Adapt-O Pillow: A Smart Orientation-Based Inflatable Pillow System

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ABSTRACT

Adapt-O Pillow is a prototype sensor-driven inflatable pillow that changes its support to suit the way a person is lying. The system integrates a chest-worn sensing unit, a main ESP32 controller, a pressure-feedback stage, a pneumatic actuator set, and a web interface for calibration and monitoring. An ESP32-C3 paired with an MPU6050 inertial sensor in the wearable unit determines body orientation and passes a stabilized orientation state to the main controller over Bluetooth. For each supported posture (back, left side, right side), the user records a preferred pillow pressure during a calibration routine. In automatic mode, an HX710B pressure-sensing interface reports the pillow's present pressure to the central controller, which compares it with the saved target. When the pressure is too low, the controller switches on the air pump and inlet solenoid valve; when it is too high, it opens the exhaust solenoid valve. A pressure tolerance band (deadband) together with orientation-stability filtering prevents needless actuator switching caused by minor pressure differences or brief body movements. The work is positioned as a prototype assistive comfort system and not as a medical diagnostic or treatment device. The project documentation covers functional implementation and qualitative behavior only; it contains no validated user study and no numerical figures for classification accuracy, pressure error, response time, battery endurance, or clinical outcome. This paper therefore concentrates on the architecture, control method, implementation, functional test approach, documented observations, limitations, and future development of the prototype.

Keywords— adaptive pillow, sleeping orientation, MPU6050, ESP32-C3, ESP32, pneumatic control, pressure feedback, Bluetooth, calibration, smart comfort system.

I. INTRODUCTION

Sleeping posture changes repeatedly during the night, moving between supine and side-lying positions, and the pillow support that suits one posture may not suit another. Conventional pillows have a fixed shape, so users must settle on a compromise height or firmness before going to bed. Earlier studies have looked at how pillow height, shape, pressure distribution, spinal alignment, and comfort relate to one another, and other work has shown that inertial and pressure sensors can be used to monitor sleeping position and head movement [1]–[3]. Such work demonstrates the value of sensing and personalization, yet it does not offer the closed loop proposed here, where a detected orientation selects a user-chosen pressure target and a pneumatic actuator then adjusts the pillow to match.

Adapt-O Pillow is conceived as an embedded assistive comfort prototype that brings together orientation sensing, personalized target selection, and closed-loop pressure control. A chest-worn module built around an ESP32-C3 and an MPU6050 detects the wearer's orientation. The main ESP32 receives that orientation over Bluetooth and looks up the pressure target saved for it. Feedback from the pillow chamber comes through an HX710B pressure-sensing interface, and an air pump with two solenoid-valve paths handles inflation and exhaust. A web application offers calibration, manual inflation, configuration, and live monitoring.

According to the project documentation, the system is restricted to a prototype and assistive-comfort role and is not offered as a medical diagnostic or treatment device. The distinction matters, because a working pressure-adjustment mechanism says nothing about clinical benefit.

The contribution of this work is thus the combination of orientation-aware personalization with feedback-controlled pneumatic adjustment, within an architecture that treats safety explicitly.

A. Problem Statement

A conventional pillow cannot alter its support when the sleeper turns to a different position. The problem addressed by Adapt-O Pillow is to build a prototype that recognizes the supported body orientations, assigns each one a user-chosen pressure target, and drives an inflatable pillow toward that target without constant manual adjustment. The system must also ignore momentary movements and must include conservative pressure limits and an emergency-deflation provision.

B. Objectives

- Recognize the supported sleeping orientations with an MPU6050-based chest-worn module driven by an ESP32-C3.
- Send the stabilized orientation to the central ESP32 controller wirelessly.
- Let the user calibrate and store preferred pillow pressure targets for the back, left-side, and right-side positions.
- Monitor pillow pressure continuously via the HX710B pressure-sensing interface.
- Compare measured and target pressure in a closed loop to choose inflation or exhaust and hold pressure within a set tolerance.
- Offer a web interface for calibration, manual control, configuration, and live monitoring.
- Build in prototype-level safeguards, including conservative pressure limits and manual or emergency deflation.

C. Scope and Applicability

The scope covers chest-worn orientation sensing, Bluetooth communication, pressure feedback, pneumatic actuation, user calibration, web-based monitoring, and filtering of brief movements. The prototype is aimed mainly at users who want comfort that depends on sleeping position, and at research or teaching prototypes of posture-aware adaptive accessories. The project documentation lists people with cervical discomfort as one possible comfort-related use case, but it demonstrates no treatment effect, so this paper makes no therapeutic claim.

II. RELATED WORK AND LITERATURE REVIEW

Prior work shows that sleeping position can be tracked with inertial and pressure sensors. Doheny et al. used data from a wearable accelerometer to estimate sleeping position and respiration rate, showing that inertial sensing can be fairly unobtrusive [1]. Another study of sleeping position combined an MPU6050 six-axis motion sensor with flexible sensors to follow turning movements during sleep [2]. These findings support the sensing principle used in Adapt-O Pillow, in which the inertial sensor is worn on the body and not built into the pillow.

Sensing has also been placed in the pillow itself. One smart pillow used an array of flexible triboelectric nanogenerators, which respond to pressure, to track head movement during sleep [3]. A further smart pillow embedded fiber Bragg grating sensors in pressure-sensitive silicone buttons [4]. A review of sleep-pattern technologies likewise describes pillows fitted with several force-sensitive resistors that tell supine, left-lateral, and right-lateral postures apart from the pressure distribution [5]. These systems show that pillow-based sensing can reveal posture, but Adapt-O Pillow divides the work differently: the chest-worn module detects body orientation, and the pillow pressure sensor serves mainly as feedback for pneumatic control.

Research on pillow ergonomics adds to the case for personalization. A systematic review and meta-analysis found that pillow design features can affect neck-related outcomes, although the effects on sleep quality and spinal alignment differ across designs and populations [6]. A 2026 pilot study went further, examining a personalized pillow shape and a pneumatic smart pillow intended to preserve natural cervical curvature in the supine position [7]. That study is especially relevant, since it shows pneumatic adjustment being used within an adaptive pillow concept. The Adapt-O Pillow

prototype, by contrast, concentrates on orientation-dependent user calibration and a simple closed-loop pressure controller, not on clinical validation or biomechanical optimization.

The literature therefore reveals three related technical directions: posture recognition, pressure or geometry sensing within smart sleep products, and adjustable pneumatic support. The Adapt-O Pillow architecture combines these directions at the The literature thus points to three connected technical directions: posture recognition, pressure or geometry sensing in smart sleep products, and adjustable pneumatic support. Adapt-O Pillow combines these at prototype level. Its practical research gap lies not in inventing a new sensor or actuator but in joining a wearable orientation state, position-specific user calibration, and pressure feedback in one control loop that includes stability filtering and explicit safety handling.

A. Research Gap

Many posture-monitoring systems mainly measure and classify sleep position, whereas adaptive-support systems often concentrate on pillow geometry or pressure and do not use continuously detected body orientation to trigger personalized adjustment. Adapt-O Pillow fills this integration gap by treating orientation as a control input and pressure as a feedback variable. It also lets the user define a separate target for every supported orientation instead of assuming a single correct pressure. The gap is therefore practical and architectural: linking posture-aware state detection with individualized pneumatic support in a compact embedded prototype.

III. SYSTEM ARCHITECTURE

Adapt-O Pillow uses a distributed embedded architecture made up of four logical layers. The presentation layer is the web application for calibration, manual control, configuration, and monitoring. The wearable sensing layer holds the MPU6050 and ESP32-C3, which measure motion and output a stable orientation state. The central processing layer, the main ESP32, takes in the orientation, fetches the matching target pressure, compares it with the measured pressure, and drives the pneumatic subsystem. The actuation and feedback layer comprises the HX710B interface, air pump, inlet and exhaust solenoid valves, relays, and the inflatable pillow. The hardware components are listed in Table I.

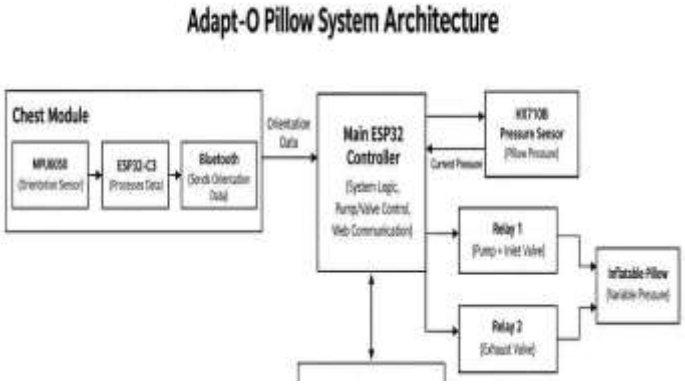


Fig. 1. Adapt-O Pillow system architecture.

Fig. 1 illustrates how the chest sensing module is kept apart from the central pneumatic controller. The split lets the orientation subsystem run independently of the pressure-control hardware and supports step-by-step development and testing. It also keeps all user interaction in the web application, so the wearable module needs no manual controls.

A. Hardware Components

Component	Function in Adapt-O Pillow
ESP32-C3 Super Mini	Wearable controller; processes MPU6050 readings and sends the stable orientation data.
MPU6050	Six-axis inertial sensor supplying acceleration and angular-rate data for orientation detection.
Main ESP32	Central processing, pressure comparison, pneumatic actuation, and web-application communication.
HX710B interface	Supplies pillow air-pressure feedback to the main ESP32.
Air pump	Delivers air during inflation.
Inlet solenoid valve	Opens the air path used for inflation.
Exhaust solenoid valve	Vents air when pressure is to be reduced.
Two relays	Switch the pump/inlet path and the exhaust valve.
Inflatable pillow and air pipe	Physical pneumatic support element and its connecting path.
Portable battery	Powers the wearable chest module.

TABLE I
HARDWARE COMPONENTS AND THEIR FUNCTIONS

B. Software and Communication

The wearable firmware reads accelerometer and gyroscope data and filters it so that brief, unsteady movements do not immediately alter the pillow state. The main-controller firmware handles target selection, pressure comparison, deadband logic, and actuator control. Bluetooth links the wearable ESP32-C3 to the main ESP32 wirelessly. The web application provides calibration, manual inflation, monitoring, and configuration to the user. The ESP32 platform offers the Bluetooth and embedded processing needed for this distributed design [8], and the MPU6050 supplies the inertial sensing required in the wearable module [9].

IV. METHODOLOGY

The methodology follows an iterative, modular development model, as set out in the project documentation [10]. The wearable module, main controller, pneumatic assembly, and web interface are built and tested individually before being integrated. Working this way makes debugging easier than attempting to debug a complete hardware-software system all at once.

A. Orientation Detection

The MPU6050 in the wearable module measures acceleration and angular movement, and the ESP32-C3 processes these readings to determine body orientation. The supported states are Back, Left Side, and Right Side. Since a sleeper may shift slightly without meaning to change position, the orientation state is filtered for stability: a new state is accepted for automatic adjustment only once it has persisted for a defined period. Short transients are therefore kept from turning into unnecessary pneumatic commands.

B. Personalized Calibration

Calibration is driven by the user. For a chosen sleeping position, the web interface allows manual inflation until the user reaches a comfortable setting, and that pressure is then stored as the target for the orientation. The same steps are repeated for the other supported positions. The outcome is a simple orientation-to-pressure mapping chosen by the user, in place of one fixed pressure for everyone.

C. Closed-Loop Pressure Regulation

In automatic operation, the central ESP32 repeatedly reads the current pillow pressure from the HX710B interface, retrieves the target for the current stable orientation, and computes the difference between target and measured pressure. When the measured pressure is under the target range, the pump and inlet path are switched on. When it is over the target range, the exhaust path is opened. When it falls inside the defined deadband, no pneumatic correction is made.

Let P_t be the stored target pressure and P_c the measured pressure. The control error is then $e = P_t - P_c$. Conceptually, the documented policy is to inflate when e exceeds the upper tolerance boundary, exhaust when e is below the lower tolerance boundary, and hold when e is inside the deadband. The project documentation gives no numerical tolerance, so none is assigned here.

D. Safety-Oriented Control

Safety is built into the design from the start. The project documentation calls for conservative pressure limits, controlled inflation rates, and a manual or emergency deflation method, and it also requires mechanical and electrical safeguards, since software alone must not be relied on to prevent excess pressure. Early testing is planned without a person using the pillow, with controlled human testing allowed only after the pneumatic system and deadband logic have been checked.

V. SYSTEM DESIGN AND MODULES

A. Wearable Sensing Module

The wearable module consists of the ESP32-C3, the MPU6050, a portable battery, and a clip or magnetic mount. Its job is sensing, not pneumatic control: it turns inertial measurements into a stable orientation state and sends that state over Bluetooth. Keeping the

module this simple limits the control hardware the user has to wear.

B. Main Control and Processing Module

The main ESP32 is the decision-making unit. It takes in the orientation state, finds the stored pressure target, reads the current pressure, and chooses the actuator state. It also passes system information to the web application. In this way the controller ties together the sensing, calibration, feedback, and actuation layers.

C. Pneumatic Actuation Module

The pneumatic module comprises the air pump, inlet solenoid valve, exhaust solenoid valve, two relays, air pipe, and inflatable pillow. Inflation activates the pump and inlet path; pressure reduction activates the exhaust valve. Having separate inlet and exhaust paths gives explicit control in both directions of pressure change.

D. Pressure Feedback Module

The HX710B pressure-sensing interface supplies the feedback that closed-loop operation needs. In contrast to an open-loop, timer-based method, the controller does not assume that a fixed pump run time always yields the same pressure. It compares measured pressure with the target again and again, so the control logic can accommodate differences in starting pressure and operating conditions.

E. Web Application and Calibration Module

The web application lets the user pick a sleeping position, control inflation manually, save target pressures, and view the present system state. The documented monitoring variables are detected orientation, actual pressure, target pressure, pump status, and valve status. The interface thus serves both for calibration and for observing the system. Fig. 2 summarizes these interactions.

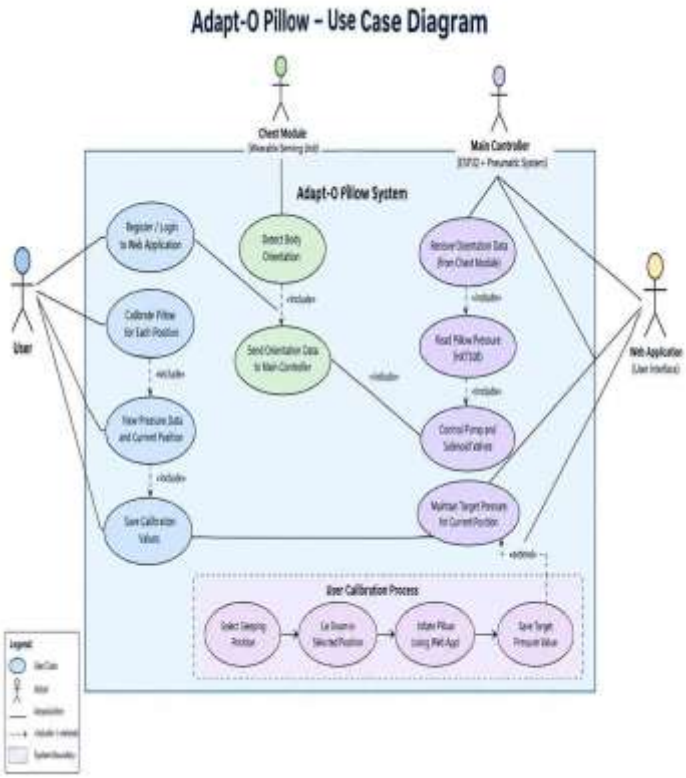


Fig. 2. Use-case view of user, web application, wearable module, main controller, and pneumatic functions.

F. Data Model

The data model is built around four categories. The User Calibration Profile holds the target pressures for the supported orientations. Orientation State is the posture derived from MPU6050 measurements. Pressure Data covers the current pressure, target pressure, and tolerance information used in comparison. Hardware Status describes the operating state of the pump and solenoid valves. Parts of these states are shown in the web interface for calibration and monitoring. Table II lists the modules and their responsibilities, and Fig. 3 gives an overview of the model.

System module	Primary responsibility	Main information handled
Wearable sensing	Sense orientation and stabilize it	MPU6050 readings; orientation state
Central controller	Choose target and run control	Orientation, target pressure, measured pressure
Pressure feedback	Measure pneumatic condition	Present pillow pressure
Pneumatic actuation	Alter pillow pressure	Pump and valve states
Web application	Calibration and monitoring	User targets and live status

Safety control	**Restrict unsafe or unstable actions**	**Pressure limits, deadband, deflation state**

TABLE II
SYSTEM MODULES AND RESPONSIBILITIES

VI. CONTROL FLOW AND UML-BASED INTERACTION

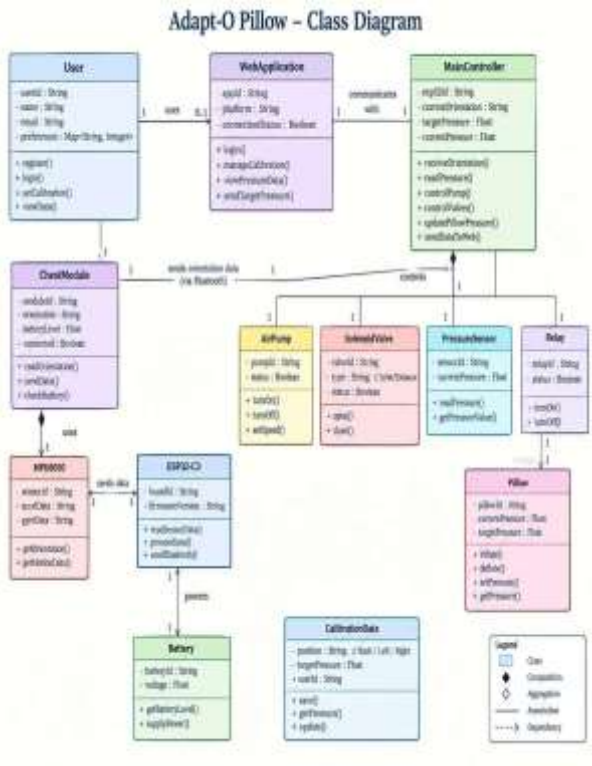


Fig. 3. Class/data model overview of the Adapt-O Pillow system.

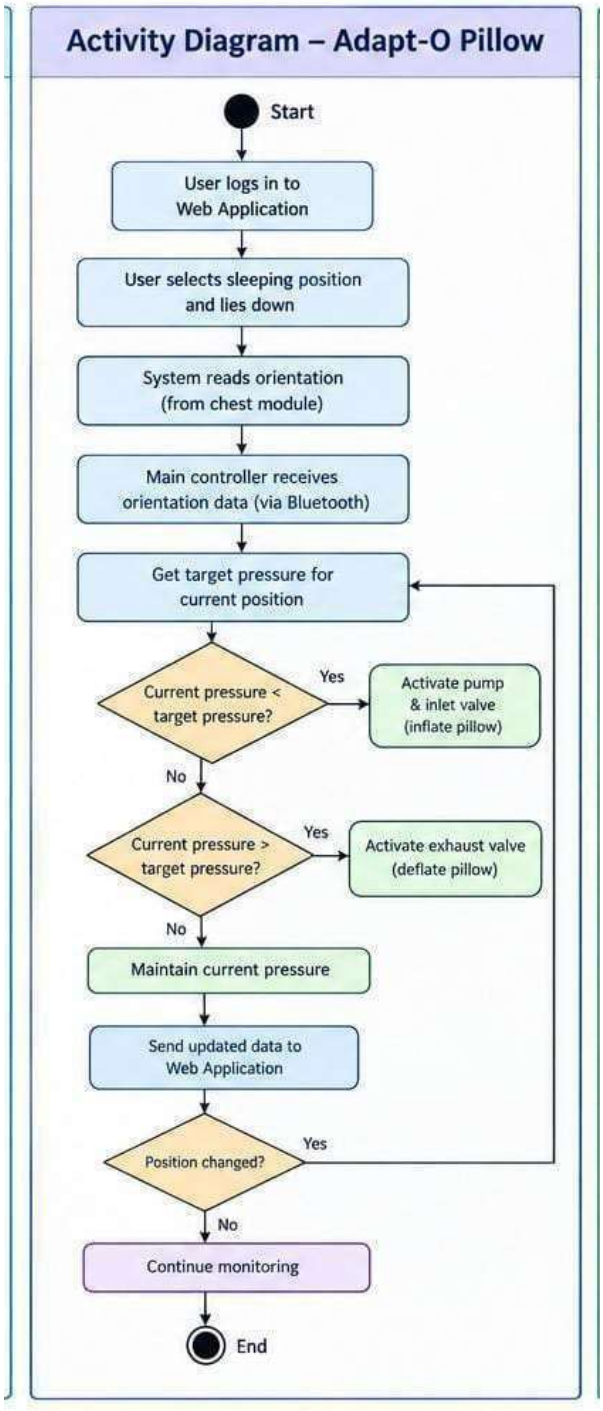


Fig. 4. Activity flow for orientation detection and closed-loop pressure adjustment.

Fig. 4 shows the activity flow, which starts with orientation sensing. The wearable module processes MPU6050 readings, filters out momentary movement, and sends the stable state. The main ESP32 then picks the stored target pressure and reads the present pressure,

after which the controller branches to inflate, exhaust, or hold depending on the comparison. The loop repeats for as long as the system stays in automatic mode. As a result, a recognized orientation never maps straight to a single irreversible actuator command; orientation fixes the target, and pressure feedback decides which pneumatic action is needed.

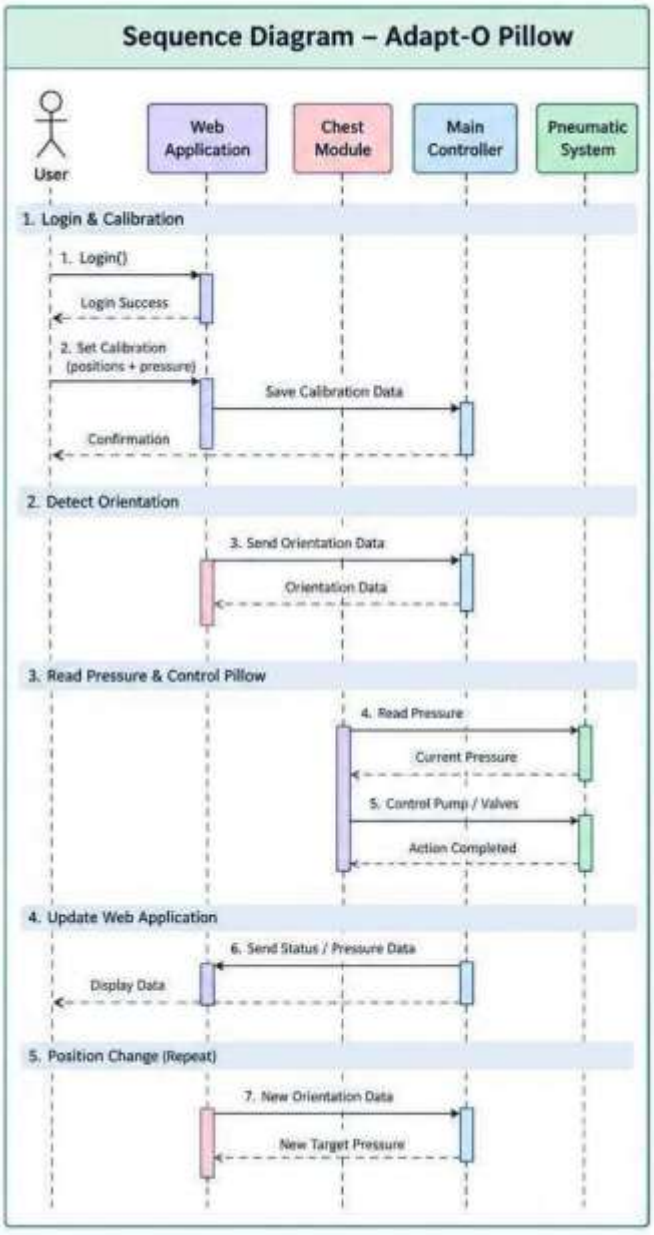


Fig. 5. Sequence diagram for calibration and automatic pillow adjustment.

The sequence model separates calibration from automatic operation. During calibration, the user interacts with the web application and manually adjusts the pillow before saving a target. During automatic operation, the chest module detects a position change, the main controller receives the orientation, the corresponding target is selected, and the pneumatic system adjusts the pillow until the feedback state reaches the permitted range. This Fig. 5 shows the sequence model, which keeps calibration and automatic operation apart. In calibration, the user works through the web application, adjusting the pillow manually and then saving a target. In automatic operation, the chest module detects a change in position, the main controller receives the new orientation and selects the matching target, and the pneumatic system adjusts the pillow until the feedback reaches the permitted range. Keeping the two modes separate avoids confusing the calibration procedure with the automatic control loop.

VII. IMPLEMENTATION

A. Embedded Firmware

Embedded firmware is split between the ESP32-C3 wearable and the main ESP32. The wearable firmware handles inertial data and outputs a stable orientation. The main-controller firmware looks up targets, measures pressure, applies the deadband comparison, switches actuators, and manages system communication. The split follows the documented architecture and keeps orientation processing separate from pneumatic hardware control.

B. Wireless Communication

Bluetooth carries the orientation information from the wearable unit to the main controller. Because only the processed orientation state is needed for the control decision, only that state is transmitted, which keeps the boundary between sensing and actuation clear. The project documentation reports neither packet loss nor communication latency, so no numerical wireless-performance claim is made.

C. Closed-Loop Adjustment

The main controller continually evaluates measured pressure against the target. The deadband keeps the pump and valves from switching on small deviations, which matters in

pneumatic systems because switching right at the target can cause oscillation, needless component activity, or an unsteady user experience. The project documentation defines the deadband concept but gives no numerical value.

D. Calibration and Monitoring

The web interface is the direct route to personalization. Instead of applying preset pressures from an outside standard, the system lets the user set preferred values for each supported position. The interface also shows live orientation, pressure, and actuator status, so these can be observed during development and testing.

VIII. TESTING, OBSERVATIONS, AND RESULTS

The project documentation describes testing as a phased process. The first validation stage runs without anyone using the pillow, so the pneumatic system, pressure limits, valves, and deadband logic can be checked before controlled human involvement. Human testing may follow once the pneumatic subsystem is judged safe enough for controlled evaluation. The modular architecture also allows each subsystem to be tested before full integration.

A. Functional Test Scenarios

- Orientation transition: check that the wearable module detects changes among back, left-side, and right-side states and does not respond at once to a brief transient movement.
- Target selection: check that a stable orientation picks the matching user-saved pressure target.
- Inflation: check that a pressure below the target range switches on the pump and inlet path.
- Exhaust: check that a pressure above the target range opens the exhaust valve.
- Deadband behavior: check that pressure inside the permitted range causes no unnecessary actuator switching.
- Calibration: check that a user can adjust pressure manually and save a target for each supported position.
- Monitoring: check that the web interface shows orientation, current pressure, target pressure, pump status, and valve status.
- Safety: check the conservative pressure limits and the availability of manual or emergency deflation before any human testing.

The available documentation mainly records functional implementation and intended behavior. It contains no controlled experimental data from which orientation-classification accuracy, pressure-regulation error, response time, Bluetooth packet-loss rate, battery endurance, comfort scores, participant numbers, or statistical significance could be computed. This paper therefore reports no numerical performance values, and its results are confined to the documented functional behavior and the defined test strategy (Table III).

Test area	Expected functional behavior	Quantitative result reported?
Orientation sensing	A stable, supported orientation is transmitted once filtering is done	No
Pressure feedback	Current pressure is available for target Present pressure is available for comparison with the target	No
Inflation	Pump and inlet path switch on when pressure is under the target range	No
Deflation	Exhaust path opens when pressure is over the target range	No
Deadband	Small deviations do not trigger rapid switching	No
Calibration	User can store position-specific pressure targets	No
Web monitoring	System state is shown in real time	No
Safety	Conservative limits and manual/emergency deflation are provided	No

TABLE III
DOCUMENTED FUNCTIONAL TEST AREAS

IX. DISCUSSION

The central design feature of Adapt-O Pillow is that support follows orientation, rather than pillow pressure being a fixed setting. Stable orientation acts as a high-level control input, and the pressure sensor provides the low-level feedback needed to reach the matching target. This split is useful technically because posture recognition and pressure regulation work on different time scales and data.

Placing the sensor on the chest is also notable. A sensor in the pillow could observe pressure at the head or neck directly, but a chest-mounted inertial sensor gives an explicit signal of body orientation. Earlier research has shown that wearable inertial sensing can estimate sleeping position [1], [2]. Adapt-O Pillow applies this established principle inside a control architecture instead of using it only for monitoring.

Personalized calibration is another key element. The system does not assume that one pressure suits every user or every sleeping position; instead, the user builds a small profile of preferred targets. This fits the wider research trend toward personalized pillow geometry and support [6], [7], while staying deliberately simpler because the project makes no attempt at biomechanical optimization.

Filtering and the deadband deal with two different kinds of instability. Orientation filtering stops a brief body movement from registering as a change of position, and the pressure deadband stops small pressure deviations from making the pump and valves switch rapidly. Together they give a steadier control loop. How effective they are, however, should be measured in future testing and not assumed from the architecture alone.

Safety remains a practical constraint. An inflatable support can become uncomfortable or unsafe if pressure is not limited or if an actuator stays on unexpectedly. The project's requirement that safety not depend on software alone is therefore important. Mechanical and electrical protections, conservative limits, controlled inflation, and emergency deflation should each be verified independently before extended human use.

X. APPLICATIONS

- Smart sleep-support prototypes whose pillow support changes with the detected sleeping orientation.
- Personalized pillow-adjustment systems in which users keep separate comfort settings for different positions.
- Assistive comfort accessories that show embedded sensing combined with pneumatic feedback control.
- IoT -based sleep-environment prototypes that combine local sensing, wireless communication, and web monitoring.
- Research on adaptive furniture and accessories, where a physical support surface responds to the user's detected state.
- Teaching and research platforms for studying sensor fusion, embedded control, Bluetooth communication, and pneumatic actuation.

These applications outline the technical scope of the prototype only; they must not be read as evidence that the system diagnoses, prevents, or treats any medical condition.

XI. LIMITATIONS

- The project is a prototype and needs wider validation before any claim about real-world performance can be made.
- Only the documented orientations of back, left side, and right side are covered.
- Orientation stability relies on sensor placement and calibration.
- The project documentation gives no numerical measurements of accuracy, pressure error, response time, battery life, or communication reliability.
- The pneumatic subsystem brings physical response limits and needs independent safety verification.
- The system relies on wireless communication between the wearable and the central controller.
- User comfort and long-duration sleep behavior have not been established by a documented controlled user study.
- The stored pressure values are personal comfort settings, not medically validated treatment pressures.

XII. FUTURE SCOPE

- Extend orientation recognition to more sleep positions and transitional states.

- Assess more advanced orientation-classification algorithms and, where the data justify it, machine-learning methods.
- Add quantitative pressure-control metrics such as settling time, overshoot, steady-state error, and actuator duty cycle.
- Improve automatic personalization by learning stable user preferences over repeated calibration sessions.
- Build a more compact wearable and pneumatic hardware package.
- Improve battery management and measure endurance under realistic operating conditions.
- Upgrade the web or mobile interface for setup, visualization, logging, and configuration.
- Run larger controlled user studies on comfort, stability, usability, and repeatability.
- Add independent hardware safety mechanisms and fault detection for the pump, valves, pressure sensing, and wireless link.
- Explore multi-zone pneumatic pillows that offer different support across the pillow surface.

XIII. CONCLUSION

Adapt-O Pillow presents a prototype architecture for an orientation-aware inflatable pillow that brings together wearable inertial sensing, Bluetooth communication, user calibration, pressure feedback, and pneumatic actuation. Its core idea is to turn a detected stable sleeping orientation into a personalized pressure target and then use closed-loop feedback to bring the pillow to that target. Posture recognition is thereby kept apart from low-level pressure regulation, giving a clear structure for step-by-step implementation and testing.

The documented prototype integrates ESP32-C3/MPU6050 sensing, a main ESP32 controller, an HX710B pressure-feedback path, pump and solenoid-valve actuation, and a web application into a coherent whole. Filtering and deadband logic limit unnecessary changes, and conservative pressure limits with manual or emergency deflation are specified as safeguards. The system is deliberately presented as an assistive comfort prototype, not a medical device.

The chief limitation of the present work is that no quantitative evaluation is documented. Future work should measure orientation-recognition performance, pressure-regulation behavior, communication reliability, energy use, and user-centered outcomes under controlled conditions. Such an evaluation would show how well the architecture performs beyond functional prototype operation.

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