Sentinel: Unobtrusive Physiological Regulation

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Sedentary activities such as office and desk work have been shown to increase the incidence of mental health issues including stress, anxiety, and depression. Guided and deep breathing techniques can help to alleviate these issues, but these exercises require intentional engagement which requires conscious effort, limiting viability in cases where context switching is unfeasible such as focused work. Haptic guidance can support deep breathing without interfering with focus, but existing interventions are high friction, requiring manual triggering or wearable sensors which limit user engagement. Sentinel is a modular somatic breathing guidance system which provides physiological measures through indirect ballistocardiography and encourages structured breathing with a pneumatic backrest.

I. Introduction / Background

The links between sedentary behaviour, particularly in occupational settings, and mental health issues are well explored in literature[1]. Increasing computerisation and automation in the workplace have led to a general reduction in physical occupational activities in favour of seated desk work[2]. While public awareness of these issues is rising [1], [3], many proposed solutions rely on active engagement in the management techniques which can be fundamentally incompatible with the "flow states" of high-focus work [4], [5], [6]. Prior work has shown that interrupted work can increase stress and frustration, suggesting that the relaxation benefits of stress management methods might be inhibited by this effect[7], [8].

Slow, structured breathing exercises have been shown to reduce stress indicators including cortisol and heart rate[9], [10] and improve mood [11] even in short bursts. Passive interventions without conscious initiation may be beneficial simply because they don't rely on the user's cognitive bandwidth to trigger. Auditory, tactile and olfactory stimuli can remain peripheral because their neural systems evolved in part for continuous autonomic monitoring, whereas visual processing is tightly coupled to focal attention and goal-directed action [12], [13]. Calm technology research therefore increasingly explores sound and haptics as low-bandwidth modalities[14], [15], a space with significant cross-over with stress reduction research.

Wearable devices can provide consistent monitoring but in practice have user engagement issues are common. In addition to the general privacy concerns of a wearable device acting as a constant reminder of monitoring[16], users may find the devices physically uncomfortable due to the extra weight of sensors, batteries and processing compared to regular clothing or accessories or the need for some sensors to have close contact to the skin[17]. Charging and maintenance of wearable devices also requires mental bandwidth which may not be conducive to a low-stress experience[17].

Smart furniture research can resolve some of the issues inherent to wearables and active interventions by allowing for systems to literally be embedded as "part of the furniture" without direct user setup [18], [19]. For instance, smart beds allow for non-obtrusive sleep analysis [20] and automatic adjustment to avoid bed sores [21] while smart carpets can provide passive gait analysis and fall monitoring [22], [23]. Given the increasing time spent in seated positions, smart chairs also provide a clear vector for intervention.

II. Related Work

A. Low-focus breathing guidance

Zepf et al. explore the use of seat-back haptic pulses as an aid to stress management while driving [24]. The test system described uses a Zephyr BioModule chest-mounted biosensor for heart and respiration rate monitoring, triggering the haptics at a rate slightly below the user's measured respiration rate whenever it exceeds their resting rate. While this reduced the users' average respiratory rates compared to the baseline, the effect was not statistically significant. A wearable sensor for subtle pneumatic-haptic feedback [25], again using the Zephyr BioModule for sensing, was found to provide a statistically significant reduction in breathing rates without an increase in mental load during a passive test, but in a follow-up study requiring active participation across walking, driving and office work did not achieve a statistically significant reduction [26].

Breathm uses linear actuators to provide a simulated abdominal breathing motion tuned to the user's breathing, detected using a barometric pressure sensor all inside a "huggable" cushion [27]. This provided a statistically significant reduction in breathing rate when tested without additional tasks or stimuli. While effective, the cushion design needed to be held to achieve reliable measurements and feedback, limiting viability for focused activities. Prior work implies that these methods would be effective due to subconscious synchronization of biological rhythms to external signals [28].

B. Unobtrusive physiological monitoring

Most continuous physiological monitoring depends on direct physical contact through wearable devices, which tends to offer more consistent data during movement compared to remote techniques [29]. This comes at the cost of an additional mental load attributed to the use of a wearable device [8].

Unobtrusive monitoring methods allow physiological data collection without this mental load. Optical methods such as infrared and depth sensing allow for non-contact measurement of respiration and heart rates[30], [31], while signal distortion and interference from bodies in RF signals can be used to monitor breathing and movement using a standard Wi-Fi router[32]. Stress levels can even be estimated from the cadence of a user's typing [33].

C. Healthy Furniture

Given that modern life often involves large amounts of sitting or lying down, furniture like beds and seating present an ideal chassis for physiological monitoring. Prior work has demonstrated the combination of pressure sensors to measure prolonged sitting and posture with multiple notification modalities to encourage movement [34], [35].

A 'smart chair' integrating several monitoring features including heart rate, sitting time and posture has been proposed in prior work, although at the time of writing any implementation or testing not been explored beyond an initial proposal, and no feedback mechanisms beyond mobile notifications have been suggested [36].

III. Imagined or Existing Prototype Sketches/Drawings/Photos

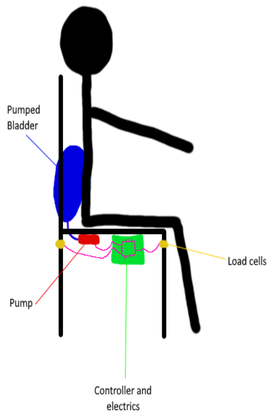

Figure 1 – System sketch

A. System design

The proposed system consists of three core components mounted on a chair. Load cells situated on the legs will capture BCG signals. This will be used to calculate a stress indicator based on a combination of physiological indicators. When stress exceeds the baseline, a pumped bladder on the back is used to provide a calming breath-like sensation.

This system is intended to be expandable with additional sensors and actuators. For instance, skin conduction, a core indicator of arousal, could be included through the use of conductive fabric pads on the armrests while an IR heat array could measure skin temperature. These additional sensors can be integrated to the stress indicator to improve estimation reliability.

B. MVP Prototype

Since the proposed functionality of the Sentinel system is sensor and actuator agnostic, the MVP design prioritizes the use of components which are already stocked or salvageable from e-waste to limit initial development costs. The controller logic should be reusable through prototype iterations to reduce development time. As such, the initial design used three core components: an electrocardiogram (ECG) using a spare sensing circuit from a past project, a Raspberry Pi Pico for logic and control, and a fan to provide a cooling airflow.

1) Components

a) Power Supply

To provide 12V power for the pump driver, a spare trigger module (Manufacturer ELFJMZP) is used in combination with a compatible USB-C PD adapter as a lightweight power supply. The supply ground is wired to common ground, and positive to ULN2003 positive terminal.

b) AD8232 Heart Rate Monitor

An AD8232 board was salvaged from a previous project to provide a ground-truth ECG signal for the MVP prototype. To reduce signal noise from the motor, the AD8232 ground is connected to a separate ground pin on the Pi Pico controller. The analogue output from the AD8232 is read from the Pico's ADC.

For ease of use, the AD8232 is connected via liquid gel electrodes to the skin, with Left Arm (LA) and Right Arm (RA) connected at the respective wrists and Right Leg (RL) connected just below the right elbow. Wrist electrodes provide a less reliable signal but are less invasive than chest mounting [37].

c) Pump Driver

In the proposed prototype system, a single channel from a ULN2003 stepper drive board is used to drive a pump at 12V from the Pico's PWM output. For the purposes of the MVP, a fan salvaged from e-waste provides variable cooling since reducing ambient temperature has been shown to aid in reducing stress indicators [38].

d) Raspberry Pi Pico

A low-cost Raspberry Pi Pico is used as the control unit for the MVP. This was primarily a result of availability, although the PIO capabilities of the Pico series does offer some advantages for consistent sensor timing compared to ESP32 units for this project.

2) Circuit Configuration

The core circuitry is assembled as seen in Figure 3 on a breadboard, barring the ULN2003 board, trigger module which could not be reliably mounted so these are kept separate, as well as the fan and ECG wires which needed to be moveable for functionality. For MVP purposes these were allowed to remain free, although in actual application these would benefit from a 3D-printed housing to hold the stepper and trigger module in particular.

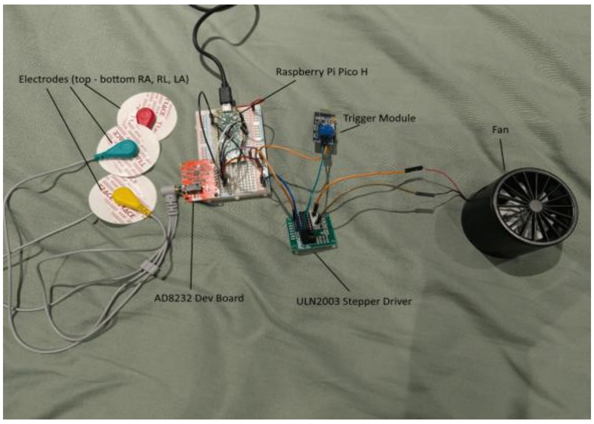

Figure 2 – The assembled MVP circuit

3) Software

CircuitPython is used to program the Pi Pico microcontroller. A naïve estimate of heart rate is based on a "beat" occurring when the ECG signal exceeds 150% of the 1.65V baseline, with a short (200ms) refractory period to prevent double-triggering. The time between beats is calculated and BPM averaged over 15 beats for a simple smoothing effect.

Where BPM exceeds a 100bpm (upper bound for resting heart rate [39]), the fan is activated, with duty cycle ramping between 0 (at the threshold) to 70% at 150bpm. This avoids a squealing sound the fan produces at high speeds which is both annoying and not conducive to reducing stress.

The ECG data collection code was developed based on an Arduino sample [40] ported to CircuitPython. The Teleplot plugin for VSCode [41] was used to log the ECG trace and resultant BPM and fan speeds which were used with Matplotlib[42] to produce the plots in **Error! Reference source not found.**.

4) MVP Post-Mortem

In keeping with the responsible innovation goals of the project, this MVP was developed under the ethos "nothing purchased, nothing permanent". In other words, no new components could be purchased to aid in development of the prototype, and non-consumable components should be used in such a way that they could be easily disassembled and re-used. While these restrictions definitely led to some interesting solutions to challenges, such as adapting a stepper driver to run a pump (and then a fan) and an informative deep dive on the inner workings of a medical PAT sensor, they also caused some unnecessary complexity and awkward design solutions like bare wires pressed into header pins for want of a screw terminal connector.

A sample of the raw ECG data along with calculated heart rates and resultant fan speeds is shown in **Error! Reference source not found.**. Since the sensors were mounted on the wrists rather than the chest, this signal was contaminated with EMG signals resulting from muscle activations, but fortunately this didn't appear to affect the signal to noise ratio from the R peaks of the ECG. In order to produce a "real"-looking ECG trace, the combination of a bandpass filter and exponential moving average would give better looking results at the cost of possibly reducing accuracy. This would probably be necessary in the event that visualization were wanted in a later prototype, but definitely falls out of scope for the MVP and initial prototypes.

C. Proposed Prototype

1) Ballistocardiography Module

The BCG module is built around a single load cell placed underneath the seated user. This method has previously been validated using a piezoelectric sensor built into the seat of a chair [43], however the limited lifespan of piezo sensors limits long-term viability. Instead, a set of four smaller load cells will be used for BCG sensors. S-Type load cells allow the chair base to be bolted to the load cells, which are then bolted to the chair seat. This would add approx 80mm to the seat without impacting stability.

This design is fairly flexible to chair designs given that most chairs with 4+ legs have at least 4 bolt fasteners connecting the legs and the seat. For chairs without such fasteners, the load cells could instead be integrated into a cushioned pad to be placed on top of the seat. The load cells will be connected to an ADS1256 Analogue-Digital Converter (ADC). This gives significantly higher resolution than the onboard ADC on the Pi Pico (24-bit vs 12-bit), allowing approximately 20 bits of noise-free resolution for a reliable resolution of around 4mN (0.4g). Given that the pre-dampened longitudinal force applied from the J-wave of the heartbeat is approximately 10g [44], this signal should be sufficient to detect the heart rate and will definitely be sufficient for respiration.

To improve signal to noise, the ADS1256 and load sensors can be provided a clean 5v signal using an LDO and sampled at higher than necessary speeds in combination with a low-pass filter to improve effective resolution.

2) *Air Bladder*

A simple airtight weld can be formed in thermoplastic polyurethane (TPU)-coated fabrics through heat sealing layers together [45]. A fully-enclosed cushion can be created relatively simply, with a polyurethane (PU) tube for inflation and deflation which can then be connected to a standard push-fit pneumatic adapter such as the KJH-04-M6. Connecting the bladder to the common port of a 3/2 solenoid valve, with one side open and the other connected to a pump allows for controlled inflation and free deflation. To avoid a risk of overinflation an adjustable pressure relief valve can be added between the switching valve and the bladder.

3) *Mounting*

The core electronics of the system can be mounted inside a simple 3D printed enclosure. This would ideally be mounted on the underside of a chair to keep it out of the way, although it could also be fitted to the backrest depending on space requirements.

4) *Software*

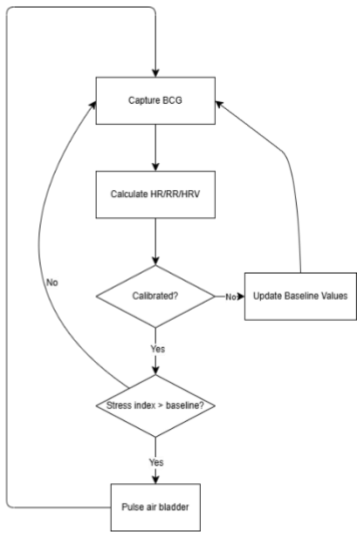

Figure 3 - Overall logic loop

Figure 6 shows a high-level overview of the system logic. The fundamentals of the software will be fairly similar to the MVP, with a simple loop of measuring biometric data, calculating associated values and triggering the actuation if physiological stress indicators exceed a value. The added potential complexity comes from the data provided from BCG, namely the combination of respiratory rate, heart rate and (by extension) heart rate variability (HRV). By combining these values, a “stress index” can be calculated based on multiple indicators, providing a more reliable overview than any single measure. Measuring respiratory rate also allows the pulse rate of the air bladder to be tuned to slightly below the user’s actual breathing rate, aiding in relaxation.

5) *Non-standard Component Sourcing*

Where possible, suppliers with UK operations are listed although some components would only be feasible to obtain through suppliers like AliExpress.

Component	Primary Source
ADS1256	ThePiHut (AD/DA board)
Load cell	Amazon/eBay/AliExpress (PSD-S1 type)
Air pump	ThePiHut
3/2 Valve	ThePiHut
Relief valve	RS
TPU Nylon	Faulty dry bags/camping equipment

IV. RESPONSIBLE INNOVATION

Where possible, components used in the MVP prototype have been obtained as salvage from e-waste devices or spare parts from previous projects in order to reduce development costs and improve sustainability in the fabrication process. The proposed prototype design is largely setting-agnostic, with the intention that it can be installed in a user’s existing seating and re-used if the chair is replaced in order to reduce the generation of e-waste from the project, and avoid the general waste of requiring a new case.

Although the proposed system provides physiological measures, no data is logged by default to protect privacy. Any data collected for debugging purposes should be minimal and avoid any identifying information such as user age, sex or name.

V. AUTHOR BIO(S) / EXPERIENCES

The majority of my personal projects are small solutions for bespoke home automation such as simple seat and bed occupancy sensors, a coaster to measure water intake and adding smart control capabilities to “dumb” lamps. During my undergraduate studies, I explored the development of non-contact respiratory monitoring using the time-of-flight sensing capabilities of a Microsoft Kinect V2. This kickstarted my interest in low-friction physiological monitoring, which expanded further during my degree studies.

My current work focuses on the development of techniques for the personal fabrication of output devices through additive manufacturing, with a particular interest in non-standard interaction modalities such as form-agnostic displays and controllable scent release interfaces. As part of this, I am currently developing a low-cost electronic nose system which iterates on prior work in the space [46]. I additionally contributed a recycling technique to convert waste plastic into reusable FFF printing filament for Printegrated Circuits, with the submitted paper receiving special recognition for sustainability at the TEI 2026 conference (https://dl.acm.org/doi/10.1145/3731459.3773307).

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