

GROUP-43

Smart Sensing System for Bone Crack Detection

TEAM MEMBERS

Abhinn Goyal (B23108)

Abhey Kumar (B23391)

Riya Chaudhary (B23174)

Kartik Verma (B23140)

Thacker Vyom Amitbhai (B23417)

Dhruv (B23396)

September 6, 2024

With the guidance of:-

Faculty Mentor: Dr. Anirban Sarkar
`anirban@iitmandi.ac.in`

Under the supervision of:-

Student Mentor: Vershita Yadav
`b22281@students.iitmandi.ac.in`

Teaching Assistant: Arumugraj
`s21035@students.iitmandi.ac.in`

Contents

Introduction to the Problem Statement and its Need

Smart sensing systems for bone crack detection are a significant advancement in medical diagnostics, particularly for orthopedic health. Traditional methods like X-rays, CT scans, and MRIs are often invasive, time-consuming, and costly. They can also miss microfractures or early-stage damage, leading to delayed treatment and longer recovery times. Smart sensing systems address these issues by integrating biomechanical sensors, data processing algorithms, and machine learning techniques to detect subtle changes in bone structure. These sensors, embedded in wearable devices or applied externally, capture signals like vibrations, acoustic emissions, or electrical signals indicating stress or damage. Analyzing this data in real-time enables early fracture detection and timely intervention. Machine learning algorithms improve diagnostic accuracy by distinguishing between normal and abnormal bone behavior, reducing false positives. This approach minimizes hospital visits and supports continuous monitoring, especially for high-risk groups like the elderly or athletes. As the global population ages and personalized healthcare demand rises, smart sensing technologies offer a promising, non-invasive alternative to traditional methods, enhancing patient outcomes and reducing costs.

Problem Statement

Traditional bone fracture detection methods, such as X-rays, CT scans, and MRIs, face significant challenges related to accessibility, cost, and patient safety. These techniques require expensive equipment and specialized facilities, limiting their availability in rural or underserved areas. High costs for both the equipment and professional interpretation create financial barriers for patients and healthcare systems, potentially delaying diagnosis and treatment. Moreover, X-rays and CT scans involve radiation exposure, which

poses long-term health risks, especially for those needing frequent monitoring, such as athletes or elderly patients. This risk is particularly concerning for vulnerable populations like children and pregnant women. Additionally, traditional methods may not detect early-stage or microfractures, leading to undiagnosed injuries, delayed treatment, and persistent pain or mobility issues. A smart sensing system offers a promising alternative by being

portable, accessible, and affordable while providing accurate fracture detection. This system would use non-invasive sensors to monitor bone health in real-time, eliminating the need for large medical equipment and avoiding harmful radiation. It would be suitable for use at home or in remote areas, allowing for more frequent monitoring and early detection of microfractures. The system should:

- Accurately detect even subtle bone fractures.
- Be affordable and accessible in remote locations.
- Be non-invasive and portable to reduce discomfort and risk.
- Ensure data privacy and security.

Need for the Problem Statement

The limitations of traditional bone fracture detection underscore the need for smart sensing systems that improve accessibility, accuracy, cost-effectiveness, non-invasiveness, and portability.

- **Accessibility :** Traditional imaging methods like X-rays and CT scans are limited to specialized facilities, making them inaccessible to many, especially in rural areas. In emergencies, this lack of access can delay treatment. Smart sensing systems, being portable and easy to use, can be deployed in homes, rural clinics, and emergency situations, enabling real-time bone health monitoring without the need for travel to specialized centers.
- **Accuracy :** Traditional methods often miss subtle fractures like microfractures, leading to delayed treatment. Smart sensing systems, using advanced sensors and data processing, detect even the smallest bone defects by monitoring biomechanical signals. This improved accuracy allows for early intervention, preventing further complications.
- **Cost-effectiveness:** Traditional diagnostic equipment is expensive, and the associated costs of maintenance and specialist interpretation add to the financial burden on patients and healthcare providers. Smart sensing systems offer a more affordable alternative by reducing the need for expensive machinery and frequent hospital visits, enabling regular monitoring at home and lowering overall healthcare expenses.
- **Non-invasiveness:** X-rays and CT scans expose patients to ionizing radiation, posing health risks, particularly for vulnerable groups. Smart sensing systems, using safe technologies like biomechanical sensors or ultrasound, eliminate these risks, making them suitable for long-term monitoring without the concern of radiation exposure.
- **Portability:** Traditional imaging equipment is large and stationary, limiting its use to specific facilities. Smart sensing systems, being lightweight and compact, can be used in various settings, including homes, sports fields, and remote locations. Their portability allows for immediate, real-time feedback, enhancing the ability to provide timely care in diverse environments.

Specification to Define the Problem Statement

The key specifications for the smart sensing system are designed to address the critical shortcomings of traditional bone fracture detection methods. Each specification highlights essential aspects required for the system to be effective, safe, and versatile in real-world applications. Let's delve into each requirement in detail:

System Requirements

- **Non-invasiveness:** Unlike traditional methods that expose patients to harmful radiation, the smart sensing system should be non-invasive, using safe technologies like biomechanical sensors, ultrasound, or electromagnetic waves. This makes it suitable for frequent monitoring without health risks, particularly for individuals requiring long-term or continuous observation, such as those with chronic conditions or athletes.
- **Portability:** The smart sensing system should be compact and lightweight, allowing for easy transport and use in various settings, from hospitals to remote locations. Portability ensures that patients, especially in underserved areas, can access bone health monitoring without traveling to specialized centers. This feature is crucial for rapid diagnosis and immediate care in emergencies.
- **Real-time monitoring:** The system should enable real-time monitoring of bone health, continuously tracking biomechanical signals to detect fractures as they develop. Unlike traditional methods, this continuous oversight allows for early intervention, reducing the risk of further injury. Real-time monitoring is particularly valuable for high-risk groups and can be integrated with alerts to prompt timely medical attention when abnormalities are detected.

Sensor Specifications

The sensor specifications for the smart sensing system are critical for detecting biomechanical signals and assessing bone health. Key specifications include sensitivity, durability, and wireless capability, each of which plays a vital role in the system's effectiveness:

- **Sensitivity:** The sensor must be highly sensitive to detect minor biomechanical changes, such as bone vibrations or shifts, that signal potential fractures. This precision is crucial for early detection in at-risk patients, like athletes or those with osteoporosis, to prevent more severe injuries.
- **Durability:** Sensors need to be reliable over extended periods without requiring frequent maintenance. This ensures consistent performance, especially in continuous monitoring scenarios, such as with athletes or in remote healthcare settings, where durability reduces the need for replacements and makes the system more cost-effective.
- **Wireless capability:** Wireless sensors are essential for real-time data transmission, allowing continuous monitoring without delays. This feature supports remote healthcare, enabling data to be sent directly to providers or integrated with mobile devices, making the system portable and accessible in various environments

Algorithm Specifications

The algorithm specifications for the smart sensing system are critical to ensure accurate, real-time detection of bone fractures across diverse conditions. These specifications are described as follows:

- **Accuracy:** Algorithms should accurately identify patterns in sensor data that indicate bone fractures. Accurate detection minimizes false positives and negatives, ensuring reliable fracture detection and diagnosis across a range of bone conditions.
- **Sensitivity:** The algorithms must be sensitive enough to detect subtle changes in biomechanical signals, such as early-stage microfractures or stress fractures. High sensitivity enables early intervention and prevents further complications by detecting fractures before they worsen.
- **Efficiency:** Efficiency is essential for real-time processing and analysis of sensor data. Efficient algorithms minimize latency and computational load, allowing for continuous monitoring and timely feedback without delay. This is critical for portable and wearable systems where power and processing resources are limited.
- **Adaptability:** The algorithms must be adaptable to different bone types, fracture patterns, and individual variations. By accounting for variations in bone structure, density, and condition, the system can provide accurate results for a wide range of patients, including those with osteoporosis or other bone health issues.

User Interface Specifications

The user interface specifications are crucial for ensuring that the smart sensing system is user-friendly and effective, particularly for non-medical users. The specifications are outlined as follows:

- **Intuitive design:** The user interface should be designed to be simple and easy to navigate, even for individuals without a medical background. This ensures that all users, including patients and caregivers, can effectively interact with the system and interpret the results without confusion.
- **Real-time visualization:** The system should display real-time visualization of sensor data and analysis results, allowing users to monitor bone health continuously. This provides immediate feedback, enabling users to take timely actions if any abnormalities are detected.
- **Alert system:** The interface should include an alert system that notifies users of potential fractures or significant changes in bone health. These alerts can be visual or auditory, helping users respond quickly to any emerging issues, ensuring proactive health management.

By carefully considering these specifications, a smart sensing system for bone crack detection can be developed to address the limitations of traditional methods, providing a more accessible, accurate, and effective solution for diagnosing bone fractures.

Listing of All Possible Solutions

1. Ultrasound-Based Fracture Detection

- **How it works:** High-frequency sound waves are sent into the bone. The echoes that return are analyzed for irregularities that might indicate a fracture.
- **Pros:** Portable, non-invasive, real-time analysis.
- **Cons:** Requires skilled technicians, may have lower resolution than other methods.
- **Applications:** Emergency rooms, remote locations.

2. X-Ray Imaging

- **How it works:** Traditional X-rays visualize bone structure, revealing fractures. Enhanced techniques like Digital Radiography (DR) and Computed Tomography (CT) provide more detail.
- **Pros:** Widely used, effective for most fractures.
- **Cons:** Exposure to radiation, not always portable, expensive for high-resolution imaging.
- **Applications:** Hospitals, clinics, diagnostic centers.

3. Acoustic Emission Detection

- **How it works:** Detects sound waves emitted by micro-cracks. Sensors are attached to the bone or skin.
- **Pros:** Non-invasive, portable, detects micro-cracks early.
- **Cons:** Requires precise calibration, can be sensitive to noise.
- **Applications:** Early fracture detection in athletes, high-risk populations.

4. Infrared Thermography

- **How it works:** Detects temperature variations on the skin. Fractures often cause inflammation, leading to temperature changes.
- **Pros:** Non-invasive, contactless, portable.
- **Cons:** Limited by resolution for deep fractures.
- **Applications:** Field use, sports medicine, monitoring recovery.

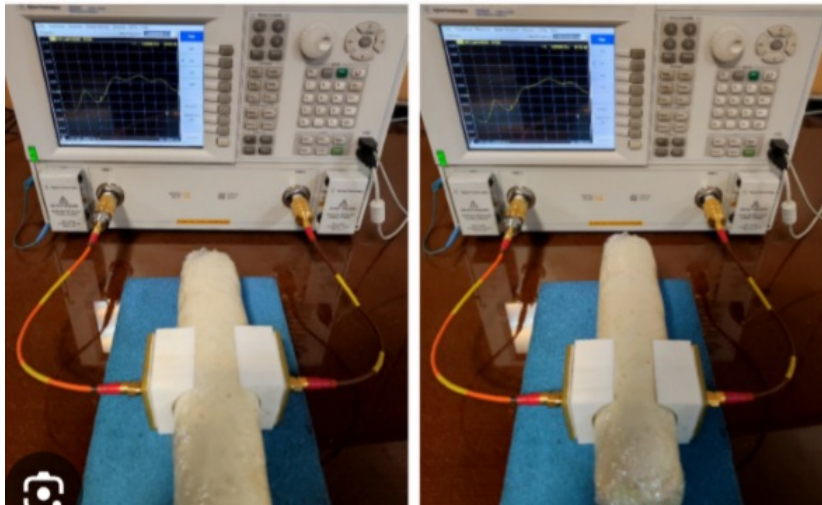


Figure 1: Infrared Thermography Device

5. Magnetic Resonance Imaging (MRI)

- **How it works:** Uses magnetic fields and radio waves to create detailed images of bone and surrounding tissues.
- **Pros:** High resolution, detects soft tissue damage.
- **Cons:** Expensive, not portable, time-consuming, requires specialized equipment.
- **Applications:** Hospitals, advanced medical facilities.

6. Wearable Sensor-Based Detection

- **How it works:** Wearable sensors monitor mechanical stress on bones. Sudden changes indicate potential fractures.
- **Pros:** Continuous monitoring, non-invasive, can be integrated with AI.



Figure 2: Typical MRI Machine

- **Cons:** Requires ongoing calibration, may be sensitive to false positives.
- **Applications:** Monitoring high-risk individuals, athletes, or elderly patients.

7. AI and Machine Learning for Fracture Detection

- **How it works:** Machine learning models analyze imaging data to automatically detect fractures.
- **Pros:** Enhances diagnostic accuracy and speed, adaptable to various imaging techniques.
- **Cons:** Requires large datasets for training and robust validation.
- **Applications:** Supplementing human diagnosis in hospitals and clinics.

8. Microwave-Based Bone Crack Detection

- **How it works:** Microwave signals are used to probe bone structures. Variations in the microwave signal can indicate the presence of fractures or other abnormalities.
- **Pros:** Non-invasive, portable, capable of detecting fractures without radiation.
- **Cons:** Requires precise calibration, effectiveness depends on tissue and bone composition.
- **Applications:** Remote diagnostics, emergency settings, portable fracture detection.

9. Vibration Analysis

- **How it works:** Small mechanical vibrations are introduced into the bone, and the response is measured. Changes indicate structural anomalies.
- **Pros:** Non-invasive, portable, cost-effective.
- **Cons:** Requires precise measurement and calibration, limited resolution for complex fractures.
- **Applications:** Quick screenings in sports or remote environments.

10. Optical Coherence Tomography (OCT)

- **How it works:** Uses light waves to capture micrometer-resolution images of bone surfaces.
- **Pros:** High-resolution imaging, non-invasive.
- **Cons:** Limited to small or accessible bones, expensive equipment.
- **Applications:** Research settings, small bone fractures (e.g., fingers, toes).

11. Electrical Impedance Tomography (EIT)

- **How it works:** Measures electrical conductivity of bone tissue. Changes indicate fractures or cracks.
- **Pros:** Non-invasive, relatively low-cost, portable.
- **Cons:** Lower resolution than X-ray or MRI, affected by surrounding tissue properties.

- **Applications:** Early fracture detection, particularly where radiation-based imaging is undesirable.

12. Bone Densitometry (DEXA)

- **How it works:** Measures bone density. Can identify fractures by showing areas of reduced bone mass.
- **Pros:** Accurate measurement of bone health, non-invasive, minimal radiation exposure.
- **Cons:** Primarily designed for bone density assessment rather than fracture detection.
- **Applications:** Osteoporosis management and fracture risk assessment.

13. Piezoelectric Sensors

- **How it works:** Detect mechanical stress and convert it into electrical signals.
- **Pros:** Compact, sensitive to mechanical changes, suitable for continuous monitoring.
- **Cons:** Requires careful placement and calibration, can be sensitive to external vibrations.
- **Applications:** Implantable or wearable devices for continuous monitoring of bone health.

14. Photoacoustic Imaging

- **How it works:** Uses laser-induced ultrasound to create images of tissue, including bones.
- **Pros:** Non-invasive, high contrast, capable of deep tissue imaging.
- **Cons:** Limited availability, requires advanced equipment and expertise.
- **Applications:** Research, advanced clinical diagnostics, specialized imaging.

15. Near-Infrared Spectroscopy (NIRS)

- **How it works:** Measures the absorption of near-infrared light by bone tissue.
- **Pros:** Non-invasive, portable, relatively low cost.
- **Cons:** Limited depth penetration, most effective for superficial bones.
- **Applications:** Field screening, monitoring shallow bone fractures.

Statistical Analysis of Solutions

While Performing Statistical Evaluation, we considered the following points and gave each idea, a score out of 10.

A: Cost of the Idea ($(30000/\text{Amount}) * 10$)

B: Availability of Parts

C: Ease of Manufacturing/Assembly

D: Fulfilment of Purpose

E: Ergonomics / Aesthetics

F: Integration of Power Source

G: Integration of Electronics

H: Timebound Manufacturing Feasibility

I : Maintenance/Service Cost

J: Overall Feel/Confidence in the Solution

K: Overall Score

| Index | A | B | C | D | E | F | G | H | I | J | K |
|-------|-----|----|----|----|----|----|----|----|---|----|------|
| 3.1 | 9 | 8 | 10 | 11 | 9 | 10 | 10 | 9 | 9 | 10 | 95 |
| 3.2 | 10 | 8 | 10 | 10 | 9 | 10 | 10 | 9 | 7 | 10 | 93 |
| 3.3 | 8 | 7 | 7 | 11 | 8 | 10 | 8 | 8 | 9 | 8 | 84 |
| 3.4 | 11 | 9 | 8 | 9 | 8 | 10 | 9 | 9 | 7 | 10 | 90 |
| 3.5 | 7 | 6 | 7 | 11 | 9 | 10 | 8 | 8 | 8 | 8 | 82 |
| 3.6 | 8 | 8 | 7 | 10 | 9 | 10 | 8 | 8 | 8 | 7 | 83 |
| 3.7 | 7.5 | 6 | 6 | 11 | 10 | 10 | 9 | 8 | 8 | 7 | 82.5 |
| 3.8 | 8 | 8 | 8 | 10 | 7 | 10 | 9 | 9 | 9 | 9 | 87 |
| 3.9 | 12 | 10 | 10 | 8 | 10 | 8 | 8 | 10 | 8 | 6 | 90 |
| 3.10 | 10 | 8 | 9 | 8 | 9 | 9 | 8 | 8 | 8 | 6 | 83 |
| 3.11 | 5.5 | 6 | 6 | 9 | 7 | 8 | 7 | 6 | 5 | 5 | 64.5 |
| 3.12 | 6.5 | 6 | 6 | 8 | 6 | 8 | 6 | 6 | 5 | 5 | 62.5 |

Detailed Solution: Microwave-Based Bone Crack Detection System

System Overview

The objective of this system is to detect bone cracks using microwaves. The system operates with antennas at a frequency of 2.4 GHz and employs an octagonal antenna arrangement to analyze S11 data for fracture detection.

System Components

Antennas and Arrangement

- **Antennas:** Eight antennas are arranged in an octagonal pattern around the bone. These antennas will operate at a frequency of 2.4 GHz to emit and receive microwave signals.
- **Antenna Design:** Microstrip patch antennas are suitable for this frequency due to their compact design and ease of integration.

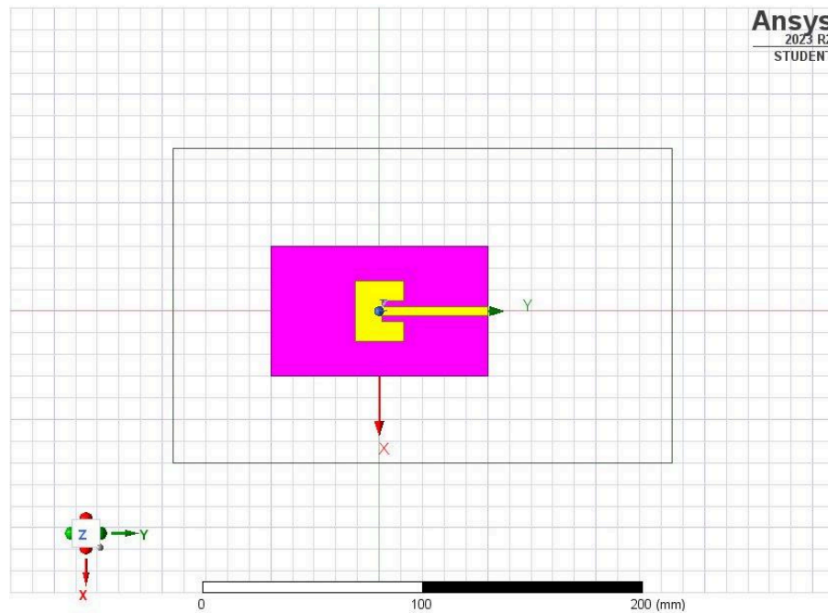


Figure 3: Antenna Design

Power Dividers

- **Configuration:** Two 1-to-4 power dividers will be used to distribute the signal from the microwave source to the eight antennas.
- **Design:** Ensure that the power dividers are designed to operate efficiently at 2.4 GHz with minimal signal loss.

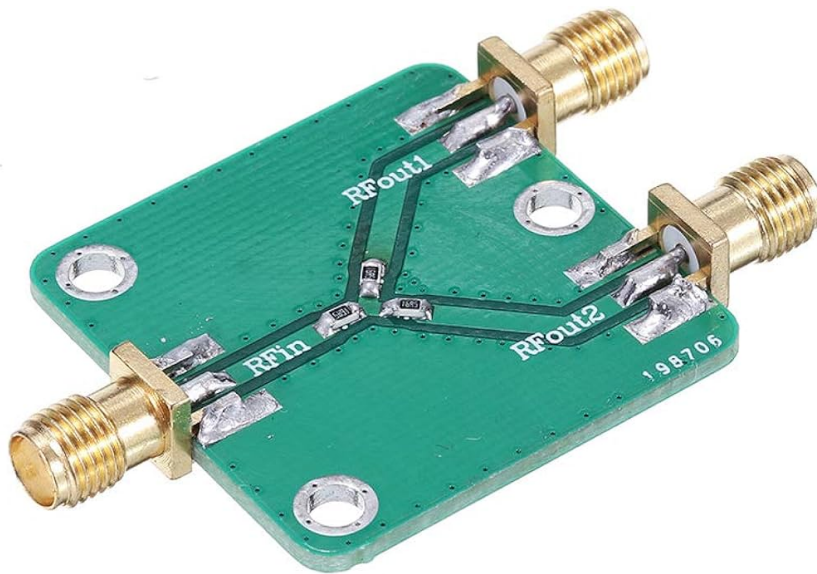


Figure 4: Power Divider Image

System Design

Microwave Signal Transmission

- **Source:** A microwave signal generator set to 2.4 GHz will provide the signal.



Figure 5: Example VNA

- **Power Dividers:** Two 1-to-4 power dividers will split the signal into eight paths, each connecting to one of the antennas.

Antenna Configuration

- **Arrangement:** Place the eight antennas in an octagonal pattern around the bone. Ensure even distribution to cover the entire circumference of the bone.

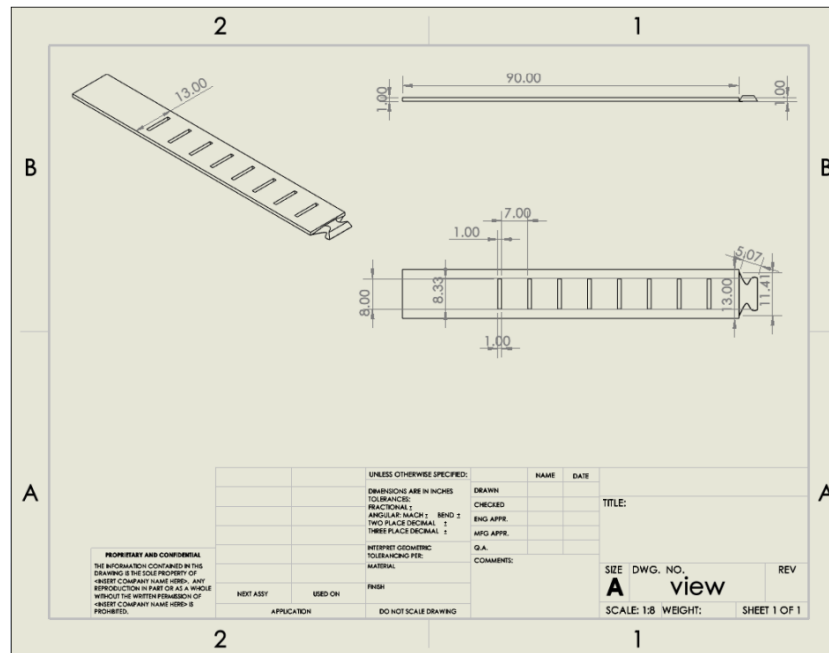


Figure 6: Antenna Configuration

Signal Reception

- **S11 Measurement:** Each antenna will measure the S11 parameter, which indicates the amount of microwave signal reflected back from the bone. Changes in the S11 value can signal potential cracks or fractures.

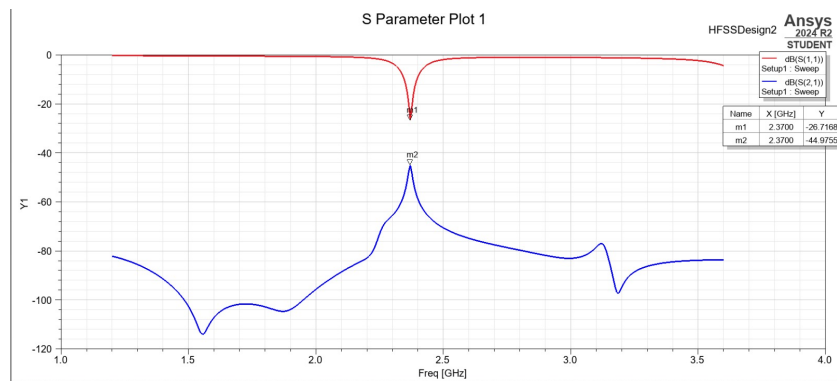


Figure 7: Typical s11 parameter plot

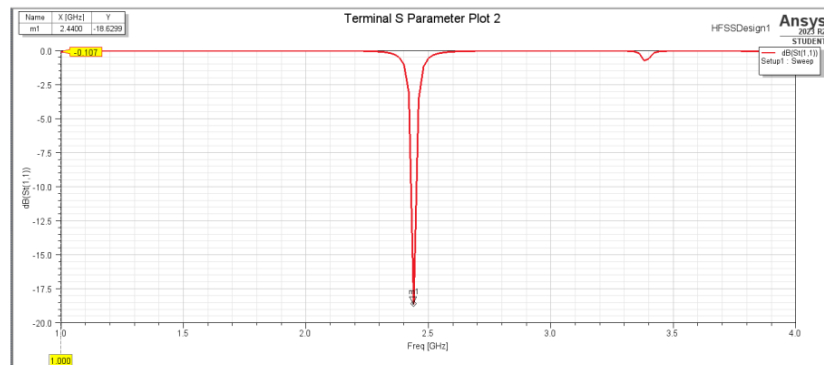


Figure 8: Another plot of s11 parameter

Imaging and Data Analysis

Data Collection

- **Measurement:** Collect S11 data from all eight antennas. This data reflects the changes caused by any cracks or fractures in the bone.

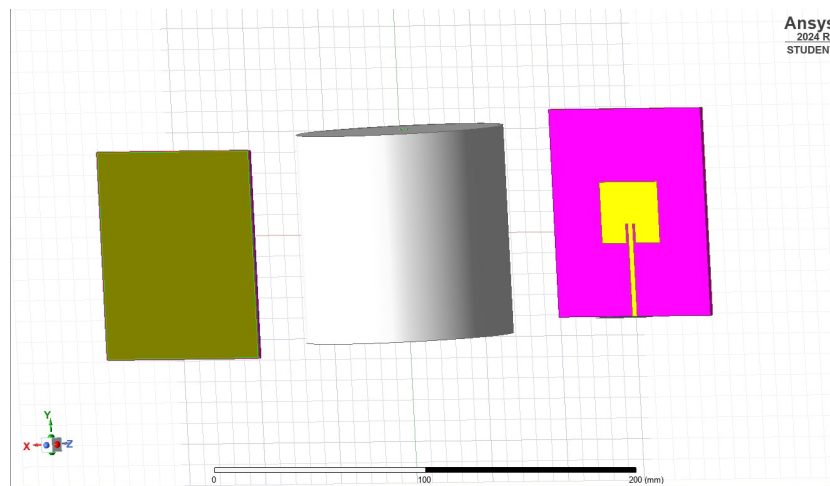


Figure 9: Simulation

Data Processing

- **Data Analysis:** Analyze the S11 data to detect anomalies. Fractures or cracks in the bone will alter the reflection pattern, creating noticeable changes in the S11 values.
- **Imaging:** Generate an image or map of the bone based on the analyzed S11 data. Areas with significant deviations from baseline measurements (healthy bone) will be highlighted to indicate potential fractures.

Interpretation

- **Fracture Detection:** Compare the collected S11 data with baseline measurements to identify abnormal patterns. The resulting image will help in diagnosing fractures by highlighting areas of concern.

Summary

- **Design:** Use eight microstrip patch antennas operating at 2.4 GHz, arranged in an octagonal pattern around the bone. Employ two 1-to-4 power dividers to distribute the signal.
- **Signal Transmission:** Emit the 2.4 GHz signal from the generator, divide it, and send it to each antenna.
- **Reception:** Measure and analyze the S11 data from each antenna.
- **Imaging:** Create images based on the S11 data to detect and visualize potential fractures.

Bench marking of the Proposed Solution

1. **Accuracy:** The microwave-based model excels in detecting subtle fractures that may be missed by X-rays or ultrasounds. Its ability to capture small material changes in the bone structure provides a distinct advantage over traditional methods, potentially increasing the detection of minor or hairline fractures.
2. **Sensitivity:** With proper tuning and antenna arrangement, the microwave-based system offers high sensitivity, enabling it to detect even small or hidden bone cracks that other methods, like X-rays or ultrasounds, may not easily capture. This makes it highly effective for early-stage fracture diagnosis.
3. **Processing Time:** Once optimized, the microwave-based model has the potential for real-time or near-real-time detection, comparable to or faster than MRI and CT scans. This makes it ideal for quick diagnostics, reducing wait times and improving patient throughput in clinical settings.
4. **Portability:** The microwave system, due to the compact and lightweight nature of microstrip antennas, offers a high level of portability. This is a significant advantage over bulky CT or MRI machines, making it ideal for field use, mobile health units, or in settings with limited infrastructure.
5. **Cost-Effectiveness:** The use of microstrip antennas and simple electronics makes the microwave-based model a cost-effective alternative, especially when compared to the high costs of MRI and CT scans. With reduced equipment and operational costs, it offers an affordable solution for widespread adoption in medical diagnostics.

Conceptual Design

The CAD model used to visualize the design of the smart sensing system is attached here.

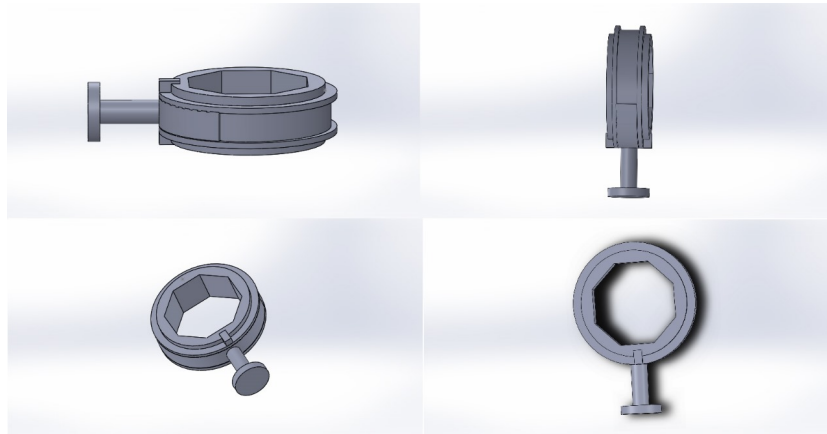


Figure 10: CAD Model.

This CAD model depicts a potential design for a wearable or implantable device to detect bone cracks. The octagonal housing, likely made of a biocompatible material such as microplast, latex or synthetic rubbers, includes electronic components and antennae. Connecting wires are combined with power dividers to ensure equal power division among all the antennae and hence reduce the scope of errors. Microwaves interact differently with healthy and cracked bone, allowing the device to detect changes in bone structure. The device processes microwave signals to identify patterns associated with bone cracks. The system's code then processes s11 data and transmits information for image processing and analysis for further detection.

Bill of Materials

| Item Name | Cost per Unit | Quantity | Approx. Cost |
|------------------------------|---------------|----------|--------------|
| Connectors | 800 | 20 | 16000 |
| 3D-Printing | 10000 | 1 | 10000 |
| Miscellaneous/Other Expenses | | | 4000 |
| Total | | | 30000 |

Figure 11: Bill of materials.