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Design and Development of a Cost-Effective Automated Multi-Posture Hospital Bed

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Abstract:

This paper presents the design and development of a Cost-Effective Automated Multi Posture Hospital Bed equipped with integrated fall detection and pressure ulcer prevention functionalities, aimed at enhancing patient safety and comfort in clinical and home care settings. The system addresses common challenges faced by bedridden patients, including pressure ulcers, limited mobility, and the risk of falling, through a combination of mechanical automation, smart sensing, and pneumatic support mechanisms. The bed structure allows for dynamic adjustment of the headrest, leg rest, and height using high-load linear actuators, which are controlled by an ESP32 microcontroller. The system employs Force Sensitive Resistor (FSR) sensors to monitor pressure distribution, temperature sensors to detect localized heat buildup, and an Inertial Measurement Unit (IMU) to identify abnormal postures or potential falls. A custom-designed pneumatic sheet inflates and deflates in specific zones based on real-time sensor input, ensuring continuous pressure relief and reducing the risk of pressure ulcers. Data from the sensors is processed and used to trigger automatic repositioning or caregiver alerts, thereby reducing the physical workload on healthcare providers while ensuring proactive patient care. The entire system is compact, cost-effective, and designed with scalability in mind. The prototype demonstrates a viable solution for improving patient care, especially in low-resource environments. This project contributes to the growing field of smart healthcare systems by offering a multifunctional, sensor-driven hospital bed that can be integrated into modern medical infrastructure.

Keywords: Automated Hospital Bed, Fall Detection, Pressure Ulcer Prevention, ESP32 Microcontroller, Smart Healthcare, Sensor-Based Monitoring

Introduction:

To help in the recovery process of patients, healthcare facilities require hospital beds that are comfortable and safe. Patients who experience prolonged time in bed are often infected, injured, or of advanced medical conditions [1]. It may lead to such serious complications as a pressure sore and hypertension. It is sad to note that although advanced automated beds are critical in the delivery of healthcare, not all hospitals in Pakistan, India, and Africa, given their low income, are able to afford them [2]. These integrated systems reduce caregivers' workloads, as manual repositioning has to be done very frequently. The bed has three DC motor linear actuators powered by an ESP32 microcontroller to allow the ease of changing the height, head, and foot section [3].

Moreover, wireless connectivity will provide flexibility to caregivers both in a hospital and home-care environment by enabling them to operate and supervise the bed using web interfaces or mobile applications [2]. With the application of inexpensive components and local production method, this intelligent hospital bed provides the state-of-the-art features at a small fraction of the cost of traditional luxury-priced models. Its application is aimed in nursing homes, home-care, and hospitals where chronically ill patients or the elderly require specialized services. The system reduces the workload on the caregivers, enhances patient comfort, as well as protects against such issues as falls and pressure ulcers [4].

Ultimately, being a comparatively affordable smart hospital bed will become a pivotal step towards better health practices that increase patient safety, strengthen the effectiveness of treatment, and allow the less-fortunate medical establishments to deliver quality care [5].

Cost Analysis Table:

Compared to commercial systems, which usually cost between PKR 400,000 and 600,000, the suggested smart hospital bed costs about PKR 180,000. This reduction is accomplished by removing costly proprietary modules and using locally fabricated components, low-cost sensors, and open-source ESP32 controller. Long-term costs are further decreased by the modular design's ease of maintenance and component replacement. All things considered, the suggested plan provides a cost-effective alternative without sacrificing necessary functionality or patient comfort [6].

S.no	Component/Material	Quantity	Unit Cost (PKR)	Total Cost (PKR)
1	Linear Actuators (Head, Foot, Height sections)	3	12000	36000
2	ESP32 Microcontroller (Wi-Fi + BLE)	1	2500	2500
3	FSR (Force Sensitive Resistors)	4	1500	6000
4	Temperature Sensor (DHT22 or AHT20)	1	800	800
5	Gyroscope/Accelerometer (MPU6050)	1	1200	1200
6	Air Compressor (12V, 150 PSI)	1	8000	8000
7	Solenoid Valves for Air Flow Control	2	2500	5000
8	Pressure Redistribution Sheet (Custom Fabrication)	1	12000	12000
9	TFT/LCD Display Module	1	2000	2000
10	Relay Modules, MOSFETs, Motor Drivers	-	-	4000
11	Steel Frame and Mechanical Fabrication	-	-	40000
12	PU Foam + Medical Mattress	1	9000	9000
13	Caster Wheels, Hinges, Fasteners, Sliding Rods	-	-	6000
14	Power Supply (12V/24V + Backup Battery System)	1	5000	5000
15	Wiring, PCB, Connectors, Mounting Boards	-	-	5000
16	Development & Testing Tools	-	-	3000
17	Miscellaneous (Paint, Packing, Repairs)	-	-	4500
Total Estimated Cost				180,000 PKR

Material & Method Used:

The fabrication of the hospital bed frame was made of mild steel square and rectangular tubes due to their high durability and cost to strength ratio. Three DC motor linear actuators were selected to control the angle of the head/foot portion (0-75 degrees backrest, 15-45 degrees footrest), as well as the height (9-30 inches). Due to the low power consumption, and integrated Wi-Fi/Bluetooth connectivity, the ESP32 microcontroller formed the core of the control system. Some of the electronic interface components included MOSFETs, 24V relays, H-bridge motor drivers, and a buck converter to control voltage. The system employed various safety and monitoring sensors such as an MPU6050 accelerator-gyroscope sensor to keep track of patient movement and detect falls, temperature sensors (DHT22AHT20) to detect localized heat gain, and Force Sensitive Resistors (FSR) to detect pressure distribution.

The sensors were then built into a specifically designed pressure-redistribution mattress constantly offloading the pressure by inflating and deflating air cells via solenoid valves and a 12V compressor. The additional components included pneumatic pipes, pressure system air nozzles, caster wheels to move around, and a medical grade foam mattress.

Wireless connectivity was achieved with the Blynk IoT platform, which allowed caregivers to operate a smartphone or web application to adjust the positions of a bed and track the condition of a patient. Motion smoothness, stress distribution and ergonomic compliance of the bed structure and actuator locations were virtually tested during the Creo Parametric 5.0 CAD modelling phase of the design process. The steel frame was created in terms of accuracy in cutting, arc welding, grinding and anti-corrosive finishing after validation. To make the adjustable parts run well, mechanical joints were assembled using hinges and bearings. Electronic components were programmed and tested in the Arduino IDE.

The ESP32 microcontroller was coded in order to accept sensor input and control actuators to correct posture, detect flips, and inflate a mattress. To differentiate the safe movements of the bed and the risky behavior of the patient, the fall detection algorithm synthesized the accelerator and load cell data and sent alerts to the caregivers in real-time. The pressure ulcer prevention system was checked by observing changes in surface pressure when the loads of the patient were varied under simulated conditions to ensure that at the most essential moments the redistribution of the pressure happened automatically. The finished prototype was made by connecting the manufactured bed frame, actuators, sensors and the pneumatic mattress.

The test confirmed the bed was providing good pressure relievers, reliable fall detection and smooth adjustments with no noise. It was designed all at an approximate of PKR 180,000, which is significantly lower than the cost of imported luxury smart hospital beds.

This turns it to be an attractive alternative to healthcare facilities that have limited funds.

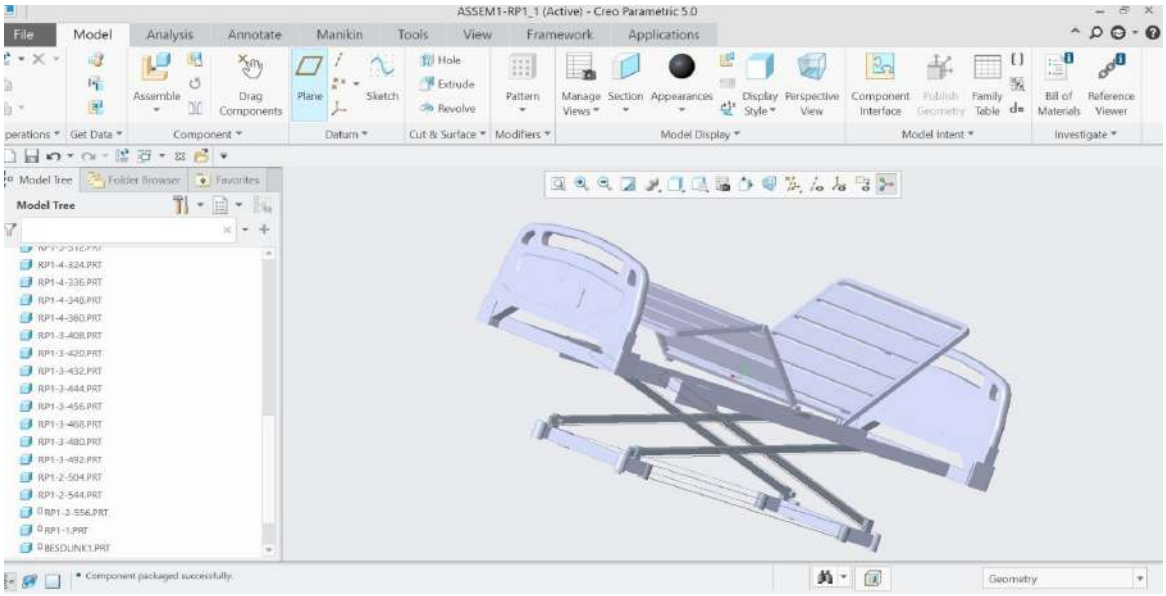

Figure 1 Mechanical design Creo

Figure 2 Final Model (Lowest Height)

Result & Discussion:

Using the fall detection and pressure ulcer prevention coupled with mechanical adjustments, the developed automated multi-posture hospital bed managed to fulfill its design objectives at an affordable price. Although the three DC linear actuators made it possible to make noiseless and smooth adjustments to the head, foot and height parts,

structural testing ensured that the mild steel frame was stable to the weight of up to 200 kg without giving way [7].

These automated features enhanced patient ergonomics through providing flexible positioning, which enhanced circulation and respiratory support as well as post-surgery recovery, and reduced caregiver's workload significantly compared to manual traditional bed [8]. Sensors were also effective in ensuring comfort and safety of the patients [9]. By properly detecting simulated falls and sending real-time notifications with the help of the Blynk IoT application, the fall sensor based on the MPU6050 IMU and load sensors provided a timely response by the caregivers. The pneumatic mattress equipped with temperature and pressure sensors reduced the number of persistent pressure points and localized heat by dynamic redistribution of body weight. Its testing to decrease the risk of pressure ulcers that are common in elderly and immobilized patients was tested and proven. Combining these systems provided feasible solutions to the issues that were found in the field survey and they included patient immobility, discomfort and injury risk. The prototype cost around PKR 180,000, a considerably small amount in comparison with the prices of imported automated beds, which lie between PKR 250,000 and 500,000. This renders it feasible in low-resource environments such as hospitals, nursing homes, and home care environments.

The system still maintained a low cost without compromising on comfort and safety in providing the necessary characteristics of high-end hospital beds [10]. Nonetheless, more clinical trials in the long term should be performed to ensure user satisfaction and durability. Future development of AI-driven posture recognition, offline fall detection, and connection to the hospital-wide IoT infrastructure can be achieved [11]. Altogether, the project demonstrates a valuable healthcare innovation that balances the affordability, usefulness, and accessibility, which makes a substantial contribution to the modern system of patient care.

Conclusion:

The current and modernized mechatronic solutions have the capability of dealing with critical needs in healthcare as is evident in the design and development process of an automated multi-posture hospital bed, which is affordable. Pneumatic pressure redistribution, mechanical automation, and intelligent sensing were paired to decrease the chance of falls, enhance patient comfort, and avert pressure ulcers. The state-of-the-art capabilities of the bed could be used in hospitals and care centers with limited resources due to the ESP32-based control, wireless monitoring, and affordable components.

The testing confirmed the smart hospital bed ensured proper alerts during simulated fall events, the ability to adjust the posture accurately and seamlessly and has reduced caregiver's workload. Also, the possibility of the pneumatic mattress to adjust temperature

and pressure contributed to minimizing the discomfort of patients and maximizing safety. The prototype costs PKR 180,000 in total and comes with considerable value both in use in hospital and home-care environment and provide a competitive option to expensive imported beds. In every way, this project indicates that the health delivery system can be improved with the help of locally manufactured, affordable smart medical equipment. The proposed system is effective toward the management of patients in nursing facilities, hospitals, and home-care facilities since it fills the gap between cost and functionality. To expand its contribution to the creation of smart healthcare technologies, the future research may focus on large-scale clinical trials, better IoT connectivity, and AI-based monitoring.

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