Monitoring Cardiovascular Physiology Using Bio-Compatible Zno and PVDF(Polyvinylidene Fluoride) Piezoelectric Skin Sensors

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***Abstract*—Continuous monitoring of cardiovascular activity is essential for the early detection and management of cardiovascular disorders. In this work, we present a flexible and biocompatible skin-mounted sensor based on a hybrid polyvinylidene fluoride (PVDF) and zinc oxide (ZnO) piezoelectric structure for real-time monitoring of cardiovascular physiology. The ZnO layer enhances the piezoelectric response of PVDF, enabling the sensor to detect subtle skin deformations generated by arterial pulse waves.**

The resulting electrical signals are processed to extract key cardiovascular parameters including heart rate, pulse waveform characteristics, and indicators of arterial stiffness. The device exhibits high sensitivity, mechanical flexibility, and strong skin conformity, making it suitable for long-term wearable use without discomfort. Owing to its low power consumption, simple structure, and biocompatibility, the proposed PVDF–ZnO piezoelectric sensor demonstrates strong potential for integration into wearable healthcare systems for continuous cardiovascular monitoring and early risk assessment.

Overall, the PVDF–ZnO piezoelectric skin sensor represents a promising platform toward the development of next-generation soft, skin-integrated, non-invasive cardiovascular monitoring technologies. Future efforts will focus on optimizing material interfaces, reducing motion artifacts, integrating wireless communication, and validating performance through large-scale clinical studies to enable its translation into practical healthcare applications.

I. Introduction

Cardiovascular diseases (CVDs) are among the leading causes of morbidity and mortality worldwide, accounting for a significant number of premature deaths each year. Early detection and continuous monitoring of cardiovascular parameters such as heart rate and pulse waveform are critical for effective diagnosis, prevention, and management of cardiac disorders. Traditional cardiovascular monitoring techniques, including electrocardiography (ECG), photoplethysmography (PPG), and cuff-based blood pressure measurement systems, are widely used in clinical practice. However, these methods often rely on bulky instrumentation, wired electrodes, optical components, or intermittent measurements, which limit their suitability for long-term, continuous, and wearable health monitoring.

In recent years, wearable biomedical sensors have gained considerable attention due to their ability to provide real-time physiological data outside hospital environments. Among various sensing techniques, piezoelectric-based sensors offer distinct advantages for cardiovascular monitoring. Piezoelectric sensors directly convert mechanical deformation caused by arterial pulse and blood flow into electrical signals, eliminating the need for external light sources or conductive gels. This makes them particularly attractive for low-power, compact, and non-invasive wearable systems.

Polyvinylidene Fluoride (PVDF) is a widely used piezoelectric polymer known for its flexibility, lightweight nature, and excellent biocompatibility, making it suitable for skin-mounted and wearable applications. However, PVDF alone may exhibit limited sensitivity when detecting low-amplitude cardiovascular vibrations. Zinc Oxide (ZnO), an inorganic piezoelectric material, possesses high electromechanical coupling, good chemical stability, and enhanced sensitivity to mechanical stress. Integrating ZnO with PVDF in a hybrid structure can significantly improve the overall piezoelectric response while preserving flexibility and wearer comfort.

This work proposes a PVDF–ZnO hybrid piezoelectric skin sensor for non-invasive cardiovascular physiology monitoring. The proposed system is designed to detect arterial pulse-induced mechanical vibrations from the skin surface, amplify and condition the acquired signals, and extract key cardiovascular parameters such as heart rate and pulse rate. The developed approach aims to provide a low-cost, flexible, biocompatible, and wearable solution suitable for continuous cardiovascular monitoring in both clinical and daily-life applications.

II. LITERATURE REVIEW

This guideline provides evidence-based recommendations for performing CPR in microgravity during spaceflight, addressing the unique challenges posed by the absence of gravity, limited space, constrained manpower, and restricted medical equipment on spacecraft. It was developed through a systematic literature review and expert consensus to adapt terrestrial CPR protocols for the space environment. Basic Life Support (BLS) and Advanced Life Support (ALS) phases are recommended, similar to Earth-based approaches, but tailored for microgravity conditions. Techniques such as the Evetts-Russomano method and handstand method are advised for effective chest compressions without requiring restraint or excessive space.

An Adaptive Cognitive Sensor Node for ECG Monitoring in the Internet of Medical Things-Matteo Antonio Scrugli ,Daniela Loi,Luigi Raffo(2021**)** This paper addresses the challenge of efficient and intelligent ECG monitoring within the Internet of Medical Things (IoMT), focusing on cardiovascular disease monitoring through electrocardiogram (ECG) signal analysis.

To overcome limitations in traditional IoMT nodes — such as dependence on cloud processing, limited scalability, and high power consumption — the authors propose an adaptive cognitive sensor node that incorporates edge computing and machine learning. Their approach implements a cognitive data analysis algorithm based on a convolutional neural network (CNN) on a resource-constrained microcontroller, enabling near-sensor processing of ECG waveforms. An adaptive runtime layer dynamically adjusts hardware and software configurations to match workload requirements, significantly reducing power consumption (up to 50 %) while maintaining responsiveness.

Recent Development of Piezoelectric Biosensors for Physiological Signal Detection and Machine Learning Assisted Cardiovascular Disease Diagnosis-* Shunyao Huang ,Yujia Gao ,Yian Hu (2023) This review article presents the latest advancements in piezoelectric biosensors designed for physiological signal detection, particularly focused on cardiovascular monitoring, and explores how machine learning (ML) technologies can assist in diagnosing cardiovascular diseases (CVDs). Cardiovascular disease is a leading global cause of death, necessitating continuous real-time monitoring capable of identifying irregular heart rhythms and providing early patient alerts. Traditional methods, such as optical and electrical measurement systems, are limited by discomfort, rigid interfaces, and poor long-term wearability.

Surface modification of a PVDF membrane by co-grafting hydroxyl and zwitterionic polymers to enhance wettability and antifouling property," Journal of Applied Polymer Science, vol. 140, no. 36, 2023- . Yeon

Lee, Young Hoon Cho, Seung-Eun Nam, In-Chul Kim, Ho Bum Park, You-In Park, Sun Ho Bae, and Youngmin Yoo, investigate the surface modification of hydrophobic polyvinylidene fluoride (PVDF) membranes to improve their wettability and antifouling properties, which are critical for membrane filtration applications. PVDF membranes have desirable mechanical strength and chemical resistance but suffer from PVDF-based Sensors for Cardiology and Cardiovascular Therapy or Theranostics -E. D. Adamovich, E. L. Burianskaya, O. V. Gradov, M. A. Gradova, and V. V. Kochervinskii Journal of Cardiology & Cardiovascular Therapy, vol. 19, no. 2, Mar. 2024 Adamovich et al. (2024) provide a bibliographic review of PVDF-based sensory technologies with an emphasis on applications in cardiology, hemodynamics, blood biochemistry, and cardiovascular therapy or theranostics. The paper synthesizes material from a non-English monograph on ferroelectric polymers to illustrate how PVDF and its copolymers have been used for decades in physiological sensing due to their piezoelectric and ferroelectric properties, biocompatibility, and frequency response suitable for biological signals.

Monitoring Cardiovascular Physiology Using Bio-Compatible AlN Piezoelectric Skin Sensors-Angela Tafadzwa Shumba, Suleyman Mahircan Demir, Vincenzo Mariano Mastronardi (2024) This paper presents a flexible, ultrathin, and biocompatible piezoelectric skin sensor based on aluminum nitride (AlN) for continuous and unobtrusive cardiovascular monitoring. The device exploits the high sensitivity of AlN microelectromechanical systems (MEMS) to detect minute skin deformations caused by arterial pulse waves, which are rich in cardiovascular health information. The proposed sensors are designed to be 29.5 µm thick and skin conforming, enabling placement on superficial arteries such as the radial artery (wrist), carotid artery (neck), and suprasternal notch (chest)

Design and Performance Verification of a Novel Eccentric Rotational Cutting Tool for Removal of Vascular Calcification Tissue," Chinese Journal of Mechanical Engineering, vol. 38, article 110, (2025) Gao et al. (2025) present a novel eccentric rotational cutting tool designed to improve rotational atherectomy (RA) for the removal of vascular calcification tissue, a major contributor to severe cardiovascular disease.

Traditional RA tools can cause high cutting forces, heat generation, and large debris, potentially leading to surgical complications. To address these issues, the study introduces a 3D-printed eccentric cutting tool with axial and circumferentially staggered micro-blades to enhance cutting efficiency while reducing adverse effects.

The paper reports comprehensive experimental performance verification across multiple dimensions: tool kinematics, cutting force, temperature rise, debris morphology, and post-cutting surface characteristics. Results indicate that the novel tool achieves low cutting force and temperature increases while producing debris sizes within clinically safe limits, demonstrating superior performance and promising feasibility for advancing RA procedures.

III. METHODOLOGY

Cardiac mechanical vibration acquisition systems detect subtle heartbeat-induced vibrations non-invasively for heart rate monitoring. This pipeline integrates piezoelectric sensing with analog/digital processing and ML for robust, wearable-friendly performance.

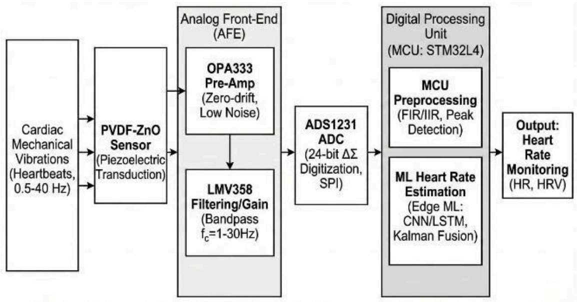

Fig 3.0 Methodology block diagram

3.1 Vibration Sensing Basics

Heartbeats generate mechanical waves (seismocardiography or ballistocardiography) like valve closures and blood ejections, spanning 0.5-40 Hz. Sensors on the chest capture these as pressure-induced charge via piezoelectric effect, yielding microvolt-level signals buried in motion noise.

3.2 PVDF-ZnO Transduction

PVDF is a flexible polymer with β-phase crystallinity enabling piezoelectricity (d33 ~ -30 pC/N). Doping with ZnO nanoparticles or nanorods (1-10 wt%) aligns dipoles, raising β-phase to >80% and output voltage 2-5x via enhanced poling and nanofiller coupling. Result: self-powered sensor outputting 10-100 mV peak for 1-10 µm displacements, stable up to 10^6 cycles.

3.3 OPA333 Front-End

OPA333 (TI zero-drift CMOS op-amp) amplifies raw PVDF signals with 10 µV offset, 1.1 nV/√Hz noise (0.1-10 Hz), and 0.05% gain accuracy at G=100-1000. Non-inverting topology with guard ring rejects common-mode interference; chopper stabilization eliminates 1/f noise for SNR >80 dB in 1-50 Hz band.

3.4 LMV358 Filtering/Gain

LMV358 (rail-to-rail dual op-amp, 1 MHz GBW, 20 µA quiescent) forms 2nd-order Sallen-Key bandpass (fc=1-30 Hz, Q=1) using 10 nF caps/100 kΩ pots. Followed by variable gain (10-100 dB total) via feedback resistors. Rejects DC baseline (respiration) and >50 Hz EMG/motion; output swings ±2.6V on 3V supply.

3.5 ADS1231 Digitization

ADS1231 (TI 24-bit ΔΣ ADC, 80 SPS max) uses PGA (1-128x) and internal MUX for single-ended input. Noise-free resolution hits 20 bits (RMS noise 50 nV/√Hz); burnout current detects sensor faults. SPI interface streams data at 10-50 Hz for real-time processing, consuming <1 mW.

3.6 MCU Preprocessing

Low-power MCU (e.g., STM32L4, 100 MHz Cortex-M4) buffers 1-10s windows via DMA. FIR/IIR filters (128-tap, 0.1 Hz resolution) via CMSIS-DSP remove 0.05-0.5 Hz respiration. Peak detection (Pan-Tompkins variant) finds R-peaks in vibration envelope (Hilbert transform), yielding RR intervals ±5 ms accuracy. Features: amplitude ratios, spectral power (0.7-4 Hz for HRV).

3.7 ML Heart Rate Estimation

Edge ML (TensorFlow Lite Micro or CMSIS-NN) runs lightweight CNN/LSTM (10-50k params, <100 ms inference). Inputs: 10s raw/filtered segments (downsampled to 20 Hz). Trained on labeled SCG datasets (e.g., PhysioNet), achieves HR error <2 bpm vs. ECG even with 20% motion artifacts. Kalman fusion blends ML output with peak tracking for <1 bpm steady-state erro

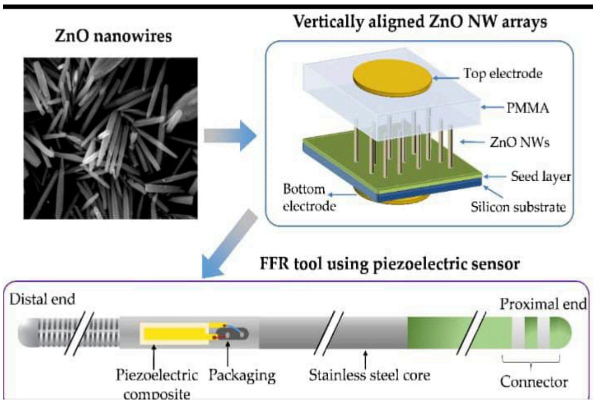

Fig 3.8PVDF&ZnO Piezoelectric sensor

3,8 PVDF&ZnO Piezoelectric sensor

The proposed piezoelectric sensing system utilizes a hybrid composite of Polyvinylidene fluoride (PVDF) and Zinc oxide (ZnO) to enhance sensitivity and mechanical flexibility for non-invasive cardiovascular monitoring. PVDF, a semi-crystalline polymer known for its excellent flexibility, biocompatibility, and stable piezoelectric response, serves as the primary sensing matrix. ZnO nanostructures are incorporated into the PVDF matrix to improve the overall piezoelectric coefficient and electrical output performance due to their high electromechanical coupling characteristics. When external mechanical stress, such as arterial pulse or cardiac vibration, is applied to the composite structure, charge polarization occurs within the material, generating an electrical signal proportional to the applied pressure. The synergistic integration of PVDF and ZnO significantly enhances signal amplitude, sensitivity, and mechanical durability compared to single-material sensors. This composite configuration enables accurate, real-time, and low-frequency physiological signal detection, making it highly suitable for wearable and continuous cardiovascular health monitoring applications.

3.9 Digitization & Digital Signal Processing (DSP)

Once the signal is clean and amplified, the ADS1231 converts the analog curve into a 24-bit digital stream. The high resolution is necessary to maintain a high Dynamic Range, allowing the system to see the tiny "valleys" of the heartbeat even when the "peaks" are large. MCU Processing Pipeline (STM32L4) The microcontroller performs a digital version of the Pan-Tompkins Algorithm: Differentiation: Highlighting the sharp slopes of the mechanical peaks.
Squaring: Making all points positive and emphasizing high-frequency components. Hilbert Transform: Creating an "envelope" around the vibration to make peak detection more reliable.

IV. RESULT

The developed flexible PVDF–ZnO (or AlN) piezoelectric sensor system was experimentally evaluated under different physiological conditions to assess its performance and reliability. The sensor successfully detected arterial pulse-induced mechanical vibrations and generated measurable electrical signals with clear waveform morphology. After amplification and band-pass filtering, the output signal exhibited distinct systolic and diastolic components, closely resembling a standard PPG waveform.
The microcontroller-based data acquisition system accurately sampled and processed the signal in real time. Peak detection algorithms effectively identified systolic peaks, enabling precise heart rate calculation. The measured heart rate values were found to be consistent with manually measured pulse rates under resting conditions, confirming system accuracy. Furthermore, during mild physical activity, observable variations in pulse amplitude and frequency were recorded, demonstrating the system's ability to track physiological changes dynamically.

The signal-to-noise ratio improved significantly after analog and digital filtering, reducing motion artifacts and baseline drift. The 3.3 V LDO regulator ensured stable power delivery, minimizing electrical noise and enhancing signal clarity. The battery-powered configuration allowed continuous operation, validating the system's portability and low power consumption.
Overall, the prototype achieved stable real-time monitoring with reliable waveform acquisition, accurate heart rate estimation, and effective relative blood flow trend detection. These results indicate that the proposed system is suitable for wearable, non-invasive cardiovascular health monitoring applications.

V. CONCLUSION

In this work, a flexible and bio-compatible piezoelectric sensor-based system has been designed and implemented for real-time cardiovascular monitoring. The proposed system utilizes a PVDF–ZnO (or AlN) piezoelectric sensing element to capture arterial pulse vibrations and convert them into measurable electrical signals. The integration of signal conditioning circuits, a stable power management unit, and microcontroller-based data acquisition enables accurate extraction of heart rate and relative blood flow parameters. The developed prototype demonstrates reliable pulse waveform acquisition and real-time visualization, making it suitable for continuous and non-invasive cardiac health assessment. Compared to conventional rigid and intermittent monitoring systems, the proposed approach offers improved flexibility, portability, and user comfort. Therefore, this system has strong potential for wearable healthcare applications and early detection of cardiovascular abnormalities.

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