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Mini-Vent - An Economical Miniaturised Intensive Care Unit System

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Abstract - *The COVID-19 pandemic brought severe challenges to healthcare systems worldwide. India faced shortages of critical medical equipment, overwhelmed hospitals, and an urgent need for innovative solutions. In response, We at our ATL robotics laboratory developed a cost-effective emergency ICU and ventilation system. This system provided an affordable alternative to complex ventilators, making it accessible in resource-limited settings. It was designed for ease of use, requiring minimal specialised training, and featured an intuitive interface to allow healthcare providers to focus on patient care. Tailored for specific emergency scenarios, the automated ICU system delivered reliable respiratory support, helping to alleviate the burden on overwhelmed healthcare facilities.*

The pandemic disrupted global supply chains, leading to shortages of essential medical equipment and straining healthcare infrastructure. The lack of ventilators worsened patient outcomes, highlighting the need for quick solutions. Healthcare workers were overburdened, emphasising the necessity of automated systems. Our system was designed to work effectively in diverse healthcare contexts and included a remote monitoring system, enabling healthcare providers and medical experts to monitor patients without physical interaction.

***Key Words*: Emergency ICU ventilation system, Cost-effective medical solution, Automated respiratory support, Respiratory support, Health care accessibility, Absence of Remote monitoring system**

1. Introduction

The COVID-19 pandemic brought to light significant gaps in global healthcare systems. Hospitals were inundated, essential medical supplies were scarce, and healthcare workers were stretched thin. To address these challenges, our robotics laboratory developed an innovative solution: a cost-effective emergency ICU and ventilation system. This system was designed to be intuitive and automated, providing crucial respiratory support in emergency situations. This research paper aims to provide an in-depth analysis of our project, focusing on its design, implementation, and real-world impact. The intuitive design of the emergency ICU and ventilation system was one of its key features. It was engineered with a user-friendly interface that allowed healthcare providers to operate it with minimal training. The system was automated, reducing the need for constant manual intervention and allowing healthcare workers to focus more on patient care. The design also incorporated specific settings for different emergent scenarios, making it adaptable and efficient. This meant that the system could be tailored to the specific needs of a patient, providing personalised care. Furthermore, the system was designed to be robust and reliable, ensuring that it could function effectively even in high-pressure situations. In essence, the intuitive design of the system was all about making it as easy as possible to use while still providing high-quality, life-sustaining care. This combination of simplicity and effectiveness is what made the system a trailblazing contribution to emergent healthcare solutions.

2. Methodology

The COVID-19 pandemic brought to light significant gaps in global healthcare systems. Hospitals were inundated, essential medical supplies were scarce, and healthcare workers were stretched thin. To address these challenges, our robotics laboratory developed an innovative solution: a cost-effective emergency ICU and ventilation system. This system was designed to be intuitive and automated, providing crucial respiratory support in emergency situations. This research paper aims to provide an in-depth analysis of our project, focusing on its design, implementation, and real-world impact. The intuitive design of the emergency ICU and ventilation system was one of its key features. It was engineered with a user-friendly interface that allowed healthcare providers to operate it with minimal training. The system was automated, reducing the need for constant manual intervention and allowing healthcare workers to focus more on patient care. The design also incorporated specific settings for different emergent scenarios, making it adaptable and efficient. This meant that the system could be tailored to the specific needs of a patient, providing personalised care. Furthermore, the system was designed to be robust and reliable, ensuring that it could function effectively even in high-pressure situations. In essence, the intuitive design of the system was all about making it as easy as possible to use while still providing high-quality, life-sustaining care.

2.1 Development of Ventilator Model

Our developed ventilator is an electromechanical device that automates the compression of an airbag resuscitator to deliver airflow to patients in emergencies. The foundational concepts from OxyGEN project for this device were retained due to its proven effectiveness in medical testing, which showed promising results in both animal and human preclinical trials.

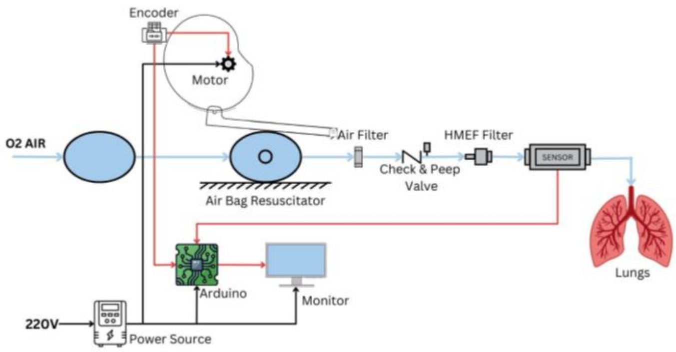

Fig. 1 Scheme of the low-cost mechanical ventilation system OxygenIP.PE.

Figure 1 shows a scheme of the prototype and its components. This equipment was designed to provide a volume-controlled ventilation (VCV), the main ventilation parameters for the emergency use are available according to, these parameters can be selected by the medical staff for the patient requirements.

The prototype is designed to mimic the breathing process of human lungs. It operates by using a DC motor that provides rotational force to a specially shaped cam. This cam then moves a follower in an oscillating motion, which compresses an airbag. The compression of the airbag increases air pressure, creating airflow that assists in patient breathing. The device can be adjusted manually with different cams based on the patient's respiratory needs as determined by healthcare professionals.

The ventilator underwent several development stages. Initially, the mechanical components were redesigned to replicate the ventilation patterns of existing validated equipment, with improvements for more consistent performance and durability for extended use. Concurrently, a mathematical model of the mechanical ventilation system was developed, which helped in understanding how the physical aspects of the system could influence the ventilation provided over time.

Fig. 2 Frontal View of our prototype.

Fig. 3 Top View of our prototype

2.2 Sensors and Receptors

2.2.1 Blood Oxygen Level Sensor

The sensor is placed on a body part, such as a finger or earlobe, and continuously monitors the oxygen levels, enabling the detection of hypoxaemia or low oxygen saturation. The real-time SPO2 data provided by this sensor is vital for the effective management and monitoring of the patient's respiratory function within the Mini-Vent system.

2.2.2 Electrocardiogram (ECG) Sensor

The ECG sensor, which consists of multiple electrodes is placed on the patient's body and is used for transmitting the electrical data to the monitoring system, allowing for the detection of any abnormalities, such as arrhythmias or cardiac ischaemia. This real-time cardiac monitoring is essential for the comprehensive care of ventilated patients, as it allows for timely intervention and appropriate adjustments to the ventilation parameters to maintain optimal cardiovascular and respiratory support.

2.2.3 Electromyography (EMG) Sensor

In the context of Mini-Vent, the EMG sensor is used to assess the patient's respiratory muscle activity, providing valuable insights into neuromuscular function and coordination. By monitoring the electrical activity of the diaphragm and other respiratory muscles, the EMG sensor is helpful to clinicians in optimising ventilator settings and detecting any signs of respiratory muscle fatigue or dysfunction, enabling timely intervention and improved patient outcomes.

2.2.3 Pressure Flow Sensor

These sensors measure the pressure and flow of the air being delivered to the patient's airways, providing real-time data to the ventilator control system. By continuously monitoring these parameters, the ventilator can adjust its output to maintain the desired pressure and flow profiles, which are crucial for effective gas exchange and lung mechanics. The feedback from these sensors enables the ventilator to optimise its performance and deliver the appropriate ventilatory support to the patient, improving clinical outcomes and patient safety.

2.2.5 Temperature Sensors

In Mini-Vent systems, temperature sensors within the breathing circuit ensure the air delivered to patients is at a safe temperature. These sensors help maintain the right temperature and humidity, preventing complications and optimising respiratory support for better clinical outcomes.

2.2.6 Humidity Sensors and Humidifiers

Humidity sensors and humidifiers are vital in ventilators to ensure the air provided to patients is adequately moist, preventing dryness that can damage delicate lung tissues. These components work together to measure and adjust humidity levels, enhancing patient comfort and aiding in effective respiratory therapy.

2.2.7 Humidity Oxygen and Carbon Dioxide Sensors

NDIR CO2 sensors operate by detecting specific wavelengths of infrared energy absorbed by CO2 molecules, providing accurate, long-term stable measurements unaffected by other gases. Together, these sensors play a critical role in customising ventilation therapy, ensuring optimal oxygenation and carbon dioxide removal, and thereby significantly influencing the success of patient treatment and recovery.

2.3 Other Components

The Ventilator Mechanism in the Mini-Vent system comprises several essential components designed to facilitate positive pressure ventilation, ensuring adequate oxygenation and ventilation for patients in respiratory distress.

2.3.1 Valves

The ventilator system utilises check valves to control the direction of airflow. During inhalation, the check valves open to allow air from the pumps to flow into the patient's airway. But during exhalation, the check valves close, preventing exhaled air from flowing back towards the pumps. This one-way flow control maintains positive pressure in the respiratory circuit, vital for proper lung inflation.

Additionally, PEEP (Positive End-Expiratory Pressure) valves create a baseline positive pressure at the end of exhalation. This PEEP helps keep the alveoli open, improving oxygenation and preventing lung collapse. The combination of check valves and PEEP valves, along with other ventilator components, enables precise regulation of airflow and pressure to optimise ventilation support for the patient.

2.3.2 Control Mechanism

The control mechanisms regulate ventilation parameters and monitor patient status. Sensors track pressure, flow, and volume, providing real-time feedback. Actuators use this data to precisely control the air pumps and valves. The Raspberry pi 4B Microcontroller coordinates the system, running algorithms to optimise ventilation and adapt to patient needs.

2.3.3 Tubing

The control mechanisms regulate ventilation parameters and monitor patient status. Sensors track pressure, flow, and volume, providing real-time feedback. Actuators use this data to precisely control the air pumps and valves. Microcontrollers coordinate the system, running algorithms to optimise ventilation and adapt to patient needs.

2.3.4 Microcontroller

This mechanical ventilation system utilises a microcontroller, specifically a Raspberry Pi 4B, to provide enhanced monitoring and control capabilities. The Raspberry Pi plays a crucial role in this mechanism by implementing important algorithms to monitor the patient's vital signs and ensure synchronisation of the mechanical ventilation.

The Raspberry Pi is responsible for collecting data from various sensors integrated into the system, such as flow metres, pressure sensors, and angular position sensors. These sensors provide real-time information about the air volume, pressure, and flow delivered to the patient. The microcontroller then processes this data and generates ventilation curves to be displayed on the system's 7-inch display, allowing medical staff to closely monitor the patient's respiratory parameters.

Additionally, the Raspberry Pi runs a control algorithm that maintains a constant rotational speed of the DC motor, which drives the cam-based compression mechanism. This algorithm adjusts the motor's current to compensate for changes in the system's requirements, ensuring a consistent respiratory rate and ventilation profile, even as the patient's condition or the ventilation parameters change over time.

The feedback loop established by the Raspberry Pi, the sensors, and the control algorithm allows the OxyGEN system to adapt to the patient's needs, providing a robust and reliable mechanical ventilation solution. This integration of advanced monitoring and control capabilities, facilitated by the Raspberry Pi, enhances the overall performance and safety of the low-cost mechanical ventilator, making it a valuable tool in emergency medical contexts where traditional ventilators may be in short supply.

The Raspberry pi is also responsible for data acquisition from various sensors and facilitating communication with the backend server through Wi-Fi connectivity. To achieve this, the Raspberry pi 4B utilises its built-in Wi-Fi module to establish a connection with the backend server, enabling seamless data transmission. Upon collecting sensor data, such as blood oxygen levels, ECG readings, and other vital signs, the microcontroller constructs a POST request containing the acquired sensor data as parameters and sends it to the designated endpoint of the backend server's API. These parameters typically include key-value pairs representing different sensor readings, timestamps, and other relevant metadata. For example, the POST request may include parameters such as "bloodOxygenLevel," "ecg," "emg," "timestamp," etc.

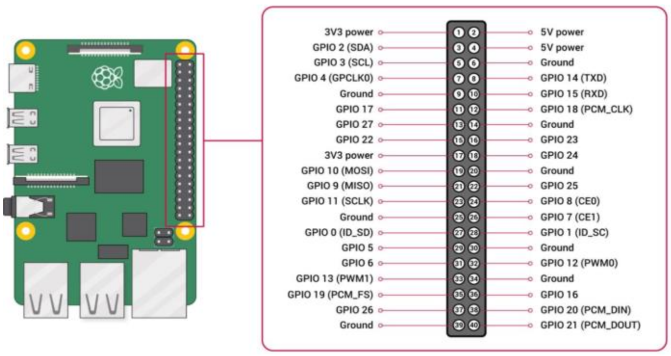

Fig. 4 Labelled diagram of GPIO pins on raspberry Pi 4-B

2.3.5 Monitoring Display

The mechanical ventilation system we have designed offers flexible monitoring options to accommodate the diverse needs and resources in emergency medical settings. While the system is equipped with a dedicated Adafruit PiTFT 3.5" Touch Screen display, the microcontroller-based architecture enables the use of alternative monitoring solutions, such as laptop screens.

2.3.6 MicroSD Card Modules

An optional MicroSD card provides additional storage capacity for logging data and system configuration settings. It allows for the recording of historical patient data and system logs, facilitating retrospective analysis, quality improvement initiatives, and compliance with regulatory requirements.

2.3.7 Power Supply

The Mini-Vent system requires a reliable power source, either from a battery or an external power supply, to ensure uninterrupted operation. This power supply delivers electricity to all components of the system, including sensors, actuators, and communication modules, ensuring continuous monitoring and ventilation support for patients in need.

2.3.8 Enclosure

The protective enclosure houses all Mini-Vent components, safeguarding them from external factors such as dust, moisture, and physical damage. It ensures the portability and durability of the system, allowing for safe deployment in various healthcare settings, including hospitals, clinics, and emergency response units.

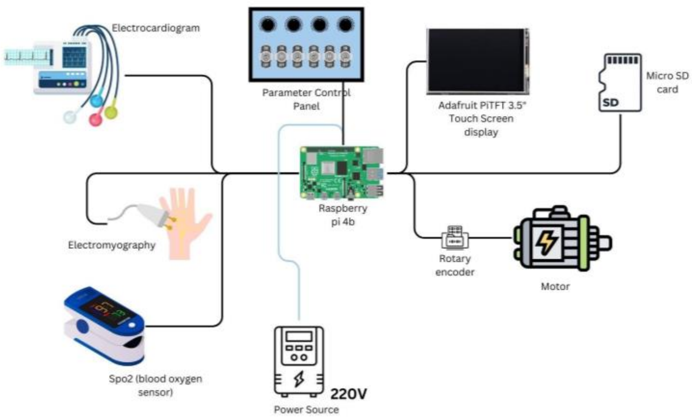

Fig. 5 Microcontroller connectivity with labelled components

3. Ventilator Dynamics

3.1 Airbag Compression mechanism

Figure 5 illustrates the internal compression system of the ventilator, which includes a cam attached to the shaft of a DC motor and a swinging follower anchored to the ventilator case's wall. To enhance the durability of the equipment, the oscillator arm, bearing supports, and shafts underwent a redesign. The roller was coated with vulcanised rubber to minimise friction, vibrations, and operational noise, thus improving the control and efficiency of the DC motor. The performance of the machine is determined not only by the execution of its primary function but also by the consistent interaction of its components during movement, which affects the precision and longevity of the ventilation curves. While this equipment is designed for short-term emergency use in patients, its lifespan can be extended through airbag replacement.

3.2 Respiration Rate Control

In this system, the breathing rate is determined by how often the cam rotates. As the airbag is compressed and its internal pressure increases, the DC motor's efficiency is affected, leading to a slower angular velocity. Therefore, a control algorithm was created to set a consistent rotation frequency and maintain it throughout the operation. The algorithm receives the current speed of the motor and adjusts the DC motor's input to correct any deviations, ensuring a steady respiration rate.

3.3 Ventilator Parameter Monitoring

The angular position is utilised to forecast the ventilation curves with the aid of a calibrated mathematical model. Once the sensor captures the data, it's transmitted to a Raspberry Pi computer, which processes the information and displays it on an Adafruit Touch Screen. The screen visualises the data as graphs, offering crucial information for the medical team to analyse the ventilation patterns.

3.4 Conceptual model of compression mechanism

The ventilation system uses a cam-oscillator arm mechanism designed by Protofy, with the cam contour defined by a MATLAB algorithm. To accurately reproduce the original ventilation curves (pressure, volume, flow over time), the dynamic interactions linking physical measures like size, spacing, and placement to the curves must be understood. Figure 6 shows the cam-oscillator follower mechanism.

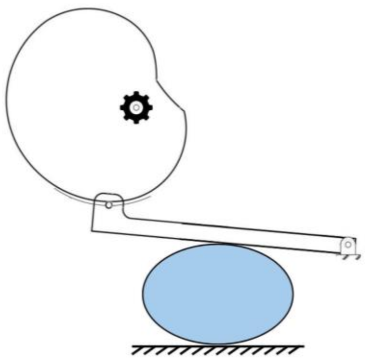

Fig. 6 Compression mechanism model.

The movement between the follower and the cam in the device is controlled by their contact, which is maintained by a spring. Three fundamental motion principles were established: one for the movement relationship between the cam and follower, another for their speeds, and a third for their acceleration rates. These principles were crucial in establishing the mathematical model in this ventilator.

3.5. Mathematical Modelling

In creating this ventilator prototype, it was important to understand how its parts work together to manage key functions like air pressure and flow. A mathematical model helped map out these interactions by considering the forces at play within the device. By studying how different components moved and affected each other, and through testing, it was possible to adjust the device's design. This ensured that it could replicate the desired breathing patterns, even if different parts are used.

The detailed mathematical modelling and analysis of the cam-based mechanical ventilation system, including the relationships between the physical mechanism parameters and the ventilation variables over time, is provided in the work by Calderón et al. [reference]. The results regarding power analysis, measured pressure, volume, airflow, and other estimations are explained in depth in this same paper "Design and analysis of a mechanical ventilation".

4. Software Solutions and Remote Monitoring System

The absence of a remote monitoring system in traditional healthcare setups poses significant challenges. Without real-time data access, healthcare providers struggle to monitor patient status effectively, leading to delays in intervention and compromised patient care. This gap becomes particularly pronounced in critical care scenarios like those requiring ventilator support, where continuous monitoring is paramount. Therefore, the integration of a remote monitoring system for Mini-Vent addresses this critical need by enabling healthcare professionals to remotely monitor patient vitals, ensuring timely intervention and improved patient outcomes. The remote monitoring system comes in the form of a web application that can be accessed from any device having a browser. The app registers a user and lets the user make patient accounts for every person using the Mini-Vent and then access the patient account for getting a detailed view on the patient vitals.

4.1. Working of the Application Programming Interface (API)

The API for the Mini-Vent system serves as a crucial component in enabling seamless communication and interaction between the Mini-Vent and the accompanying mobile application. The API has been developed using Express.js, a robust and efficient web application framework for Node.js, and TypeScript, the API incorporates various middleware, libraries, and custom modules to provide comprehensive authentication, data storage, and retrieval functionalities. The API consists mainly of routes & endpoints that call specific controller functions to perform different kinds of operations. The API establishes a connection with a MongoDB which is a NoSQL database and performs various CRUD operations in the database. The API also facilitates the data retrieval and storage of all the patient's vitals collected by the Raspberry pi 4B and is posted on a specific endpoint of the API.

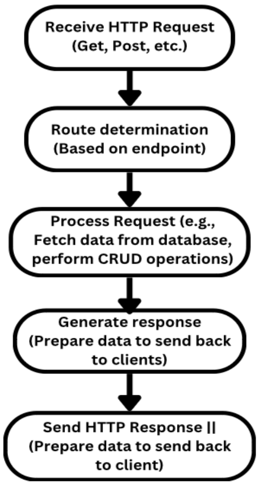

Fig. 7 Working of the API Pipeline

4.1.1. User Authentication and Security using Passport.js

To ensure secure user authentication and data integrity, the system's API leverages Passport.js, a popular authentication

middleware for Node.js applications. Passport.js supports various authentication strategies, including local authentication using usernames and passwords, providing a robust and extensible authentication framework.

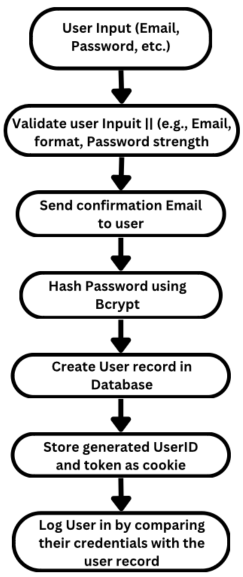

Fig. 8 User authentication and Security Pipeline

4.1.2. User Registration

During the user registration process, the API receives the user's credential data, including their username and password, from the client application. Before storing the user's password in the MongoDB database, it undergoes a secure hashing process using bcrypt, a robust cryptographic hashing function. This measure safeguards the user's sensitive information by storing only a hashed representation of the password, rather than the plaintext version.

Upon successful registration, the API generates a unique authentication token or session identifier, which is returned to the client for subsequent authenticated requests. Concurrently, a new user profile is created in the database, storing essential user information such as the username, email, and a unique user ID. This step ensures proper user management and facilitates the association of data within the system. The user also receives a verification email to verify that the email they're using belongs to them.

The registration process is orchestrated by invoking the appropriate Passport.js authentication middleware, which securely hashes the user's password using bcrypt. Once the password is hashed, the "signup" function defined in the authentication controller is called, facilitating the creation of a new user profile in the database with the provided user information and the hashed password.

4.1.3. User Login

Similarly, during the login process, the API verifies the provided username and password against the hashed password stored in the database. If the credentials match, an authentication token is generated and provided to the client, granting access to protected resources and functionalities within the system.

The login process follows a similar flow, leveraging Passport.js authentication middleware to verify the provided credentials against the securely stored hashed password. Upon successful authentication, an access token is issued, enabling the client to access protected resources and functionality within the system.

Through this robust authentication mechanism, the system ensures the confidentiality and integrity of user data, while providing a secure and user-friendly authentication experience.

4.1.4. User Routes and API Endpoints

The user routes establish dedicated endpoints within the API to manage user-related tasks, such as registration, authentication, and profile management. These routes facilitate interactions between the frontend application and the backend server, allowing users to create accounts, log in securely, and update their profile information.

By defining routes for user operations, the system ensures proper handling of user data, authentication processes, and user account management. This structured approach enhances the functionality and security of the Mini-Vent system, providing users with a seamless experience while accessing and managing their accounts.

Upon receiving a valid authentication token or session identifier from the client, the corresponding route retrieves the user's profile information from the database using the userId associated with the token. The requested user data is then serialised and returned to the client in a structured JSON format, ensuring secure and efficient data retrieval.

4.1.5. Patient Management and Data Operation

The Patient Data Management system employs a comprehensive approach to patient data management, ensuring efficient storage, retrieval, and manipulation of patient records. Through the Patient Controller and dedicated patient routes, the system implements robust mechanisms for handling patient data operations.

4.1.6. Patient Routes and API Endpoints

The patient routes define dedicated endpoints within the API for handling patient-related operations, such as creating, retrieving, updating, and deleting patient records. These routes provide a structured interface for interacting with patient data stored in the database, enabling seamless integration with the frontend application.

By specifying routes for each CRUD (Create, Read, Update, Delete) operation, the patient routes ensure consistent and efficient data management, enhancing the overall functionality and usability of the Mini-Vent system.

Through these patient routes, the frontend application can securely interact with the backend server, facilitating the creation and management of patient records, retrieving patient information, updating existing data, and removing records as needed. This structured approach promotes modularity, scalability, and maintainability within the codebase, while also ensuring proper access control and data security.

4.2. Web Interface Development for Remote monitoring using React.js

The web interface served as a crucial tool in enabling remote monitoring and management of the Mini-Vent system. Its significance lay in providing healthcare providers with real-time access to vital patient data, ensuring prompt decision-making and intervention. The web application also provides interfaces to register a user account and log into that account. Also facilitates registering patients by entering the basic details of a specific patient and communicating with the API to store these details. Moreover, the dashboard facilitated trend analysis and data visualisation, empowering users to identify critical patterns and anomalies efficiently. Its accessibility from any internet-enabled device ensured continuous oversight of patient conditions, ultimately optimising patient care and system efficiency.

To construct the web dashboard for the Mini-Vent, React.js emerged as the cornerstone of our development approach. Leveraging React's component-based architecture, we meticulously crafted a user interface (UI) composed of modular, reusable components.

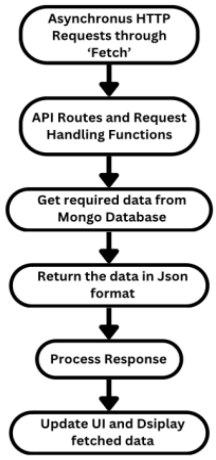

Fig. 9 Working of Web interface

4.2.1. Data Retrieval Mechanism

Within our React components, we meticulously defined functions responsible for orchestrating the retrieval of data from the API endpoints. Employing asynchronous HTTP requests via the native browser API 'fetch', we seamlessly fetched real-time data from the backend server. These functions send requests to specific API routes, which invoke the corresponding backend functions to perform the desired operations. The requested data is fetched from the MongoDB database and returned in JSON format. The received data is then processed and dynamically rendered within the React components, providing users with up-to-date information.

4.2.2. Graphical Representation

To visually depict trends and insights gleaned from the data, we seamlessly integrated powerful graph plotting libraries like Chart.js into our React components. By passing the fetched data as props to these graph plotting components, we facilitated the generation of dynamic and visually appealing graphs, enabling users to glean actionable insights at a glance. This graphical representation of data enhances the dashboard's usability and aids in effective decision-making.

4.2.3. Event Handling and Interactivity

To enhance the user experience, we adeptly implemented event handling mechanisms using React's event system.

By adding event listeners to interactive UI elements such as buttons or dropdowns, we empowered users to seamlessly interact with the dashboard, triggering actions such as data refreshes or alarm acknowledgments. This interactivity ensured a responsive and engaging user experience, enabling healthcare professionals to efficiently navigate and interact with the dashboard.

4.3. Virtual Monitor

Fig. 10 Web monitoring interface

6. Conclusion

In conclusion, this research study explored the development and implementation of the Mini-Vent, a portable and affordable ventilation system designed to address the critical shortage of intensive care solutions in resource-constrained settings. The findings demonstrate the potential of the Mini-Vent in improving access to life-saving technology.

Through rigorous testing and analysis, the Mini-Vent system exhibited its ability to provide reliable and effective ventilation support, while also offering real-time monitoring capabilities. The user-friendly interface and comprehensive educational resources ensure that users can operate the system with ease, even in non-hospital settings. However, certain challenges, such as maintaining optimal performance in extreme environmental conditions, were identified and addressed through system optimizations and enhancements.

The results of this study provide valuable insights into the performance and impact of the Mini-Vent system. Simulations and real-world testing demonstrated the system's ability to deliver consistent and accurate ventilation support, while also ensuring data security and patient privacy. By making critical care more accessible and affordable, the Mini-Vent has the potential to save countless lives and alleviate the burden on healthcare systems, particularly during times of crisis.

6.1. Future Work

Future Work in this research could focus on expanding Mini-Vent's potential impact. This could consist of following points:

6.1.1. Telemetry and Remote Monitoring

Integrating advanced telemetry capabilities would allow healthcare professionals to monitor and control the Mini-Vent system remotely, enabling real-time adjustments and interventions based on patient needs.

6.1.2. Predictive Analytics

Incorporating machine learning algorithms and predictive analytics could enable the Mini-Vent system to anticipate and prevent potential complications, such as respiratory distress, by analysing patient data and identifying early warning signs.

6.1.3. Modular Design

Developing a modular architecture for the Mini-Vent system would facilitate easier upgrades, customization, and maintenance, allowing the system to adapt to evolving healthcare needs and technological advancements.

6.1.4. Expanded Sensor Integration

Integrating additional sensors, such as those for monitoring blood pressure, temperature, and other vital signs, would provide a more comprehensive picture of a patient's health status and enable more informed decision-making.

6.1.5. Clinical Validation

Conducting extensive clinical trials and validation studies to further demonstrate the efficacy, safety, and reliability of the Mini-Vent system in real-world settings, across diverse patient populations and healthcare contexts.

By pursuing these areas of future work, the Mini-vent system can continue to evolve and make significant strides in improving access to critical care, saving lives, and transforming healthcare in resource-constrained settings.

6.2 Limitations

While the Mini-Vent system shows great promise in addressing the critical shortage of affordable and accessible intensive care solutions, there are several limitations to this review study that should be acknowledged.

6.2.1. Limited Real-World Testing and Sample Size

The study's limitations include insufficient real-world testing across diverse clinical settings and a relatively small sample size, both in terms of Mini-Vent units tested and participants involved in user experience evaluations. These limitations may impact the generalizability of the findings, the system's performance in actual patient care scenarios, and the identification of potential issues or areas for improvement.

6.2.2. User Training and Adoption

While the study emphasises the user-friendly nature of the Mini-Vent system and provides educational resources, it does not fully explore the challenges associated with user training and adoption, particularly in low-resource settings where technological literacy may be limited.

6.2.3. Regulatory and Legal Considerations

The study does not delve into the regulatory and legal aspects of deploying the Mini-Vent system in various healthcare contexts. Ensuring compliance with local and international regulations, as well as addressing potential legal liabilities, is essential for the successful implementation of the system.

Acknowledging these limitations helps to provide a balanced perspective on the current state of the Mini-Vent system and highlights areas where further research and development efforts can be directed to address these challenges and strengthen the system's potential impact.

7. Acknowledgment

We would like to acknowledge our mentors at ATL robotics laboratory for helping us with the technical details while conducting the test runs and creating a prototype of this ventilator.

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