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Design and Development of a Low-Cost Continuous / Automatic Positive Airway Pressure Device for Obstructive Sleep Apnea Management

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Abstract: Obstructive Sleep Apnea (OSA) is a widespread yet significantly underdiagnosed condition in India, largely due to low awareness and the prohibitive cost of diagnostic and therapeutic equipment. Commercial CPAP and APAP machines, though clinically effective, remain inaccessible to a vast majority of the Indian population due to economic constraints and infrastructural limitations. This paper presents a novel, low-cost solution leveraging 3D printing and smartphone-based adaptive control to deliver APAP therapy. By offloading computational control and user interface functions to a connected Android smartphone, the proposed system eliminates the need for expensive onboard processors, displays, and complex firmware. The integration of real-time USB communication, AI-driven control logic, and centralized data management through mobile applications not only reduces manufacturing costs by up to 30% but also enhances performance, upgradeability, and patient personalization. This design presents a viable alternative for sleep apnea management in low-resource settings and opens a path for broader adoption through modular hardware and scalable mobile software infrastructure.

1. INTRODUCTION

Obstructive Sleep Apnea (OSA) is a prevalent but underdiagnosed sleep disorder affecting millions of people globally. This is also valid for a large segment of the Indian population. In India, studies have estimated the prevalence of OSA ranges between 3.6% and 13.7% depending on diagnostic methods and geographic conditions [1, 2]. However, due to lack of awareness, insufficient screening, and prohibitively high diagnostic and treatment costs, the actual number of individuals affected by sleep apnea is likely to be much higher.

OSA leads to disrupted sleep, daytime drowsiness, cardiovascular risks, and reduced quality of life. It disproportionately affects obese individuals and those with lifestyle-related comorbidities—both of which are rising in India. Despite the high burden, awareness and diagnosis remain extremely low, especially in rural areas [3]. A study from Bhopal found that 60% of diagnosed patients did not purchase CPAP devices, citing cost as the primary barrier [4].

India's healthcare system, while progressing, still suffers from severe urban-rural gap areas, lack of public infrastructure, and very low per capita expenditure on health of individuals [5, 6]. The high cost of CPAP/APAP devices—often ranging between INR 35,000 to 80,000—places treatment beyond the reach of average Indian, particularly when per capita annual income is under INR 1 Lakh. [Source: Ministry of Statistics and Program Implementation, Posted by PIB on 02 August 2023].

Thus, there is a pressing need for a low-cost, scalable, and clinically effective PAP solution that remains accessible to India's economically constrained populations, especially located in rural and semi urban areas.

2. BACKGROUND AND EXISTING SOLUTIONS

The first use of nasal CPAP in OSA therapy was introduced in 1981 by Colin Sullivan [7]. Since then, PAP machines have come a long way as feature-rich, closed-source devices manufactured by companies like ResMed and Philips Respironics. These systems deliver performance but remain unaffordable to most Indian patients due to high import duties and lack of insurance reimbursement.

CPAP and APAP devices rely on real-time airway pressure changes to prevent apneic episodes. Once adopted fully the therapy is effective, however, the user adoption in India remains low, with multiple studies highlighting poor access, high upfront costs, low awareness, and low physician recommendation rates as barriers [8, 2]. Even among those who receive prescriptions, long-term adherence is poor.

Open-source projects like the low-cost CPAP [9] demonstrate the feasibility of a PAP systems development. However, these often lack adaptability, APAP functionality, or clinical-grade monitoring and have not been localized for Indian use cases. Further reduction of cost is expected to ensure greater reach of APAP solution to every household in need.

In this context, the present work proposes not just a cost reduction through hardware innovation, but a paradigm shift by decentralizing computational control to smartphones—devices already owned by a large fraction of the Indian population [10, 11]. This innovation provides scalability, integration of AI/ML, and automatic software upgrades without needing expensive hardware replacements or any type of human intervention.

3. SYSTEM DESIGN

The proposed device consists of several integrated components designed for efficiency, affordability, and adaptability. It includes a blower unit, utilizing a brushless DC centrifugal fan that can generate pressure in the range of 4 to 20 cm H_2O, with a corresponding flow rate of 20 to 60 liters per minute. This airflow is changed based on input from a pressure sensor, such as the MPXV7002DP or a Honeywell TruStability sensor, both of which offer the precision required for reliable APAP control. The system also includes a flow sensor for detection of apnea event.

Microcontroller based logic control can be implemented with device, such as an Arduino Nano, which primarily manages USB communication with a connected smartphone and controls the power and thereby RPM of blower. The smartphone, running an Android-based application, functions as the main interface and algorithm brain, responsible for interpreting real-time sensor data and issuing commands for adaptive control.

All components are housed in a suitable enclosure that can be 3D-printed with durable plastic, designed with internal sound-dampening features and mount for the blower fan to reduce operational noise. Since the housing is 3D printed, flow measurement can be integrated within the volume of enclosure with a venturi tube that reduces pressure drop during flow measurement.

Standard 12V external power adaptor can be used with an internal power distribution circuit providing regulated 5V outputs for the microcontroller, sensors, and USB phone charging. This modular design emphasizes both clinical effectiveness and practical deployment in cost-sensitive environments.

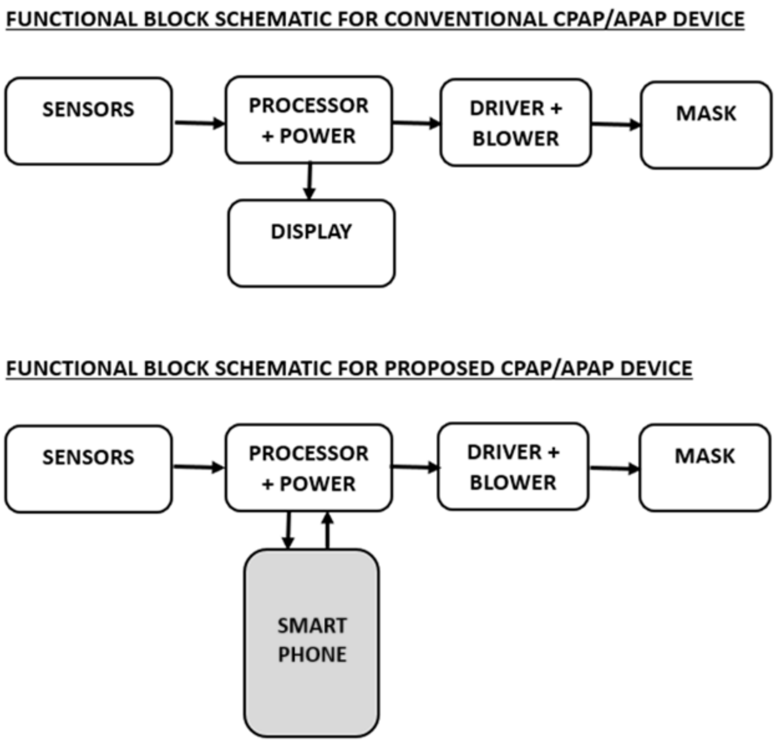

Fig. 1. Comparison of conventional vs. proposed configuration of CPAP/APAP device

4. SMARTPHONE BASED CONTROL AND SOFTWARE DESIGN

The innovation of the proposed approach lies in running the APAP control logic from the embedded microcontroller to a smartphone. Instead of processing data locally, the Arduino controller present in the device has the only role of interfacing with pressure and flow sensors, capturing real-time physiological data and feeding this data it to a connected smartphone via a USB cable.

Once the data is received by the smartphone, it is processed using AI-based (or rule-based) control algorithms implemented within a dedicatedly developed mobile application. The smartphone then determines the appropriate response (such as adjusting the blower speed) and sends these control commands back to the microcontroller to actuate the device accordingly. This real-time communication enables precise and dynamic pressure adjustments without relying on complex embedded systems.

The proposed architecture provides many advantages. It eliminates the need for a built-in display, high-performance processors, or complex firmware within the device. By offloading computational complexity to the smartphone, the hardware is significantly simplified, which in turn reduces cost, size, power consumption, and developmental effort. Moreover, it enhances the system's upgradeability and personalization ability, as mobile apps can be easily updated or tailored to user-specific requirements through centralized servers.

5. COST REDUCTION AND OPTIMIZATION

The design strategically eliminates a display within the device, transferring all user interface functions to the smartphone application. One bi-color LED can be added to show status and activity or error signal on the device. This approach not only simplifies the physical layout of the device but also reduces the bill of materials (BOM), contributing to overall reduction in cost. Commensurate to this minimalistic hardware philosophy, the microcontroller is treated merely as a peripheral interface device, responsible for basic sensor readings and actuation commands. This enables the use of a simpler and more economical microcontroller, further lowering hardware costs. Arduino nano is now available in industrial grade quality which can offer reliability which can be commensurate with the expectation from such low-cost device.

Powering the entire system is a single 12V wall adapter, which supplies energy to all internal components—including the blower, microcontroller and sensors also enables required support for phone charging overnight as it will be an essential need in this approach. One of the most significant advantages of this architecture is its upgradeability. Because the control logic and user interface are encapsulated within the mobile app, software updates can introduce new features, improved algorithms, or UI enhancements without requiring any changes or upgrades to the physical hardware.

Initial simulations and bench testing of the system have yielded promising results. The use of direct USB communication between the microcontroller and smartphone has significantly reduced pressure control latency (as against earlier effort of connecting device via Bluetooth wireless connectivity), enabling faster and more responsive adjustments. The app update rate exceeds 10 Hz, which has proven to be sufficient for maintaining effective and stable APAP control.

Moreover, the CPU usage of the mobile app remained under 10% even on mid-range Android devices, demonstrating that the processing demands of the control logic and data visualization are well within the capabilities of widely available smartphones. Additionally, the removal of the display and reduction in microcontroller complexity have resulted in a manufacturing cost that is approximately 30% lower than previous prototypes, further supporting the device’s goal of affordability and accessibility.

Individuals engage with their mobile devices for a very large duration. However, use of sleep therapy and mobile usage are mutually exclusive. Moreover, it is a common practice to anyway keep mobile in charging mode for next day use. This favorably yield towards successful adoption of proposed approach.

6. NOVEL CONTRIBUTIONS AND INNOVATION

This system introduces a mobile-based adaptive control loop that shifts the core functions of control logic, apnea event detection, and pressure regulation to the smartphone. By leveraging mobile computing capabilities, the system can integrate AI models for apnea prediction and pressure tuning, which can be continually refined and personalized based on individual user data. This adaptive capability ensures the therapy becomes more responsive and tailored over time.

A major advantage of this architecture is its simplified data management. All logging, analytics, and remote synchronization are handled directly by the mobile device, enabling seamless data export, long-term storage, and cloud backup without additional hardware. As usage data accumulates, the integrated AI models can be further trained on user-specific patterns, leading to smarter pressure regulation and improved comfort.

Perhaps most importantly, the upgrade path is smartphone-driven. Enhancements to the control algorithm, interface updates, or diagnostic features can be rolled out entirely through app updates, eliminating the need for hardware redesign or reconfiguration, thus making the system both future-proof and highly scalable.

7. INTEGRATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Proposed approach opens up avenues for ease in AI/ML integration in APAP solution. Sever based connectivity allows information collection on large scale, which typically is the fodder for training and implementing AI models. AI can be implemented in following areas once the central processing is moved out of device and is accessible in mobile application.

7.1Apnea Event Detection

AI can analyze sensor data such as airflow, pressure, and oxygen saturation levels to detect signs of apnea events in real time. Machine learning models trained on representative datasets can recognize patterns indicative of apnea episodes, bringing out early detection and intervention in time to maintain uninterrupted apnea therapy.

7.2 Adaptive Pressure Control

ML model can dynamically adjust air pressure based on the user’s breathing patterns. By employing reinforcement learning or predictive models, the system can optimize pressure levels throughout the night, ensuring both therapeutic effectiveness and comfort. This adaptability can significantly improve adherence score in the therapy.

7.3 Personalized Treatment

AI can tailor the therapy to the needs of individual patient profile by utilizing user’s historical data and preferences. By learning from trends in past usage, such as pressure tolerance and apnea frequency, the system fine-tunes parameters to improve outcomes over time, enabling a more patient-centric approach to PAP therapy. Adherence scores, leakage related events due to higher pressure, posture related discomfort currently remain unaddressed in conventional therapy. ML models can be very helpful in addressing such issues.

7.4 Real-Time Data Processing and Predictive Approach

AI can process incoming data from pressure and flow sensors to deliver immediate insights. It detects anomalies or emerging trends in the patient's respiratory patterns, triggering alerts or automated adjustments to ensure optimal therapeutic performance and prevent treatment disruptions. AI based solutions are predictive in nature and, therefore, can be more effective than conventional methods which take action after the event occurs. AI models can forecast future breathing patterns based on historical data, allowing the system to preemptively adjust air pressure. This anticipatory approach can prevent apnea episodes before they occur, uplifting effectiveness of treatment.

7.5 User Behavior Analysis

By analyzing long-term usage data—such as preferred pressure settings, sleep duration, and usage consistency—AI models can identify behavioral patterns. This insightfulness allows the system to implement optimizations, detect adherence issues, and promote better usage through personalized feedback.

7.6 Smart Notifications and Alerts

The AI engine can continuously monitor user data and send real-time notifications when irregularities get detected, such as persistent pressure deviations or inconsistent usage patterns. These alerts prompt users to take corrective action or consult healthcare professionals before issues escalate.

7.7 Data-Driven Insights for Doctors

Accumulated sensor and usage data are analyzed to generate comprehensive insights for healthcare providers. AI enables doctors to understand therapy trends, evaluate progress, and make informed adjustments to treatment plans based on evidence rather than subjective reporting. This approach can extend to a maturity level where need for expert opinion also can be alleviated with AI based modeling. This can be very helpful in Indian context which already has a skewed doctor to patient ratio.

7.8 Voice Assistance

Through natural language processing, the system supports voice commands for hands-free interaction. Users can query their sleep statistics, adjust settings, or receive alerts verbally, making the device more accessible and user-friendly, especially during night-time operation. This feature is also very effective in Indian context where instructions in local language is more effective than English to improve adoption of therapy and thereby improve adherence.

7.9 Sleep Quality Prediction

AI can estimate sleep quality using sensor data and behavioral patterns, offering actionable recommendations for improvement. This might include adjusting therapy parameters or providing sleep hygiene tips, thereby encouraging better adherence and long-term health outcomes. Today, a separate sleep study is conducted for diagnosis purpose before adapting the therapy that calls for specialized setups. The proposed approach can embed diagnostic capabilities within the device and eliminate the need for special diagnostic tools. This can improve diagnosis scenario of sleep apnea in India by manifold.

8. CONCLUSION

This paper introduces a transformative approach to the design of CPAP/APAP therapy devices, combining the cost effective hardware solution with high-performance smartphone-based control. The proposed architecture successfully decentralizes processing, adding sophisticated, AI-enhanced control algorithms to operate from a mobile while maintaining simple, reliable hardware inside the device. Early results are encouraging in terms of reduction in cost, size, and complexity compared to traditional APAP systems—achieved without compromising performance or adaptability. The use of 3D-printed components, open-source firmware, and Android-based applications makes the system not only cost-effective but also scalable and user-customizable. Moreover, the shift of computation and data storage to smartphones facilitates easier upgrades, user-specific AI model training, and improved access for users and clinicians. This innovation holds the potential to democratize sleep apnea therapy in India and other resource-constrained regions of the world, especially the third world countries, bringing essential care within reach of millions, which are left untreated currently.

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