Optimizing Piezoelectric Energy Harvesters: A Comprehensive Review of GWO-GA Techniques

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Abstract— **The process of turning the environment's discarded vibrational energy into useful electrical energy is known as energy harvesting. The approach of vibration energy collecting is selected because it can be used to develop devices that are smaller and more effective. Piezoelectric Energy Harvesters (PEHs) are preferred over other forms of energy collecting devices including electrostatic, electromagnetic, and piezoelectric ones because of their versatility and adaptability. Lead zirconate titanate, or PZT-5H, is the most widely used piezoelectric material. It is selected for its power generating efficiency and versatility. The analysis indicates that more time is needed to determine the proper dimensions of the energy harvester for the planned piezoelectric devices. By applying optimisation approaches, the design factors of the piezoelectric energy harvester are optimised, contributing significantly to the system's increased efficacy. The PEH's design parameters are optimised through the application of optimisation techniques including Genetic Algorithm (GA), Grey Wolf Optimisation (GWO), and GWO-based GA (GWO-GA).**

Keywords— Energy Harvesting, Piezoelectric Energy Harvesters (PEH), Grey Wolf Optimization (GWO), Genetic Algorithm (GA), etc.

I. INTRODUCTION

Thanks to the significant progress made in the semiconductor sector, it is now possible to produce smaller electrical devices. The health care industry, which has achieved great strides in the field of bio-implants recently, has a new avenue to pursue as a result of the devices' miniaturization. Wireless sensor nodes (WSNs) are used in many different domains, such as gathering data from the ocean's deepest depths [1,] implementing data distribution-based applications [2, 3], managing the possible negative effects of volcanoes [4, 5], rescuing people from avalanches [6], and monitoring subsurface environments.

Consequently, it is imperative to take the required and effective action to accomplish or resolve the replacement of a battery-operated equipment. Since the traditional battery-operated system has few downsides, an energy collecting method has been used instead. Energy harvesting is transforming ambient energy into a different form. Renewable energy from the sun, wind, water movement, and waves in the ocean is abundant in the environment. Low-power electronic devices or sensors are not suitable for the macro-scale power generation provided by these renewable sources.

In addition to these energy sources, walking, running, and a variety of other physical activities cause the human body to produce mechanical and thermal energy. Harvesting energy from these tiny energy sources may be a workable way to address the issue of decreased battery life and frequent replacement. The essential distinction between the energy harvesting approach and standard approaches is displayed in Table 1. The health care and disaster management council is therefore calling for the urgent development of gadgets that have longer battery lives and do not require frequent battery replacement. This issue can be solved with energy harvesting without endangering or contaminating the environment.

Table 1: Battery operated versus energy harvesting sensor

S. No.	Features	Battery Operated Sensor	Energy Harvesting Sensor
1	Source of Energy	Charged battery	Environment/Human Body
2	Predictability	High, battery models	Low
3	Constraint	Energy efficient, long life battery	Energy-neutral
4	Preservation Cost	High, recharging and replacing the battery	Low, Self-sustaining
5	Quality of service	As low as possible	As high as possible

In the past ten years, various methods of energy conversion have been documented, including solar, thermal, chemical, RF radiation, and mechanical vibration. The various ambient energy sources and their corresponding requirements are compiled in Table 2. Of all these techniques, mechanical vibration is the most often used since it can produce enough energy to run low-power gadgets. The mechanically based energy harvester may transform mechanical vibrations from machines, waste rotations, and human movement, including heart and lung motion, blood circulation, muscular contraction, and relational movement, into electrical energy. The various methods of converting mechanical vibration energy into electrical energy that is helpful include piezoelectric mechanism [11–13], electrostatic method [8–10], and electromagnetic method [11–12].

Without the need for an external voltage source, mechanical vibration can be converted into electricity using a piezoelectric energy harvester (PZEH). In contrast to electrostatic and electromagnetic mechanisms, it aids in the construction of this mechanism's straightforward architecture. Because the piezoelectric mechanism's architecture is straightforward, it can be made smaller, which is more advantageous for MEMS technology, which requires the creation of structures by micromachining. Therefore, piezoelectric energy harvesters and MEMS technology can work together seamlessly. In comparison to the other two methods, it also has a higher electromechanical coupling impact. These benefits make PZEH superior to others, and throughout the past ten years, it has been extensively researched.

Table 2: Comparison between the different ambient energy sources

Energy Source	Transducer	Output Power	Requirement
Solar (Indoor)	Photovoltaic Cells	10-100 µ*W/cm2*	Indoor Light 1-10 *W/m2*
Solar (Outdoor)	Photovoltaic Cells	10-100 µ *W/cm2*	Indoor Light 1-10 *W/m2*
Air Flow	Micro Windmill	20 µW/cm2	5 m/s wind speed
RF Radiation	RF Antenna	10 µW/cm2	MPE limit 1-5 mW/cm2
Thermal	Thermoelectric generator	20 µW/cm2	Temperature Gradient >10oC

A. *Piezoelectric Energy Harvesting (PEH)*

The Curie Brothers, Pierre and Jacques, noticed the direct piezoelectric effect on crystals and recognized that the application of mechanical force causes the materials to become electric polarized, which led to the discovery of the phenomenon of piezoelectricity in 1880 [14]. The phenomenon known as the "inverse piezoelectric effect" occurs when an electric field is applied in the direction of the polarization of piezoelectric sensor devices, producing mechanical force [14]. The constitutive equations of piezoelectric materials, which combine the mechanical and electrical properties of the crystal, represent the piezoelectric effect [15].

B. *MODES OF PEH*

An essential feature of the energy harvester is its functioning mode, which is the basis for the modeling of the PEH. The three types of piezoelectric working modes are the longitudinal mode (d31 mode), transverse mode (d33 mode), and piezotronic mode. The PEH's d31 and d33 operating modes are depicted in Figure 1 [17]. The d31 mode describes the applied force's direction as being perpendicular to the direction of the voltage the PEH generates, while the d33 mode's direction of application and the difference in voltage potentials are the same.

The linear link between electrical and mechanical properties is demonstrated by the piezoelectric materials. The direct piezoelectric effect is the ability of piezoelectric materials to produce electrical energy when external stress is applied to their surface. An electric field applied across the piezoelectric plate will cause mechanical deformation in the plate. The reverse piezoelectric effect is the name given to this occurrence. While Figure 2b depicts a deflection in the PZ plate when an external electric field is placed across the plate, Figure 2a illustrates the direct piezoelectric action, in which the applied force produces the electric current

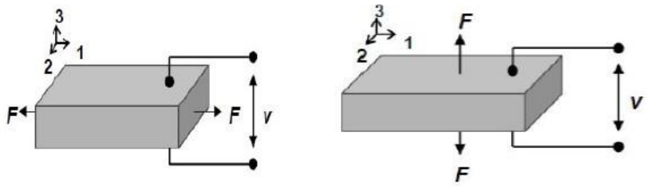

FIGURE 1: PEH MODES

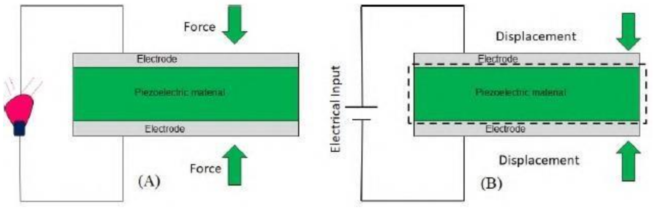

Figure 2: (a) Direct piezoelectric effect (b) Reverse piezoelectric effect

II. RELATED WORKS

In order to create voltage using coils, Karami (2011) modeled a cantilever beam energy harvester with piezoelectric patches at the base and a stationary magnet at the tip. Sunithamani and colleagues (2014) used COMSOL to optimize a unimorph piezoelectric energy harvester, resulting in a 21.92µW output. In models and experiments, Jayarathne et al. (2017) reported minimum voltages of 5.99 V and 3.65 V. Sunithamani & Lakshmi (2015) achieved 25.92µW by optimizing the substrate and piezoelectric thicknesses. In 2018, Balguvhar and Bhalla extracted 0.20µW from vibrations of bridges. A bimorph PEH with a 24.6µW output was created by Tsukamoto et al. (2018) for low-frequency vibrations. With asymmetrical PZT films, Dong et al. (2019) created a bimorph micromachined harvester that produced 26.90mW/cm³.A robust PEH was developed by Yang et al. (2021) for self-powered monitoring. In order to monitor health, Dipta et al. (2019) created a tapered cantilever that produces 3.61 µW and 8.5 V at 101 Hz. Sriramadas et al. used a multistep thickness profile to improve bimorph PEH performance by 90%. Variable thickness beams increase EH performance by 3.6 times, according to Paquin et al. In their comparison of tapered beams, Ibrahim et al. found that thickness truncation raises power by 6.4% while lowering resonance frequency by 18%. Improved power generation and efficiency were shown in variable cross-section and thickness PZEH, respectively, by Zhang et al. and Kundu et al.

S. No.	**Title**	**Year**	**MethoDology**	**Advantage**	**Limitation**
1	Enhancement of vibration based piezoelectric energy harvester using hybrid	2020	Hybrid GA-GWO	Improved efficiency and performance	Complexity in implementation

	optimization techniques				
2	Design of Piezoelectric Energy Harvester Using Intelligent Optimization Techniques	2021	Genetic Algorithm (GA), Grey Wolf Optimization (GWO)	Higher energy output, optimized design	High computational cost
3	Numerical and experimental analysis of piezoelectric vibration energy harvester	2021	GA, GWO	Enhanced power generation	Limited experimental validation
4	The New Techniques for Piezoelectric Energy Harvesting: Design, Optimization, Applications, and Analysis	2021	FEM, Hybrid methods	Broad applicability, innovative techniques	General focus, lacks specific case studies
5	Enhancing the Output Performance of Energy Harvesters Using GWO-GA	2022	GWO-GA	Increased output performance	Complexity in real-world application
6	Optimization of Piezoelectric Energy Harvesters for Low-Frequency Applications	2022	GA, GWO	Effective for low-frequency vibrations	Requires precise tuning
7	Parametric study and optimization of piezoelectric energy harvesters	2023	GA, GWO	Parametric optimization, versatile applications	Requires extensive computational resources
8	Design and optimization of high-performance piezoelectric energy harvesters	2023	GWO-GA	High performance, robust design	High development cost

9	Advanced Hybrid Optimization Techniques for Piezoelectric Energy Harvesters	2024	Hybrid GA-GWO	Synergistic benefits, high optimization accuracy	Implementation challenges
10	Hybrid Optimization Approaches for Efficient Piezoelectric Energy Harvesters	2024	GWO-GA	Efficient energy harvesting, reduced losses	Complex algorithms

Table 1: Showing Recent works on PEHs

III. PEH RSWH STRUCTURE-EXPERIMENTAL ANALYSIS USING GWO-GA ALGORITHM

A. Genetic Algorithm (GA)

GA is a metaheuristic optimization method that combines crossover, mutation, and selection processes to resemble biological evolution.

GA Procedure:

i. Selection Operator: Chooses parents from the general public by techniques such as tournament or roulette wheel selection.
ii. Crossover Operator: Using methods such as one-point or two-point crossover, this operator joins two chromosomes (parents) to create a new chromosome (offspring).
iii. Mutation Operator: By employing random resetting or bit-wise inversion, this operator modifies chromosomal genes to promote population variety.

B. Grey Wolf Optimization (GWO) Technique

GWO divides wolves into alpha, beta, delta, and omega groups in order to replicate the hunting habits of grey wolves.

GWO Process:

Initialization: Set the population's initial values.

i. Fitness Assessment: Determine each person's level of fitness.
ii. Revisions for Alpha, Beta, and Delta: Determine the top three options.
iii. Update positions based on alpha, beta, and delta positions when encircling the prey.
iv. Hunting: Repeat till the end condition is satisfied.

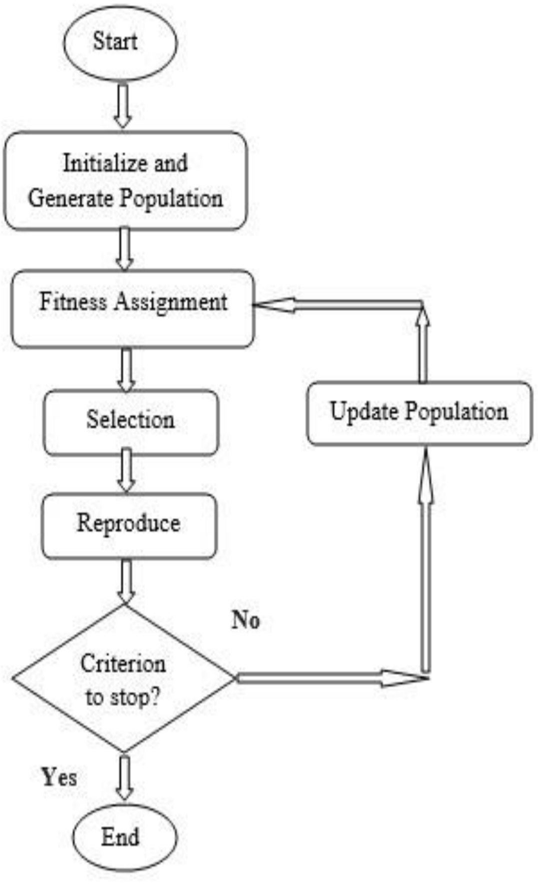

Figure 4: GA Flowchart

C. Grey Wolf Optimizer based Genetic Algorithm

Using GWO (population size, parameter a, coefficient vectors *A* and B) to minimize the potential energy function, the GA parameters (crossover and mutation rate) are adjusted in this technique. In Figure 5, the flowchart is displayed. Additionally, the maximum number of iterations as well as the number of variables and solutions in each division are initialized. All during the initialization process, the initial set of population X(t) is generated at random. The GWO technique is used in the context of the entire population X(t). The population X(t) is then given the GA parameters, which comprise the crossover rate and the mutation rate. Each partition in the population has a size of v with regard to β, and the subpopulations are represented by X'(t). Where β is the number of solutions in each partition, and v is the number of variables in each partition. Every sub-partition X'(t) is subject to the cross over operator, while the entire population X(t) is subject to the mutation operator. As a result, the solutions are updated and run until the maximum number of iterations, at which point the optimal solution is displayed. Using this procedure, the GWO-GA optimization is carried out in order to maximize the energy harvester's performance by optimizing the design factors of the RSWH PEH.

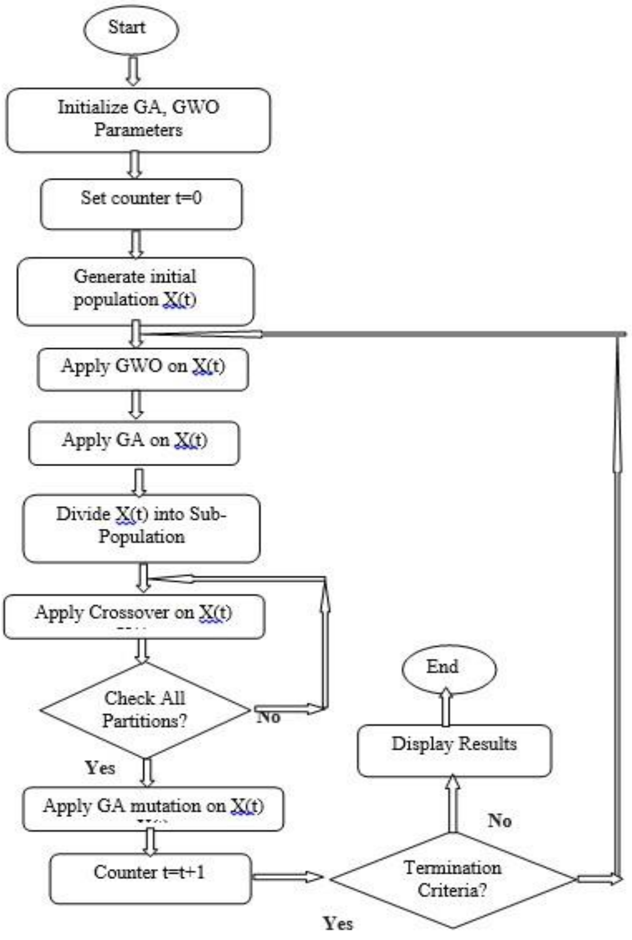

Figure 5: GWO-GA Flowchart

IV. RESULTS AND DISCUSSION

Analysis of Eigen Frequency:

Under various accelerations of 0.1g and 1.0g, the optimized RSWH (Resonant Standing Wave Harvester) structure made of PZT-5H material underwent an eigenfrequency analysis. Table 4 provides a summary of the findings. With a frequency of 55.7 Hz at 1.0g acceleration, it was found that the GWO-GA (Grey Wolf Optimization - Genetic Algorithm) approach produced the lowest eigen frequency. This was less than the frequencies achieved at the same acceleration of 77.35 Hz and 66.5 Hz using the Genetic Algorithm and Grey Wolf Optimization alone. The GWO-GA technique's ability to reduce eigen frequency suggests a more effective energy harvesting capacity at lower frequencies.

Analysis of Stress and Displacement:

In order to assess the mechanical performance of the RSWH structure under boundary load circumstances, displacement and stress analyses were carried out. The maximum stress of 6.5 MPa at 1.0g acceleration was created by the PZT-5H material employing the GWO-GA approach, as indicated in Table 5. This stress was higher than the stresses produced by GA (5.5 MPa) and GWO (6.2 MPa) under the same conditions. Comparatively, Table 6 shows that the GWO-GA approach produced a maximum displacement of 0.0092 meters at 1.0g acceleration, which was noticeably more than the GA and GWO techniques.

Analysis of Voltage:

The RSWH structure's voltage output was examined under various loading scenarios. With a frequency of 55.5 Hz and a resistive load of 1000 kΩ, the PZT-5H material at 1.0g acceleration generated a maximum voltage of 16.81V and 0.42V, respectively, under the GWO-GA technique. This illustrates how well the GWO-GA optimization method works to increase voltage output under various load scenarios

Analysis of Sensitivity:

Sensitivity analysis was used with the PZT-5H material to evaluate the voltage sensitivity (VS) and charge sensitivity (CS) of the RSWH structure. The maximum VS of 0.24 V/g and CS of 0.75 pC/g displayed by the GWO-GA optimized structure at 1.0g acceleration demonstrated the great sensitivity of the energy harvester under these circumstances. For this application, the GWO-GA methodology is a better optimization strategy than GA and GWO because it performed better in terms of sensitivity.

Analysis of Efficiency:
After the effectiveness of the RSWH structure was examined, it was discovered that, under resistive load circumstances, the PZT-5H material could attain a maximum efficiency of 74.5%. The GWO-GA optimized RSWH structure's excellent efficiency highlights its potential for efficient energy harvesting applications.

V. CONCLUSION

The GWO-GA hybrid technique delivers significant gains over the other optimization strategies (GA, GWO, and GWO-GA) when compared to the performance of the RSWH structure. With PZT-5H material in particular, this approach greatly improves eigen frequency reduction, stress and displacement handling, voltage output, sensitivity, and overall efficiency. These developments highlight the usefulness of hybrid optimization techniques for piezoelectric energy harvester optimization, highlighting their pivotal significance in the development of the area.Noise contamination is still a recurring problem in digital image processing, particularly when images are sent across noisy communication lines. In this work, unique FPGA and VLSI-based filtering algorithms that preserve important image features while efficiently suppressing noise are introduced. Using the FAF filter in a multiresolution structure improves the visual quality and common picture denoising, which is noteworthy. For effective picture denoising, the suggested FAF structure for VLSI implementation shows low power consumption and decreased space needs.

In summary, the GWO-GA hybrid optimization method offers a potential direction for further study and improvement in addition to improving the performance of piezoelectric energy harvesters. In a similar vein, cutting-edge image processing filtering algorithms enhance digital communication by reducing noise-related problems and enhancing the dependability and quality of transmitted images. These developments greatly assist both sectors, underscoring the significance of ongoing innovation in optimization and filtering methods.

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