TED UNIVERSITY

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Department of Computer Engineering

CMPE 491 - Senior Project High-Level Design Report

3D-EcoMap

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1.Introduction

In today’s rapidly urbanizing world, optimizing travel routes is critical not only for cost savings but also for reducing environmental impact. As the number of vehicles on the road continues to increase, the urgency to reduce fuel consumption and emissions also increases. However, traditional navigation systems often rely on 2D maps that prioritize distance and traffic conditions only, ignoring the impact of road topography on fuel efficiency. 3D-EcoMap aims to address these issues by offering a flatter, slightly longer route rather than a shorter route with steep slopes, which can lead to significantly more fuel consumption. Our project offers an eco-friendly driving experience.

1.1 Purpose of the System

The purpose of the 3D-EcoMap system is to provide an innovative navigation solution that helps users find the most fuel-efficient routes by considering road slopes and topography. Unlike traditional navigation systems that focus only on distance and traffic, 3D-EcoMap integrates slope analysis into route optimization, reducing fuel consumption and environmental impact. The system aims to enhance users' driving experience by offering 3D visualizations of routes and providing real-time insights into the fuel efficiency of different paths. Ultimately, the goal is to contribute to more sustainable and cost-effective driving choices.

1.2 Design Goals

Extensibility and Modularity: 3D-EcoMap is designed with a modular architecture, allowing new features and components to be integrated seamlessly without affecting the core functionality. This modularity ensures that the system can evolve with emerging technologies, such as enhanced topographic data analysis or AI-driven route optimization. Developers can easily add new map layers, algorithms, and user interface elements, ensuring the system remains adaptable to future needs.

Maintainability and Reusability: The system architecture follows clean code principles and standardized frameworks, making it easy to maintain and update. Code is written in a reusable manner, enabling components to be repurposed across different projects or expanded upon for future development. Documentation is comprehensive, providing clear guidance for developers to troubleshoot, modify, or upgrade specific modules without requiring extensive retraining.

Usability: 3D-EcoMap prioritizes user experience by offering an intuitive and visually engaging interface. Users can easily interpret 3D visualizations of routes, with color-coded slopes indicating fuel efficiency. The system includes customizable preferences, allowing drivers to select eco-friendly routes based on fuel savings or estimated travel time. User feedback loops and usability testing are embedded in the development process to ensure continuous improvements.

Performance: The system is optimized for quick route calculations and real-time data processing. Efficient algorithms ensure minimal latency when analyzing topography and suggesting routes. The use of advanced caching techniques and parallel processing enhances responsiveness, even during peak usage times. Performance benchmarks are regularly assessed to maintain optimal speed and reliability.

Availability: 3D-EcoMap is designed to be highly available by implementing redundant servers and failover mechanisms. This ensures uninterrupted access to the navigation system, even during maintenance or unexpected downtime. Offline functionality is also provided, allowing users to download maps and route data in advance for use in areas with limited connectivity.

Scalability: The system is scalable to accommodate growing numbers of users and expanding datasets. By utilizing distributed computing and local storage solutions, 3D-EcoMap can handle large volumes of topographic data and support real-time processing for thousands of simultaneous users. The architecture supports horizontal scaling, enabling the system to expand as demand increases without significant performance degradation.

1.3 Definitions, Acronyms, and Abbreviations

3D Model: A digital representation of a physical object or space that includes height, width, and depth.

***A Algorithm**:** A pathfinding algorithm used to find the shortest or most efficient path from one point to another on a map, using heuristics to improve search efficiency.

Authentication: The process of verifying a user's identity, usually by requiring a username and password.

Dijkstra's Algorithm: A graph search algorithm used to find the shortest path between nodes in a graph.

Pathfinding Algorithm: A set of rules or procedures used to determine the best path from a starting point to a destination.

Route Optimization: The process of determining the most efficient route, considering factors like distance, fuel consumption, and time.

Slope Analysis: The evaluation of road inclines to assess how they affect fuel efficiency and vehicle performance.

3D-EcoMap: The system designed to provide fuel-efficient route suggestions by analyzing road slopes and topography.

UI (User Interface): The part of the application that users interact with, such as buttons, menus, and maps.

1.4 Overview

3D-EcoMap is an innovative navigation system designed to optimize travel routes by integrating road topography into route calculations. The primary goal is to reduce fuel consumption and minimize environmental impact by suggesting flatter, more fuel-efficient routes even if they are slightly longer.

The application leverages 3D mapping technology to analyze road slopes and offer eco-friendly route alternatives. The core of the application is developed in Python , with additional data processing and AI-based optimization modules.

Users can visualize routes in 3D, gaining insights into potential fuel savings based on topographic analysis. The system will include interactive features for route customization and real-time traffic data integration. Data collected from route logs will be processed through a local server infrastructure, ensuring user privacy and reliability.

Ultimately, 3D-EcoMap aims to promote sustainable driving habits and contribute to a greener future by making environmentally conscious navigation decisions more accessible and practical for drivers.

2. Current Software Architecture (if any)

As far as we know, there is no existing software architecture for the 3D-EcoMap system. This provides an opportunity to design and implement a modern architecture that meets the system's specific needs effectively.

3. Proposed Software Architecture

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The architecture of our system can be described as follows. In the presented system, each service will be given the task of doing its own work by using the microservice architecture. Encryption and processing of data in the backend will be done with Java Spring, storage with MySQL, and AI operations with Python, which has the most powerful libraries in this regard. The communication of Python and Java services will be done using Kafka Topic with the help of Apache Kafka technology, which is the fastest communication method at the moment. Necessary integrations and library usage in the backend service will be provided with Apache Maven. The rest of the document includes information about these systems and their details.

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3.2 Subsystem Decomposition

Image Processing and 3D Modelling Service: This service is responsible for transforming 2D satellite images into 3D models and analyzing road slopes.

Image Processing Algorithms: Use deep learning models and image processing techniques to create 3D models from 2D images.

Slope Analysis Module: Analyze the generated 3D models to extract slope data and assess the impact on fuel efficiency.

Route Optimization Service: This service handles pathfinding and route optimization using slope data.

Pathfinding Algorithms: Implement Dijkstra and A* algorithms to compute the most fuel-efficient routes by integrating slope analysis.

Fuel Efficiency Module: Calculate and recommend routes that balance distance and slope to minimize fuel consumption.

Web-Based Visualization Service : This subsystem provides a web platform for users to interact with the system and visualize routes.

3D Visualization: Develop a WebGL-based interface allowing users to view 3D models of routes and slopes.

Responsive Design: Ensure cross-platform accessibility using Spring Boot and web technologies.

Backend Service: Backend service will be responsible for holding and storing the data that we collect from the application. It entails:

Database: A database system will store user data, route data, and slope analysis results.

Encryption: Implement encryption and decryption algorithms to protect sensitive user data.

Apache Kafka: Apache Kafka will serve as an event distribution platform to connect different microservices.

Microservices Communication: Use Kafka to facilitate non-blocking communication between the image processing, route optimization, and visualization services, ensuring smooth data flow and scalability.

3.3 Hardware/Software Mapping

Our users will be able to use the 3D-EcoMap application via a web interface. The system processes user input (such as route queries) in the frontend and sends the data to the backend for slope analysis and route optimization. Communication between the frontend and backend services will be handled via REST API.

REST API REST is a software architectural style that describes a uniform interface between physically separate components, often across the Internet in a client-server architecture. REST API will serve as the interface connecting the web-based frontend with backend services, ensuring seamless data exchange and system functionality.

User Device:

- User Interface
- 3D Visualization

Backend Service:

- REST API
- Route Optimization
- Database

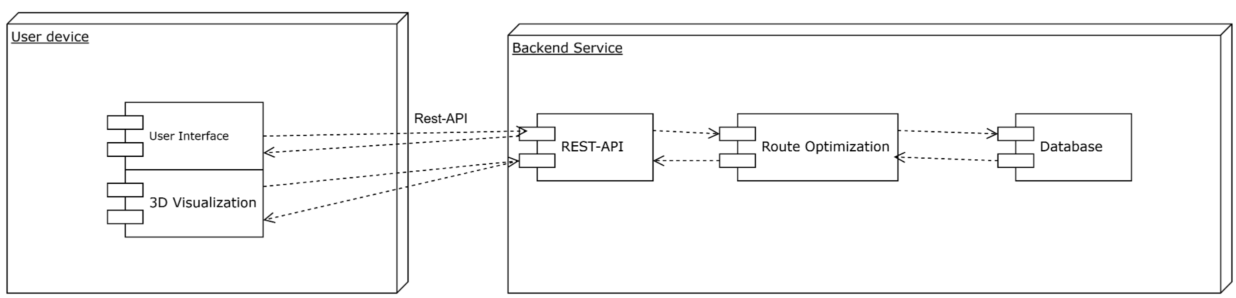

Figure 1: Mapping of Application

3.4 Persistent Data Management

Persistent data management is critical for ensuring the efficient storage, retrieval, and consistency of the large geospatial datasets handled by the 3DEcoMap system. This section details the design considerations, database structure, and strategies for maintaining data integrity and performance.

1. Database Selection : We selected PostGIS, an extension of PostgreSQL, as our primary database due to its strong compatibility with geospatial data and adherence to open standards. It enables efficient spatial data queries, supports calculations such as distance measurement and slope analysis, and facilitates the storage of 3D models and satellite imagery.

2. Data Schema Design

The database schema is designed with several key tables to support functionality:

Satellite_Images: Captures metadata for raw satellite imagery, including columns for image_id, acquisition_date, resolution, and file_path.

3D_Models: Stores metadata for generated 3D models, with columns such as model_id, image_id, generated_date, and file_path.

Slope_Data: Contains slope information for detected road segments, structured with slope_id, model_id, road_segment_id, and slope_percentage.

Routes: Records optimized vehicle routes, with columns for route_id, start_point, end_point, distance, and fuel_efficiency_score.

Users: Manages user details for authentication and preferences, including user_id, username, role, and preferences.

3. Data Access and Retrieval: We ensure efficient data access through spatial indexing to optimize searches for road segments and slopes. Common tasks, such as retrieving slope data for specific regions, are supported by predefined queries. To enhance performance, frequently accessed data like popular routes or 3D models is cached in memory for faster retrieval.

4. Backup and Recovery: Our backup strategy includes full backups conducted monthly and incremental backups performed weekly. Backups are securely stored in cloud storage to ensure disaster recovery capabilities. A comprehensive recovery plan is in place to restore data from backups in the event of a failure.

5. Data Integrity and Consistency: We use ACID-compliant transactions to maintain data consistency during updates. Validation rules, such as constraints on slope values, are enforced to uphold data integrity. Additionally, audit logging is implemented to record all data changes, enabling modification tracking and ensuring accountability.

3.5 Access Control and Security

Access control and security are essential to protect the sensitive data managed by 3DEcoMap, including satellite imagery, 3D models, and user information. This section details the strategies for user authentication, authorization, and overall system security.

1. User Authentication: For user authentication, we use OAuth 2.0, which enables secure single sign-on (SSO) and token-based authentication to strengthen security. User passwords are hashed using bcrypt, and strong password policies, including minimum length and complexity, are enforced to ensure secure access.

2. Authorization: Authorization is managed through Role-Based Access Control (RBAC). Users are assigned specific roles (e.g., Administrator, Regular User, Viewer) with distinct permissions. Administrators have full access to system features, Regular Users can generate and view data, and Viewers have read-only access to 3D maps and routes. Granular permissions are also in place for critical actions, such as data deletion or route modification.

3. Data Protection: Sensitive data, including user credentials and 3D models, is encrypted using AES-256 for storage and SSL/TLS for secure communication. Database access is restricted to authorized applications and IP addresses, and API requests are protected with time-limited access tokens to prevent unauthorized access

4. Monitoring and Auditing: All access and modification activities are logged, including user IDs and timestamps. Machine learning algorithms detect unusual behavior, like failed login attempts, while regular security audits help identify vulnerabilities and ensure compliance with security standards.

5. Mitigation of Common Threats: SQL injection is prevented with parameterized queries and input validation, while user inputs are sanitized to block cross-site scripting (XSS). To protect against denial-of-service (DoS) attacks, rate limiting and load balancing are used to handle high traffic and maintain system stability.

6. Security Best Practices: We follow the least privilege principle, giving users and subsystems only the permissions they need. Regular updates fix security issues, and a secure development process ensures security is a priority throughout development.

3.6 Global Software Control

The 3D-EcoMap system uses an event-driven design, where user actions control the flow and changes in the application. Every user action starts a series of steps that move the application through various stages, from checking the inputs to showing the results.

User Flow and Event Handling

1. **Login and Authentication:** The user begins at the login page, where they provide their info.. If successful, they are directed to the main interface. We will have a secure authentication system to ensure data security during login.
2. **Route Selection:** After logging in the user is prompted to enter a start and destination location. Input validation is performed to ensure locations are valid and serviceable.
3. **3D Map Interaction:** Based on the input, the system processes the route and renders a 3D map for the user. Users can see the fuel efficiency insights by selecting a road.

The system tracks user actions like clicks, typing, or interacting with the map using event listeners on the frontend. These actions are then sent to the backend, where the system handles more complex tasks like analyzing slopes and finding the best routes. This keeps everything running smoothly for the user. When switching between different views, such as showing routes or slopes, animations of our system elevates the user experience.

3.7 Boundary Conditions

The 3D-EcoMap system is designed to handle three main boundary conditions: Initialization, Termination, and Failure.

Initialization: When we start the application, users are greeted with a welcome screen offering three options: log in, sign up, or exit. Returning users can log in with their credentials to access their dashboard, while new users can easily sign up. Clicking "Exit" closes the application. After logging in, users enter their starting and destination points for route planning. Once validated, we display the 3D map with routes and fuel efficiency details.

Termination: Users can exit the application at any time by selecting "Exit" on the welcome screen or using the "Logout" or "Exit" options in the map interface. Upon exit, we securely save user preferences and session details, and cancel any ongoing route calculations to free up system resources.

Failure: We handle different types of failures. If satellite or slope data is missing, the system notifies the user and switches to cached or 2D data. In case of a crash, user credentials remain safe, but unsaved progress is lost. If the internet connection is lost, the system will try to reconnect, and if it fails, it will ask the user to try again later. If the map can't render, we switch to 2D mode. All failures are logged, and failure messages provide clear guidance, like "Unable to retrieve satellite data. Switching to cached data" or "Unexpected error. Please restart the application."

4. Subsystem Services

The 3D-EcoMap system includes various subsystems that work together to provide efficient, reliable, and user-friendly services. These subsystems are designed to manage the different functionalities of the system, ensuring smooth operation and a seamless experience for users.

User Management: The User Management subsystem is responsible for handling user accounts, authentication, and authorization. It enables users to create accounts, log in securely, and manage their profiles. The system uses OAuth 2.0 for secure authentication and role-based access control (RBAC) for managing permissions, ensuring that users have appropriate access to features based on their roles.

Data Management: This subsystem handles the storage, retrieval, and processing of all geospatial data. It ensures the proper management of satellite imagery, 3D models, and slope data. It also handles the data's spatial indexing for efficient querying and processing, enabling users to generate accurate routes and visualizations. Data is organized and stored securely in the database, with regular backups to ensure consistency and availability.

Route Optimization: The Route Optimization subsystem calculates and suggests the most efficient routes for users, based on factors such as distance, fuel efficiency, and terrain. It uses algorithms to generate optimized paths, ensuring that users can plan routes that minimize fuel consumption and travel time. The system updates routes dynamically in response to user inputs and real-time data, ensuring the most accurate recommendations.

Map Rendering: The Map Rendering subsystem is responsible for displaying 3D and 2D maps. It ensures smooth visualization of routes, satellite imagery, and 3D models. The system adjusts the level of detail based on available data and the user's preferences, ensuring efficient map rendering even in cases of limited data or system limitations.

Security and Privacy: The Security and Privacy subsystem ensures the protection of user data and system integrity. It uses encryption for data at rest and in transit, applying strict access control policies to prevent unauthorized access. The system also conducts regular security audits and employs methods like intrusion detection to ensure that user information and system resources remain secure.

Analytics and Reporting: The Analytics and Reporting subsystem collects and processes usage data to generate insights into system performance and user behavior. This subsystem supports decision-making by providing detailed reports and analytics, helping to improve system functionality, user experience, and route optimization algorithms over time.

Each of these subsystems is essential for the overall performance of the 3D-EcoMap system, ensuring that all processes work efficiently and deliver a high-quality user experience.

5. Glossary

3D Model: A digital shape that shows the height, width, and depth of something.

A* Algorithm: A way to find the best path between two places, using some guesses to make it faster.

Authentication: Checking if someone is allowed to use the system.

Cloud Resources: Online tools and storage that help run programs without needing a powerful computer.

CPU (Central Processing Unit): The "brain" of the computer that runs programs and handles tasks.

Dijkstra's Algorithm: A method to find the shortest way between places on a map.

Fuel Efficiency: How much fuel a vehicle uses to travel a certain distance.

Geospatial Data: Information about where things are on a map.

GPU (Graphics Processing Unit): A part of the computer that helps make graphics look good, especially for 3D models.

Pathfinding Algorithm: A way to figure out the best route from one place to another.

Satellite Imagery: Pictures of Earth taken from space.

Slope Analysis: Checking how steep a road or hill is and how it affects things like fuel use.

Topography: How the land looks, including hills, valleys, and flat areas.

WebGL: A tool that helps show 3D graphics in a web browser.

3D-EcoMap: The project that finds the best routes by looking at road slopes and fuel use.

Environmental Impact: How human actions affect nature, like pollution or cutting down trees.

Route Optimization: Finding the best way to get somewhere while saving time, fuel, or both.

Scalability: How well a system can handle more users or bigger tasks.

Slope Data: Information about how steep the roads are.

User Interface (UI): The buttons and screens people use to interact with an app.

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