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Smart Tracking Assistance for Balance and Locomotion Enhancement (STABLE): A Novel Rehabilitation Shoe for Real Time Gait Correction and Support

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Author Note

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Abstract

Walking impairments affect millions worldwide, reducing independence and increasing the risk of falls, yet current assistive devices primarily provide passive support without actively retraining gait mechanics. This paper presents STABLE (Smart Tracking Assistance for Balance and Locomotion Enhancement), a wearable rehabilitation shoe that integrates real-time pressure sensing, gyroscopic orientation tracking, corrective piston-based actuation, and haptic feedback to stabilize and retrain walking patterns. Unlike conventional orthotics, STABLE establishes a personalized baseline during calibration, allowing its embedded control system to detect deviations in plantar pressure or foot rotation and respond with mechanical corrections alongside vibrational cues that reinforce proper gait. The system's closed-loop architecture ensures rapid detection and correction at high frequency, while onboard logging and wireless communication allow long-term progress tracking by patients and therapists. By combining immediate stabilization with neuromuscular training, STABLE represents a proactive, adaptive, and user-centered advance in mobility rehabilitation technology.

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Introduction

Mobility is one of the most essential aspects of human function, forming the foundation for independence, physical activity, and social participation. For millions of individuals worldwide, however, walking is unstable or severely impaired due to neurological, musculoskeletal, or age-related conditions. In the United States alone, approximately 19.9 million adults—roughly 12.1% of the adult population—report difficulty walking or climbing stairs, making mobility impairment the largest single disability category. Among older adults, gait instability becomes increasingly common, with nearly 35% of those over the age of 70 experiencing severe difficulty with walking and balance. This prevalence highlights mobility impairment not as a niche issue, but as a widespread public health challenge with profound physical and psychological consequences.

The impacts of impaired walking extend far beyond difficulty with locomotion itself. Individuals with unstable gait often experience increased rates of falls, hospitalizations, and long-term injuries such as hip fractures. Falls remain the leading cause of injury-related deaths among adults over 65, according to CDC statistics, accounting for thousands of fatalities and billions of dollars in healthcare costs annually. Beyond physical injuries, instability contributes to reduced confidence, activity avoidance, and depression, creating a feedback loop that further degrades health. As physical activity decreases, patients experience accelerated muscle atrophy, joint stiffness, and reduced cardiovascular fitness, compounding the initial impairment and leading to greater dependence on caregivers. Thus, gait instability must be addressed not only for immediate safety but also to prevent cascading declines in health and well-being.

Underlying causes of gait impairment are varied, ranging from neurological disorders such as Parkinson's disease, multiple sclerosis, or post-stroke motor deficits, to musculoskeletal problems such as arthritis, osteoporosis, or ligament damage. Age-related factors such as sarcopenia, vestibular dysfunction, and slowed reflexes further exacerbate instability, particularly in older populations. A particularly overlooked factor is the development of maladaptive gait compensations, such as limping, dragging a foot, or shifting weight abnormally, which may temporarily reduce pain but reinforce long-term biomechanical problems. These compensations increase fatigue, destabilize posture, and elevate the likelihood of falls. Left unaddressed, maladaptive walking patterns erode confidence in independent mobility and accelerate the transition to sedentary lifestyles.

Traditional interventions have made progress but remain fundamentally limited. Rehabilitation therapies are effective but require repeated clinical visits, extensive therapist supervision, and strong patient compliance, which can be difficult to sustain. Assistive devices such as canes, walkers, and orthotic shoes provide stability but function as passive supports; they help users remain mobile but do not actively retrain correct walking mechanics. Even advanced robotic exoskeletons, while capable of restoring locomotion in severely impaired individuals, are prohibitively expensive and often impractical for daily use. Importantly, few existing solutions combine portability, affordability, and real-time adaptive correction in a way that integrates seamlessly into everyday life. This leaves a large gap for a technology that can deliver both immediate stability and rehabilitative training simultaneously.

The STABLE system (Smart Tracking Assistance for Balance and Locomotion Enhancement) was developed to bridge this gap by integrating embedded sensing, corrective actuation, and haptic feedback into a compact, wearable form factor. By continuously monitoring plantar pressure distribution and foot orientation, STABLE identifies deviations from a user's personalized baseline in real time. When abnormalities occur, the system responds with corrective piston-based adjustments and vibrational cues that both stabilize the user and reinforce proper gait awareness. Unlike traditional devices that provide passive assistance, STABLE employs a proactive, adaptive approach to both prevent falls and train neuromuscular pathways toward lasting improvement. In doing so, it represents a significant advance in mobility rehabilitation technology, designed to restore independence and confidence in populations disproportionately affected by walking difficulties.

Objective

The primary objective of STABLE (Smart Tracking Assistance for Balance and Locomotion Enhancement) is to create a proactive, wearable rehabilitation system that not only assists walking but also retrains proper gait mechanics. Unlike traditional aids that provide passive structural support, STABLE is designed to monitor, detect, and actively correct deviations in foot pressure distribution and orientation in real time. This proactive design ensures that instability is addressed before it escalates into falls or injuries. Beyond safety, the system is intended to accelerate neuromuscular rehabilitation by reinforcing correct gait through continuous sensory feedback. In this way, STABLE functions as both an assistive device for immediate stability and a therapeutic trainer for long-term improvement.

The first major objective is continuous biomechanical monitoring of the foot during walking. By embedding pressure sensors into five critical plantar regions and coupling them with gyroscopic orientation tracking, STABLE captures detailed information on how weight and motion are distributed. These measurements are taken at high sampling frequencies (≥ 50 Hz) to ensure that even subtle gait abnormalities are detected. Monitoring is not limited to raw sensor values but is contextualized against a personalized baseline recorded during calibration. This ensures that corrections are tailored to the unique biomechanics of each individual rather than based on generic thresholds.

The second objective is adaptive mechanical correction using actuator-based intervention. Each plantar region contains opposing pistons that can raise or lower sections of the shoe sole to redistribute pressure when imbalances are detected. Similarly, deviations in foot rotation or tilt are counteracted through controlled micro-adjustments guided by gyroscope data. These interventions are subtle but perceptible, nudging the user's gait back into alignment without causing discomfort or overcorrection. Such mechanical adaptability transforms the shoe from a passive support structure into an active rehabilitation tool.

The third objective is haptic reinforcement of proper gait mechanics. When corrective interventions occur, vibration motors in the affected foot region are activated to notify the user of improper form. This creates a sensory association between biomechanical correction and user awareness, reinforcing learning through repetition. Over time, users develop proprioceptive sensitivity to gait deviations, enabling them to consciously adjust even in the absence of corrective forces. This coupling of mechanical correction with sensory feedback accelerates neuromuscular retraining, ensuring that improvements are retained beyond device use.

The final objective is data-driven rehabilitation tracking to support patients and therapists. STABLE logs all sensor data, corrective actions, and feedback events, storing them locally or transmitting them via Bluetooth or Wi-Fi for long-term analysis. This data provides therapists with objective metrics on progress, allowing them to adapt rehabilitation plans to each patient's needs. By combining independent operation with therapist oversight, the device functions as a hybrid between a self-sufficient assistive aid and a clinical rehabilitation tool.

Through these combined objectives, STABLE advances mobility technology from reactive assistance to proactive, adaptive rehabilitation.

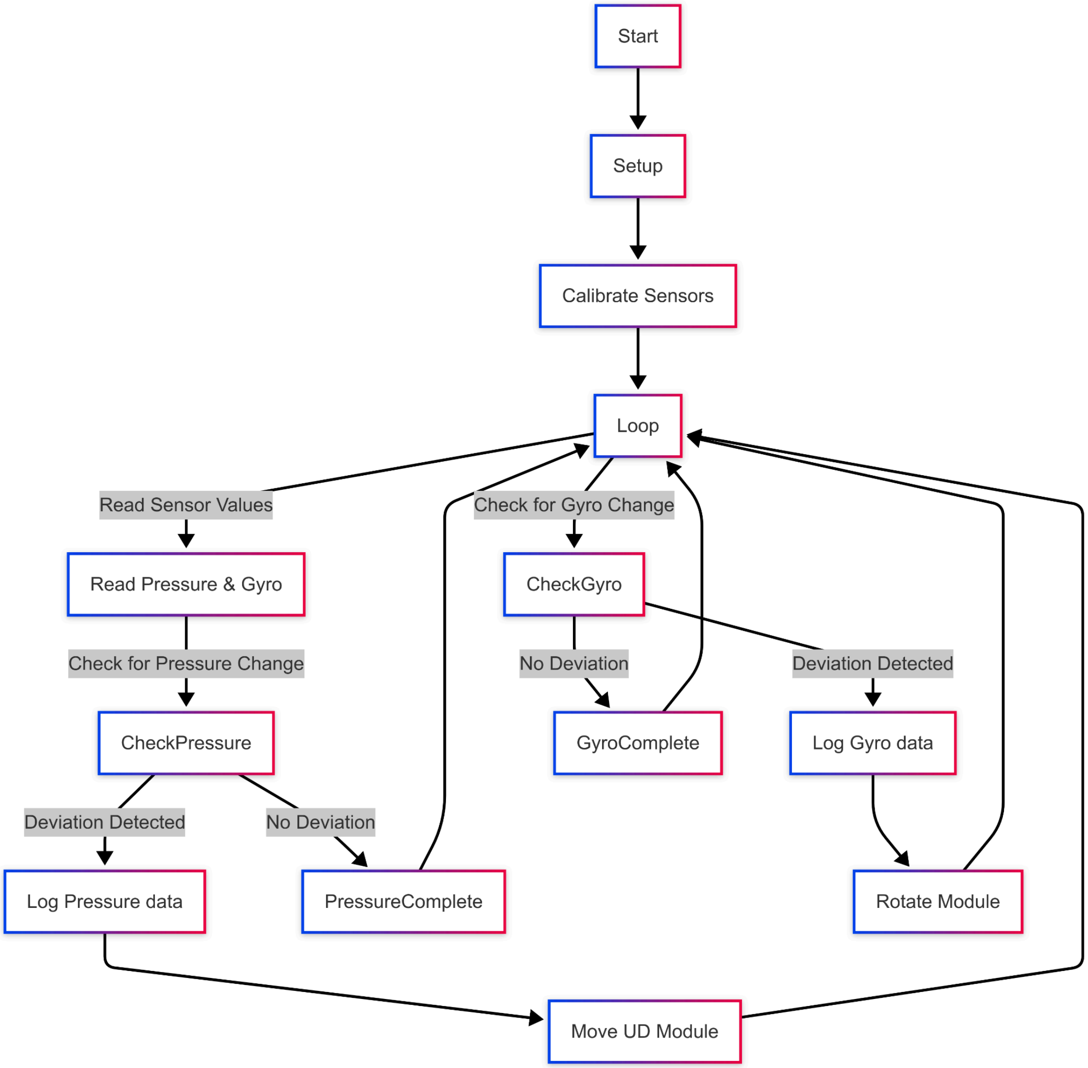


Figure 1. Flowchart of STABLE System Reactivity Towards Potential Threats

Design Specifications

The STABLE system was designed as a wearable rehabilitation platform that integrates multiple sensing, actuation, and feedback technologies into a shoe-like form factor. Its architecture follows the principles of safety-critical embedded system design, emphasizing fault tolerance, redundancy, and user comfort. The system is divided into five major subsystems: (1) pressure sensing, (2) orientation tracking, (3) corrective actuation, (4) haptic feedback, and (5) data logging and communication. Each subsystem is coordinated by a central microcontroller unit (MCU), which executes a closed-loop control algorithm that ensures timely intervention during walking. All electronics are embedded into a flame-retardant ABS enclosure within the shoe sole, balancing durability, safety, and weight considerations.

At the core of STABLE’s monitoring capability is the pressure sensing subsystem, which continuously measures load distribution across the plantar surface. The shoe sole is divided into five distinct regions: heel, medial midfoot, lateral midfoot, forefoot, and toe. Each region is embedded with force-sensitive resistors (FSRs) or capacitive load sensors that output variable resistance proportional to applied force. The sensors operate at a sampling frequency of 50–100 Hz, providing high-resolution temporal data that captures dynamic walking cycles. These measurements allow the system to detect abnormalities such as asymmetry, excessive heel striking, or toe dragging.

Sensor signals are routed through an analog-to-digital conversion (ADC) interface on the MCU. To minimize noise, each sensor channel includes an RC low-pass filter with a cutoff frequency of ~20 Hz, which smooths signal fluctuations caused by rapid gait transitions. Calibration routines normalize raw sensor outputs to account for manufacturing tolerances and individual differences in weight. Baseline data collected during initialization is stored in EEPROM or flash memory, enabling comparisons between normal and abnormal walking events. By employing both relative (percent load distribution) and absolute (force magnitude) metrics, the subsystem ensures robustness across different walking speeds and body types.

In addition to pressure monitoring, STABLE incorporates an orientation tracking subsystem to measure angular deviations of the foot. This subsystem uses a 6-axis inertial measurement unit (IMU), typically combining a 3-axis accelerometer and 3-axis gyroscope. The gyroscope provides angular velocity data for detecting rotational deviations, while the accelerometer measures tilt relative to gravity. Data fusion is performed using a complementary filter or Kalman filter to reduce drift and noise, ensuring accurate angle estimation during continuous walking. This combined orientation profile is critical for detecting improper strike angles, excessive pronation/supination, or foot drag.

Sensor placement is optimized near the midsole, where vibrations and accelerations most accurately reflect the foot's global orientation. Sampling is performed at ≥100 Hz to capture high-frequency deviations during dynamic gait phases such as heel-strike and toe-off. Raw IMU data is pre-processed by the MCU to calculate orientation in terms of pitch, roll, and yaw angles. Correction thresholds are established at ±10° for medial-lateral tilt and ±8° for rotational misalignment, based on biomechanical research on healthy gait ranges. When these thresholds are exceeded, the subsystem flags a deviation and initiates corrective measures.

The corrective actuation subsystem is responsible for redistributing plantar pressure and adjusting foot alignment in real time. Each of the five plantar regions is equipped with dual opposing pistons or miniature linear actuators. These pistons can raise or lower their respective sole section by up to 5 mm, sufficient to counteract uneven loading patterns without compromising comfort. When one side of the foot experiences excessive pressure, the overloaded piston elevates while the opposing one depresses, restoring balance in under 100 ms. This corrective adjustment ensures that users are guided back to a more stable and natural walking pattern.

Actuator motion is controlled by an H-bridge driver circuit connected to the MCU, allowing bi-directional control of piston extension and retraction. Safety constraints are implemented in firmware, limiting both maximum displacement and force output to prevent discomfort or injury. A closed-loop feedback system is employed, using Hall-effect sensors or potentiometers to track piston position and ensure accuracy. The actuators are powered by a dedicated 7.4V Li-ion battery pack with voltage regulation, as their power requirements exceed those of the sensors and MCU. Together, these elements provide a reliable and responsive mechanical correction mechanism.

While mechanical corrections stabilize gait physically, the haptic feedback subsystem provides sensory reinforcement to promote learning. Each plantar region is paired with a vibration motor capable of delivering targeted feedback when corrective action occurs. The motors are activated at frequencies between 150–250 Hz, which fall within the range of optimal tactile sensitivity for the human foot. Feedback intensity is scaled according to the severity of deviation, ensuring subtle cues for minor corrections and stronger vibrations for major ones. This graded feedback reinforces proprioceptive awareness, teaching users to recognize and adjust their gait consciously.

To prevent habituation, the vibration patterns alternate between pulsed and continuous modes, based on the duration of corrections. For instance, a brief pulse may indicate a minor heel-strike error, while a longer sequence may accompany more significant pronation correction. These patterns are pre-programmed in firmware and can be customized for user preferences during setup. Importantly, haptic signals are synchronized with mechanical corrections, ensuring that users perceive a direct association between instability and feedback. Over repeated use, this pairing accelerates neuromuscular retraining and improves gait even when the device is not worn.

STABLE is not only an assistive device but also a rehabilitation tool, made possible by its data logging and communication subsystem. All raw sensor data, detected deviations, actuator responses, and haptic events are timestamped and stored in onboard non-volatile memory. Data compression algorithms ensure efficient use of storage, allowing up to several weeks of walking logs to be retained. Periodically, this data can be transmitted wirelessly to an external device for long-term analysis. Communication is facilitated by a Bluetooth Low Energy (BLE) module or an optional Wi-Fi interface.

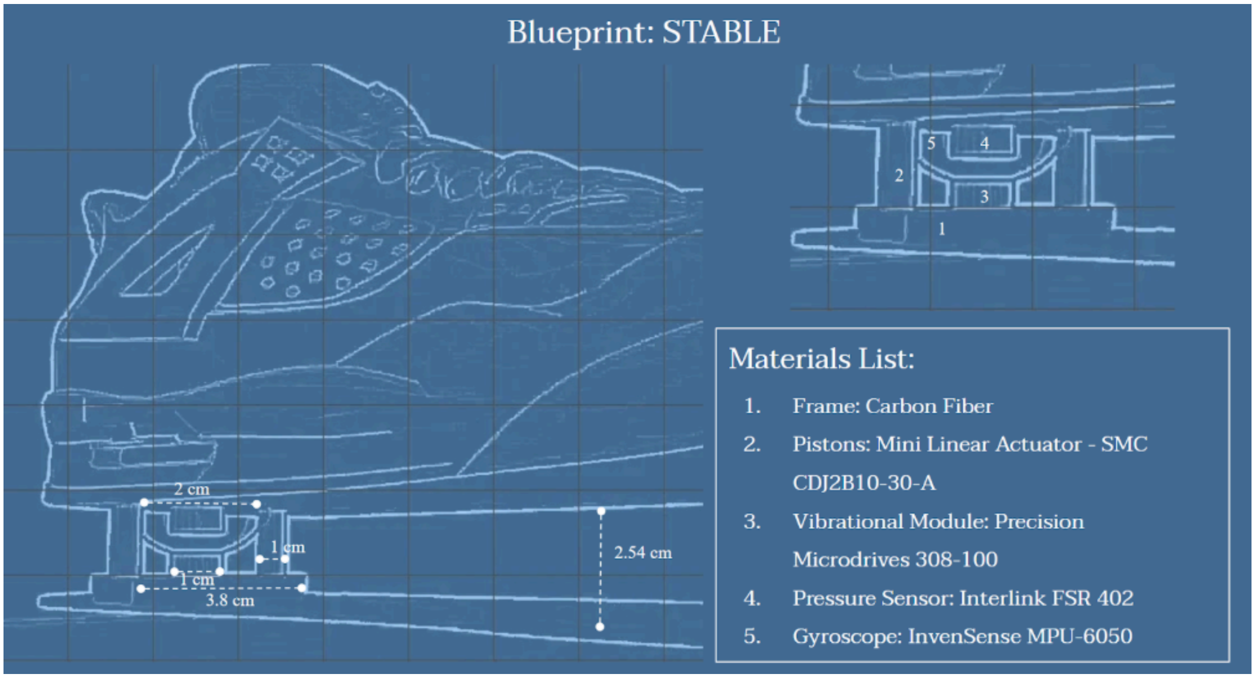
The transmitted data can be integrated into a mobile app or cloud platform for visualization. Patients can track daily improvements, while therapists can analyze gait metrics such as symmetry, balance index, and corrective intervention frequency. This functionality supports personalized rehabilitation plans and evidence-based therapy adjustments. For security, data transfer is encrypted using AES-128 or higher protocols to protect patient privacy. In advanced implementations, integration with healthcare IoT systems enables real-time therapist monitoring and automated progress reporting.

Since STABLE is designed for daily wear, power efficiency is a critical design specification. The system operates primarily on a 7.4V rechargeable Li-ion battery pack, with step-down voltage regulation to supply 5V and 3.3V rails for the MCU and sensors. Average current draw ranges from 100 mA during idle monitoring to 400 mA during peak actuation and feedback events. Power optimization techniques such as duty cycling, low-power sleep modes, and interrupt-driven wakeups are implemented in firmware to extend battery life. On a typical charge, the system provides 6–8 hours of continuous operation, sufficient for daily rehabilitation sessions.

Battery charging is managed by a TP4056 charging module with integrated overcharge, over-discharge, and short-circuit protection. A backup capacitor array ensures smooth transitions during high-current actuator spikes. In the event of complete battery depletion, the device retains calibration data and logs in non-volatile memory, ensuring continuity of operation once recharged. Optional inductive charging coils embedded in the shoe sole allow for wireless charging, improving convenience for elderly users. Together, these specifications ensure that STABLE is both portable and user-friendly.

The entire system is orchestrated by a low-power MCU, such as an ESP32 or ARM Cortex-M series processor. The MCU coordinates sensing, processing, actuation, and feedback in a deterministic real-time loop. Firmware is structured around a finite state machine (FSM) with operational states including Normal, Warning, Correction, Feedback, and Shutdown. Each state transition is triggered by sensor thresholds or time-based conditions, ensuring predictable and traceable responses. Watchdog timers and error detection routines protect against firmware lockups, while redundant sensor checks enhance fault tolerance.

Safety remains central to the system's design. All actuators are mechanically limited to prevent excessive displacement, and firmware imposes strict bounds on force outputs. Electrical isolation is achieved through opto-isolated drivers, minimizing risk during high-current actuator switching. The housing is fabricated from UL94-V0 flame-retardant ABS, capable of withstanding internal temperatures of up to 85°C. PCB layout adheres to IEC creepage and clearance guidelines to prevent short circuits, even in humid environments. Together, these safety measures ensure that STABLE operates reliably and securely in real-world rehabilitation contexts.



Materials List:

1. Frame: Carbon Fiber
2. Pistons: Mini Linear Actuator - SMC CDJ2B10-30-A
3. Vibrational Module: Precision Microdrives 308-100
4. Pressure Sensor: Interlink FSR 402
5. Gyroscope: InvenSense MPU-6050

Figure 2. Blueprint of STABLE: Illustration of Design with Component Specifications

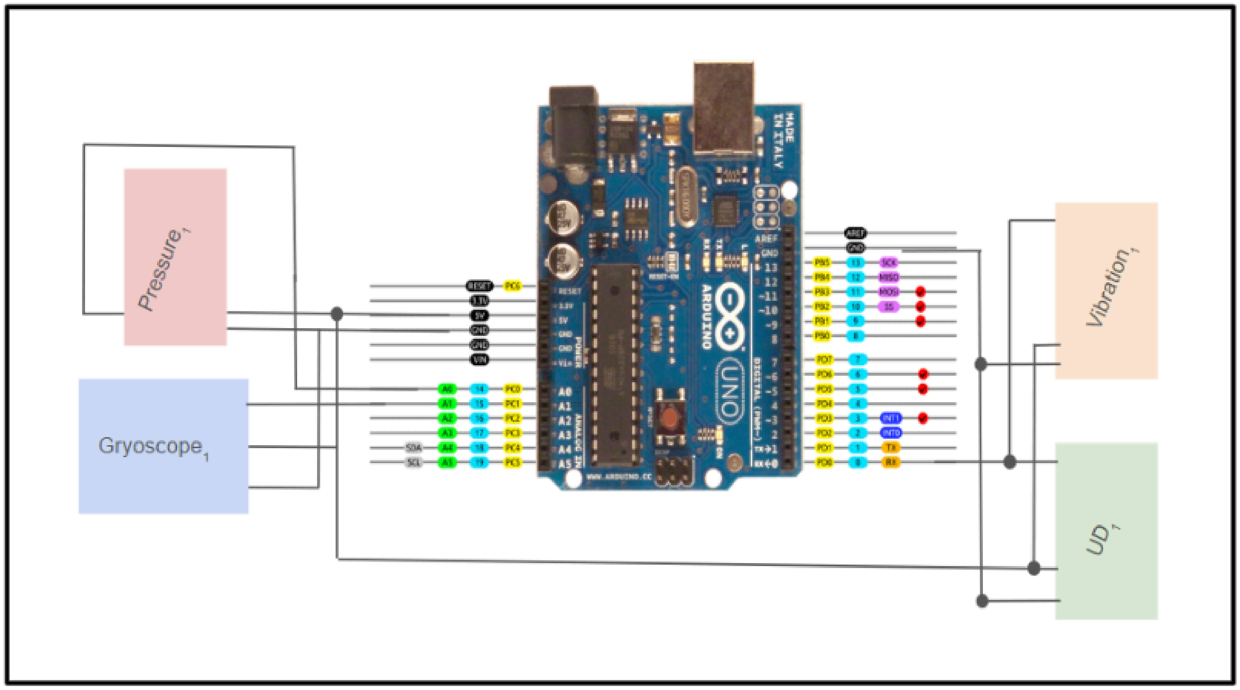


Figure 3. Simplified Circuit Diagram

Algorithm Description

The proposed system implements a real-time sensor monitoring and actuation framework integrating five pressure sensors, five gyroscopic sensors, and corresponding actuator modules, including up–down (UD) movement, rotational, and vibration units. The system is initialized by assigning all analog and digital pins to specific sensors and actuators. Let the pressure sensor readings be denoted by the vector $P = [P_1,P_2,P_3,P_4,P_5]$ and gyroscopic readings by $G=[G_1,G_2,G_3,G_4,G_5]$, where P_i, $G_i \in [0,1023]$ represent the analog-to-digital converted sensor values. Corresponding calibration values are stored as $P_{cal} = [P_1^{cal},\ldots,P_5^{cal}]$ and $G_{cal} = [G_1^{cal},\ldots,G_5^{cal}]$. The calibration process is mathematically expressed as:

$$P_i^{\text{cal}} = \text{ADC}(S_i^{\text{pressure, initial}}), \quad G_i^{\text{cal}} = \text{ADC}(S_i^{\text{gyro, initial}}), \quad i \in \{1,\ldots,5\}$$

where ADC(·) represents the analog-to-digital conversion function, and $S_i^{\text{pressure,initial}}$ and $S_i^{\text{gyro,initial}}$ denote the raw initial sensor voltages.

During the monitoring loop, the system computes deviations of each sensor from its calibrated baseline:

$$\Delta P_i = P_i^{\text{current}} - P_i^{\text{cal}}, \quad \Delta G_i = G_i^{\text{current}} - G_i^{\text{cal}}$$

where ΔP_i and ΔG_i are the scalar deviations for pressure and gyroscope sensors, respectively. These deviations serve as the inputs for actuator control and event logging. A positive $\Delta P_i > 0$ indicates increased pressure, while a negative value $\Delta P_i < 0$ indicates a decrease. Similarly, $\Delta G_i > 0$ corresponds to clockwise angular deviation, and $\Delta G_i < 0$ corresponds to counterclockwise deviation.

The actuator system converts sensor deviations into proportional mechanical responses. For pressure-induced UD module movement, the displacement U_i is modeled as a linear mapping:

$$U_i = k_P \cdot |\Delta P_i|, \quad k_P = \mathrm{PRESSURE\_TO\_UD\_RATIO}$$

For gyroscope-induced rotational actuation, the angular correction Θ_i is similarly defined:

$$\Theta_i = k_G \cdot |\Delta G_i|, \quad k_G = \mathrm{GYRO\_TO\_ROTATION\_RATIO}$$

The system applies an opposite-direction correction for gyroscopic deviation, yielding the effective actuator command vector:

$$\mathbf{A}_i^{\text{rotation}} = -\mathrm{sign}(\Delta G_i) \cdot \Theta_i$$

while the UD modules follow:

$$\mathbf{A}_i^{\text{UD}} = \mathrm{sign}(\Delta P_i) \cdot U_i$$

Vibration modules are triggered simultaneously with each actuation, providing tactile feedback and confirming mechanical execution.

To track deviations over time, the system defines a timestamp function t=millis(). For a deviation event starting at t_0 and ending at t_f, the event duration is:

$$\Delta t_i = t_f - t_0$$

Event logs are stored as a structured tuple:

$$\mathrm{Event}_i = \left(P_i^{\text{sensor}}, \Delta P_i \text{ or } \Delta G_i, \Delta t_i, \mathrm{type}(\Delta_i), t_0\right)$$

$$\text{where } \mathrm{type}(\Delta_i) = \begin{cases} \text{Positive} & \Delta_i > 0 \\ \text{Negative} & \Delta_i < 0 \end{cases}.$$

This logging ensures that every mechanical correction, whether translational or rotational, is quantitatively recorded alongside its temporal and directional characteristics.

The system approximates actuation duration T_i as proportional to the magnitude of the movement:

$$T_i = \alpha \cdot |\mathbf{A}_i|, \quad \alpha = 10\ \mathrm{ms/unit}$$

During this interval, the actuator and vibration pins are held high:

$$\mathrm{pinState}(i) = \begin{cases} \mathrm{HIGH} & t \in [t_0, t_0 + T_i] \\ \mathrm{LOW} & t > t_0 + T_i \end{cases}$$

This mathematical abstraction ensures that actuator displacement scales proportionally with the detected sensor deviation while integrating real-time constraints for sequential event handling.

The overall system can be described as a discrete-time, sensor-actuator feedback loop:

$$\forall t_n, \quad \mathbf{P}(t_n), \mathbf{G}(t_n) \xrightarrow{\Delta} \mathbf{A}^{\mathrm{UD}}(t_n), \mathbf{A}^{\mathrm{rotation}}(t_n) \xrightarrow{T_i} \mathrm{Event\ Log}_i(t_n)$$

where $t_n = n \cdot \Delta t$, $\Delta t = 100$ ms is the loop interval. This loop continuously monitors deviations, executes proportional corrections, and logs all events, producing a closed-loop control system that combines mechanical actuation with temporal analytics.

The algorithm integrates sensor deviation calculation, proportional actuator response, temporal event logging, and tactile feedback into a mathematically defined control system. Equations for deviation allow precise prediction of system outputs for given sensor inputs. The resulting framework is suitable for experimental and real-time applications.

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