

# FINDING CRITICAL MIDDLE POINT USING WIRELESS SENSOR NETWORKS FOR STRUCTURAL HEALTH MONITORING

*S. Dinesh Kumar<sup>1</sup>, S. Suganpriyan<sup>2</sup>*

## ABSTRACT

Structural Health Monitoring (SHM) plays a crucial role in ensuring the safety and reliability of civil infrastructure by enabling early detection of structural damage. Wireless Sensor Networks (WSNs) have emerged as an effective solution for SHM due to their scalability, flexibility, and ease of deployment. This paper proposes a WSN-based approach for identifying a structure's critical middle point through the analysis of vibration and strain data collected from distributed sensor nodes. The proposed methodology consists of data acquisition, feature extraction, damage index formulation, critical point identification, and optimized sensor deployment. Experimental validation was conducted using a beam-like structural model equipped with uniformly distributed wireless sensors. Performance evaluation, based on peak acceleration, strain variation, and damage index metrics, demonstrates that the mid-span sensor consistently records the highest structural response. Graphical results further validate the accuracy and reliability of the proposed system in detecting the structure's critical region. The wireless framework significantly reduces cabling requirements while ensuring efficient damage localization. Overall, the proposed method provides a cost-effective, scalable, and efficient solution for critical point identification in SHM applications and establishes a foundation for future integration with machine learning techniques and real-time monitoring systems.

**Keywords :** Wireless Sensor Networks, Structural Health Monitoring, Critical Middle Point Detection, Damage Index

## I. INTRODUCTION

A cluster of two or more interconnected computer systems is called a network. Computer networks come in two varieties. Both wired and wireless networks are involved. The key features of networks are their architecture, protocol, and topology. Computers or other wireless devices are linked together to create a network without the need for cables in

wireless networks. Any kind of computer network that connects network nodes via wireless data connections is referred to as a wireless network. Every system can also function as a sensor or a node. A sensor network is on the way. Sensor networks are created when a collection of sensor devices comes together.

Wireless Sensor Networks (WSNs) are widely dispersed autonomous sensors that track environmental or physical parameters like temperature, sound, pressure, vibration, etc. and transmit their data to a base station via the network. Numerous sensor nodes make up Wireless Sensor Networks (WSN). The sensor nodes can be placed inside or in close proximity to the phenomenon being detected. A sensor is a device that transforms sound and physical phenomena, such as motion, vibration, heat, and light, into electrical signals. Bi-directional networks, which are more recent, are also used to regulate sensor activity. Military uses like battlefield surveillance spurred the development of wireless sensor networks, which are now employed in numerous commercial and consumer applications, such as structural health monitoring, industrial procedure monitoring and control, and so forth. A radio transceiver with an internal antenna or a connection to an external antenna, a microcontroller, and an electronic circuit for interacting with the sensors are the usual components of each such sensor network node. WSN topologies range from a trouble-free network to a sophisticated multi-hop wireless mesh network.

WSNs ought to be able to self-configure and withstand changes in topology, such as node death. Additionally, it keeps the base station and sensor nodes connected. Additionally, it guarantees connectivity within a specific range. The following are a few traits of sensor networks:

The complete system needs to be built with requirements of small size and high quantity and operation without tethers and affordable pricing. The system operates under restrictions of energy consumption and processing power and data transfer capabilities. The system requires a compact design that needs a corresponding small power source. The system needs to deliver affordable power management through its basic processing unit and limited range communication system. The system needs to function without maintenance requirements and without battery replacement for its ad-hoc deployment. The network achieves longer operational time through its design which prevents any transmission of

Department of Computer Science and Engineering<sup>1</sup>  
Karpagam Academy of Higher Education, Coimbatore, India<sup>1</sup>  
sdineshkumar039@gmail.com<sup>1</sup>

Department of Computer Science and Engineering<sup>2</sup>  
Mahendra institute of Technology, Salem, TN, India<sup>2</sup>  
suganpriyans@mahendratech.org<sup>2</sup>

\* Corresponding Author

unprocessed information. Wireless sensor networks (WSNs) have become the primary technology used in Structural Health Monitoring applications which leave wired networks behind. Structural health monitoring (SHM) operates as an essential instrument for engineers to establish the secure maintenance of essential infrastructure. SHM uses multiple sensing technologies together with an embedded measurement system to acquire and store and process data in real-time. The recent progress in sensor technology enables wireless sensor networks (WSNs) to deliver enhanced performance and reduced operational costs which make them suitable for various use cases that include structural monitoring and scientific research and target tracking. The various bridge and building and tunnel and aircraft and nuclear plant civil structures function as sophisticated engineering systems which sustain the prosperity of society. Structural health monitoring (SHM) serves as a primary system that helps maintain the structural integrity of these buildings. WSNs have emerged as a versatile solution for SHM because they can be implemented in different areas while delivering better performance than wired systems. The Golden Gate Bridge in the US and the Guangzhou New TV Tower (GNTVT) in China serve as two distinct examples of this architectural style. SHM systems need to track structure health status which includes damage detection while providing continuous monitoring and instant analysis. The WSN-based SHM system requires SHM specifications while WSN technology shows its operational limitations which prevent successful achievement of these goals. The engineering requirements do not apply to WSN deployments because they allow sensor node placement which helps design networks that maintain operational connectivity while delivering secure data transmissions. The base station (BS) needs to collect all sensor location data which supports structural health monitoring (SHM) after the sensor system has been installed and structural research has been conducted. Wireless sensors face multiple limitations which include the requirements for flawless transmission of data for operational systems and their ability to handle equipment failures and their limitations in power usage and data transmission capacity and other operational factors. The WSN system deployed for SHM becomes more likely to experience failures because of multiple factors which include 1) physical structural modeling constraint 2) irregular communication 3) distant between the sensors 4) quick energy depletion of some sensors 5) irregular communication distance that is transmitting data from a sensor to another sensor or the BS over large structures is not reliable. The system must solve two main issues when any type of WSN fault emerges because it needs to handle two tasks which involve

monitoring data and maintaining operational capacity during sensor failures. The computer science (CS) field has conducted multiple studies about fault tolerance issues which emerge in various WSN applications. The SHM applications do not consider this fault. The structure of this paper follows these principal sections. The second section presents research work related to the topic. Section 3 the proposed CMSHM algorithm. The Results and discussions are given in Section 4. The paper concludes in Section 5 which provides the final statement.

## II. RELATED WORK AND BACKGROUND

The applications of SHM are moving towards the utilization of WSN technology, which enables the precise collection of signals through the utilization of WSN technology having high synchronization accuracy[2]. It can also be observed from the sensor deployment section the sensor deployment view of the system. The engineering field provides numerous optimal sensor deployment techniques which have been implemented by the researchers on the wired network system as indicated by the various sources [10][13][15][16]. The researchers have tested various wireless sensor devices for their effectiveness in the structural monitoring field as indicated by the source [1]. The deployed WSN system for structural monitoring only encounters sensor faults and wireless sensor transmission faults and separation problems encountered in the WSN system[3]. The study on WSN deployment has indicated remarkable efficiency through the sensor deployment feasibility assessment, which was established during their validation on SPEM deployment work done by Bo Li et al.. [13] proposed the placement of the sensor based on civil requirements and the placement of the sensor based on computer science requirements. The sensor placement system offers various evaluation methods that assist users in evaluating placement sites through various evaluation steps[4]. The system's optimization process involves two major components that are networking connectivity and the problems of data routing; these components aim to ensure energy efficiency. The system's optimization introduces a new method of Sensor Placement through the use of a method called "Effective Independence EFI Method" (SPEM). To use the Effective Independence method, sensor placement must take place using the sensor placement process, thus ensuring that no grid/tree structure deployments are used[5]. The Effective Independence placement method offers the appropriate location of the sensor. The system shows how SHM framework components combine to handle topology control data routing and energy efficiency operations. The system suffers from two main problems which require computer

system resources to meet civil engineering placement standards that lead to missing essential structure location points. It also fails to recover from fault in wireless sensors while monitoring[6]. The SHM applications increasingly use WSN technology which enables accurate signal collection through WSN technology that achieves high synchronization accuracy. The sensor deployment process shows the sensor deployment view of the system. The engineering field provides various optimal sensor deployment methods that researchers have applied to wired network systems according to sources [11][14].

According to source [8], multiple wireless sensor devices had been tested by the researchers to determine their effectiveness for the structural health monitoring application. It is observed that only minor sensor faults, transmission faults, and WSN separation problems take place in the WSN system deployed for structural monitoring. The WSN deployment study demonstrates impressive achievements via sensor deployment feasibility assessment that they defined in validation of their work in performing deployment of SPEM. Bo Li et al. [13] defined sensor placement on civil requirements and sensor placement on computer science requirements[7]. The sensor placement system allows users to evaluate placement sites via multiple steps of evaluation via evaluation methods that the system offers. The system optimization process of system performance uses two main components derived from networking connectivity and data routing issues with goals of attaining efficiency[12]. However, a new method via optimization of system performance defines a new method of attaining sensor placement via the use of EQUI-Method denoted as SPEM. The Effective Independence EQUI method entails sensor placement via sensor placement process and hence prevents standard grid and tree design[9]. The Effective Independence placement method offers users with appropriate placement of sensor placement. The system demonstrates how components of SHM framework integrate to offer services in data routing and energy efficiency via topology control[17]. Two major problems the system suffers from require computer system resources to meet civil engineering placement standards, leading to the loss of some essential structure location points. The number and positions of sensors and traffic also determine the usability of a system in terms of coverage, connectivity, lifetime, cost, etc. The research shows how random device deployment affects connectivity and lifetime performance in extensive WSN networks which use different types of devices. The deployment of the RNs can have a significant impact on connectivity and lifetime of a WSN system. The first method of the system operates to balance RNs energy consumption throughout the network which

results in extended system operational time. The Relay Nodes which are away from the Base Station will dissipate energy faster than the RNs closer to the BS due to the larger transmission distance. This is because the traffics are built up on RNs closer to the BS since the relaying is performed from far to near. For this, the system requires two groups of sensors; one will collect data while the other group transmits the collected data to the base station.

They may not satisfy distance constraints among the placement of sensors. The proposed CSMHM tries to overcome the distance problem and deploy the sensors for monitoring the structure using wireless sensor networks so as to extend the lifetime of sensors.

### III. METHODOLOGY AND SYSTEM ARCHITECTURE

The proposed system uses a Wireless Sensor Network (WSN) model that seeks to identify the critical midpoint in the structure that allows for proper execution of the structural health assessment. The proposed methodology starts off with a strategic positioning of wireless sensor nodes at equal intervals across the structure so that a comprehensive and thorough coverage of the structure is obtained. The wireless nodes have units that measure the vibration and strain experienced by the structure as a means of measuring its movement and holding up under various conditions. The wireless nodes continue collecting data that they transmit wirelessly and send to a cluster head that processes the data while eliminating noise interference. The system that the researchers proposed in their framework allows for proper monitoring of the structural health, while the critical midpoint in the structure is located using Wireless Sensor Network (WSN) monitoring. The varying benefits provided by this system come as a result of the design of the system for energy efficiency without compromising data transfer or damage assessment. The system uses nodes as sensors for the structuring of data, which is then processed by cluster heads before being fully evaluated by the base station.

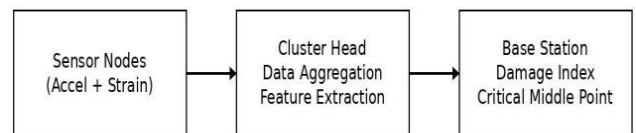


Fig 1. WSN-based SHM System

#### A. Overview of WSN-based SHM System

The WSN-based Structural Health Monitoring system continuously monitors the physical well-being of the structure by continuously gathering information related to the vibrations and strain measurements. Sensor nodes are strategically placed at various points along the structures,

especially at points of loading and at mid-span points.

These communication nodes/sensors communicate via wireless communication with neighboring cluster heads that employ low power communication protocols. Data aggregation and feature extraction processes are employed by the cluster heads in the communication network. Thus, the data is communicated to the base station for damage analysis. The damage index location of the communication/sensor node is identified; this is the critical middle point of the structure.

This architecture reduces extensive wiring needs, provides real-time monitoring facilities, and is also scalable.

### B. Sensor Node Design

Each sensor node is a miniature and energy-constrained device. It is designed to be deployed for long-term operation. Each sensor node has the following components:

**Sensing Unit:** It comprises accelerometers, which measure vibration, and strain gauges, which measure deformation.

**Processing Unit:** This unit consists of a low power micro controller that processes the raw data from the sensor.

**Communication Unit:** A wireless transceiver facilitates data transfer to the cluster head.

**Power Unit:** A battery or a module that harvests energy will be used as a power supply to the sensor node.

These sensor nodes work in periodic sensing modes that help them save energy. The data is sent at regular intervals only when significant structural changes are sensed.

### C. Cluster Head and Base Station Functions

Cluster Heads (CHs) are vital in minimizing communication overhead and power consumption. The basic functions of cluster heads include:

Information collection from various sensor nodes  
Combining the data and filtering out irrelevant data  
Important data is obtained from the entire process, e.g., peak acceleration and change in strain. In the Base Station (BS), decision-making occurs on a global scale. The overall objectives here include: Receiving aggregated data from various cluster leaders to determine the damage index for every location of the sensors. Identifying the middle point where there is a maximum damage index. Drawing visual reports for the maintenance crew. This hierarchy helps in increasing the overall reliability of the systems and structuring an efficient monitoring process.

## III. MATHEMATICAL MODELING

### A. Damage Index Formulation

Assume  $A_i$  and  $S_i$  are peak acceleration and strain

measurements corresponding to the peak measurements of the  $i^{\text{th}}$  sensor node. To facilitate a suitable comparison, it is assumed that the measurements are normalized over their respective peak measurements. Normalized acceleration measurements  $A_i^{\text{norms}}$  and normalized strain measurements  $S_i^{\text{norms}}$  can be represented as follows:

$$A_i^{\text{norms}} = \frac{A_i}{\max(A)}, S_i^{\text{norms}} = \frac{S_i}{\max(S)} \quad (1)$$

Finally, the damage index DI<sub>i</sub> for the sensor node itself is computed as a weighted combination of the features:

$$DI_i = \alpha A_i^{\text{norms}} + \beta S_i^{\text{norms}} \quad (2)$$

where  $\alpha$  and  $\beta$  are weighting factors subject to the constraint  $\alpha + \beta = 1$ . Such a damage index can quantify the severity of damage to the structure at individual sensor locations.

### B. Critical Middle Point Determination

The critical middle point of the structure is determined by finding the node of the sensor where the maximum damage index is present. The mathematically formulated equation for determining the critical sensor location CCC is as follows:

$$C = \text{argmax}(DI_i) \quad (3)$$

Sensor node corresponding to maximum value indicates area of maximum stress concentration and potential structural vulnerability.

## IV. DATA SET DESCRIPTION

The used dataset in this research work consists of sensor deployment information, vibration, and strain measurements, and processed features for machine learning readiness.

### A. Sensor Deployment Dataset

Five wireless sensor nodes S1 to S5 were deployed uniformly along the structure in equal intervals. Every sensor location has its position, node ID, and sensing capability associated with it. Fig 2: Peak acceleration across sensor networks. The coordinate positions of sensors and the deployment order of each sensor are included in the dataset for spatial analysis. Thus, Table 1 presents.

Table I. Sensor Deployment Peak Acceleration

Sensor ID	Position (m)	Peak Acceleration (m/s <sup>2</sup> )	Strain (μμ)
S1	0	1.8	120
S2	2	2.4	210
S3	4	3.9	420
S4	6	2.6	260
S5	8	1.9	140

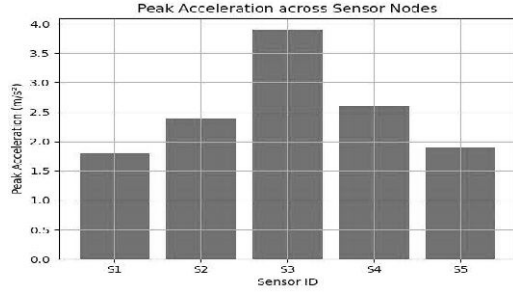


Fig. 2. Peak acceleration across sensor networks

### A. Vibration and Strain Data

Each sensor node measures the vibration and strain values. These values are measured while the measurement system is excited. Vibration values measure the dynamic behavior of the structures. Strain values measure the properties of deformation fig 3 strain distribution across sensor nodes. From these primary values, which are obtained, peak acceleration values can be obtained. In addition, maximum strain values can also be obtained. These are the most significant values used to evaluate damage Table 2.

Table II. Vibration and strain signals

Sensor ID	Position (m)	Strain ( $\text{\AA}\mu\text{\AA}$ )	Damage Index
S1	0	120	0.21
S2	2	210	0.46
S3	4	420	0.89
S4	6	260	0.52
S5	8	140	0.27

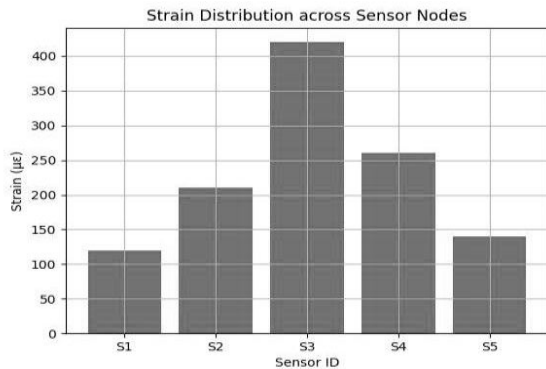


Fig. 3. Strain distribution across sensor nodes

### C. Machine Learning Dataset Preparation

For extensibility, the collected data is represented as a machine learning-ready data set. The data set consists of feature vectors represented by normalized acceleration, normalized strain, and damage index values Table 3. Additionally, each data set has an assigned label indicating the structural condition, thus supporting supervised learning for damage classification and prediction fig 4 index variation across sensor nodes.

Table III. Strain and damage index values

Sensor ID	Position (m)	Strain ( $\text{\AA}\mu\text{\AA}$ )	Damage Index
S1	0	120	0.21
S2	2	210	0.46
S3	4	420	0.89
S4	6	260	0.52
S5	8	140	0.27

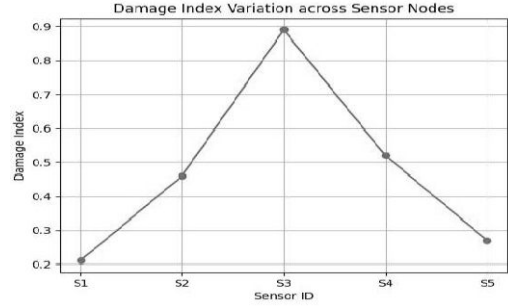


Fig. 4. Damage index variation across sensor nodes

## V. RESULTS AND PERFORMANCE ANALYSIS

This section assesses the effectiveness of the developed Wireless Sensor Network (WSN)-based approach for determining the critical middle point of a structure on the basis of experimental validation and result analysis.

### A. Experimental Setup

The experimental setup was realized on a beam-like structural model with a total of five wireless sensor nodes (S1-S5) equally distributed in space along the structure, as depicted in the figure. Each of the sensor nodes was provided with vibration and strain sensors to measure the overall response of the structure under controlled conditions of excitation. The data collected by the sensors was transmitted wirelessly to a base station using a cluster-based wireless communication protocol. The collected data was pre-processed, and key features such as peak values of acceleration and maximum values of strains were extracted for further analysis. A damage index was calculated at each location of the sensors in order to evaluate the degree of response of the structure and identify a critical middle point.

### B. Evaluation Metrics

The following metrics were used to assess the performance of the system: peak acceleration, strain magnitude, and damage index. Peak acceleration demonstrates the intensity of vibration in each sensor position, while strain describes the deformation that the structure has undergone. From these normalized values, vibration and strain give a combined view of structural severity, represented by the damage index. Besides these, the accuracy of critical middle point identification was taken as

one of the key performance indicators.

### C. Graphical Analysis

Graphical analysis was performed using bar and line graphs to visualize peak acceleration variation, strain, and the damage index across sensor nodes. From all three graphs, the maximum value is obtained from sensor S3, placed at the mid-span of the structure. This points out a clear peak at the center that indeed validates the effectiveness of the proposed methodology for localizing the critical structural region.

### D. Discussion of Results

The experimental data proves that the proposed novel system for carrying out WSN-based SHM successfully identifies the most critical middle point of a given structure. Such trends align well with theoretical considerations in terms of mechanics of structures, in which the most stressful point is associated with the middle point of the structure. Wireless sensor networks improve system scalability and make this system easier to deploy.

## VI. APPLICATIONS AND USE CASES

The proposed Wireless Sensor Network (WSN)-based structural health monitoring system can be effectively applied across a wide range of civil infrastructure to ensure safety, reliability, and long-term sustainability.

### A. Bridge Monitoring

The bridges are under continuous exposure to dynamic loads resulting from traffic, wind, and environmental factors. In this regard, it is notable that the proposed system promotes a continuous evaluation of the structures with respect to vibrations and strains within strategic areas such as the center point and supports. Identification of the critical center point is facilitated through damage index analysis, with a consequent early detection of fatigue, cracks, and weakening of structures. An advantage of wireless sensing technology is its ability to reduce complexities and enhance its applicability over long-span bridges.

### B. Building and Infrastructure Safety

In buildings and larger infrastructure systems, damage may also accrue due to aging, seismic activity, or excessive loading. The proposed method of SHM using a WSN would facilitate real-time monitoring of structural behavior in columns, beams, and floors. This would enable engineers to identify the major areas with high damage indices so that they could carry out repairs accordingly. This proposed system could be used in post-earthquake damage assessment and safety evaluation of high-rise buildings.

### C. Heritage Structure Preservation

Non-invasive and continuous monitoring is required for heritage structures in order to retain their historical value. The proposed system presents a low-power and minimally intrusive solution to monitor the vibration and strain without tampering with the structure. It will identify critical stress zones so that preventive conservation measures can be planned to ensure long-time preservation of monuments, temples, and historical buildings while maintaining structural authenticity.

### D. Bridge Monitoring

Bridges are constantly subjected to dynamic loads due to traffic, wind, and environmental conditions. The suggested system provides vibration and strain monitoring from critical locations like mid-span and support regions continuously. By defining the critical middle point through damage index analysis, early detection of fatigue, cracks, and structural weakening is achieved. The wireless sensor network avoids installation difficulties and thus supports scalable deployment along long-span bridges for on-time maintenance and improvement in structural safety.

### E. Building and Infrastructure Safety

In buildings and large infrastructure applications, structural damage may occur as a result of ageing, seismic activity, or overloading. The opportune WSN-based SHM approach facilitates the real-time monitoring of structural responses under a column, beam, or floor. The ability of the critical area identification method to locate critical locations on the basis of high damage index values is very important for structural engineers. This SHM approach is appropriate for damage assessment after an earthquake or safety analysis of high-rise buildings.

### F. Heritage Structure Preservation

The need to monitor heritage structures arises because these need non-invasive and continuous monitoring to preserve their heritage value. The proposed system offers a low-power non-invasive option for monitoring vibrations and strain without interfering with these structures. Preventive conservation can thus be carried out by identifying critical stress zones so that these structures are preserved with monumentality and authenticity intact, including temples and historic buildings.

## V. CONCLUSION AND FUTURE WORK

The proposed Wireless Sensor Network (WSN) - based structural health monitoring system may be further taken forward in various directions to make it more precise,

intelligent, and effective. For example, it may be taken forward by incorporating various aspects of machine learning techniques with a view to making it more intelligent and effective. For instance, various supervised learning algorithms like Support Vector Machines (SVM), Random Forests, Artificial Neural Networks (ANN), etc., may be adapted to efficiently classify between healthy and unhealthy structural states by analyzing historical datasets corresponding to various forms of structural vibrations. Similarly, it may be possible to make it even more precise with efficient deep learning algorithms that may be effective in identifying structural damage even in early stages of damage development. Similarly, real-time structural health monitoring capabilities may be built into the proposed structural health monitoring system by incorporating end devices with characteristics of edge computing, enabling immediate identification of critical portions of structures. Similarly, IoT platforms may be utilized to make it more effective. With a view to making it more effective, communication protocols may be used that are more energy-efficient so that a longer lifetime may be ensured.

This paper proposes a Wireless Sensor Network-based approach for determining the critical middle point of a structure for structural health monitoring applications. In this regard, the paper proposes a methodology for determining the critical middle point of a structure. The results of the experimental investigation showed the efficacy of the approach in accurately determining the region of maximum response. The results also showed that the mesh placed at the middle span of the structure recorded the maximum values of vibration sensors, strain sensors, and damage index. The approach is also efficient as it becomes easier to implement more sensors using the wireless sensors. Overall, the proposed approach is reliable, cost-effective, and efficient for determining the critical middle point of a structure.

### REFERENCES

- [1] R. L. Siegel, K. D. Miller, H. E. Fuchs, and A. Jemal, "Cancer Statistics, 2022," *CA: A Cancer Journal for Clinicians*, vol. 72, no. 1, pp. 7-33, 2022.]
- [2] N. Smaoui Zghal and N. Derbel, "Melanoma Skin Cancer Detection based on Image Processing," *Current Medical Imaging Reviews*, vol. 16, no. 1, pp. 50-58, 2020.
- [3] G. Argenziano, H. P. Soyer, V. De Giorgi, D. Piccolo, P. Carli, M. Delfino, A. Ferrari, R. Hofmann-Wellenhof, D. Massi, G. Mazzocchetti, M. Scalvenzi, and I. H. Wolf, "Dermoscopy: A Tutorial," *EDRA Medical Publishing & New Media*, Milan, 2002.
- [4] A. Esteva, B. Kuprel, R. A. Novoa, J. Ko, S. M. Swetter, H. M. Blau, and S. Thrun, "Dermatologist-level Classification of Skin Cancer with Deep Neural Networks," *Nature*, vol. 542, no. 7639, pp. 115-118, 2017.
- [5] R. D. Seeja and A. Suresh, "Deep Learning Based Skin Lesion Segmentation and Classification of Melanoma Using Support Vector Machine (SVM)," *Asian Pacific Journal of Cancer Prevention*, vol. 20, no. 5, pp. 1555-1561, 2019.
- [6] M. E. Celebi, H. A. Kingravi, B. Uddin, H. Iyatomi, Y. A. Aslandogan, W. V. Stoecker, and R. H. Moss, "A Methodological Approach to the Classification of Dermoscopy Images," *Computerized Medical Imaging and Graphics*, vol. 31, no. 6, pp. 362-373, 2007.
- [7] W. Stolz, A. Riemann, A. B. Coggnetta, L. Pillet, W. Abmayr, D. Holzel, P. Bilek, F. Nachbar, M. Landthaler, and O. Braun-Falco, "ABCD Rule of Dermoscopy: A New Practical Method for Early Recognition of Malignant Melanoma," *European Journal of Dermatology*, vol. 4, no. 7, pp. 521-527, 1994.
- [8] A. Esteva, B. Kuprel, R. A. Novoa, J. Ko, S. M. Swetter, H. M. Blau, and S. Thrun, "Dermatologist-level Classification of Skin Cancer with Deep Neural Networks," *Nature*, vol. 542, no. 7639, pp. 115-118, 2017.
- [9] K. He, X. Zhang, S. Ren, and J. Sun, "Deep Residual Learning for Image Recognition," *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 770-778, 2016.
- [10] G. Huang, Z. Liu, L. Van Der Maaten, and K. Q. Weinberger, "Densely Connected Convolutional Networks," *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 4700-4708, 2017.
- [11] M. Tan and Q. Le, "EfficientNet: Rethinking Model Scaling for Convolutional Neural Networks," *International Conference on Machine Learning*, pp. 6105-6114, 2019.
- [12] A. G. Howard, M. Zhu, B. Chen, D. Kalenichenko, W. Wang, T. Weyand, M. Andreetto, and H. Adam, "MobileNets: Efficient Convolutional Neural Networks for Mobile Vision Applications," *arXiv preprint arXiv:1704.04861*, 2017.
- [13] N. C. Codella, D. Gutman, M. E. Celebi, B. Helba, M. A. Marchetti, S. W. Dusza, A. Kalloo, K. Liopyris, N. Mishra, H. Kittler, and A. Halpern, "Skin Lesion Analysis Toward Melanoma Detection: A Challenge at the 2017 International Symposium on Biomedical Imaging (ISBI)," *arXiv preprint arXiv:1710.05006*, 2017.

- [14] P. Tschandl, C. Rosendahl, and H. Kittler, "The HAM10000 Dataset, A Large Collection of Multi-Source Dermatoscopic Images of Common Pigmented Skin Lesions," *Scientific Data*, vol. 5, no. 1, pp. 1-9, 2018.
- [15] L. R. Soenksen, T. Kassis, S. T. Conover, B. Marti-Fuster, J. S. Birkenfeld, J. Tucker-Schwartz, A. Naseem, R. R. Stavert, C. C. Kim, M. M. Senna, et al., "Using deep learning for dermatologist-level detection of suspicious pigmented skin lesions from wide-field images," *Sci. Transl. Med.*, vol. 13, no. 581, Art. no. eabb3652, Feb. 2021, doi: 10.1126/scitranslmed.abb3652.
- [16] E. J. Topol, "High-Performance Medicine: The Convergence of Human and Artificial Intelligence," *Nature Medicine*, vol. 25, no. 1, pp. 44-56, 2019.
- [17] M. Tan and Q. V. Le, "MixConv: Mixed Depthwise Convolutional Kernels," *British Machine Vision Conference*, 2019.