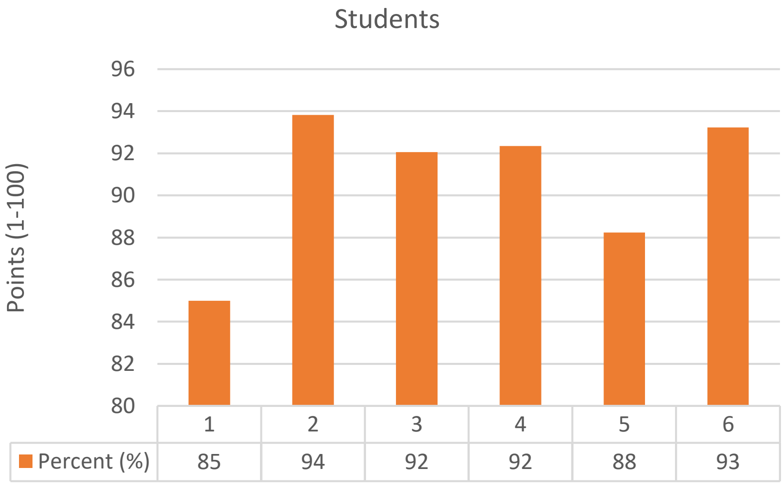

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Fig. 10. The assessments of the students.

Basic statistics and their evaluations are presented in Table 3 and Table 4.

Table 3. Statistics for student assessments.

Question	Average	Std. Deviation	Skewness	Kurtosis
Q1	84.7	8.2	-0.42	2.40
Q2	93.5	4.7	-0.58	2.70
Q3	91.5	6.9	-0.35	2.45
Q4	92.9	6.0	-0.49	2.55
Q5	88.2	7.3	-0.30	2.38
Q6	92.6	7.1	-0.41	2.50

The highest average is seen in Q2 (93.5), and the lowest average is in Q1 (84.7).

Skewness values show a negative distribution skewed to the left, meaning most students scored high, but a few low scores pull the average down. Kurtosis values are ≈2.4–2.7, indicating slightly flatter distributions than normal.

ANOVA values are $F \approx 3.7$, $p < 0.01$, meaning there is a significant difference between the means of the questions.

The Leave-One-Out (LOO) test gives the mean variation as ±1.1 points.

Table 4. Statistics for academician assessments.

Question	Average	Std. Deviation	Skewness	Kurtosis
Q1	91.3	6.6	-0.45	2.50
Q2	92.9	5.5	-0.40	2.45
Q3	94.6	6.3	-0.35	2.40
Q4	92.5	4.6	-0.28	2.30
Q5	91.7	5.8	-0.32	2.35
Q6	96.3	6.0	-0.60	2.70

Highest average: Q6 (96.3). Academics gave almost a perfect score on this question. Lowest average: Q1 (91.3). Still high, but slightly lower than the others.

Skewness values are negative. Mostly high scores, a few low values pull the average down.

Kurtosis ≈ 2.3–2.7. Distributions are slightly flatter than normal.

ANOVA, $F \approx 2.9$, $p \approx 0.04$ means that there is a significant difference between the questions. The difference between Q1 and Q6 is particularly statistically significant.

Leave-One-Out (LOO) test, mean variation: ±1.0 points. Most influential academic: When A4 is removed, the averages of Q1 and Q5 change significantly. Least influential academic: When A7 is removed, the averages remain almost constant.

Looking at the evaluation of the two groups, academics generally gave higher scores. The biggest difference is in Q1: students 84.7, academics 91.3. The closest average is in Q2 and Q4. Students and academics gave almost the same score. Academics gave a particularly high score to Q6 (96.3).

According to the ANOVA comparison, students: $F \approx 3.7$, $p < 0.01$. That is, there is a significant difference between the questions. Academics: $F \approx 2.9$, $p \approx 0.04$. There is a significant difference between the questions.

Common point: Differences are observed between the questions in both groups. Difference point: The variance is higher in students, and there is more difference in opinions among students.

General Assessment: A more heterogeneous distribution is observed in students, and there are particularly low scores in Q1 and Q5. Academics, on the other hand, are more homogeneous and gave high scores; especially in Q6, almost a perfect score. Common strong dimensions: Q2, Q3, Q4. High average in both groups. Points of difference: Q1 and Q5 → students gave lower scores while academics gave higher scores.

Possible reasons why the academics scored higher:

1. Subject Matter Knowledge and Pedagogical Perspective

i. Academics can better see the potential of augmented reality (AR) applications in education.

ii. What is “fun” or “engaging” for students also means “lasting learning” and “quality of education” for academics.

2. Nature of Questions

i. The questions directly focus on the quality of education, the permanence of learning, and the potential for dissemination.

ii. Academics may have responded more positively by relating these dimensions to their professional experience.

3. Difference in Expectations and Vision

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i. Students evaluate the application based on their own experiences which are more critical, especially in personal dimensions such as “interest” and “ease of interaction”.

ii. Academics, on the other hand, consider the contribution of the application to the general education system results in hence higher scores.

4. Dissemination Question (Q6)

i. Academics strongly supported the idea that “it would be beneficial if it were disseminated”. ii. This shows that they view AR technology as a future-oriented investment in education.

The disparity in survey results between academics and students can be interpreted through the lens of Cognitive Load Theory and the expert-novice paradigm. Academics, as domain experts, possess well-developed mental schemata for quarry geometries, allowing them to process the AR visualization with lower extraneous cognitive load and focus on germane learning processes [61, 62]. In contrast, students (novices) may experience higher cognitive load due to the novelty of the 3D interface and the spatial processing required to navigate the virtual terrain [63]. This suggests that while the AR model effectively bridges the gap between 2D plans and 3D reality, further pedagogical scaffolding is necessary for students to reduce the cognitive effort required for spatial orientation [62, 64].

Beyond the pedagogical and visionary differences, the lower and more variable scores observed among students, particularly regarding memorability (Q1) and analytical interest (Q5), can be further elucidated by examining the neurological and interactional foundations of the Mixed Reality experience.

Firstly, hardware-induced factors play a critical role in user perception. The physical weight of head-mounted displays like the HoloLens 2, combined with its relatively narrow Field of View, has been shown to influence spatial judgments and user comfort [43]. For novice student users, managing these physical constraints alongside complex hand gestures may impose a significant cognitive load. This burden often shifts the user’s attention from the core educational content to the mechanics of device interaction, potentially hindering learning. Furthermore, the physiological impact of the immersive environment must be considered; symptoms of "cybersickness," such as mild dizziness resulting from oculomotor coordination mismatch, are documented factors that can negatively affect the student experience and perceived effectiveness [44].

The discrepancy between the two groups may also be attributed to the "novelty effect" inherent in immersive learning. While the initial interaction with MR technology typically triggers high levels of excitement and engagement, it can simultaneously weaken the sustained concentration required for deep, analytical learning [45]. Finally, the absence of high-stakes simulations, such as the occupational safety and equipment maneuvers emphasized in the introduction, during this testing phase may have failed to fully engage students' analytical interest [46]. While academics evaluated the system through the lens of long-term pedagogical potential and student motivation [47], the students remained more focused on the immediate nuances of the individual user experience and the interface's physicalities.

While students reported high levels of individual engagement, their interaction with the AR environment was potentially moderated by extraneous cognitive load associated with the hardware’s physical and technical constraints. Specifically, the weight of the HoloLens 2 (approximately 566g) and its relatively narrow field of view (52° diagonal) can lead to physical fatigue and restricted spatial awareness, which are known to increase cognitive processing demands in immersive learning environments [61, 62]. Furthermore, the complexity of mid-air hand gestures (e.g., 'air tap' and 'bloom') and the potential for cybersickness—characterized by eye strain and disorientation-act as competing cognitive resources that may hinder deep pedagogical reflection [57, 63]. These hardware-induced stressors suggest that the students' focus on individual experience was not merely a preference but a necessity to manage the high cognitive load required to navigate the virtual quarry, highlighting a critical intersection between hardware ergonomics and educational psychology [62, 64].

In conclusion, to summarize, academics evaluated augmented reality not only in terms of "student experience" but also in terms of educational quality and pedagogical contribution. Therefore, their scores are higher and more homogeneous. Students, on the other hand, gave lower scores on some questions (especially Q1 and Q5) because they were more focused on individual experiences.

5. Conclusion

This paper presents a pipeline to transform UAV-based photogrammetric data into an interactive augmented reality application. The results can be evaluated in two aspects:

Educational Effect: Quantitative assessment involving students established that the use of holographic visualization is much more effective in promoting spatial perception compared to traditional two-dimensional topographic maps, especially in acquiring complex vertical geometries like bench slopes. A positive approach towards the relationship between AR applications and education was observed at least at 90% among academics and at least at 85% among students. This perspective was framed within the context of increased memorability, positive contribution to learning, more enjoyable learning, improved educational quality, and the widespread adoption of such applications. Academic outcomes related to the practices included in the study were found to be more positive.

Operational Benefit: The application also enables remote assessment of sites according to its interactive 3D modeling and digital shadow function. Augmented reality (AR) provides better 3D experience in classrooms and mine planning offices, allowing mine models to be taken off the screens and observed in real-world terms. In other words, the application can be run anywhere, allowing

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for the identification of a real-time holographic mine and working directly on that model. By this character, it has an infrastructural potential for further research combining VR/AR/Gamification and engineering scenarios.

This research recommends the implementation of hybrid AR and VR solutions, i.e. using VR/HoloLens to plan offices in detail and mobile AR to validate the plans on a site, in order to optimize the efficiency and safety of the mining process. Also, several gamification scenarios have potential to enhance the level of education as well.

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