MAARG: Monitoring And Assessment of Road by Geo-citizens - A multi-sensor location aware system for road infrastructure management

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by

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CERTIFICATE

It is certified that the work contained in this thesis, titled 'MAARG: Monitoring And Assessment of Road by Geo-citizens - A multi-sensor location aware system for road infrastructure management' by Bhavana Gannu, has been carried out undermy supervision and is not submitted elsewhere for a degree.

Date	Adviser: Prof. K.S. Rajan

Dedicated to the memory of my grandfather

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Champions keep playing until they get it right. Billie Jean King

Abstract

The idea behind building a road surface and condition monitoring system is that in a developing country like India, we would like to create a sustainable system that can, with the help of geo-citizens, monitor road quality. This task is crucial to the municipal and city authorities to conduct as there is not enough manpower to monitor large road networks of the growing metropolises in the country. This semi-automated location-aware system can augment and help provide critical inputs to infrastructure/road managers in their tasks and deliver results like no other system currently in use.

A crucial aspect of urban infrastructure management in cities is the continuous monitoring and maintenance of roads. Specific departments employed by governing authorities track road deterioration and ensure timely repair and maintenance of roads. Traditional methods in this domain use high-power laser or radar sensors and thereby go on to become intricate and demanding. Apart from the methods in data collection, the process of gathering, assimilating, and post-processing of data is an expensive and time-consuming task with low coverage and often in need of assistance from experts. Additionally, frequent data collection is essential to generate efficient and accountable results. High-end systems are inefficient in covering large areas at frequent and/or regular intervals of time, which leads to complexity in activity planning.

In previous work, we have established that smartphone sensors can be used to determine the surface type and condition of the road. In the current thesis, we use the same algorithm for classification and build over it to develop a system that can address these above-listed challenges in an ever-expanding urban environment. MAARG system consists of three subsystems: Data Collection, Data Processing, and Data Analytics and Visualization subsystems. The mobile application developed serves as a data collection medium for raw data collection and training data collection. Geo-citizens can upload the data collected to a central server. The uploaded data is verified offline and then pushed to a processing server. The processing server runs the classification algorithm and labels it. This data is fused together and divided into logical segments. A majority voting and amalgamation algorithm then consume this data and arrives at the final output that is saved in the database.

MAARG system includes a WebGIS dashboard comprising a back-end Express server that analyses and aggregates information from multiple inputs and showcases it on a browser with the OpenStreetMap as a

background layer (WMS). While the proposed system not only uses tracking information but also image information to give an optimized understanding of the road infrastructure. Hence, MAARG processes positional information and attaches an on-the-fly analysis of the data collected from different sensors. This is achieved by collating multiple users data efficiently. This acts as an input to the query engine and visualizer where the users can visualize different spatiotemporal queries.

MAARG system is an innovative, collaborative system for road condition monitoring leveraging the existing technologies by information fusion approach. Derived from geo-citizenship, we envision an ecosystem operating through a mobile application on smartphones of geo-citizens for large data collection and executing centralized processing. Prime advantages of such a platform are the multiplicity of data points and the crowd-sourcing model.

Data collection from numerous sources ensures statistical advantage and expandable coverage for the monitoring system. Crowd-sourcing model provides reliable coverage and eliminates the need for deploying specialized road monitoring tools. This system is also dynamic to meet the increasing demand and prioritizes the areas of high usage. Overall, the MAARG system can disrupt the existing traditional methods and serve as an alternate innovative solution. This thesis primarily presents the architecture and system design of the three subsystems of the road monitoring system.

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Chapter 1

Introduction

1.1 Infrastructure Monitoring Systems

In today's world, the maintenance of roads is a crucial task for any municipality. Traditional methods used for road monitoring include high-power laser or radar sensors which have low coverage. For example, LASER Road Imaging System (LRIS) in 2005 [1] and similar laser systems like IBEO Laser [2], and PPS [3]. Regardless of the method of collecting, the process of gathering, assimilating, and post-processing of data is an expensive and time-consuming task requiring experts in the field. Additionally, for a system to generate efficient and accountable results, a frequent collection of data is necessary. High-end systems are incapable of covering large areas at frequent intervals of time. Hence, we can understand that there is a need for a system that provides continuous coverage, high frequency, and robust data.

Taking into view the above challenges, we introduce a new and innovative collaborative system for road monitoring leveraging the existing technologies by an information fusion approach. The mobile application on the smartphones of geo-citizens coordinates the data collection and reports back to a central server for assimilation and further processing. The multiplicity of data points and anonymity of the users establishes robustness and the crowd-sourced model ensures frequent and continuous coverage. A smart-phone based system for road monitoring is a good fit for city municipalities because it avoids the need for specialized road monitoring infrastructure.

1.2 Monitoring

The following sections describe in detail the understanding of what is monitoring and how it can be beneficial in the case of roads.

1.2.1 What is monitoring?

Monitoring and evaluation (M&E) are employed to assess the performance of activities, establishments, and programs created by governments and other organizations. Enhancing current and future management of results is the goal. These activities can be monitored by a continuous assessment using elaborate data from the ongoing process or from data collected once the activity is completed.[4] For different infrastructures daily, weekly, monthly, quarterly, and yearly tracking of activities and systematic organizing of data is required.

1.2.2 When should monitoring take place?

Monitoring should ideally be a continuous process that takes place at regular intervals. Monitoring should be conducted at every stage of road construction, with data collected, analyzed, and used on a continuous basis. To get the best benefit out of monitoring, it should take place in three phases.

1.2.2.1 Pre-facto monitoring or Process Monitoring

Quality tests like a ring-ball test to determine the softening point of bitumen are deployed to ensure quality during the laying of any road. The test uses two sets of brass rings and steel balls to analyze and arrive at the correct temperature to heat a bituminous binder. [5]

1.2.2.2 Monitoring during road laying

Road processing machines are used to lay roads and are available in varying sizes and features. There are methods to monitor the path taken by a road processing machine that drives on a land surface and works on adjusting the vertical height accordingly. Monitoring of a road processing machine is done by analyzing 3D positional data of the element and other sensors attached. [6]

1.2.2.3 Post-facto monitoring or Performance Monitoring

This thesis focuses on post-facto monitoring of roads. Generally, post the laying of a road, deterioration varies with respect to the usage and weather conditions of each road. Any road in India has to be designed such that it survives one monsoon season, failing which it is said to not adhere to the standards.

1.3 Existing Approaches Towards Road Monitoring

1.3.1 Manual Monitoring

Despite the advent of technology over the past decade, the use of manual or paper-based surveys in collecting data with regard to monitoring has been a common standard. This could be because of the cost-intensive software development cycle or could be the lack of professional knowledge in this domain. Also, the existing digital solutions for these purposes may lack the ease of use or specific skills and functions required to perform certain tasks. However, traditional paper-based systems have numerous shortcomings. For example, manual entry of data may lead to errors which may reduce the quality of data. Errors can also occur in transcribing and digitizing the data. The cost of logistics can also be very high in these cases.

1.3.2 Satellite and Aerial Based Monitoring

LANDSAT and other satellites

Most of the research conducted on satellite images in the previous decade and before that was limited to the extraction of roads from satellite imagery. For example, in [7] we see the use of multi-spectral high-resolution satellite images to automatically extracted roads. This data even though useful for road extraction, cannot be used for monitoring. In remote sensing data like LANDSAT or even other data with 1 m resolution, details of the road are difficult to capture but only show the road from a bird's eye view where the entire road appears like a line. The brightness of the road is also not captured, nor is the texture of the road. There are newer studies like Qiqi Zhu et. al. [8] and Jiguang Dai et. al. [9] which were able to extract better resolution of the road but are far away from other sensor-based road monitoring systems.

Jengo et. al. [10] shows an approach to utilize hyperspectral sensor parameters' data for pothole detection and aerial imagery for verifying the condition and pothole location. This study used two types of data: hyperspectral imagery as well as aerial imagery. The hyperspectral images were used for spectral detection of the road condition and the aerial images for the selection of training pixels from the ground truth.

The study was conducted in the state of California in the USA, where the road conditions were labeled as substandard for driving. One of the approaches, namely the Rule Generator used a classification and regression tree (CART) to determine the dependency of different variables such as spectral bands, elevation, slope, and vegetation indices on each other statistically. It produced good results with an accuracy of 68% using Quick, Unbiased, and Efficient Statistical Tree (QUEST) and Classification Rule with Unbiased Interaction Selection and Estimation (CRUISE) algorithms. But, it clearly states in the paper that the robustness of this algorithm and some other measure of texture needs to be fine-tuned to get useful output.

UAV Based road monitoring

In agricultural lands, there are many unpaved roads, and with alternating seasons of heavy traffic machinery and rains, many of these roads are severely damaged. Heavy farm machinery can cause more damage to these roads than a series of smaller vehicles. Local governments are responsible for the maintenance of unpaved roads. Zhang,et. al[11] presents a system to assess unpaved roads and map them using a hybrid approach consisting of UAV-based Remote Sensing of Road Condition (UAVRS) and Predictive Road Condition Modeling using Remote Sensing Data (PRCM).

Image processing algorithms were developed to study the condition of the road. This system uses a modified airframe helicopter weighing 6.1 kilograms and is navigated using Rotomotion Automatic Flight Control System hardware (AFCS) and custom Mission Control System software (MCS). The first prototype data collection was done in Rapid City, South Dakota. It is required to maintain the altitude of the UAV at 50m to capture the surface accurately.

The evaluation is done by processing 2D images to detect distress on the road, photogrammetric analysis of 3D imagery, and fusion of both of these to arrive at the final result. The drawback of this system is that it can show potholes but not the full picture.

1.3.3 Onsite Monitoring

Measuring road roughness using a compact profilometer and ArcGIS

With a large variety of necessities throughout the globe, high-quality road management is subject to increasing demand from the perspective of customer-oriented levels of service. In recent years, road management are requested to form a visible map of a road network to observe conditions. To satisfy these needs, this study was conducted as follows.

[12] details a study conducted in two cities in Japan and outlines Pavement Management System(PMS). The study consists of the following: 1) Road Profiler to collect data - The compact profiler consisted of multiple sensors like a GPS sensor, a portable computer, two small accelerometers to monitor acceleration, and an amplifier. GPS sensor was used to gather data like traveling speed and measurement position and was placed at the vehicle's front panel at any corner. The study also details out some criteria for expressways etc., and these exceptions were applied to the classification. This study explains a technique for visualizing collected IRI information as an attribute in a geographic system (GIS).

2) Mapping two cities - Two cities in part of Hokkaido, Japan which has a population of 1 lakh, were selected for the study. The collected data from these cities were analyzed and mapped according to the IRI scale. This analysis was repeated across all seasons to compare conditions. This study recommends that it's necessary to build a pavement management system (PMS) keeping in mind road category, a network of places, and analysis and management of road conditions in winter quantitatively.

3) Estimating the ride quality - In the final part of this study, the authors estimated the ride quality by taking into consideration the inner wheel path and outer wheel path profiles mounted on the survey vehicle(KITDS). The functional and structural conditions of different roads were determined by pavement evaluations and were proposed that routine evaluations like the above can be helpful in maintenance and planning.

The final results establish that using the above method of IWD and OWD analysis helps the PMS to be more efficient. Though this is an efficient system, it is expensive and time-consuming to be done at regular intervals.

Haul road defect identification using haul truck

Mine haul road maintenance [13] is crucial as there is a high rate of deterioration on these roads which makes maintenance important. If roads are not maintained, it can lead to higher expenditure on maintaining the vehicle. On the other side, if excessive amounts are spent on road maintenance, it may not lead to help the vehicle maintenance cost. Additionally, the maintenance of paved roads and running of haul vehicles are two different entities, and paved road maintenance uses specific equipment to conduct profiling. However, the cost is altogether billed to the mining company.

In the past, there were some methods developed that predict maintenance, which can help in areas where traffic can be modeled, but in the case of mining systems, modeling is a complex task. [13] proposes using haul truck response to assist the road maintenance. This approach has two uses: first is that the response can be used to find a set of road defects present, and second is that it tries to predict the roughness of the road qualitatively.

[13]Hugo D et al. uses a mathematical model with more priority on road defect reconstruction. The entire vehicle is first calibrated and then used to collect readings to run the mathematical model. The intrinsic reaction properties of the truck relating to road artifacts estimation were contemplated, and some relationship between deliberate suspension movement and road harshness was estimated with a fast profilometer.

This method proposes on-site monitoring without using traditional road profiling equipment, which reduces the cost to the mining company. But this method can only be applied to haul roads and vehicles used on haul roads and is not robust enough to be expanded to other roads.

Road Artifacts from Road Surface Video Clip

[14] Huidrom et al. states that assessment of road artifacts like potholes, cracks, and patches is usually done by using distress data collection and processing this data. The systems used for this evaluation can be classified broadly into 1) manual, 2) sensor and 3) imagery-based systems. However, analysis of the collected raw video clips for distress assessment remains predominantly being done manually, which can be costly in terms of both money and time, which slows down road maintenance management.

[14] proposes a solution to assess the video imagery of roads in India without using the manual intervention. It uses a technique based on the standard deviation of pixel intensities, the shape of the distress, and the average width to determine the distress category. The resulting frames of the video were divided into four categories like frames with potholes, with cracks, with patches, and without any of the above. Testing of this algorithm was done using a Windows OS with Visual Studio and OpenCV library. The results were evaluated through accuracy and precision-recall metrics and compared with the strategies given by earlier researchers also as current practices within the field. The results from the techniques can be utilized for concluding the maintenance levels of Indian roads and taking additional acceptable actions for repair and rehabilitation.

This work only proposed a system that can analyze the video clips of roads and segregate the frames on the basis of them having any road artifacts or not. This method fails in case of the presence of any black paint or other markings on the road.

1.4 Research Objectives

Towards developing a solution that can provide appropriate solutions to the above gaps, this thesis sets forth the following objectives to be addressed.

- Develop a robust and crowd-sourced data collection model to ensure frequent and continuous coverage of roads.
- Develop a system that leverages information level fusion to derive the location-specific road condition and surface characteristics.
- Develop and show use cases where the spatiotemporal visualization tool can be adopted to perform various analytics and assess the road infrastructure.

1.5 Thesis Structure

This thesis is organized into the following chapters:

- Chapter 2 describes the background survey done on existing methods for road monitoring ranging from high cost to low cost.
- Chapter 3 details the principles on which the design and development of this system are based, including the different strategies considered, the technology stack chosen, and the critical reasoning of architecture.
- Chapter 4 gives the description of the functionalities and methodology used in each module, their interaction with each other, and the medium of interaction
- Chapter 5 shows the application of this tool on a case study done on roads to establish the robustness of the system, build and test the hypotheses proposed by documenting results from the analytics and visualization tool
- Chapter 6 shows a comparison of MAARG system with the existing road monitoring systems.
- Chapter 7 concludes this thesis by summarizing the work done in this thesis and proposes future work in this field.

Chapter 2

Related Work

In this section we address the relevant previous work done in the field of road monitoring. We start off by giving examples of the widely used passive sensing methods, analytical methods, and finally active sensing methods. In this chapter, we classify the different methods with respect to the method of data collection in an efficient and scalable way.

2.1 Passive Sensing

Passive sensing in the current scenario is limited to manual reporting of any road damages via Twitter or dedicated government apps like ”My GHMC” where citizens can report potholes, cracks, and other artifacts on the road. [15]

This kind of citizen feedback though useful to the municipalities, there is no framework where the changes made in response to these complaints are tracked by the larger population. The work in this field is very limited to none.

Let us consider the following example, if there are 90 potholes on a particular road and authorities have claimed to fix 30, we have the pre and post-condition to verify if that case is true. Through analysis in the MAARG (Monitoring And Assessment of Road by Geo-citizens) system we can determine if these are the same potholes fixed or new ones are formed based on the data points collected.

2.2 Post Sensing (Analysis)

Enterprise Resource Planning (ERP) systems are used by authorities to plan their resources around road laying. These surveys are usually paper-based as in [16], where the survey is conducted in determining parameters to be considered.

The skilled opinion survey was conducted by formulating the questionnaire to calculate the weightage of every parameter for deciding the priority of road sections for maintenance exploiting the Analytic Hierarchy Process. The form consisted of 2 levels. Level 1 comparison included the main factors influencing pavement maintenance, and level 2 enclosed the sub-classification of things thought of in level one.

These provide some perspective in terms of prioritization of planning road laying activities but don't give a full picture of the target area.

2.3 Active Sensing

2.3.1 High Cost Sensors

Ground penetrating radar (GPR)[17] signal processing is a nondestructive technique, currently performed by many agencies involved in road management and particularly promising for soil characteristics interpretation. Benedetto et al. addresses the reliability of a well-defined signal processing algorithm for inspecting pavements. Though this radar system can produce high-quality data, it is very expensive to maintain and the rate of data collection is low.

2.3.2 Low-cost Sensors

- **Nericell**

  In Nericell, [18] smartphones are used to collect sensor data from microphone, GSM radio, accelerometer, and GPS to detect various road artifacts like potholes, road bumps, and also vehicle phenomena like braking and honking. Nericell is set in the context of a developing country, India, which needs a system like this that includes low-cost sensors and analyses patterns in disorganized traffic conditions, which are unique to developing countries. It also deals with the heterogeneous mix of different vehicles that include smaller vehicles like bikes and 3-wheelers and larger vehicles like buses and cars.

  In Nericell, an accelerometer is placed in a random orientation and is corrected using virtual reorientation. It also includes localization techniques and honk detection to enhance the results. This system introduces the idea of using data captured from several unique sensors and combining them to save energy.

  Although Nericell is a promising tool, it only addresses the sensing part of the road monitoring system that analyses road conditions to a large extent. It does not include any feedback or recheck mechanism where these changes can be compared and verified. It does not cover the information about road surface type, which authorities require, together with the condition to plan road laying activities.

- **Roadroid**

  Roadroid [19] uses vibration sensors in smartphones of users to collect data and analyze road roughness. It uses the international roughness index (IRI) scale to report its results. It proposes that continuous monitoring of roads can be achieved by repeating the experiment multiple times over a time period so that the changes in roads can be observed.

  Continuous information gathering may provide early warnings of changes and damage. It can also propose new ways to guide newer larger surveys for strategic quality management and pavement designing within the operational road maintenance. The data gathered on a smartphone may not be able to compete with the Class 1 data of precision profiles and high-performing sensors, but it is still providing a powerful way of road condition classification. As Class 1 data is extremely pricey to gather, it can not be done typically in smaller intervals of time and advanced systems conjointly demand complicated data analysis and take an extended time to deliver. Smartphone-based data gathering will meet each of these challenges.

  Roadroid mainly concentrates on Class 2 and Class 3 data. It presents condition change reports for many roads in Sweden and provides different statistics comparing conditions across different time periods. It proposes a new road class standard and uses it to classify roads. They also explore the option of using smartphones on bicycle pathways. This system is extremely movable and easy to use for everyone to make use of.

  Roadroid is a powerful tool in the space of road monitoring, but it fails to address some key elements. The data aggregator used in Roadroid only aggregates CSV files from various sources. It does not address the geo-citizen approach of collecting data from different commuters in order to increase accuracy.

  Camera data, though collected in case of a pothole detected on the road, only acts as a reference and does not have a place in the final classification of the road. Roadroid is set in a developed country, viz. Sweden has roads that are of fairly consistent texture. In a developing country like India, where both condition and surface type change constantly in roads, it will not be able to produce a detail-oriented map.

- **Other Crowd-sourced Monitoring**

  Monitoring based on crowd-sourced data has been a part of many projects over the recent past.

Air-quality monitoring based on crowd-sourced data has been gaining popularity. AirCloud [20] uses a different set of data sources as input to an air quality analytics engine to classify the data based on GPS location. The combination of a large number of sensors' data and a powerful cloud-based analytical engine gives AirCloud a way to achieve good accuracy at a low cost.

Crowd-based data is also used in systems and methods for providing passive crowd-sourced alternate route recommendations [21].

The amalgamation of spatial data from the variety of resources on the internet, being either legislative, commercially, or voluntarily driven, may be a major demand for the establishment of a fully integrated geospatial web. The fusion techniques involved may be information fusion or sensor fusion, or data fusion. Each of these holds an important role in moving forward technological research and understanding. Even though most of the satellite data in today's world serves a specific purpose, it is essential to also make use of faster and cheaper ways to obtain data. Information fusion techniques also need to be deployed in order to leverage its ability to show relationships between different parameters that are otherwise difficult to gauge.[22].

Through the MAARG system, we aim to achieve a low-cost, easy-to-use, robust, and effective framework for road monitoring that can leverage information fusion of the results obtained from images and accelerometer and also smartphones of geo-citizens.

Chapter 3

Development Methodology of MAARG Road Monitoring System

This thesis describes a collaborative road monitoring system in order to provide a framework for monitoring roads and performing spatio-temporal analysis on data collected. This introduces a Data Analytics and Visualization system (DAV) and enables users to perform various types of queries on data. Additionally, interactive map-based visualization is provided to the user. Most of the current road monitoring systems fail to display surface-type information along with the road condition, which plays a key role in planning repair activities for authorities. This system attempts to find a solution to the above problem by fusion of information from different sensor inputs, that are all available on a mobile platform.

To understand this further, it is important to know the technical and non-technical criteria of a road monitoring system. The following sections present different functional and non-functional requirements, propose design principles and answer critical reasoning questions regarding MAARG Road Monitoring System.

3.1 Requirements for a road monitoring system

An efficient road monitoring system satisfies the following criteria:

- **Survey** area to collect the data
- **Identify** key area of damage
- **Store** information about damage accurately (location) with surface type and condition
- **Report** the status to authorities to act upon
- **Survey** area again to check if revision has been made; this serves as a feedback to the system

Road monitoring frameworks must be enabled by rich support by geo-citizens who are daily commuters that can monitor the crucial aspects of the surrounding environment to identify changes, inspect the information gathered to comprehend the potential results of changes, report if an adaptation is needed and finally survey about the changes made and continue to provide the required service.

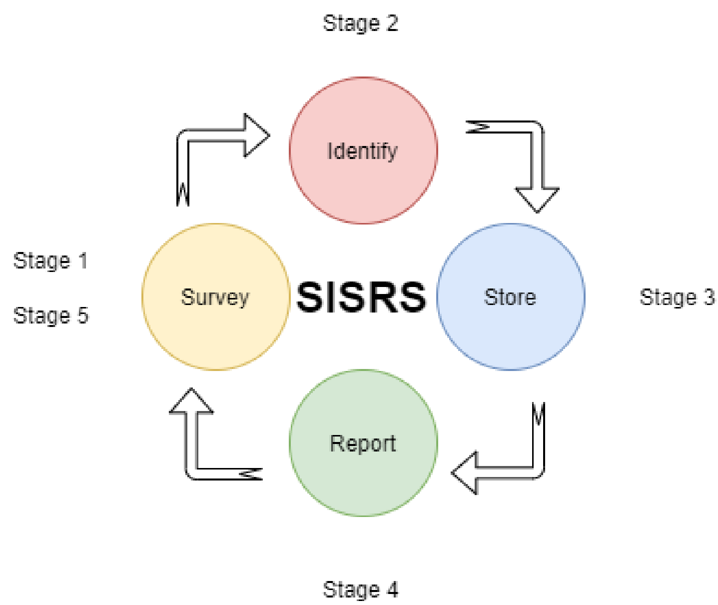

Figure 3.1 Requirements of Road Monitoring System

3.2 Non-functional criteria for a monitoring system

This section introduces some fundamental non-functional criteria which are needed to understand the later part of the thesis.

3.2.1 Usability

For any software system, the aspect of usability is crucial to adhere to the needs of the consumers of the system. ”Usability is a quality attribute that assesses how easy user interfaces are to use. The word usability also refers to methods for improving ease-of-use during the design process.” [23]

Usability is defined by 5 quality components [23]:

- **Learnability:** How simple is it for users to achieve fundamental tasks on the first occasion?
  Reasoning:
  Mobile app - MAARG app has a simple-to-use interface, where users need to sign up and then proceed to collect the data.
  DAV - DAV module has a minimalist UI which is easy to navigate

- **Efficiency:** When users have taken up the task, how rapidly would they be able to perform?
  Reasoning:
  Mobile app - The provision of initial training examples will help the users to easily adapt to the interface.
  DAV - Simple UI of DAV makes it easy to use the application

- **Memorability:** When users come back to the task after a time of not utilizing it, how effectively would they be able to restore capability?
  Reasoning:
  Mobile app - Each component is labeled appropriately in order to avoid confusion between the different modules.
  DAV - Each tab in DAV has its designated responsibility which is labeled clearly

- **Errors:** What number of mistakes do users make, how extreme are these mistakes, and how effective would they be able to recover from the errors?
  Reasoning:
  Mobile app - If a user makes an error in uploading the data or collecting, the app will intimate them by showing error dialogues.
  DAV - As the DAV module only has a login, data viewing, and view analysis, the errors users can commit are minimal.

- **Satisfaction:** How enjoyable is it to utilize the application?
  Reasoning:
  Mobile app - The application only consists of three screens and a simple interface. Hence, the users will not be facing any issues in understanding and utilizing it.
  DAV - This module has a tabular approach with cleanly divided responsibilities, hence it makes it easy for the user to use.

3.2.2 Robustness

Robustness of a software system is defined by the ability of a system to work consistently in a variety of conditions. MAARG has been implemented by using well-documented code with consistent version control. The system can produce identical results when given identical inputs. For example, the IRI class terminology used in MAARG is a universal one, and this helps in standardizing the results no matter the nature of the input data provided.

MAARG also relies on build tools and package managers for installation, with strict adherence to versions for each third-party package used.

3.2.3 Modularity

Modularity means creating logical partitioning of different components of software systems such that each of the modules can be separated or merged independently. This means that the system is highly flexible and easily manageable using data linking. We are trying to reduce the complexity of the system by modularizing the complete system into three subsystems. This is advantageous in the context that each part of this modularized system can be upgraded or replaced individually. For example, in this prototype we only deal with an android app. put in the future an iOS App can be added. The data processing subsystem code here is written in python language, but later it can be replaced by any other server. This is the advantage of using a modular system.

3.2.4 Extensibility

Extensibility is a software system engineering principle where the implementation takes future growth into account. The term extensibility can even be seen as a general measure of the flexibility needed to increase a system's functionality and therefore the level of effort needed to implement the extension. Extensions may be through the addition of recent features or through modification of existing functionality. The central theme is to produce enhancements while minimizing the impact on existing system functions.

An extensible system is one whose internal structure and knowledge flow are minimally or not littered with new or changed feature sets, for example, MAARG mobile app can have a change in functionality in the future, but the core features should not be affected by the new changes introduced. Because the MAARG system can be used for a long and will be modified for new features and added functionalities demanded by users, extensibility enables expansion or addition to the systems capabilities and facilitates systematic reuse.

MAARG is designed by the principle of separating work elements into coherent modules, in order to avoid conventional software development issues including low cohesion and high coupling and allow for continued development.

3.3 System Design Criteria

The system architecture (Figure 3.2) is a distributed client-server application structure that partitions tasks between the provider and requester of a service. The detailed architecture is described in the below subsections. The mobile application is used to collect and train data which is in turn uploaded to the data infusion server. The data infusion service is responsible for streamlining the flow of parsing and storage of data. This data is processed by the data processing server and stored in the database. In this case, the client consumes the processed data to show an interactive visualization where users can run spatio-temporal queries on this data.

3.3.1 Critical Reasoning of Design Approach

MAARG design process can be perceived as a series of well-defined steps that explain the conceptualization of the monitoring problem. The benefit of having a structured design is, it can give a clear understanding of how this problem is being solved. It also makes it easier to concentrate on the problem accurately.

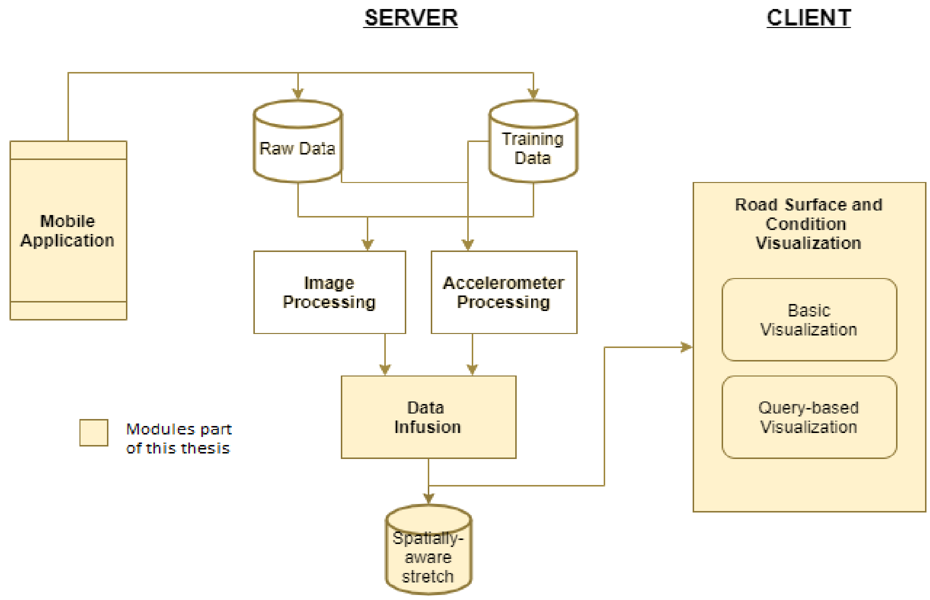

Figure 3.2 Architecture of the system

3.3.1.1 Modular approach

The key principle followed is the ”divide and conquer” strategy where the problem has been broken down into several smaller problems and each of these is embedded into different modules of MAARG. Any well-structured design should have high cohesion and low coupling. MAARG comprises of different modules that communicate with each other efficiently.

3.3.1.2 Batch processing

Data uploaded by the user is processed batch-wise. This means that the MAARG server processes data bundled together, leading to an increase in efficiency.

3.3.1.3 Scrubbing of data

Scrubbing data means the process of cleaning data, which removes any data that is incomplete, incorrect, or has a large amount is noise. Noisy data in the MAARG system can be due to cloudy weather, shadows, etc. Currently, this process is conducted in an offline mode.

3.3.1.4 Collaborative model

For a system to be able to generate robust output, there are two approaches. 1) By procuring more sample data from different sources 2) by covering a larger area at the same time. As approach 2 is not in the scope of the current thesis, we have chosen approach 1. As a part of the scaling up of the

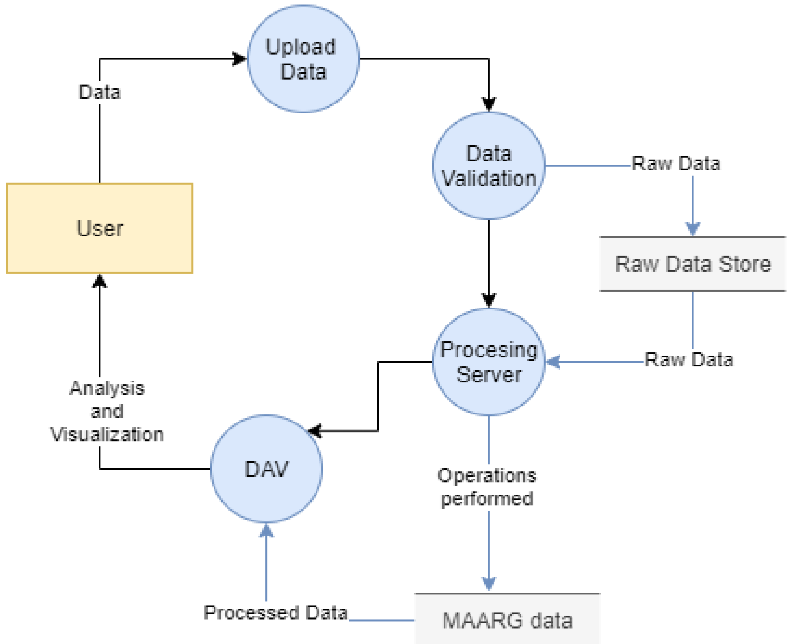

Figure 3.3 Data Interoperability

system, we have analyzed repeated samples of the same area as highlighted in the case study chapter of this thesis(Chapter 5). It is observed that the samples that contain flaws are automatically isolated and discarded from the final output based on the fact that the multiplicity of "good" data will eventually eliminate the "bad" data. For example, for a stretch of road, if 2 users report a **poor** state and 1 user report a **good** state, then the majority rule applies here which hear by eliminates the flawed data.

3.3.1.5 Data Interoperability

Data Interoperability addresses the ability of a software system to create, exchange, and consume data that can lead to having a clear understanding of the context and meaning of data. In the case of the MAARG system, data interoperability helps create a standard protocol between each subsystem. Raw data collected on the smartphone is uploaded to a structured table in the SQL database. This serves as input to the processing server, which performs different operations on the raw data and uploads it to another table. The processed data is an input to the analytics and visualization subsystem. This is described in Figure 3.3.

3.3.2 Critical Reasoning of Technology Stack

All the technologies used in MAARG are open source and the different components are described below.

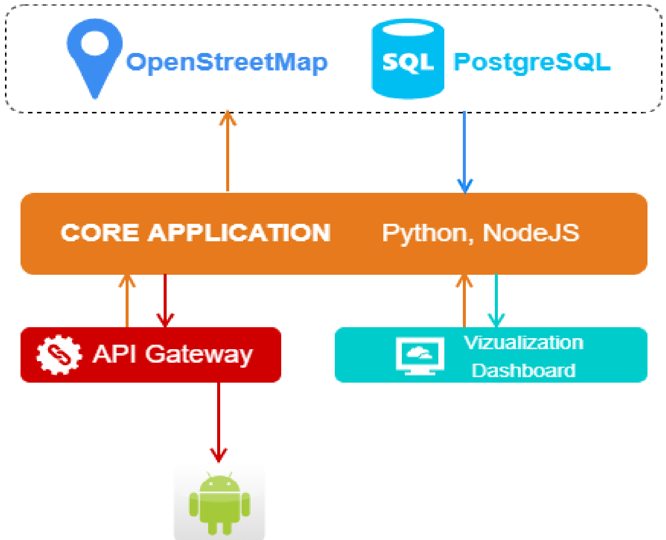

Figure 3.4 Technology Stack

3.3.2.1 Front-end Technologies

- **React JS**

  React JS is a JavaScript framework built by Facebook and is completely open-source. [24]

  1. The main advantage of React JS over other frameworks is Virtual DOM. DOM (document object model) is a logical structure of documents in HTML, XHTML, or XML formats.[25] In simpler words, it is a viewing agreement on data inputs and outputs, which has a tree form. Web browsers use layout engines to transform or parse the representation HTML syntax into a document object model, which can be seen in browsers. The main concern about traditional DOM construct is the way it processes changes, i.e., user inputs, queries, and so on. The engine continually checks the difference caused by these changes to give the required response. To respond appropriately, it also needs to update the DOM trees of the entire document, which is not practically valid because DOM trees are relatively large today, containing thousands of HTML elements. [25]

     React manages to increase the speed of updating UI by using its innovative virtual DOM. Unlike other frameworks that work with the Real DOM, ReactJS uses its abstract copy; the Virtual DOM. It updates even minimalistic changes applied by the user but doesn't affect other parts of the interface. [25]
  2. One-direction data flow in ReactJS provides a stable code. [25]
  3. Permission to reuse React components significantly saves time in development. [25]
  4. An open-source Facebook library: constantly developing and open to the community. [25]

5. Redux: convenient state container which can be used to preserve application state. [25]

- **Leaflet JS**

  Leaflet is a leading open-source JavaScript library for mobile-friendly interactive maps. Weighing just about 39 KB of JavaScript code, it has all the mapping features used in most application development.

  Leaflet is designed with usability, performance, and simplicity in mind. It works efficiently across all major web desktop and mobile platforms can be extended with lots of additional plugins, has a simple-to-use and well-documented API, and has an easy, readable source code. [26]

  1. Runs on JavaScript, one of the most commonly used languages for web applications. As our front-end framework also runs on JS, it is cohesive with other components.
  2. Supported by a large and enthusiastic community
  3. Small size makes it lightweight and maneuverable

Mobile OS

- **Android OS**

  Android is a mobile OS based on the Linux kernel and uses different open-source software designed keeping in view touchscreen mobile devices such as smartphones and tablets.[27] After its release in 2008, Android is used by 2.5 billion active devices.

  1. Android OS is widely used by more than 90% of smartphone users in India.
  2. Android Studio provided by Google is a complete package that can be used for developing Android apps. It is free software.
  3. Android apps can be developed in any OS, Windows or Mac, or Linux.

3.3.2.2 Back-end Technologies

- **Express JS**

  Continuing our tech stack on the JavaScript platform, Express.js, or simply Express, is a web application framework for Node.js, released as free and open-source software under the MIT License. It is designed for building APIs and backends for web applications. It has been called the de facto standard server framework for Node.js.

  Express is a feature-rich Node.js framework that is robust, minimal, and flexible, and can be used for both mobile and web applications.

  1. Express' extremely powerful routing API allowed us to perform various tasks like building a REST API by using route parameters and query strings.

2. Express takes advantage of Node's NPM(Node Package Manager) to distribute and install countless plugins made by third parties, which we could utilize in enhancing the APIs offered in MAARG. [28]
3. Express.js is somewhat of an old web application framework and is also the most widely used, it has matured during this time. The huge community backing it and being way ahead of other competitors makes it a top choice. [28]
4. Setting up a new Express project takes only a few steps. Setting up a new Express project takes only a few steps. A package.json file contains all the necessary packages required and a simple npm install will set it up. This facilitates our use case in which this system can be used by multiple organizations for monitoring. [28]

- **Python**

  Python is a high-level, general-purpose, interpreted programming language. It is garbage-collected and dynamically typed.[29]

1. Python code can be easily readable as its syntax mainly contains English-like sentences. The syntax rules of Python allow users to express concepts without writing much code.
2. Object-oriented, functional programming, and structured (particularly, procedural) are all the supported programming paradigms. Python is often described as an "all-included" language due to its comprehensive standard library.
3. Python has rich support from the developer community as it was created around 30 years, which gives it a lot of time for any programming language to mature and develop into a mainstream one. Python is liked by developers as it has a plethora of documentation and other resources available. The official documentation is also very elaborate. It is easy to learn and code for users of the beginning or advance level. [30]
4. Due to the high popularity of Python, there are many ready-to-use packages available for Python. In the past decade, it has become the most used language for AI/ML applications.

3.3.2.3 Database Technology

- **PostGreSQL**

  PostgreSQL is an open-source RDBMS that is Linux based and functions with objects are used as a relational component in DBMS. Structured Query Language(SQL) is used to access the tables of the database, hence, it is also known as Postgres. [6][31]

1. Very feature rich
2. GIS add-on functionality
3. It runs on all operating systems

4. It has user-defined data types.
5. PostgreSQL also supports image, video, and audio storage and also supports graphical data. [31]
6. Well-documented
7. Strong access-control framework [31]

3.3.2.4 Version Control

- **Git and Github**

  As the MAARG system goes through constant changes, it is essential to have a good version control system in place.

  1. Git is the most preferred version control software by developers worldwide.
  2. Git has a developer-friendly command line interface
  3. Documentation for git is also easily available
  4. Github is a service built over Git, it allows for easy collaboration between different collaborators.

3.3.2.5 WebGIS

- **OpenStreetMap**

  OpenStreetMap also known as OSM is a collaborative map database that is open-source, free, and editable. MAARG uses OSM as a web map service layer to plot the visualization output after processing.

  1. OSM has rich data compared to any other free map data source.
  2. It has a large community backing which makes it a reliable data source.

3.4 System Objectives

MAARG system has been built over the following objectives:

Easy to use smart-phone application for data collection

- Simple user registration and login
- Basic storage system for on-board data storage

- Data upload feature to enable the user to upload the collected data periodically to the central server
- Develop a smart-phone based data collection application that has an easy-to-use and interactive interface through which geo-citizens can intuitively record and upload data.

Processing server for data dissemination

- Show user-uploaded data
- Handle data upload from different sources
- Clean data discrepancies

Visualization module to visually represent in an intuitive manner

- Allow user to search different areas
- Provide options to select different wards
- Provide time-series data
- Overlay data on the map

Analytical model to show results

- Create useful analytics about different data obtained
- Provide statistics about data obtained from different sources chronologically
- Answer critical questions about road conditions in the city

Chapter 4

Components of MAARG Road Monitoring System

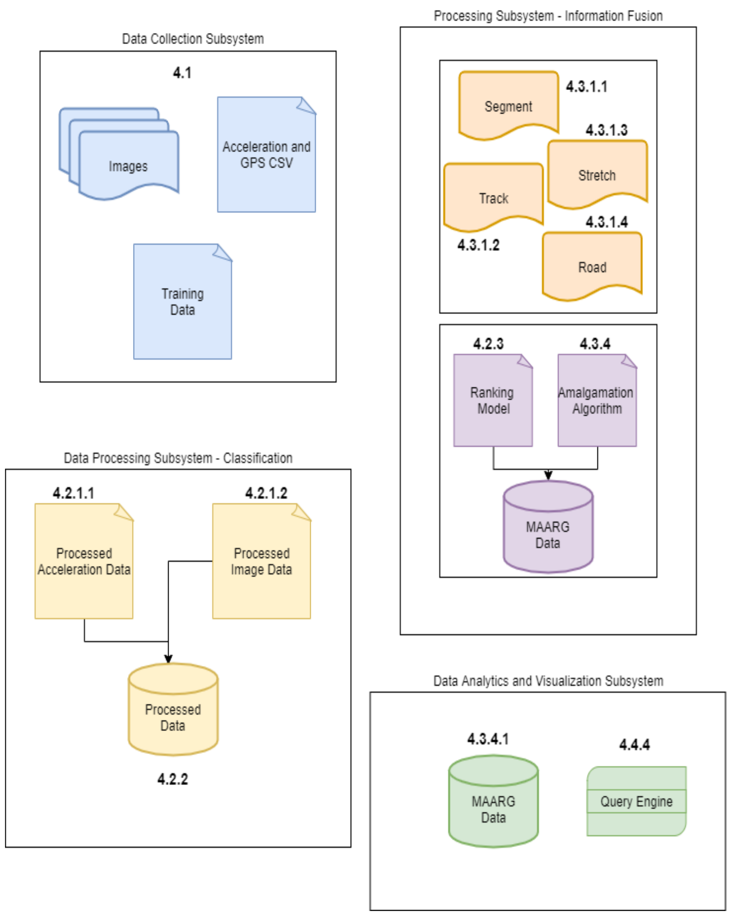

Figure 4.1 Subsystems in MAARG

MAARG system consists of three main subsystems. Figure 4.1 is a detailed architecture diagram of the MAARG system showing the various modules which have been divided into - Data Collection, Data Processing and Data Analysis and Visualization subsystems. Each module in the figure is labeled according to the section number in this chapter, which may be referred to for a detailed description of that module or sub-system.

4.1 Data Collection Subsystem - Mobile Application

MAARG app is a smartphone-based application that is mainly used for the collection of training data and raw data. In this system, we have opted towards collecting data in a seamless manner using the smartphone as it enables the scaling of the system across large regions. The application consists of two modes, data collection mode, and training mode. The smartphone running this application should have a camera with a minimum of 5 MP resolution, and an accelerometer sensor and should run on Android OS. The 5 MP resolution makes sure that the collected images are of good resolution. Once user registers and logs on to the application, they see three different options. All required information and a user guide are provided on the MAARG website. Users are required to carefully mount the phone to the dashboard of the vehicle in a well-oriented position. Data collection mode, when switched on captures the road image at defined intervals along with 3-axis acceleration data and GPS location.

4.1.1 Mobile Application Architecture

In building a user-friendly application, we had to consider the following criteria:

- **Determining the type of environment -** In determining the type of operating system to develop the initial app, the main criteria considered is the type of target audience. As we are developing the system in India, where the number of Android users is staggeringly high as compared to that of iOS, Android was the choice. Another criterion was the ease of development with Android OS. The application can be developed using any i.e. Windows, Linux, or Mac environment whereas an iOS application requires a Mac computer. Due to these reasons, we chose to develop our application with AndroidOS.

- **Considering bandwidth -** There are times when connectivity is either infrequent or not available at all. Such a case was also considered, and to enable this option the application stores the collected data files locally till the user finds a reliable data connection and then uploads it to the central server. We refer to this as the offline mode of data collection and the option in which data is readily transferred as it is collected in the online mode.

- **Designing the User Interface -** The user interface was designed to be easy to use for every user irrespective of whether he has a prior experience with data collection applications. The UI was kept as simple as possible with a minimum number of screens.

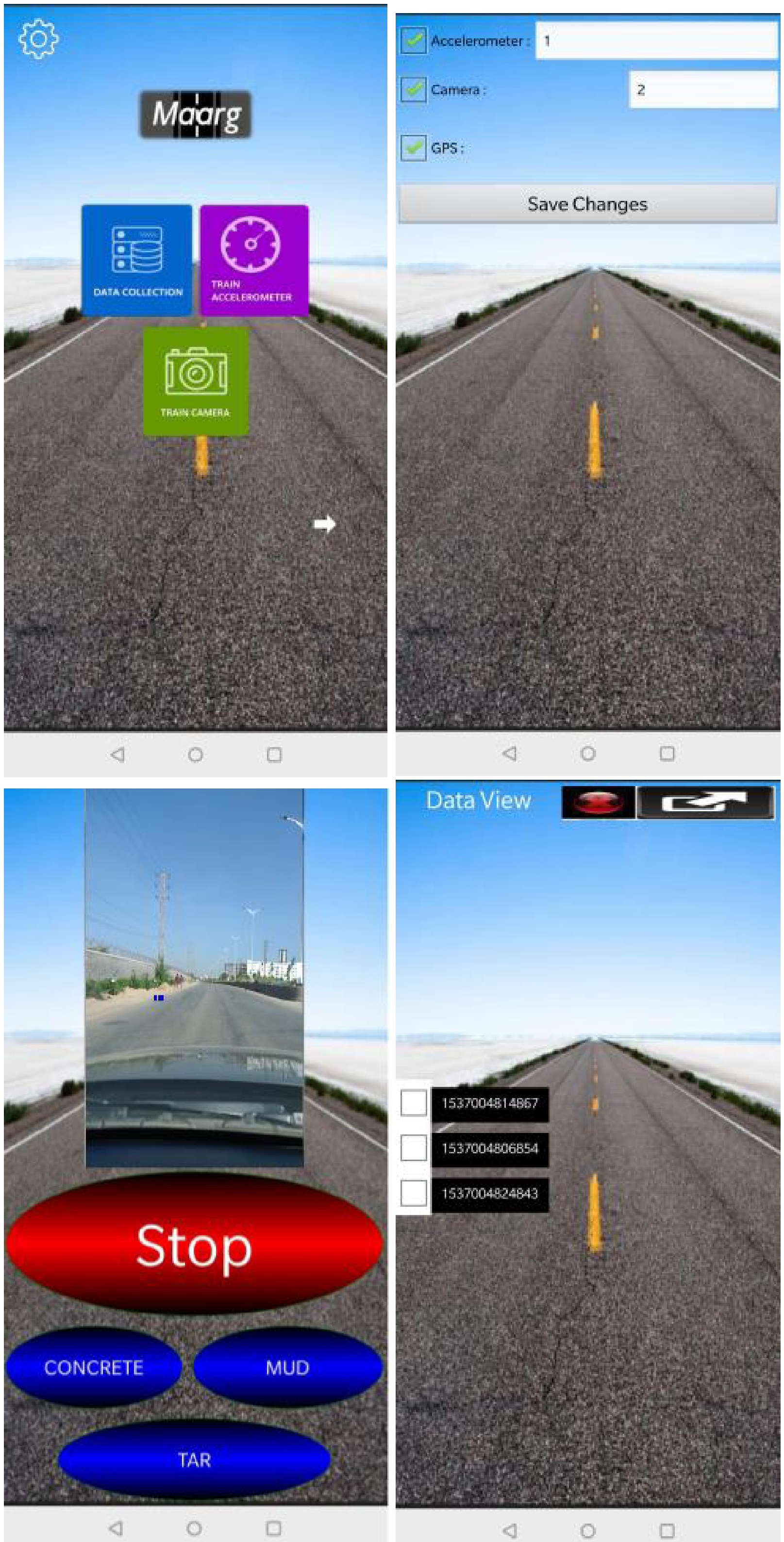

Figure 4.2 Mobile Application

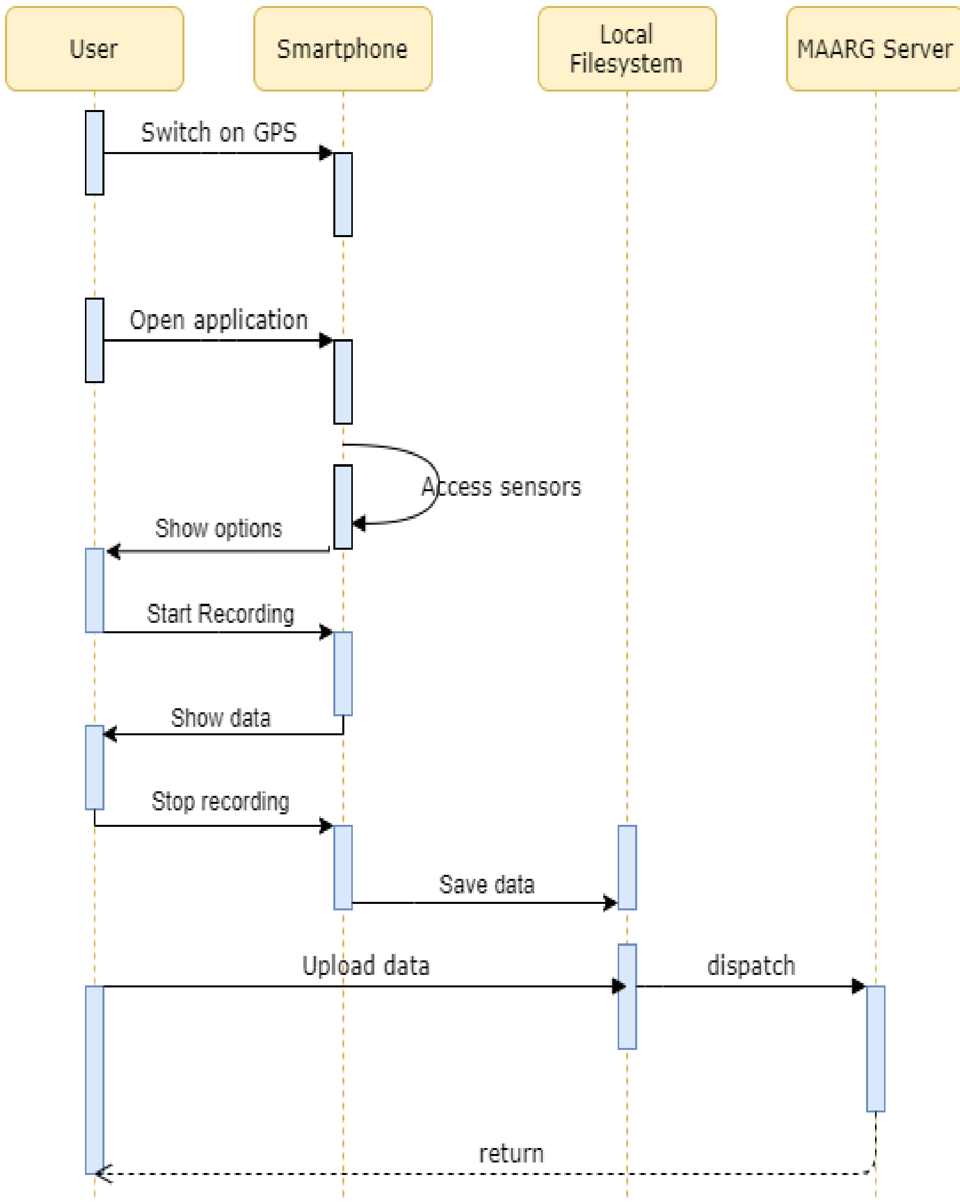

Figure 4.3 User interaction with mobile app

4.1.2 Settings Page

The app contains a settings page where users can set the frequency of capture for acceleration and camera sensors. Figure 4.2 Users can also enable /disable the GPS sensor on this page. By default, acceleration data is collected at 15Hz and the camera at 1Hz.

4.1.3 Training Module

The application also has a training mode, separately each for accelerometer and image training, to help the algorithm detect and store the user-annotated data.

The training module on the MAARG app is divided into two parts :

4.1.3.1 Acceleration Data Training

Users can record different sample data for training the acceleration or condition classifier. The options available are good, satisfactory, unsatisfactory, and poor, as per the IRI classes. (International Roughness Index) [32]

User clicks on **Start** $\rightarrow$**Condition Type** $\rightarrow$**Stop**

Acceleration training data is used to determine the condition of the road.

4.1.3.2 Image Data Training

Different road images can also be captured by users through the MAARG app and trained to choose the road surface type. The options available are concrete, tar, and mud road type.

User clicks on **Start** $\rightarrow$**Surface Type** $\rightarrow$**Stop**

Image training data is used to determine the surface type of the road.

4.1.4 Requirements and features

The mobile application has the following requirements:

- **GPS switched on** - For the data to be collected accurately and useful for analysis, the GPS sensor on the smartphone should be switched on

- **On-board storage** - Sufficient storage space should be available on the device. MAARG app by default collects one image per second and the size of each image depends on the camera resolution.

- **Network Connectivity** - As the MAARG app has onboard storage built in, smartphones need not be connected to the internet at all times. Data transfer can be done via any WiFi or other network after data collection.

4.2 Data Processing Subsystem

The android application stores the data and uploads it to the central server which is then infused into a predefined model on a database. Training data obtained from the user is validated offline and saved to a separate database. Image data is processed to obtain the road surface while the accelerometer and GPS data are used for identifying road conditions and location information. The classification is based on a standalone algorithm as reported in (Rajamohan, D. et al, 2015). The road condition classification is based on the international roughness index (IRI) classes, viz., good, satisfactory, unsatisfactory, and poor. The final road surface types are Bitumen (tar), Concrete, and Mud. As per the current system, the model adapts into a more accurate model with increasing accuracy with prolonged usage and the addition of more data, and the nearest class to the data is assigned by the classifier.

Location and time-stamped information of the road condition and surface is then stored for each part-segment of the road in a PostGIS database. The segmented approach is taken to allow collating multiple user-provided information and for validating the same. This sub-system can only process data with no shadows and water on the road.

Algorithm 1 User data processing

Require: Data collected by a user through Android App
Ensure: Data is correctly stored in a Database

STEPS:

- User records road data on their smartphone

- User uploads track data to the database

- Any training data recorded by the user is uploaded to the training database

- Each track is first map-matched to remove any GPS error and correct the track information

- The corrected track is classified into different classes using the k-nn algorithm

- Classified Data is divided into segments

- Segments are stored in a table

4.2.1 Classification Module

4.2.1.1 Road Condition Estimator

Figure 4.4 shows the algorithm used to determine the road condition.

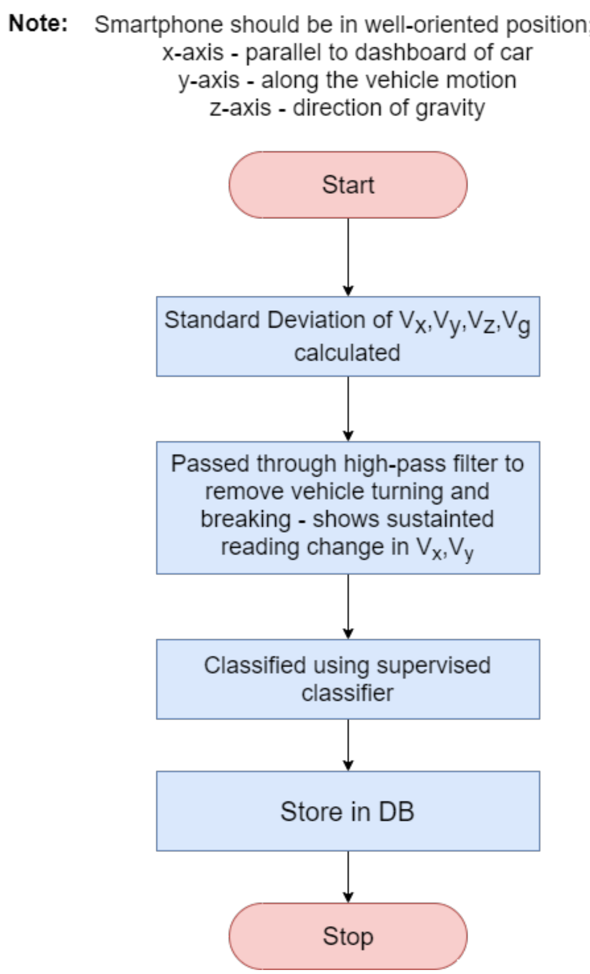

Figure 4.4 Road Condition Estimator

4.2.1.2 Road Surface Type Classification

Figure 4.5 shows the algorithm used to determine the road surface type.

4.2.2 Database Architecture

The database architecture described is a high-level design.

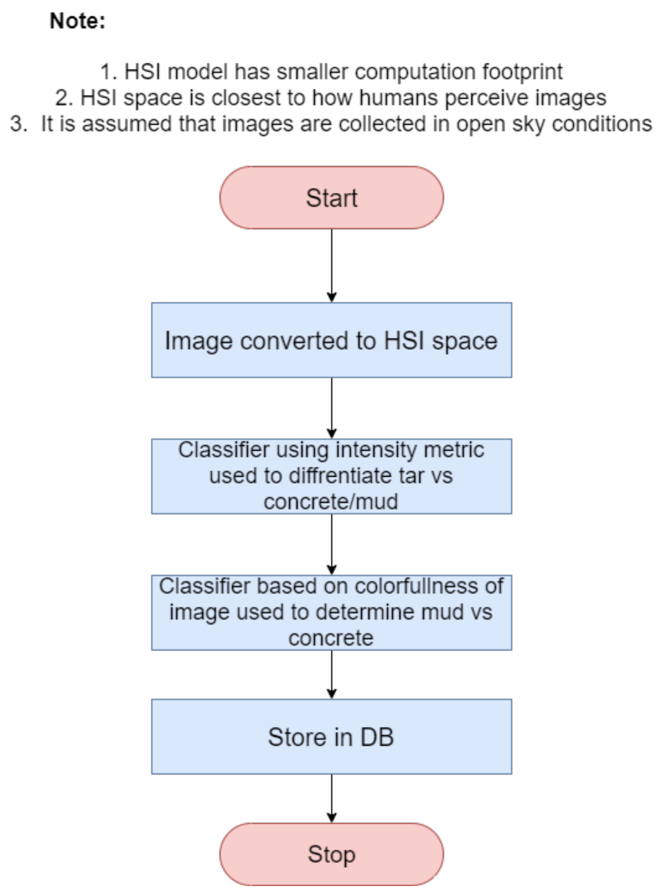

Figure 4.5 Road Surface Type Classification using hue(H), saturation(S), intensity(I) space

There are three types of tables: Raw data, Training Data, and MAARG data (segmented output).

Raw data includes the basic user information table and user-collected data table. Training data includes user-given training data and manually labeled data. MAARG data is the final classified data that is mapped to the segments. The roads are divided into segments and stored for reference. This acts as the base for the entire querying architecture. Each segment is the road divided into 3 m^2 blocks and given a unique id. All the ids are unique alphanumeric GUID (Globally Unique Identifier). MAARG data acts as input to the querying platform.

4.2.3 Ranking model

The Ranking Model is a crucial step for obtaining the final result. In a machine learning context, Ensemble Learning is a method in which results from multiple classifiers are combined via majority or plurality voting to arrive at a conclusion. This method is widely used to improve the performance of (function approximation, classification, prediction, etc.) models or tries to reduce the occurrence of poor results. Ensemble model can be used in highly secured private applications, large-scale data with reusable models, anomaly detection, multiple sources of data, and distributed computing.

Hard voting is a model in which results from multiple classifiers are ensembled via majority voting. Soft voting is a model where each classifier arrives at a probabilistic outcome and the final result is the average of the probabilities calculated by individual algorithms.

In the case of MAARG, we need to combine the result of a single kNN model (k-nearest neighbor) on different data sets of the roads.

Steps followed in determining rank:

1. KNN model is calculated and saved based on the training data.

2. When a new data set is uploaded to the MAARG server, the kNN model is run and its results are saved in the processed data table.

3. This data is then divided into meaningful segments.

4. Each segment has a surface and condition type associated.

5. To understand the ranking model further, let us take an example of Road No. 1. (See Table 4.1)

   Users A, B, and C have together contributed towards collecting data for 50% of Road No. 1.

   Stretch (50% of Road No. l) - has 10 Segments

User	Segments Contributed	Day
A	Seg 1, Seg 2, Seg 3, Seg 4	Day1
B	Seg 3, Seg 4, Seg 5, Seg 6, Seg 7, Seg 8, Seg 9, Seg 10	Day10
C	Seg 4, Seg 5, Seg 6, Seg 7	Day20

   Table 4.1 Sample data for Ranking Model

   The majority rule applied to Segment 3,4,5,6,7 to determine the final result.

6. **Note:** A, B, and C contributions in the above example need to be within 30 days from each other, if a new user D contributes on day 31, then users B, C, and D data are considered to determine the final result.

4.3 Information fusion model

Information fusion involves achieving three objectives which are demarcated as
a. *compactness* of information that deals with how any particular data is uniquely and concisely represented,
b. *extensiveness* of the information that measures the number of attributes associated
c. *factuality* of the information that shows how true the data is to the real world.
The proposed system intends to conform to a novel model that adheres to the aforementioned principles.

4.3.1 Taxonomy of Information fusion model

Taking into view the above-mentioned criteria and to solve the gaps in data collection, this thesis presents a qualitative method to characterize and evaluate road monitoring using the following taxonomy:

4.3.1.1 Segment

A segment is the smallest tangible unit that can be classified into one of 12 categories as shown in Figure 4.6.

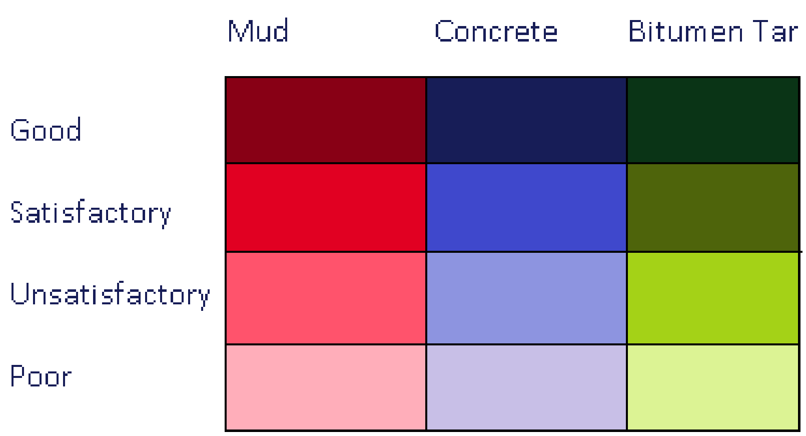

Figure 4.6 Legend for different classes

4.3.1.2 Track

A track is comprised of multiple classified segments. Each track is contributed by an individual user. For example, Figure 4.7 refers to a track contributed by a single user for the Gachibowli road. And stored as a record for each user as shown in Table 4.1 above. Do note that each track can be of different lengths or a number of segments. Tracks collected on different periods of time are treated as different tracks even if they are from the same user.

4.3.1.3 Stretch

A stretch also termed a spatially-aware stretch, is comprised of multiple segments of data contributed by multiple users. We use a maximum voting algorithm to determine the classes assigned to the different segments in a stretch.

Figure 4.7 Gachibowli road

4.3.1.4 Road

In our model, a road consists of multiple sequential spatially aware stretches. And the outcome is similar to the common understanding of a road, between two nodes or vertices.

4.3.2 Reasoning behind Information Fusion

The following section describes the reasoning behind information fusion used in the MAARG system.

4.3.2.1 What is information fusion conducted in MAARG?

Once the classifier assigns a label for surface and condition separately, this information is fused together and represented using a unique color and label for each of the 12 possible combinations as shown in Figure 4.6.

4.3.2.2 Can these independently show the same result?

At each segment level, it is necessary to know the surface type and its condition associated. The reason behind this is that for authorities to plan road laying activity, it is necessary to set the priority according to the extent of damage on the road. In addition to this, it is essential to know the surface type of the road.

4.3.3 Challenge in Information fusion

As the current system deals with a diverse stream of data, there arises a problem of standardizing this data to conclude some meaningful information. We segregate the problems into two categories a. *accuracy* which means that using low-cost devices we should get the accuracy close to high-end systems and b. *result conflict* which arises due to the multiplicity of the data, in which case there are multiple conclusions made for the same attribute of the data.

4.3.4 Amalgamation Algorithm

Instead of from high-accuracy single-track data, getting multiple tracks and amalgamating them into a single stretch helps improve the data consistency in the crowd-sourced model. This also in turn improves the accuracy. But, this also poses the challenge of duplicity and gaps in the data. Hence we introduce an amalgamation algorithm for generating a single result for each segment of the road/stretch. It is described stepwise below.

Algorithm 2 Amalgamation of segments

Require: SegmentIDs of segments belonging to different users
Ensure: Each segment has an associated class

STEPS:

-For each stretch, get a list of associated classified segments

- By the principle of majority voting, assign the final class to each segment

- Arrive at the final spatially-aware stretch by combining all the final segments and storing them in a separate table

4.3.4.1 Database Design

The Figure 4.10 are the tables we have designed to efficiently store the data and extract information.

4.4 Data Analytics and Visualization Subsystem

MAARG system includes a WebGIS dashboard comprising a back-end Express server that analyses and aggregates information from multiple inputs and showcases it on a browser with the OpenStreetMap as a background layer (WMS). For systems such as traffic monitoring systems, only tracking, and positional information are used. While the proposed system not only uses tracking information but also

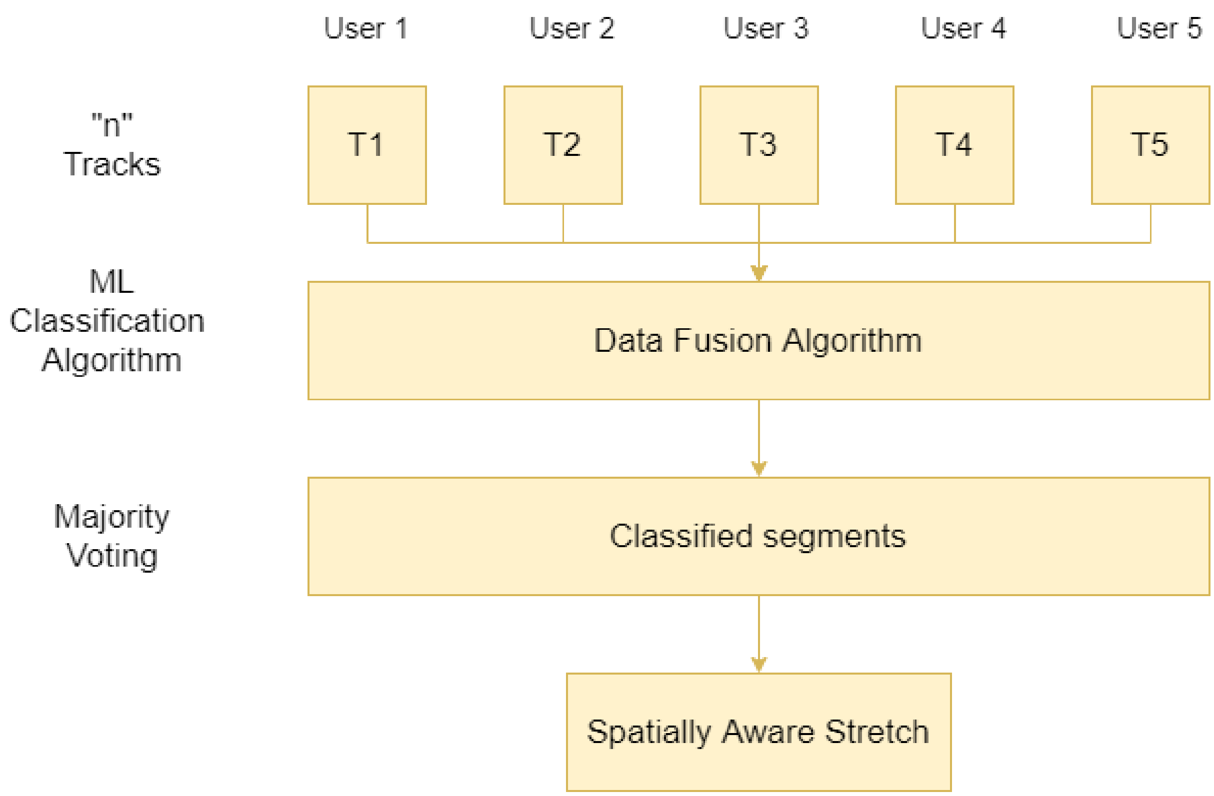

Figure 4.8 Information fusion flowchart

image information to give an optimized understanding of the road infrastructure. Hence, MAARG processes positional information and attaches the fly analysis of the data collected from different sensors. This is achieved by collating data from multiple data efficiently.

4.4.1 Data Analytics in MAARG

The core purpose of any data analytical system is to consume input data that can or cannot be related and convert it into meaningful information. This gives the end user better reasoning and understanding of the ground truth which supports decision-making. Analytics in MAARG is done by post-processing. Once data is collected, classified, and divided into segments, a majority voting module evaluates the classified segments, and the final results are stored according to that. The model based on the number of collaborators is used to rank each of the segments. An analytical system provides a framework for querying the system. The default visualization is the most recently recorded road condition and surface in a color-coded way based on the IRI classes.

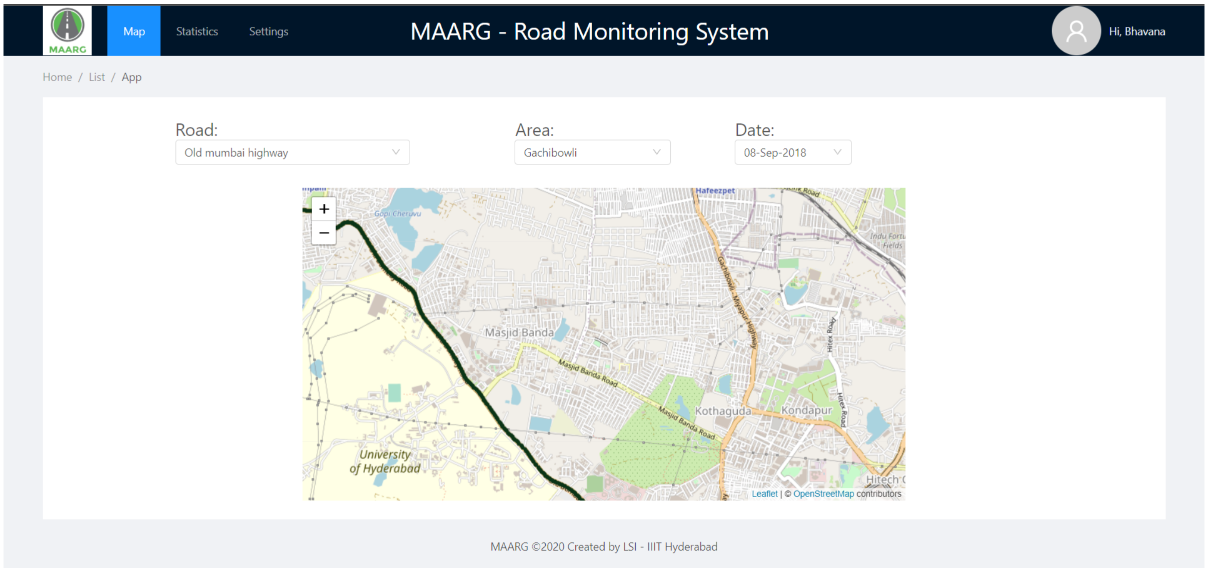

Figure 4.9 Snapshot of the visualization tool

4.4.2 Query Engine and Visualization

An assumption has been made that even though commuters travel through different lanes on a multi-lane road, we do not distinguish the lanes to provide the outcome. Let us take an example of the Old Mumbai highway in Hyderabad, which is a 3-lane road in both directions or sides. The left and right side of the road is distinguished by the direction of the GPS track. In our experiments, we observed that commuters prefer to take the lane that is free from potholes. Hence, a majority vote of all user data collected for the stretch of road is taken for each segment and the final verdict is allocated to each side of the road. The visualization module will be discussed in more detail in the case study for better understanding.

4.4.3 Basic Visualization

The basic visualization shows the most current classification according to the 12 classes mentioned in 4.3.1.1. Users can zoom into any particular area with markers, and click on the marker to view the recent road image available for that segment.

There are three options for users to choose from:

4.4.3.1 Road drop-down

Different named road options are available in this drop-down. In our current scenario, we have four different road data available. Once a road is chosen, only the most recent data on that road is displayed.

Road Name	%Good	%Satisfactory	%Unsatisfactoty	%Poor	Date
Old Mumbai Highway	93	0	0	7	10-12-2018
Old Mumbai Highway	95	0	0	5	21-09-2019
Osmania University Road	85	9	0	6	11-1-2018
Osmania University Road	94	0	1	5	03-01-2019
IIIT Main Road	98	0	1	1	10-12-2018
IIIT Main Road	97	0	0	3	21-09-2019
Gachibowli Road	78	13	0	9	10-12-2018
Gachibowli Road	67	17	0	16	21-09-2019

Table 4.2 Current state of selected roads in Hyderabad city

4.4.3.2 Area drop-down

Different areas of a city are available in this drop-down. Currently, Tarnaka and Gachibowli are the two options in this drop-down. Once a user selects an area, the most recent data collected in that area is shown.

4.4.3.3 Date drop-down

The date of collection of each data set is shown in this drop-down. Once a user selects a date, the data collected on that date is shown. If a new survey is not done, the database shows the data from the latest collected data.

4.4.4 Query-Based Visualization

The system supports two types of queries as given below:

Spatial Queries: Analysis of the road based on a polygonal region, like a municipality ward can be opted.

Temporal Queries: Queries based on different periods can also be performed for different roads.

Using this tool we are able to answer the following queries as per data shown in Table 4.2:

4.4.4.1 Spatial Queries

Road length: 10 km

Road with least change in condition: Old Mumbai highway, IIIT Main road

Analysis of current road : Old Mumbai Highway - This road is 95% good.

4.4.4.2 Temporal Queries

Road length: 10 km

Analysis of status change of a road over a time period Status change of Old Mumbai Highway over the past 1 year - negligible

Current state of roads in any city In sample data collected from Hyderabad, over 80% of the roads have good condition.

We can understand from the above analysis that we have built a spatially-aware knowledge base from the existing system.

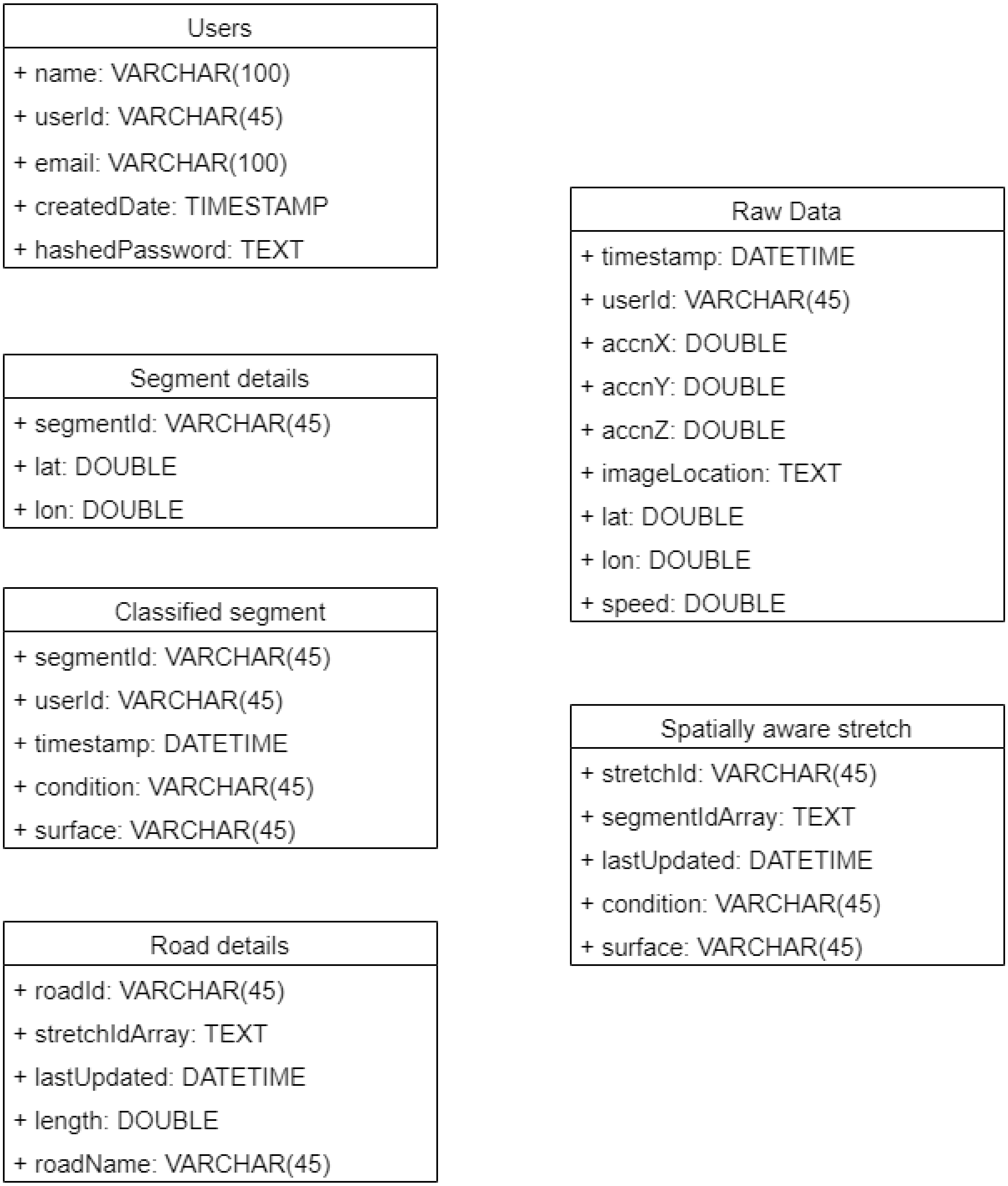

Figure 4.10 Database Details

Chapter 5

Case Study

The proof of concept of the system has been deployed and data was collected on a stretch of around 40 km in the Gachibowli and Tarnaka areas of Hyderabad, India for 5 unique users(with 5 different devices) for a period of 1-year variation for validating the concepts and verifying the proposed models. Outputs shown in the previous section are an outcome of the study area. As we can observe from Table 2, different users contribute varied lengths of data on different days.

The processed data obtained can be major of two types. First, the segments of data obtained from different users do not overlap. When this case occurs, the result is reported and visualized without any further processing. A second case arises when the segments obtained are overlapped. Based on the analysis each segment can have a different result, then a rule-based approach is adopted to arrive at the final result. The rules, in the order of preference, are the majority class table within the same class followed by the most recent class label assigned to the segment.

5.1 User contributed data

The prototype was tested with 5 unique users contributing data from nearby areas as shown in Table 5.1

As multiple users can contribute to the same area, upon analysis we discovered that the actual distance that is unique is only 22 km.

User	Kilometers
User 1	14 km
User 2	12 km
User 3	4 km
User 4	5 km
User 5	5 km

Table 5.1 User contributions

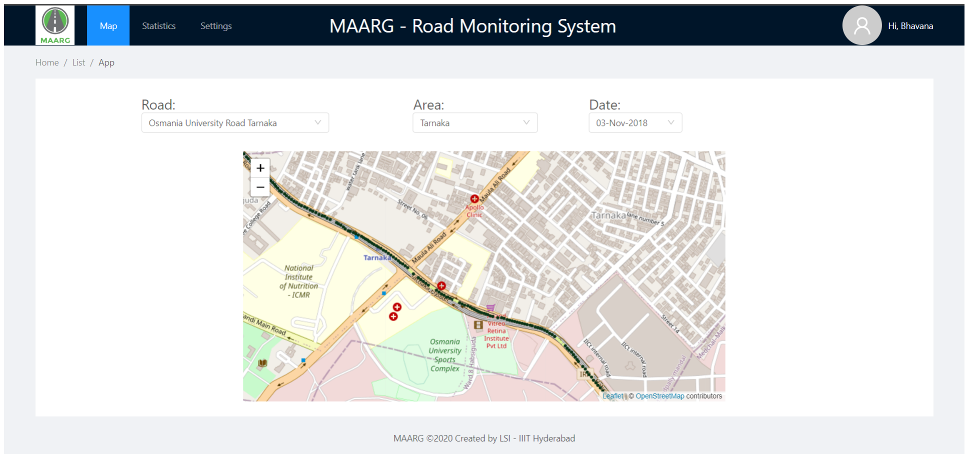

Figure 5.1 Contribution by User 4 in Tarnaka area

From Figure 5.1 we can infer that the road connecting Mettuguda and Tarnaka is largely good, except for a few artifacts on the road, which are recorded as poor condition.

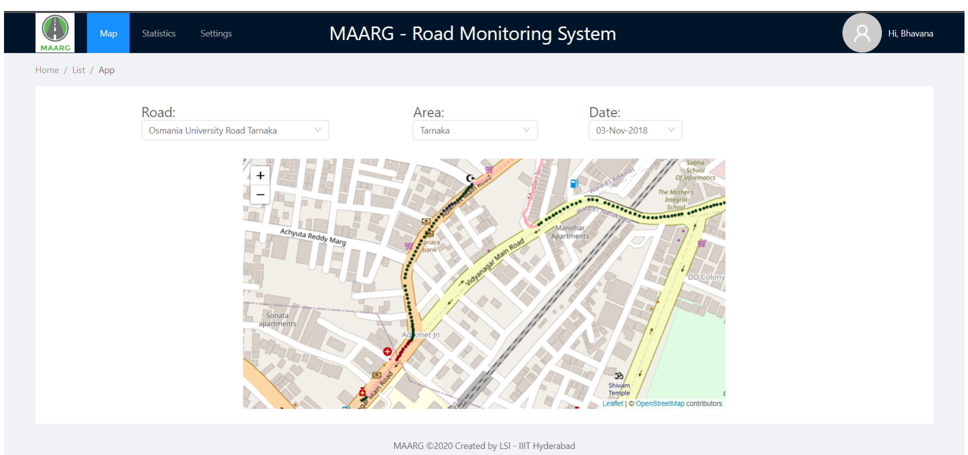

Figure 5.2 Contribution by User 5 in Vidyanagar area

From Figure 5.2 we can infer that the road connecting Shivam road and Vidyanagar is partially classified as mud and partially as tar road. Though most of it is a good road, there are patches of the road that are poor condition.

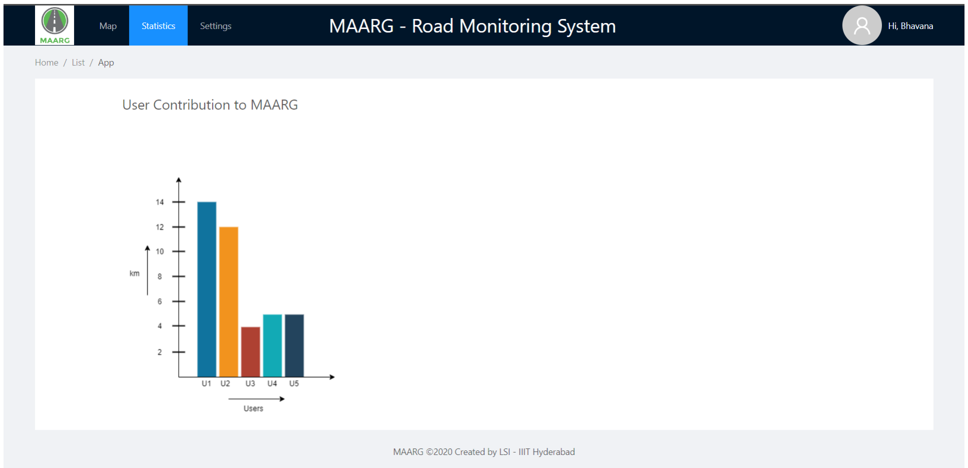

Figure 5.3 Contribution by users

5.2 Spatial Distribution

5.2.1 Majority Rule

The majority ranking example from section 4.2.3 is applied when multiple users contribute data for the same area.

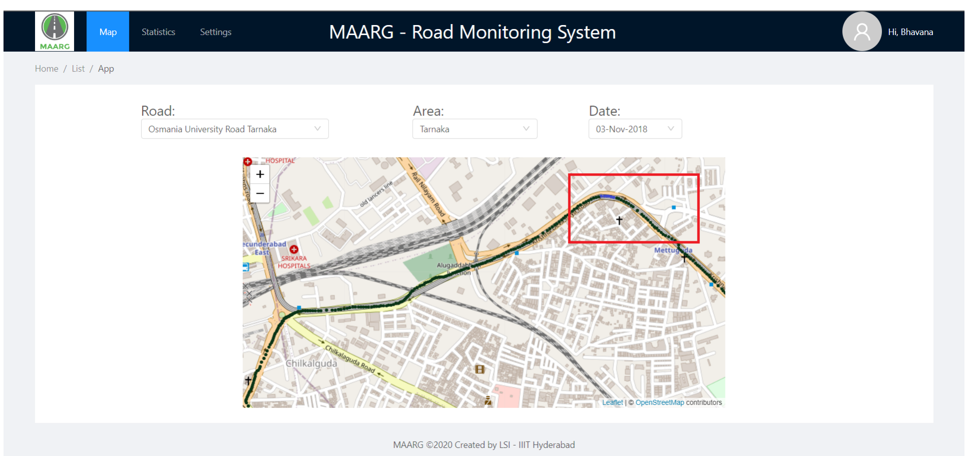

Figure 5.4 Alugadda Bavi to Mettuguda - Figure shows a red box around the classes which are different in both

Area selected: Tarnaka

Road Selected: Tarnaka road from Mettuguda

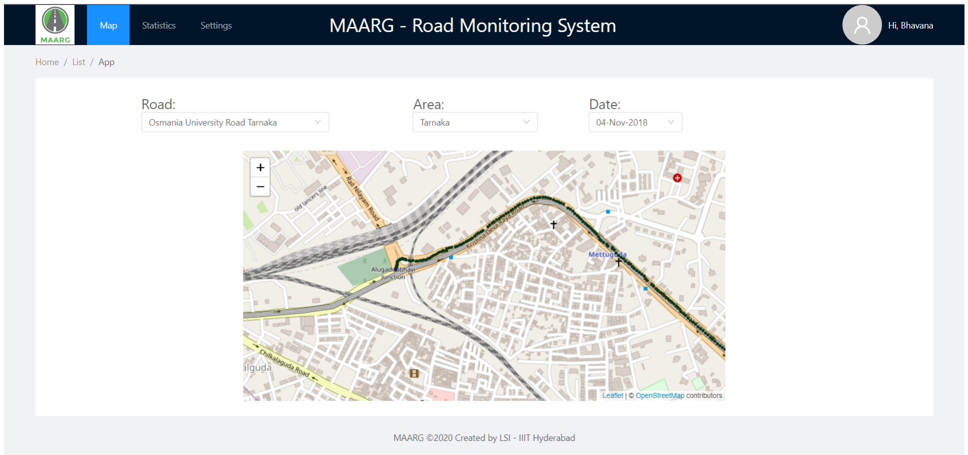

Figure 5.5 Mettuguda to Tarnaka

Contributors: User 4, 5

Ranking Applied: Yes

Date Selected: Default, (Date of the latest data is shown - in the above case 4th Nov 2018)

Result: In the above example, the data from both users is processed. As both users have contributed data within 30 days of time, it is taken into consideration as being within the boundary limit of recentness. In other words, the fact that both users have contributed overlapping data in a short interval of time, we assume that it can be used for showing the recent result.

Additionally, as voting is tied between two users, the latest is taken as the result class.

5.2.2 No overlaps

A case in which there are no overlaps is the case where data from different users can directly be combined together to show the result.

Area selected: Gachibowli

Road Selected: Old Mumbai Highway (IIIT Road)

Contributors: User 1, 2, 3

Ranking Applied: No

Date Selected: Default, (Date of the latest data is shown)

Result: Figure 5.6

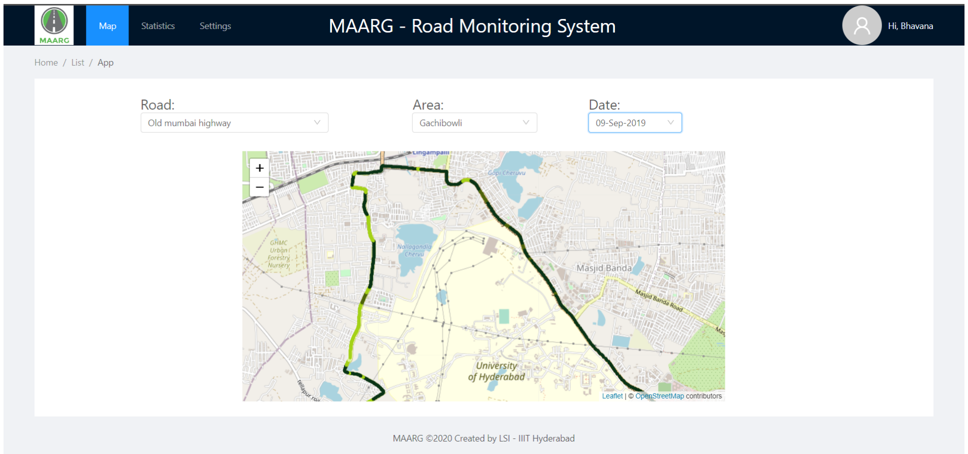

Figure 5.6 IIIT - Gachibowli Road

5.3 Time Variant

In the next case, we can discuss about the time-variant changes that arise in the area of interest.

If we compare the example shown in the previous section, of Figure 5.6 and refer it against Figure 5.7, we can see that some parts of the road have deteriorated in 5.6 because of the monsoon season or it could also be the case that many construction activities have taken place in the nearby region.

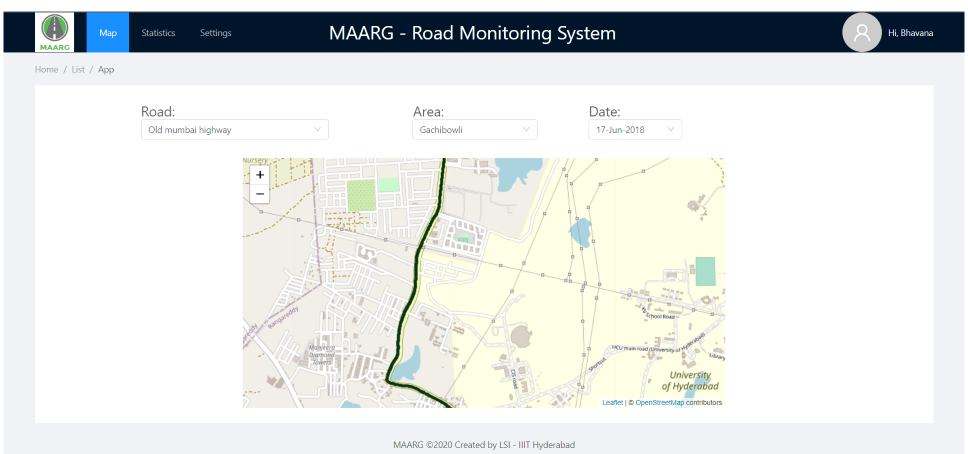

Figure 5.7 IIIT - Gachibowli Road

5.4 Summary

Looking at all the different kinds of visualizations the MAARG system shows in the time period analyzed it is safe to say that the visualizations obtained from MAARG can be used to efficiently monitor and assess roads. For example, when we compare Figure 5.7 with Figure 5.6, we can observe changes in the condition of the road. In the case of construction activities, road surface change can also be observed if the road has been dug out. The pre and post-condition of the road are analyzed effectively.

In addition to this, analysis like the road with the least amount of change as well as roads with the highest variance can also be an output. This ensures that there is an accountability of the authorities towards road monitoring and repair.

The analysis of different roads and visualization of their results establish the MAARG system as a powerful tool that is useful in monitoring and maintenance of roads.

Chapter 6

Comparison of existing road monitoring systems

6.1 Overview

In the previous chapters, we have seen the rich feature set of the MAARG system. In the following section, we compare the existing road monitoring systems and show how the MAARG system adds a unique value.

Table 6.1 illustrates the existing road monitoring systems compared to MAARG. The following are the criteria for comparison:

- **Image Based Data Used** - if image-based data is used in the system for analysis
- **Server-side data analysis** - if collected data is processed on the data collection device or processed on a central server
- **GIS Mapping** - mapping the obtained results on a map to show road conditions in different parts of a city
- **Shows surface type information** - classification of road base on tar, concrete and mud
- **Shows road condition** - classification of road based on good, satisfactory, unsatisfactory, and poor
- **Developing country** - in developing countries, the road surface can change rapidly(from mud to tar to concrete) depending on where the data is collected(cities vs. villages vs towns). It is also crucial for the municipal and city authorities to conduct such low-cost surveys as there is not enough manpower to monitor large road networks of the growing metropolises in the country.
- **Crowd-sourced** - the multiplicity of data points and the ability to have a majority voting are the main advantages of a crowd-sourced model
- **Smartphone based** - as smartphones provide ease of use and are an easily available commodity for users

- **Needs specialized equipment** - can be an additional burden to obtain specialized equipment to collect data
- **Comparison over a period** - used to show the effectiveness of the system and acts as a rich source of information for the road authorities

The following are the systems that were compared:

- **SODiCS** [33] (Spatial and Temporal Omnidirectional Video Distribution and Collection System) is a system that mainly targets collecting road video data in case of a disaster that can help in the live tracking and assessment of the damage. It uses specialized sensors in addition to a smartphone to collect different sensor data and map it on a web GIS map. It does not process the collected data to show condition but acts as a data transmission system.
- **RoADS** [34] uses the 3-axis accelerometer, gyroscope, and GPS sensor on a smartphone to monitor roads. It is a real-time-based system where authorities can find out the condition of the road immediately. It applies stationary wavelet transform analysis to remove the effects of external features such as slope and speed.
- **Road Alert** [35] uses smartphone sensors and IOT sensors to collect road data and fuses the data on the basis of GPS points to arrive at a score. It depicts a crowd-sourced model where users can upload collected data via a mobile app.
- **Smart Patrolling** [36] uses smartphone data from different users to mark the potholes and bumps detected on a map. It mainly focuses on a few areas in Chandigarh, India, to conduct its testing. It uses machine learning algorithms to arrive at the results but fails to depict the surface-type information.
- **CRSM** [37] uses specialized equipment mounted on the vehicle to detect potholes and assess road conditions. It is a crowd-sourced model where users can upload their collected data to the central server for processing. The final map depicts the location of different potholes in Shenzhen's urban area.
- **Nericell** [18] as mentioned in section 2.3.2 is a system where smartphones are used to collect sensor data from microphone, GSM radio, accelerometer, and GPS to detect various road artifacts like potholes, road bumps and also vehicle phenomena like braking and honking. Although Nericell is a promising tool, it does not include any feedback or recheck mechanism where these changes can be compared and verified.
- **Roadroid** [19] as mentioned in section 2.3.2 uses vibration sensors in smartphones of users to collect data and analyze the road roughness. Camera data, though collected in case of a pothole detected on the road, only acts as a reference and does not have a place in the final classification of the road.

System	**MAARG**	SODiCS	RoADS	Road Alert	Smart Patrolling	Nericell	Roadroid	CRSM
Image Based Data Used	**YES**	YES	NO	YES	YES	NO	YES	YES
Server-side Data Analysis	**YES**	YES	YES	NO	YES	YES	YES	YES
GIS Mapping	**YES**	YES	NO	YES	YES	NO	YES	YES
Shows surface type information	**YES**	NO	NO	NO	NO	NO	NO	NO
Shows road condition	**YES**	NO	YES	YES	NO	YES	YES	NO
Developing country	**YES**	NO	NO	YES	YES	YES	NO	NO
Crowd-sourced	**YES**	NO	NO	YES	NO	NO	NO	YES
Smartphone based	**YES**	YES	YES	YES	YES	NO	YES	NO
Needs specialized equipment	**NO**	YES	NO	YES	NO	YES	NO	YES
Comparison over a period	**YES**	NO	NO	NO	YES	NO	YES	NO

Table 6.1 Comparison of road monitoring systems

6.2 Comparison of key-features

6.2.1 Usage of image-based data

If we look at the other systems compared, they either use camera as the primary sensor for source of data (ex. SODiCS [33]) or only rely on other sensors like acclerometer (ex. Nericell [18]). MAARG provides unique value by using image-based data to determine the surface type.

6.2.2 Usage of accelerometer sensor

The 3-axis accelerometer gives the acceleration in the x,y, and z axes, determining road condition. Systems like Nericell [18] use this as a primary sensor and use threshold-based heuristics to detect potholes.

6.2.3 GIS Mapping

GIS Mapping tool provides the system users great value by depicting the current conditions of the road. In addition to this, MAARG also provides a visual interface to compare it with past conditions. Most other systems only provide a final analysis to the user, whereas MAARG provides an interactive analysis over time.

6.2.4 Server-side data processing

Server-side data processing is crucial as this gives us the ability to update the processing algorithm as and when required. If the processing is done on a data collection device, it must be updated manually occasionally, which can be an overhead.

6.2.5 Accuracy

MAARG uses low-cost smartphone sensors instead of specialized machinery and relies on the multiplicity of data to get more accurate results over a period.

6.2.6 System usability

MAARG focuses on giving making a highly usable system that is simple to understand and used by anyone without any specialized training. It used several usability principles like learnability, efficiency, (Refer 3.2), etc. to develop a user-friendly system.

Chapter 7

Conclusion and Future work

In this thesis, we have addressed the possibility of building a road monitoring system that satisfies all essential criteria of a monitoring system and provides a solution by fusing information from different sensor sources. It gives the authorities an idea about the roads that are not being monitored or are frequently changing state using the visualization tool.

MAARG uses a robust and crowd-sourced data collection model to ensure frequent and continuous coverage of roads. The easy-to-use mobile application helps users with frequent data collection and thus increasing the accuracy of the data. MAARG includes a training module to help the algorithm detect and store user-annotated data.

MAARG uses information-level fusion to derive the location-specific road condition and surface characteristics. In the data processing subsystem (Refer section 4.2), the android application stores the data and uploads it to the central server, which is then infused into a predefined model on a database based on the timestamp and location. A segmented approach is taken for collating multiple user-provided information and validation.

MAARG has a DAV(Data Analytics and Visualization) subsystem that enables users to perform various types of queries on data. Most of the current road monitoring systems fail to display surface-type information along with the road condition, which plays a key role in planning repair activities for authorities. This system attempts to find a solution to the above problem by the fusion of information from different sensor inputs that are all available on a smartphone. The DAV subsystem can handle different types of spatio-temporal visualizations and provide a rich analysis platform.

A smart-phone based system for road monitoring is a good fit for city municipalities because it avoids the need for specialized road monitoring infrastructure. In the future, it is hoped that this tool can be used to generate geo-tagged statistics on road infrastructure assessment. For example, some roads deteriorate more rapidly, whereas others have a longer life; the engineering reasons for this can be investigated as our DAV can highlight such regions. The system can also be used to make an event-based road condition cause analysis based on available data.

The system currently collates and displays the data in near real-time, providing the various stake-holders with a ready reference on the road surface and condition characteristics. This system proposes an innovative crowd-sourced model to monitor road surface and condition. Crowd-sourcing for such applications can be implemented by 1) Geo-citizens, 2) Office staff of related agencies like municipalities or city corporations, and 3) Campaign or mission modes which are one-time events. The current model is a generic approach that can be used in any of these modes of crowd-sourcing. It is expected that multiple contributions will not only help validate such crowd-sourced data but also be a model for infrastructure monitoring and assessment. In the future, this system can also aim to leverage new and improved classifiers for data processing. The offline verification module can also be automated once enough training data is available. This system can also be extended to other infrastructure monitoring like street lighting, road cleaning, etc.

Related Publications

- Rajamohan, Deepak, Bhavana Gannu, and Krishnan Sundara Rajan. ”MAARGHA: A prototype system for road condition and surface type estimation by fusing multi-sensor data.” ISPRS International Journal of Geo-Information 4, no. 3 (2015): 1225-1245.
- Bhavana Gannu, and Krishnan Sundara Rajan. ”MAARG: GEO-PROCESSING AND INFORMATION FUSION APPROACH FOR ROAD CONDITION AND SURFACE MONITORING”, Proceedings of the 39th Asian Conference on Remote Sensing. Kaula Lumpur, Malaysia. Oct 15-19, 2018.
- Bhavana Gannu, K.S.Rajan. ”DAV - Data Analytics and Visualization System for Roads”, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., V-4-2020, 3338, https://doi.org/10.5194/isprs-annals-V-4-2020-33-2020, 2020.

Bibliography

[1] Kelvin CP Wang and Omar Smadi. Automated imaging technologies for pavement distress surveys. *Transportation Research Circular*, (E-C156), 2011.

[2] Si-Jie Yu. Digitizing and 3d modeling of road surface using an integrated multisensory approach. *Report of the project in lieu of Masters Thesis, University of Tennessee*, 2005.

[3] Pavement profile scanner (pps) white paper. https://www.phnx-sci.com/PPS/Home.html [Accessed on 27-July-2020].

[4] UNDP Evaluation Office. United nations development programme evaluation office - handbook on monitoring and evaluating for results. *United Nations Development Programme: New York*, 2002.

[5] The Constructor. *Ring-Ball Test for Softening Point of Bitumen, Asphalt and Coal Tar*. https://theconstructor.org/practical-guide/ring-ball-softening-point-bitumen-asphalt-tar/2571/ [Accessed on 27-July-2020].

[6] Andreas Buehlmann, Peter A Stegmaier, and Volker Kuch. Method and device for monitoring a road processing machine, January 5 2010. US Patent 7,643,923.

[7] Alexander Buslaev, Selim S Seferbekov, Vladimir Iglovikov, and Alexey Shvets. Fully convolutional network for automatic road extraction from satellite imagery. In *CVPR Workshops*, volume 207, page 210, 2018.

[8] Qiqi Zhu, Yanan Zhang, Lizeng Wang, Yanfei Zhong, Qingfeng Guan, Xiaoyan Lu, Liangpei Zhang, and Deren Li. A global context-aware and batch-independent network for road extraction from vhr satellite imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, 175:353–365, 2021.

[9] Jiguang Dai, Tingting Zhu, Yang Wang, Rongchen Ma, and Xinxin Fang. Road extraction from high-resolution satellite images based on multiple descriptors. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 13:227–240, 2020.

[10] Christopher M Jengo, David Hughes, Joseph D LaVeigne, and Ivan Curtis. Pothole detection and road condition assessment using hyperspectral imagery. In *Proceedings of the American Society for Photogrammetry & Remote Sensing (ASPRS) 2005 Annual Conference*, pages 7–11, 2005.

[11] Chunsun Zhang et al. An uav-based photogrammetric mapping system for road condition assessment. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*, 37:627–632, 2008.

[12] Nueraihemaitijiang Abulizi, Akira Kawamura, Kazuya Tomiyama, and Shun Fujita. Measuring and evaluating of road roughness conditions with a compact road profiler and arcgis. *Journal of Traffic and Transportation Engineering (English Edition)*, 3(5):398–411, 2016.

[13] Daniel Hugo, Philippus Stephanus Heyns, RJ Thompson, and Alex T Visser. Haul road defect identification using measured truck response. *Journal of Terramechanics*, 45(3):79–88, 2008.

[14] Lokeshwor Huidrom, Lalit Kumar Das, and SK Sud. Method for automated assessment of potholes, cracks and patches from road surface video clips. *Procedia-Social and Behavioral Sciences*, 104(2013):312–321, 2013.

[15] Center for Good Governance, Hyderabad. *My GHMC*. https://play.google.com/store/apps/details?id=cgg.gov.ghmc [Accessed on 27-July-2020].

[16] Akash C Prakasan, Devesh Tiwari, Yogesh U Shah, and Manoranjan Parida. Pavement maintenance prioritization of urban roads using analytical hierarchy process. *International Journal of Pavement Research & Technology*, 8(2), 2015.

[17] Andrea Benedetto, Francesco Benedetto, Maria Rosaria De Blasiis, and Gaetano Giunta. Reliability of signal processing technique for pavement damages detection and classification using ground penetrating radar. *IEEE Sensors Journal*, 5(3):471–480, 2005.

[18] Prashanth Mohan, Venkata N Padmanabhan, and Ramachandran Ramjee. Nericell: rich monitoring of road and traffic conditions using mobile smartphones. In *Proceedings of the 6th ACM conference on Embedded network sensor systems*, pages 323–336, 2008.

[19] Lars Forslöf and Hans Jones. Roadroid: Continuous road condition monitoring with smart phones. *Journal of Civil Engineering and Architecture*, 9(4):485–496, 2015.

[20] Yun Cheng, Xiucheng Li, Zhijun Li, Shouxu Jiang, Yilong Li, Ji Jia, and Xiaofan Jiang. Aircloud: a cloud-based air-quality monitoring system for everyone. In *Proceedings of the 12th ACM Conference on Embedded Network Sensor Systems*, pages 251–265, 2014.

[21] Scott Curtis, Eric P Halber, Gregory M Evans, and Steven L Petersen. Passive crowd-sourced map updates and alternate route recommendations, December 31 2013. US Patent 8,620,532.

[22] Michael Schmitt and Xiao Xiang Zhu. Data fusion and remote sensing: An ever-growing relationship. *IEEE Geoscience and Remote Sensing Magazine*, 4(4):6–23, 2016.

[23] Jakob Nielsen. Ten usability heuristics, 2005.

[24] altexsoft. *The Good and the Bad of ReactJS and React Native*, 2018. https://www.altexsoft.com/blog/engineering/the-good-and-the-bad-of-reactjs-and-react-native/ [Accessed on 08-July-2020].

[25] altexsoft. *Pros and Cons of ReactJS and React Native — AltexSoft.*, 2020. https://www.altexsoft.com/blog/engineering/the-good-and-the-bad-of-reactjs-and-react-native/ [Accessed on 08-July-2020].

[26] Vladimir Agafonkin. *LeafletJS - Overview*. https://leafletjs.com/ [Accessed on 10-Jan-2022].

[27] Wikipedia. *Android (operating system) - Wikipedia*. https://en.wikipedia.org/wiki/Android [Accessed on 27-July-2020].

[28] Slant. *Slant - 34 Best web frameworks to create a web REST API.* https://www.slant.co/topics/1397/ best-web-frameworks-to-create-a-web-rest-api [Accessed on 27-July-2020].

[29] Young Butterfly. *Python Programming Language - Youngbutterfly*. https://youngbutterfly.in/class/python-programming-language/ [Accessed on 27-July-2020].

[30] upGrad. *Top 10 Reasons Why Python is So Popular With Developers*, 2020. https://www.upgrad.com/blog/reasons-why-python-popular-with-developers/ [Accessed on 27-July-2020].

[31] Educba. *What is PostgreSQL? — Features — Advantages and Disadvantages*. https://www.educba.com/what-is-postgresql/ [Accessed on 27-July-2020].

[32] Michael W Sayers. The little book of profiling: basic information about measuring and interpreting road profiles. Technical report, University of Michigan, Ann Arbor, Transportation Research Institute, 1998.

[33] Kenta Ito, Go Hirakawa, and Yoshitaka Shibata. Sodics on challenged communication environment. In *2014 Eighth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, pages 152–158. IEEE, 2014.

[34] Fatjon Seraj, Berend Jan van der Zwaag, Arta Dilo, Tamara Luarasi, and Paul Havinga. Roads: A road pavement monitoring system for anomaly detection using smart phones. In *Big data analytics in the social and ubiquitous context*, pages 128–146. Springer, 2015.

[35] Avik Ghose, Provat Biswas, Chirabrata Bhaumik, Monika Sharma, Arpan Pal, and Abhinav Jha. Road condition monitoring and alert application: Using in-vehicle smartphone as internet-connected sensor. In *2012 IEEE international conference on pervasive computing and communications workshops*, pages 489–491. IEEE, 2012.

[36] Gurdit Singh, Divya Bansal, Sanjeev Sofat, and Naveen Aggarwal. Smart patrolling: An efficient road surface monitoring using smartphone sensors and crowdsourcing. *Pervasive and Mobile Computing*, 40:71–88, 2017.

[37] Kongyang Chen, Guang Tan, Mingming Lu, and Jie Wu. Crsm: a practical crowdsourcing-based road surface monitoring system. *Wireless Networks*, 22(3):765–779, 2016.