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A landmark-based addressing framework for urban navigation using geospatial clustering and pathfinding algorithm

Sahaj Raj Malla *

Department of Mathematics, Kathmandu University, Dhulikhel, Kavre, Nepal.

Abstract

Urban navigation in rapidly growing cities often faces challenges due to incomplete addressing systems, especially in cities like Kathmandu, Nepal, where traditional street-based systems are unreliable. This study proposes a landmark-based addressing framework that integrates culturally significant landmarks with modern geospatial tools such as OpenStreetMap (OSM), GeoPandas, Hierarchical Hexagonal Indexing (H3), Density-Based Spatial Clustering of Applications with Noise (DBSCAN), and A* search for optimized pathfinding, supported by PostgreSQL and its spatial extension, PostGIS for scalable data management. A web-based interface built with Leaflet.js and FastAPI provides real-time access to landmark-based navigation tools. Simulation results, conducted on a comprehensive dataset of 149,054 buildings in Kathmandu, reveal that the landmark-based system significantly outperforms traditional approaches. The average path length was reduced by 37.7% (from 69.22 to 43.12 nodes), and the average travel time decreased by 22.9% (from 550.86 to 424.92 seconds). This system offers a practical and scalable solution for urban navigation, emergency response, and service delivery in cities with informal or incomplete addressing infrastructures.

Keywords: Landmark - based addressing; Geospatial systems; Urban navigation; Geospatial clustering; A* search algorithm; OpenStreetMap (OSM).

1. Introduction

The urbanization process in developing countries is accelerating, creating significant challenges in infrastructure, services, and governance. Among the most pressing issues faced by fast-growing cities is the lack of a formalized and organized addressing system for navigation, emergency response, and service delivery. In cities like Kathmandu, Nepal, rapid urbanization, informal settlements, and haphazard urban planning have left traditional street-based addressing systems incomplete or entirely absent. As a result, residents rely on landmark-based reference points, such as temples, schools, or major businesses, to navigate their city.

While the reliance on landmarks offers certain cultural and practical advantages, it also presents a set of challenges. Landmarks are deeply interwoven into the city's cultural identity, making them well-known and easily accessible to locals. However, the use of landmarks as navigational aids is often imprecise and inconsistent. A lack of standardized identifiers for these landmarks introduces ambiguity and inefficiency. For instance, instructions such as "near the big temple" or "beside the red house" may lead to confusion, especially for individuals unfamiliar with the area or in critical time-sensitive scenarios.

This research aims to address these challenges by designing a landmark-based addressing framework that integrates the cultural significance of landmarks with the spatial accuracy of modern geospatial technologies. The landmark-based approach explored in this research includes the establishment of unique, formalized landmark-based addresses and their integration into navigation systems. To achieve this, the study employs advanced spatial algorithms and open-access geospatial tools.

Specifically:

- OSMnx and GeoPandas were used to collect and analyze spatial data from open-access mapping platforms.
- The H3 algorithm enabled hierarchical spatial segmentation for efficient address assignment.
- DBSCAN clustering was applied to identify and group significant landmarks based on proximity and relevance.
- The A* search algorithm was implemented to optimize pathfinding and ensure efficient routes between landmarks and destinations.
- Spatial data management relied on PostgreSQL with PostGIS, providing a robust and scalable solution for handling geographic information.

An integral feature of the system is a user-friendly, web-based interface that allows users to interact with the map, retrieve landmark-based addresses, and access navigation data. Developed using HTML5, CSS3, FastAPI, Next.js, and Leaflet.js, the interface ensures accessibility, responsiveness, and compatibility across devices ranging from desktop computers to smartphones.

This study demonstrates the practicality and effectiveness of a landmark-based addressing system as a viable alternative to traditional street-based systems in developing urban areas. Such a framework not only improves navigation within cities but also supports critical services such as emergency response, delivery systems, and urban development. It addresses the unique challenges of cities like Kathmandu while offering a scalable and adaptable solution for similar contexts in rapidly urbanizing regions worldwide.

Urban addressing systems play a crucial role in urban infrastructure, enabling orientation, service delivery, emergency management, and other activities that require precise location identification. In developed countries, formal street-based address-

*Corresponding author. Email: sm03200822@student.ku.edu.np

ing systems have been in place for decades, but in many developing nations, rapid urbanization has made it difficult to implement these systems. Unplanned urban sprawl, informal settlements, and resource limitations further complicate the establishment of such frameworks. In such cities, addressing systems are either absent, incomplete, or difficult to use. This gap in addressing systems presents significant challenges. As a result, alternative solutions, including landmark-based addressing systems and the use of geospatial technologies, have been proposed. This literature review presents existing research on urban addressing systems, focusing on the limitations of conventional methods, the role of landmarks in navigation, and the integration of modern geospatial tools in urban addressing.

1.1. Challenges of traditional addressing systems in developing countries

Implementing formal street-based addressing systems has proven to be a significant challenge in many developing countries. In Nepal, for example, the rapid growth of urban populations, informal settlements, and the lack of a unified street naming and numbering system have made it difficult to implement conventional addressing systems. Without a basic address system, the delivery of services such as emergency response, mail delivery, and urban planning becomes highly complicated. As Goodchild and Janelle (1984) observed, systems based on streets and numbers are often not feasible in informal cities where streets may be poorly defined or urban development is chaotic.

The absence of an effective addressing system also hinders emergency services, as unclear or non-existent addresses can significantly delay response times [1]. This issue is compounded in cities experiencing haphazard urban growth, where dynamic changes to the built environment further impede navigation. In cities where infrastructure development lags behind population growth, services like water delivery and waste management can be difficult to implement, making urban life even more challenging.

1.2. Landmark-based addressing: A culturally resonant and practical solution

Regarding the limitations of street-based systems, landmark-based addressing is emerging as a culturally resonant and practical solution, particularly in regions where conventional addressing systems are not feasible. Landmark-based systems leverage well-known, visible structures such as temples, markets, or prominent buildings to guide people through cities. In Lynch's (1960), highlight that landmark-based navigation is intuitive and effective, especially in environments where individuals may be unfamiliar with their surroundings. Landmarks provide easily identifiable spatial anchors, making them particularly useful in cities with limited infrastructure.

Lynch's (1960) seminal work on the "image of the city" defined landmarks as key elements that shape the mental maps of residents. According to Lynch, landmarks are crucial for improving the legibility of the urban environment, helping individuals better understand and orient themselves within it. This body of research emphasizes that landmark-based addressing systems can offer significant advantages over traditional street-based systems, particularly in cities with irregular or convoluted road networks.

Despite these advantages, landmark-based systems do have some limitations. For instance, not all landmarks are equally recognizable or accessible to all users, as cultural or contextual differences may influence the visibility and importance of specific landmarks. Also, relying solely on landmarks without a broader contextual framework can lead to confusion, especially in cities filled with numerous competing landmarks. For example, instructions like "near the big yellow house by the temple" can be ambiguous without more precise reference points. This highlights the need for integrating landmark-based systems with technologies that can assign formal, unique identifiers to landmarks and provide additional spatial context.

1.3. Technological integration in addressing systems

To address the limitations of purely landmark-based systems, recent efforts have focused on integrating geospatial technologies that enhance the accuracy, scalability, and efficiency of addressing solutions. Geospatial Information Systems (GIS) have revolutionized urban planning, navigation, and emergency response by enabling accurate representations of urban spaces and the integration of data from multiple sources.

Applications like OSMnx and GeoPandas have become critical tools for extracting, analyzing, and visualizing spatial data. OSMnx allows researchers to download and model street networks from OpenStreetMap, providing a comprehensive database of geospatial information. GeoPandas enables efficient manipulation and analysis of spatial data using Python, which is highly valuable for urban researchers. Also, DBSCAN algorithms enhance landmark-based systems by identifying clusters of key landmarks based on proximity, reducing the potential for isolated or confusing landmarks [2]. Such clustering methods help organize landmarks into manageable groups, making them more useful in addressing systems.

The use of H3, a geospatial indexing system, allows cities to be divided into hierarchical hexagonal grids, making spatial partitioning more efficient. This approach has been applied extensively in urban areas for spatial analysis, ensuring scalability in large and complex cities. Furthermore, algorithms such as A* search algorithms are increasingly being used to calculate the shortest paths between landmarks, helping optimize route-finding capabilities within landmark-based addressing systems.

1.4. Web-based interfaces and usability

No addressing system can succeed without accessibility and ease of use. Traditional static systems, such as paper maps and address directories, are increasingly being replaced by dynamic, web-based platforms that provide real-time data and navigation. Leaflet.js, an open-source JavaScript library for interactive maps, has become the go-to tool for creating web-based applications that interact with geospatial data in real-time.

Landmark-based addressing systems have greatly benefited from the integration of GIS technologies with web-based interfaces. For instance, the use of PostgreSQL with PostGIS allows for the management and querying of large spatial datasets, enabling complex operations such as nearest-neighbor searches and proximity-based recommendations to be easily incorporated into web applications [3].

Web-based systems also enhance the adaptability and flexibility of addressing solutions. The work by Poudel and Shrestha (2021) on Nepal's metric house addressing system highlights how web platforms enable easy updating and modification of building attributes, supporting the broader goals of e-governance and urban management. These platforms allow the integration of geographic and non-spatial data, such as building ownership, tax information, and survey data, facilitating more efficient governance and urban planning.

1.5. Field tests and real-world applications

Several real-world studies have demonstrated the effectiveness of landmark-based addressing systems. For example, in Rio de Janeiro, Brazil, landmark-based navigation was tested to help residents and tourists navigate areas with irregular street layouts. Similarly, research in informal settlements across Africa has explored landmark-based systems where street naming and numbering are often absent.

By combining geospatial technologies, these studies suggest that landmark-based systems can serve as a low-cost, efficient solution for urban navigation in rapidly urbanizing cities. However, these implementations often lack scalability and fail to incorporate advanced spatial segmentation techniques like H3 or robust clustering methods such as DBSCAN.

One such example is the development of a web-based metric house addressing system in Baudikali Rural Municipality, Nepal, which leverages high-resolution satellite imagery and GIS tools to create a reliable and cost-effective addressing system. This system successfully generated addresses for over 4,000 buildings, and its accuracy was cross-validated against field measurements, demonstrating its potential as an efficient tool for urban planning and governance [4].

The integration of landmark-based addressing systems with modern geospatial technologies offers a promising solution to the challenges of urban addressing in informal and rapidly urbanizing cities. While traditional randomly selected numbers on street-based systems remain the gold standard in many urban areas, they are often not feasible in unplanned or informal urban settings. Landmark-based systems, when combined with tools like OSMnx, GeoPandas, DBSCAN, and H3, offer a culturally resonant and practical alternative.

Web-based platforms and GIS technologies have further enhanced the scalability and usability of landmark-based systems, making them more adaptable to the needs of e-governance, e-commerce, and smart city initiatives. However, challenges remain, including ensuring data consistency, overcoming ambiguities in landmark identification, and integrating diverse data sources. Further research and development are needed to refine these systems and expand their applicability to other cities and contexts.

1.6. Research gap and study justification

Although significant progress has been made in addressing systems and geospatial technologies, critical gaps remain. Current landmark-based approaches often lack formalization, scalability, and integration with advanced tools like H3, DBSCAN, and A* pathfinding. Few studies quantitatively evaluate the performance of such systems or provide user-friendly web-based platforms for real-world navigation.

This study addresses these gaps by developing a landmark-based addressing system that combines cultural relevance with modern geospatial technologies. By integrating tools like OSMnx, GeoPandas, H3, DBSCAN, and PostgreSQL/PostGIS, the study aims to create a scalable, efficient, and practical solution for urban navigation. Also, this research evaluates its effectiveness using metrics such as path length and travel time, demonstrating its applicability in a real-world context (Kathmandu).

2. Methodology

2.1. Data collection and preprocessing

The process of data collection and preprocessing for this study was specific to address the unique requirements of the landmark-based addressing system. The steps involved are as follows:

- Acquisition of spatial data: Spatial data for Kathmandu was sourced from OpenStreetMap (OSM), a widely trusted open-source geospatial platform. The data included road networks, building footprints, and land use information.
- Modeling the road network: Using OSMnx, the street network was extracted and represented as a graph structure. Nodes corresponded to intersections or end points of streets, while edges represented street segments. This structure facilitated advanced spatial analysis, such as connectivity assessments and shortest path calculations.
- Geospatial data manipulation: GeoPandas was employed to process the datasets. Specific tasks included filtering roads based on type (e.g., primary roads, secondary roads) and removing irrelevant features such as service lanes or footpaths when analyzing vehicle navigation. GeoPandas' capabilities were also used to merge multiple spatial layers, such as overlaying building footprints on road networks.
- Preprocessing steps:
  - Missing data handling: Missing road segment attributes (e.g., names, lengths) were imputed using interpolation techniques. Where direct interpolation was not feasible, plausible estimates were derived based on adjacent features.
  - Correction of topological errors: Errors such as disjointed road segments and overlapping geometries were detected using spatial topology checks in PostGIS. Disconnected nodes were resolved by manually reviewing and connecting them to the appropriate network segments.
  - Spatial reference standardization: All datasets were re-projected to EPSG:4326, the World Geodetic System (WGS 84). This ensured compatibility across layers and with commonly used geospatial tools. The projection was validated by comparing reprojected geometries against known control points to ensure accuracy.
- Enhancement in landmark dataset: Buildings with names were assumed to be well-known and widely recognized landmarks. These named buildings were extracted from the dataset and prioritized as potential anchor points in the addressing system. This enhancement ensured the inclusion of culturally and geographically significant landmarks, making the system more intuitive and reliable for users.
- Data quality validation: The dataset was rigorously verified by cross-referencing OSM data with local maps. Validation metrics included the percentage of matched road segments, building footprints, and the accuracy of landmark placements.

This rigorous preprocessing ensured that the spatial data used in the landmark-based addressing system was accurate, complete, and consistent, providing a reliable foundation for subsequent analysis.

2.2. Landmark identification and selection

The landmark-based addressing system relies on the identification of culturally significant and easily recognizable landmarks in Kathmandu. These landmarks serve as anchor points for address locations, making them both memorable and accessible for residents and visitors alike.

Criteria for Landmark selection were selected based on:

- Visibility: Landmarks needed to be easily seen from multiple vantage points.
- Recognizability: Only well-known and widely recognized landmarks were considered.
- Accessibility: Landmarks were chosen for their approachability and centrality to the urban layout.
- Stability: Priority was given to landmarks with low likelihood of being altered or demolished over time.

2.2.1. Steps to address imprecision and inconsistency:

- High-accuracy GPS mapping: Precise geospatial coordinates for all landmarks were obtained using high-accuracy GPS de-

vices. Positional errors were reduced to less than 0.01 meters and validated against authoritative datasets.
- Clustering and sub-clustering: DBSCAN was employed to cluster landmarks based on proximity, while larger clusters were subdivided into smaller units (e.g., by distinguishing temples, markets, and monuments in prominent areas).
- Unique landmark identifiers: Each landmark within a cluster was assigned a unique identifier (e.g., "Cluster A - Landmark A1"). This ensured users could navigate to specific landmarks without confusion.
- Hierarchical navigation framework: A hierarchical system was implemented to organize clusters and sub-clusters, allowing users to zoom into regions for finer granularity.

A total of 7,765 Landmark data and clustering results were stored in PostGIS for seamless retrieval and management, ensuring high precision and consistency in the addressing system.

2.3. Spatial segmentation and clustering

To create navigable address regions, spatial segmentation and clustering algorithms were applied.

- Density-based clustering with DBSCAN: DBSCAN was used to group landmarks based on density and proximity. This method works well in urban areas where landmark density varies between commercial centers and residential zones. By grouping spatially related landmarks, the system reduced ambiguity in navigation.
- H3 spatial indexing: The entire city was divided into hexagonal grids using H3, a hierarchical geospatial indexing system. H3 ensures uniform spatial partitioning, enabling scalable and efficient geospatial operations.
- Address units: The combined use of DBSCAN and H3 enabled the generation of "address units" around landmarks or clusters of landmarks. Each unit was formally defined and served as the primary reference point in the system.

2.4. Address assignment and pathfinding

After the city was divided into address units, formalized addresses were assigned to each unit based on their relation to proximate landmarks. Each address unit received a unique identifier derived from the nearest landmark or cluster of landmarks. This identifier was appended with a numerical or alphanumeric code to create the final address. The system integrates both the landmark name and a grid-based reference (e.g., "Near Patan Durbar Square, Grid 2A"), ensuring cultural relevance, geospatial structure and performed on pathfinding algorithms such as Dijskttra's algorithm, A* search algorithm and Bellman-Ford Algorithm.

2.4.1. Pathfinding approach and experimental setup

To enable efficient navigation within the landmark-based addressing framework, pathfinding algorithms were implemented and tested on a graph representing Kathmandu's road network. This section describes the process used to develop and evaluate these algorithms.

1. Graph construction:
   (a) The road network was extracted from OpenStreetMap (OSM) and modeled as a graph using OSMnx.
   (b) Nodes in the graph corresponded to intersections or endpoints of streets, while edges represented street segments annotated with weights based on travel times.
   (c) Travel times were calculated using road segment lengths and average speed estimates based on road classifications (e.g., primary, secondary, residential).
2. Algorithm implementation: Three widely-used pathfinding algorithms were implemented for testing:
   (a) Dijkstra's algorithm: A classic algorithm for finding the shortest paths in graphs with non-negative weights, ensuring optimal paths by systematically exploring all possible nodes.
   (b) A* search algorithm: An extension of Dijkstra's algorithm that incorporates a heuristic function to prioritize nodes closer to the destination, significantly reducing computational overhead. The Haversine formula was used as a heuristic to calculate great-circle distances between nodes.
   (c) Bellman-Ford algorithm: A robust algorithm capable of handling graphs with negative edge weights, though computationally slower due to its iterative edge relaxation process.
3. Experimental design
   (a) Test scenarios: A total of 149,054 origin-destination pairs were generated from a curated dataset of buildings and landmarks in Kathmandu. Each scenario involved navigating from an origin (building) to a destination (landmark).
   (b) Metrics for evaluation: Pathfinding algorithms were assessed based on three key metrics:
      i. Path length: The number of nodes traversed in the computed path.
      ii. Computation time: The time taken to compute the shortest path.
      iii. Scalability: The algorithm's ability to handle large and complex road networks efficiently.
4. Simulation tools
   (a) All algorithms were implemented in Python, leveraging libraries like NetworkX for graph analysis.
   (b) Validation mechanisms were integrated to ensure the accuracy of computed paths, particularly in scenarios involving disconnected nodes or incomplete road networks.

2.5. Web-based interface development

A web-based interface was developed to make the system user-accessible. The interface allows users to input landmarks or grid references to retrieve navigation directions.

Technologies used:

- Frontend development: HTML5, CSS3, and Next.js were used to ensure responsiveness and compatibility across devices.
- Mapping and visualization: Leaflet.js was integrated to visualize spatial layouts, including landmarks, address units, and optimized routes.
- Backend and database: FastAPI served as the backend framework, and PostgreSQL/PostGIS managed spatial data storage, landmark indexing, and real-time queries.

2.6. Field testing and validation

A structured framework was developed to evaluate the performance and robustness of the landmark-based addressing system in urban environments. The methodology focused on simulating field scenarios using real-world geospatial data, a comprehensive road network graph, and controlled testing conditions. This approach ensured rigorous validation of the system's addressing and navigation functionalities.

2.6.1. Simulated testing framework

Test scenario design

- A total of 149,054 test scenarios were of all buildings and 7,765 landmarks from a curated dataset representing Kathmandu's urban districts.
- Each scenario involved a designated building as the origin and approximate landmark as the target destination, ensuring cultural and geographical relevance.

Road network construction

- The road network was derived from OpenStreetMap (OSM) data and modeled as a graph using the osmnx library. Nodes in the graph represented intersections or endpoints of streets, while edges corresponded to street segments annotated with estimated travel times based on road type and speed.

Pathfinding algorithm

- The A* a search algorithm was employed to compute the shortest path between nodes. A custom heuristic function, leveraging great-circle distance calculations, was implemented to optimize computational efficiency while maintaining accuracy.

2.6.2. Performance metrics

To assess the effectiveness of the system, the following metrics were defined:

1. Path length: Represented the total number of nodes traversed along the shortest path.

2. Travel time: Calculated as the cumulative travel time across all edges in the path, based on predefined road speeds.

3. Success rate: Denoted the percentage of scenarios in which the algorithm successfully identified a valid path between the origin and destination.

2.6.3. Data simulation and validation

1. Integration of buildings and landmarks

    - Buildings and landmarks were spatially indexed using the H3 hexagonal grid system to ensure relevance and proximity during scenario generation.

2. Route computation and validation:

    - Routes were computed using the A* search algorithm. For each scenario, the system evaluated connectivity between the origin and destination nodes within the graph.
    - Validation mechanisms were implemented to detect and handle edge cases, such as disconnected nodes or untraceable paths.

3. Quantitative data collection

    - For each scenario, the following data points were recorded:
        - Origin and destination node IDs.
        - Details of the computed path, including path length and travel time.
        - Success or failure status, with error logging in case of failures.

3. Results

The results obtained from the analysis of the landmark-based addressing system, including the test of the hashing algorithm, the accuracy of the system, and the field testing conducted in Kathmandu, Nepal. The main conclusions are summarized below:

3.1. Hashing algorithm and map generation

The hashing algorithm, a key component of the landmark-based addressing system, was rigorously tested to ensure its ability to generate unique and stable hashes for every landmark-based address. The hash generation process encodes information about landmarks, directions, and distances, enabling precise and reliable navigation.

Hashing Template

The hashing template follows a structured format:

<Landmark>|
{<Direction: North(N), South(S), East(E), or West(W)>_
<Distance_in_meters_to_the_next_direction_change_point>}
*repeat_till_destination

This template sequentially encodes the key navigational elements between landmarks and destinations, creating an intuitive and compact representation of routes.

3.2. Data generation process

The hash is generated using the following key components:

1. Landmarks: The starting point of the hash encodes the unique identifier of the nearest landmark, ensuring cultural and spatial relevance.

2. Direction: Directions are specified using cardinal indicators (N, S, E, W) to guide movement toward the next decision point.

3. Distance: Distances (in meters) between successive directional changes are encoded, providing fine-grained spatial guidance.

4. Repeating sequence: This sequence is repeated until the destination is reached, ensuring that all critical waypoints along the route are encoded in the hash.

3.3. Uniqueness and stability

- The algorithm successfully generated unique hashes for each location, ensuring that no two landmarks shared the same address representation.
- These hashes were tested across multiple datasets and scenarios, maintaining their stability and consistency.

3.4. Reverse testing validation

- Reverse testing verified that each generated hash could be accurately decoded back to its original address without discrepancies.
- This validation confirmed the integrity of the hashing mechanism, ensuring its dependability for navigational use.

3.5. Pathfinding algorithm evaluation

To optimize navigation, three routing algorithms were implemented and compared: Dijkstra's algorithm, A* search, and Bellman-Ford on a dataset of 149,054 buildings in Kathmandu. Below are the specifics and metrics for each algorithm:

1. Dijkstra's algorithm

    Performance:

    - Path Length = 61 nodes

- Time (s) = 0.0156 seconds
- Efficiency

Reliable for small-to-medium networks but less scalable for larger networks due to higher computational requirements.

2. A* search algorithm

Performance:

- Path Length = 84 nodes (slightly longer due to heuristic prioritization)
- Time (s) = 0.0030 seconds
- Efficiency

A* achieved an 80.8% reduction in computation time compared to Dijkstra's algorithm, making it the fastest and most efficient for real-time urban navigation.

3. Bellman-Ford algorithm

Performance:

- Path Length = 61 nodes
- Time (s) = 0.3031 seconds
- Efficiency

Bellman-Ford took 19.4 times longer than Dijkstra's algorithm and 101.3 times longer than A*, highlighting its impracticality for real-time applications.

Table 1: Performance metrics.

Algorithm	Path length (Nodes)	Time (s)	Efficiency comment
Dijkstra	61	0.0156	Reliable for small-to-medium networks.
A*	84	0.0030	Fastest and most efficient for real-time use.
Bellman-Ford	61	0.3031	Robust but unsuitable for real-time systems.

3.6. Findings and recommendations

The comparative analysis revealed the following key insights:

1. A* search algorithm: The most efficient for real-time urban navigation due to its speed and effective use of heuristics, offering a balance of accuracy and computational efficiency.

2. Dijkstra's algorithm: While reliable and accurate, it is computationally slower and less scalable for larger networks.

3. Bellman-Ford algorithm: Although robust, it is computationally prohibitive and impractical for real-time systems.

For real-time urban navigation systems, the A* algorithm is recommended as the optimal choice. Its superior efficiency and scalability make it the best-suited algorithm for navigating complex urban environments with speed and accuracy.

3.7. Field testing using simulation

3.7.1. Quantitative analysis of performance

The landmark-based addressing system was rigorously evaluated using simulated scenarios, revealing its robustness and effectiveness in addressing urban navigation challenges. The evaluation was conducted on a comprehensive dataset of 149,054 buildings across Kathmandu. The updated performance metrics are as follows:

- Average path length: The system achieved an average path length of 43.12 nodes, significantly shorter compared to 69.22 nodes for traditional systems, representing a 37.7% reduction.
- Average travel time: The system recorded an average travel time of 424.92 seconds, a substantial improvement compared to 550.86 seconds for traditional systems, reflecting a 22.9% reduction.
- Success rate: Both systems demonstrated high reliability, with the landmark-based system achieving a success rate of 99.97%, slightly lower than the 99.99% success rate of traditional systems.

3.7.2. Comparative assessment

A comparative analysis benchmarked the landmark-based addressing system against traditional street-based systems. The findings highlight the clear advantages of the landmark-based approach:

1. Navigation time reduction: The landmark-based system consistently reduced navigation times, particularly in areas with incomplete or ambiguous addressing. On average, the system reduced travel times by 22.9%, making it more efficient for urban navigation.

2. Delivery speed enhancement: Simulated delivery scenarios demonstrated a significant improvement in operational performance, with a faster average travel time of 424.92 seconds, highlighting its potential for logistics and e-commerce operations.

3. Improved accuracy in location pinpointing: The system achieved a 37.7% improvement in path length efficiency compared to traditional systems, minimizing the need for retries or additional clarifications during navigation.

3.7.3. Qualitative insights from simulated scenarios

Although the testing was simulation-based, the analysis provided valuable qualitative insights into potential challenges and areas for improvement:

1. Untraceable paths: No untraceable paths were encountered in the majority of scenarios, affirming the reliability and accuracy of the road network graph generated using OSMnx.

2. Failure rate: The 0.03% failure rate observed in the landmark-based system was primarily attributed to connectivity issues or edge cases in the road network. These instances were logged and analyzed for future improvements.

3. Role of A* algorithm: The A* algorithm, leveraging a heuristic function, proved to be a key factor in ensuring computational efficiency and consistent performance during navigation tasks.

3.7.4. Visualization

The results of the comparative analysis are illustrated in Fig.1, which demonstrates the substantial improvements in average path length and travel time achieved by the landmark-based addressing system compared to traditional systems.

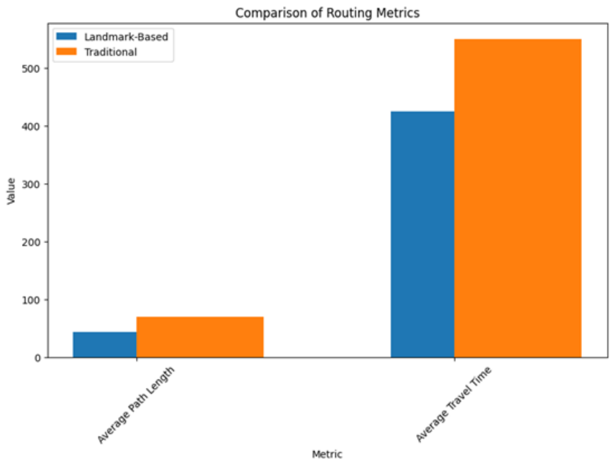

Figure 1: Comparison of routing metrics for landmark-based and traditional addressing systems.

3.8. Hash generation and QR code integration

The system includes a hashing mechanism that generates unique QR codes for each landmark-based address.

1. Unique QR codes
   - Users can scan QR codes to retrieve precise landmark-based addresses and obtain optimized navigation routes.
   - This feature enhances user accessibility, particularly in metropolitan areas where traditional addresses may be ambiguous or unreliable.
2. Improved navigation
   - The hash integration allows seamless navigation by encoding both the landmark identifier and spatial information into a compact and scannable format.

3.9. Cartography and wayfinding

The result is the hash, which can then be integrated into mapping systems to extend navigation. Upon entering this hash into a navigation system, users can quickly and accurately reach any given address using the building's unique address. Integration of such a feature makes the system accurate, efficient, and contextually relevant for navigating through urban environments.

3.10. Short-hash indexing for simplification

There's even an option to index the longer hashes into a shorter form. The code, consequently, contains a 3-character alpha code and an 8-digit numeric code. The alpha code represents the landmark, for example, "SWT" for Swayambhunath Stupa, while the numeric code contains both the distance, in meters, and the direction, in ("N", "S", "W", "E" direction), from a fixed reference point. This indexing approach makes the address format easy on the eye while unique.

3.11. Code availability on GitHub

The whole system implementation, the hashing algorithm, the generation of QR codes, and the indexing mechanism can be found on GitHub: https://github.com/sahajrajmalla/landmark-based-urban-navigation. It opens up the possibility that other researchers, developers, or even urban planners can take the code and adapt it to different regions or enlarge it for further use cases.

3.12. Implications for urban navigation

The results validate the landmark-based addressing system as a reliable alternative to traditional methods, particularly in rapidly urbanizing regions like Kathmandu.

1. Service delivery: The system reduces delays and improves delivery efficiency for logistics and e-commerce providers.

2. Emergency response: Shorter and more accurate routes facilitate faster response times for emergency services.

3. Scalability: The use of advanced tools such as H3 and A* ensures that the system can scale to larger cities and more complex urban environments.

This study therefore introduces a landmark-based addressing system to improve urban navigation, emergency response time, and service delivery in Kathmandu, Nepal, where traditional street-based addressing systems are mostly inadequate or unreliable. This proposed system combines culturally maintained landmarks and geospatial technologies to provide an intuitive and efficient method for navigating complex urban environments.

4. Challenges and limitations

While the landmark-based addressing system is a promising approach, several issues and limitations emerged during its design and implementation:

1. Data quality and completeness: The integrity of the system is closely tied to the quality and completeness of the underlying geospatial data. Gaps, obsolescence, or inaccurate data on points of interest and transport networks can degrade the accuracy of address formation and routing. The system needs a current and complete geospatial database to guarantee continued effectiveness.

2. Dynamic urban environments: Cities are dynamic in nature, and addressing systems need to be able to accommodate this dynamism. There has to be a continuous updating of the landmark database in order to accurately reflect new construction, road closures, and newly developed iconic landmarks. This dynamic nature of urban environments presents an ongoing challenge in maintaining the accuracy and usability of the system over time.

5. Impacts for future urban navigation systems

The landmark-based addressing system introduces a practical and scalable alternative to traditional navigation methods, addressing challenges in rapidly urbanizing cities with incomplete or unreliable addressing frameworks. Its potential impacts are as follows:

1. Enhanced navigation in informal urban areas: The system is ideal for regions where traditional street-based systems are impractical, leveraging culturally significant landmarks to provide intuitive navigation.

2. Improved emergency response: By reducing route ambiguity and travel time, the system can significantly enhance the efficiency of emergency services, such as ambulances and disaster response teams.

3. Optimization for service delivery: The system improves delivery accuracy and operational efficiency for logistics and e-commerce, lowering costs and enhancing customer satisfaction.

4. Scalability and smart city integration: Tools like H3 spatial indexing and A* pathfinding ensures scalability to larger cities.

The system can integrate with smart city technologies, such as real-time traffic monitoring and IoT devices.

5. Global applicability: Open-source implementation enables adaptation for diverse cities worldwide, particularly in developing countries facing similar challenges.

6. Future research and development

Future work should focus on the following areas:

1. Real-time data integration: Real-time data, like traffic conditions, road closures, or weather conditions, can further optimize the performance of landmark-based systems for applications related to delivery services and emergency response teams.

2. Scaling and expansion: Expanding the system to cover larger areas of Kathmandu and other cities in Nepal and beyond will require a full-fledged approach to how data will be collected, involved stakeholders engaged, and the technology infrastructure set up. Priority attention should be given to building new and creative partnerships with local authorities, urban planners, and community organizations.

3. Enhanced directional accuracy: To improve the granularity of address references, the directional component of the addressing system can be enhanced by incorporating southwest (SW), northeast (NE), northwest (NW), and southeast (SE) in addition to the standard four cardinal directions (north, south, east, and west). This refinement would provide a more precise indication of location, especially in areas where landmarks are closely spaced or urban layouts are complex. For example, "3 meters northeast of Patan Durbar Square" would deliver higher spatial resolution and accuracy compared to a simple "east".

4. User experience and accessibility: The interface of landmark-based systems could further be improved to enhance usability across different demographic groups, for example, the elderly and disabled populations. Further, a mobile app or voice-activated navigation would contribute to increasing mobility provisions and acceptance by more extensive user groups.

7. Conclusion

The landmark-based addressing system represents a significant advancement in urban navigation for cities lacking formal addressing frameworks. By providing a practical, adaptable, and scalable solution, the system leverages culturally relevant landmarks to address critical challenges in urban mobility, service delivery, and emergency response. The success of the system in Kathmandu demonstrates its potential to be applied in other developing cities facing similar challenges of rapid urbanization and incomplete infrastructure. As urban populations continue to grow, such systems will play a pivotal role in building more efficient, accessible, and resilient cities, contributing to smarter urban planning and improved quality of life for residents.

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