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Augmented Reality-Based Outdoor Navigation System for Urban Firefighting: A Case of Dar es Salaam, Tanzania

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Abstract

Objective: This study aimed to develop an Augmented Reality (AR) based system for outdoor navigation to aid fire truck drivers in reaching incident areas during emergency response in Dar es Salaam, Tanzania. It involved developing three modules: an emergency incident reporting mobile application to improve incident localization, a route planning module to enable the visualization of routes and their conditions, and the AR navigation module to deliver real-time AR-based navigation instructions. **Methods:** Web AR technologies, specifically WebXR and Three.js, were employed to render AR navigation instructions based on a preselected route from the route planning module, which was developed using the Google Maps JavaScript, Places, and Routes APIs, and complemented with an added layer of house data by leveraging QGIS. Ionic Framework was used to develop the emergency incident reporting platform. The system's effectiveness was evaluated through User Acceptance Testing (UAT) with 45 Dar es Salaam civilians and 5 fire brigade officers. **Findings:** The developed system improves incident localization through automatic location sharing via the emergency incident reporting platform and searchable address data via the custom geospatial dataset. It also improves the clarity of navigation instructions through its AR navigation module and routing decisions with its route planning module. During system validation, 91% of the participating civilians completed the emergency incident reporting task without prior training. Furthermore, all the participating officers reported clearer navigation instructions for the AR component, with particular appreciation for the route planning module. Although no direct comparison with existing methods was conducted, validation results revealed the system's potential in improving emergency response in Dar es Salaam. **Novelty:** This study presents a context-aware AR navigation system integrated with a custom geospatial dataset that lacks in most previous studies and existing solutions. This integration enhances incident localization, route planning, and navigation, essential factors in improving emergency response.

Keywords: Emergency Response; Outdoor Navigation; WebXR; Augmented Reality; Urban Fires

1 Introduction

The devastating impacts of urban fires cannot be overlooked. Urban fires, defined as any fire incident in an urbanized area, result in more than 300,000 deaths annually worldwide[1]. Rapid increase in population density and vehicular ownership, along with complex urban infrastructure, fuel the occurrence and propagation of urban fires while posing unique challenges in urban firefighting[2]. Destruction of properties, including infrastructure, buildings, and vehicles, makes urban fires a disaster not just to human beings' physical and psychological well-being[3], but also economic[4]. Furthermore, urban fires, like other types of fires, lead to environmental degradation, ultimately impacting our climate and contributing to global warming[5].

The impacts of urban fires are more pronounced in developing countries due to various reasons, including poor urban planning, increased urbanization, poor emergency management, inadequate emergency response equipment, and poor infrastructure[5]. In Tanzania, for instance, 1,854 fire incidents were registered in 2022, resulting in 32 deaths and 66 injuries[6]. These statistics rose in 2023, in which 2,076 fire incidents were registered, resulting in 38 deaths and 146 injuries[7]. Dar es Salaam, Tanzania's commercial capital and its most populous city[8], is also its leading region in registering fire incidents[9]. Moreover, the city faces rapid urbanization[10], a factor highly associated with increased fire incidents[11] and complicated firefighting efforts[12]. Between 1967 and 2019, Dar es Salaam's population tripled, and it is projected to surpass 10 million by 2030 if current trends continue[13]. These factors underscore the need to improve firefighting operations in Dar es Salaam through technological innovations.

Various studies have integrated different technologies at different stages of firefighting to improve emergency response. For instance, a study by[14] utilized drone technology to assess fire incident sites. Similarly, a study by[15] used drones equipped with fire extinguishing balls to assess fire incident sites and extinguish urban fires in efforts to improve the precision of urban firefighting with unmanned technologies. A study by[16] developed robotic firefighting to minimize firefighter casualties and fatalities.

Augmented Reality (AR) is a branch of Extended Reality (XR) technologies that superimposes digital content into the real world, enabling users to interact with both real and virtual environments simultaneously through devices such as head-mounted displays (HMDs), smartphones, and tablets[17]. AR has also been utilized in various studies to improve outdoor navigation in emergency response. In a study by[18], an AR-based ambulance dispatch system was developed to guide emergency responders to road accident sites. The system utilized vibration sensors to detect vehicle accidents and GPS to capture the location coordinates. This study, however, totally relied on Google Maps for spatial information, which, despite its outstanding performance in mapping, it lacks detailed geospatial data in certain regions, especially developing regions like Dar es Salaam.

A Mobile Augmented Reality System (MARS) was proposed in a study by[19]. The proposed system leveraged preexisting building image markers for building evacuation and GPS for outdoor navigation instructions. This system, however, placed less emphasis on outdoor routing challenges such as traffic conditions. Another study by[20], leveraged university campus landmarks to overlay digital cues in the AR scenery for emergency response and evacuation. However, this study relied on campus-specific features for AR overlay, making system scalability to larger areas, such as districts and regions, harder.

This study presents two novel contributions that address limitations in existing AR-based emergency response systems. First: context-aware geospatial data integration. Unlike[18], which relied exclusively on commercial mapping services, this study integrates a custom house-level geospatial dataset. This integration addresses a gap in the lack of detailed spatial granularity, which is a problem in developing urban regions such as Dar es Salaam. While most commercial mapping solutions, such as Google Maps, offer street-level identification, this study offers house-level incident localization, which is extremely important for faster location identification, especially in densely populated developing regions such as Dar es Salaam.

Second: integrated emergency response workflow. Existing studies addressed isolated components of emergency response, such as incident reporting and navigation[18], navigation, and evacuation[19],[20]. This study presents an integrated system that seamlessly connects incident reporting, traffic-aware route planning, and real-time AR navigation in a unified workflow specifically designed for urban firefighting operations. Additionally, to better accommodate the diversity of device platforms, which is common in institutions like the fire brigade, this study proposes a web-based AR solution. The web-based AR solution will also reduce the consumption of users' device storage, hence providing a more lightweight AR navigation experience. The remainder of this paper is structured as follows: Section 2 presents Methodology, Section 3 presents Results and Discussion, and Section 4 concludes the paper.

2 Methodology

This section presents the methods and tools used to develop and validate the developed system. It is subdivided into four main sub-sections: geospatial data acquisition, geospatial data preprocessing, system development, and system validation.

2.1 System Architecture Overview

The study employed a modular architecture with three interconnected modules in system design and development:

1. A cross-platform incident reporting mobile application: for incident reporting.
2. A route planning subsystem: for managing reports from the incident reporting platforms and other reporting means, such as the 114 dial, and planning routes for both cases.
3. A web AR navigation component: for rendering route directions based on a preselected route in the route planning module.

The system's workflow is modeled in an activity diagram, as shown in Figure 1. It should be noted that, for the case of this study, the fire brigade personnel interacting with the system, particularly the route planning and AR navigation modules, are at times referred to as the administrator.

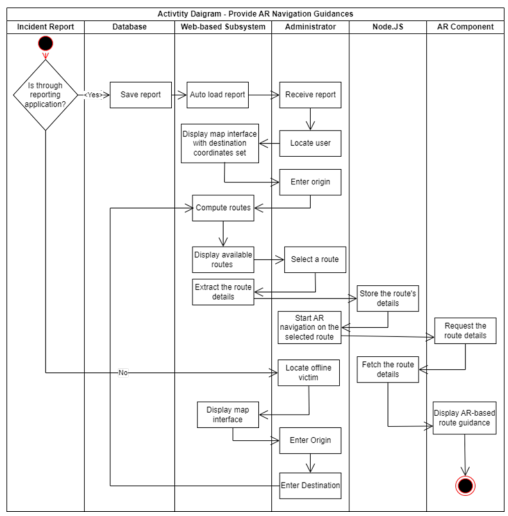

Fig 1. Activity Diagram illustrating the system's core functionality of receiving AR navigation guidance

2.2 Geospatial Data Acquisition

In this study, the first source of geospatial data was Google Maps, which was used as the base map, acquired through its JavaScript API in the Google Developer Console. A secondary geospatial dataset of houses was then acquired from the OpenStreetMap (OSM) in Quantum Geographic Information System (QGIS) using the QuickOSM plugin. This data was used to complement the base map by enhancing spatial accuracy and incident localization, especially for incidents that will be reported via the 114 hotline. The data was initially of 692 MB size (see Figure 2). When this data in its original size was integrated into the system, it tremendously impacted the system's performance; therefore, necessitating thorough data preprocessing.

2.3 Geospatial Data Preprocessing and Integration

The house data layer was preprocessed in QGIS in three phases. QGIS provided the needed environment and tools for every phase. After visualizing the data in rows and columns, the first phase involved removing all the unnecessary columns in the dataset, retaining only the building identifier and street columns.

The second phase involved removing all records with null or invalid values. In this phase, records with null values in each column were filtered and deleted. Then, every record for each column was observed to check the validity of the data. In order for a building identity to be valid, it had to either be a number only or a string with a format like: MKS/MBN/XXX, where XXX denotes a number and the first two entries (MKS and MBN) are strings. For the street column, for the value to be valid, it had to be a string, as Dar es Salaam streets are in string.

The third and final phase involved spatial cleaning. In spatial cleaning, building polygons were visualized in a map canvas. In this 2D map view, every building was observed, and every open building was closed to ensure that each building's outline was complete. The final output in 4MB size (see Figure 3) was exported into GeoJSON format and integrated into the base map.

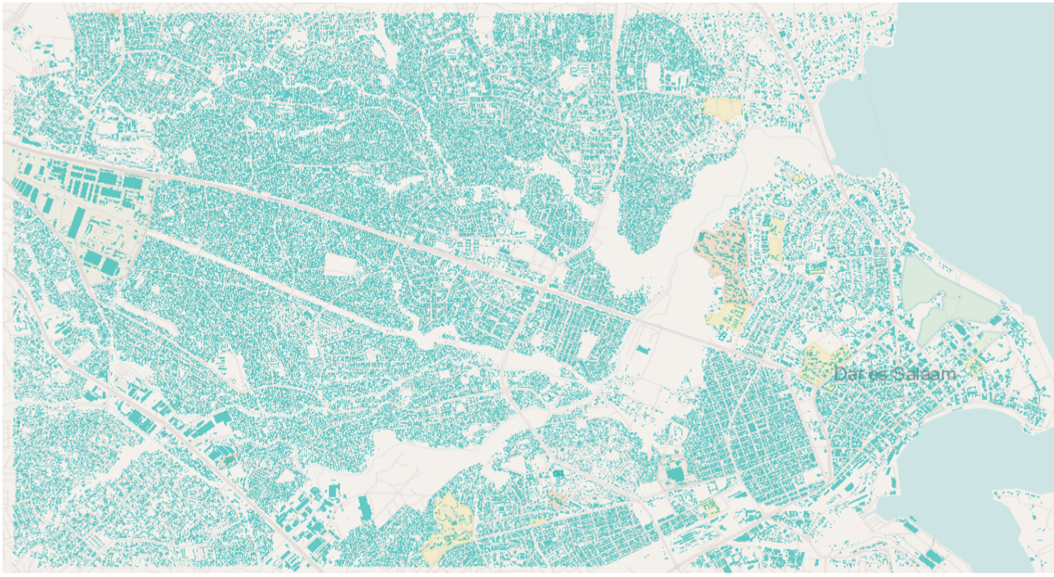

Fig 2. Custom Geospatial Data before Preprocessing

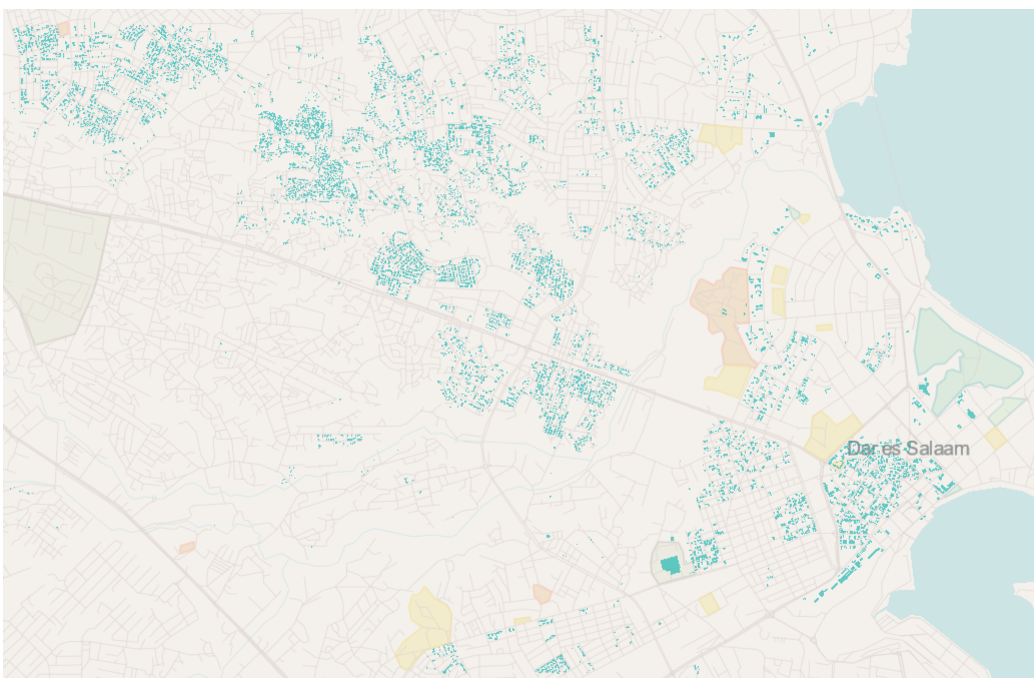

Fig 3. Custom Geospatial Data after Preprocessing

2.4 System Development

2.4.1. Emergency Incident Reporting Platform

The emergency incident reporting platform was designed to be used by civilians to report emergency incidents to the fire brigade in Dar es Salaam. Its front-end was developed using the Ionic Framework, enabling the development of three platforms: Android, iOS, and web, in a single Angular code. Its backend was developed using PHP, and the database used was MySQL. The application uses GPS to track the reporter's location during incident reporting for improved incident localization.

2.4.2. Route Planning Module

The route planning module was designed to be operated by the fire brigade personnel to manage and respond to emergency incidents. The module communicates with the emergency incident reporting module via a single MySQL database used for both modules. It was developed using PHP and integrates several Google Maps APIs, other than the JavaScript API mentioned in subsection 2.2. It also integrates the Places API to implement autocomplete in the base map's data and to geocode the location inputs, and the Routes API to compute routes in a traffic-aware mode. Both these APIs were obtained in the Google Developer Console. Additionally, the module is also incorporated with live traffic data from Google for deeper traffic insights.

Another significant feature of this module is a custom autocomplete apart from the autocomplete offered by the Places API. This autocomplete queries the custom-added house data layer by just typing in any part of the address. This functionality, along with arrow placement in the building on the map, is achieved through JavaScript. A client-side script filters address strings from the integrated GeoJSON data continuously and returns matching results accordingly as the user inputs in the input fields. This feature is relevant to ensure smooth querying of the added geospatial data in the system, particularly important for incidents reported in the 114 dial, as they do not come with location tags. In the 114 call, a user can therefore just provide their house address and be reached accordingly. Once a route is selected, its waypoints are decoded using the Google Maps polyline algorithm, and this waypoint data, alongside the ID and relevant metadata, are sent to a Node.js server. This Node.js server is built with the Express framework and hosted on Render for better accessibility.

2.4.3. AR Navigation Component

The AR navigation module was implemented using the WebXR API and the Three.js library. WebXR was used to implement immersive AR experiences by leveraging device sensors. Table 1 illustrates the sensors along with their purposes. Three.js, on the other hand, was used to create and display the navigation elements in 3D through its geometry and material features.

Table 1. Device sensors and their uses

Sensor	Use
Magnetometer	For calibration and direction
Accelerometer	To track movement and orientation
Gyroscope	To track angular velocity
GPS	To track location
Camera	For continuous capture of the environment for AR overlay

This module's operation begins with fetching a route's data from the Node.js server (stored in JSON after the administrator selects a route in the route planning module). Routes are fetched based on their IDs. The module then uses the Haversine formula to transform the fetched waypoints data into AR space coordinates, whereas the navigation elements developed with Three.js in the form of directional arrows are placed in each space coordinate from the first one, and the destination marker is placed in the last coordinate. The module uses a reticle and AR hit testing to anchor these objects on the road surface.

2.5 System Validation

For system validation, the study used a quasi-experimental setup involving User Acceptance Testing (UAT) with two target groups:

1. Civilians: The emergency incident application was deployed on Android, and its APK file was created in Android Studio and distributed to 45 residents of Dar es Salaam for a 2-day testing period.
2. Fire Brigade Personnel: The route planning and AR navigation modules were tested at the Ilala Fire Station with 5 personnel on the following day after a 2-day testing period by the civilians. The data from the civilians' inputs were used for testing at the fire brigade.

Participants performed predefined tasks using the system's module(s) to which they were provided access. Civilians were asked to register, log in, and report an emergency incident, as well as interact with different other features of the application in either Swahili or English, depending on their language preferences. The fire brigade personnel, on the other hand, were asked to select a route based on their selected origin and destination for both incidents reported via the emergency incident reporting application (using the civilians' data) and outside the emergency incident reporting application. In short distances, the personnel were also tasked to follow AR navigation instructions for a preselected route.

Both groups were provided with post-task surveys for system validation to assess various aspects of the system's modules with which they had interacted. The results of the civilians for each validation aspect were computed by taking the mean score of user responses based on a 5-point Likert Scale (1 = Strongly Disagree, 2 = Disagree, 3 = Not Sure, 4 = Agree, 5 = Strongly Agree); while the results of the fire brigade personnel were treated and analyzed as they were. The post-task surveys were mainly focused on evaluating the system modules in five main criteria described below:

1. Usability: The ease of use and navigation of the system modules.
2. Learnability: The ability of new users to understand and complete tasks in the modules.
3. Usefulness: The perceived potential of the system module(s) to improve emergency response.
4. Spatial Accuracy: The perceived precision of the location data and route guidance.
5. Responsiveness: The time taken to compute and render route and navigation instructions.

3 Results and Discussion

This section presents the study's output, findings, and implications. It is subdivided into two main subsections: system output, which discusses the system's modules, and system validation, which discusses validation results and their implications.

3.1 System Output

This research study builds on previous research[18],[19],[20] that used AR technology to enhance emergency response, particularly in outdoor navigation and evacuation. Despite the use of Dar es Salaam as this study's case area, its results have broader relevance across Tanzania and other urbanized developing regions.

The system's first module, the emergency incident reporting mobile application, provides an alternative to the often congested 114 dial and therefore reduces the problem of delayed reporting. The application supports both Swahili and English, with users selecting their preferred language during registration. This bilingual support improves accessibility by enabling both the local civilians and English-speaking visitors to report emergency incidents. Furthermore, as illustrated in Figure 4, the application enables automatic location capture, reducing errors and delays associated with verbal descriptions of the incident location. Moreover, this platform improves accessibility for individuals with speech impairment by enabling them to make incident reports without the need for voice, as is the case with 114 dial. It should be noted that this group accounts for 27% of the people with disabilities in Tanzania[21]. These accessibility features align with growing research efforts[22],[23] toward inclusive technological solutions.

Fig 4. (a) and (b) depict the emergency incident platform in English and Swahili, respectively

The system's second module, the route planning module, consists of an interactive map that enables the administrator to compute different routes to reach a destination from a particular origin. It enables the administrator to input the origin by automatically capturing their current location. It also enables route computation for remote origins through map clicks and autocomplete searches for both datasets: the base map and the custom house data layer. This module pre-fills the destinations for reports made via the emergency reporting platform and enables the handling of emergency reports made via the 114 hotline by letting the administrator manually input the destination through map clicks and autocomplete searches in the same manner as for the origin. Figure 5 illustrates the route planning module, where three routes were drawn between the selected origin and destination. Below the map, each route's distance and estimated travel time are shown to aid route selection. Figure 6 demonstrates real-time traffic data visualization in the module.

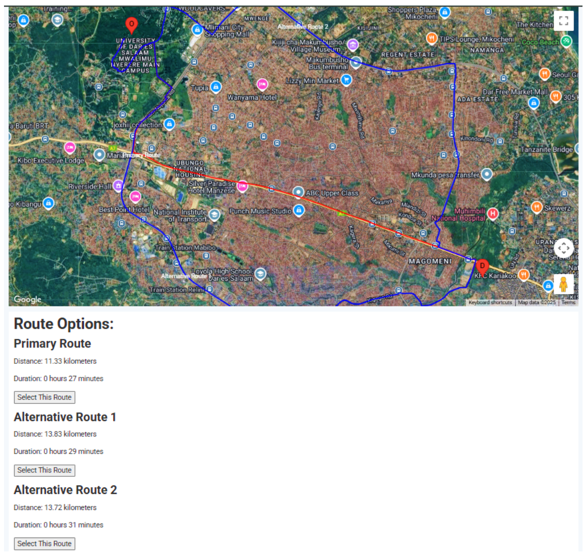

Fig 5. Route Planning Module. The red colored route is the best route with the least estimated arrival time; the subsequent routes are displayed in different shades of blue. Each route is labeled: Primary Route, Alternative Route 1, Alternative Route 2

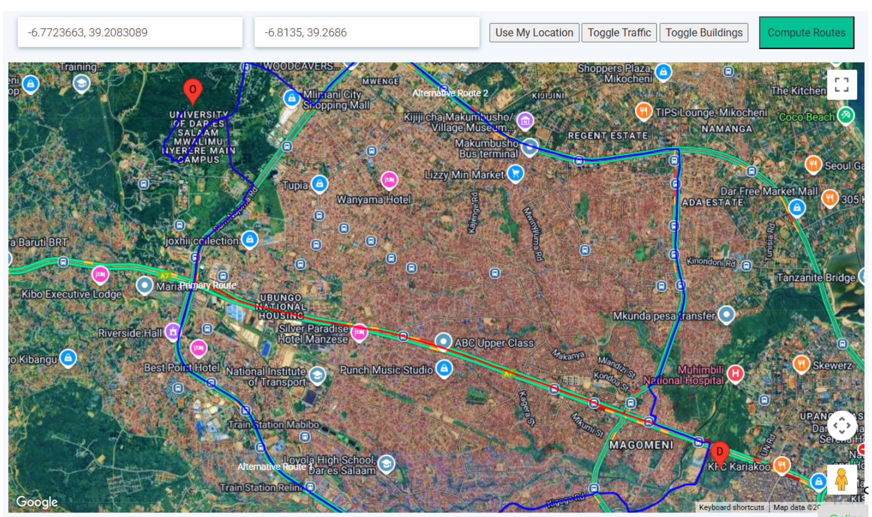

Fig 6. Traffic Data Visualization; green color indicates no traffic delays, orange color indicates moderate traffic, red color indicates heavy traffic, with a darker shade of Red indicating severe congestion

The system's third module, the AR navigation module, uses 3D navigation cues on an AR scene to provide navigation guidance to the firetruck driver. The AR scene, as depicted in Figure 7(a), includes road arrows, heading information, and a debugging section displaying loaded waypoints, distance, and an error message if there is one. It also includes a destination marker that marks the final waypoint. The device loading the AR navigation can be installed in the fire truck using a car smartphone or tablet holder, as illustrated in Figure 7(b), for a better hands-free experience. The route planning and the AR navigation modules help locate the incident areas with better route insights and clearer navigation instructions, removing any delays associated with route selection and unclear directions.

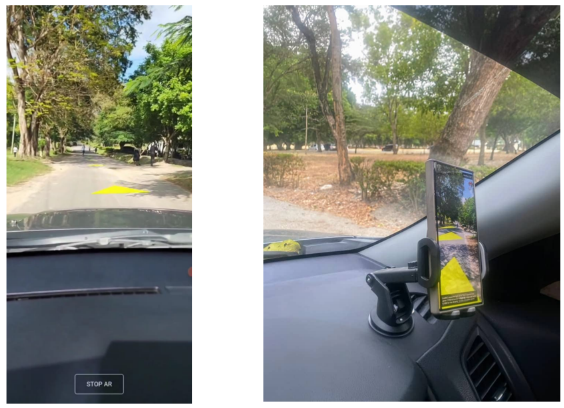

Fig 7. (a) depicting the AR scene and (b) illustrating the loading device attached on a car holder for a hands-free experience

3.2 System Validation

From the participating civilians, 91% of the participants completed the incident reporting task without prior training. The remaining 9% completed the task after a maximum of two training cycles. These results indicate the usability and learnability of the application's design. On usefulness, 80% of the civilian participants were confident that the incident reporting platform would help improve fire rescue response times.

Furthermore, all 5 participating officers appreciated the system's ease of use and the system's value in their operations. On assessing spatial accuracy and responsiveness, 3 of the 5 officers agreed that the system's accuracy fits their operational needs, with the remaining 2 neutral. The officers also provided constructive recommendations for the system: they advised on mapping fire hydrants on the map and visualizing them in AR navigation, which is vital, especially with the ongoing construction activities in Dar es Salaam. The construction activities leave most of the fire hydrants covered up and harder to notice. The officers also advised on including other important stakeholders, such as Tanzania Energy Supply and Company Limited (TANESCO), in the system. Including TANESCO is crucial for fire incidents involving electrical infrastructure.

4 Conclusion

This study has explored the potential of integrating AR, mobile, and geospatial technologies to streamline fire emergency response, from incident reporting to real-time navigation to incident sites, in the context of Dar es Salaam, Tanzania, as a case of a developing urban region. Unlike previous studies[20],[22] that neglected routing traffic analysis and a study by[18] that solely relied on available software for geospatial data, this study incorporates a custom house data layer to optimize location searches, an incident reporting platform for better incident localization, and live traffic data to support route planning.

Strengths and Weaknesses: The strength of this study lies in the complete workflow of fire emergency response from incident reporting to navigating to the incident site. Another strength is the usability and learnability of the modules, as well as the cross-platform support for each of its modules. Nevertheless, this study acknowledges some limitations. The emergency incident reporting platform lacks accessibility features for individuals with visual impairment, who account for over 55% of the disabled population in Tanzania[21]. Furthermore, the effectiveness of the system depends on the performance of the device sensors, which vary across devices.

Enhancements: Despite the efforts to include bilingual support in the emergency incident reporting platform, accommodating more languages and implementing translations could be highly beneficial, given Dar es Salaam's diverse population. Additionally, the study can benefit from the recommendations provided by the fire brigade participating officers, including TANESCO, and mapping fire hydrants into the system.

Future Work: Future studies could research the cognitive load imposed on drivers when using AR-based outdoor navigation in emergency contexts and the role that Artificial Intelligence (AI) can play to help with drivers' cognitive overload and fatigue. This study can also benefit from Natural Language Processing to improve language accessibility for the emergency incidents reporting application.

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