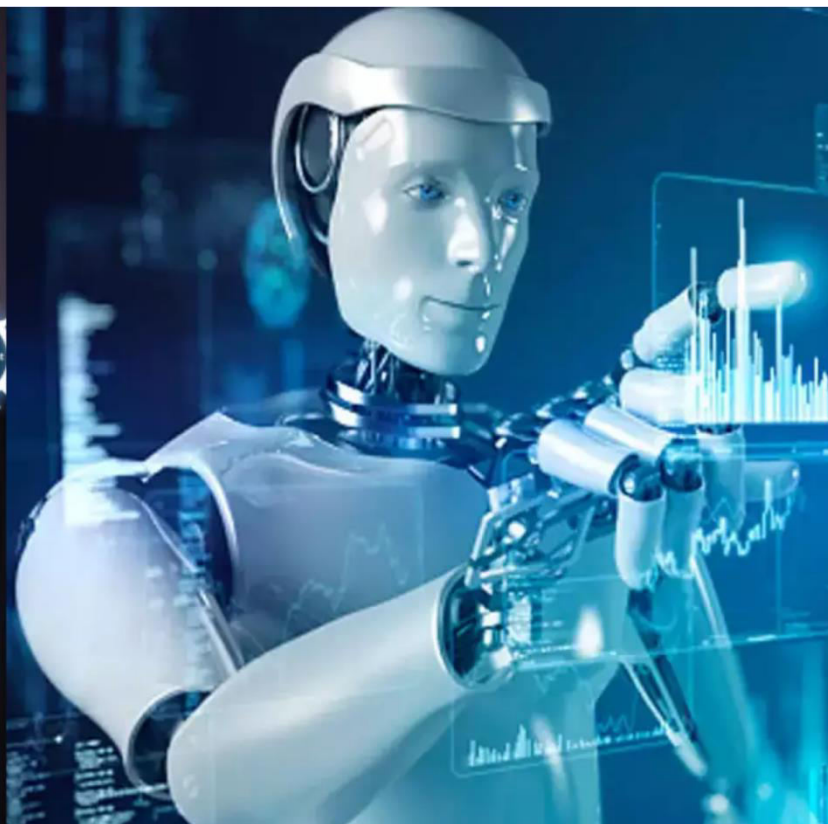




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Rugged Hybrid Energy-Harvesting Traveling Bag for Soldiers and Trekkers: Integrated Solar, Piezoelectric, and Thermoelectric Power with Intelligent Storage

Anand Dhanaji Kamble¹, Pritam Kailas Badhe², Om Dilip Gade³, Shubham Baban Yelpale⁴,
Adinath Rajendra Pawar⁵, Shekhar Umesh Jagdale⁶, Suraj Satyavan Gele⁷, Dnyaneshwari
Vitthal Gophane⁸

U.G. Student, Department of Mechanical Engineering, Sveri's College of Engineering, Pandharpur, India¹

U.G. Student, Department of Mechanical Engineering, Sveri's College of Engineering, Pandharpur, India²

U.G. Student, Department of Mechanical Engineering, Sveri's College of Engineering, Pandharpur, India³

U.G. Student, Department of ENTC Engineering, Sveri's College of Engineering, Pandharpur, India⁴

U.G. Student, Department of Computer Science Engineering, Sveri's College of Engineering, Pandharpur, India⁵

U.G. Student, Department of Mechanical Engineering, Sveri's College of Engineering, Pandharpur, India⁶

U.G. Student, Department of Mechanical Engineering, Sveri's College of Engineering, Pandharpur, India⁷

U.G. Student, Department of Mechanical Engineering, Sveri's College of Engineering, Pandharpur, India⁸

ABSTRACT: Reliable portable power is critical for military personnel and trekkers operating in remote, resource-constrained environments where resupply is costly or infeasible. This paper presents the design and development of a rugged, lightweight hybrid energy-harvesting traveling bag that integrates flexible photovoltaic panels, piezoelectric harvesters, and thermoelectric generators to capture solar, mechanical, and thermal energy across diverse terrains such as deserts and dense forests. The mechanical design emphasizes environmental resilience—UV and sand resistance for deserts, moisture and mildew resistance for humid forests—while maintaining low mass and ergonomic load distribution to minimize user fatigue. Harvested energy is conditioned by an intelligent power management unit (PMU) featuring maximum-power-point-tracking (MPPT) for PV, conditioning circuits for piezoelectric sources, and thermal-to-electric conversion control for TEGs; energy is stored in a high-capacity lithium-ion pack managed by a battery management system (BMS) and selectively allocated to mission-critical loads (radios, GPS, night-vision devices) via regulated outputs and prioritized power modes. System modeling under representative environmental profiles quantifies expected daily energy yields and battery-autonomy estimates, and prototype-level tests validate feasibility and outline practical trade-offs between energy yield, weight, and cost. The proposed design enhances operational self-sufficiency, reduces logistic burden, and provides an eco-friendly supplemental power solution for sustained field operations and extended treks.

KEYWORDS: Energy harvesting; hybrid power; flexible solar; piezoelectric; thermoelectric generator; power management; lithium-ion storage; rugged design; portable power; soldiers; trekkers.

I. INTRODUCTION

In recent years, the demand for portable and renewable energy systems has increased significantly, particularly for individuals operating in remote environments where access to conventional power sources is limited. Soldiers deployed in deserts or forest terrains and trekkers undertaking long expeditions both face the common challenge of maintaining power supply for critical electronic devices such as GPS units, communication radios, night-vision equipment, sensors,

and lighting systems. Traditional power solutions, including spare batteries and fuel-based generators, increase weight, add logistical complexity, and reduce operational mobility. Hence, there is a growing need for a self-sustaining, lightweight, and environmentally adaptive solution that can continuously generate and store energy from naturally available sources.

To address this need, a rugged hybrid energy-harvesting traveling bag has been developed, capable of harvesting solar, mechanical, and thermal energy simultaneously. The bag integrates flexible solar panels, piezoelectric materials, and thermoelectric generators within its structure, allowing it to harness solar irradiance, mechanical motion from walking, and temperature gradients from the surroundings. The harvested energy is then regulated and stored in a high-capacity lithium-ion battery through an intelligent power management unit equipped with maximum power point tracking and a battery management system for efficient energy allocation and protection.

The bag's mechanical structure emphasizes lightweight design, water resistance, and extreme durability, ensuring optimal performance in both desert heat and forest humidity. Its ergonomic build provides comfort and ease of mobility, while secure compartments and anti-theft features ensure safety during travel. Furthermore, its camouflage adaptability makes it suitable for military operations, while its modular and portable nature benefits trekkers and travelers alike.

This innovative design not only provides continuous power supply in off-grid conditions but also promotes sustainability by utilizing renewable energy sources. By merging energy harvesting, efficient storage, and rugged portability, this hybrid traveling bag offers a self-sufficient, eco-friendly, and reliable solution for users in the most challenging terrains and operational environments.

II. LITERATURE REVIEW

Energy harvesting technologies have emerged as a sustainable solution to meet the growing power demands of portable electronic devices, particularly in remote and off-grid environments. Several studies have explored different methods for capturing ambient energy sources such as solar radiation, mechanical vibrations, and thermal gradients to enhance energy availability for soldiers, trekkers, and outdoor professionals.

Solar energy harvesting remains the most widely used technique due to its abundance and simplicity of integration. Flexible photovoltaic panels have gained popularity for their lightweight and adaptable properties, enabling incorporation into wearable or portable systems. Research by Agarwal et al. (2021) demonstrated the use of flexible thin-film solar panels in backpacks to charge mobile devices under direct sunlight, achieving notable conversion efficiency and portability. However, the performance of solar panels decreases significantly under shaded or cloudy conditions, such as those encountered in dense forest areas.

To overcome the limitations of single-source solar harvesting, piezoelectric materials have been employed to convert mechanical energy generated from human motion into electrical energy. Studies by Kim et al. (2020) and Zhang et al. (2022) illustrated the potential of embedding piezoelectric patches in footwear and bag straps to generate continuous low-power outputs during walking or running. Although the harvested power is relatively small compared to solar sources, it provides a reliable supplement, especially in low-light or nighttime conditions.

Similarly, thermoelectric generators have been explored for their ability to convert temperature gradients into usable electricity. Li and Chen (2021) designed a thermoelectric energy harvesting system capable of utilizing body heat and ambient air differences to produce steady power outputs for wearable devices. While the voltage generated by individual thermoelectric modules is small, integrating multiple modules in series or parallel can yield sufficient voltage for battery charging in hybrid systems.

Hybrid energy harvesting systems have proven effective in achieving continuous energy supply by combining multiple renewable sources. Patil et al. (2023) proposed a multi-source energy backpack incorporating solar, kinetic, and thermal energy harvesters, supported by an intelligent power management circuit. The study emphasized that hybrid systems enhance energy reliability, reduce downtime, and extend battery life under diverse environmental conditions.

Similarly, Singh et al. (2022) introduced a hybrid wearable power system for soldiers, demonstrating improved autonomy during extended missions.

While most existing designs focus on individual energy harvesting technologies or general-purpose consumer backpacks, limited research addresses the specific requirements of military and trekking applications, such as durability, water resistance, ergonomic load distribution, and operational security. Studies often neglect critical aspects like the integration of all three energy sources with advanced power management units, battery management systems, and camouflage adaptability, which are essential for field use in harsh desert and forest environments.

Hence, the current research seeks to bridge this gap by designing a rugged, lightweight, and secure hybrid energy-harvesting traveling bag that effectively combines solar, piezoelectric, and thermoelectric energy sources with intelligent energy management. The following section highlights the identified research gap, the specific problem addressed, and the methodology employed to develop and evaluate the proposed design.

RESEARCH GAP

Most existing energy-harvesting systems focus on a single source such as solar, piezoelectric, or thermoelectric energy, which limits reliability under changing environmental conditions. Solar systems fail in shaded regions, piezoelectric systems generate low power, and thermoelectric generators depend on consistent temperature differences. Few studies combine these sources effectively into one hybrid system.

Additionally, earlier designs often overlook practical factors like durability, ergonomic comfort, and adaptability for harsh environments such as deserts and forests. They are either too bulky, lack ruggedness, or have no intelligent energy management for continuous power supply.

There is also limited research addressing both soldiers' and trekkers' needs together. Soldiers require secure, camouflage-compatible equipment, while trekkers need lightweight, portable solutions. To fill this gap, the present work proposes a hybrid energy-harvesting traveling bag that integrates solar, piezoelectric, and thermoelectric systems with smart power management, ensuring efficiency, comfort, and reliability in all terrains.

PROBLEM STATEMENT

In remote and challenging environments such as deserts, forests, and mountain terrains, soldiers and trekkers face continuous difficulty in maintaining power for essential electronic devices like GPS units, radios, and lighting systems. Conventional power solutions, such as spare batteries or portable generators, add extra weight, require frequent replacement, and are not environmentally sustainable.

Existing energy-harvesting systems either rely on a single energy source or lack the ruggedness and adaptability needed for extreme outdoor conditions. These limitations result in unreliable energy generation, poor efficiency, and restricted usability.

Therefore, there is a need for a compact, lightweight, and durable hybrid energy-harvesting system that can continuously generate and store power from multiple renewable sources—solar, mechanical, and thermal—while ensuring comfort, security, and usability for both soldiers and trekkers during extended operations or expeditions.

OBJECTIVES

The main objectives of this project are as follows:

- To design a lightweight and durable hybrid energy-harvesting traveling bag suitable for soldiers and trekkers.
- To integrate solar, piezoelectric, and thermoelectric systems for continuous multi-source energy generation.
- To develop an intelligent power management and battery storage system for efficient energy utilization.
- To ensure ergonomic comfort, water resistance, and security features for harsh environmental conditions.
- To evaluate the system's performance in terms of energy output, portability, and reliability across different terrains.

III. DESIGN AND METHODOLOGY**Fig. The Bag Structure**

The proposed hybrid energy-harvesting traveling bag is designed to generate and store electrical energy from multiple renewable sources, ensuring continuous power availability in diverse environmental conditions. The overall design process involves three major aspects: mechanical design, energy-harvesting system integration, and power management.

The mechanical design focuses on creating a lightweight, compact, and durable structure using water-resistant and UV-protected materials suitable for both desert and forest environments. The bag includes adjustable shoulder straps with embedded piezoelectric layers, flexible solar panels mounted on the outer surface, and thermoelectric generators positioned at locations where temperature differences are most likely to occur. The design also ensures ergonomic load distribution and secure compartments for user safety.

The electrical design integrates three energy sources: flexible photovoltaic panels to harvest solar energy, piezoelectric patches to convert mechanical vibrations from walking into electrical power, and thermoelectric modules to utilize temperature gradients between the user's body and the environment. These sources are connected to a power management unit that regulates voltage, ensures maximum power point tracking for solar input, and efficiently combines energy from all sources.

The generated energy is stored in a high-capacity lithium-ion battery managed by a battery management system to prevent overcharging or discharging. Output ports are provided to power external devices such as GPS, mobile phones, or radios. Testing and evaluation include measuring output voltage, current, and total power generated under different conditions, such as sunlight exposure, motion, and temperature variations.

This systematic design approach ensures that the hybrid energy-harvesting traveling bag remains lightweight, reliable, and efficient while providing an eco-friendly power solution for both soldiers and trekkers.

Volume 14, Issue 10, October 2025**[DOI: 10.15680/IJIRSET.2025.1410049]****IV. WORKING PRINCIPLE**

The hybrid energy-harvesting traveling bag operates by converting natural and mechanical energies from the environment into electrical energy using three integrated sources: solar, piezoelectric, and thermoelectric systems.

During daytime operation, flexible solar panels mounted on the outer surface capture sunlight and convert it into electrical energy through the photovoltaic effect. This energy forms the primary source of power, especially in open terrains like deserts. Simultaneously, piezoelectric elements embedded in the shoulder straps and base of the bag generate small amounts of electrical energy from mechanical vibrations and pressure created by walking or movement.

In environments with noticeable temperature differences, thermoelectric generators utilize the Seebeck effect to convert heat flow between the user's body and the surrounding air into additional electricity. All three sources feed their outputs into a power management unit, which regulates and balances the input, ensuring stable charging and efficient distribution.

The regulated power is stored in a lithium-ion battery managed by a battery management system to prevent overcharging and ensure stable voltage output. The stored energy can then be used to power essential devices such as GPS units, mobile phones, and radios, providing a continuous and eco-friendly power supply even in remote and harsh environments.

ADVANTAGES

Advantages of the project are as listed below:

- Provides continuous and renewable power supply from multiple energy sources.
- Reduces dependence on external charging or battery replacement.
- Lightweight, durable, and suitable for harsh environmental conditions.
- Ergonomic and comfortable design for long-term use by soldiers and trekkers.
- Enhances safety and mobility by ensuring uninterrupted operation of essential devices.

APPLICATIONS

Applications of the project are as follows:

- Used by soldiers in remote or hostile terrains to power communication, navigation, and surveillance equipment.
- Helpful for trekkers and mountaineers to charge portable devices like GPS units, mobile phones, and cameras during long expeditions.
- Suitable for disaster relief teams and rescue operations where power sources are unavailable.
- Can be used by researchers and surveyors working in isolated field locations.
- Applicable for camping, hiking, and outdoor adventure activities requiring lightweight and sustainable energy solutions.

V. FUTURE SCOPE

- Integration of wireless charging modules to power multiple devices simultaneously.
- Use of advanced lightweight composite materials to further reduce overall weight.
- Incorporation of smart sensors and IoT connectivity for real-time power monitoring.
- Development of detachable and modular energy units for easier maintenance and upgrades.
- Expansion of storage capacity using solid-state or graphene-based batteries for improved efficiency and lifespan.

VI. CONCLUSION

The hybrid energy-harvesting traveling bag provides a sustainable and practical solution for meeting portable power needs in remote environments. By combining solar, piezoelectric, and thermoelectric energy sources, it ensures continuous electricity generation under varying environmental conditions. The integration of an intelligent power management and battery system enhances efficiency, reliability, and safety, while the lightweight and durable design ensures comfort and usability for both soldiers and trekkers. This innovative approach not only reduces dependence on external power supplies but also supports eco-friendly and self-sufficient operations in challenging terrains. With

further optimization and integration of smart features, the proposed design has strong potential to become a versatile and essential tool for defense, adventure, and emergency applications.

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