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ML Driven Predictive Maintenance and Life Span Detection for Bridges

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Abstract: *Ensuring the longevity and safety of bridge infrastructure is vital for public safety, efficient transportation, reducing incidents, and maintaining economic stability. This paper introduces an innovative software model that predicts the durability, remaining lifespan, and required maintenance of bridges by leveraging cutting-edge technologies such as computer vision, Internet of Things (IoT) sensors, and machine learning algorithms.*

The software aims to mitigate the risk of bridge failures by employing an assessment system that integrates historical data with real-time inputs. Through the use of computer vision and non-destructive testing methods, the system identifies structural issues. Machine learning algorithms then analyze environmental conditions and traffic patterns to evaluate the bridge's durability.

The proposed system efficiently operates through four main phases: user interaction, historical data analysis, real-time data collection, and predictive analysis. These phases collectively generate a comprehensive report on the bridge's condition, providing proactive solutions for maintenance challenges through the intelligent application of machine learning algorithms. Ultimately, this software model not only enhances the preventive maintenance of bridges but also promotes informed decision-making and resource allocation by relevant authorities. By continuously monitoring and analysing bridge conditions, the system ensures timely actions and extends the lifespan of critical infrastructure, thereby contributing to overall public safety and economic stability.

Keywords: Predictive Maintenance, Machine Learning, Computer Vision, Internet of Things (IoT), Non-Destructive Testing, Life Span Assessment, Real- Time Monitoring

I. INTRODUCTION

As we all know that in today's era the bridges are very crucial component of our transport infrastructures. But sometimes due to improper maintenance or other reasons like improper designs, less quality materials the accidents are occurs. These accidents causes various types of losses like human lives, financial losses, sometimes it also effect the environment.

Traditionally, the visual inspections of the bridges are taken manually by Humans. But it is difficult perform on the large bridges and the bridges located at hazardous or remote areas. Also there are several disadvantages of this inspection like it is labor intensive, time consuming and subject to human errors. Although, the accuracy of this inspection is depend upon the experience, skill and knowledge of that person.

So our project provides an effective solution on this disaster. It will helps or prevents these bridge accidents. We provide the unique solution which uses the technologies likes Computer Vision, machine Learning Algorithms, Real-Time Data Gathering & IOT Model in the cheapest & effective way.

II. LITERATURE SURVEY

2.1 Automated Crack Detection on Concrete Bridges

Objective of this paper is that develop an automated system using computer vision technique and machine learning for detecting crack in concrete bridge.

Research on this paper provide how this paper primarily deal with artificial intelligences to detect the crack on concrete bridges.

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In this paper it uses high quality camera with the computer vision technique to capture the images of concrete bridge surface.

Then this image is analysis by ML model along with various parameters to detect the cracks on surface. Because of this techniques, it reduces the need of manual inspection by human and also increase the accuracy of detection.

Advantage of this paper is reducing the need of manual inspection, which can be time-consuming and prone to human errors.

Real-time monitoring and detection However, it has several disadvantage like limitation under environmental conditions. It's detection accuracy vary depending on environmental conditions and the quality of image of captured by camera and also it only focus visual crack detection not account for structure issue of concrete bridge.

Future scope of this paper is to improve ML algorithm for detection varying environmental conditions. And integrate additional sensor for better analysis. [1]

2.2 Predictive Maintenance - Bridging Artificial Intelligence and IoT Sensors

The primarily objective on this paper is to predict maintenance of bridge by analyzing real-time sensor data using the IoT sensor and Artificial intelligences to prevent failures.

This paper highlights how the Artificial intelligences and IoT technologies are combines to enable to predictive maintenance of bridge.

It explore the integration of IoT sensors to gathers real-time data and that AI algorithm to analyze that data to predict when the maintenance is needed to bridge.

Predictive maintenances just like foresee equipment issue before then become critical and reduce the cost. It is preventive approach.

The Advantage of this paper are it focus on preventing failure means future damages to bridge, which can save money and prevent damages. And also integrates both AI and IoT, which allow continuous monitoring multiple parameters of bridge. Because of use of predictive model enables proactive rather than reactive maintenance.

This paper cover the disadvantage of previous that it also account for structure issue of bridge.

However, it has several disadvantages like it heavily depend accurate data gather by IoT Sensor which may face challenges like sensor failure and noise. And also requirements sensor networking and data storage, making it costly to implement.

The future scope of this paper is Advance sensor technology, develop better predictive models, integrate with broader IoT systems, and conduct real-world testing. [2]

2.3 Application of Artificial Intelligence Technology in Bridge Construction and Maintenance

The primarily objective of this paper is explore AI application in bridge construction and maintenance, including smart material, predictive maintenances and UAV inspection.

This paper offer a boarder view of how the artificial intelligences is applied to entire life cycle of bridge construction and maintenances. It discusses predictive maintenance, real-time monitoring, smart material and the use of UAV's means drones for inspection of bridge from air. In this AI is applied for bridge construction in which its role to decide the construction material based on the environmental condition where we construct bridge. For inspection of bridge drones are used and it is equipment with high quality camera, IoT Sensor and AI algorithm. So data collected by drones is analogize by AI algorithm for detect any kind of damage on bridge.

The advantages of this paper is it cover the wide range of Artificial Intelligence, from construction to maintenances of bridge. It detection accuracy is going beyond the detection of visual cracks by introducing the UAVs and IoT Sensors. And also by using AI it improving safety and efficiency in bridge management.

However, It has several disadvantages is this paper cover to many things and does not focus of specific, actionable application like first paper. And the other hand because of used of advance technology my required significant investment in both AI technology and hardware, such as UAVs and IoT sensors.

The future scope of this paper is to expand use of AI application, including new technology, and improve version of AI algorithms for accurate detection. [3]

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III. EXISTING SYSTEM

3.1 IBM Maximo Application Suite

IBM Maximo is a powerful tool for managing maintenance of bridge. It used Internet of Things (IoT) by gathering real-time data and advanced analytics to help to predict the maintenance of bridge based actual condition of the assists. One of the important part of Maximo is Maximo predict, which is best for predicting when the maintenances is needed for important structures like bridges. To predict the future problem or issue it uses the past recorded data and data from IoT sensors. And then that data is analysis by machine learning, it can foresee assets will start to fail, this help prevent future risks for bridge and allowing better planning of maintenance work.

It also uses IBM Watson® Machine Learning to improve its predictions, making it easier to foresee asset failures. This help to reduce risk during operations, lower maintenance cost and longer life of bridge. [4]

3.2 Siemens Predictive Maintenance System

Siemens uses the Artificial intelligence (AI) and digital twin technology for complex system like bridge to accurate predictive maintenances of bridge. This platform collect data from IoT sensors which are place on bridge, which monitors things like temperature, humidity, and stress on the structure of bridge. By using machine learning that data is analysis then the system spot any kind of future damage on bridge means early sign of damages and suggest maintenance actions.

The new technology uses in that is digital twin of the bridge. By using this we continuously monitor or updates data from the sensors and providing a virtual view of bridge's condition. This system helps to manage a plan of maintenances before serious problem occurs. And extending the lifespan of bridge. [5]

3.3 Drones and Sensors for Bridge Monitoring

This system uses drone, also called as UAV's, to inspect the bridge from air. This is game changer in inspection of bridge from air. The drones is equip with high-quality camera and IoT sensors. The drone takes high-quality image and videos of bridge, which are then analyzed by artificial intelligences algorithm to spot any potential damage, like cracks or rust. This inspection technique makes inspection easier and faster to inspect the bridge, and also in hard-to-reach places where difficult to go to human, and improves safety by reducing need for manual inspection.

By providing timely understanding bridge conditions, this system allows for proactive maintenance strategies, and reducing the risk of severe failures. The use of drones not only improve inspection accuracy but also reduces the need for costly and disturbance of manual inspections.[6]

3.4 VSL's Predictive Maintenance Initiative

VSL, in collaboration with the Chair in Construction 4.0 at Centrale Lille in France, has started a research project on improving predictive maintenance for prestressed concrete structures. This project used a large set of data and machine learning techniques to analyze historical inspection reports and data, non-destructive testing results, and other related data. By identifying the patterns of any kind of physical damage like cracks and structure issues, then the system can guide decision-making for bridge maintenance by forecasting the future condition of the bridge.

The primary objective of this system including the improving the quality of condition of assessment, increasing early warning times for significantly structure future damages and minimizing the maintenances cost while maximum traffic load on bridge.[7]

IV. METHODOLOGY

4.1 Data Collection:

As for the machine learning algorithms the data is very important to train and test model. The accuracy of the ml model will depend on this input data. Thus, we emphasis on collecting the real-time data through various ways like IoT sensors, computer vision and various Api's, etc. Mainly the data parameters like temperature, humidity, pollution levels, rain, etc. are collected using the API's which makes easier and cheaper to get the real-time data.

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Also, we use the IoT sensors to collect the data about the traffic, water levels or intensity of the rivers (if Present). It helps to get the accurate data which definitely enhances the accuracy of our model.

4.2 Features & Parameters:

As we know the bridges are the very crucial component in our transport infrastructure. Various factors like its structural factors, Traffic factors like daily traffic, Vehicle classification, Environmental factors, etc. affect the lifespan and durability of the bridge. Also, we consider minimum value, average value and maximum value of every feature such that with the age of the bridge we can easily conclude the overall effect of these parameters on the bridge. So in lesser data points we can cover a wide range of the scope.

4.3 Machine Learning Model Selection:

Once the whole dataset is prepared, we need to select the proper machine learning algorithm which will have the high accuracy and prediction speed. Also, we need to use the supervised machine learning algorithm. So, as usual we use the classification algorithm for predicting the maintenance and regression algorithms for predicting the lifespan and durability of the bridge. In our project we use the Random Forest Classifier and Random Forest Regressor for making the prediction.

V. IMPLEMENTATION AND EXPERIMENTAL SETUP

5.1 Technology's Used:

Programming Languages: Python (for ML Models), JavaScript (React for frontend and Node.js for backend) and Java (For connection purpose).
Machine Learning Frameworks: Sci-kit learn (for ml algorithms like Random Forest Classifier and Random Forest Regressor)
Computer Vision Framework: OpenCv (for implementing the computer vision)
Database: XAMPP-MySQL (for backend

5.2 Other Frameworks:

Node.js: for retriving of the data from the database and prediction result through java API's
React.js: For developing the UI interface and connect with the node API's.
Mapbox: for interactive maps in UI

5.3 Hardware Requirements

Sr. No	Name	Specifications	Qty
1	Computer System	i5-12th gen or more 8 GB ram or more 10 GB free space or more	2 (one for server and one for client)
2	Router or any other network adapter (for establishing network)	2.4 GHz or 5.0 GHz	1
3	Arduino Board	16 MHz ceramic resonator	1 per Bridge
4	NodeMCU ESP32	240 MHz SRAM 512kB Memory 4 MB	1 per Bridge
5	Water Level Sensor	Depend upon height of bridge	1 per Bridge
6	Starin Gauge Sensor (For determining the load)		1 per bridge
7	Camera (to deterging the traffic)	4k resolution	1 per bridge

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5.4 Experimental and Testing Setup:

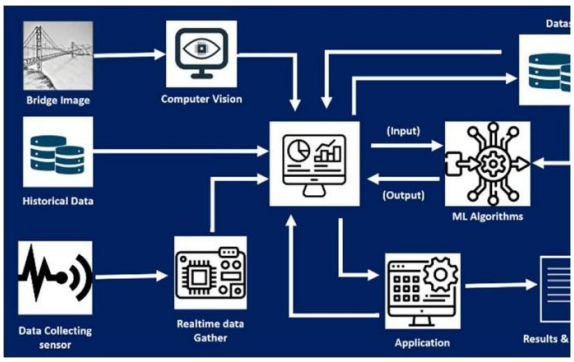
First of all, we need to setup each and every component on the server pc in the above sequence:

1. Setting the Database in xampp configure the bind-address to 0.0.0.0 or comment it in the C:\xampp\mysql\bin\my.ini file
2. Start the mysql and apache server in the xampp.
3. Import the database in the mysql server.
4. Then to java servlets folder and paste to this C:\xampp\tomcat\webapps directory.
5. After that start the tomcat server.
6. Navigate to the python files directory and run the MainML.py file.
7. Now Navigate to the node.js backend folder and run the command `node server.js`.
8. Then navigate to the react project directory and run the command `npm run dev`.
9. Then in the command prompt two url's are display one to run on the same machine and second to run on the another machine on the network.

Prerequites for setup:

1. Node.js
2. React Framework
3. Python 3.12.7
4. JDK 21.0.4

VI. ARCHITECTURE



Our Whole project is divided into the different components as shown in the above diagram. Every component of our project should has the independent functioning and connected to each other by the data transmission protocol UDP. These connections are mainly managed with the help of the java servlets and java.net package.

The complete architecture is start form the Application which is created using the React.js. The React.js make the connection only with the node.js and java API's or servlets. The Node.js is mainly used to fetch the data form the database and transmit to the react components.

Then the java servlet's are mainly used to insert the data in the database. At the time of the insertion of the data the java servlet's gathers the various real-time data about the bridge also establish's the connection with the sensors related to that bridge.

Then the java APIs are used to make the connection between the Machine learning models and the React Program. i.e. it will act as the intermediatory between the User Interface and the backend models. When the user want to predict the maintenance all the data will be gathered by this api and send to the python program in the proper format in which these programs can be understand then the python program use the transferred data to make prediction about the maintenance and other factors to the java program then the java program again send this data to the React server where the React fetch the data and prepare the proper report which is displayed to the end user.

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After the user interface the database is the important component which stores all the necessary data about the user this data is continuously updated according the real-time gathered data. This data will be updated by the java programs. These java program fetch this data form various API's like open weather and from sensors installed at the bridge.

Now there are also some additional program which runs at the background and scanning the bridges and predict there is need of the predicting the maintenance for any bridge before the time according the factors make impact on it.

Then, the dataset will come which is the very crucial component of every machine learning model. This dataset will consist of various features which covers very wide scope. It contains the features like various traffic factors, construction factors and environmental factors.

After the dataset we need to feed it to the machine learning models. Thus for the machine learning models we use the Random Fores Regressor and the Random Forest Classifier. We feed this data according to each model for predicting the maintenance, lifespan, and maintenance of the bridge.

The computer vison is implemented to detect the cracks and traffic parameters on the bridge.

All this data is collected by the java program's and stored in the database for the further use.

6.1 Working Flow

The Working flow of the project is start when user interact with the interface then the interface should consist of the various options at its slide-bar. This slide bar consist of the options like recommendation, predict maintenance, add bridge, view bridges, add users, etc.

In the under the recommendation section there will be the list of bridges which are recommended by our machine learning algorithms which requires to check its maintenance and its durability then there a user can able to check the complete requirement of its maintenance along with the complete report of the bridge.

Also, we require to check the maintenance of every bridge between some time period. This functionality is available under the predict maintenance function. Here the user can predict the maintenance of the bridge by pressing the predict next to every bridge.

After pressing the predict the user will be redirected to report where the complete report of the bridge is created and displayed to the user. This report consists of the statistics of the various factors which affects the bridge quality.

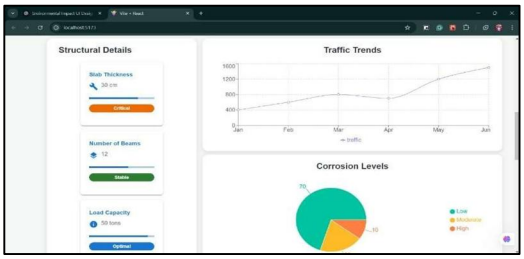
Whenever the user predict the maintenance of the certain bridge. The react make a request to the java servlet then the servlet gather all the data require to predict the maintenance and send to the python machine learning program and then the python program will send the output to the java program. Once the java servlet receives the result the result will me be send to the react.

The connection between the java and python program will be handled with the UDP protocol. And these java servlet host using the tomcat server.

Then at the backend mainly the java program's are work to gather all the data form various data sources and update the data in the database according to the data gathered.

VII. RESULTS & DISCUSSION

Every time the when the user predict the maintenance of the bridge the report will be displayed to the user the report should consist of the various factors. Some of the output of the report are as above:



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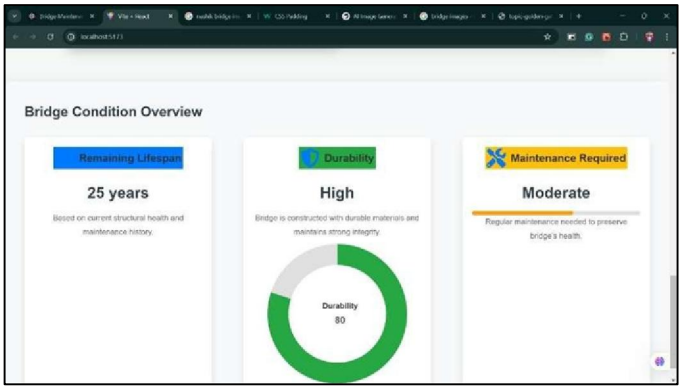
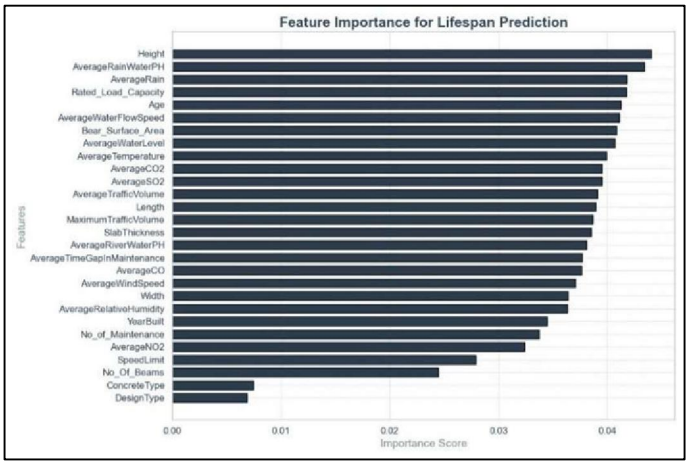
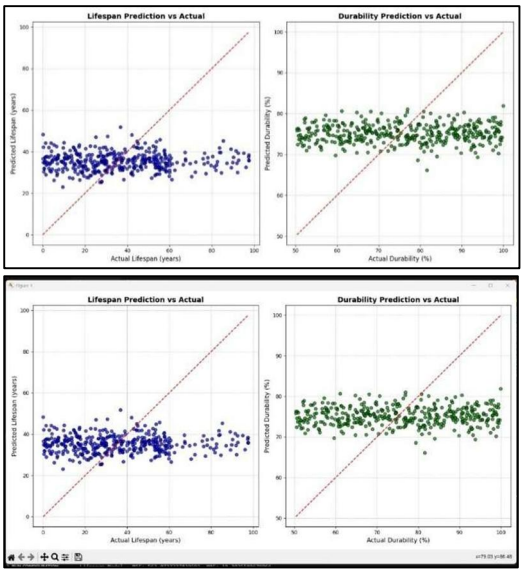


The stats of our machine learning algorithms are as above:

```
[Running] python -u "c:\Users\sarvadnya\Desktop\Major project interface\test.py"
Lifespan Model - MSE: 563.0737227839593, MAE: 19.2025589678066
Durability Model - MSE: 209.54816725582216, MAE: 12.598247966897313

[Done] exited with code=0 in 80.558 seconds
```





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VIII. ADVANTAGES

Faster prediction

Our project highly emphasis on the faster & accurate results. It provides the result of every input data under a second.

Use of Realtime data

For the we need to give a certain data to the algorithms.

So, we provide the Realtime data using various API's and IoT. Which increase the accuracy of our model.

Low cost

One of the main goals of our project is low cost. To achieve this, we use various API which will help to collect the Realtime data in negligible cost

Provides semi - automated server

Once all the sensors are installed on the bridge then excluding taking photos of bridge for computer Vision all the data are collected automatically without any human interaction.

Requires less configuration server

With the minimum requirements like 4/8 GB RAM or any 3.0 GHz or more clock speed CPU once the ML model will able to handle more than 1000 bridges once a day.

IX. LIMITATIONS

Data Related to Bridge

Acquiring the necessary data for deep analysis of the bridge. Like difficulty in getting overall bridge information – structural components, environmental factors, historical records and functional phase.

The comprehensive data collection required for bridge analysis presents a significant challenge due to the unique constraints inherent to each structure. These individual constraints necessitate careful consideration and often complicate the process of acquiring complete and relevant datasets, making this task particularly arduous.

Managing Model Updates in Response to Evolving Data.

As dataset changes then the model will require more time to train.

As the real-time application the data that is incoming is constantly being generated means each time the data related to bridge is different from the previous one.

So, this new data might affect the training process of model.

If the previous bridge having some common attributes in latest bridge, then the mix data will also affect the training process

If the dataset is not training regularly the n the performance can be sometime degrade.

Possible areas:

- Finding new patterns
- Forgotten data (previous)
- Size increases
- Distribution of data values

The Need of Accurate Computer Vision

Accurate assessment of bridge condition is very important. if some of the crucial data is ignored the serial impact will occur on model output which is the report of bridge.

The critical nature of bridge infrastructure demands a highly specialized and accurate approach, requiring significant effort in data acquisition, model development, and validation.

10.4 Inconsistent data from APIs

Our project, which relies on getting data from external APIs for a bridge analysis, faces a significant limitation due to inconsistencies within the data provided by these APIs. These inconsistencies can negatively impact the performance and reliability of our machine learning models.

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ML models Problem when the inconsistent data is coming from APIs: -

- Training Challenges
- Prediction Errors
- Model Instability

Variability in Crack Appearance and type of bridge:

Cracks can vary significantly in width, length, orientation, shape, and location. They can also be neglected by shadows, debris, or other surface features. This variability makes it challenging to develop models.

Models trained on one type of bridge or crack might not generalize well to other types of bridges or cracks due to variations in design, materials, and environmental conditions

X. CONCLUSION AND FUTURE SCOPE

In Conclusion, this paper is able to predict the accurate maintenance of the bridges and the remaining life span of the bridge. By leveraging advanced data analytics, sensors technologies and predictive modeling.

The proposed machine learning-driven predictive maintenance system for bridges provides a proactive and cost-effective approach to ensuring structural stability and durability. By integrating computer vision, IoT sensors, and machine learning algorithms, the system enables real-time monitoring and accurate predictions of maintenance needs. The ability to assess structural conditions, and forecast lifespan significantly enhances bridge safety, minimizes unexpected failures, and optimizes maintenance schedules. This model not only reduces financial and human losses due to bridge failures but also optimizes resource allocation for infrastructure maintenance authorities.

Future advancements in this research can focus on improving the accuracy and strength of predictive models by incorporating advanced deep learning techniques. Enhancements in IoT sensor technology, such as self-powered or AI-enhanced sensors, could further improve real-time data collection. Expanding the dataset with case studies and incorporating AI-driven irregularity detection could refine the model's predictive capability.

Lastly, extending this approach to other infrastructure components like tunnels and dams could broaden its impact on public safety and infrastructure management.

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