

SMART PATIENT BED FOR PRESSURE- INJURY PREVENTION

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1. Introduction

1.1 Problem

Bedridden or otherwise mobility-impaired patients can often remain in the same position for long periods of time, potentially leading to many pressure-related injuries such as ulcers or bedsores. These injuries are concentrated on areas of the body under the most stress when laying down, such as the hips and lower back. As the amount of time the patient is motionless increases, the more the blood flow is restricted and the tissue is damaged. The Agency for Healthcare Research and Quality (AHRQ) reports that more than 2.5 million people in the U.S. develop ulcers from prolonged single-area pressure and identifies frequent repositioning as being among the most critical preventative measures [1].

Preventing these kinds of injuries is not only a matter of public health but also poses to benefit the economics of hospitals with better preventative measures. According to an economic analysis concerned with hospital-acquired pressure injuries (HAPI), the entire United States in 2016 alone was estimated to have spent over \$26 billion in annual healthcare costs treating HAPI's [2], further demonstrating a need for improved preventative practices.

Current preventative measures rely on the discretion of the caregivers in charge of overseeing these patients. Under their assessment, patients are repositioned and assessed on a semi-regular basis. However, following a set repositioning schedule for many patients can be difficult to balance. Additionally, this system does not continuously measure where any pressure is building between assessments to allow for personalized prevention plans.

1.2 Solution

Our proposed solution to this problem is to create a low-cost sensing pad that sits underneath the patient and continuously measures the pressure distribution and positioning. The pad will contain an array of pressure sensors arranged in a grid, focused on the hips/lower back region (where pressure-related injuries are most prominent). Then, the array will feed its readings into a microcontroller to analyze and readout which regions are experiencing prolonged pressure. Not only will this system identify regions of prolonged pressure, but also alert caregivers via Bluetooth to tend to that patient. This provides a significant and novel improvement over the existing preventative practices for pressure-related injuries.

A more in-depth description of the system will be expanded in the subsystem overview later in the proposal, but the following visual aid will show roughly how the system will operate.

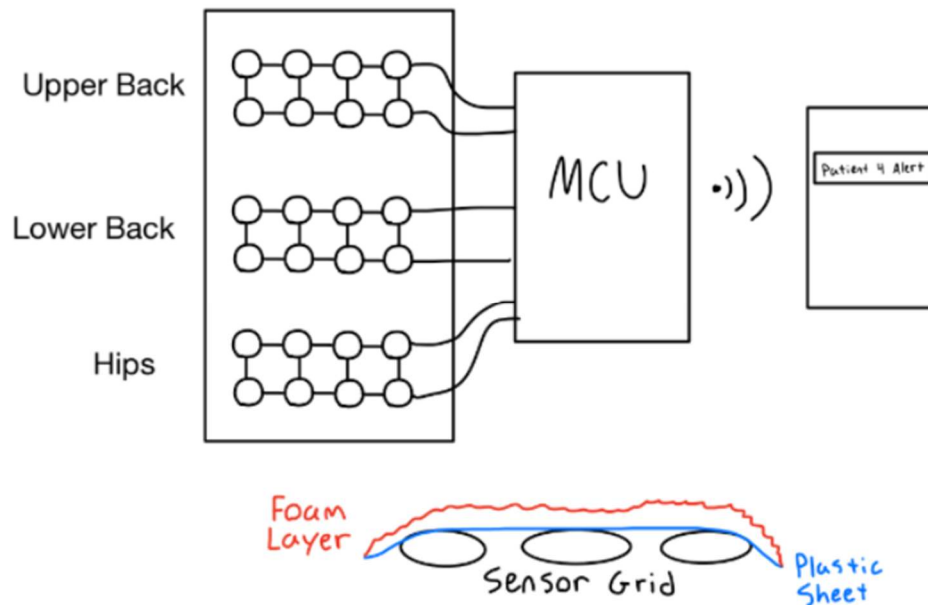


Figure 1: Visual Representation of Proposed Solution

At a high level, the readings from the sensing array are sent to the MCU to be interpreted and eventually converted to an alert for the caregiving staff to tend to their patients. As for the physical implementation, we plan to encapsulate the sensor grid in a plastic sheet to ensure the components do not prod the patient. Additionally, a foam layer will be fixed to the top of the sheet where it will contact the patient to ensure comfort for the patient as well as preventing our components from being crushed under their weight. The regions being sensed in this image serve only as an example, but the grid pattern is accurate to our current design plans.

1.3 Requirements

The high-level requirements we will use to prove a sufficient and functioning project are as follows:

- The pressure-sensing pad contains at least 16 individual sensors capable of providing pressure and spatial information about the patient's pressure distribution.
- The pressure data collected by the sensing pad is processed and converted to a definitive "needs repositioning of _____ area" or "does not require repositioning" depending on user-defined thresholds for what duration is to be considered as "prolonged" long enough for concern.
- The feedback generated by the MCU is converted to a Bluetooth signal capable of alerting a nearby (of a caregiver, e.g.) phone to its status within 30 seconds of the established pressure threshold being reached.

2. Design

2.1 Block Diagram

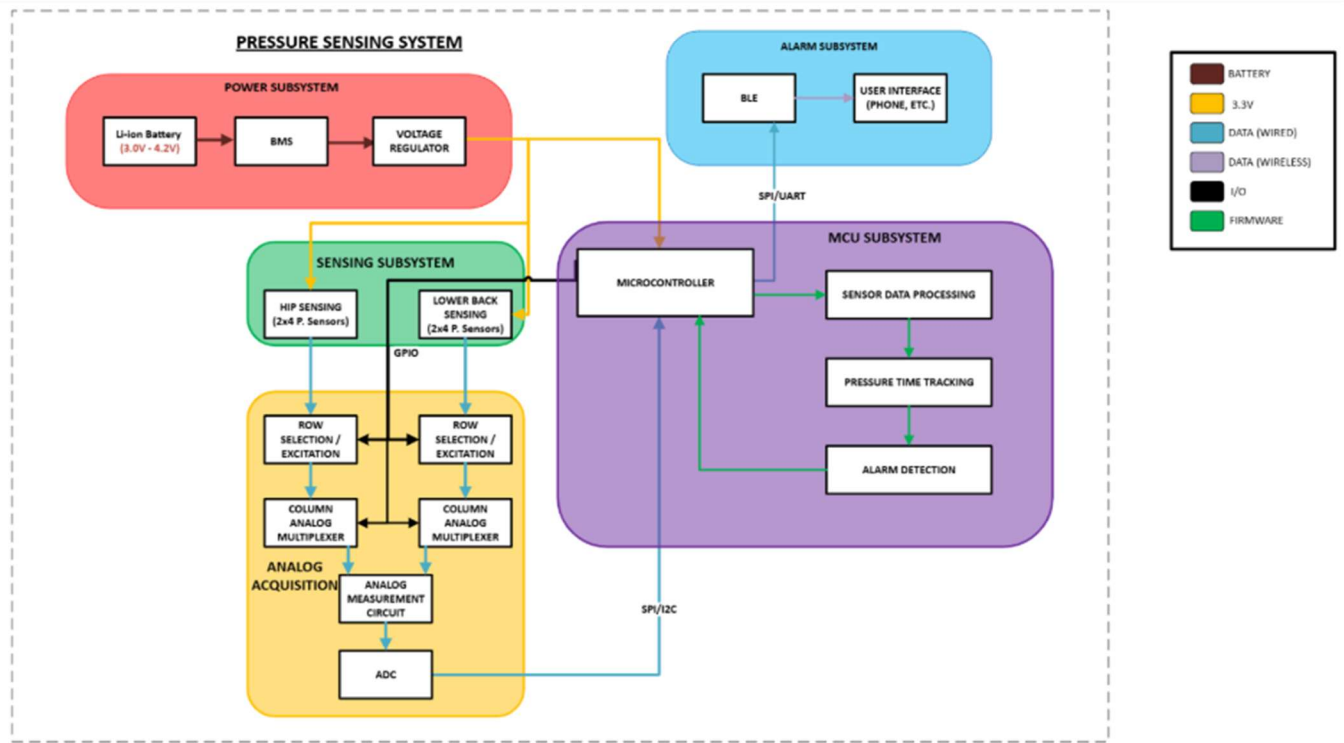


Figure 2: Block Diagram of Proposed Solution

2.2 Subsystems

2.2.1 Sensing Subsystem

The sensing subsystem provides the physical interface between the patient and the pressure-monitoring electronics. The sensing pad consists of 16 resistive pressure sensors divided into two independent 2×4 arrays, with one array positioned beneath the patient's hips and the second positioned beneath the lower back. When pressure is applied to an individual sensor, its electrical resistance changes, allowing the applied pressure to be electrically measured. Dividing the sensors into two smaller arrays reduces the number of possible unintended current paths associated with a larger resistive matrix while also allowing the sensing pad to remain compact and portable. The sensing subsystem is powered from the regulated 3.3 V rail provided by the power subsystem. Each 2×4 array interfaces with the analog acquisition subsystem through two row connections and four column connections. The microcontroller controls the row-selection and column-multiplexing circuitry using digital GPIO signals, allowing individual sensing locations to be sequentially selected. The resulting sensor resistance is converted into an analog voltage by the analog acquisition subsystem and subsequently measured by the ADC. By independently monitoring the 16 sensing locations, this subsystem provides the spatial pressure information required by the MCU subsystem to determine where pressure is being applied and how long that pressure persists.

Requirements:

- The sensing subsystem shall contain at least 16 individually measurable pressure-sensitive locations.
- The 16 sensing locations shall be divided into two independent 2×4 arrays, corresponding to the lower-back and hip regions.
- Each sensor shall exhibit a measurable electrical resistance change in response to an applied load within the intended operating range.
- Each 2×4 array shall provide 2 row and 4 column electrical connections to the analog acquisition subsystem.
- The sensing circuitry shall be compatible with the system's regulated 3.3 V supply.
- The architecture shall allow all 16 sensing locations to be individually addressed and distinguished, preserving the spatial location of each measurement.
- Measurements from the two arrays shall remain distinguishable, so the processing subsystem can determine whether the hip region, lower-back region, or neither region requires repositioning.

2.2.2 Analog Acquisition Subsystem

The analog acquisition subsystem acts as the electrical interface between the pressure-sensing subsystem and the MCU subsystem. Because each pressure sensor produces a change in resistance rather than a directly measurable digital value, the analog acquisition circuitry will convert the resistance of the selected sensor into an analog voltage using a voltage-divider or similar measurement circuit. Each of the two 2×4 sensor arrays interfaces with the acquisition subsystem through 2 row connections and 4 column connections. Row-selection circuitry will selectively excite the desired row, while a 4-to-1 analog multiplexer will select one of the four columns, allowing an individual sensor within each array to be measured. The MCU will control the row-selection and multiplexer address lines using 3.3 V GPIO signals, sequentially selecting each of the 16 pressure sensors. After each sensor is selected, the analog signal will be allowed to settle before its voltage is sampled by an ADC. This scanning process will repeat continuously, providing the MCU with measurements from all 16 sensing locations that can be used to construct a pressure map and track sustained pressure. Initial testing will determine whether the selected microcontroller's internal ADC provides sufficient resolution, stability, and noise performance. If greater measurement performance is required, an external ADC communicating with the MCU through SPI or I²C will be incorporated into the design.

Requirements:

- The subsystem shall be capable of acquiring measurements from all 16 sensing locations.
- The subsystem shall provide independent selection of the 2 rows and 4 columns associated with each sensing array.
- The analog multiplexing circuitry shall allow the MCU to select one intended sensing location at a time for measurement.
- The row-selection and multiplexer control circuitry shall accept 3.3 V-compatible GPIO logic from the MCU.

- The analog measurement circuit shall convert the selected sensor's resistance into a voltage that remains within the allowable input range of the selected ADC.
- The ADC shall provide sufficient resolution to reliably distinguish between pressure states required by the MCU's user-defined pressure threshold. The minimum ADC resolution will be established through sensor characterization.
- The subsystem shall preserve the identity of each measurement so that every ADC result can be associated with one of the 16 physical sensing locations.
- A complete scan of all 16 sensors shall occur sufficiently faster than the system's 30-second alarm-response requirement so that sensor acquisition does not prevent an alarm from being transmitted within that period.

2.2.3 MCU Subsystem

The MCU subsystem serves as the primary processing and control unit of the pressure-sensing system. The microcontroller will operate using 3.3 V logic and will control the row-selection and analog-multiplexer circuitry through GPIO signals while receiving digitized measurements from the analog acquisition subsystem. For each of the 16 pressure-sensing locations, the MCU will continuously compare new measurements with previous measurements to identify meaningful changes in applied pressure. A short history of sensor measurements may be maintained and filtered to reduce the effect of noise and brief pressure fluctuations; the required number of samples and filtering methods will be determined through system testing. Once sustained pressure is detected at a sensing location, the MCU will independently track the duration of that pressure and determine the appropriate alert state, such as normal, reposition soon, or reposition immediately. Performing the pressure analysis, timing, and alarm decision locally ensures that alarm determination does not depend on a continuous Bluetooth connection to an external device. The Bluetooth subsystem is therefore only required to communicate the pressure and alarm status generated by the MCU to the user interface. This architecture allows the primary pressure-monitoring algorithm to continue operating even if the wireless connection is temporarily interrupted.

Requirements:

- The MCU shall operate with 3.3 V-compatible digital logic.
- The MCU shall provide sufficient GPIO connections to control the row-selection and column-multiplexing circuitry required to address all 16 sensing locations.
- The MCU shall receive a digital measurement corresponding to each of the 16 individually identifiable sensor locations.
- The MCU shall maintain the spatial association between each measurement and its corresponding sensor location/monitored body region.
- The MCU shall compare current measurements with previous measurements and implement sufficient filtering/change detection to prevent brief fluctuations from being treated as sustained pressure. Filtering parameters shall be established through system testing.
- The MCU shall allow a pressure threshold used for alarm determination to be defined or configured.

- The MCU shall allow the duration to define prolonged pressure to be defined or configured.
- The MCU shall independently track the duration for which the defined pressure condition persists in each monitored region.
- The MCU shall generate a definitive output indicating at minimum “lower back requires repositioning,” “hips require repositioning,” or “repositioning not required.”
- Pressure processing, duration tracking, and repositioning determination shall continue without an active Bluetooth connection.
- Once the defined pressure-duration threshold has been reached, the MCU shall provide the resulting alarm information to the communication subsystem quickly enough to permit the complete system to satisfy its 30-second notification requirement.

2.2.4 Alarm Subsystem

The alarm subsystem provides wireless communication between the pressure-monitoring system and an external user device. After the MCU processes the pressure measurements and determines the current alarm state, this information will be provided to a Bluetooth Low Energy (BLE) interface for wireless transmission. BLE functionality may be integrated into the selected microcontroller or implemented using a separate BLE module, depending on the final component selection. The subsystem will transmit the current system status, including whether the patient is in a normal, reposition soon, or reposition immediately state, to a BLE-capable external device such as a smartphone, tablet, or computer. The purpose of the external device is to allow a caregiver or user to remotely monitor the status of the sensing pad without requiring a physical connection to the system. Development of a dedicated graphical mobile application is not required for the operation of this subsystem; the primary requirement is that alarm information can be successfully transmitted and accessed by a compatible external device. Because alarm determination occurs locally within the MCU subsystem, loss of the Bluetooth connection will not interrupt pressure monitoring, timing, or alarm-state determination.

Requirements:

- The subsystem shall use Bluetooth Low Energy (BLE) to transmit the repositioning status generated by the MCU.
- The subsystem shall transmit at minimum enough information to distinguish “lower back requires repositioning,” “hips require repositioning,” and “repositioning not required.”
- The BLE interface shall be implemented either internally within the MCU or using an external BLE-capable device.
- If an external BLE device is used, its electrical interface shall be compatible with the MCU's 3.3 V logic.
- The transmitted alarm information shall be receivable and interpretable by at least one BLE-capable external device.
- When a BLE connection is available, an alarm generated after the established pressure-duration threshold is reached shall be communicated to the external device within 30 seconds of that threshold being reached.

- The subsystem shall not be required for local pressure acquisition, duration tracking, or repositioning determination.
- Following a temporary BLE disconnection, the subsystem shall be capable of re-establishing communication without requiring the pressure-monitoring system to be reset.

2.2.5 Power Subsystem

The power subsystem provides the electrical energy required to operate the sensing, analog acquisition, MCU, and BLE subsystems while allowing the pressure-sensing pad to operate without a continuous wired connection. The system will use an off-the-shelf rechargeable battery solution with appropriate charging and protection circuitry. The battery will be rechargeable through an external low-voltage power source, such as a USB wall adapter, allowing the device to be recharged without removing the battery. Voltage-regulation circuitry will convert the battery output to the regulated 3.3 V rail required by the system electronics. The power subsystem contributes to the overall design by allowing continuous operation of the sensing, processing, and wireless communication functions while maintaining the portability of the pressure-sensing pad.

Requirements:

- The power subsystem shall use a rechargeable battery capable of operating the pressure-monitoring system without a continuous connection to wall power.
- The battery solution shall include appropriate charging and battery-protection circuitry, either integrated into the battery pack/module or provided by an off-the-shelf charging module.
- The battery shall be rechargeable from an external low-voltage DC source, such as a USB power adapter, without requiring the battery to be removed from the device.
- The power subsystem shall provide a regulated 3.3 V supply to the sensing, analog acquisition, MCU, and BLE circuitry.
- The regulated output shall remain within the acceptable supply-voltage range of all components connected to the 3.3 V rail throughout normal battery operation.
- The power subsystem shall be capable of supplying at least the maximum simultaneous current demand of the sensing, analog acquisition, MCU, and BLE subsystems without the 3.3 V rail falling outside its required operating range.
- The rechargeable battery shall provide sufficient capacity for the system to continuously perform 16-sensor acquisition, pressure processing and timing, alarm determination, and BLE communication for the required operating period between charges.
- The power subsystem shall maintain sufficient power for the MCU and BLE subsystem to meet the overall requirement that an alarm be communicated to a connected external device within 30 seconds of the established pressure-duration threshold being reached.

2.3 Tolerance Analysis

One potential risk to the success of completing the pressure sensor system is measurement error caused by unintended current paths, or ghost currents, within our pressure-sensor matrices. Each sensing region uses 2 x 4 resistive matrices to reduce the number of electrical connections to individually monitor eight pressure sensors. However, when multiple sensors experience pressure simultaneously, unselected sensors may create alternative conductive paths between the active row and selected column. These paths can change the effective resistance measured by the analog acquisition subsystem and therefore distort the resulting pressure map.

A simplified worst-case analysis can demonstrate the magnitude of this effect. Assuming a selected sensor has resistance $R_s = 10\text{k Ohms}$, and an unintended path is formed through three additional sensors each having resistance of 10k Ohms ; the unwanted path has a total resistance of $R_t = 30\text{k Ohms}$. The effective resistance seen by the measurement circuit becomes $R_{eq} = (1/R_s + 1/R_t)^{-1} = 7.5\text{k Ohms}$. This represents a 25% error from the intended 10k Ohm measurement.

To mitigate this risk, the analog acquisition subsystem will use controlled row-selection/excitation and column multiplexing so that only the desired sensing location is connected to the measurement path. The electrical states of the unselected rows and columns will be chosen to minimize alternative current paths. The effectiveness of this approach will be experimentally verified by comparing the measurement of an individual sensor when neighboring sensors are unloaded and when neighboring sensors are simultaneously loaded. If multiplexing alone does not provide sufficient isolation, additional analog switches or isolation elements will be incorporated into the acquisition circuitry.

3. Ethics, Safety, and Societal Impact

The IEEE Code of Ethics dictates that engineers should hold the safety and health of the public as the highest priority and disclose any potentially harmful side effects thoroughly before sharing with the public [3]. Due to this project's use residing primarily in the medical field, preserving patient safety and welfare is chief among ethical considerations, and we intend to adhere to that.

Our ethical design choices consist of incorporating a foam pad above the sensing pad to ensure patient comfort is maximized, even if it will make sensing pressure over time more difficult. Additionally, we will ensure that the alarm that goes off to signal excessive prolonged pressure is not needlessly embarrassing or shaming, only alerting the caregiver in charge of that patient. This system is to be treated as nothing more than a monitor and alert aid, to be supplemented by expert clinical judgement before any action is taken. This system will not replace the caregiver but rather help in their care and assessment of their patients, ensuring we follow the IEEE requirement that our project is honest and realistic when stating our technical claims and capabilities [3].

Several safety features must also be addressed during the development of our project. We will ensure that all components utilize a low-voltage power source, and any exposed conductive materials are secured inside of the plastic covering. This enclosure will also prevent the patient from being poked,

prodded, or otherwise made uncomfortable by any electronic components we develop. All materials that contact the patient or the patient's bed will be encased in foam to further maximize comfort and prevent potential damage to the bed itself. Furthermore, the system will be non-obstructive insofar as its existence will not prevent the normal repositioning tactics employed by the caregivers. Additionally, we are under no false idea that this system will operate forever under extensive and intense use. We would ensure to thoroughly explain to anyone using this system that the lack of an alarm does not guarantee the safety of the patient, and that normal checkups would still be required as if the system was not in place. This is only to catch preventable pressure-related injuries before they happen, and in the event of a failure in our system and the inability to alert a caregiver of the situation, normal procedures must stay in effect. We can develop a simple LED display to identify the caregiver when the system is operational to prevent such a situation from happening.

The nature of our project will be simply a research prototype and not a clinically approved device. All testing will be done strictly on the members of our team and with expressed, informed, and verbal consent prior to trials.

As for the societal impact of our project, the upside is rather intriguing. Firstly, it will improve the working lives of the caregivers in charge of bedridden or mobility-impaired patients, serving as an aid in ensuring their patients receive the best care possible. Needless to say, it will also benefit the patients themselves, as millions of patients per year could avoid a pressure-related injury and greatly improve their quality of life. As discussed before, the economic impact could also be quite significant, with healthcare costs reducing massively and benefiting the overall healthcare system. This low-cost platform would provide the monitoring capabilities of much more expensive machines while using relatively simple components, granting this aid to areas of the country/world previously unable to implement it. During our development process, we will ensure to reduce waste and develop a prototype capable of being reproduced with non-harmful substances to prevent any negative impact on the environment.

References

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