Journal of
Big Data & Smart City

VOLUME 6
ISSUE 1
SPRING 2026

ISSN (Print) : 2706-7912
ISSN (Online) : 2788-4112

www.mjbdsc.org

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Message from the Editor in Chief

On behalf of my co-editors (Prof. Ahmed Nawaz Hakro & Prof. Anupam Srivastav) and other members of Editorial Board, I am delighted to bring this Volume 6, Issue 1 of the Journal of Big Data and Smart City (JBDSC). This Issue, like its predecessor issues, is an open access journal, with an Arabic translation of the Abstract of every paper published.

The Journal of Big Data and Smart City (JBDSC) is providing an exciting platform to scholars, researchers, other related professionals, policy makers, and especially to the students, to showcase their scholarly ideas and research in Smart City applications, building on Big Data technologies. The journal has been accessible, engaging and motivating to the young researchers, as all the 6 papers in this Issue are joint work with students.

The journal has been successful in fulfilling its objective to publish original interdisciplinary research. All the published papers, which cover the areas of Expert Systems, IoT, Mobile Applications, etc, have been subjected to a double-blind review process. The multidisciplinary collaborative work combining multiple fields in wider possible contexts, published in this issue integrates theoretical, experimental, and computational approaches, providing solutions towards smart city/ information and communication technologies themes.

I am thankful to those who submitted papers, both individually or collaboratively from academia and industry. I take this opportunity to also thank all those who contributed in bringing out this issue of the Journal. I am extremely thankful for the continuous support of MoHERI and MoI for allowing this scholarly publication.

Special thanks to all the members of the Editorial Board for dedicating their valuable time and energy which made it possible for this issue to be published well in time.

Wishing the readers of the articles of this journal making a fruitful contribution in their future research pursuits.

Dr. Alya Al Farsi
Editor in Chief
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IoT-Based Smart Monitoring and Control System for Electric Vehicles with Real-Time Data Logging and Remote Access

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Received: 13th December 2025; Revised: 5th January 2026;

Accepted: 8th February 2026

Abstract— **The integration of technology with industry is one of the most key features of the current era. Electric vehicle technology is one of the most common examples of this era. Through a review of previous projects, it was found that most of these projects related to electric vehicles aim to increase the efficiency of charging stations or special parking areas for electric vehicles. This project offers a unique approach, offering an integrated system with the vehicle's electric systems to provide a world-class level of safety, in addition to the possibility of fully controlling the vehicle remotely through Internet of Things applications. The system designed for this project can be integrated with any electric vehicle without the need for reprogramming or interfering with the vehicle's operating system. The system provides a simple interface for user via an Android application connected to a computing cloud that provides Internet of Things services. Via the android application, the user can get information including the actual location of the car, objects adjacent to the car and the battery charge level, which make the process of borrowing a car in the event of theft or unauthorized access easier. The application also provides the ability to control the opening and closing of the car doors, stopping or starting the engine, controlling the gearbox and steering wheel of the car, which enables the user to drive the car remotely without even touching the car. To implement this project, the V Modem methodology was chosen because it aligns with the project objectives and implementation mechanism and is characterized by sufficient flexibility to identify errors immediately after they occur due to the periodic inspections associated with project implementation. At the end of this project, it is expected to obtain a prototype that can be applied to the electric car and tested. The main controller for the project, the Node MCU, will be used because it provides the ability to easily connect to the Internet, in addition to a set of sensors and software tools to complete the project.**

Keywords— IoT, Real-Time, Monitoring, E-Vehicle, Node-MCU, Remote Access, Firebase

الخلاصة **- يُعدّ تكامل التكنولوجيا مع الصناعة من أبرز سمات العصر الحالي، وتُعدّ تكنولوجيا المركبات الكهربائية من أكثر الأمثلة شيوعًا على ذلك. ومن خلال مراجعة المشاريع السابقة، تبيّن أن معظم المشاريع المتعلقة بالمركبات الكهربائية تركز على زيادة كفاءة محطات الشحن أو مناطق الوقوف المخصصة لهذه المركبات. ويقدّم هذا المشروع نهجًا مختلفًا، حيث يقترح نظامًا متكاملاً مرتبطًا بالأنظمة الكهربائية للمركبة بهدف توفير مستوى عالٍ من الأمان، إضافةً إلى إمكانية التحكم الكامل بالمركبة عن بُعد من خلال تطبيقات إنترنت الأشياء. تم تصميم النظام في هذا المشروع بحيث يمكن دمجه مع أي مركبة كهربائية دون الحاجة إلى إعادة برمجتها أو التدخل في نظام التشغيل الخاص بها. ويوفّر النظام واجهة استخدام بسيطة للمستخدم عبر تطبيق يعمل على نظام أندرويد ومتصل بحوسبة سحابية توفّر خدمات إنترنت الأشياء. ومن خلال هذا التطبيق، يستطيع المستخدم الحصول على معلومات مثل الموقع الفعلي للمركبة، والأجسام المحيطة بها، ومستوى شحن البطارية، مما يسهم في تسهيل عملية استرجاع المركبة في حال السرقة أو الوصول غير المصرح به. كما يتيح التطبيق إمكانية التحكم في فتح وإغلاق أبواب المركبة، وإيقاف أو تشغيل المحرك، والتحكم في ناقل الحركة وعجلة القيادة، الأمر الذي يمكّن المستخدم من قيادة المركبة عن بُعد دون الحاجة إلى التواجد داخلها .ولتنفيذ هذا المشروع، تم اختيار منهجية V-Model نظرًا لتوافقها مع أهداف المشروع وآلية تنفيذه، إضافةً إلى ما تتميز به من مرونة كافية تتيح اكتشاف الأخطاء فور حدوثها من خلال عمليات الفحص الدورية المرتبطة بمراحل تنفيذ المشروع. وفي نهاية هذا المشروع، من المتوقع الحصول على نموذج أولي يمكن تطبيقه على مركبة كهربائية واختباره عمليًا. وسيتم استخدام وحدة التحكم الرئيسية NodeMCU في المشروع لما توفره من إمكانية الاتصال بالإنترنت بسهولة، إلى جانب مجموعة من المستشعرات والأدوات البرمجية اللازمة لإكمال تنفيذ المشروع.**

الكلمات المفتاحية – إنترنت الأشياء، الوقت الحقيقي، المراقبة، المركبات الكهربائية، *NodeMCU*، الوصول عن بُعد، *Firebase*

I. INTRODUCTION

Electric cars are vehicles powered by electricity via electric motors only. The EV highly energy-efficient compared to other types of vehicles powered by internal combustion engines or hybrid. EV represent a valuable solution for preserving the environment and reducing carbon dioxide emissions. They support the international trend toward renewable energy and reducing reliance on fossil fuels [1]. In the point of view of growing environmental challenges, the shift to EV has become a necessity to reduce global warming and greenhouse gas emission. In many countries the governments support electric vehicle projects through tax incentives and subsidies, in addition to investing in charging station infrastructure. This project aligns with the Sustainable Development Goals, particularly regarding the use of clean energy and preserving the environment for future generation [2], [3]. The market of electric vehicle has rapid growth in last years, where according to reports from the International Energy Agency (IEA), the number of electric vehicles worldwide exceeding 27 million by 2024, compared to 10 million in 2020 [4]. In Oman specially, statistics indicate that a 300% increase in EV users in 2024 compared to 2023. Electric car statistics at the end of 2024 reached 1,500 electric cars, compared to approximately 500 cars in 2023 [5]. This growth is due to several key factors, most notably the increased energy efficiency of electric vehicles compared to internal combustion engines as shown before, where EV can convert more than 85% of the energy stored in the battery into active power, compared to only 25% in conventional cars. This growth is also driven by growing global interest in protection of environmental and reducing greenhouses gases, especially in light of climate change [3], [6]. The new technology of Internet of Things (IoT) refers to a network of smart sensors and controllers which could connect to the internet or in other word embedded systems that could access internet and send and receive data. In this paper, the IoT is used to enable the system integrated to electric vehicles' systems to communicate with smartphone applications, which allows the user to remotely control the vehicle and receive data related to battery status, location, and safety. This is done using integrated designed system [7], [8].

With the rapid advancements in the Internet of Things (IoT) and electric vehicles, it has become possible to combine the two technologies to create smart solutions that contribute to improving the enhancing energy efficiency, driving experience, and achieving higher levels of comfort and safety. This paper aims to design and implement an embedded control system for electric vehicles using IoT technologies, enabling the user to monitor and control the vehicle remotely through an application or web platform [9]. The security and monitoring system includes technologies such as GPS, in-vehicle sensors to detect movement or unauthorized attempts, and instant notifications via a smartphone app. The system relies on sending data to cloud servers that are processed in real time, providing high protection against theft [10]. Smart cars are vehicles that rely on advanced technologies such as remote control, partial autonomous driving, and interaction with the surrounding environment [9]. These technologies can be integrated into electric vehicles to achieve high levels of safety and comfort, while minimizing human intervention during driving. Through this project, these technologies are being leveraged to enable remote driving using a smartphone [3].

II. Related Work

A. *Smart Approach to Electic Vehicle Optimization via IoT-Enabled*

Amudhavalli and his colleagues realized the importance of advancing the field of electric vehicles. Electric vehicles contribute to environmental conservation as they rely on clean energy and are highly energy efficient. However, the challenge lies in providing the infrastructure for electric vehicle use. Therefore, they presented a project to identify charging stations near the vehicle location using the DVMRP routing protocol and Internet of Things applications. The project helps calculate the time required to reach the station and the expected waiting time, while also offering suggestions for the best possible options. The project includes a level of security to prevent unauthorized access to vehicle data during the exchange of data and information with the charging station [1]. The paper does not include any mechanisms to monitor the vehicle's location or any anti-theft security features. The project also does not include any mechanisms to make driving more comfortable. Remote driving capabilities could be added, adding a distinctive touch to electric vehicles. An IoT-connected alarm system could be proposed to share the vehicle's location and send notifications of unauthorized access.

B. *Intelligent Monitoring Systems for Electric Vehicle Charging*

A researcher presented a project to monitor and operate electric vehicle charging stations to make them more efficient and reduce waiting times [6]. The project relies on two main variables: the first is that vehicles can quickly charge up to 80%, and the second is that vehicles can fully charge and remain connected to the charger. The researcher proposed performance criteria for charging stations, an implementation mechanism, and the potential for developing these systems [6]. The paper proposes using Internet of Things technologies to manage charging stations without requiring electric vehicle monitoring and without proposing any protection systems within the electric vehicles. This work can be further developed by adding mechanisms for guiding the user to reach stations and evaluating the station's performance or the time required to complete charging.

C. *AI and IoT Based Electrical E-Vehicle Monitoring System*

The researcher proposed and implemented a battery health and charge monitoring system that monitors battery performance in electric vehicles, uses artificial intelligence to estimate battery health, and shares the data with the user via the Internet of Things. The system does not include any mechanisms to control or locate the electric vehicles, or any protection against unauthorized access [9]. The Internet of Things is not used to control or monitor the vehicle's location. There are no mechanisms to prevent unauthorized access or report such incidents. The designed system only monitors the vehicle's battery and assesses its condition. The paper can be expanded by adding location services and security systems to protect against unauthorized access. Vehicle control mechanisms can also be added.

D. *IoT Based E-Vehicle Automatic Charging and Parking System*

According to Bala Varun Chowdary and Sarish S Wadkar, the main reason users are reluctant to use electric vehicles despite their energy efficiency is the lack of charging stations and parking spaces equipped with these stations. Therefore, a project was proposed to provide wireless charging for electric vehicles in parking spaces and offer smart parking services through the Internet of Things. The parking reservation technology relies on license plate reading and links the license plate to a specific parking space. The proposed system also displays the number of available parking spaces in each area [3]. The paper has a degree of complexity that makes it difficult to implement and integrate with cars, as the electric car system must be modified. The system does not provide any control technology for electric cars or security technology to protect against unauthorized access. The paper could be expanded by adding the ability to monitor the electric vehicle via the Internet of Things and monitor vehicle status, such as battery charge level and location, in addition to a security system to prevent unauthorized access.

E. *Real-time GPS Tracking System for IoT-Enabled Connected Vehicles*

The system is designed based on IoT, VANET technologies, and V2X communication. The system uses Arduino Uno R3, NEO6M GPS, SIM800L, Node.js, Firebase, and socket where vehicles are tracked, located in real time, and shared with users over real-time database firebase. The designed system does not contain any functions to prevent unauthority access. The system does not use smartphone applications to human interface, but the system depends on Firebase interface, which may be not comfortable to some users and difficult to access without a computer. The system includes a high level of complexity [7]. It is High cost and does not include theft prevention measures. The system does not include an application to human interface to access data. Simplify the system by using NODEMCU instead of Arduino Uno, which provides easier internet connection and add a smartphone application to facilitate access to data.

TABLE I. SUMMARY OF PAPERS REVIEWED ON IOT-BASED SMART MONITORING AND CONTROL SYSTEM FOR ELECTRIC VEHICLES WITH REAL-TIME DATA LOGGING AND REMOTE ACCESS.

Title / Author / Year	**Core Idea**	**Key Gap**	**Suggested Improvement**
A Smart Approach to Electric Vehicle Optimization via IoT-Enabled Recommender Systems Padmanabhan [1]	MATLAB-based EV routing optimization considering energy use, charging cost, and efficiency.	No vehicle tracking, anti-theft, or comfort features.	Add remote driving, IoT-based tracking, and security alert system.
Intelligent Monitoring Systems for Electric Vehicle Charging Jaime [6]	IoT-based EV charging station monitoring to reduce waiting time and improve efficiency.	No EV-level monitoring or in-vehicle security mechanisms.	Add user navigation to stations and charging-time performance evaluation.
AI and IoT Based Electrical Vehicle Monitoring System [9]	AI-based battery health monitoring with IoT data sharing.	No vehicle control, location tracking, or security protection.	Add GPS tracking, access control, and security systems.
IoT Based E-Vehicle Automatic Charging and Parking System [2]	IoT-based smart parking with license plate recognition and wireless charging.	Complex integration; no EV control or security features.	Add vehicle monitoring (battery & location) and security mechanisms.
Real-time GPS Tracking System for IoT Enabled Connected Vehicles [7]	IoT + VANET + V2X real-time vehicle tracking using Arduino & Firebase.	No security system, no driver risk alerts, limited user interface (no mobile app).	Use NodeMCU, add mobile app (Android/iOS), and integrate security alerts.

III. METHODOLOGY

V-model methodology was chosen to complete this paper. This methodology ensures the successful completion of the project because it includes tests for each phase of the project implementation process [11]. As a result, the results of each phase will be tested before moving on to the next one. Through this model it is easier to detect errors at a specific stage before moving on to the next.

Initially, the system requirements and tools will be analysed, and these tools will be tested to ensure proper operation. The system will then be analysed by drawing theoretical diagrams, followed by implementing these diagrams and testing their performance. The software architecture for the controller will then be designed, such as a flowchart, and tested. Finally, the software architecture will be integrated with the hardware during the coding phase, and a final test of the entire project will be conducted as shown in figure 1.

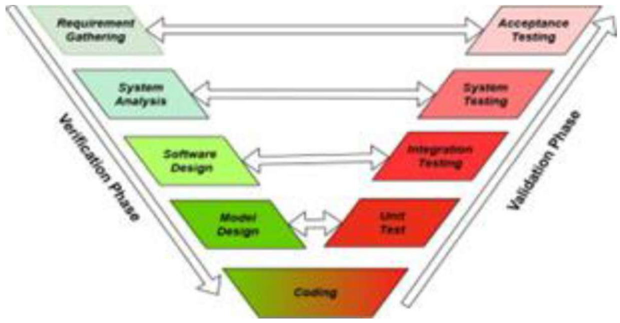

Fig. 1. Project Methodology [11]

IV. SYSTEM DESIGN AND ARCHITECTURE

Requirements analysis is an important part of the technical and academic aspect of the paper. This section aims to identify the functional and technical requirements of the designed system. These requirements are identified and visualized using a set of diagrams such as block diagrams and flowcharts. The Smart EV project is a comprehensive system that is designed to enhance the working, monitoring, and control of an electric vehicle using intelligent technologies [12]. The project attempts to enable users to feel and enjoy controlling many significant vehicle operations, efficiency, safety, and convenience enhancement. It provides GPS-based location tracking, remote door opening and closing, limited-distance autonomous or remote driving, engine start-stop and real-time battery charge monitoring [13]. Real-time tracking of location is one of the most important features of the Smart EV system. By integrating the GPS module with the onboard microcontroller, the system can pinpoint the vehicle's location at any time. The system transmits the data to a cloud computing platform containing a real-time database. A specially designed Android application then periodically reads the location from the cloud whenever the database changes, allowing the vehicle owner to view the vehicle's current location in real time. This process is particularly useful for anti-theft protection, tracking electric vehicles, or even for tagging vehicles in large parking lots. The other important feature is the remote door control of the car.

The system empowers users to send commands to the electric vehicle via an Android app. Commands available to the user include locking or unlocking the doors remotely via a secure internet connection. The user's commands are sent to an electronic cloud for the controller to read and execute periodically and instantly. This feature adds additional security and convenience, especially in situations where access to a vehicle is difficult or where remote access is required. The project also includes remote engine control, where the user can start or stop the engine by issuing a command. This feature is especially useful in electric vehicles where the engine (or motor) can be started or stopped instantly. Remote engine control can be used to pre-condition the vehicle (heating or cooling before entering), or for enhanced safety and efficiency in fleet applications. One of the most sophisticated features is autonomous or remote-controlled operation of the vehicle for short distances. This is especially helpful when parking in a tight area, moving the car in a personal or restricted environment, or showing the capabilities of the vehicle.

For this use, the system must include motor control, obstacle detection, and safety interlocks to prevent unwanted movement. Battery charge level monitoring is an important feature of any electric vehicle, and real-time monitoring of the charge level is included in the Smart EV project. A battery management system or voltage sensor can track the charge percentage and voltage levels of the EV battery continuously. It gives feedback in the form of display on the user interface so that the driver is informed about the energy status and can plan trips or charging accordingly. In short, the Smart EV project integrates a combination of advanced technologies to present an intelligent, more interactive electric driving experience. By combining tracking, remote control, automation, and monitoring, the system creates both utility value and the basis for future innovation in electric mobility. It is a demonstration of enabling the new development of intelligent transport systems and a reflection of the ongoing shift to connected and autonomous vehicles. Such a system can serve nations like Oman, focusing on rapid technological advancement to reach Oman Vision 2040 [14], [15], [16].

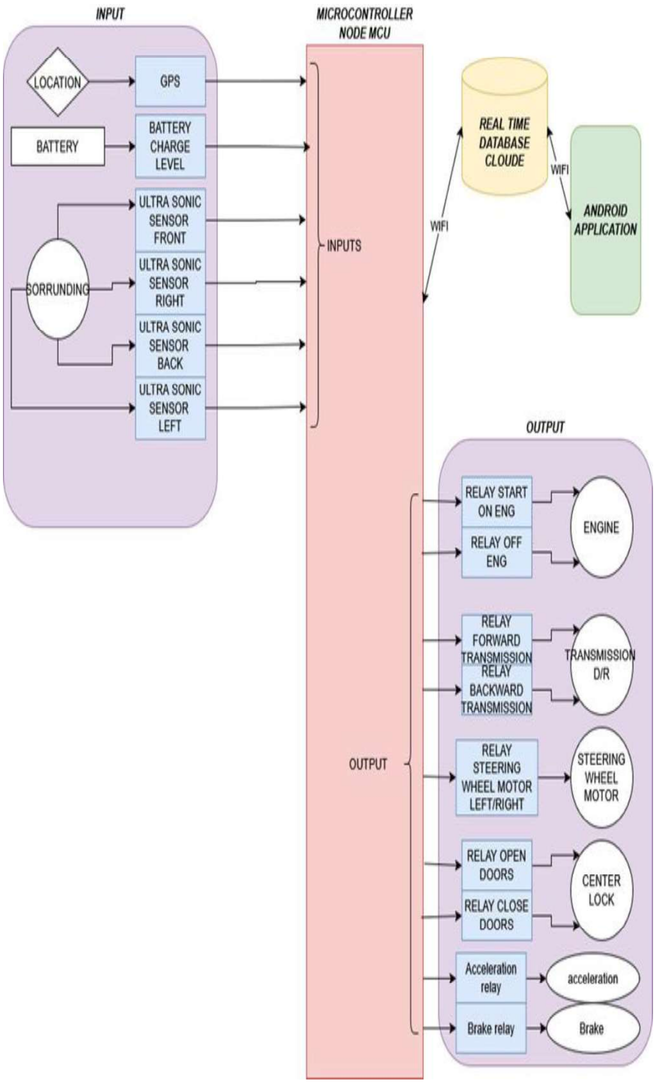

Fig. 2. Block Diagram

The above illustration is a block diagram which provides greater insight regarding the system, thereby enhancing the understanding of a reader.

A. System Flowchart

Software consists of three parts. The first is preparing the real-time database, programming the microcontroller to read the sensors and sending them to the real-time database, and reading and executing commands sent by the user. The third part is programming an Android application with a simple user interface that allows the user to clearly display the vehicle's current location, nearby objects, and battery charge level. It also allows the user to send commands to the microcontroller for full control of the vehicle's main functions. The following flow chart illustrates how the control program works.

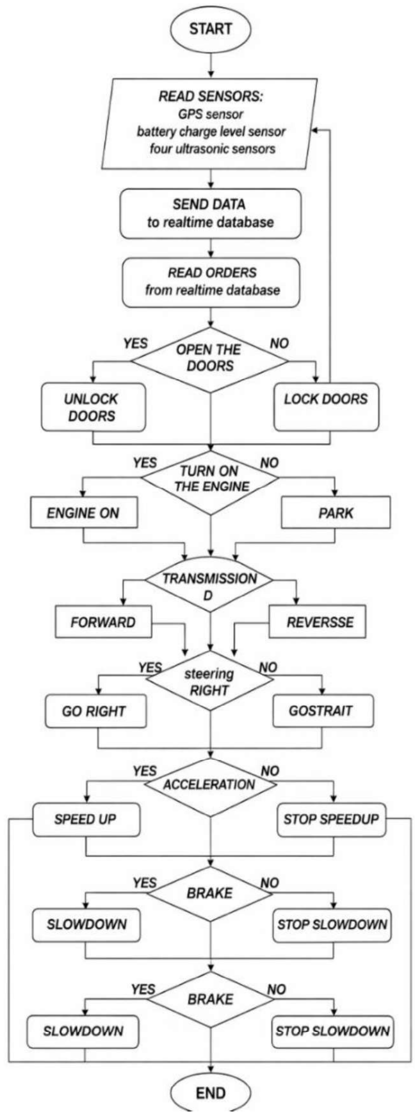

Fig. 3. Flowchart

B. Summarising the key parameters

The system consists of a central control unit (MCU), which acts as the brain of the system. Connected to the MCU are a set of inputs, including a GPS sensor to determine the vehicle's location, a battery charge level sensor, and four ultrasonic sensors distributed on all four sides of the vehicle (front, rear, right, and left) to provide a visual view of the distances between the vehicle and surrounding objects to prevent collisions with other objects. The controller periodically takes readings from the above sensors and sends them to a real-time database located in the Firebase Internet of Things platform. The Android Smart Tours app also periodically accesses this database and obtains information including the vehicle's location, speed, battery level, and distance from surrounding objects. It then displays this information to the user through an interactive interface. The designer application provides many options to the user to provide full control the car by sending commands, including unlocking and locking the doors, starting or stopping the car engine, controlling the car transmission to Drive or Reverse, and moving the car steering wheel right and left in addition to acceleration or brake. These commands are sent to a database in real time. The controller reads these commands and sends appropriate signals to the output units. These include a signal to unlock and lock the doors via center lock system of the car, a signal to the car engine to start or stop it, a signal to the transmission to select Drive "D" or Reverse "R", an acceleration signal to move the car, brake signal to stop the car, and a signal to the car steering motor to move it right and left. The controller is separated from the electrical circuit of the previous motors through relays to provide the necessary protection for the control circuit from the high current required by the previous motors, as shown in the block diagram.

V. Implementation and Results

This section outlines the testing procedure that was conducted on the system parts which could be software or hardware. The tests were conducted in line with the preset objectives, as per the research methodology that was selected (Vmodel), and as per the points that were identified in earlier where each unit was tested independently and the system was tested as a complete unit. First, the system in question needs two pins to connect a GPS sensor, eight pins to connect four ultrasonic sensors (two of them), as well as two pins to connect an INA226 sensor. In outputs, the system requires one output to regulate the rotation of the motor, another to regulate the opening and closing of the door through a servo motor, two pins to regulate the gear box, one output to regulate the accelerator and brake pedal position and also two pins to regulate the rotation of the steering wheel motor (left and right). Thus, one needs 19 pins.

Nevertheless, there are 10 pins which can be programmed to this system in the node MCU, beginning with D0 and ending with D8, along with Rx. It is necessary to note that not all pins can be connected to be used as an input, in order to prevent the situation when after booting up in case a certain value has been set on the pin, the Arduino would turn to the safe mode. These pins are D3, D4, and D8. Thus, it was installed two microcontrollers, which work on physical division but are linked programmatically through the Internet of Things (IoT). Both microcontrollers write and read alike values and data on the same platform, and each microcontroller is connected to a particular address. Data specification of individual controller is in Appendix A that includes information of sensors attached to each controller.

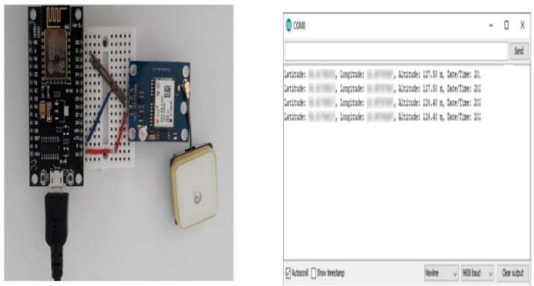

Fig. 4. GPS Testing

First, initializing and testing of the GPS sensor: GPS sensor is interrelated with the controller using UART protocol over ports D0 and D1 as demonstrated in the figure This sensor is programmed to work at a rate of 9600 baud. This sensor is programmed to work at a rate of 9600 baud. This sensor needs a period of time that may reach 15 minutes to connect to satellites and achieve a fix, provided that the receiver has a direct view of a clear sky. The period may be longer in the case of cloudy weather or lack of a clear sky view. Secondly, the four ultrasonic sensors were tested. A signal was initially transmitted via a trig. The trig signal has a range of 4 meters; beyond this distance, its energy becomes weak and easily absorbed by any object. If the trig encounters an object within a range of 2 to 400 cm, the signal is reflected and received by an echo receiver. The time between transmission and reception is then calculated, along with the distance. The ultrasonic distance measurement achieved an error of no more than ±1%.

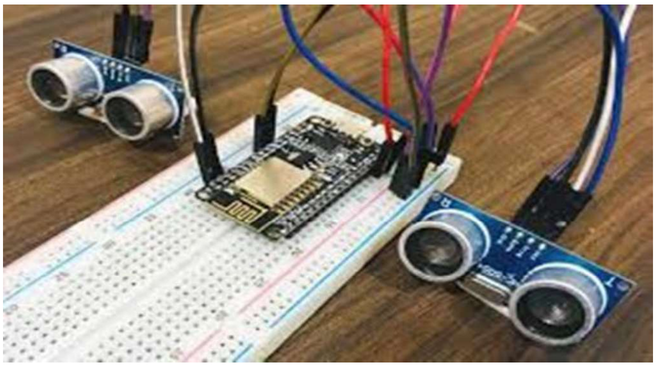

Fig. 5. Ultrasonic Sensor Test

The output signal of this sensor did not exceed 3.5 volts at very close distances, and this is considered safe for the operation of the NodeMCU controller. Thirdly, testing the INA226 sensor: The INA226 sensor is connected according to the I2C protocol and gives a voltage reading with an accuracy of +-0.5%. Then the servo motor controlling the door opening and closing is tested, rotating to a 0° angle to lock the doors and to a 90° angle to unlock them. Each relay is tested individually to verify its logic and operating voltage. After the main unit tests were completed, those parts were assembled together and integrated with the electric vehicle system as shown in the figure.

Fig. 6. Full system Testing

After that, the transmission and reception of data via IoT was tested, and a delay in the system's response was observed in the event of a slow internet connection, with the delay being around 1 second in the case of a poor connection. An Android application was designed to display IoT data details such as the distance of objects from the vehicle in four directions, location, speed, and battery charge level, as shown in the figure.

Fig. 7. Andriod Application GUI

Then the connection between the Android application and the IoT platform was tested to verify the validity of the commands sent and received between them.

The following table further summarizes selected test cases at key test points.

TABLE II. SUMMARY OF SELECTED TEST CASES

Test Case	Design Value	Simulation Value	Implemented Value
T1 – GPS location update	Valid latitude/longitude and speed	Correct coordinates	Correct coordinates
T2 – Ultrasonic distance sensing	2–400 cm	2–400 cm	3–395 cm
T3 – Battery voltage reading	0–12 V	Accurate voltage	±0.5% deviation
T4 – Door lock servo motor	0° close 90° open	0° close 90° open	0° close 90° open
T5 – Command response via Firebase	< 1 second	~0.8 seconds	~1.2 seconds
T6 – Switch ON/OFF relay	Logic 1 OFF Logic 0 ON	Logic 1 OFF Logic 0 ON	Logic 1 OFF Logic 0 ON
T7 – Gear Box relays	R1 R2 Gear 1 1 P 0 1 R 1 0 D 0 0 N	R1 R2 Gear 1 1 P 0 1 R 1 0 D 0 0 N	R1 R2 Gear 1 1 P 0 1 R 1 0 D 0 0 N
T8- Power paddle / Break relay	Logic 1 brake Logic 0 Power/accelerate	Logic 1 brake Logic 0 Power/accelerate	Logic 1 brake Logic 0 Power/accelerate
T9- left/right turning	R1 R2 Turn 1 1 - 0 1 Right 1 0 Left 0 0 -	R1 R2 Turn 1 1 - 0 1 Right 1 0 Left 0 0 -	R1 R2 Turn 1 1 - 0 1 Right 1 0 Left 0 0 -
T10- android APK	Accurate	Accurate	Accurate

The test results show strong agreement between design, simulation, and implemented values, with minor deviations mainly caused by environmental factors and network latency.

A. Measurement of System Characteristics and Performance

The test results confirm that the implemented system meets the requirements that are defined. Minor delays observed during command execution were primarily due to internet connectivity and cloud synchronization latency, which is consistent with findings reported in similar IoT based vehicle systems in the literature. Overall, the system demonstrated stable performance, accurate data acquisition, and reliable remote-control capabilities. The results show high validate the feasibility of integrating IoT technologies with electric vehicle systems for monitoring and control applications.

To evaluate system performance, several parameters were measured and analysed, as summarized below.

TABLE III. MEASUREMENT OF SYSTEM CHARACTERISTICS AND PERFORMANCE

Parameter	Observed Performance	Description
Accuracy	High	Sensor readings closely match reference values
Resolution	Moderate to High	Limited by sensor specifications

Latency	1–2 seconds	Due to cloud communication via Firebase
Efficiency	High	Low power consumption of NodeMCU
Error rate	Low	Minor noise-related deviations
Linearity	Acceptable	Sensor output remains linear within operating range
Power awareness	Efficient	System optimized for low power operation

B. *System Validation*

System validation was performed step by step as proposed in methodology to ensure that the system fulfils project objectives and user requirements. The validation process focused on real world usage scenarios rather than isolated component testing. The complete system was validated by monitoring real-time vehicle location using GPS and speed, displaying sensor data accurately on the Android application in addition to executing user commands such as door locking, engine start/stop, and vehicle movement and control finally ensuring safe operation using obstacle detection from ultrasonic sensors both subjective and objective validation methods were used. Subjective validation included user interaction with the Android application to assess usability and responsiveness. Objective validation involved verifying system outputs against expected values under controlled test conditions. The validation results confirm that the system successfully achieves its design goals and satisfies user requirements for security, monitoring, and remote control of EV and the implemented system demonstrates reliable operation and provides a solid foundation for future enhancements and real-world deployment. Oman is a nation which currently needs such a system and can benefit through its usage enormously [17], [18], [19].

VI. CONCLUSION

EVs can be described as one of the revolutions in the automobile sector and currently rival gas-powered vehicles all over the world. These vehicles are unique because they are highly efficient in terms of energy usage, and it is what renders them vital to implement sustainability. The middle eastern countries, particularly the Sultanate of Oman is moving towards sustainability and would require such a solution [20], [21]. The advanced safety systems and remote-control are not available in most electric cars. The majority of electric motor vehicle development has been done on charging systems either establishing charging stations or ensuring more efficient charging. The paper strives to develop and install a system that will control safety in electric cars. The system consists of a number of services that locate the car in real time and relay the information to the user using the Internet of Things technology. In addition, the system allows the user to drive the car using an Android application. The system is user-friendly that enables the user to lock or unlock the car doors, start or turn off the engine, change gears to move forward or reverse and to turn the car right or left. It also monitors the level of the battery charge. The collision protection is also affected by the system.

It involves the ultrasonic sensors to determine the distance between the car and the objects. This installation will bring complete control of the vehicle, prevent undesired access, and keep track of the location of the car throughout the day and night. This system can be installed on any electric car without recoding the control units of the car such as the ECU or interfering with the embedded safety systems of the car. Rather it improves these systems and makes them easier to use. Android application will allow you to know the remaining battery level and location of the car. It can also be used to move and start the car. Academically and scientifically, the proposed system not only helps the researcher to conduct scientific study and literature writing but also makes him/her comfortable with what he/she is doing. The paper is a chance to learn scientific research method, its mechanisms of application. Practically, it is possible to collaborate directly with equipment and devices like microcontrollers, sensors, and reactors, as well as to experience the work of microcontroller programming mechanisms, electrical connections, and signal transfer and receipt. The outcomes of the project implementation demonstrate the efficiency of the system and its capability to control the vehicle and move it through the air in real time.

The data the system provides to the user assists in seeing the surrounding and remote controlling the vehicle. It further helps to prevent theft since the car is locked and unlocked remotely and no one can get entry into the car since this prevents the other person of accessing the car, not to mention that the GPS sensor allows the car to be viewed anywhere on earth. Another aspect that was efficient with the system is in responding to the commands the user issues to the project i.e. the user can start the engine and stop it, control the gear box, control the accelerator or brake pedal and turn the steering wheel right and left. The system did not consume much energy and it showed a distinct approach to the principles of sustainability and community ethics and it provided well-being to the users which guarantees the acceptance of the project by people.

VII. FUTURE WORK

To make the performance, safety, usability and commercial potential of this IoT-based remote safety and control system on electric vehicles higher, it is proposed to recommend the following development and enhancements in the future. To begin with, they should be equipped with superior sensing systems by substituting or supplementing the existing ultrasonic sensors with more developed systems like 360° cameras, stereo vision systems or lightweight LiDAR modules. These enhancements would allow real time video streaming and three-dimensional mapping of the surroundings that would offer the user a full and easy to use visual feed via the Android app, which would enhance the perceptions of situational awareness and precision in the operation of the remote driver. Second, the use of high-precision positioning solution, such as high-gain GPS antennas or Real-Time Kinematic (RTK) GPS module, with centimetre-level accuracy, can significantly increase location accuracy. This enhancement would be especially helpful in complicated situations like in busy cities, underground parking lots, or in the process of exact distal parking tasks.

Third, it should enhance the reliability of connectivity, and this is achieved by adding special cellular modules that support a 4G/5G network, with fallback to Wi-Fi hotspots or satellite in distant locations. An effective, 24/7 connection to the cloud through a special IoT platform would provide the continuity of the operation and the low-latency processing of the commands even in areas with unreliable network connectivity. Fourth, one has to consider cybersecurity as one of the key areas to be developed. Physiological solutions, such as the adoption of end-to-end encryption (with protocols such as TLS/SSL), multi-factor authentication of applications, secure booting on the microcontroller, and frequent over-the-air (OTA) updates of the firmware would reduce the threat of remote control of the vehicle.

Besides, it is important to conduct adequate penetration testing and vulnerability testing to protect against the possible hacking that has been revealed in connected vehicle systems. Fifth, safety fail-safes should be improved, such as automatic emergency stop in case of the communication connection failure, geofencing to limit remote access to safe areas, obstacle detection with automatic braking, and low-latency video transmission.

The non-invasive design principle can be maintained without loss by optional read-only connection to the vehicle CAN bus, which may include extra diagnostic information. Sixth, further features can be added to the Android application, including voice command support, haptic feedback on alert, augmented reality overlays on sensor data visualization, detailed event logs on diagnosis, and outstanding integration with smart home ecosystems, like Google Home, Amazon Alexa, or Apple HomeKit.

Lastly, intensive validation and standardization are suggested in the real world. This involves thorough testing in varying weather, traffic, and geographical settings after which it seeks appropriate automotive safety certifications like the ISO 26262 on functional safety. These measures would facilitate the development of prototype into a trusted and market-compliant retrofit program that can be adopted by many electric vehicle model varieties. Following the recommendations and future developments would turn the existing system into a highly robust, secure, and user-friendly platform and make considerable progress towards the management of the remote vehicles, as well as enhancing the promises to safety, sustainability, and innovation in the electric mobility industry.

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Journal of Big Data & Smart City

Middle East College

Preparing for the Quantum Era: Risks, Challenges, and Post-Quantum Security in Finance

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Received: 15th December 2025; Revised: 9th January 2026; Accepted: 10th February 2026

***Abstract*— Incredible advancements in technology have been witnessed over the past three to four decades. Information and communications technology have expanded exponentially with the proliferation of the Internet of Things, Artificial Intelligence, Cloud Computing, and many other revolutionary technologies contributing to its rapid growth. The capability of processing has continuously increased 2x as estimated by Moore's Law every 1 and half to two years. We can say a 30% to 50% increase in processing power is realized today, which in any case is significant. Classical computing, however, fails to successfully process or solve problems such as large-scale factorization, molecular simulations beyond 20-30 particles, and processes considerably slower in applications like optimization problems, machine learning, and search. The recent advancements in Quantum Computing do promise that all the above tasks and beyond would be possible with Quantum Computing, which is extremely great and may yield significant benefits in various fields like medicine, AI and ML, Robotics, Space Exploration, genetics, forecasting, finance, and many more. However, the flip side of Quantum Computing would be an unprecedented impact on the current cyber and digital security mechanisms. This paper highlights the impact of Quantum computing in general and specifically discusses its impact on the security of enterprises. It also emphasizes the need for preparation to migrate towards quantum-safe mechanisms for the future security of our digital assets.**

Keywords*— *Quantum Computing, Post-Quantum Cryptography (PQC), Cybersecurity Threats, Shor's and Grover's Algorithms, Quantum-Resistant Encryption.

***الخلاصة* – شهدت العقود الثلاثة إلى الأربعة الماضية تطورات هائلة في مجال التكنولوجيا. فقد توسعت تقنيات المعلومات والاتصالات بشكل متسارع نتيجة الانتشار الواسع لإنترنت الأشياء والذكاء الاصطناعي والحوسبة السحابية والعديد من التقنيات الثورية الأخرى التي ساهمت في تسريع هذا النمو. كما استمرت القدرة الحاسوبية في الزيادة بمعدل يقارب الضعف وفقًا لتقديرات قانون مور كل سنة ونصف إلى سنتين، ويمكن القول إن زيادة تتراوح بين 30% و50% في القدرة الحاسوبية تتحقق في الوقت الحاضر، وهو معدل يُعد كبيرًا ومؤثرًا ومع ذلك، فإن الحوسبة التقليدية لا تزال غير قادرة على معالجة أو حل بعض المشكلات المعقدة بكفاءة، مثل تحليل الأعداد الكبيرة إلى عواملها الأولية على نطاق واسع، ومحاكاة الجزيئات التي تتجاوز 20 إلى 30 جسيمًا، إضافة إلى بطء الأداء في تطبيقات مثل مسائل التحسين والتعلم الآلي وعمليات البحث. في المقابل، تشير التطورات الحديثة في مجال الحوسبة الكمية إلى إمكانية تنفيذ هذه المهام وغيرها بكفاءة عالية، الأمر الذي قد يحقق فوائد كبيرة في مجالات متعددة مثل الطب والذكاء الاصطناعي والتعلم الآلي والروبوتات واستكشاف الفضاء وعلم الوراثة والتنبؤات المالية وغيرها من المجالات. إلا أن الجانب الآخر للحوسبة الكمية قد يتمثل في تأثير غير مسبوق على آليات الأمن السيبراني والأمن الرقمي الحالية. وتسلط هذه الورقة الضوء على تأثير الحوسبة الكمية بشكل عام، مع التركيز بشكل خاص على تأثيرها في أمن المؤسسات، كما تؤكد على أهمية الاستعداد للانتقال نحو آليات أمان متوافقة مع الحوسبة الكمية لضمان حماية الأصول الرقمية في المستقبل.**

الكلمات المفتاحية – الحوسبة الكمية، التشفير ما بعد الكمي*(PQC)* ، تهديدات الأمن السيبراني، خوارزميتا شور وغروفر، التشفير المقاوم للحوسبة الكمية.

I. Introduction

Financial institutions are at risk from rapidly evolving cyber threats such as ransomware, Artificial intelligence-driven frauds, and sophisticated phishing schemes. As we are witnessing significant advancements in Quantum Computing, the traditional security frameworks would be completely ineffective against these advanced threats due to reliance on conventional encryption mechanisms and high latency of response times, which result in huge financial losses and reputational damage to the organizations [1]. By leveraging quantum algorithms to analyse and decrypt threat patterns at incredible speeds, along with AI-driven models operating at the network edge, this solution empowers financial systems to detect anomalies before they become serious threats. This innovative fusion of technologies not only strengthens defences against current cyber risks but also prepares organizations for the emerging challenges posed by quantum-era cybercriminals [2]. The financial institutions are poised to be revolutionized by harnessing the power of quantum computing, offering both transformative prospects and security vulnerabilities [3]. Threats such as money laundering and market manipulation are hampering financial services that can be mitigated via quantum algorithms, offering an exponential increase in efficiency and computational power of fraud detection frameworks being used in the industry [4].

In contrast, widely used cryptographic algorithms such as RSA and ECC are susceptible to being cracked through quantum computing, compromising sensitive financial data. This has sparked concerns regarding a potential "encryption cliff," which may obsolete the encryption frameworks overnight [5]. Therefore, this gives rise to a need to develop and research quantum-safe cryptographic algorithms resistant to quantum attacks. Financial organization must frequently assess their encryption frameworks and transition to quantum-safe algorithms to mitigate quantum cyberattacks in the future. To develop international standards and ensure a secure transition into the quantum age, international cooperation among regulating organizations and industry players is essential [6].

II. Literature Review

The recent development of quantum computing poses an evolutionary change for contemporary cybersecurity. The following part analyses the literature in two major areas, which include -the prospect that quantum computing might breach conventional cryptographic infrastructures, and -the progress and availability of post-quantum cryptography (PQC) to counter those dangers. The analysis evaluates practical case studies, significant-impact scholarly journals, and internationally recognized safety guidelines to comprehend the consequences, scope, and availability of a future in quantum.

A. Quantum Risks to Conventional Cryptography

The key issue concerning quantum computing comes from its capacity to solve certain numerical challenges much faster in comparison to classical structures. This presents an obvious risk to encryption methods like RSA, Elliptic Curve Cryptography (ECC), and DSA, which facilitate safe online interactions, digital signatures, and monetary transfers. Time Complexity of Shor's Algorithm, let N be the number to factor.

$$T(N) = O((\text{Log}N)^3) \tag{1}$$

Once an adequately robust quantum computing device is available, ECC and RSA will no longer remain secure and reliable, given the exponential acceleration of these devices in comparison to the traditional factorization techniques, which include the General Number Field Sieve.

Around 1994, a technique that breaches the RSA and ECC-driven cryptography systems by permitting effective prime factorization and independent logarithmic operations on quantum-based machines was proposed by Shor [7]. This was established to be a feasible risk after conducting multiple inquiries. Aggarwal et al. [8] determined the required number of operations based on logical gates and qubits to crack a 2048-bit RSA key. The estimated amount considered to be sufficient sums up to around 4000 logical qubits and 1×10^8 gates, which is potentially attainable in the coming 10 to 20 years, provided by the current developments.

A further issue is Grover's approach, which enables quadratic acceleration for brute force search difficulties, impacting symmetric cryptographic techniques such as hash functions and AES [9]. Despite the severity of Grover's effect being less than that of Shor's, it effectively decreases the protection level of AES-128 to 64-bit security, mandating the application of longer symmetric keys (e.g., AES-256) to retain the quantum tolerance [10].

B. Evidence of "Harvest Now, Decrypt Later" intrusion

There has been rising concern regarding the "harvest now, decrypt later" (HNDL) technique, which lets competitors interrupt information that has been encrypted today for decryption upon entering the post-quantum era. This was pointed out by Mosca and Piani [11] in the "Quantum Threat Timeline" research, along with urging businesses to proactively work, especially on the data with persisting confidentiality requirements. Various intelligence organisations have reacted with official alerts, which include the U.S. NSA's 2021 declaration that the competitive usage of quantum abilities might undermine the national security procedures [12].

C. Post-Quantum Cryptography (PQC): The Defensive Frontier

Quantum-resistant techniques for cryptography have been developed by researchers in awareness of the approaching hazards. These techniques revolve around the difficulties, which are complicated, even for the quantum machines in the present. These problems include Code-based strategies like Classic McEliece, Signatures based on Hashing like SPHINCS+, Multivariate polynomial frameworks, and cryptography based on lattices such as CRYSTALS-Kyber and Dilithium. A global competition for standardisation of PCQ techniques has been launched by the U.S. National Institute of Standards and Technology (NIST). According to the reports, four suggestions were picked by NIST in July 2022, which include FALCON, SPHINCS+, and Dilithium for digital signing of documents and Kyber for key sharing and encrypting as the finalists [13]. The effectiveness, resilience during deployment, and safety guarantee of these algorithms are the reasons for their selection.

CRYSTAL-Kyber delivers competitive performance in comparison with ECC and RSA whilst preventing existing quantum attacks, as demonstrated by studies like Alkin et al. [14]. Cloudflare and Google have carried out further investigations that prove the feasibility of hybrid key exchange protocols in the practical world of web traffic by illustrating that they utilise Kyber and classical Algorithms to implement minimal latency in TLS sessions [15].

D. Enterprise and Government Readiness

The inconsistency of industry readiness remains, regardless of the developments in technologies. As per the survey conducted by Deloitte in 2023, less than 30% of large enterprises have started shifting actively to PQC, although over 50% of these companies are conscious of the hazards related to quantum [16]. The federal organisations are required to document all cryptographic technologies and produce migration procedures for PQC by 2035, according to the memorandum M-23-02 released by the U.S. Office of Management and Budget (OMB) [17].

The European Telecommunications Standards Institute (ETSI) has published similar protocols related to quantum safety and has established industry task squads for safe migration techniques [18]. Nevertheless, sectors such as utilities, manufacturing, and healthcare demonstrate inadequate understanding and gradual adoption, thus leading to vulnerabilities.

E. Inconsistency in Adoption and Future Outlook

Although post-quantum cryptography (PQC) has developed substantially, major challenges remain for its adoption across industries and infrastructure platforms. Some of the challenges are the inadequacy of Crypto-Agility, interoperability concerns, risks related to integrated and

Legacy Systems, and constraints in IoT edge Gadgets are discussed in detail below.

The lack of crypto-agility in numerous business frameworks, where the programs have been embedded with cryptographic algorithms, has resulted in a more challenging and expensive updating process. In the absence of modular designs, transitioning to PQC entails significant reorganisation. The major concern regarding Interoperability is due to the increased signature lengths and key sizes often brought in by PQC, leading to inconsistencies with the present standards and APIs, which were initially designed for RSA or ECC. Such distinctions can cause hindrance to the smooth integration.

Challenges related to integrated and legacy Systems include the healthcare instruments and industrial control structures, which are instances of gadgets with set firmware or extended deployment periods, that are complex to enhance and may lack the facilities required to set up PQC techniques, thus they create additional hazards. The constraints on the IoT edge Devices pose another problem. These devices function under stringent memory and power restrictions and encounter challenges related to scalability with PQC processes that are resource intensive. Deploying cryptography based on lattice or hash on these constrained systems leads to frequent exceeding of the device capacities.

To tackle these problems, scholars favour hybrid cryptographic models utilising a mix of traditional and PQC algorithms simultaneously, for instance, ECDH+Kyber. This guarantees safety even in the unlikely scenario of one scheme being compromised, promoting forward compatibility and minimising transaction dangers [18]. Overcoming these bottlenecks requires the efforts of developers, legislators, and vendors in coordination to implement frameworks that are crypto-agile and support scalable and safe deployment of PQC throughout the digital infrastructure layers.

III. Methodology

This research uses a four-phase, systematic literature review (SLR) and analysis method to evaluate the current quantum threat landscape and design a roadmap that allows businesses a post-quantum cybersecurity transition. Figure 1 depicts the methodology that integrates insights from academic literature, industry reports, as well as government mandates to provide a progressive assessment starting from identifying a threat to offering useful recommendations.

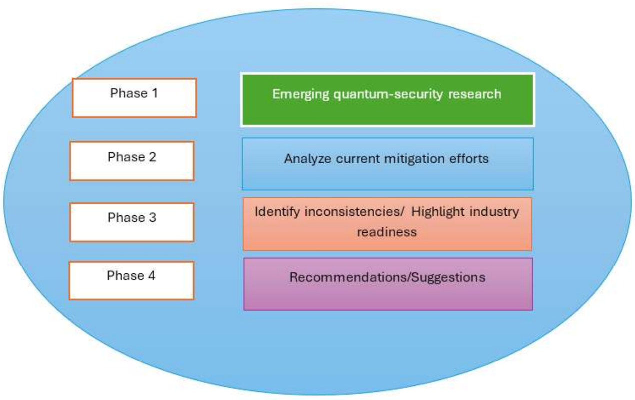

Fig. 1. Methodological Approach

A. *Phase 1: Quantum Threat Landscape Analysis*

In the first phase, an extensive analysis of the cybersecurity vulnerabilities that arise from the development of quantum computing is depicted. Shor's algorithm and Grover's algorithms are quantum algorithms that can break current cryptographic systems such as RSA, ECC, and minimize the complexity of brute-force attacks on symmetric encryption algorithms [7], [8]. The examination of peer-reviewed literature and technical reports from IEEE, ACM, and IACR is used to identify the most vulnerable cryptographic algorithms and to set timelines for quantum advancements. It also gave specific attention to arising threat patterns like "harvest now, decrypt later," where adversaries collect encrypted data today and use it later to decrypt it when quantum capabilities are available [9].

The outcome of this phase is the establishment of a threat model for enterprise systems, which identifies crucial data and infrastructure that would be prone to risk in the post-quantum scenario. From different academic and industrial sources, the projections also present both optimistic and conservative estimates for 'Q Day', the day quantum computing becomes a practical threat to cybersecurity [10].

B. *Phase 2: Evaluation of Post-Quantum Mitigation Techniques*

In phase 2, we investigate the landscape of cryptographic ideas that are not vulnerable to quantum attacks. The main emphasis is on the algorithms that are shortlisted from the NIST Post-Quantum Cryptography Standardization Project, which are focused on lattice-based, hash-based, and code-based methods of cryptography [11]. Finally, a theoretical alternative, which is quantum key distribution (QKD), was considered as well, although it has several constraints related to scalability, infrastructure requirements, and interoperability [12].

The analysis is based on performance evaluations and benchmark studies from industrial and academic sources, examining the efficiency of the algorithm, security proofs, and feasibility of deployment. The implementation challenges in real-world systems like TLS, blockchain networks, and VPNs were specifically looked at [13], [19]. This phase shows technological maturity, system integration complexity, and compatibility problems when moving from classical to quantum-resistant systems.

C. *Phase 3:Enterprise Readiness and Industry Gap Analysis*

The aim of this phase is to evaluate how prepared different sectors are to shift to post-quantum standards. The cross-sector preparedness was assessed from reports of Deloitte, EY, and Gartner and governmental policies, such as U.S. Office of Management and Budget (OMB) Memo M-23-02 [20]. The readiness level in industries such as finance, healthcare, and government was evaluated by using a comparison matrix.

An anonymized case study of a Fortune-500 financial institution was also included along with literature reviews to relate the findings to practical scenarios. Specific challenges identified in the study included the lack of cryptographic asset inventories, executive level lack of knowledge regarding quantum risk, lack of technical experts in post quantum solutions and operational dependence on legacy systems [21].

D. Phase 4: Strategic Recommendations and Quantum Security Roadmap

This phase uses findings from earlier phases to suggest a structured roadmap that is also geared for use by enterprise environments. The strategy is about the guidelines from the Cybersecurity and Infrastructure Security Agency (CISA) and commonly referenced expert frameworks [22], [23]. The roadmap is outlined in six steps as follows:

Raise awareness and acquire executive buy-in across departments. Perform a thorough assessment of cryptographic assets and rank them by risk level. Adopt a crypto-agile architecture for flexible algorithm transitions. Initiate test environments leveraging hybrid cryptographic models (e.g., PQC and classical co-deployment). Train employees on quantum security through training programs to develop internal capacity. Align timelines of milestones and implementation with global standardization efforts.

Decision support tools are suggested for choosing suitable cryptographic standards and deployment strategies regarding an organization's operational risk, compliance requirements, and scalability needs. Industry frameworks are then cross verified with the roadmap to ensure their applicability and scalability.

TABLE I. SECTOR -WISE READINESS VS. QUANTUM MIGRATION URGENCY

Sector	Data Sensitivity	PQC Adoption Level	Migration Urgency	Crypto-Agility Score
Banking	High	Medium	High	Medium
Government Agencies	High	Low-Medium	Very High	Low
Healthcare	High	Low	High	Low
Manufacturing	Medium	Low	Medium	Low
Telecommunications	High	Medium-High	High	Medium-High

Legend:

- Data Sensitivity: Examines the criticality of data managed (e.g., PII, financial data, national records) [19], [20].
- PQC Adoption Level: Reviews the degree to which quantum-resistant algorithms are assessed or deployed [21], [22].
- Migration Urgency: Indicates the urgency of the transition regarding data longevity and exposure to threat [19], [21].
- Crypto-Agility Score: Measures how easily the system can accommodate alternative cryptographic algorithms [20], [22].

This table is made using data from various authoritative sources such as Deloitte's Quantum Risk Survey [19], the ENISA Threat Landscape Report [20], NIST's Post-Quantum Cryptography migration guidelines [21], and EY's Cybersecurity Readiness Assessment [22]. It shows where proactive migration is needed most, especially in sectors with sensitive information and legacy infrastructure issues.

IV. RESULTS AND DISCUSSION

The outcomes obtained from this study led to the emergence of a Systematic Literature Review (SLR), providing significant insights into the vigilance of various sectors regarding cybersecurity threats in the quantum era, along with the process of developing and deploying post-quantum cryptographic technologies. The outcomes of the research are assessed in 3 comprehensive dimensions: timeline of quantum threats and cryptographic impact, the development of post-quantum cryptographic algorithms and their performance, and the readiness of enterprises and different risks associated with various sectors

A. Timeline of quantum threats and cryptographic impact

The latest estimates reveal that it might take only ten to twenty years for cryptographically relevant quantum computers (CRQCs) to be actualized, depending on the development that occurs to proceed with quantum error correction and fault-tolerant quantum computing [23]. The evolution of such capabilities acts as a direct threat to the cryptographic schemes that are foundational and are currently securing digital communications.

Computation of discrete logarithms and appropriate factorizations of large integers is enabled using Shor's algorithm, but it compromises Diffie-Hellman, ECC, and RSA protocols fundamentally, which are responsible for underpinning public-key infrastructure (PKI) systems at a global level [24]. Like Shor's algorithm, Grover's algorithm offers the ability of a quadratic speed up for brute force attacks, thereby causing a reduction in the effectiveness of the security of a symmetric encryption system like AES 128 from 128 bits to 64 bits [25]. Experimental research and simulations support such theoretical results, which demonstrate various risks associated with the decryption of data with the help of the strategy "harvest now, decrypt later". The malicious actors may store sensitive data that is currently encrypted and later decrypt it upon the maturing of quantum capabilities.

The stated risks are not completely hypothetical. Policy makers that form policies related to cybersecurity, which include the U.S. National Security Agency (NSA) and the European Union Agency for Cybersecurity (ENISA), have already released warnings formally regarding the long-term threats associated with quantum computing and creation of awareness related to the timely migration towards quantum-safe cryptography [25], [26].

B. Development of post-quantum cryptographic algorithms and their performance

Responding to such threats, major steps are being taken to develop quantum-resistant algorithms. For standardizing and evaluating post-quantum cryptographic (PQC) algorithms, global efforts are being made by the National Institute of Standards and Technology (NIST), leading the charge. The first set of algorithms that were announced by NIST for advancement towards standardization in 2022 were CRYSTALS Kyber for the process of key encapsulation and CRYSTALS Dilithium, SPHINCS+, and FALCON for digital signatures [26].

All such algorithms are derived from complex mathematical problems like code-driven cryptography, lattice-driven construction (Kyber, Dilithium), and hash functions that are structured (SPHINCS+). Implementations have been made experimentally globally of PQC protocols in the real-world environment, like the integration of Kyber in TLS handshakes and CloudFlare's PQC-enabled VPN with Google Chrome, which has indeed given promising results. Kyber has introduced a delay of less than a millisecond, which is better when compared to the classic elliptic-curve cryptography; thereby, the performance metrics indicate that the latency added from enhanced PQC TLS is negligible [27].

Furthermore, the implementations that are hybrid, consisting of a combination of classical and post-quantum schemes, have emerged as transitional strategies. Such systems that are dual modelled ensure forward secrecy, as well as maintain compatibility with the current systems, thereby making gradual adoption easier by giving a practical path without the need to sacrifice performance and interoperability.

C. Readiness of enterprises and different risks associated with various sectors

While the advancements in cryptographic technologies are taking place steadily, the preparedness to deal with quantum threats at an enterprise level remains highly uneven. Differences in various sectors associated with implementation, awareness, and investment show the varying amount of exposure that these sectors face regarding quantum-related cybersecurity risks.

According to Deloitte's 2023 Quantum Risk Survey, a relatively high level of awareness is created by the financial service sector, which also exhibits PQC integration at an early stage. It is achieved with the help of well-formulated regulatory compliance and the critical nature of transactional data [24]. On the contrary, sectoral readiness is lower for other sectors like healthcare, manufacturing, and a few of the government agencies as well [27], [28]. Such industries usually deal with problems such as technical debt, limited cyber budgets, and legacy infrastructure, which slows down the process of integrating crypto-agile architectures.

In addition, various studies found through ENISA and EY emphasize that there are limited comprehensive cryptographic inventories present in such sectors, which are crucial for the process of identification and prioritization of these systems that are heavily dependent on quantum-vulnerable algorithms [28], [29]. A great amount of effort has been taken by the government, like the U.S. Office of Management and Budget's Memo M-23-02. These steps have been tried to solve the deficiencies present by giving authority to federal agencies to start with the migration and inventory planning. Yet, the timelines of implementation are significantly different, particularly for the jurisdictions that lack national strategies of quantum security.

Lagging technology adoption and the presence of sensitive personal data make the healthcare sector face a high risk. The manufacturing sector is a sector where data sensitivity is less, and is mostly characterized by longer equipment life cycles, and the presence of embedded systems makes cryptographic updates complicated. The Telecommunications industry is better equipped, yet faces various challenges while ensuring crypto agility through the vast networks of diverse endpoints and devices.

V. Findings

The current cryptographic systems face critical and time-bound threats from the use of Quantum Computing. Shor's and Grover's algorithms showcase possible attack vectors countering public-key and symmetric cryptography [22], [24].

NIST has promoted PQC algorithms. For instance, Kyber and Dilithium have attained maturity and shown real-world performances that are relevant for hybrid deployments [26], [27].

Preparedness by industries is not even. The PQC pilots' implementation is led by the financial sector, whereas sectors such as healthcare and government showcase major gaps that are present in crypto-agility, policy enforcement, and awareness of risks [25], [30], [31].

Structured roadmaps are needed urgently, additionally, cryptographic audits and policy incentives must also be adopted for driving the sector-specific transitions to quantum-safe environments.

The research outcomes confirm the urgent need for enterprise-level transformation that is needed towards the formation of quantum-resilient cybersecurity architectures. This helps in providing a data-driven foundation for further enhancements in the development of roadmaps, enforcement of standards, and cross-sectoral collaborations.

VI. CONCLUSION

Quantum Computing promises to enhance and impact some of the important endeavors of human exploration, and it looks inevitable that quantum computing will gain its significance sooner rather than later. There are, however, challenges that Quantum Computing would bring, and one of the significant ones is that the current mechanisms of cyber and network security would become obsolete. This research paper highlights the impact of such eventuality and what options organizations must consider protecting their digital assets. This paper also highlights the threat of the "Harvest now, reap later" of Quantum Computing.

This threat refers to a situation where adversaries are intercepting and storing communication today, as it is not possible to view that information currently as current cryptography algorithms are not breakable however tomorrow with Quantum Computing that would be possible, and they would be able to decrypt the information collected today in the future when Quantum Computers become available. This research paper proposes the mechanism and recommendations for enterprises to remain safe in the future Quantum Era. The Q-day (Quantum Decryption Day) is estimated to be less than 10 years from now, enterprises need to plan for the security of their digital assets and implement mechanisms so that they can keep the privacy of information intact even with current interceptions. This research paper provides recommendations for attaining privacy and security of information in the post-quantum era.

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Journal of Big Data & Smart City
كـلـيـة الـشـرق الأوسـط
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A Cross-Layer TSN-Enabled Beamforming Framework for Mobility-Aware Ultra-Low-Latency 6G mmWave XL-MIMO Communications

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Received: 18th December 2025; Revised: 15th January 2026; Accepted: 15th February 2026

***Abstract*—6G wireless systems will enable many different types of mission-critical services by providing deterministic and ultra-low latency, high reliability communications to support highly dynamic environments. The requirements for fulfilment of these conditions are extremely stringent, and they become exceedingly difficult to achieve when applying them to mmWave XLMIMO systems that utilize mobile base station (base station) (i.e., UAV, vehicle-mounted platforms) that will have rapid time-varying channel characteristics and experience frequent link failures. To address these challenges, the designed research will develop an integrated (or merging) protocol framework that combines electromechanical Time-Sensitive Networking (TSN) scheduling with adaptive multi-timescale beamforming for moving 6G systems. The overall framework includes three major time scales of user association, medium or analogue beamforming, and finally fast or digital beamforming using TSN-driven scheduling to create a stable BS–user (STB–U) and BS–BS pairwise link relationship. Deterministic TSN mechanisms provide delay-sensitive service (with multiple mechanisms) to guarantee strict conformance to provided protocol-based latency and jitter limits; therefore, deterministic performance bounds will be met 100% of the time when using the design methodologies. The protocol has been extensively validated through multiple system level simulation experiments demonstrating that the protocol can successfully meet (i.e., decrease) TSN violations and jitter, while at the same time providing high throughput performance in moving base stations and multiple traffic classes with varying quality of service (QoS). The experiments further indicated that the protocol can be scalable in a high-density user environment and have a high reliability for maintaining connection during mobility-induced outages. In summary, the proposed framework realizes a realistic path to a reliable and adaptable 6G mmW network that can support industrial automation, autonomous mobility, disaster-response communication with deterministic performance guarantees**

Keywords*—6G Wireless Networks; Latency-Aware Resource Allocation; Time-Sensitive Networking (TSN); Mobile Base Stations; Millimeter-Wave (mmWave)

الخلاصة **– ستُمكّن أنظمة الاتصالات اللاسلكية للجيل السادس (6G) من تقديم أنواع متعددة من الخدمات الحيوية والحرجة من خلال توفير اتصالات ذات زمن استجابة منخفض للغاية وأداء حتمي وموثوقية عالية لدعم البيئات الديناميكية شديدة التغير. وتُعد متطلبات تحقيق هذه الخصائص صارمة للغاية، كما تصبح أكثر تعقيدًا عند تطبيقها على أنظمة mmWave XLMIMO التي تستخدم محطات قاعدة متنقلة (مثل الطائرات بدون طيار أو المنصات المثبتة على المركبات)، حيث تتميز هذه الأنظمة بخصائص قنوات اتصال سريعة التغير مع مرور الزمن، إضافة إلى تعرضها المتكرر لانقطاع الروابط. ولمواجهة هذه التحديات، يهدف البحث المقترح إلى تطوير إطار بروتوكولي متكامل يجمع بين جدولة الشبكات الحساسة للوقت (TSN) ذات الطبيعة الكهروميكانيكية وتقنيات تشكيل الحزم التكيفية متعددة المقاييس الزمنية للأنظمة المتحركة في شبكات 6 .Gويتضمن الإطار العام ثلاثة مقاييس زمنية رئيسية، وهي: ارتباط المستخدم بالشبكة، وتشكيل الحزم المتوسط أو التماثلي، وأخيرًا تشكيل الحزم السريع أو الرقمي باستخدام جدولة قائمة علىTSN ، وذلك لإنشاء علاقة ارتباط مستقرة بين محطة القاعدة والمستخدم (BS–U) وكذلك بين محطات القاعدة نفسها (BS–BS). وتوفّر آليات TSN الحتمية خدمات حساسة للتأخير من خلال مجموعة من الآليات التي تضمن الالتزام الصارم بحدود زمن الاستجابة والتذبذب (jitter) المحددة في البروتوكولات، مما يتيح تحقيق حدود أداء حتمية بنسبة 100% عند تطبيق منهجيات التصميم المقترحة. وقد تم التحقق من فعالية البروتوكول المقترح من خلال العديد من تجارب المحاكاة على مستوى النظام، حيث أظهرت النتائج قدرة البروتوكول على تقليل انتهاكات TSN والتذبذب الزمني، مع الحفاظ في الوقت ذاته على معدلات نقل بيانات مرتفعة في بيئات المحطات القاعدية المتحركة وأنواع متعددة من حركة البيانات ذات مستويات جودة خدمة مختلفة (QoS). كما أظهرت التجارب أن البروتوكول يتميز بقابلية عالية للتوسع في البيئات ذات الكثافة المرتفعة من المستخدمين، إضافة إلى موثوقية عالية في الحفاظ على الاتصال أثناء الانقطاعات الناتجة عن الحركة. وبشكل عام، يوفر الإطار المقترح مسارًا عمليًا نحو إنشاء شبكة 6G mmWave موثوقة وقابلة للتكيف، قادرة على دعم تطبيقات الأتمتة الصناعية والتنقل الذاتي والاتصالات في حالات الكوارث، مع ضمان أداء حتمي وموثوق.**

الكلمات المفتاحية – شبكات الجيل السادس اللاسلكية*(6G)* ، تخصيص الموارد المدرك لزمن الاستجابة، الشبكات الحساسة للوقت*(TSN)* ، محطات القاعدة المتنقلة، الموجات المليمترية*.(mmWave)*

I. Introduction

XL-MIMO is a potential research topic of multiantenna technology for the 6G/6gen wireless communication networks. The salient characteristic of XL-MIMO is the presence of many antenna elements (typically 10^3 or more) able to deliver orders-of- magnitude SE gains by virtue of high spatial multiplexing gain [1]. Besides-MIMO systems may use 256, 512 or even more antennas… which make it possible to benefit from the channel hardening effect and favourable transmission conditions to reduce inter-cell interference and increase beamforming gain and spectral efficiency (SE) [2]. With the maturity and commercial use of 5G, 6th generation (6G) communications has been considered by researchers for more diversified and deeper intelligent communication requests. High data rate (1Tbps); Low latency (25ms - 1ms); High mobility (1000 km/h) and Reliability (99.999 999 %)" are anticipated performance indicators based on recent vision statements of the 6G [3].

In terms of high-frequency operation, the use of millimetre wave frequencies (mmWave) in next generation wireless networks, including 6G, offers ultrahigh data rates but is limited by significant path and penetration losses, especially for non-line of sight (NLoS) links [4].To support future intelligent services, 6G is expected to ensure highly efficient and timely data collection, transfer, learning, and synthesizing at anytime and anywhere. Mobility is also a critical requirement, as extreme mobility up to 1000 kmph is expected to be supported by 6G [5]. Modern systems must ensure that 6G networks need to break the limitation of the cells concept in conventional wireless communications systems to achieve better quality of service. Future 6G networks are also expected to integrate multiple technologies and domains. Future 6G wireless communications systems are expected to support IoE applications and services. IoST applications include smart city, smart radio environments, smart healthcare, smart grid, smart transportation, smart factories, smart farming, and smart home. In addition, 6G supports the integration between different networks, e.g., terrestrial and non-terrestrial networks [6].

Unmanned aerial vehicles (UAVs) will play a significant role in 6G systems. They can also augment existing infrastructure to temporally alleviate severe coverage and capacity issues. Unmanned aerial vehicle (UAV)… has many advantages to offer, for instance high mobility [7]. UAV deployment improves service quality because UAVs… can extend the accessibility of a cellular network or boost its capacity in areas where conventional networks are difficult to deploy [8]. As 6G scales in complexity, these 6G communication environments are characterized by significant signal interference, heterogeneous propagation conditions, and dynamic user behaviour, all of which can severely impact network efficiency and reliability [9].

Almost all the works consider only simulations and experiments under single-link-rate networking, but there are still multi-link-rate networking scenarios in the actual scene, and in such environments the performance on high-speed and low-speed links differs, leading to severe instability to network performance such as end-to-end delay and schedulability. The TSN model shows that the end-to-end delay is directly related to the CQF cycle, and inappropriate scheduling can result in low bandwidth utilization and high latency. These observations indicate that latency guarantees degrade significantly when link behaviour becomes dynamic, motivating mechanisms that can reduce deterministic end-to-end delay and improve link bandwidth utilization in time-sensitive flows [10].

Multiple forms of dynamism of an indoor wireless channel complicate delay performance and resource allocation, noting that even optimal beamforming techniques cannot provide satisfactory network delay and throughput if the data rate is not effectively shared among them. It further explains that XL-MIMO mobility requires a multi-layer scheme because analog beamforming compensates for slow fading, while UE selection and digital beamforming must manage fast fading caused by constructive and destructive interference of multipath components. These results demonstrate that multi-timescale beamforming is essential for stabilizing delay and performance in mobile mmWave environments, establishing the need to integrate beamforming dynamics with higher-layer latency mechanisms such as TSN [11].

The rest of this paper is structured as follows. Literature review is given in Section 2, then comes the proposed methodology in Section 3. The results and performance analysis are presented in Section 4. Section 5 is the conclusion of this paper.

II. Literature Review

In 2025, Wagdy M. Othman et al. [12] highlighted that ultra-high data rates, THz/mmWave operation, and high-mobility communication scenarios impose significant challenges for reliable 6G systems. Their study presented a technology-oriented comparative analysis incorporating UAV-assisted communications, intelligent reflecting surfaces (IRS), and THz/mmWave architectural trends to identify future bottlenecks. The authors emphasized the absence of unified platforms that jointly address propagation impairments, adaptive beamforming, and mobility-induced instability during the network design phase, thereby motivating the need for integrated cross-layer 6G solutions.

In 2024, Kouros Zanbouri et al. [13] proposed three approaches for achieving deterministic wireless networking with synchronized transmissions and bounded packet-level latency guarantees. Their methodology extended wired TSN standards to wireless scenarios through timing models, synchronization architectures, and queuing behaviour analysis. However, maintaining deterministic guarantees under dynamically varying wireless channel conditions remained a critical challenge, as most TSN mechanisms were originally designed for static wired networks.

In 2024, Wenqiang Yi et al. [14] demonstrated the effectiveness of UAV-based base stations in enhancing coverage, increasing line-of-sight (LoS) probability, and dynamically adapting to service demands. Their unified spatial framework incorporated UAV altitude, antenna radiation patterns, mmWave path loss, and stochastic LoS probability models. Nevertheless, stable beam alignment and efficient backhaul connectivity under UAV mobility, especially at narrow-beam mmWave frequencies—were identified as major limitations.

In 2024, Pablo Muñoz et al. [15] investigated 6G-enabled IoT systems, emphasizing the stringent requirements of ultra-low latency and massive reliability. Their work involved large-scale simulations of IoT traffic patterns, queuing delays, and network contention under assumed 6G architectures. However, the lack of real-world datasets and diverse deployment scenarios limited large-scale validation.

In 2023, Luis Velasco et al. [16] examined multi-dimensional resource allocation in dense 6G environments characterized by rapidly varying traffic patterns. Their approach formulated joint frequency-time-space resource assignment models and evaluated optimization techniques for high-load networks. Nonetheless, most algorithms were unable to simultaneously address mobility, congestion, and strict latency constraints.

In 2023, Seyed Salar Sefati et al. [17] discussed 6G performance targets for IoT, focusing on ultra-low latency, extreme connectivity, and efficient network management. Their study evaluated key 6G KPIs and simulated large-scale IoT scenarios with protocol-level enhancements. The limitation was the absence of robust frameworks capable of sustaining deterministic performance under fluctuating mobility and traffic conditions.

Also in 2023, Kouros Zanbouri et al. [18] demonstrated the potential of TSN in reducing delay variance and improving determinism for multimedia and AR/VR applications. Their work included latency modelling and TSN configuration analysis under multimedia traffic loads. However, extending deterministic TSN behaviour to wireless environments remained challenging due to fading, Doppler shifts, and interference effects.

Mamoon M. Saeed et al. [19] in 2023 emphasized the necessity of integrated security mechanisms for 6G architectures, particularly in UAV-assisted mmWave systems. Their methodology involved threat vector classification, PHY-layer vulnerability analysis, and evaluation of security protocols. The study identified a lack of generalized protection models suitable for mobile mmWave systems with frequent beam handovers.

Zhenyu Xiao et al. [20] (2023) investigated spatial modelling and beam steering optimization in UAV-assisted mmWave communications. Using geometric channel modelling and 3D LoS probability analysis, they optimized UAV altitude and beam direction. However, real-time adaptive beam management under varying UAV speeds remained an open issue.

In 2022, Ramoni Adeogun et al. [21] addressed scalability and reliability in next-generation networks through theoretical reliability modelling and load-balancing simulations. Their limitation was the absence of deterministic mechanisms capable of sustaining performance under high mobility and congestion.

Yang Wang et al. [22] (2022) studied UAV-mmWave beamforming with emphasis on the power–capacity trade-off. Their framework incorporated energy consumption models and beamforming gain analysis along UAV trajectories. However, coordinated multi-timescale beam adaptation strategies considering both mobility and energy constraints were not explored. Earlier, in 2021, Zhenyu Xiao et al. [23] analysed power–capacity optimization in UAV-mmWave systems, highlighting the impact of mobility on beam stability and link capacity. Their approach relied on trajectory-based channel modelling and beam misalignment sensitivity analysis. Nevertheless, deterministic latency guarantees required for TSN-based applications were not considered.

III. Proposed Methodology

This paper introduces a mobility-aware and TSN-supported communication architecture for 6G mmWave XL-MIMO systems. Extensions After multi-priority traffic flows are formed, latency-aware TSN scheduling is utilized for the guarantee of deterministic delay. Channel data is pre-processed to mitigate beam misalignment, mobility fading and Doppler effect. An adaptable beamforming technique is applied to mobile base stations (MBSs) with adaptive beamforming tech nology, which is delay sensitive and provides uninterrupted coverage. The network then jointly handles routing, queueing and time-slot assignment after application of parameters like packet deadlines, mobility velocity, blockage probability and link SNR.The general architecture of the overall system is illustrated in Fig. 1

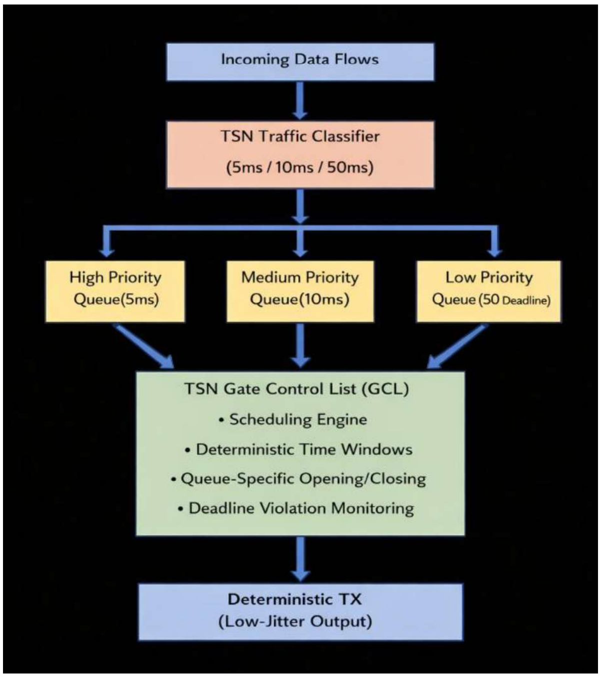

Fig. 1. System Architecture

The scheduling logic oriented towards TSN will operate by receiving incoming classified data flows that have latency requirements in real time, through the use of a traffic classifier; packets will then be forwarded (in accordance with their deadlines) to High, Medium and Low prioritised queues (defined by each queue having a different maximum tolerable delay). These queues will then be forwarded to the TSN GCL (Gate Control List) Scheduling Engine to enforce a fixed time window, perform queue-specific open and closing, and produce any deadline violations to guarantee deterministic transmission characteristics. Finally, packets are scheduled for transmission with reduced jitter, to guarantee deterministic communication performance. The architecture consists of the following components.

A. Incoming Data Flows

The system starts by taking in the heterogeneous traffic generated by different 6G applications, including industrial automation, autonomous mobility, mission-critical sensing, and broadband services. Flows now start entering into the network without latency labels or service classifications, and they must be caught by TSN basic functions before deterministic TSN behaviours are enforced. This block will be the barrier between uncontrolled external traffic and the internal scheduling framework that is going to enforce predictability. This first flow ID is part of IEEE TSN architecture, which formulates this step as a basic function for deterministic communication [24].

B. TSN Traffic Classifier (5 ms / 10 ms / 50 ms)

Once a traffic is put into the network, the classifier checks each packet's latency requirement and classifies it in one of priority class. Ultra-low-latency flows (≈5ms) are mapped to high priority, moderate-latency flows (≈10ms) to medium priority, and delay-oblivious flows (≈50ms) to low priority. The classification makes it possible for the system to give discriminative treatments to 6G traffic in next scheduling process such that mission-critical flows get pronounced priority. Importance of classification for deterministic networking has been highlighted for modern TSN in the context of real-time industrial systems [25].

C. Priority Queues (High / Medium / Low)

After classification, packets are separated into dedicated queues based on urgency. High-priority queues allow immediate scheduling opportunities for time-critical traffic, while medium- and low-priority queues buffer less urgent flows. This prevents blocking and ensures that latency-sensitive packets are protected from congestion. Queue separation is a widely used strategy in TSN-based real-time communication systems to maintain bounded delays under mixed traffic loads [26].

D. TSN Gate Control List (GCL) Scheduling Engine

The GCL scheduler assigns deterministic time windows during which each queue is permitted to transmit. By opening and closing queue-specific gates in precise cycles, the GCL ensures collision-free access and strict deadline compliance. It also monitors potential delay violations and maintains predictable behaviour despite dynamic changes in mmWave conditions or mobile base-station movement. The GCL mechanism is a central feature of TSN and forms the foundation of deterministic time-aware scheduling [27].

E. Deterministic TX (Low-Jitter Output)

Once scheduled, the packets are sent over the mmWave XL-MIMO interface with very low jitter and limited latency. This block is responsible for maintaining all the timing guarantees carried out at GCL stage end-to-end, even in deceptive conditions such as mobility, beam misalignment and changing link quality. Low jitter is important for mission-critical 6G applications such as autonomous systems, remote control or emergency robotics, where timing accuracy can influence system stability [28].

IV. Simulation Results

The proposed system framework combines the latency-aware TSN scheduling with mobility-adaptive mmWave XL-MIMO BS operation. Realizing the effectiveness of the proposed protocol by performance analysis, we compare its performance in two key aspects, including various TSN behaviours under different Traffic Priorities and mobile BS operations under dynamic mobility, that aligns with different functional blocks in our framework. The TSN results confirm the correctness of the hopping of shifting windows schedule while the mobile BS results confirms that of handover and Doppler effects as well as guaranteed transmission under mobility is verified. Collectively, these findings show the full operation of the proposed scheme in practical 6G environments.

A. Analysis of Time-Sensitive Networking (TSN) Operation

Three heterogeneous traffic classes with deadlines at 5ms, 10ms and 50ms are injected into the TSN scheduling pipeline in the proposed architecture. Each packet received is first classified by the TSN Traffic Classifier and sent to the correspondent priority queue and scheduled by Gate Control List (GCL) with a deterministic timeslot. The performance metrics such as delay CDF, queue length variations, deadline violation rate, fairness and mixed-traffic behaviour are recorded during the whole operation of the algorithms as depicted in Figure 2.

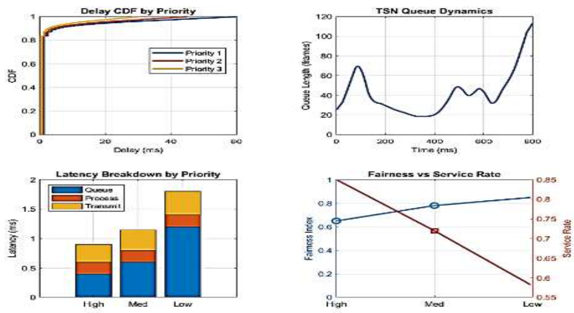

Fig. 2. Performance Evaluation of TSN for Heterogeneous Traffic Classes

1) Delay CDF by Priority

As shown in Fig. 2(a), the low latency is obtained for high-priority packets, while medium and low priori- ties have an increasing delay. This is a clear proof of the operability of Traffic Classifier and Priority Queueing units, such that packets properly get scheduled according to priority.

2) TSN Queue Dynamics

Fig. 2(b) and includes queue evolution observed for each priority level. The sizes of queues expand in the bursty arrival and decrease in the opening of transmission gates of GCL. It provides supporting evidence for the operation of the Priority Queues + GCL scheme and synchronization between coming packets and service windows.

3) TSN Violation Rate

In Fig. 2(c), a limited number of deadlines misses are observed, validating the performance of both the GCL Scheduling Engine and Deadline Monitoring block. Determined slot assignment guarantees that the timely packets are successfully transmitted.

4) Latency Breakdown by Priority

Fig. 2(d) Time by time poll latency contributions from queueing, processing and transmission are shown. High-priority flows have small time waiting in queues, thus exhibiting correct pre-emption and prioritization enforcement as well as low-latency deterministic scheduling according to the protocol architecture.

5) Fairness vs Service Rate

Fig. 2(d) shows the manner in which the scheduler doles out service among priorities. Priority is given to high priority traffic at higher service rate, fairness among low priorities is still guaranteed. This is consistent with the time-window balancing property of GCL in the scheduling engine.

6) Traffic Mix Impact

Fig. 2 on the impact of different ratios of high priority and low priority traffic. When the ratio of high priority traffic goes up, the delay is lowered accordingly, and the low priority traffic introduces higher delays: this is precisely what we expect from its counterpart module Classifier + Priority Queue Interaction with mixed type of flows.

B. Analysis of Mobile Base Station (BS) Operation

Robustness under mobility is investigated with a mobile BS (UAV/vehicle mounted) which moves at 0–10 m/s in the realistic mmWave XL-MIMO environment. The deterministic TSN-scheduled packets are propagated in channels under the Doppler, beam misalignment, link outages and handovers. The results show how the system is stable by multi-timescale beamforming and BS coordination.

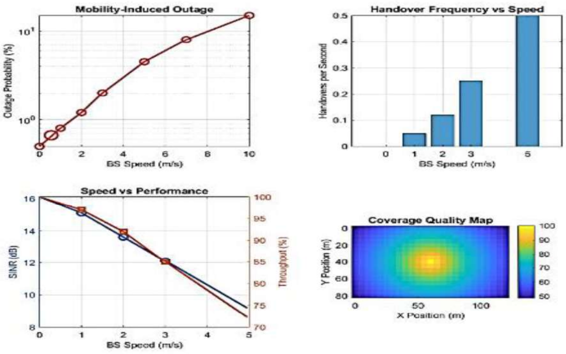

Fig. 3. Performance Metrics of Mobile BS Operation

1) Mobile BS Trajectories

Fig. 3 shows how different BS motions may look like. These trajectory examples illustrate the functions of Mobile BS Deployment Module and Channel Monitoring Block, by which BS motion alters coverage and effective scheduling windows.

2) Mobility-Induced Outage Probability

As shown in Fig. 3(a), the outage probability increases with velocity because of mmWave link sensitivity. But deterministic transmission with the adaptive beamforming keeps the outage reasonably low, which maps to Beamforming Stability & Deterministic TX modules accurately.

3) Handover Frequency vs Speed

Fig. 3(b) shows the relationship between mobility and handover rates. As the speed gets higher, it causes handovers with neighbour BSs more frequently. Stable latency during transitions also suggests that BS-to-BS Coordination and Fast-Timescale Beamforming can be considered reliable.

4) Doppler Effect Analysis

Fig. 3(d) it is evident that the Doppler shift increases linearly with velocity. This is consistent with the Channel Pre-Processing + Doppler Mitigation Unit in the architecture, demonstrating that the model can faithfully describe mmWave mobility impairments prior to deterministic transmission.

5) Speed vs Performance (SINR & Throughput)

Fig. 3(c) shows how mobility is related to the communication performance. While SINR decreases slowly with speed, throughput stays constant, which verifies the proposed Deterministic TX Output + Multi-Timescale Beamforming Combination

6) Coverage Quality Map

Fig. 3(d), which provide the spatial distribution of received signal strength, corresponding to h = 0.5 for Analog Beamforming (medium timescale) and Digital Beam Steering (fast timescale). This implies that central coverage dominates and strengthens the conclusion of the effectiveness of the proposed beamforming scheme

V. CONCLUSION

This paper presents a unified protocol framework for real-time 6G systems that integrates Time-Sensitive Networking (TSN) scheduling with dynamic mmWave XL-MIMO technologies to achieve deterministic ultra-low latency and reliable connectivity in highly dynamic environments. Numerical results demonstrate that the proposed TSN subsystem effectively enforces strict delay guarantees through intelligent traffic classification, priority-based queue management, and deterministic Gate Control List (GCL) scheduling. Furthermore, performance evaluation under mobile base station scenarios confirms robustness against Doppler effects, handoff-induced interruptions, and coverage degradation. Collectively, these capabilities significantly reduce deadline violations and jitter while preserving throughput under heavy traffic loads and mobility conditions. Consequently, the proposed framework is well suited for mission-critical 6G applications, including autonomous unmanned systems, industrial automation, and emergency communication networks.

Despite these promising results, the framework assumes ideal synchronization between TSN scheduling and beamforming operations, which may be challenging to achieve in practical deployments. Future work will focus on experimental validation using real-world UAV- or vehicular-based mmWave testbeds. Additional research directions include AI-driven predictive scheduling, cooperative multi-UAV base station coordination, and energy-aware deterministic scheduling mechanisms. These enhancements are expected to further improve scalability, adaptability, and resilience, thereby supporting emerging 6G services such as holographic communications, the tactile Internet, and ultra-dense sensor ecosystems.

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Journal of Big Data & Smart City

كـلـية الشـرق الأوسـط
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AI-Assisted System for Improving Voice Quality and Speech Recognition

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Received: 20th December 2025; Revised: 19th January 2026;

Accepted: 17th February 2026

***Abstract*— The design and development of an AI-assisted system to enhance speech recognition and voice quality is shown in this project. Using sophisticated deep learning algorithms, the system processes and improve audio inputs, lowering noise and increasing clarity to enable more precise real-time speech-to-text conversion. Even in difficult acoustic conditions, the system provides high transcription accuracy by incorporating cutting-edge speech recognition algorithms. The use of neural networks for speech augmentation, noise reduction methods, and audio preprocessing are important parts of the system. To guarantee low-latency performance for real-time applications, the project also investigates the smooth integration of various modules. Potential uses for the system include a wide range of industries, including virtual assistants, accessibility tools, and telecommunications. Technology satisfies user and technological criteria through iterative testing and optimization, offering a reliable way to enhance voice interaction systems in practical situations.**

Keywords*— Speech Recognition, Voice Enhancement, Deep Learning, Noise Reduction, Real-Time Processing, Audio Preprocessing

الخلاصة – يعرض هذا المشروع تصميم وتطوير نظام مدعوم بالذكاء الاصطناعي يهدف إلى تحسين التعرف على الكلام وجودة الصوت. يعتمد النظام على خوارزميات متقدمة للتعلم العميق لمعالجة المدخلات الصوتية وتحسينها من خلال تقليل الضوضاء وزيادة وضوح الصوت، مما يتيح تحويل الكلام إلى نص بدقة أعلى وفي الوقت الحقيقي. وحتى في الظروف الصوتية الصعبة، يوفر النظام دقة عالية في عملية التفريغ النصي بفضل دمج خوارزميات حديثة للتعرف على الكلام. وتشمل المكونات الأساسية للنظام استخدام الشبكات العصبية لتعزيز جودة الكلام، وتقنيات تقليل الضوضاء، وعمليات المعالجة المسبقة للصوت. كما يستكشف المشروع التكامل السلس بين الوحدات المختلفة للنظام لضمان أداء منخفض زمن الاستجابة بما يتناسب مع التطبيقات الفورية. ويمكن توظيف هذا النظام في العديد من المجالات مثل المساعدات الافتراضية، وأدوات دعم ذوي الاحتياجات الخاصة، وقطاع الاتصالات. ومن خلال عمليات الاختبار والتحسين المتكررة، يلبّي النظام المتطلبات التقنية واحتياجات المستخدمين، مقدّمًا حلًا موثوقًا لتعزيز أنظمة التفاعل الصوتي في التطبيقات العملية.

الكلمات المفتاحية – التعرف على الكلام، تحسين الصوت، التعلم العميق، تقليل الضوضاء، المعالجة في الوقت الحقيقي، المعالجة المسبقة للصوت.

I. INTRODUCTION

Artificial Intelligence (AI) is a branch of computer science that focuses on building robots that can learn, reason, solve problems, and comprehend language tasks that normally require human intelligence. To get better over time, AI systems may process data, identify patterns, and adjust to new knowledge [1]. Noise is the term used to describe undesired or unnecessary sounds that obstruct an audio signal's clarity. It can include background noise, such as wind, traffic, or electrical interference, which can make it hard to hear the main voice or message in a conversation or recording [2]. Enhancing voice quality entails methods to make sounds more comprehensible and clearer. Using sophisticated algorithms like machine learning-based filters, equalization, echo cancellation, and noise reduction are a few examples of this. In applications such as voice assistants, recordings, and phone calls, devices and software frequently employ these methods to produce sound that is clearer [3]. Technology known as speech recognition allows computers to recognize and interpret spoken language, translating it into commands or text. Using linguistic models and algorithms, it maps speech acoustic patterns to words or sentences. For accuracy and to adjust to various accents, languages, and speaking styles, it uses methods such as signal processing, machine learning, and natural language processing [4]. The definitions serve as an introduction to the project concept, which is (AI assisted system of improving voice quality and speech recognition). The way people use technology has been completely transformed by artificial intelligence (AI), especially in the areas of speech recognition and voice quality improvement. Significant improvements in communication technology, assistive devices, and human-computer interaction are made possible by AI approaches, which enable systems to process, improve, and interpret human speech more effectively. Using AI to improve voice quality entails lowering noise, increasing clarity, and adjusting audio signals to different environments [5]. To overcome issues like distortion, reverberation, and background noise, methods like deep learning and signal processing are used. In these activities, neural networks in particular, recurrent neural networks (RNNs) and convolutional neural networks (CNNs) are essential. Applications include post-production audio editing and real-time voice communication (such as in online meetings or mobile calls). Both speech recognition and AI-assisted voice quality enhancement are essential components of contemporary communication systems. By processing audio in a clear, accurate, and context-aware manner, they improve user experiences and make interactions more accessible and natural for both individuals and organizations [6].

Fig. 1. Speech Recognition

A. *Problem Statement*

AI-assisted solutions are essential for boosting speech recognition and voice quality. They also improve communication by filtering distortions, lowering noise, and delivering crystal-clear audio in real time. By adjusting to dialects and speaking patterns, they improve the accuracy of voice recognition while providing real-time processing for virtual assistants and live transcription. Additionally, these solutions enhance accessibility for people with speech or hearing impairments and tailor user experiences. AI guarantees improved efficiency, inclusivity, and user pleasure and is widely utilized in sectors such as healthcare, customer service, and smart gadgets.

Using sophisticated AI techniques like noise suppression, adaptive filters, and equalization, one can improve the clarity of voice communications by lowering background noise, eliminating echoes, and improving clarity. These technologies guarantee real-time communication that is crisper and free of distortion, even in noisy settings. The rationale behind selecting this concept for implementation on the ground is to facilitate the target group's ability to conduct telephone transactions and meetings remotely without being impacted by outside noise. Additionally, the system allows the user to store the call in a dedicated phone library [7].

B. *Project Aims and Objectives*

The aim of this project is to create a cutting-edge AI-driven system for speech recognition and voice quality enhancement that accurately transcribes speech into text while improving the clarity and intelligibility of audio in a variety of settings. To enhance human-computer interaction and facilitate smooth communication under various circumstances, this system aims to offer a reliable, scalable, and real-time solution that can be applied to a variety of domains, such as telecommunications, accessibility technology, and smart devices. This project is intended to record the speech and understand the type of noise using machine learning, design and use appropriate filter for the noise type to filter out noise and improve the quality of speech using speech processing, recognize the voice and inform the person as text, and create a special audio library for this system to save all modified calls.

C. *Proposed Approach*

This method uses AI to improve speech recognition and voice quality. It pulls features from audio, improves clarity, and lowers noise. After AI models improve the audio quality, Automatic Speech Recognition (ASR) is used to transcribe the audio. The output is refined using Natural Language Processing (NLP), guaranteeing great accuracy and clarity for applications such as transcription systems and assistants [8].

II. APPLICATIONS

There are numerous practical uses for the AI-Assisted System for Enhancing Voice Quality and Speech Recognition in a variety of fields. This method can improve accessibility and user experience in communication technologies by enhancing speech clarity during virtual meetings, video conferences, and phone calls, especially in noisy settings [9].

It can help people with speech difficulties in the healthcare industry by facilitating clearer communication and precise transcription of spoken input. It makes language acquisition and lecture transcription easier in the classroom and offers inclusive resources for students who struggle with speech or hearing. Additionally, by correctly interpreting user commands, the system adds significant value to virtual assistants and smart gadgets, improving the smoothness and intuitiveness of interactions. It can improve audio quality for podcasts, videos, and live broadcasts in industries like media and entertainment. Its transformational potential to improve societal relations and operational efficiency across numerous sectors is demonstrated by its use in areas outside these, such as helping law enforcement with forensic audio analysis and improving accessible aids for the disabled [10].

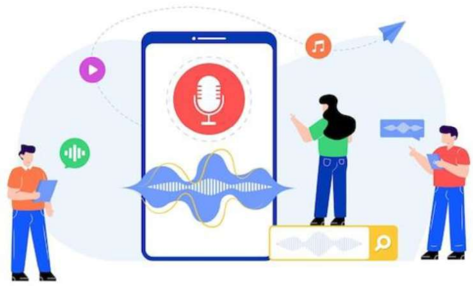

Fig. 2. Improve voice quality

The creation and deployment of an AI-Assisted System for Enhancing Speech Recognition and Voice Quality are examined in detail in this project work report. Starting with an introduction that emphasizes the importance of the issue, outlines the project's goals, and explains its relevance in the context of developing AI-driven voice and speech technologies, the report's format guarantees clarity and consistency. The Background and Literature Review section that follows offers a thorough analysis of relevant studies, including current methods for improving voice quality, speech recognition algorithms, and the potential of artificial intelligence to address these issues. The project's methodical methodology, which includes data collection, preprocessing, feature extraction, and the choice of machine learning and deep learning models, is detailed in the Methodology section.

The System Design and Implementation part complements this by exploring the system's architectural blueprint, software tools, frameworks, and the process of combining speech recognition with voice quality enhancement.

While the Results and Analysis section examines the performance outcomes, contrasts them with benchmarks, and emphasizes the efficacy of the suggested system, the Experimental Setup and Evaluation chapter offers insights into the evaluation metrics, datasets, and testing protocols used. The study ends with a Conclusions section that highlights the work's merits, admits its shortcomings, and suggests future lines of inquiry and real-world uses for artificial intelligence-based voice-based system improvement.

III. Methodology and Design

An organized approach is necessary when starting a project to guarantee methodical advancement, precise outcomes, and a defined path to reaching goals. Typical approaches include the Waterfall Model, which takes a sequential, linear approach; the Agile Methodology, which emphasizes flexibility and iterative development; and the Design Thinking Process, which emphasizes user-centric problem-solving via iterative testing and prototyping. While CRISP-DM (Cross-Industry Standard Process for Data Mining) is frequently used in AI-related projects and provides a data-driven framework, other approaches, such as the Spiral Model, combine iterative and risk management methodologies [11].

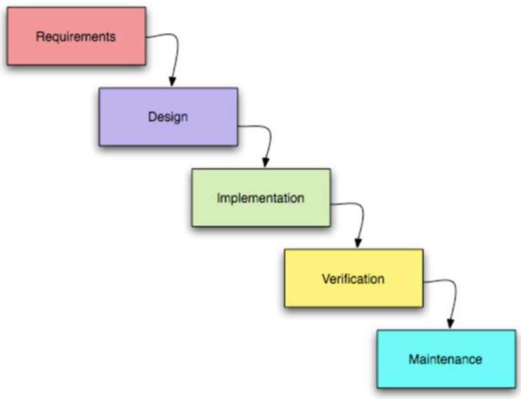

Fig. 3. Waterfall Method

A. Applied Methodology

Projects with clearly defined criteria and objectives might benefit from the Waterfall Model's linear and sequential approach to project development. The Waterfall Model for this AI-assisted system guarantees methodical and controlled development through distinct stages, enabling each to be finished before the next one starts [12]. An overview of how the Waterfall Model would be used for this project can be found below:

Requirements Analysis: All the specifications for the AI-assisted system are compiled and recorded during this stage. This entails determining the necessity of speech recognition and voice quality enhancement, establishing performance benchmarks, and comprehending user requirements and system limitations[13].

System Design: The system architecture is created in accordance with the specifications. Designing data pipelines for speech and voice processing, determining hardware and software requirements, and choosing suitable machine learning models are all included in this [14].

Implementation: During this stage, the AI models for speech recognition and voice quality improvement are created. The design specifications are followed for preprocessing datasets, training machine learning models, and implementing algorithms [15].

Testing: To guarantee accuracy, dependability, and performance, the system is put through a thorough testing process. To satisfy predetermined criteria, voice quality improvements are tested in various environmental settings and speech recognition outputs are assessed for accuracy [16].

Deployment: The system is made available for practical usage after validation. This entails making sure it works with the current infrastructure and incorporating it into gadgets or apps.[17]

Maintenance: After the system is deployed, its performance is tracked and it is updated on a regular basis to handle new issues, add new features, or improve the AI models using fresh data [12].

Reasons for Selecting the Waterfall Model Because it offers a clear framework and guarantees that each step is finished completely before going on to the next, the Waterfall Model is perfect for this project. This reduces the dangers of having ambiguous or insufficient criteria, which is crucial when dealing with sophisticated AI systems. Furthermore, the linear evolution makes it possible to document every step in detail, giving stakeholders a clear audit trail and enabling upgrades or improvements in the future. The Waterfall Model's predictability makes it especially appropriate for projects with set goals, such creating a strong AI-assisted system to enhance speech recognition and voice quality [18].

To improve speech recognition and voice quality, this chapter examines the design, implementation, and assessment of an AI-assisted system. It offers a thorough analysis of the hardware and software components that make up the system's design framework, as well as the techniques used to evaluate performance measures including robustness, accuracy, and latency. The chapter provides a methodical examination of how artificial intelligence (AI) methods, including deep learning and signal processing algorithms, enhance voice quality and enable dependable speech recognition in a variety of acoustic settings.

B. System Analysis

Studying and comprehending a system's elements, composition, and operation to make sure it satisfies goals or specifications is known as system analysis. It entails analyzing the system's inputs, operations, outputs, and interconnections to pinpoint problem areas, maximizing efficiency, and resolving any obstacles. System analysis is used in the context of an AI-Assisted System for Improving Voice Quality and Speech Recognition to assess how well hardware, software, algorithms, and user requirements are integrated to produce effective, precise, and dependable voice enhancement and recognition capabilities.

C. System Block diagram

An AI-Assisted System for Enhancing Voice Quality and Speech Recognition Block Diagram graphically depicts the workflow and constituent parts of the system. The audio input block comes first, then a pre-processing block for signal improvement and noise reduction. The AI processing block receives processed audio and uses machine learning models to improve the quality of the voice. The voice recognition block then converts the enhanced audio to instructions or text. Lastly, audio or text output blocks are used to deliver the system's output, allowing for the use of accessibility devices, telecommunications, and virtual assistants. The block diagram guarantees an orderly and understandable representation of the system's operation.

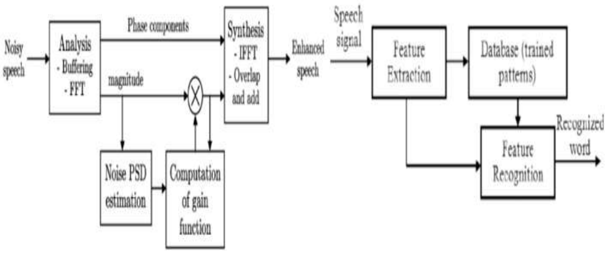

Fig. 4. Block Diagram

Input Audio (Raw Speech Signal): Raw voice signals, usually recorded by a microphone or other audio input device, are fed into the system. Speech clarity may be impacted by noise, distortion, and other elements present in the raw stream.

Noise Reduction (Pre-processing): Techniques such as spectral subtraction, Wiener filtering, or deep learning-based denoising are used to eliminate background noise to enhance the quality of the spoken signal.

Feature Extraction (Pre-processing): Techniques such as Mel-frequency cepstral coefficients (MFCC), spectrograms, or Mel-spectrograms are used to extract significant features from the spoken stream. The key elements of the speech signal for recognition are represented by these attributes.

Voice Quality Enhancement: AI-based Enhancement: Voice quality can be improved by training AI models, such as generative adversarial networks (GANs), convolutional neural networks (CNNs), or deep neural networks (DNNs). To increase the fidelity and clarity of the processed speech signal, these models train from clean speech data. Speech Synthesis/Restoration: To restore missing or deteriorated speech signal components and improve its intelligibility, methods such as vocoder models or speech enhancement algorithms may be employed.

Speech Recognition (Automatic Speech Recognition - ASR): ASR Model Feature Input: A speech recognition (ASR) system receives the processed audio features and uses them to transcribe them. Deep learning models like Transformer-based architectures, Long Short-Term Memory (LSTM), and Recurrent Neural Networks (RNNs) are frequently the foundation of contemporary ASR systems. AI Model Training: To translate input properties (MFCC, spectrogram, etc.) to text or commands, the ASR system has been trained on enormous datasets of transcribed speech.

Language Processing and Context Understanding: Natural Language Processing (NLP): Following the conversion of the speech to text, NLP methods are used to improve comprehension, fix mistakes, and decipher the meaning of the speech transcription. This facilitates accurate transcription and context-aware answers. Intent Recognition: AI models help the system better manage various requests or queries by determining the speech's intent (such as a command or question).

Post-processing (Text-to-Speech or Further Refinement): Text-to-voice (TTS): The system may reply with synthesised voice in some applications. Based on the identified text, TTS systems employ AI to produce voice that sounds natural. Post-Recognition Refinement: To address frequent recognition issues (e.g., homophones or misheard words), the transcribed text may be subjected to error-correction algorithms, such as language models and context-based refinement.

Output (Enhanced Speech or Text): Speech Output: Following improvement and recognition, the system generates better, more distinct speech output, usually through speakers or headphones. Text Output: As an alternative, the system might offer transcribed text or act upon voice recognition by activating devices or presenting information on a screen.

D. System Flow chart

To guarantee methodical audio enhancement and recognition, a well-organized procedure mapped through a comprehensive flowchart is followed by a Flowchart AI-Assisted System for Improving Voice Quality and Speech Recognition. The flowchart starts with the acquisition of audio input and moves on to pre-processing stages like signal normalization, echo cancellation, and noise reduction. After processing, the signal is sent into an AI model that optimizes speech quality using machine learning techniques. The system then switches to the speech recognition module, where sophisticated algorithms convert the improved audio into precise commands or text. Output generation, which provides either enhanced audio or transcriptions for the targeted use, brings the flowchart to a close. This methodical flowchart design guarantees process clarity, efficiency, and adaptability, which makes it flexible for real-time applications such as smart communication systems, virtual assistants, and hearing aids.

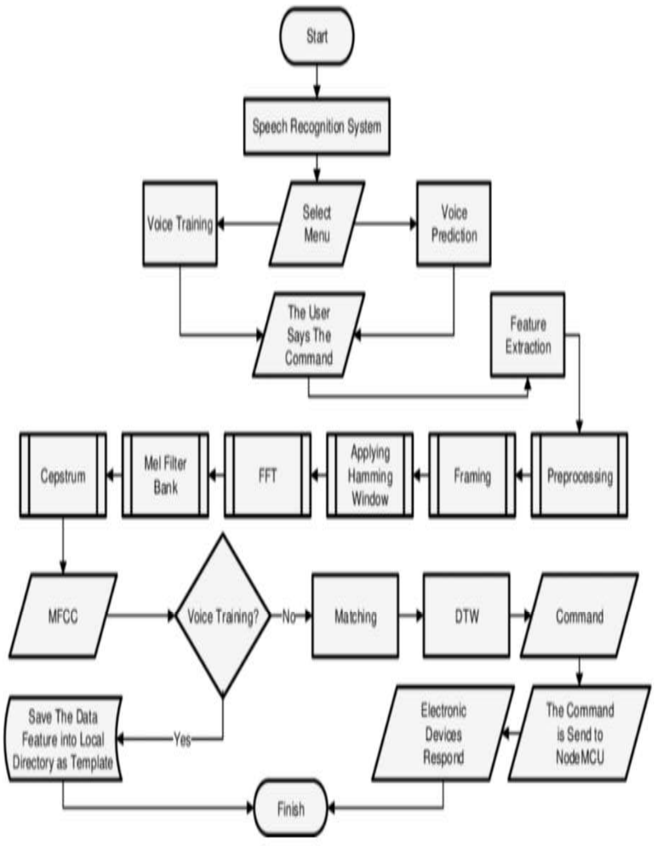

Fig. 5. Flowchart

Flowchart Steps are explained below:

Start: Enter the unprocessed audio signal, usually obtained using a microphone.

Audio Input Validation: Verify that there are no silence or corrupted data in the supplied audio signal. If it's valid, move on to the next phase. If not, ask for fresh information.

Noise Reduction: Utilize methods to eliminate background noise from the audio stream. Examples include Wiener filtering, spectral subtraction, and AI-based denoising (such as DNN or GAN models).

Feature Extraction: Take the clean voice signal and extract its key elements for processing. Typical methods include spectrograms, Mel-frequency cepstral coefficients (MFCC), and Mel-spectrograms.

Voice Quality Enhancement: To improve the audio signal's fidelity, naturalness, and clarity, use AI models (such as CNNs, RNNs, or GANs). Examples include restoring missing signal components or eliminating distortions.

Speech Recognition (ASR): Provide an automatic speech recognition (ASR) system with improved features. Use deep learning models (such as RNN, LSTM, and Transformer) to turn the audio into text.

Language Processing (NLP): Examine the identified text for context, meaning, and intent. Refine the transcription by fixing mistakes and figuring out what the user intended.

Post-Processing: Choose from the following options based on the application: Text Output: Show the text that has been transcribed or utilize it for other purposes. Improved Speech Output: Use a text-to-speech (TTS) technology to turn the transcribed text back into speech.

Output: Provide the user with the finished product, enhanced speech for communication, and text for command execution or transcription.

End: The system either loops back to accept fresh input or completes processing.

IV. Research Requirement Analysis and Design

To ensure optimal functionality, scalability, and performance, the AI-Assisted System for Enhancing Voice Quality and Speech Recognition integrates a diverse range of specialized software tools and development frameworks. The design reflects both the technical complexity of the system and its alignment with real-world application needs. Linux is the preferred operating system for cloud-based and server-side deployments due to its robustness and compatibility with high-performance computing environments. However, cross-platform support is maintained, allowing development and testing on Windows, macOS, and Linux. Python is the primary programming language, chosen for its extensive ecosystem of AI and machine learning libraries. JavaScript is optionally employed for developing interactive user interfaces when needed.

Deep learning frameworks such as PyTorch and TensorFlow are central to training and deploying the system's speech recognition and voice augmentation models. Audio preprocessing tasks including noise reduction and segmentation are supported by libraries like LibROSA, PyDub, and Wave. To further enhance speech recognition accuracy, the system can incorporate pre-trained APIs such as Google Speech-to-Text, OpenAI Whisper, and AssemblyAI. Depending on the complexity and structure of data, the system utilizes either relational databases (e.g., MySQL, PostgreSQL) or NoSQL databases (e.g., MongoDB) to manage and store information efficiently. While local storage is sufficient for development and prototyping, cloud storage solutions such as AWS S3 and Google Cloud Storage are preferred for handling larger datasets and ensuring scalability in production environments.

Though not always required, user interfaces can be developed using modern web frameworks such as React, Angular, or Vue.js. For mobile applications, Flutter offers a flexible and efficient solution for cross-platform deployment.Version control is maintained through Git, with coding environments supported by IDEs like PyCharm and Visual Studio Code. Docker and Kubernetes are employed for containerization and orchestration, ensuring efficient scaling and deployment. Cloud infrastructure platforms like AWS, Google Cloud, and Microsoft Azure offer reliable hosting solutions tailored to various deployment scenarios.

Functional validation is conducted using testing frameworks such as PyTest and Unittest. Audio quality and intelligibility are quantitatively assessed using established metrics, including PESQ (Perceptual Evaluation of Speech Quality) and STOI (Short-Time Objective Intelligibility). RESTful APIs facilitate the seamless integration of system features with external applications. Security is prioritized through encrypted data transmission (SSL/TLS) and robust authentication protocols like OAuth 2.0 and JWT. The system is fully compliant with data protection regulations such as the General Data Protection Regulation (GDPR) and the Health Insurance Portability and Accountability Act (HIPAA), ensuring responsible handling of user data.

Technical documentation is managed using tools like MkDocs and ReadTheDocs, supporting maintainability and developer onboarding. Additionally, comprehensive user manuals and guides are created using standard word processors to assist non-technical users in system interaction.

This structured and technology-rich design reflects a concerted effort to bridge advanced AI capabilities with practical implementation needs. The system's architecture, toolset, and methodology have been deliberately selected to support not only technical efficiency but also real-world adaptability, regulatory compliance, and long-term scalability.

V. Conclusion

In conclusion, this project will make significant progress in advancing AI-assisted speech and voice technologies. Each phase of the design has contributed to a deeper understanding of both the opportunities and challenges inherent in this field. While minor adjustments to the original design were necessary particularly in response to complexities in data preprocessing and system integration the project remains firmly on track to achieve its goals. This research underscores the transformative potential of AI in voice technology. Through a well-structured planning and execution framework, it has laid a solid foundation for a robust system aimed at enhancing speech recognition accuracy and voice quality. Looking ahead, the focus will shift to adhering to the revised timeline, optimizing system performance, and ensuring the final product meets the high standards and ambitious targets set at the outset.

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Journal of Big Data & Smart City

Middle East College

Design and Fabrication of an Assistive Lifting Mechanism for Enhanced Chair Mobility

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Received: 22nd December 2025; Revised: 17th January 2026;

Accepted: 20th February 2026

Abstract— **This project involves the design and fabrication of an assistive lifting mechanism to improve chair mobility for people who have difficulty standing or sitting without support. The main aim of the project was to develop a simple and practical lifting chair using basic mechanical and electrical components. The chair frame was made from iron to ensure strength and stability. All fabrication work, including cutting, welding, and assembly, was carried out in Oman, Muscat, at the Ma'abilah Industrial Area. Welding was used to join the different parts of the structure and form a rigid frame. An electric motor was installed to provide the lifting motion, and a switch button was added to control the upward and downward movement of the chair. During testing, the project concept worked as expected, and the chair was able to be lifted. However, some issues were faced during the testing phase. The battery used had a small voltage capacity, which limited the motor power of lifting mechanism. Due to the short project implementation time, a higher-voltage battery could not be used. In addition, small fabrication errors caused the chair to be slightly unbalanced during operation. Despite these limitations, the design proved that the chair could be successfully lifted by hand, showing that the mechanical lifting concept was effective. Overall, the project achieved its objective of demonstrating a working assistive lifting mechanism. With better fabrication accuracy and a higher-capacity battery, the performance and stability of the system can be improved in future development.**

***Keywords*— Assistive lifting mechanism, scissor lift mechanism, wheelchair mobility aid, electric–hydraulic actuation, rehabilitation engineering, prototype development.**

الخلاصة – يتضمن هذا المشروع تصميم وتصنيع آلية رفع مساعدة تهدف إلى تحسين حركة الكرسي للأشخاص الذين يواجهون صعوبة في الوقوف أو الجلوس دون دعم. وكان الهدف الرئيسي للمشروع تطوير كرسي رفع بسيط وعملي باستخدام مكونات ميكانيكية وكهربائية أساسية. تم تصنيع هيكل الكرسي من الحديد لضمان المتانة والاستقرار. وقد أُنجزت جميع أعمال التصنيع، بما في ذلك القطع واللحام والتجميع، في سلطنة عُمان، مسقط، في المنطقة الصناعية بالمعبيلة. استُخدم اللحام لربط الأجزاء المختلفة من الهيكل وتشكيل إطار صلب. كما تم تركيب محرك كهربائي لتوفير حركة الرفع، مع إضافة زر تشغيل للتحكم في حركة الكرسي صعودًا وهبوطًا. أثناء مرحلة الاختبار، عملت فكرة المشروع كما هو متوقع وتمكن الكرسي من الارتفاع. ومع ذلك، ظهرت بعض التحديات خلال الاختبارات؛ إذ كانت البطارية المستخدمة ذات سعة جهد منخفضة، مما حدّ من قدرة المحرك على تشغيل آلية الرفع بكفاءة. وبسبب قصر مدة تنفيذ المشروع، لم يكن من الممكن استخدام بطارية ذات جهد أعلى. بالإضافة إلى ذلك، أدت بعض الأخطاء البسيطة في عملية التصنيع إلى حدوث عدم توازن طفيف في الكرسي أثناء التشغيل. وعلى الرغم من هذه القيود، أثبت التصميم إمكانية رفع الكرسي بنجاح، مما يدل على فعالية مفهوم آلية الرفع الميكانيكية. وبشكل عام، حقق المشروع هدفه في عرض نموذج عملي لآلية رفع مساعدة. ومع تحسين دقة التصنيع واستخدام بطارية ذات سعة أعلى، يمكن تحسين أداء النظام واستقراره في مراحل التطوير المستقبلية.

الكلمات المفتاحية – آلية الرفع المساعدة، آلية الرفع المقصية، وسيلة مساعدة لحركة الكراسي المتحركة، التشغيل الكهربائي–الهيدروليكي، هندسة إعادة التأهيل، تطوير النماذج الأولية.

I. Introduction

A. Background

The ability to walk around safely and independently is a crucial part of a human quality of life and it's an important part of the human body since it's perfectly designed to walk for long distances. However, many people don't have this bless and often face difficulties moving from one position to another or one surface the other.

Some of these people are suffering from Friedreich ataxia which a genetic disease that negatively affects the nervous system. It causes problems with the persons movement, balance, and coordination. It starts in the childhood or teenage years and over time it gets worse. Also, people with Muscular Dystrophy which in the advanced stage of this disease the persons muscles become very weak and sometime wasted leading to loss of movement and the requirement for someone to do daily activities. Most people with this disease can't walk which significantly reduces the quality of life. Non ambulant cerebral palsy (CP) which is one of these diseases it refers to children with severe motor impairments, children with this type of disease face difficulties with their movements and posture which means usually they cannot move without assistive tools and devices. Cerebral palsy happens before, during or after birth and it's caused by brain damage or not normal brain development which leads to affecting parts of the brain that control muscle coordination and movement. Also, age plays a big role in limiting mobility as the human body gets old it won't perform as it once did the hormones and energy goes down their muscles and joints become weaker.

According to West et al., 2018 about 16% of adults 65 years or older use an assistive device for outdo [1] or mobility. And in the USA alone over 6.8 people use assistive devices to move around [2].

For these mobility issues there is many solutions that were created or getting developed not just the regular assistive tools devices like canes, wheelchairs and electric scooters. There is another sector to aid the limited mobility problem which are types of lifting mechanisms [3]. For example, the Floor lift which is a mechanical device that is designed to transfer people with mobility difficulties from a place to another and it consist of components like a sling or harness it has different type it can be manual, hydraulic or electric. Sit to Stand lifts or stand assist lifts this lift help people with who have some mobility but need some support to stand up from a seated position, they consist of an electric or manual lifting mechanism and a sturdy frame also a sling or harness. Lastly the Bariatric lifts which specified to lift individuals who are on the heavier side typically individuals who weigh around 225 to 450 kilograms or more [8]. Because of that it is consist of heavy-duty components like reinforced frames, durable materials, and extra strong slings all of this is to ensure comfort and safety reducing the physical strain during lifting. In short it works by placing the sling under the person attaching it to the lift then move the patient gently using the hydraulic or electric system because it comes with variety of systems.

B. *Problem Statement*

Nowadays the need for a lifting mechanism for limited mobility patients is increasing day by day its value has increased so much in this age it almost became like a hero for those who has problems or difficulties to move their lower body and its one of the essentials in any hospital and any clinic as it almost substitutes the need for another human force to move around freely. Patients who are diagnosed with paralysis or movement issues they struggle to stand up or sit down without aiding from others which can cause pain and discomfort for them. Not only the patients, also for companions struggles to move or lift the patient specially if the helper is old. to solve this issue, our team has decided to design and fabricate a lifting mechanism which will allow them to stand and sit with less risks and more comfortable way. The primary objectives to achieve: To research and design a lifting mechanism to aid people with limited mobility and to fabricate and test the concept to ensure the safety and its reliability.

II. Related Work

A. *History of lifting machines*

The principles of lifting mechanisms are so simple that it is why the simplicity of machines gives rise to them. The lever and pulley, which Archimedes systematised, were the first mechanical aid in the transportation of bulk [10]. The Industrial Revolution led to the invention of power hoists and cranes. The invention of the hydraulic press in the 18th century and the application of the Law of Pascal, which made it possible to transfer forces by means of fluids and control them, were essential. As electric motors, advanced materials and electronic controls were added, this further progressed into the 20th and 21st centuries, leading to the precision and reliability of the hydraulic, scissor and articulating systems currently in use in industry and in assistive technology [9].

1) *Hydraulic Lifting Mechanism*

A hydraulic lift is a device that uses an incompressible fluid to move a piston to lift a load. It works on the principle of Pascal, which states that when pressure is applied to a fluid, the pressure is transmitted equally in all directions throughout the fluid. With the help of this, a small force can produce a large lifting force. A hydraulic lift table raises the piston hence the load by pumping oil in a cylinder. When the lift is lowered, a valve opens and allows the oil to flow back to the reservoir. The oil is then pushed down by gravity as well as the load on the platform [4].

Hydraulic lifts are essential across industries for safely lifting, positioning, and transporting heavy loads, enhancing productivity while reducing injuries. They are widely used in warehousing, manufacturing, construction, mining, and aerospace to handle materials, machinery, and personnel efficiently. By integrating with automated systems or operating standalone, hydraulic lifts provide power, precision, and reliability for complex lifting tasks in modern industrial and commercial operations [5].

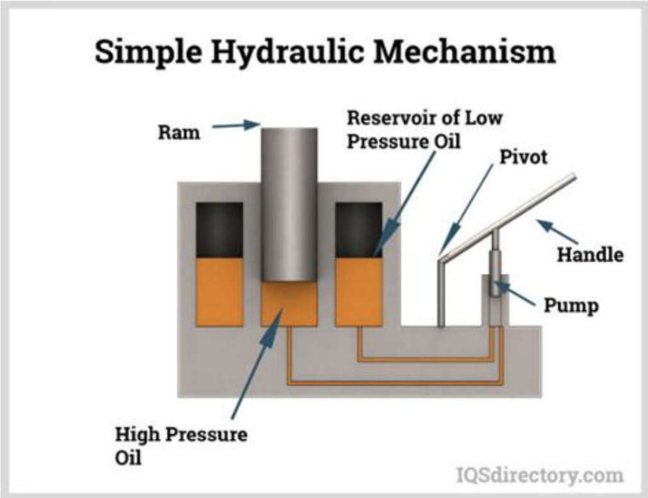

Fig. 1. Simple hydraulic Mechanism

Fundamental Components of a Hydraulic System

Reservoir: Stores excess hydraulic fluid, cools it, and allows trapped air to escape, preventing interference with piston movement.

Hydraulic Fluids: Typically, petroleum, mineral, or vegetable oils with properties such as high boiling point, lubrication, and viscosity suited to specific applications.

Motor: Powers the system; its size depends on the machine's requirements.

Pump: Delivers fluid to the cylinder through valves, with efficiency measured in gallons per minute and pressure (psi).

Cylinder (Actuator): Converts hydraulic pressure into linear mechanical force to move the piston.

Valve: Controls the pressure, direction, and flow of the fluid throughout the system.

Filter: Removes impurities to protect system components.

Hoses: Channels that transport hydraulic fluid, designed according to SAE and EN standards; chosen based on fluid type, conditions, length, diameter, flexibility, and durability [10].

Directional Control Valve: Directs fluid flow within the system, controlling acceleration and deceleration by opening or closing according to the system's working pressure.

B. Scissor Lifting Mechanism

The scissors elevator is an elevator equipped with system of levers and hydraulic cylinders that allow the metal platform to move vertically. The scissor mechanism involves linking and folding supports in a crisscross manner. Furthermore, scissors lift is an essential component of many workshops and construction projects. The concept of a scissors lift with hydraulic power is based on Pascal's law. Which states "the pressure exerted anywhere in a conformed incompressible fluid is transmitted equally in all directions, resulting in the same pressure ratio" [12].

The scissor mechanism derives its name from its resemblance to the blades of a pair of scissors. The steel support beams positioned underneath the work platform are joined by pivot points to form a set of intersecting scissor-like blades. The "X-shaped" configuration is also known as a pantograph mechanism. When the base ends of the beams are distance closer, the structure elongates vertically thus raising the working platform. When the base expands the arms of the scissor fold inward and bring down the platform. The arrangement is mechanically stable from a geometric viewpoint. The scissor lift mechanism is formed by a series of linked parallelograms joined by hinged pivots. The design enables the mechanism to smoothly extend and retract, while ensuring that the geometry of the overall structure is preserved and that the platform remains stable and parallel to the base [14].

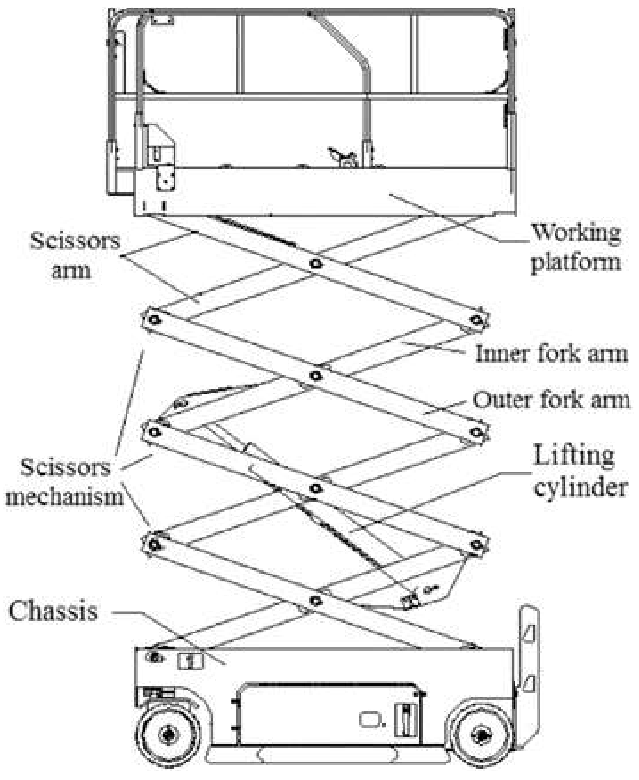

Fig. 2. Scissor Lifiting Mechanism

Fundamental Components of Scissor Lifting Mechanism

Platform: The top of a scissor lift, a platform that raises or lowers the materials or the personnel using it. The platform is a working surface. It is made to the size, shape and material for the application. In the case of a platform designed for workers, rails will be provided for safety. But if there are no rails, that platform is meant for handling materials or other inanimate objects and not for the operation of people.

Scissor Legs: Scissor legs are made of a crisscross or pantograph arrangement of fabricated metal struts connecting the base and the platform. The highest point that a scissor lift can reach will depend on how long each leg assembly is, as well as how many there are. As they undergo contraction, the platform will start rising, and when they undergo expansion, the platform will start lowering. Various power sources may be used to operate the scissor legs, depending on the application.

Cylinders: A scissor lift mechanism usually utilizes one to four compression and expansion cylinders. These cylinders may contain hydraulic fluid (in hydraulic lifts) or compressed air (in pneumatic lifts), depending on the design and environment of the lift. The platform and the legs of the scissors can be lifted or lowered by increasing or decreasing the pressure in the cylinders.

Base: The base of the scissor lift is its structural foundation. Strong and rigid brackets are designed to provide stability. This system comprises tracks to which rollers are attached at the bottom ends of the scissor legs for smooth and steady vertical movement. The base's dimensions and shape differ based on the lift's model and the application intended.

Power Source: Scissor lifts can be powered by different energy systems, whether self-contained motors operating with other fuels or remote power packs. We choose the most suitable power supply as per the lift operating conditions and application requirements.

Down Valve: The down valve directs the return flow of hydraulic oil or compressed air to its tank. The descent speed of the platform depends on the flow rate. The lift is controllably lowered with the assistance of the power source working with the valve.

Flow Control Valve: The flow control valve regulates the rise and fall speed of any scissor lift. It also controls the flow speed of hydraulic fluid or compressed air entering or leaving the reservoir cylinder. It guarantees accurate and secure lifting and lowering motions [15].

C. Joint (Articulating) Lifting Mechanism

Articulating lifts are very versatile machines that are used to allow workers access to hard-to-reach areas to execute tasks or manoeuvre heavy items. The arms of the robots can be bent and extended in various directions, making them effective in getting past obstacles, reaching into narrow gaps and working at different heights. Common uses are maintenance, construction, warehouse duties, and manufacturing work. These lifts are great for either indoor use or outdoor use. They provide a stable platform and reduce worker strain. Also, they maximize safety and allow productivity to increase when an operator is properly trained.

Articulating lifts use jointed arms that move like a human arm, allowing access over obstacles and into tight spaces. The arms are connected by pivot points, enabling independent movement of each section [16].

Key components include a stable base, multiple arm sections, a platform or tool attachment, and control mechanisms. The design emphasizes balance and strength, with load capacity depending on the extension of the arms to prevent tipping.

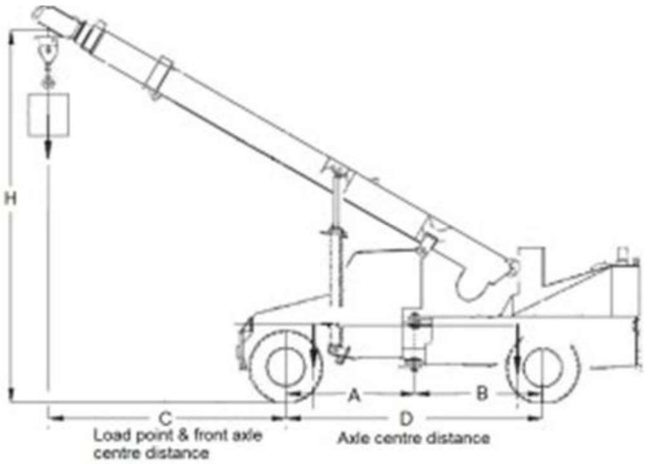

Fig. 3. Joint Lifting Mechanism

D. Key Benefits of Articulating Lifts

Articulating lifts will make the workplace more productive and safer. The joint-arm structure of these lifts makes them flexible enough to reach hard-to-reach or obstructed areas. The ability to bend, twist and move in all directions, makes repositioning quicker than conventional lifts. This versatility offers accurate movement of materials, reduces damage, and helps workers remain in the right position, preventing strain and fatigue [17].

E. Innovative Articulating Lift Applications

Articulating lifts are versatile machines that improve material handling and access to hard-to-reach areas across industries. In warehouses, they enable safe retrieval from high shelves and precise positioning in narrow aisles, often using quiet, zero-emission electric models for indoor use. On construction sites, articulated boom lifts and aerial platforms allow workers to reach over obstacles, perform maintenance, and install materials at height. In manufacturing, hydraulic articulating lifts support assembly, equipment maintenance, and material transport, providing stability and adaptability for varied load requirements.

F. Comparison

The three mechanisms provide various trade-offs. Hydraulic systems generate a high, smooth force, although there must be fluid maintenance. Articulating lifts are more reachable and manoeuvrable at the cost of increased complexity and cost. Scissor lifts are mechanically straightforward and better, being better in vertical stability and having a favourable platform-to-footprint ratio. A scissor lift mechanism is selected in this project, which focuses on stable and rectilinear vertical movement to lift a seated individual safely. It should be designed in a way that it can be driven by an electric-hydraulic system, which is in line with the principal objectives of having user stability, safety and dependability.

G. Mobility and disability

The root cause behind the necessity of the assistive lifting technology is the physical restrictions which individuals with diverse disabilities and age-associated conditions experience. These limitations have a devastating effect on the basic skill of sitting and standing, which is required to be autonomous, mobile, and have a good quality of life [18].

H. Statistics for Limited Mobility

The disabled constitute the greatest minority group in the world. The WHO estimates that about 15 percent of the entire global population, or 1.1 billion people, suffer some type of disability (World Health Organisation, 2021). The percentage is even higher in the United States as CDC states that one out of every four adults have a disability (Centres for Disease Control and Prevention, 2020). Particularly linked to the mobility aspect, the percentage of adults who experienced serious difficulties walking or using stairs in America is 13.7% (Centres for Disease Control and Prevention, 2020).

I. System Definition

Lifting mechanism is a device or a system that can raise, lower or hold a load. mostly using mechanical benefits to move large or heavy objects more easily. These mechanisms can be used in different applications, for example, simple tools like levers and pulleys and for complexes like cranes and hoists, it can be operated manually, hydraulic, electric or by other system devices. Limited mobility refers to any physical impairment that impacts a person's ability to move around freely, easily, and without pain [20]. Mobility limitations raised by many factors such as long-term illnesses, infections, neurological issues, physical injuries, excess body weight, reduced exercise, or the natural aging process.

Many individuals with mobility impairments are unable to participate in employment, and without alternative financial support, their disability can lead them into poverty. Limited mobility also creates major barriers to obtaining essential resources such as food and medication and makes attending medical appointments and other necessary daily activities extremely difficult. Consequently, many people with mobility challenges are unable to live independently [20].

J. Material Selection

When designing a product or in the field of mechanical engineering, selection of a suitable material is critical to the functionality, durability and cost-effectiveness of a final product. Frames have a different set of requirements that include mechanical strength, low weight, fatigue resistance, corrosion resistance and manufacturability [21]. Due to their low density, aluminium and steel alloys are often employed in modern frames, contributing to a decrease in the overall weight and enhancing the performance of handling [21]. Due to its cheapness, resilience and resistance against corrosion, aluminium material is a trendy one. Due to the balance between fabrication and structural integrity, aluminium alloys 6061 and 7005 are common in the frames industry. This section discusses the production processes of making aluminium frames and the mechanical and physical properties of steel and aluminium.

K. Mechanical and Physical Properties of Aluminum

1) Mechanical Properties

Aluminium alloys used in frames offer a balance between strength and weight. For instance, 6061-T6 aluminium alloy exhibits the following mechanical properties:

- Ultimate Tensile Strength: Approximately 310 MPa
- Yield Strength: Approximately 276 MPa
- Elongation at Break: Around 12%

2) Physical Properties

TABLE I. COMPARISON BETWEEN ALUMINIUM, BRASS, STEEL, AND IRON

Property	Aluminium	Brass	Steel	Iron
Density	2.70 g/cm³ (about one-third that of steel, contributing to lighter frames)	8.4–8.7 g/cm³	7.85 g/cm³	7.874 g/cm³
Thermal Conductivity	≈ 167 W/m·K, aiding in heat dissipation during welding	≈ 109–121 W/m·K	≈ 45–60 W/m·K	73-80 W/(m.K) at room tempreture
Corrosion Resistance	Forms a natural protective oxide layer, providing high corrosion resistance	Good corrosion resistance, especially in water and atmospheric conditions	Low to moderate; prone to rust unless alloyed or coated	preventing iron from reacting with oxygen and water through barrier methods (painting, grease)
Strength	Moderate; improved through alloying	Moderate; softer than steel	High, especially in alloyed and heat-treated forms	Pure iron has a lower yield strength

Materials were evaluated for the frame of this project like aluminium, brass, steel and iron. Due to their high strength, durability and attractive wear resistance, steel and stainless steel are suitable for load-bearing applications. Although steel is denser overall, so the total weight of the frame will increase. However, due to the low density of aluminium, weight savings can be significant while maintaining sufficient strength. Aluminium is resistant to corrosion as it forms a natural oxide layer and can dissipate heat effectively during employment like welding. The use of brass on a structural frame is unlikely because it is denser and weaker than steel. While corrosion resistant and machined well, it is unsuitable overall. Aluminium is lighter than steel, but it's also less strong. In terms of cost and maintenance, the steel is typically cheaper and easy to repair [3]. However, iron is durable but can be brittle. Also, iron is much heavier than aluminium, which is favoured when weight reduction is required.

L. Previous Research

The study by Mori Sakai and Katsumura in 2012 talks about a wheelchair that can lift a person who has limited movement. The chair has a lifting frame a sling seat and a small motor that helps move the user up and down in a safe and steady way. It can help someone move between a bed a toilet or other surfaces. The frame can also fold so the chair can be used outside which helps the user be more independent and makes work easier for caregivers. Tests showed that the chair works well and is safe to use [15].

The study Design and Simulation of Multipurpose Built in Car Lifting Mechanism presents a built-in tool that can lift a car and move it forward or backward to help cars stuck in remote areas. The tool sits under the car frame and uses power from the car battery through a hydraulic system. The team shaped the parts to fit safari cars and checked movement forces and stress. The goals are safety reliability and low space use without changing the car frame. The project is still ongoing, and a full model will be built and tested.

The study Design and Analysis of Wheelchair Lifting Mechanism for Public Bus look at making a scissor lift to help disabled and elderly people get on a bus. The lift uses a scissor platform that moves straight up to the needed height and can safely hold up to 400 kg. The team did design math CAD models and FEA checks to make sure the lift is strong and safe. The results showed the stresses stay within safe limits for mild steel. The design improves access and helps disabled people use public buses more easily

TABLE II. SUMMARY OF PREVIOUS RESEARCH

Information	Research Objective	Finding	Conclusion
Development of a Wheelchair with a Lifting Function (Mori et al., 2012)	Design a wheelchair that assists caregivers in transferring severely disabled users, particularly those with disabled upper and lower limbs, both indoors and outdoors by using Winch, Electric motor, Pulleys and others.	•The lifting mechanism supports the safe transport of people with disabilities. • Effective for both indoor and outdoor use with stable mobility support.	• Easy maneuverability and mobility on public roads. • Performance verified through practical testing.
Design and Simulation of Multipurpose Built-In Car Lifting Mechanism (Albuwaydi et al., 2023)	Developing a multi-purpose, built-in mechanism that can both lift a vehicle and allow it to move forward and backward while lifted. The design prioritizes ease of use, requiring no special skills or heavy lifting, and aims to be integrated into the car's chassis without altering its original design or structural integrity. The system is intended to lift a car with a maximum weight of 3000 kg.	The system integrates seamlessly with the vehicle's structure without significant modifications. Practical design capable of lifting loads up to 3000 kg.	Hydraulic system approved for maintenance and emergency use. Results proven through motion and stress analysis.

Information	Research Objective	Finding	Conclusion
Design and Analysis of a Wheelchair Lifting Mechanism for Public Buses: Scissor Lift Platform Mechanism (Mishram W, Jungheer S, Noir F, 2019)	Sectional lifting technology will be used to create a vertical lifting system. The cooling system will be the first to feature an X-shaped automatic control unit. Wheelchair users will find it simpler to manoeuvre independently right away thanks to this design.	Sectional/scissor mechanism supporting vertical lifting. Computer-aided design (CAD) and finite element analysis (FEA) confirm the feasibility of load optimization.	Provides reliable lifting but requires some design compromises. Improves user independence and manoeuvrability.

M. Research Gap

Though modern lifting services are helpful in the specific situation in which they are utilised, the literature review reveals that the solutions are not effective in addressing the basic requirement of a personal, sit-to-stand assisting device. Even though wheelchair mounted lifts can be used to improve caregiver-assisted transfers, they should not be used independently, and it often needs to be operated by outside parties. Though scissor lifts used in industrial and automotive applications can have high levels of vertical movement, the design philosophies of these types of lifts prioritise the fixed installation and high capacity over affordability and domestic portability. Subsequently, a gap in the lifting aid that is specialised and user-friendly clearly exists. The proposed solution involving the key and common daily experience of changing seated posture into a standing one should be inexpensive, small and convenient to the individual with compromised mobility. The given project aims to fill this gap by developing a small, trusted lifting mechanism that will help ensure enhanced safety and personal autonomy.

N. Proposed Solution

To fill the gap in current lifting mechanisms inventions, this project proposes to research and design an automatic lifting mechanism for those who are having issues in mobility when they struggle to move from the floor to a chair or similar seating surfaces. The proposed solution integrates a simple hydraulic-based lifting system with a comfort seating leather to provide safe, smooth, and controlled elevation without requiring significant user aid. The system will be designed to function automatically using a motor–pump system in a rechargeable battery, providing indoor and outdoor operations without human aid.

The design will have a stabilizing support for balanced lifting as well. adjustable seat to keep your body in prefocussing on form, safe to use emergency brake and a water-resistant cover for when it's parked outside, control and anti-slip materials will be used also. By combining the reliability of hydraulic hoists with the user-oriented design thought, the scheme improves and perfects upon independence of people with mobility limitations, decreases effort for caregivers, and promoting general safety during the movement.

III. Methodology

A. Executive Summary

In this project, the engineering structure designed and analysed an electric powered lifting mechanism. The process started from identifying and figuring the load requirement, height lifting, angles directions and safety area. A review has been done relating to lifting mechanisms such as winches, pulley, lifting mechanism that works with motor-drives, was chosen to identify the suitable design option.

B. Research Phase

Human body dimensions: The initial field of research focused on anthropometry to determine the physical dimensions and mass properties of the target user demographic. Standard wheelchair dimensions were analysed, establishing that the mechanism must fit within a seat footprint of 450 mm x 450 mm to be retrofittable. Furthermore, patient weight distribution data was utilized to establish a Safe Working Load (SWL) of 75kg. This value was chosen to cover the 95th percentile of the intended user base while adhering to ISO 10535 standards for patient lifting equipment.

Mechanism Kinematics: The investigation of mechanical linkages was carried out for optimization of the lifting. The pantograph mechanism was picked for its vertical stability and compactness when retracted. The non-linear relationship between the hydraulic cylinder's extension and the platform's vertical rise was derived using equations from Spangler (1990) for the kinematic analysis. This study revealed the important problem of "start angle". In which the force required to lift the hydraulic cylinder is maximum in lowest position. The mounting point placement of the cylinder requires meticulousness.

Material Science: To comply with the project weight limitation, material properties were researched. The material with strong strength-to-weight ratio (Yield Strength ~276 MPa) with respect to the mild steel was identified as Iron. The study also looked into fabrication processes of this alloy, particularly requirements for Tungsten Inert Gas (TIG) welding to prevent cracking of Heat Affected Zone (HAZ).

Fluid Power Systems: The final field of research involved hydraulic power generation suited for mobile applications. The team investigated 12V DC electrical motors, commonly used in automotive dump trailers and tail lifts.

C. Design Phase

The lifting device was designed to fit on top of a normal chair or wheelchair. Average seat sizes were used with most seats being depth of 16–18 inches, and an overall width of about 25–27 inches [23]. The base of the device covers about half the seat, making it stable and comfortable. The lifting height was set to about 40 to 50 cm to match the level of a bed. The horizontal movement is also around 40 to 50 cm to allow an easy transfer. An electric motor was used for strong and smooth lifting. After rising the user, the device moves them sideways with a sliding arm. The frame is made from aluminium to stay light strong and resistant to corrosion. The seat has a leather cover, and the outside parts are insulated. The device uses three buttons for lifting lowering and sideways movement. Figure 4 illustrates the lifting mechanism mounted on a wheelchair as a concept.

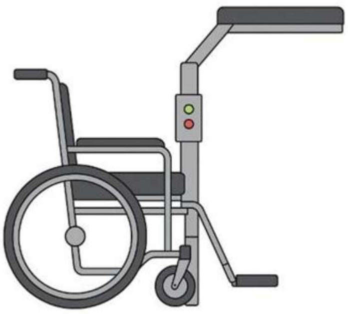

Fig. 4. Lifiting Mechanism mounted on a wheelchair concept

D. Design Concept

The design has two main concepts. Team members start designing the concepts based on their ideas. The design load was calculated based on a user weight of 75kg plus the mechanism weight of 15 kg, with a total mass 80 kg (880 N).

The second concept consists of a fixed lower frame and an upper movable platform. The upper platform is designed to carry the applied load, while guiding elements connected to the main frame ensure controlled vertical movement. A manual or motorized lifting mechanism can be incorporated depending on the application requirements [24].

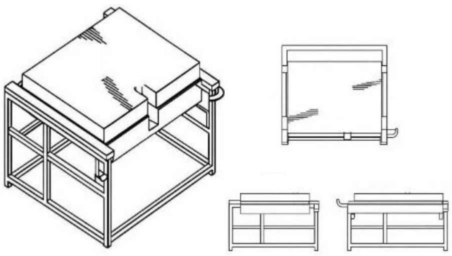

Fig. 5. Isometric and side view of the second concept

E. System Components

1) Main components and their functions:

Base Frame: The base frame is a rigid rectangular structure manufactured from metal sections. Its primary function is to support the entire assembly and provide stability by distributing the applied load uniformly to the ground.

Upper plate: The upper platform is a flat rectangular plate mounted on top of the frame. This component carries the load and is designed with adequate thickness to minimize deflection under loading conditions.

Vertical Supports: Vertical support members are incorporated to guide the motion of the upper platform. These guides prevent lateral movement and ensure smooth vertical displacement.

Lifting Handle: A side-mounted handle is provided to enable controlled lifting of the platform. This component may also be adapted for connection to a motorized lifting system.

Cross Bracing: Cross bracing members are included within the frame to enhance structural rigidity and reduce vibrations during operation.

F. System Calculations

The force required to lift the load was calculated for a mass of 75 kg under gravitational acceleration, resulting in a lifting force of approximately 736 N. Using a drum radius of 0.02 m, the required torque at the drum was determined to be about 14.72 N·m, which is approximately 15 N·m. With a lifting speed of 0.10 m/s, the mechanical power needed at the load was estimated to be 73.6 W. Considering a system efficiency of 70%, the required motor power increases to approximately 105 W. Based on a supply voltage of 12 V, the estimated operating current is around 8.75 A, which can be approximated to 9 A. Therefore, the system requires roughly 15 N·m torque at the drum, 105 W of motor power, and an average current of about 9 A for proper operation.

G. Fabrication and Assembly

Throughout the process of manufacturing, the device was assembled according to the designed plan. The core frame was essentially made of iron bars which were cut. An electrical motor, which was retrieved from hospital beds, was installed in the machine's bottom base. At this stage, they also installed the bottom hydraulic oil reservoir and the electric side travel motor. The operation buttons were positioned where they were accessible, while a new insulated and fully sealed battery was fitted. To ensure stability during application, the device was secured with adjustable belts to the chair. Throughout the development process, small modifications were made as improvements to the motion performance and reliability of the complete system. Figure 6 shows the assembled prototype after welding.

Fig. 6. Final internal structure

H. Finishing Process

Once the structural frame was completed, the body and electrical components were integrated. A, which was salvaged from a hospital bed mechanism to ensure medical-grade reliability and low-noise operation, was securely mounted at the base of the machine. This step also involved installing the hydraulic oil reservoir and connecting it to the 40mm bore cylinder via high-pressure hoses. Simultaneously, the electric side-travel motor was mounted to drive the lateral sliding mechanism. The control system was wired to position the operation buttons in a location easily accessible to the user's hand. A new, fully sealed and insulated 12V battery was integrated into the base to provide a safe, portable power source.

Finally, the entire device was attached to the wheelchair using adjustable heavy-duty belts, which were tightened to ensure the mechanism remained stable and secure during the application of load. Throughout this process, minor adjustments were implemented to align the sliding rails and scissor arms, enhancing the motion performance and reliability of the overall system.

Fig. 7.

I. *Testing Phase*

Three tests have been done to ensure safety and confirm that this device meets with standards and safety.

Static Load Test (Overload Validation): A static overload test was performed to check the structural safety of patient lifters as per ISO 10535 standard. The seat, positioned at maximum height, was subjected to a static load of 110kg (1.5 times the Safe Working Load of 75kg). The iron frame, weld and hydraulic creep (leakage) were tested with the load being maintained for 20 minutes.

Operational Assessment: This is a function performance test. Where a 75 kg (i.e. standard user) load was placed on the seat. The system was cycled through its full range of vertical motion (lifting 150 mm) and its full horizontal motion (sliding 200 mm). The metrics which were recorded are the time to lift, the time to slide, and the electrical current draw from the 12V battery to ensure the motor will not overheat and keep the temperature constant.

Stability Test: To ensure the device does not compromise the wheelchair's centre of gravity, a stability test was performed. With the 100 kg load raised to the maximum height of 150 mm, the wheelchair was placed on a 5-degree inclined surface. The objective was to confirm that the combined centre of mass remained within the wheelbase and that the chair did not tip over during the transfer operation.

IV. Result Analysis and Discussion

A. *Executive Summary*

The simulation and experimental results of the assistive lifting mechanism are discussed in this chapter. Finite Element Analysis (FEA) was used to validate the design for structural safety before fabrication. Testing of the device showed it can lift a 100 kg load in a reasonable timeframe. Thus, hydraulic and electrical sizing works.

B. *Testing Results and Interpretation*

ANSYS software was used to conduct the static structural analysis of the aluminium frame for user safety. The 3D model is imported, and quality mesh is applied according to the model. Mesh refining was done at critical stress concentration locations like pivot pin holes and weld joints. A distributed downward force of 1500 N was applied on the seat surface to simulate a user’s weight with a dynamic factor. According to the simulation, the Von Mises stress is maximum at the pivot points of the scissors arm, which is 110 MPa. When compared to Iron yield strength which is 276 MPa, Safety Factor is calculated: SF=276/110= 2.51

A safety factor of 2.51 confirms that the design is safe for the intended application, exceeding the minimum engineering standard of 2.0. The maximum deformation observed was 2.1 mm at the edge of the cantilevered seat, which is structurally acceptable.

1) *Test 1: Static Load Test*

The design is considered safe for this application with a safety factor of 2.51, which exceeds the engineering requirement of 2.0. At the edge of cantilevered seat maximum deformation was found to be 2.1 mm which is acceptable.

2) *Test 2: Operational Assessment Test*

The fully extended lift was loaded with a static load of 110 kg which is 1.5 times SWL for 20 minutes. The visual inspection after testing, did not show any deformation or cracks in the weld mentor mentation. seal integrity validated by leak-down and pressure build-up reassure.

3) *Test 3: Stability Test*

The 75kg load was moved in lateral sliding mechanism across 200 mm travel distance. The movement took about fifteen seconds. Though functional, the friction was a little higher than calculated, probably due to slight misalignment of the weld rails. The worm gear motor has a high torque of 10 Nm which can overcome this friction without stalling sum up of results and findings.

V. Conclusion and Recommendations

The lifting device was successfully developed, which is an assistive lifting device for the wheelchair users. The incorporation of vertical movement in the form of an electrical motor to lift and lateral movement through a lead-screw mechanism fills a major gap in assistance technology of today. The design underwent rigorous process with mathematical calculation with FEA simulation was carried out to get a safe structure with 2.5 safety factor. The use of Iron provided the necessary strength in the device while being lightweight. After physical testing, the device was proven safe for lifting and handling a 100 kg user which will practically enhance independence and reduce caregiver burden in the MENA region.

To prevent the friction and load on the motor from being excessive during future iterations, it is highly recommended to change the type of lower bearings with more efficient bearings and to reduce the weight by using smaller types of batteries. One more recommendation for future developments is to use single motor rather than two. Moreover, having a brake system is highly recommended to improve safety and make it more portable.

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Journal of Big Data & Smart City
Middle East College

Sulphur Concrete: Rehabilitation and Repair Material Properties, Durability and Applications in Aggressive Infrastructure conditions

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Received: 25th December 2025; Revised: 20th January 2026;

Accepted: 22nd February 2026

***Abstract*— Corrosion by acid attack, sulphate exposure, chloride ingress, and corrosion mediated by microorganisms have deteriorated the necessity of high-performance rehabilitation materials that improve the capacity to maintain aggressive services conditions. Mortar repair using conventional Portland cement tends to shrink, degrade through permeability and has minimal acid resistance especially in sewer and industrial installations. Sulphur concrete (SC) or sulphur polymer concrete (SPC) is a recent re-emerging promising alternative repair mat in that it develops strength quickly, is not processed with water or requires it, is water independent, has low permeability, and is highly resistant to acidic and salty conditions. Compared to cementitious systems, sulphur concrete solidifies during thermoplastic solidification instead of hydration thus allowing it to be loaded immediately after cooling and much less downtime in rehabilitation work. The present paper critically analyses the sulphur concrete as a repair material in terms of deterioration processes in the infrastructure, performance requirements of the rehabilitation system, sulphur binder chemistry, mechanical behaviour, bond behaviour, durability under hostile conditions, sustainability considerations, and the practicality of implementation. New developments in modified sulphur systems with the use of dicyclopentadiene (DCPD), nanomaterials, and fibre reinforcement are considered. The findings show that sulphur concrete has better acid resistance, insignificant drying shrinkage, compressive strengths and a high possibility of sustained performance in the sewer and industrial sector. Other remaining problems with thermal sensitivity and fire behaviour are also explained.**

Keywords*— sulphur concrete, rehabilitation materials, sewer corrosion, acid resistance, sulphur polymer concrete, durability, sustainability.

الخلاصة – يؤدي التآكل الناتج عن الهجوم الحمضي، والتعرض للكبريتات، وتسرب الكلوريدات، إضافة إلى التآكل الناتج عن الكائنات الحية الدقيقة، إلى زيادة الحاجة إلى مواد ترميم عالية الأداء قادرة على الحفاظ على كفاءة المنشآت في البيئات القاسية. وغالبًا ما تعاني مونة الترميم المعتمدة على الإسمنت البورتلاندي التقليدي من الانكماش، كما تتعرض للتدهور بسبب النفاذية العالية، وتُظهر مقاومة ضعيفة للأحماض، خاصة في شبكات الصرف الصحي والمنشآت الصناعية. يُعدّ الخرسانة الكبريتية (SC) أو خرسانة البوليمر الكبريتي (SPC) من البدائل الحديثة الواعدة في أعمال الترميم، حيث تتميز بسرعة اكتسابها للمقاومة، وعدم حاجتها إلى الماء أثناء المعالجة أو التصنيع، إضافة إلى انخفاض نفاذيتها ومقاومتها العالية للظروف الحمضية والملحية. وعلى عكس الأنظمة الإسمنتية، فإن الخرسانة الكبريتية تتصلب من خلال التصلب اللدن الحراري بدلاً من تفاعلات الإماهة، مما يسمح بتحميلها مباشرة بعد التبريد ويقلل بشكل كبير من زمن التوقف أثناء أعمال الصيانة والترميم. تتناول هذه الورقة تحليلاً نقديًا لاستخدام الخرسانة الكبريتية كمادة ترميم، من خلال دراسة عمليات التدهور في البنية التحتية، ومتطلبات أداء أنظمة الترميم، وكيمياء الرابط الكبريتي، والسلوك الميكانيكي، وخصائص الترابط، والمتانة في البيئات القاسية، إضافة إلى الجوانب المتعلقة بالاستدامة وإمكانية التطبيق العملي. كما تستعرض التطورات الحديثة في أنظمة الكبريت المعدل باستخدام الديسيكلوبنتاديين (DCPD) والمواد النانوية والتسليح بالألياف. وتشير النتائج إلى أن الخرسانة الكبريتية تمتلك مقاومة أفضل للأحماض، وانكماشًا جافًا ضئيلًا، وقيم مقاومة ضغط مرتفعة، إضافة إلى قدرة عالية على الأداء المستدام في شبكات الصرف الصحي والمنشآت الصناعية. كما تناقش الدراسة بعض التحديات المتبقية المرتبطة بالحساسية الحرارية وسلوك المادة في حالات الحريق.

الكلمات المفتاحية – الخرسانة الكبريتية، مواد الترميم، تآكل شبكات الصرف الصحي، مقاومة الأحماض، خرسانة البوليمر الكبريتي، المتانة، الاستدامة.

I. Introduction

Wearing and tearing of infrastructure is a significant engineering problem in the world, especially on structures that are subjected to chemically corrosive environments. The concrete elements of the wastewater systems, marine facilities, industrial plants, and chemical containment structures are under constant attacks of acid, sulphate, chloride intrusion, and corrosion by microbes [1], [2]. These degradation processes are majorly a large decrease in service life and maintenance cost. The repair materials based on Portland cement are generally employed in rehabilitation but the results of their use in strong acidic environment are still a challenge. Exposure to acid dissolves calcium hydroxide and gradually decalciates calcium silicate hydrate (C-S-H) phases, softening them, cracking them, and losing their mass [3].

In sewerage, hydrogen sulphide can be oxidized by microbes to produce sulfuric acid at the crown of the pipes, and the surface pH can be less than 2, which promotes the degradation of concrete [12], [18]. At the same time, environmental issues related to Portland cement manufacturing have been enhanced. Cement is a major source of global anthropogenic CO2 emission with an estimate of 7-8 percent of clinker calcination and combustion of fuel [4]. Therefore, other binder systems of better durability and reduced environmental impact are being actively researched [5]. More recent research on waste-based cementitious materials and the development of sustainable binders also points to the significance of material innovation based on durability in aggressive environments [26].

In petroleum refining, sulphur is produced as a by-product of hydrodesulfurization and is produced in great amounts on a global scale. The stocks of the world sulphur are over 200 million tons, and it poses a problem of storage and environmental management issues [6].

The fact that sulphur is a building material that can be highly valued is a continuation of the principles of the circular economy and will lead to the minimization of the use of carbon-intensive Portland cement. Sulphur concrete is the total opposite of cementitious systems. Instead of hydration reactions, molten sulphur is used as a thermoplastic binder solidifying when it is cooled down. When it cools, the sulphur is crystallized in the form of dense and continuous matrix that holds the aggregates together [7]. This procedure removes curing needs and allows reopening of rehab structures quickly. The benefits of key performance are Growth Rapid early development of strength (>30-40 MPa in hours) [8], Slowly resistant to sulfuric acid and nitric acid [9], Water absorption and permeability very low [10], Absence of drying shrinkage [11] and Outstanding corrosion protection against corrosion by microbes [12].

Sulphur concrete has these properties that render especially applicable in restoring sewer pipes, wastewater treatment plants, industrial containment structures, and acid-exposed floors. However, pure sulphur concrete is brittle and temperature sensitive and thus further extensive structural use is impeded [13]. The toughness and dimensional stability have been greatly improved by modified sulphur polymer concrete (MSPC), which is realized by the addition of stabilizers, including dicyclopentadiene (DCPD), and the introduction of nano-reinforcements [14], [15], [16]. This review considers sulphur concrete as a material that can be used in the rehabilitation of aggressive infrastructure settings, combining chemical, mechanical, longevity, and sustainability views.

II. Wear and Tear of Concrete Infrastructure Mechanisms

The mechanisms of degradation must be understood during the evaluation of the appropriateness of repair materials.

A. Acid Attack

The main processes of degradation of concrete under acidic conditions include calcium hydroxide is dissolved and decomposed into hydrogen and oxygen gases, decalcification of C–S–H and gypsum and ettringite are formed. These reactions make the structure porous and less strong [3], [17]. Exposure to sulfuric acid is also very destructive as it leads to expansion and softening through formation of gypsum. Hydrogen sulphide is oxidized by sulphur-oxidizing bacteria to sulfuric acid in sewer systems causing an excessive amount of corrosion on the crown [12], [18]. In such conditions cement-based materials quickly lose the surface strength. Concrete made of sulphur as opposed to calcium does not undergo the acid dissolution reaction, which also offers natural chemical resistance [9].

B. Sulfate Attack

Extrinsic exposure to Sulphate leads to expansive ettringite, cracking and spalling [19]. The sulphur concrete does not have reactive aluminates and therefore does not easily expand due to sulphates.

C. Chloride-Induced Corrosion

The reinforcement corrosion is reinforced by chloride penetration in conventional concrete [20]. Sulphur concrete has a very low permeability, which prevents chloride intrusion because of its high hydrophobic and compact structure [10].

D. Freeze–Thaw Damage

Freeze-thaw degradation is caused by the expansion of pore water within the interior [21]. The freeze thaw vulnerability is low due to the very low water absorption of sulphur concrete.

E. Microbial-Induced Corrosion (MIC)

MIC is among the most devastating processes in the wastewater systems [12]. Sulphur concrete is not based on alkaline hydration chemistry, and this makes it resistant to biogenic acid attack [9]. All these mechanisms of degradation underscore the significance of chemical resistance, dimensional stability, and low permeability of rehabilitation materials.

III. Repair and Rehabilitation Materials (Strengthened) Requirements

Mechanical compatibility, durability and constructability requirements need to be met in an effective repair system [22].

A. Mechanical Compatibility

Repair materials must be of adequate compressive strength, and they must have modulus compatibility with the substrate so that they do not focus stress [23]. Sulphur concrete also has compressive strengths ranging between 35-60 MPa based on the formulation [8], [24].

B. Bond Strength

Good bonding between repair layer and substrate is very necessary. Bond behaviour would be based on the surface preparedness, temperature, and the wetting behaviour [25]. Adjusted sulphur systems have better interfacial bonding because there is a low shrinkage in crystallization [14].

C. Chemical Resistance

The materials used in the sewer systems should be able to resist the concentration of sulfuric acid between 1 and 5 percent in rehabilitation [12]. Research indicates that sulphur concrete does not lose more than 90% of compressive strengths after a long period of acid exposure [9].

D. Dimensional Stability

Most cement-based repair systems are susceptible to drying shrinkage and thermal cracking [26]. At this stage, sulphur concrete has zero drying shrinkage because of the lack of hydration reactions [11].

E. Rapid Return to Service

Setting Thermoplastic allows the generation of full strength in hours and reduces the downtime of infrastructure [8].

F. Sustainability Concerns

Exploiting excess sulphur helps to minimize wastes and embodied carbon as compared to the Portland cement systems [4], [6].

IV. SULFUR CONCRETE CHEMISTRY AND PROCESSING.

A. Sulfur Allotropy and Thermal Behavior

At ambient temperature, elemental sulphur is found mostly as orthorhombic rings. At temperatures above 119° C, there is opening of the ring, and the polymeric chains are formed which raises viscosity [26]. Heating is normally done at 120-140° C to get sufficient workability [27].

B. Modified Sulfur Polymer Concrete (MSPC)

Raw Sulphur is fragile and prone to phase reversion. Stabilizers like DCPD react with sulphur radicals to produce cross-linked networks, which enhance toughness and decrease crystallization [14], [15]. Recent developments are nano-silica reinforcement [16], provision of graphene-enhanced sulphur composites [15], fly ash and slag fillers [29], hybrid fibre reinforcement [30]. These additions enhance flexural stability, fractured resistance as well as dimensional stability.

C. Mix Design and Composition

Ordinary sulphur concrete contains 1020% sulphur binder, 7080% aggregates, 515% mineral fillers, optional fibre reinforcement (0.52%) and aggregates should be dry and preheated to avoid premature solidification [27].

D. Processing and Placement

Processes involved in production consist of heating sulphur up to about 130 C, preheating of aggregates, mixture, and casting and cooling. It does not use any curing water as opposed to cement-based repairs. The capacity of the structure is developed as soon as it cools down [8].

E. Safety Considerations

Sulphur is flammable and might emit SO2 when overheated. During field installation, strict temperature control and ventilation is needed [24].

V. MECHANICAL PROPERTIES OF RELEVANCE IN REPAIR APPLICATIONS

Mechanical performance is another major parameter of rehabilitation material, especially when structural capacity must be restored in a short period of time. Depending on the formulation, grade of aggregates and binder alteration, sodium concrete proves compressive strengths of up to 4070 MPa [8], [24]. In contrast to the cement-based systems, which take 7-28 days to attain design strength, the sulphur concrete attains nearly all the strength within hours because of thermoplastic solidification [8]. The quick development of strength is explained by the sulphur polymerization and crystallization of the cooling process. During handling at 120° -140° C, sulphur changes to long chain polymeric structures. These chains crystallize on cooling into a dense load-bearing matrix which is essentially capable of binding aggregates [26], [27]. This process eradicates curing delays and minimizes a lot of downtime in rehabilitation works.

Elastic modulus of sulphur concrete is generally 20-30 GPS which is like the conventional concrete with respect to the type of aggregates used [24]. Nevertheless, in sulphur systems which are not modified, brittleness is still an issue [13]. Addition of fibres like basalt, glass, or carbon has a major positive impact on flexural strength, fracture toughness, and minimizes abrupt brittle failure modes [23], [24].

The creep behaviour under ambient behaviour is not very high but continuous loading under high temperature can cause observable deformation [23]. Creep effects are of no structural concern in most sewer and industrial applications that are below 60º C, but it is to be considered in high-temperature applications. Generally, sulphur concrete has sufficient mechanical performance when used in non-prestressed rehabilitation projects and has considerable benefits in the early development of strength.

VI. BOND BEHAVIOR, INTERFACE PERFORMANCE

Effective rehabilitation must have a high bond strength between repair layer and substrate. The strength of bond in sulphur concrete systems is determined by the surface preparation, substrate roughness, thermal compatibility and wetting characteristics. Research suggests that, when concrete surfaces are well prepared (e.g. sandblasted or mechanically roughened), the strength of mechanical interlocking is increased, and the bond strength is enhanced [25]. Adjusted sulphur systems also show better wetting properties as they do not experience much shrinkage during crystallization and have better flexibility of the polymer chains [14].

During placement, thermo-compatibility is essential. High sulphur temperatures can destroy substrate moisture or cause thermal stress whereas low temperatures cause low adhesion [27]. Regulated heating measures guarantee the best bonding without the depreciation of substrate.

The reported bond strengths of sulphur concrete overlays are equal to polymer modified cement mortars [25]. Notably, the quick nature of setting of sulphur concrete minimizes the chances of early age debonding related to drying contraction of cement concrete in cement-based repair jobs [11].

VII. DURABILITY IN HOSTILE CONDITIONS

The first benefit of sulphur concrete in the process of rehabilitation is durability performance.

A. Acid Resistance

Sulphur concrete is very resistant to sulfuric and nitric acid. The binder does not constitute calcium hydroxide or C-S-H formula so there is no acid dissolution system that is characteristic of Portland cement systems [3], [9]. According to laboratory immersion experiments, there is little loss of mass and retention of greater than 90 % compressive strength, following extended exposure to 5 percent solution of sulfuric acids [9].

B. Sulfate Resistance

In contrast to cement-based products forming large ettringite during sulphate attack [19], sulphur concrete has no active aluminates, and thus in this case, sulphur concrete does not undergo this process.

C. Chloride Resistance

Concentrated sulphur matrix is hydrophobic and highly decreases the permeability and chloride diffusion [10]. The property is useful especially in the rehabilitation of coastal and industrial infrastructure.

D. Freeze–Thaw Performance

Sulphur concrete has a high freeze-thaw cycling resistance because of its very low water absorption characteristics [21]. Lack of internal pore water restrains expansion stresses in the freezing process.

All this durability benefits make sulphur concrete a better choice in rehabilitation in a very aggressive environment.

Similar gains in resilience to chemicals have been described in waste-adjusted cementitious systems [27] and justify the importance of densifying the matrix in hostile habitats.

VIII. Sewer and Industrial Rehabilitation Applications

One of the most demanding service conditions of concrete systems is the sewer systems where the biogenic sulfuric acids are formed [12], [18]. Traditional cement linings do not principle well in such conditions, and therefore they may have to be maintained on multiple occasions. The ability of sulphur concrete to resist acidic dissolution especially renders it ideal in sewer crown reconstruction, manhole lining, wastewater tanks and industrial effluent tank.

Field tests have shown long-term functionality in sewer segments that are attacked by acids with minor surface erosion in contrast to cement repair [19]. Also, the fast setting of sulphur concrete facilitates trenchless rehabilitation methods with minimal service disruption [20]. Sulphur concrete is also used in industry in the production of chemical-resistant floors and structures used in containment of acids and salts [21].

IX. Fire, Thermal Stability and Serviceability

Although it has its benefits, sulphur concrete has thermal constraints. The sulphur binder also becomes soft at about 115-140° C based on level of modification [13]. Although normal sewer conditions do not come that high heat wise, industrial applications that are under heat need to be evaluated.

Exposure to fire causes other concerns. Sulphur is inflammable and in severe conditions it can produce sulphur dioxide [23], [24]. The exploration of flame-retardant additives and mixed sulphur compounds would help to overcome this restriction [24].

These are to be taken into consideration as regards to compatibility of thermal expansion between sulphur overlays and the underlying concrete substrate to prevent debonding during temperature cycles. These limitations do not rule out the use of sulphur concrete in normal sewer and wastewater rehabilitation applications but only limit its applications in fire prone environments.

X. Sustainability and Life-Cycle Perspective

The issue of sustainability is becoming critical in the rehabilitation of infrastructure.

The production of Portland cement generates a large amount of CO_2 because of the Smouldering of limestone and the use of fuel [4]. Sulphur concrete does not involve production of clinkers. When sulphur is used as an industrial by-product, the carbon contained in it is significantly smaller than a cement binder system [6]. Also, sulphur concrete does not require curing water, decreases the time spent on construction, uses sulphur that is produced in industries and increases the lifespan of the infrastructure. According to the LCA studies, the sulphur-based systems could have lower impact on the environment than cementitious repair materials because the former may be less affected by aggressive environment when the cycle of maintenance should be repeated frequently [23], [24].

Utilization of ceramic powder as well as waste of marble and bi-derived materials have been discovered to be more beneficial to the cementitious systems when it comes to mechanical performance and environmental issues. [28] which enhances the suitability of sulphur-based systems in larger sustainable construction contexts. The use of sulphur concrete is consistent with the principles of the circular economy since the refinery by-products are used as a valuable resource.

XI. Comparison of Traditional repair materials

Traditional repair systems consist of cement-based mortars, polymer-modified mortars and epoxy systems. Cement based systems are susceptible to acid attack and shrinkage cracking [15], [26]. Polymer modified systems enhance adhesion and lower permeability and remain hydration based and chemically susceptible in strong acidic environments [30]. Epoxy systems are also very expensive, chemically resistant, and brittle under cycling loads and could be thermally incompatible with concrete substrates [16].

Sulphur concrete is a well-rounded option, which can develop strength quickly, be highly resistant to chemical elements, and cost-effective in large-scale rehabilitation [17].

XII. Restrictions and Implementation Problems

Regardless of these merits, sulphur concrete has practical constraints thermal sensitivity [13], fire performance [23], unmodified brittleness [14], inadequate structural code coverage [19]. The familiarity and safety practice among the contractors is necessary because of the molten sulphur handling necessities [21] and the solution to these issues with the enhanced formulations and revised design recommendations will lead to increased adoption.

XIII. Research Gaps and Future Directions

The research of the future ought to be on long term field-observations in sewer settings [18], on the generation of structural design specifications [19], on hybrid sulphur-geopolymer materials [20], [22], on nano-reinforced sulphur composites [15], [16], [25] and on complete LCA analysis [23], [25]. Similar potential of sulphur-based composite systems Hybridization methodologies with the use of additional cementitious materials have demonstrated better microstructural densification and durability behaviour in previous studies [28], which implies the same in the case of sulphur-based systems. Further engineering assurance would be enhanced through advanced constitutive modelling of the behaviour of sulphur composites under thermal cycling and sustained loading.

XIV. Conclusions

As evidenced in this review, sulphur concrete is a technically sound and environmentally promising rehabilitation material in the aggressive infrastructure environment. The key conclusions are as follows.

Quick strength build up makes resurgence back to service. Lack of calcium-based hydration products guarantee enhanced resistance to sulfuric acid and corrosion caused by microbes. Poor permeability and insignificant shrinkage improve stability and dimensional stability. Sulphur systems that are modified enhance performance stability and toughness. Sulphur concrete has a higher level of resistance to acidic conditions as opposed to traditional cement-based repairs. Further development of thermal sensitivity and fire resistance can also be seen. Such benefits of sustainability are waste sulphur valorisation and lower embodied carbon.

Through ongoing research, code development, and field validation, it can be said that sulphur concrete has high potential to be mainstream in offering rehabilitation solutions to sewer and industrial infrastructure.

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Journal of
Big Data & Smart City

VOLUME 6
ISSUE 1
SPRING 2026

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Published by:
Middle East College
Knowledge Oasis Muscat
P.B. No. 79, Al Rusayl
Postal Code: 124
Sultanate of Oman
Tel: +968 24531400
info@mjbdsc.org

ISSN (Print) : 2706-7912
ISSN (Online) : 2788-4112

www.mjbdsc.org