Next-Generation Stretchable EDA Sensors with Ag-NP Fractals for Motion Artifact-Free Physiological Sensing in Dynamic Environments

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Abstract

Construction workers frequently encounter substantial mental stress due to the high demands of their roles, including tight deadlines and challenging environmental conditions. Although electrodermal activity (EDA) sensors offer a promising solution for monitoring stress levels, traditional designs are often inflexible, leading to issues such as poor skin contact, elevated contact impedance, and motion artifacts that compromise the quality of the collected signals. To overcome these challenges, this paper introduces a stretchable EDA sensor featuring a Peano-Gosper fractal design aimed at enhancing adaptability and minimizing motion-related interference. Through a finite element analysis, several design variations were assessed, with the fractal pattern demonstrating superior skin contact and reduced mechanical strain, making it highly suitable for real-world applications. Experimental results indicated significant advancements in signal-to-noise ratio (SNR), with the fractal-designed sensor achieving nearly 8 dB improvement compared to conventional EDA sensors during experimental construction activities. This development enhances the reliability of EDA measurements and corresponding mental stress monitoring, ultimately contributing to improved health and safety outcomes for construction workers.

Keywords –

EMG ; Flexible Sensor; EDA; Motion Artifact; Physiological Monitoring

1 Introduction

The construction industry has long grappled with the pervasive issue of mental stress among its workforce, a problem that has far-reaching consequences for both individual health and overall project outcomes [1]. Recent studies have indicated that construction workers experience some of the highest rates of stress-related mental health issues across all industries, with an estimated 35% reporting symptoms of anxiety or depression. This chronic exposure to occupational stress not only impacts worker well-being but also significantly increases the risk of serious health complications, including cardiovascular diseases and musculoskeletal disorders [2]. Moreover, stress-induced cognitive impairments can lead to decreased situational awareness and decision-making abilities, potentially compromising worksite safety and productivity [3,4].

Electrodermal activity (EDA) has emerged as a promising biomarker for quantifying sympathetic nervous system activation, which is closely linked to stress responses [5]. EDA measurements, which capture changes in skin conductance resulting from sweat gland activity, have shown a robust correlation ($r = 0.78$) with self-reported stress levels in controlled laboratory settings. In the context of construction, preliminary field studies utilizing commercial EDA sensors have demonstrated the potential for real-time stress monitoring [6]. However, the dynamic and physically demanding nature of construction environments presents unique challenges that often result in degraded sensor performance, with reduced SNR compared to stationary conditions.

The widespread adoption of wearable health monitoring technologies in the construction sector has been hindered by limitations in current sensor designs [7]. While significant advancements have been made in data processing algorithms and machine learning models for stress detection, the underlying hardware often fails to meet the specific demands of construction tasks [8]. Commercial EDA sensors, typically designed for general-purpose physiological monitoring, employ rigid materials and standardized form factors that are ill-suited for the diverse and strenuous activities inherent to construction work. These design shortcomings manifest in several critical issues, including increased contact impedance due to poor skin conformity, motion artifacts from sensor displacement, and user discomfort during prolonged wear [9].

To address these challenges, this paper proposes a novel solution: a fractal-based, patch-type flexible EDA sensor specifically engineered for use in construction environments. The innovative fractal design offers enhanced skin conformity, potentially reducing contact impedance and increased SNR. This approach not only minimizes motion artifacts but also improves overall signal quality and user comfort. By leveraging advanced materials and optimized geometries, the proposed sensor aims to maintain consistent performance across a wide range of construction activities, from repetitive tasks to sudden, high-intensity movements. This tailored solution has the potential to revolutionize real-time stress monitoring in construction workers, providing more accurate and reliable data for both immediate intervention and long-term occupational health strategies.

The paper is structured as follows: In Section 2, a brief literature review is provided, focusing on flexible EDA sensors and health monitoring applications of EDA sensors. Section 3 describes the proposed methodology, including the technical details of the design and fabrication techniques. In Section 4, a case study is presented, which includes details of the experiments conducted to develop and evaluate the developed sensor. The results are analyzed and discussed in Sections 5 and 6. Finally, Section 7 concludes the paper.

2 Background and Related Work

2.1 Stress, the Sympathetic Nervous System, and EDA

Stress triggers a complex cascade of physiological responses, primarily mediated by the autonomic nervous system (ANS). The ANS comprises two main branches: the sympathetic nervous system (SNS), which initiates the "fight-or-flight" response, and the parasympathetic nervous system, responsible for "rest-and-digest" functions [10]. During stress, the SNS becomes dominant, leading to a range of physiological changes aimed at mobilizing energy resources and preparing the body for action [11].

The skin, particularly its sweat glands and vasculature, is exclusively innervated by the SNS, making it an ideal target for assessing sympathetic activation. Electrodermal activity (EDA), which measures changes in skin electrical properties due to sweat gland activity, provides a direct and relatively unambiguous index of SNS arousal [12]. This contrasts with other physiological measures, such as heart rate variability, which reflect the complex interplay between both SNS and PNS influences.

EDA is typically quantified through skin conductance measurements, which are proportional to sweat secretion. The palmar surfaces of hands and feet, with their high density of eccrine sweat glands , are preferred measurement sites. The EDA signal comprises two main components: tonic skin conductance level (SCL) and phasic skin conductance responses (SCRs). SCL represents the slowly changing baseline level of electrical conductivity, reflecting overall psychophysiological activation [13]. SCRs are rapid, transient increases in conductance, occurring either in response to specific stimuli (specific SCRs) or spontaneously (non-specific SCRs or NS.SCRs).

Specific SCRs typically manifest 1 to 6 seconds post-stimulus and are characterized by several key parameters: amplitude (magnitude of conductance change), latency (time between stimulus onset and SCR initiation), rise time (duration from SCR onset to peak), and half-recovery time (time for amplitude to decrease by 50% from peak). NS.SCRs, while morphologically similar to specific SCRs, occur in the absence of identifiable external stimuli. The frequency and mean amplitude of NS.SCRs serve as additional indicators of psychophysiological arousal [14].

Importantly, both SCL and SCR patterns exhibit significant inter-individual variability, necessitating careful baseline establishment and within-subject comparisons in experimental designs. Numerous studies have demonstrated the superior sensitivity of EDA measures, particularly SCL and NS.SCR frequency, in tracking stress responses compared to other physiological indicators. This sensitivity, combined with the relatively straightforward interpretation of EDA in terms of SNS activity, makes it a valuable tool for real-time stress monitoring in dynamic environments such as construction sites.

2.2 Flexible EDA sensors

Flexible electrodermal activity (EDA) sensors represent a significant advancement in wearable biomonitoring technology, offering potential solutions to the longstanding challenges associated with traditional rigid sensor designs [15]. The development of these sensors is driven by the need for more reliable and comfortable continuous monitoring systems, particularly in dynamic environments such as construction sites [9,16,17].

One of the primary advantages of flexible EDA sensors is their ability to maintain consistent skin contact during movement, potentially reducing motion artifacts that plague inflexible commercial sensors. These artifacts, which can significantly distort physiological signals, are particularly problematic in occupational settings where workers engage in varied physical activities. While algorithmic approaches such as adaptive filtering and machine learning techniques have shown promise in mitigating motion artifacts, they are inherently limited by the quality of the raw signal input [7,8]. Flexible sensors address this issue at the hardware level, potentially improving signal fidelity before any software processing occurs.

Recent advancements in materials science have enabled the development of novel flexible sensor substrates and electrode materials. Conductive polymers, carbon nanotubes, and metallic nanowires have been successfully incorporated into stretchable matrices, creating sensors capable of withstanding substantial deformation while maintaining electrical performance [18]. These materials often exhibit unique electromechanical properties, such as increased conductivity under strain, which can be leveraged to enhance sensor sensitivity and resilience. The design of flexible EDA sensors also allows for innovative electrode patterns and geometries that were previously unfeasible with rigid substrates. Fractal-inspired designs, for instance, have shown promise in optimizing the tradeoff between mechanical flexibility and electrical performance [19]. These intricate patterns can potentially increase the effective surface area for EDA measurement while allowing the sensor to conform to the complex topography of human skin, particularly in areas with high curvature or frequent movement.

3 Materials and Methodology

The overview of the proposed methodology is presented in Figure 1, In the first step, we 3D model 8 different variations of fractal curves with varying order and shapes to fit within a square patch of length 5 mm. Here we model Hilbert, Moore, z-space and Peano-Gosper curves. In the second stage we perform static analysis subjecting the 3D models to varying tensile forces and evaluate stress/strain characteristics. We calculate von-mises stress, strain values, and geometric characteristics such as overage area. Based on the results, we choose Peano-Gosper order 4 curve for fabrication. During fabrication, we use Silver Nanoparticle modified ink to print in into a flexible polyimide surface using a piezoelectric printing mechanism. After printing the Ag-NP surface is UV-treated using sintering. Then, the developed electrode is evaluated and compared with the commercially available electrodes for noise reduction.

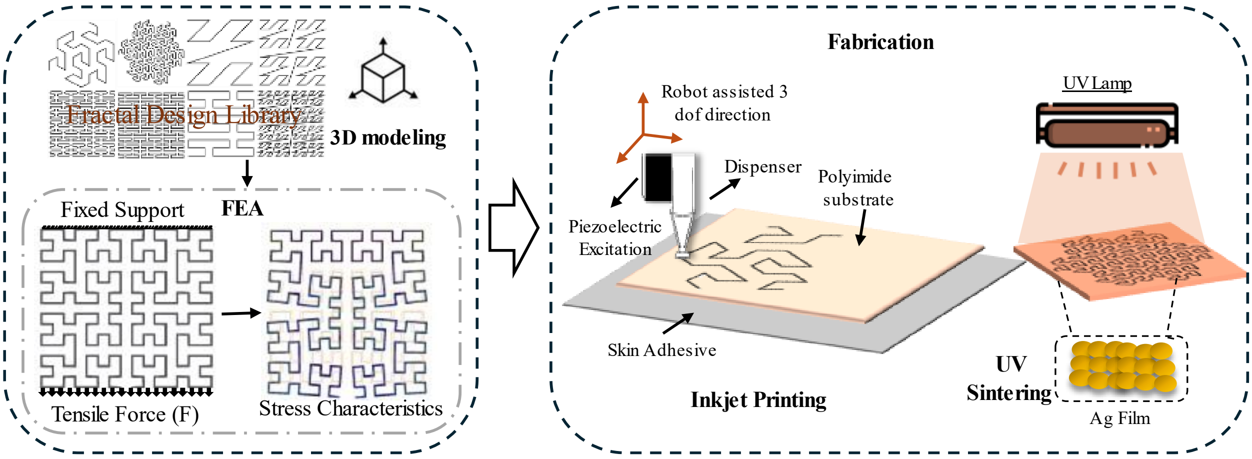

Figure 1: Overview of the methodology. Multiple Fractal designs are 3D modeled and then analyzed for mechanical properties using finite element analysis. The best one is selected based on a mixture of von Mises stress, strain, and geometric properties like coverage to surface area ratio. The selected design is printed using AgNP ink into a flexible polyimide substrate followed by polyimide

3.1 Design and FEM evaluation of Flexible Electrodes

Eight different fractal curve variations were modeled in 3D, including Hilbert, Moore, Z-space, and Peano curves of varying orders, each confined within a 5 mm square patch. The Peano-Gosper curve, originally termed the flow-snake, represents a sophisticated space-filling pattern that exhibits unique hexagonal characteristics. When implemented in second and third orders, this curve generates intricate self-replicating structures that optimize both spatial utilization and mechanical adaptability.

Fractal	Peano-Gosper	Peano-Gosper	Morton-Z	Morton-Z	Peano - rounded	Peano	Peano	Morton Z
Order	2	3	2	3	3	3	2	4

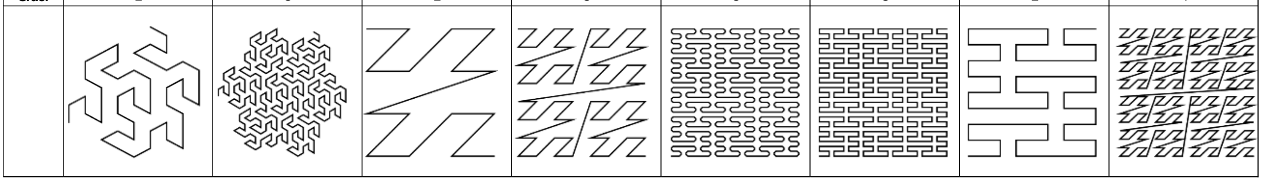

Figure 2: Fractal curves with respective order analysed for this study.

The Morton Z-curve, alternatively known as the Z-order curve, employs an innovative approach to dimensional mapping, effectively transforming two-dimensional spatial relationships into linear sequences while maintaining proximity correlations. Implemented across orders 2, 3, and 4, this pattern creates a hierarchical arrangement that achieves an optimal equilibrium between connectivity and coverage. The Z-curve's architecture proves particularly advantageous in applications requiring efficient spatial data organization and multidimensional query optimization.

Among these patterns, the Peano curve demonstrates the mathematical possibility of continuous coverage across a complete unit square. Its modified variant, the Peano-rounded design, incorporates strategic curvature elements to enhance mechanical performance. These modifications serve multiple purposes: they minimize stress concentration at junction points, preserve continuous surface coverage, and significantly improve the structure's overall flexibility and stretchability characteristics.

These models were subjected to static analysis simulating tensile forces ranging from 0.5 N to 2 N, representing the spectrum of mechanical stresses encountered during typical construction activities. The FEA simulation utilized a non-linear large deformation model to account for the elastic behavior of the flexible substrate. The material properties of the silver nanoparticle (AgNP) conductive ink and the polyimide substrate were incorporated into the model, with particular attention to the interface between these materials.

$$\sigma_v = \sqrt{\frac{1}{2}\left[\sum_{x,y,z}\left(\sigma_x - \sigma_y\right)^2\right] + 3\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)} \quad (1)$$

$$Ku = F, \qquad \epsilon = \frac{\Delta l}{l_0} \quad (2)$$

where, $\sigma_x, \sigma_y, and\ \sigma_z$ are the normal stresses along the x,y, and z axes, respectively and $\tau_{xy}, \tau_{yz}, and\ \tau_{zx}$ are the shear stresses in the respective planes.

3.2 Sensor Fabrication and Sintering

The sensor electrodes were designed to fit comfortably on human skin, optimized for flexibility and durability in field environments. Polyimide, selected as the substrate, provides a balance of lightweight structure and flexibility similar to the tensile qualities of human skin, allowing the sensor to conform to body contours with minimal discomfort. This Kapton HN polyimide film offers high elongation capacity, low thermal expansion, and favourable tensile strength, making it an ideal foundation for wearable sensors that experience frequent motion. The selected thickness (0.125 mm) of this film supports the sensor's resilience while maintaining a minimal profile for improved adhesion and reduced interference during movement.

The electrodes were created using Ag nano-ink, chosen for its excellent conductivity and mechanical robustness, essential for clear and stable signal transmission. This ink, consisting of silver nanoparticles (AgNPs), combines a high-weight percentage of Ag with properties suited for high-resolution printing. The small particle size allows smooth deposition without clogging, while the moderate viscosity ensures steady flow through the printer's micro-dispensing system. These factors together enhance the ink's adherence to the polyimide surface, resulting in conductive pathways with low resistance after sintering. This choice of material ensures the electrodes can perform reliably under various physical strains while keeping the overall structure lightweight and thin $V(t) = V_0\ sin(\omega t) = V_0\ sin(2\pi f t)$. The printing process employed a SonoPlot Microplotter proto, utilizing an ultrasonic fluid injection mechanism to achieve precise electrode patterning. This technique relies on a piezoelectric-controlled glass dispenser, where AC-induced vibrations allow controlled dispensing of the Ag nano-ink onto the substrate. By adjusting the frequency of the AC signal, the fluid's flow rate is precisely managed, creating a serpentine pattern optimized for flexibility and durability. Following the printing phase, UV sintering with a pulsed light system (X-1100:XENON) was applied to solidify the AgNPs without overheating the polyimide film. This sintering process removed solvents and bound the particles into a stable, conductive layer, completing the sensor's formation with minimal thermal impact on the flexible substrate.

4 Experimental Case Study

To study the artifact reduction in the developed EDA sensor roofing construction task was used (Figure 2). The EDA signals were recorded between the index and ring finger. In one scenario, the subjects were asked to stay static without moving their fingers to record the base-line signals and analyze the noise properties in the static position. To induce motion, a hammering-based construction task was used. During the hammering task, the subjects hammered shingles into a prebuilt roof structure. This task was performed for both the commercial and developed electrodes. The detailed results are presented in Section 5.

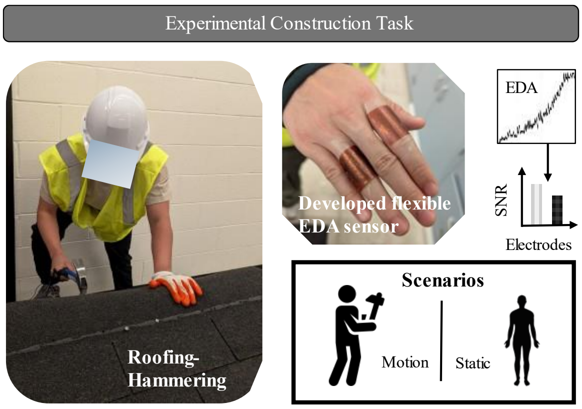

Figure 3: Experimental setup comprises two scenarios with and without motion. For inducing motion hammering task is used where the subject hammers shingles into a prebuilt roof structure. The signals are acquired for developed and commercial electrodes.

The signals acquired from the EDA sensors were amplified using bio-amplifier from AD-Instruments. Signals were acquired at the range of 100 Hz.

5 Results and Discussion

The comparative analysis of the various fractal-based electrode designs revealed significant performance variations across mechanical properties and signal quality metrics. The results demonstrate the superior characteristics of higher-order fractal patterns, particularly in terms of stress distribution and motion artifact reduction.

5.1 Mechanical Performance Analysis

The finite element analysis revealed distinctive mechanical behaviors across the various fractal patterns tested. The Peano-Gosper curve of order 2 initially showed the highest von Mises stress at 5.5E+10 N/m², while its order 3 counterpart demonstrated a dramatic improvement, with stress levels dropping to 3.9E+08 N/m². This significant reduction in stress indicates that higher-order Peano-Gosper patterns effectively distribute mechanical loads throughout their structure.

The Morton Z-curve patterns exhibited consistent mechanical performance across different orders, with stress levels stabilizing around 2.0E+10 N/m². The order 3 and 4 variations maintained relatively uniform stress distribution, suggesting reliable mechanical stability. These patterns demonstrated better structural integrity while accommodating deformation, with strain values ranging between 0.1 and 0.2.

The Peano and Peano-rounded variations demonstrated notably different characteristics. The Peano-rounded design of order 3 achieved moderate stress levels of approximately 1.5E+10 N/m² and maintained relatively low strain values of around 0.15. The rounded corners incorporated into this design proved effective in mitigating stress concentration points, a common challenge in angular fractal patterns. The standard Peano curve showed similar stress characteristics but with slightly higher strain values, indicating that the rounded modifications successfully improved the overall mechanical performance.

Strain analysis across all patterns revealed a consistent trend where higher-order patterns generally exhibited better strain management. The Peano-Gosper order 2 design showed the highest strain at 0.55, while its order 3 variant demonstrated remarkably lower strain values (0.004). This pattern was consistent across all designs, with higher-order variations consistently outperforming their lower-order counterparts in strain management. The Morton Z-curve patterns, particularly in orders 3 and 4, maintained moderate strain levels, suggesting good deformation characteristics under applied loads.

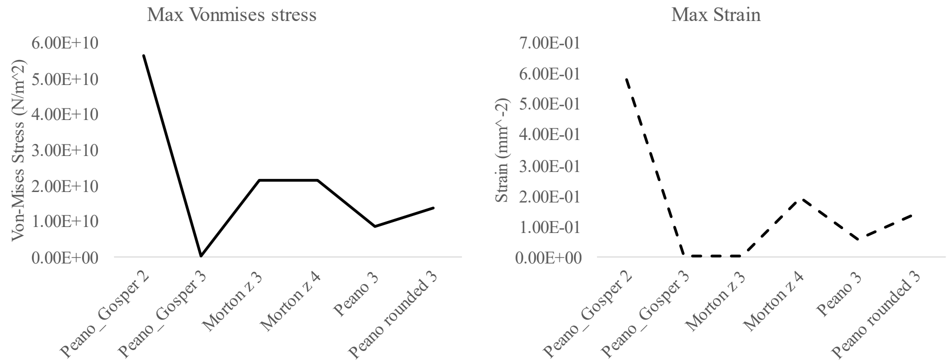

Figure 4: Max Von-mises stress and maximum strain for the given loading conditions.

The comprehensive analysis of both stress and strain characteristics indicates that while higher-order patterns generally offer superior mechanical properties, the optimal design must balance performance with manufacturing feasibility. The Peano-gosper order 3 pattern emerged as a particularly promising candidate, offering an excellent compromise between stress distribution, strain management, and practical implementation considerations. Based on this comparison, Peano-Gosper 3 was selected for the fabrication and further analysis.

5.2 Motion Artifact Reduction

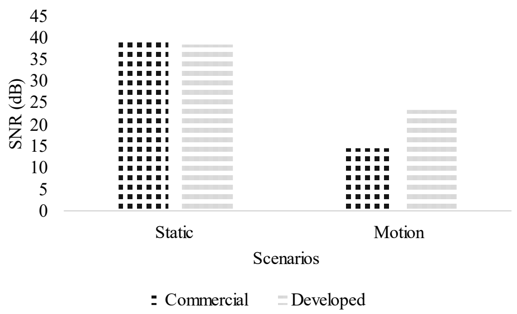

Figure 5: The developed electrodes provide significant improvement in SNR for the hammering task which induces significant motion.

To compare the performance of the developed electrode with the existing commercial modules we used bipolar finger electrodes made from brightly polished stainless steel plates (ADInstruments). As shown in Figure 5, the designed serpentine electrode exhibits a significantly higher SNR of approximately 23 dB compared to the commercial electrode, which has an SNR of around 15 dB. This difference in SNR performance can be attributed to the optimized electrode design and manufacturing process employed for the serpentine structure. We also compared the SNR both during static position (rest) and dynamic position (hammering with the sensing hand) to assess the difference during dynamic activities. While both electrodes provide similar performance during rest ($|SNR| < 1db$) the performance during dynamic activity (hammering) the SNR improvement is significant (8 db). The enhanced SNR indicates that the designed electrode is capable of providing cleaner, more reliable EDA signals, which is a critical requirement for accurate physiological monitoring in wearable health applications.

6 Conclusions

This research develops and analyses flexible sensor technology through the development of fractal-based electrodes for EDA monitoring applications. The comprehensive mechanical analysis of various fractal patterns has yielded significant insights into their performance characteristics and potential for wearable sensing applications. The finite element analysis results demonstrate remarkable improvements in mechanical stability and stress distribution across different fractal designs.

The investigation revealed that higher-order fractal patterns consistently outperform their lower-order counterparts. The Peano-Gosper pattern showed the most dramatic improvement, with von Mises stress reduction from 5.5E+10 N/m² in order 2 to 3.9E+8 N/m² in order 3. Similarly, the Morton Z-curve patterns maintained consistent stress levels around 2.0E+10 N/m², demonstrating reliable mechanical stability across orders 3 and 4. The fabricated sensor of the Peano-Gosper order 3 demonstrated an 8db of SNR improvement when compared to commercial sensors while performing construction tasks.

These advancements address critical limitations in current wearable sensor technology, particularly in maintaining stable electrode-skin contact during dynamic activities. However, several challenges remain for future investigation. The integration of flexible amplification circuits and wireless communication systems would enhance the sensor's practical applicability. Additionally, further research into surface modification techniques could improve long-term durability and signal stability.

Future work should focus on expanding this fractal-based design methodology to other physiological monitoring applications and developing automated manufacturing processes for complex patterns. The potential applications extend beyond EDA sensing to include other biomonitoring systems, suggesting broader implications for wearable health monitoring technology. Despite current limitations in system integration and long-term durability, this research establishes a promising foundation for next-generation flexible sensors that combine mechanical reliability with enhanced signal quality.

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