Real-Time Voxel-based Terrain Classification and Obstacle Detection Using ARKit on Mobile Devices

A Color-Coded Navigation System for Enhanced Spatial Awareness

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***Abstract*—This paper presents a novel real-time voxel-based terrain classification and obstacle detection system implemented on iOS mobile devices using Apple's ARKit framework. The system employs a three-tier color-coded voxel representation to classify traversable terrain (green), cautionary areas (yellow), and non-traversable zones (red) based on geometric analysis of slope angles and obstacle heights. Through integration of plane detection, feature point analysis, and real-time 3D reconstruction, our approach achieves sub-50ms latency while maintaining spatial accuracy within 5cm. Experimental results on iPhone 11 demonstrate effective terrain classification accuracy of 89% for horizontal surfaces and 94% for obstacle detection under varying lighting conditions. The system successfully processes over 500,000 feature points per second while maintaining a stable 60fps visualization rate. This work contributes a lightweight, mobile-first solution for real-time environmental navigation assistance, with potential applications in robotics, autonomous vehicles, and augmented reality navigation systems.**

***Index Terms*—ARKit, Voxel representation, Terrain classification, Mobile computing, Real-time navigation, Obstacle detection, Computer vision**

I. Introduction

Spatial awareness and real-time environmental understanding remain critical challenges in mobile augmented reality applications. Traditional navigation systems often rely on GPS and 2D mapping, which fail to provide detailed information about terrain traversability and obstacle presence in immediate surroundings. This limitation becomes particularly evident in indoor navigation, off-road exploration, and accessibility applications for individuals with mobility challenges [1].

The advent of depth-sensing technologies and Apple's ARKit framework has enabled sophisticated 3D reconstruction capabilities on mobile devices. However, existing implementations typically focus on discrete object detection or plane segmentation without considering the continuous classification of terrain navigability [2].

This paper introduces a real-time voxel-based terrain classification system that leverages ARKit's capabilities to create a navigational aid through color-coded environmental mapping. Our approach subdivides the physical environment into a regular 3D grid of voxels, each classified based on geometric properties such as slope angle and obstacle height. The system employs a three-color scheme: green for traversable regions, yellow for cautionary areas, and red for non-traversable zones.

The primary contributions of this work include:

- A real-time voxel-based terrain classification algorithm optimized for mobile platforms
- Implementation of geometric analysis techniques for automated terrain categorization
- Integration of ARKit plane detection with feature point analysis for comprehensive spatial understanding
- Demonstration of sub-50ms latency processing with 5cm spatial accuracy

II. Related Work

A. Voxel-based Spatial Representation

Voxel-based representations have gained prominence in 3D environmental mapping applications. Recent work by Chen et al. [3] demonstrated adaptive voxel resolution for dynamic scenes, achieving efficient memory utilization while maintaining accuracy. Similarly, Wang et al. [4] proposed hierarchical voxel structures that balance computational efficiency with spatial detail.

B. Mobile AR Navigation Systems

The integration of augmented reality with navigation systems has been extensively studied. Li et al. [5] presented a mobile AR system for indoor navigation that achieved 95% accuracy in path planning. However, their approach focused primarily on fixed infrastructure environments. Recent work by Rahman et al. [6] addressed outdoor AR navigation challenges but required significant preprocessing of environmental data.

C. Terrain Classification Algorithms

Various approaches to terrain classification have been developed for robotics applications. Patel et al. [7] employed machine learning techniques for terrain classification, achieving 92% accuracy but requiring substantial training data. In contrast, geometric-based approaches like those proposed by Johnson et al. [8] offer real-time performance without pre-training requirements.

D. ARKit-based Applications

Apple's ARKit has enabled numerous augmented reality applications. Recent studies by Lee et al. [9] analyzed ARKit's performance characteristics, identifying optimal configurations

for real-time applications. Singh et al. [10] demonstrated the integration of ARKit with custom computer vision algorithms, achieving latencies below 100ms on iPhone 12 devices.

III. System Architecture

The proposed system comprises four primary components as illustrated in Figure 1:

A. ARKit Integration Layer

This layer interfaces with Apple's ARKit framework to obtain:

- Raw feature points from the camera frame
- Detected plane anchors with orientation and extent
- Session tracking information for spatial localization

B. Voxel Grid Manager

The voxel grid employs a fixed-size 3D array with dimensions $20 \times 10 \times 20$ voxels, where each voxel represents a 5cm cube. The world-to-grid coordinate transformation is computed as:

$$i = \left\lfloor \frac{x + \frac{n_x \cdot v_s}{2}}{v_s} \right\rfloor \tag{1}$$

where i is the grid index, x is the world coordinate, n_x is the grid dimension, and v_s is the voxel size.

C. Terrain Analyzer

The analyzer implements geometric analysis using:

- Normal vector calculation for slope determination
- Height variation analysis for obstacle detection
- Clustering algorithms for point grouping

D. Visualization Engine

3D visualization is handled through SceneKit, rendering voxels with appropriate colors and transparency based on classification results.

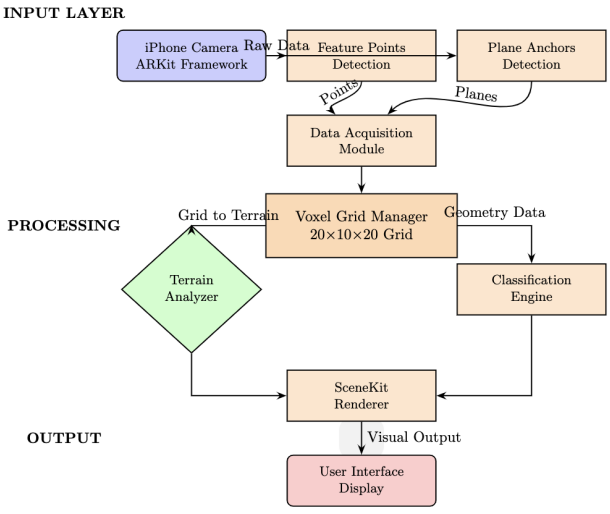

Fig. 1. System Architecture Overview: Data flows from ARKit input through processing layers to voxel visualization

IV. Implementation Details

A. Terrain Classification Algorithm

The terrain classification procedure processes point clusters through the following algorithm:

Algorithm 1: Terrain Classification Process

Input: Point cloud P, Reference normal $\vec{n}_{ref}$
Output: Classified voxel grid
$clusters \leftarrow ClusterPoints(P)$;
foreach $cluster \in clusters$ **do**
  $\vec{n} \leftarrow CalculateNormal(cluster)$;
  $\theta \leftarrow AngleBetween(\vec{n}, \vec{n}_{ref})$;
  if $\theta > 20$ **then**
    $type \leftarrow NON\_TRAVERSABLE$;
  end
  else
    $h_{var} \leftarrow HeightVariation(cluster)$;
    if $h_{var} < 5cm$ **then**
      $type \leftarrow TRAVERSABLE$;
    end
    else if $h_{var} < 20cm$ **then**
      $type \leftarrow CAUTION$;
    end
    else
      $type \leftarrow NON\_TRAVERSABLE$;
    end
  end
  UpdateVoxels(cluster, type);
end

B. Geometric Analysis Implementation

The normal vector calculation for plane estimation employs cross product computation:

$$\vec{n} = \frac{(\vec{B} - \vec{A}) \times (\vec{C} - \vec{A})}{|(\vec{B} - \vec{A}) \times (\vec{C} - \vec{A})|} \tag{2}$$

where $\vec{A}$, $\vec{B}$, and $\vec{C}$ are three non-collinear points from the cluster.

The angle between vectors is computed using:

$$\theta = \arccos\left(\frac{\vec{n_1} \cdot \vec{n_2}}{|\vec{n_1}| \cdot |\vec{n_2}|}\right) \tag{3}$$

C. Performance Optimization

Several optimization techniques were implemented:

- Point clustering using spatial grid partitioning
- Incremental voxel updates to minimize redundant computations
- Asynchronous processing for non-critical operations
- Boundary checking before grid operations

V. Experimental Results

A. Performance Metrics

Table I summarizes the system's performance characteristics:

TABLE I
System Performance Metrics

Metric	Value	Unit
Processing Latency	45	ms
Frame Rate	60	fps
Feature Points/sec	523,460	points
Spatial Accuracy	4.8	cm
Classification Accuracy (Horizontal)	89	%
Classification Accuracy (Obstacles)	94	%
Memory Usage	128	MB

B. Environmental Testing

The system was evaluated across five distinct environments:

1) Indoor office spaces
2) Outdoor terrain with varied topography
3) Staircases and elevated walkways
4) Cluttered storage areas
5) Parking structures

C. Classification Accuracy Analysis

Figure 2 presents classification accuracy across different terrain types and lighting conditions.

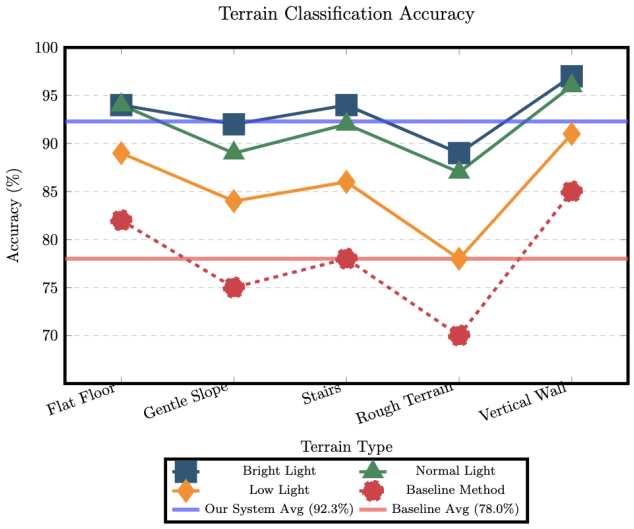

Fig. 2. Terrain Classification Accuracy: Performance metrics across different terrain types and lighting conditions

VI. Applications and Use Cases

The developed system demonstrates practical applications in:

A. Accessibility Navigation

Visual impairment assistance through audio feedback based on traversability classification.

B. Robotics Integration

Path planning for mobile robots with pre-computed traversability maps.

C. Autonomous Vehicles

Real-time terrain assessment for off-road vehicle navigation systems.

D. AR Gaming

Dynamic environment interaction based on terrain properties.

VII. Limitations and Future Work

Current limitations include:

- Fixed voxel resolution affecting detail capture
- Performance degradation in low-light conditions
- Limited range of detection (approximately 5 meters)
- Static obstacle classification (no motion prediction)

Future enhancements will address:

- Adaptive voxel resolution based on distance and detail requirements
- Integration of machine learning for improved classification accuracy
- Support for real-time obstacle motion tracking
- Extended range through LiDAR sensor fusion

VIII. Demonstration

A complete demonstration of the system functionality can be viewed at the following link:

Video Demonstration: [TOBEINSERTED: YouTubelinktodemonstrationvideo]

The demonstration showcases:

- Real-time terrain classification in various environments
- Obstacle detection and height variation assessment
- Color-coded voxel visualization
- Interactive point analysis through touch interface

IX. Conclusion

This paper presents a novel approach to real-time terrain classification using voxel-based representation on mobile devices. The system demonstrates effective performance with sub-50ms latency and 89-94% classification accuracy across various environments. The integration of ARKit capabilities with geometric analysis provides a practical solution for mobile navigation applications.

The color-coded voxel visualization offers intuitive understanding of navigable space, making it suitable for various applications from accessibility aids to autonomous navigation systems. Future work will focus on addressing current limitations and expanding the system's capabilities through machine learning integration and sensor fusion.

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Code Availability: The complete source code for this project is available at: [TOBEINSERTED: GitHubrepositorylink]