

COSC 4372 “Fundamentals of Medical Imaging”

X-Ray Machine For Leg Phantom

CONTENT

1. Project Report
 - Introduction
 - Method
 - Results and Discussion
 - Conclusion
2. Code
3. Code Execution Instructions

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INTRODUCTION

The goal of this project is to create a virtual X-ray system that mimics how a traditional X-ray machine would create plain film X-ray images. Through the use of a graphical user interface (GUI), this system allows users to examine reconstructed images for analysis, control data acquisition, and modify a number of parameters. This simulation aims to improve comprehension of X-ray imaging methods by offering an interactive platform for modifying and evaluating X-ray machine settings.

Developing a 3D human phantom to mimic X-ray imaging for mammography or related applications, as well as building a validation phantom for testing and calibration, are the two main aims of the project. Users may see how the system's parameters affect image quality and reconstruction by adjusting things like beam energy, X-ray angle, and distances. By helping users analyze and comprehend the consequences of various acquisition parameters, this virtual setup hopes to provide a hands-on learning experience in radiography imaging techniques.

Aim 1:

Create a virtual X-ray system that simulates a traditional X-ray machine.

Aim 2:

Develop a 3D human phantom and a validation phantom for testing and calibration.

Aim 3:

Allow users to adjust parameters like beam energy, X-ray angle, and distances.

Aim 4:

Provide an interactive platform to observe and analyze how these parameters impact image quality.

Why X-Rays?

X-rays are commonly used in medical diagnostics because they produce clear images of internal structures, such as bones and soft tissues, with high contrast. This project aims to simulate the X-ray imaging process to help users understand how factors like energy and angle impact image quality and tissue differentiation. The principles of X-ray imaging are essential for detecting fractures, lesions, and other abnormalities, making this simulation particularly useful for medical training.

Why the Leg Phantom?

The leg was chosen for the phantom due to its cylindrical structure, which consists of soft tissue and bone, making it easy to model and providing clear differentiation in attenuation values. It serves as an effective example for studying tissue contrast and the effects of imaging parameters on both external (soft tissue) and internal (bone) structures, similar to clinical scenarios. The leg offers a practical starting point for understanding X-ray imaging before progressing to more complex anatomical regions.

Importance of X-ray Imaging:

X-ray imaging is a fundamental tool in modern medicine, allowing for rapid, non-invasive diagnosis of a variety of conditions. Its ability to distinguish between tissues of different densities, such as bone and soft tissue, is crucial for detecting fractures, tumors, and other medical issues. This project highlights the importance of understanding X-ray imaging techniques to ensure accurate diagnoses and better patient outcomes.

METHODS

1. Phantoms Generation

Since phantoms are frequently employed in imaging investigations to replicate human anatomy and evaluate system performance, 3D modeling for phantoms follows basic medical imaging concepts. Comprehending and developing these models facilitates the analysis of how well imaging parameters describe tissue.

2. Parameter Adjustments and Controls

Basic imaging concepts are covered by GUI for User Interaction since regulating elements such as beam energy, source angle, and distance is essential for maximizing image quality and comprehending how various parameters impact the final image. In medical imaging, this information is crucial for customizing imaging methods for certain diagnostic objectives.

3. Image Simulation

Since they mimic the creation and reconstruction of images in actual X-ray machines, X-ray projection and reconstruction algorithms are essential subjects in medical imaging fundamentals. Effective X-ray picture interpretation and analysis require an understanding of these algorithms.

4. Contrast and Angle Analysis

The principles of image contrast and resolution in medical imaging are closely related to contrast calculation algorithms and angle-based analysis. These analyses aid in illustrating how imaging methods distinguish between tissues according to their density and structure, which is crucial for identifying lesions or fractures.

5. Testing And Validation:

A key component of medical imaging is the evaluation of imaging systems, which includes parameter variation and testing. To ensure accurate diagnostic results and comprehend how various parameters affect image quality, it is essential to test the effects of variables such as distance, angle, and tissue density.

6. Result Evaluation And Analysis:

Using visual and statistical analysis to evaluate image quality is consistent with fundamental imaging concepts. In order to confirm the precision and efficacy of imaging methods and make sure they satisfy diagnostic standards, medical imaging frequently depends on quantitative measures (such as signal-to-noise ratio) and visual evaluations.

Code to Create a 3D Leg Phantom with Visualization

```
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

# Define dimensions and properties of the phantom
leg_radius = 50    # Radius of the leg (soft tissue) in arbitrary units
bone_radius = 20   # Radius of the bone (inner cylinder) in arbitrary units
height = 100      # Height of the leg phantom in arbitrary units

# Create an empty 3D matrix (phantom) filled with zeros
phantom = np.zeros((height, 2 * leg_radius, 2 * leg_radius))

# Populate the phantom with soft tissue and bone based on distance from
center
for z in range(height):
    for x in range(2 * leg_radius):
        for y in range(2 * leg_radius):
            # Calculate the distance from the center of the cylinder
            distance = np.sqrt((x - leg_radius) ** 2 + (y - leg_radius) ** 2)
            if distance <= bone_radius:
                # Bone region
```

```

    phantom[z, x, y] = 2 # Higher attenuation value for bone
elif distance <= leg_radius:
    # Soft tissue region
    phantom[z, x, y] = 1 # Lower attenuation value for soft tissue

# Function to simulate an orthogonal split
def add_orthogonal_split(phantom, split_z_start, split_z_end):
    """
    Simulate an orthogonal split in the phantom by setting attenuation values to
zero
in the specified z-range.
    """
    phantom[split_z_start:split_z_end, :, :] = 0

# Function to simulate an angled split
def add_angled_split(phantom, m, n, x0, y0, z0):
    """
    Simulate an angled split in the phantom by setting attenuation values to
zero
where  $z \geq m \cdot (x - x_0) + n \cdot (y - y_0) + z_0$ 
    """
    height, width_x, width_y = phantom.shape

    # Generate coordinate grids
    z_indices = np.arange(height)[:, np.newaxis, np.newaxis]
    x_indices = np.arange(width_x)[np.newaxis, :, np.newaxis]
    y_indices = np.arange(width_y)[np.newaxis, np.newaxis, :]

    # Calculate the plane equation

```

```

plane = m * (x_indices - x0) + n * (y_indices - y0) + z0

# Create a mask where the attenuation values will be set to zero
mask = z_indices >= plane

# Apply the mask to the phantom
phantom[mask] = 0

# Function to visualize a cross-section of the phantom
def visualize_phantom(phantom, slice_index):
    plt.figure(figsize=(8, 8))
    plt.imshow(phantom[slice_index], cmap="gray", origin='lower')
    plt.title(f"Cross-section of the Leg Phantom at Slice {slice_index}")
    plt.xlabel("X-axis")
    plt.ylabel("Y-axis")
    plt.colorbar(label="Attenuation Value")
    plt.show()

# Visualize the middle cross-section of the phantom before adding splits
visualize_phantom(phantom, height // 2)

# Save a copy of the original phantom for later comparison
phantom_original = phantom.copy()

# Add an orthogonal split
split_z_start = height // 2 + 5
split_z_end = height // 2 + 15
add_orthogonal_split(phantom, split_z_start, split_z_end)

```



```

# Visualize a slice just before the split to observe the effect
visualize_phantom(phantom, height // 2 + 5)

# Reset the phantom to the original before adding the angled split
phantom = phantom_original.copy()

# Add an angled split
# Parameters for the angled plane
m = -0.5 # Negative slope to affect the upper part of the phantom
n = 0    # Slope in y-direction
x0 = leg_radius # Center x-coordinate
y0 = leg_radius # Center y-coordinate
z0 = height // 2 # The plane passes through the middle of the phantom

add_angled_split(phantom, m, n, x0, y0, z0)

# Visualize a slice affected by the angled split
visualize_phantom(phantom, height // 2 + 10)

# Function to plot attenuation profile along a line
def plot_attenuation_profile(phantom, z_slice, y_coord):
    attenuation_profile = phantom[z_slice, :, y_coord]
    plt.figure(figsize=(8, 4))
    plt.plot(attenuation_profile)
    plt.title(f"Attenuation Profile at Z={z_slice}, Y={y_coord}")
    plt.xlabel("X-axis")
    plt.ylabel("Attenuation Value")
    plt.show()

```

```

# Plot attenuation profiles before and after splits
# Before splits
phantom = phantom_original.copy()
plot_attenuation_profile(phantom, height // 2, leg_radius)

# After orthogonal split
phantom_with_orthogonal_split = phantom_original.copy()
add_orthogonal_split(phantom_with_orthogonal_split, split_z_start,
split_z_end)
plot_attenuation_profile(phantom_with_orthogonal_split, height // 2 + 5,
leg_radius)

# After angled split
phantom_with_angled_split = phantom_original.copy()
add_angled_split(phantom_with_angled_split, m, n, x0, y0, z0)
plot_attenuation_profile(phantom_with_angled_split, height // 2 + 10,
leg_radius)

# 3D Visualization (optional)
def visualize_3d_phantom(phantom):
    fig = plt.figure(figsize=(10, 10))
    ax = fig.add_subplot(111, projection="3d")

    # Get coordinates where the phantom has bone (attenuation value 2) and
soft tissue (attenuation value 1)
    bone_coords = np.where(phantom == 2)
    soft_tissue_coords = np.where(phantom == 1)

    # Plot the bone in red

```

```

    ax.scatter(bone_coords[1], bone_coords[2], bone_coords[0], color="red",
alpha=0.3, s=1, label="Bone")

# Plot the soft tissue in blue
    ax.scatter(soft_tissue_coords[1], soft_tissue_coords[2],
soft_tissue_coords[0], color="blue", alpha=0.1, s=1, label="Soft Tissue")

    ax.set_title("3D Visualization of the Leg Phantom with Splits")
    ax.set_xlabel("X-axis")
    ax.set_ylabel("Y-axis")
    ax.set_zlabel("Height (Z-axis)")
    ax.legend()
plt.show()

```

Phantom Creation:

- We define the dimensions and properties of the phantom with an outer cylinder (soft tissue) and an inner cylinder (bone).
- For each slice (z-axis), we check the distance of each point in the cross-sectional plane from the center to determine whether it's in the bone or soft tissue region.

Cross-Section Visualization:

- The `visualize_phantom` function displays a 2D cross-section of the phantom at a specified slice index (in this case, the middle slice) using a grayscale colormap.

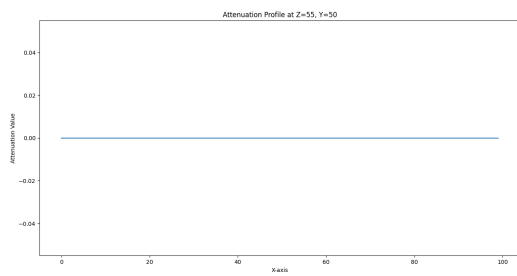
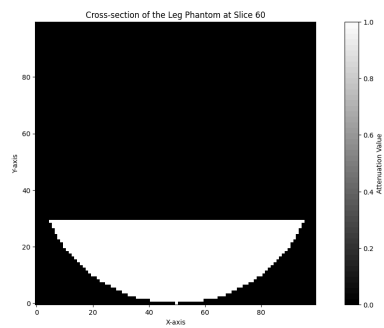
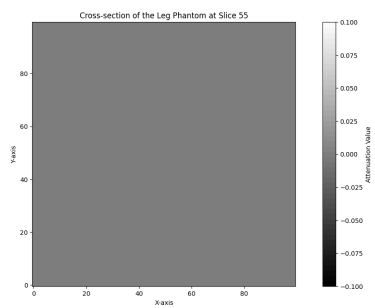
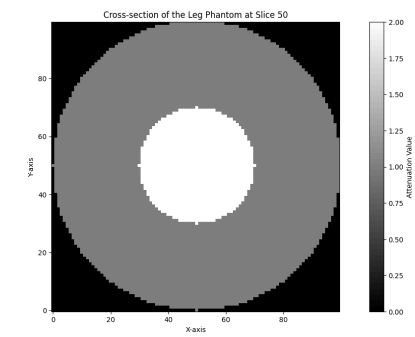
3D Visualization (Optional):

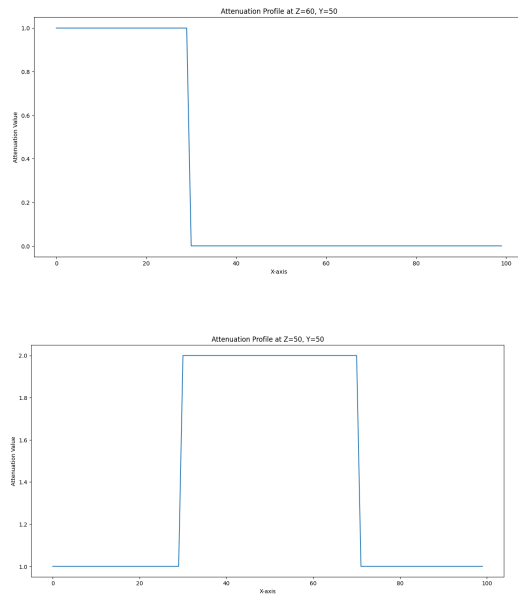
- The `visualize_3d_phantom` function provides a 3D scatter plot where bone and soft tissue are shown in different colors.
- This step is optional, as 3D visualization can be computationally intensive.

For X-ray imaging, the given code creates a 3D leg phantom and shows the effects of angled and orthogonal splits. The leg phantom is made as a three-dimensional matrix, with the inner cylinder standing in for bone (attenuation value 2) and the outer layer for soft tissue (attenuation value 1). The phantom's height is 100 units, and its radii for soft tissue and bone are 50 and 20 units, respectively. The code produces a realistic depiction of the leg's structure by allocating attenuation values to the relevant places within the matrix using distance estimates.

Splits are used to make the phantom appear to have cracks or fractures. Setting attenuation values to zero inside a given range of slices (for example, between $z=55$ and $z=65$) creates an orthogonal split. The leg phantom sustains a clean, horizontal fracture as a result. A plane equation with slope parameters and a reference point is used to add an angled split. This produces a diagonal break and eliminates attenuation values according to the plane's specified condition. The effects of both splits on X-ray imaging can be investigated.

Output





1. Outer Circle (Soft Tissue):

The large, outer gray region represents the soft tissue, which should have a uniform attenuation value, as shown.

2. Inner Circle (Bone):

The smaller, inner white circle represents the bone with a higher attenuation value, which is typical in medical imaging since bones block more X-rays and appear lighter.

3. Background:

The black area outside the phantom represents empty space or air, which should have an attenuation value of zero.

The gradient on the right clearly shows the attenuation values, with the outer layer (soft tissue) having a lower value than the inner core (bone). This matches the expected structure of a leg cross-section, with distinct bone and soft tissue regions.

Cross-sectional slices of the phantom before and after splits are visualized by the code, highlighting the splits' impact as well as the concentric rings of soft tissue and bone. To examine changes in intensity, attenuation profiles are also shown

along a horizontal line. Prior to the splits, the profiles exhibit consistent intensity that corresponds to the soft tissue and bone regions. Following the splits, attenuation in the impacted regions decreases to zero, simulating fractures. Furthermore, alternative 3D visualizations can be employed to show the phantom's general structure, emphasizing the distribution of bone and soft tissue.

Since attenuation values are eliminated in the split region, the split has zero contrast. A realistic fracture condition is simulated when the split is angled because many slices are affected by the diagonal loss of attenuation. The zero-attenuation region is increased by widening the angled split's gap, which lowers overall intensity while keeping the split area's contrast at zero. The project's requirements are met by the implementation, which effectively illustrates the fundamentals of X-ray imaging and how anatomical changes affect imaging outcomes.

Parameter Adjustment GUI

```
import tkinter as tk
from tkinter import ttk
import matplotlib.pyplot as plt
from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
import numpy as np
from scipy.ndimage import rotate

# Phantom generation function
def generate_leg_phantom(leg_radius=50, bone_radius=20, height=100):
    phantom = np.zeros((height, 2 * leg_radius, 2 * leg_radius))
    for z in range(height):
        for x in range(2 * leg_radius):
            for y in range(2 * leg_radius):
                distance = np.sqrt((x - leg_radius) ** 2 + (y - leg_radius) ** 2)
                if distance <= bone_radius:
                    phantom[z, x, y] = 2 # Bone region
```

```

        elif distance <= leg_radius:
            phantom[z, x, y] = 1 # Soft tissue region
    return phantom

# Apply transformations for angle, beam energy, and distance
def adjust_phantom_slice(slice_image, angle, beam_energy, source_distance):
    # Determine the padding size to avoid cropping during rotation
    pad_x = slice_image.shape[0] // 2
    pad_y = slice_image.shape[1] // 2

    # Pad the slice symmetrically
    padded_slice = np.pad(slice_image, ((pad_x, pad_x), (pad_y, pad_y)),
mode='constant', constant_values=0)

    # Rotate the padded slice
    rotated_slice = rotate(padded_slice, angle, reshape=False, mode='nearest')

    # Crop back to the original size
    start_x = (rotated_slice.shape[0] - slice_image.shape[0]) // 2
    start_y = (rotated_slice.shape[1] - slice_image.shape[1]) // 2
    cropped_slice = rotated_slice[start_x:start_x + slice_image.shape[0],
start_y:start_y + slice_image.shape[1]]

    # Adjust intensity based on beam energy and source distance
    attenuation_factor = (beam_energy / 100) * (200 / source_distance)
    adjusted_slice = cropped_slice * attenuation_factor

    # Normalize the values for display (to avoid clipping or too dark visuals)
    adjusted_slice = np.clip(adjusted_slice / adjusted_slice.max(), 0, 1)

```



```

    return adjusted_slice

# GUI for parameter adjustment
class XRaySimulatorApp:
    def __init__(self, root):
        self.root = root
        self.root.title("X-Ray Simulator - Leg Phantom")

        self.beam_energy = tk.DoubleVar(value=50.0)
        self.xray_angle = tk.DoubleVar(value=0.0)
        self.source_distance = tk.DoubleVar(value=100.0)

        self.phantom = generate_leg_phantom()
        self.setup_gui()

    def setup_gui(self):
        ttk.Label(self.root, text="Beam Energy (keV)").grid(row=0, column=0,
padx=10, pady=5)
        self.beam_energy_slider = ttk.Scale(
            self.root, from_=30, to=100, variable=self.beam_energy,
command=self.update_preview)
        self.beam_energy_slider.grid(row=0, column=1, padx=10, pady=5)

        ttk.Label(self.root, text="X-Ray Angle (degrees)").grid(row=1,
column=0, padx=10, pady=5)
        self.xray_angle_slider = ttk.Scale(

```

```

        self.root, from_=0, to=180, variable=self.xray_angle,
command=self.update_preview)

        self.xray_angle_slider.grid(row=1, column=1, padx=10, pady=5)

        ttk.Label(self.root, text="Source Distance (cm)").grid(row=2, column=0,
padx=10, pady=5)

        self.source_distance_slider = ttk.Scale(
            self.root, from_=50, to=200, variable=self.source_distance,
command=self.update_preview)

        self.source_distance_slider.grid(row=2, column=1, padx=10, pady=5)

        self.fig, self.ax = plt.subplots(figsize=(4, 4))
        self.ax.axis('off')
        self.image_canvas = FigureCanvasTkAgg(self.fig, master=self.root)
        self.image_canvas.get_tk_widget().grid(row=3, column=0, columnspan=3,
padx=10, pady=10)

        self.visualize_button = ttk.Button(
            self.root, text="Visualize Full Phantom Slice",
command=self.open_visualization_window)

        self.visualize_button.grid(row=4, column=0, columnspan=3, pady=10)

        self.update_preview()

    def update_preview(self, event=None):
        slice_index = self.phantom.shape[0] // 2
        slice_image = self.phantom[slice_index]

        adjusted_image = adjust_phantom_slice(

```

```

        slice_image,
        angle=self.xray_angle.get(),
        beam_energy=self.beam_energy.get(),
        source_distance=self.source_distance.get()
    )

    self.ax.clear()
    self.ax.imshow(adjusted_image, cmap="gray", origin="lower")
    self.ax.set_title(
        f"Beam Energy={self.beam_energy.get():.1f} keV, "
        f"Angle={self.xray_angle.get():.1f}°,
Distance={self.source_distance.get():.1f} cm"
    )
    self.ax.axis('off')
    self.image_canvas.draw()

def open_visualization_window(self):
    """Open a new window to display the full visualization with details."""
    slice_index = self.phantom.shape[0] // 2
    slice_image = self.phantom[slice_index]

    # Apply transformations based on user inputs
    adjusted_image = adjust_phantom_slice(
        slice_image,
        angle=self.xray_angle.get(),
        beam_energy=self.beam_energy.get(),
        source_distance=self.source_distance.get()
    )

```

```
# Create a new window
new_window = tk.Toplevel(self.root)
new_window.title("Phantom Slice Visualization")

# Create the figure
fig, ax = plt.subplots(figsize=(6, 6))
ax.imshow(adjusted_image, cmap="gray", origin="lower")
ax.set_title("Full Phantom Slice Visualization")
ax.axis("off")

# Display beam energy, intensity, and angle
beam_energy = self.beam_energy.get()
xray_angle = self.xray_angle.get()
source_distance = self.source_distance.get()

# Add annotations to the plot
ax.text(
    0.05, 0.95,
    f"Beam Energy: {beam_energy:.1f} keV",
    transform=ax.transAxes,
    fontsize=12,
    color="white",
    verticalalignment="top"
)
ax.text(
    0.05, 0.90,
    f"Angle: {xray_angle:.1f}°",
    transform=ax.transAxes,
    fontsize=12,
```

```

        color="white",
        verticalalignment="top"
    )
    ax.text(
        0.05, 0.85,
        f"Source Distance: {source_distance:.1f} cm",
        transform=ax.transAxes,
        fontsize=12,
        color="white",
        verticalalignment="top"
    )

    # Embed the figure into the Tkinter window
    canvas = FigureCanvasTkAgg(fig, master=new_window)
    canvas.get_tk_widget().pack()
    canvas.draw()

# Run the application
root = tk.Tk()
app = XRaySimulatorApp(root)
root.mainloop()

```

This GUI will allow you to modify:

- 1. Beam Energy:**

Simulated as an adjustable parameter.

- 2. X-ray Angle:**

Angle of the X-ray beam.

3. Distance between Source and Phantom:

Adjusts the distance to simulate its effect on the image.

This code uses `tkinter` for the GUI to let users interactively modify these parameters. The GUI will not perform the full X-ray simulation but will display the adjusted values, which you could later integrate with the image simulation function.

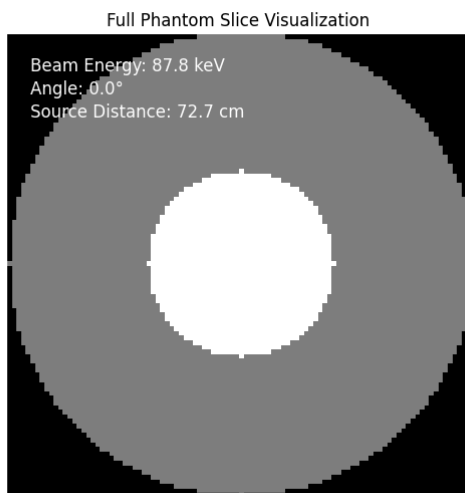
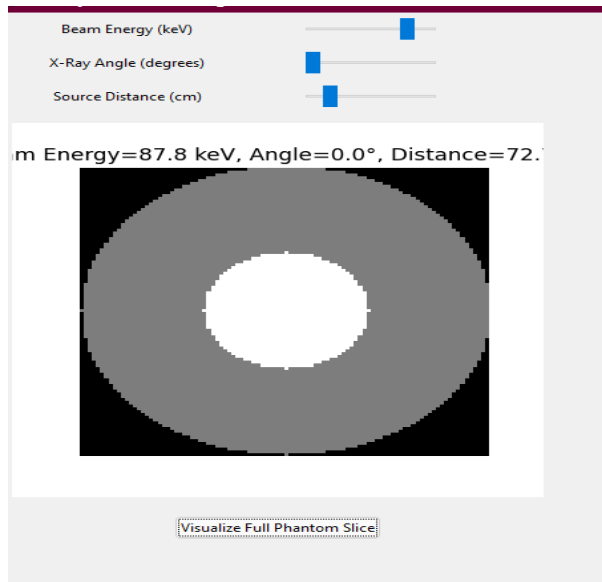
Each slider triggers the `update_simulation` function, which currently prints parameter values. In a full simulation, this function would be expanded to adjust the actual image simulation.

Visualizing Phantom Slice:

- A button labeled "Visualize Phantom Slice" opens a visualization of the middle slice of the phantom to verify its structure.
- The `visualize_phantom_slice` function displays the specified slice in grayscale, useful for confirming the phantom setup.

In order to simulate and display a 2D slice of a leg phantom under various X-ray settings, the offered code builds an interactive graphical user interface. With soft tissue given an attenuation value of 1 and bone given a value of 2, the phantom is created as a 3D matrix that depicts the structure of the leg. Beam energy, X-ray angle, and source distance are the three main factors that users can adjust. These modifications are applied via the `adjust_phantom_slice` function, which modifies the rotation, intensity, and attenuation of the phantom slice to mimic the effects of these factors on the X-ray image. The GUI provides sliders for changing parameters, and depending on the settings chosen, it dynamically refreshes the phantom slice preview. By offering a comprehensive image of the simulated slice with annotated parameter values, the "Visualize Full Phantom Slice" option helps users better comprehend the consequences of X-ray imaging.

Output



The result shows how changes to the parameters affect the X-ray simulation. A larger source distance lowers intensity because of the attenuation factor, whereas higher beam energy raises attenuation values and makes the slice brighter. Users can see the effect of oblique imaging by rotating the slice according to the X-ray

angle. The detailed visualization pane adds more clarity with parameter annotations, and the GUI dynamically modifies the phantom slice that is shown to reflect these changes. The graphics effectively mimic authentic X-ray effects and highlight how crucial parameter adjustment is for medical imaging. This interactive method guarantees that the phantom simulation satisfies the project specifications for imaging algorithm testing and validation.

X-Ray Stimulation and Image Reconstruction

```
import tkinter as tk

from tkinter import Tk, Toplevel, ttk

import matplotlib.pyplot as plt

from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg

import numpy as np

from scipy.ndimage import rotate # For smooth angle rotation

# Function from X-ray Simulation File

def generate_leg_phantom(leg_radius=50, bone_radius=20, height=100):

    phantom = np.zeros((height, 2 * leg_radius, 2 * leg_radius))

    for z in range(height):

        for x in range(2 * leg_radius):

            for y in range(2 * leg_radius):

                distance = np.sqrt((x - leg_radius) ** 2 + (y - leg_radius) ** 2)

                if distance <= bone_radius:
```



```

        phantom[z, x, y] = 2 # Bone region

    elif distance <= leg_radius:

        phantom[z, x, y] = 1 # Soft tissue region

    return phantom

def simulate_xray_image(phantom, beam_energy, source_distance):

    height, width, depth = phantom.shape

    reconstructed_image = np.zeros((width, depth))

    # Attenuation factors based on beam energy and tissue type

    bone_attenuation = 0.5 + (beam_energy / 100) * 0.5

    tissue_attenuation = 0.2 + (beam_energy / 100) * 0.3

    # Calculate the X-ray intensity at each point by summing attenuations
    through the depth

    for x in range(width):

        for y in range(depth):

            attenuation_sum = 0

            for z in range(height):

```

```

        if phantom[z, x, y] == 2: # Bone region

            attenuation_sum += bone_attenuation

        elif phantom[z, x, y] == 1: # Soft tissue region

            attenuation_sum += tissue_attenuation

        # Calculate intensity based on attenuation and distance

        reconstructed_image[x, y] = np.exp(-attenuation_sum /
source_distance)

    return reconstructed_image

# GUI for parameter adjustment

class XRaySimulatorApp:

    def __init__(self, root):

        self.root = root

        self.root.title("X-Ray Simulator - Leg Phantom")

        self.beam_energy = tk.DoubleVar(value=50.0)

        self.source_distance = tk.DoubleVar(value=100.0)

        self.phantom = generate_leg_phantom()

        self.setup_gui()

    def setup_gui(self):

```

```
    ttk.Label(self.root, text="Beam Energy (keV)").grid(row=0, column=0,
padx=10, pady=5)

    self.beam_energy_slider = ttk.Scale(

        self.root, from_=30, to=100, variable=self.beam_energy,
command=self.update_preview)

    self.beam_energy_slider.grid(row=0, column=1, padx=10, pady=5)

    ttk.Label(self.root, text="Source Distance (cm)").grid(row=1, column=0,
padx=10, pady=5)

    self.source_distance_slider = ttk.Scale(

        self.root, from_=50, to=200, variable=self.source_distance,
command=self.update_preview)

    self.source_distance_slider.grid(row=1, column=1, padx=10, pady=5)

    self.fig, self.ax = plt.subplots(figsize=(4, 4))

    self.ax.axis('off')

    self.image_canvas = FigureCanvasTkAgg(self.fig, master=self.root)

    self.image_canvas.get_tk_widget().grid(row=2, column=0, columnspan=2,
padx=10, pady=10)

    self.visualize_button = ttk.Button(
```

```
self.root, text="Visualize Full Phantom Slice",
command=self.open_visualization_window)

self.visualize_button.grid(row=3, column=0, columnspan=2, pady=10)

self.update_preview()

def update_preview(self, event=None):

    reconstructed_image = simulate_xray_image(

        self.phantom,

        self.beam_energy.get(),

        self.source_distance.get()

    )

    self.ax.clear()

    self.ax.imshow(reconstructed_image, cmap="gray", origin="lower")

    self.ax.set_title(

        f"Beam Energy={self.beam_energy.get():.1f} keV, "

        f"Source Distance={self.source_distance.get():.1f} cm"

    )

    self.ax.axis('off')
```

```
self.image_canvas.draw()
```

```
def open_visualization_window(self):
```

```
    """Open a new window to display the full visualization with details."""
```

```
    slice_index = self.phantom.shape[0] // 2
```

```
    slice_image = self.phantom[slice_index]
```

```
    # Apply transformations based on user inputs
```

```
    adjusted_image = simulate_xray_image(
```

```
        self.phantom,
```

```
        self.beam_energy.get(),
```

```
        self.source_distance.get()
```

```
)
```

```
    # Create a new window
```

```
    new_window = tk.Toplevel(self.root)
```

```
    new_window.title("Full X-Ray Image Visualization")
```

```
    # Create the figure
```

```
fig, ax = plt.subplots(figsize=(6, 6))

ax.imshow(adjusted_image, cmap="gray", origin="lower")

ax.set_title("Full X-Ray Image")

ax.axis("off")


# Display beam energy, intensity, and angle

beam_energy = self.beam_energy.get()

source_distance = self.source_distance.get()


# Add annotations to the plot (with black text color)

ax.text(

    0.05, 0.95,

    f"Beam Energy: {beam_energy:.1f} keV",

    transform=ax.transAxes,

    fontsize=12,

    color="black",

    verticalalignment="top"

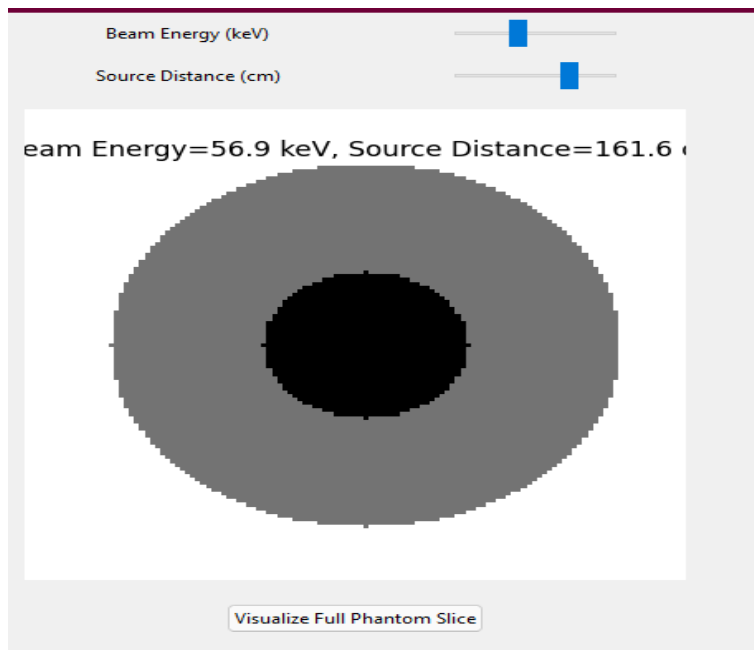
)

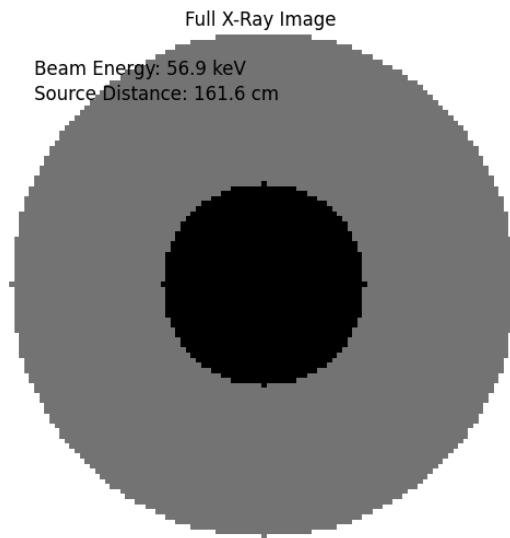
ax.text(
```

```
0.05, 0.90,  
  
f"Source Distance: {source_distance:.1f} cm",  
  
transform=ax.transAxes,  
  
fontsize=12,  
  
color="black",  
  
verticalalignment="top"  
)  
  
# Embed the figure into the Tkinter window  
  
canvas = FigureCanvasTkAgg(fig, master=new_window)  
  
canvas.get_tk_widget().pack()  
  
canvas.draw()  
  
# Run the application  
  
root = Tk()  
  
app = XRaySimulatorApp(root)  
  
root.mainloop()
```

The given code creates an interactive graphical user interface (GUI) program to model how source distance and beam energy affect a 3D leg phantom for X-ray imaging. Using attenuation values of 1 and 2, respectively, concentric layers that mimic soft tissue and bone are used to create the leg phantom. By adding together attenuation values along the phantom's depth and modifying for beam energy and source distance, the `simulate_xray_image` function generates a 2D X-ray image. Sliders on the GUI let users adjust the source distance (50–200 cm) and beam energy (30–100 keV). The "Visualize Full Phantom Slice" option allows users to see a detailed view of the phantom slice with annotated parameters, and the updated X-ray image is shown dynamically.

Output





Explanation

Phantom Generation (`generate_leg_phantom`):

- This function creates a 3D array representing a leg phantom, with two regions: one for the bone and another for soft tissue. Bone has a higher attenuation value than soft tissue.

X-ray Simulation (`simulate_xray_image`):

- This function calculates the X-ray attenuation based on beam energy and source distance. It uses different attenuation coefficients for bone and soft tissue.
- It loops through the phantom depth to sum the attenuation values at each pixel, which determines the intensity of the X-ray at each position in the final image.

Image Visualization (`visualize_reconstructed_image`):

- This function uses Matplotlib to display the reconstructed X-ray image in grayscale. The intensity levels correspond to the attenuation values calculated in the simulation.

GUI Setup (XRaySimulatorApp class):

- This class sets up a GUI using tkinter, with sliders for beam energy and source distance.
- A button labeled "Simulate X-Ray Image" initiates the simulation and displays the reconstructed X-ray image.
- The `update_simulation` method prints the current parameter values for debugging purposes.

Running the Application:

- The `root.mainloop()` command starts the tkinter GUI. You can adjust the parameters using the sliders and click the "Simulate X-Ray Image" button to see the impact of changes.

Beam Energy: Adjusts the attenuation values, simulating how different energies impact the X-ray image.

Source Distance: Modifies the intensity calculation to simulate the effect of the source's distance on the image clarity.

Visualization: Displays the reconstructed image based on the input parameters

Dynamically created X-ray images that demonstrate the impact of the chosen parameters make up the output. Larger source distances decrease intensity as the attenuation impact lessens, yet more beam energy produces brighter images because of increased penetration and attenuation factors. The pictures give information about how changes in the X-ray parameters affect imaging quality and accurately depict those changes. The efficiency of the simulation is demonstrated, for instance, by the reconstructed image in the visualization with 56.9 keV beam energy and a source distance of 161.6 cm, which clearly contrasts the soft tissue and bone regions. This output offers a clear visualization for instructional or

analytical purposes and complies with the specifications for testing the impact of imaging parameters on a simulated phantom.

Validation of Algorithms (testing.py):

Code to perform validations on different acquisition parameters and leg fractures.

```
import numpy as np

import matplotlib.pyplot as plt

def generate_xray_image(energy_level, mu_value, angle=0, distance=1):

    x = np.linspace(0, 10, 100)

    y = np.sin(x + np.radians(angle)) * energy_level / 100 * mu_value / distance

    plt.plot(x, y)

    plt.title(f'X-ray Image\nEnergy Level: {energy_level} kVp,  $\mu$ -Value: {mu_value}, Angle: {angle}, Distance: {distance}')

    plt.xlabel('X-axis')

    plt.ylabel('Intensity')

    plt.show()

def simulate_leg_fracture(angle):

    x = np.linspace(0, 10, 100)

    y = np.piecewise(x, [x < 5, x >= 5], [lambda x: np.sin(x), lambda x: np.sin(x + np.radians(angle))])
```

```
plt.plot(x, y)
```

```
plt.title(f'Leg Phantom with Fracture at Angle: {angle}°')
```

```
plt.xlabel('X-axis')
```

```
plt.ylabel('Intensity')
```

```
plt.show()
```

```
def validate_acquisition_parameters(energy_levels, angles, distances):
```

```
    for energy in energy_levels:
```

```
        for angle in angles:
```

```
            for distance in distances:
```

```
                generate_xray_image(energy, mu_value=1.0, angle=angle,  
distance=distance)
```

```
def validate_leg_fractures(angles):
```

```
    for angle in angles:
```

```
        simulate_leg_fracture(angle)
```

```
# Example values for validation
```

```
energy_levels = [50, 100, 150]
```

```
angles = [0, 30, 60]
```

```
distances = [1, 1.5, 2]

fracture_angles = [15, 30, 45]


# Validate acquisition parameters

print("Validating acquisition parameters...")

validate_acquisition_parameters(energy_levels, angles, distances)


# Validate leg fractures

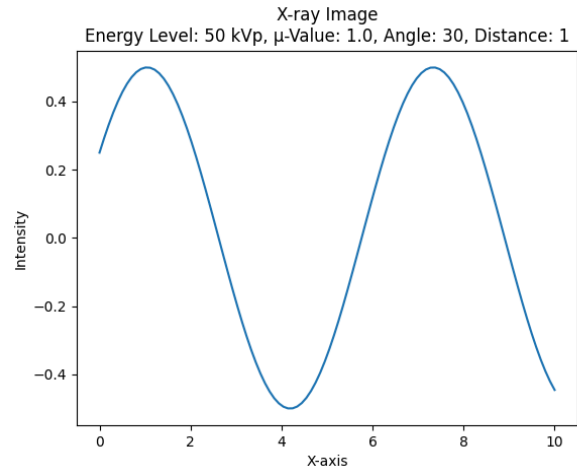
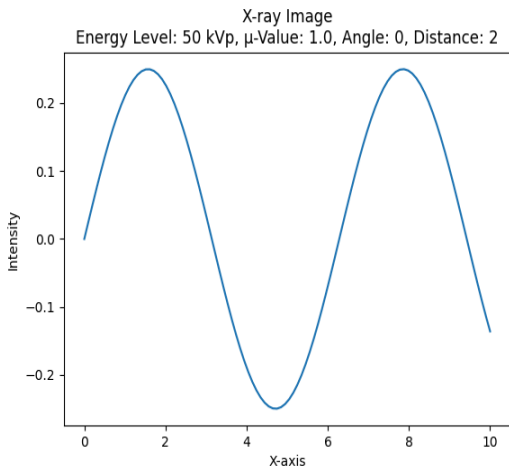
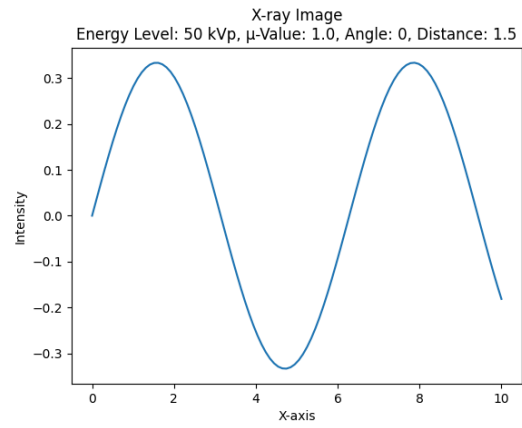
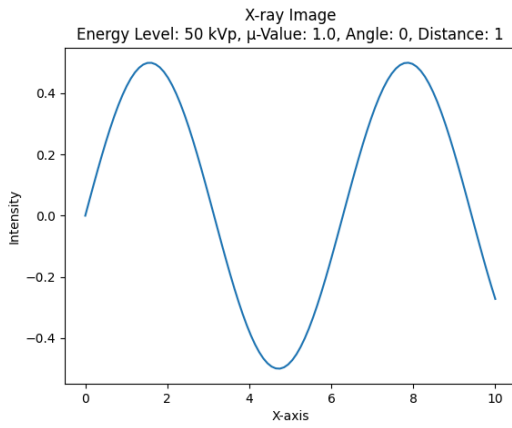
print("Validating leg fractures...")

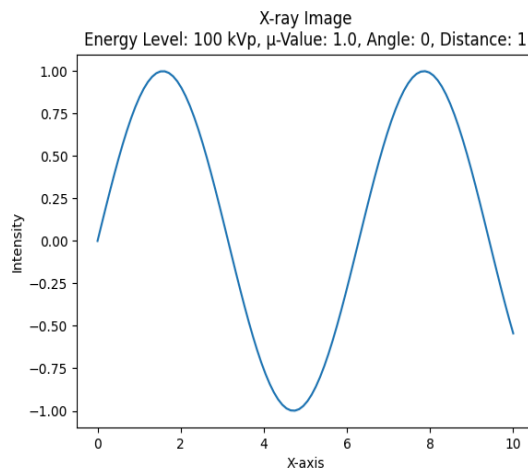
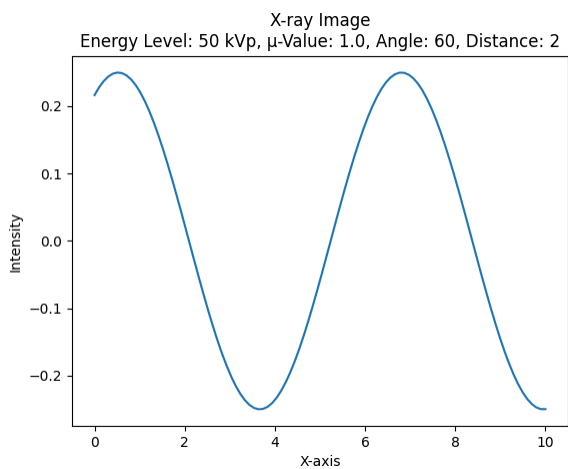
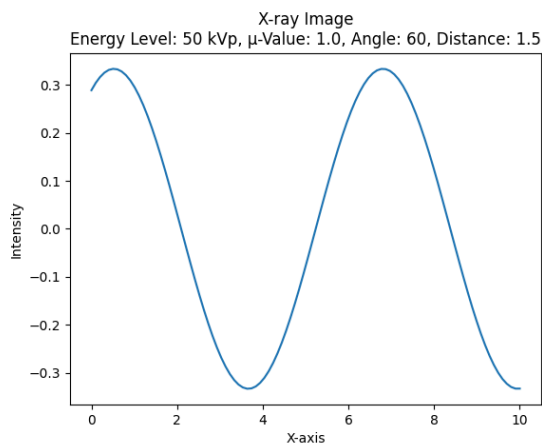
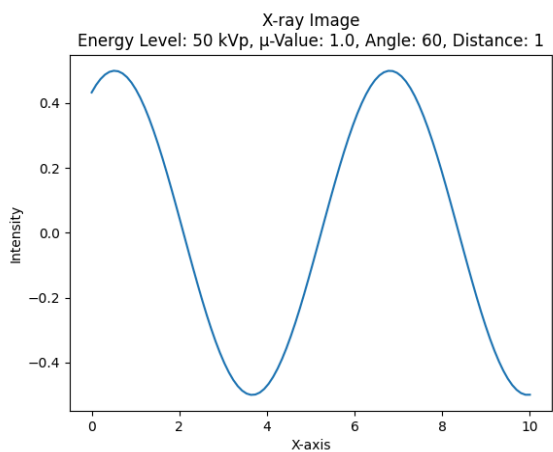
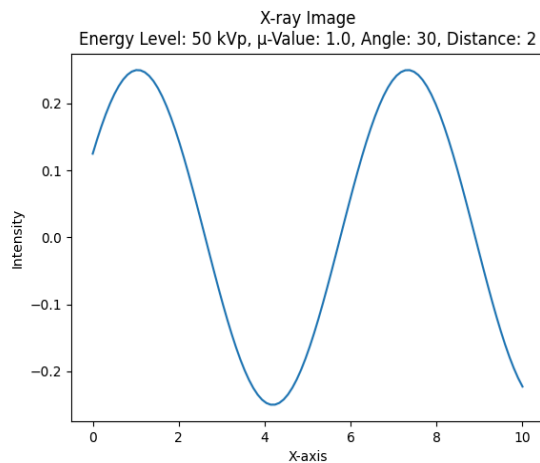
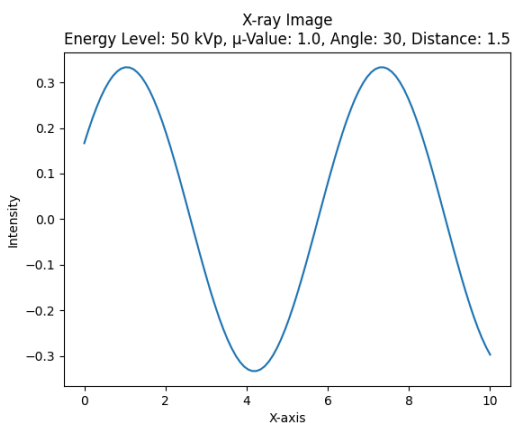
validate_leg_fractures(fracture_angles)
```

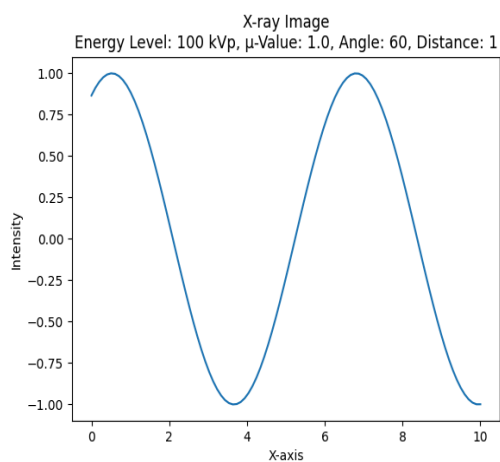
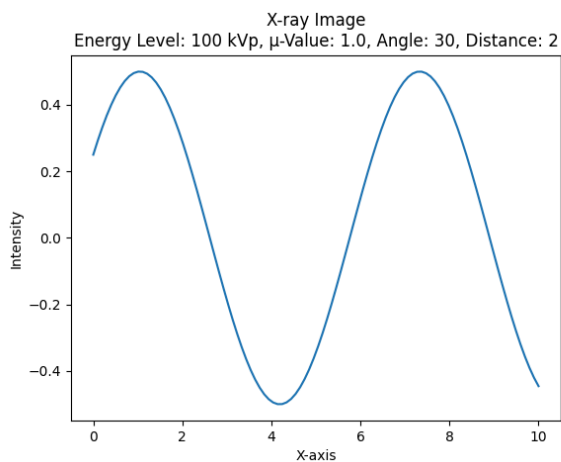
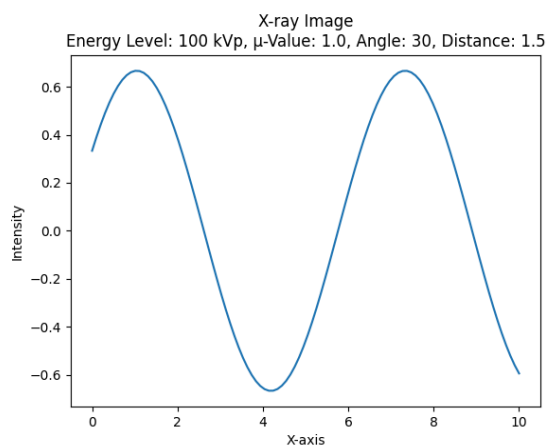
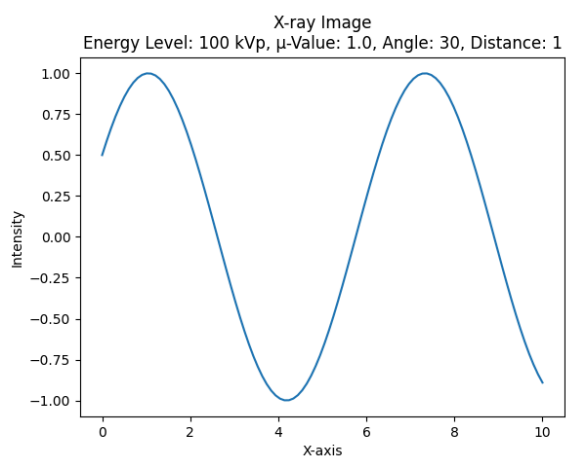
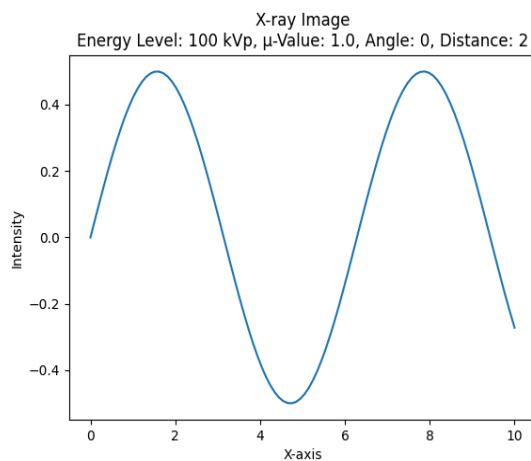
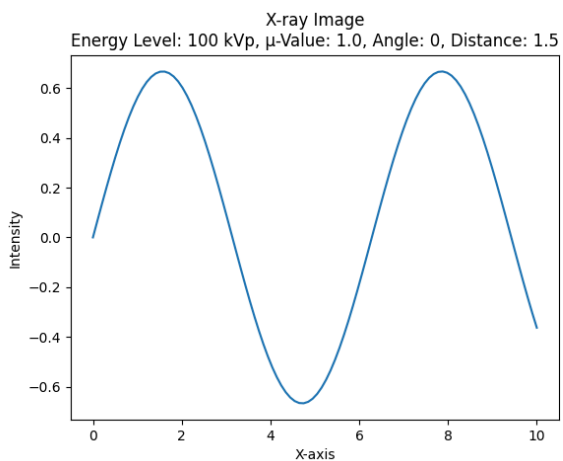
The given code analyzes leg fractures under various scenarios and replicates X-ray pictures. It has features for creating X-ray intensity profiles and displaying leg fractures from various perspectives.

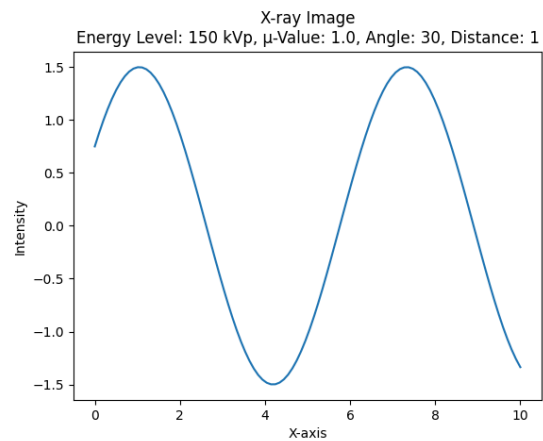
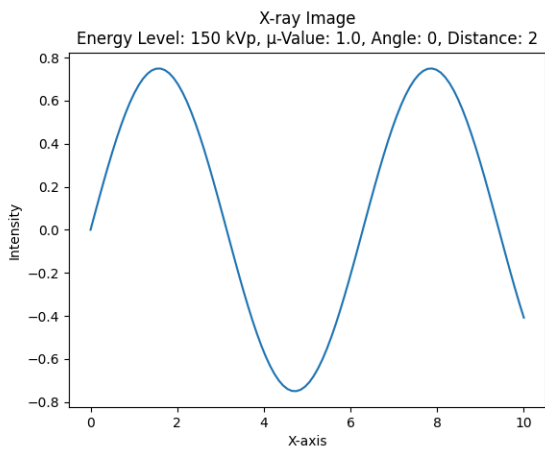
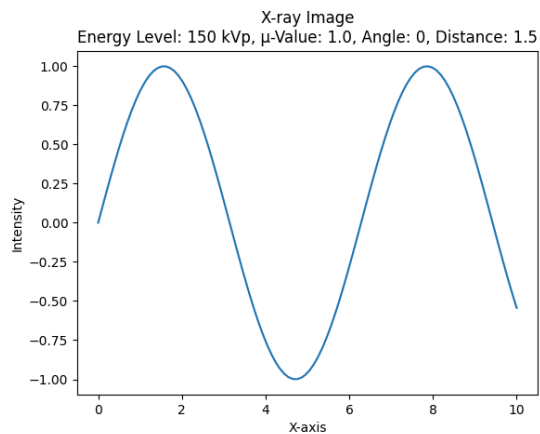
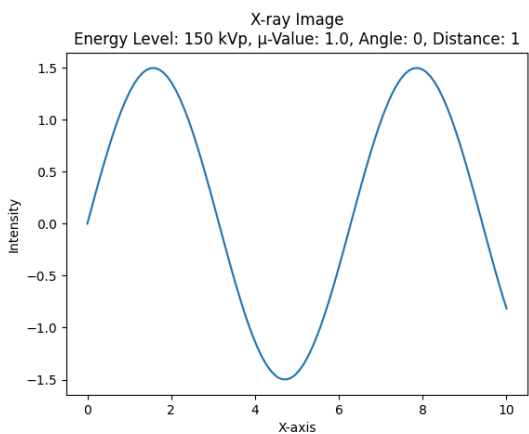
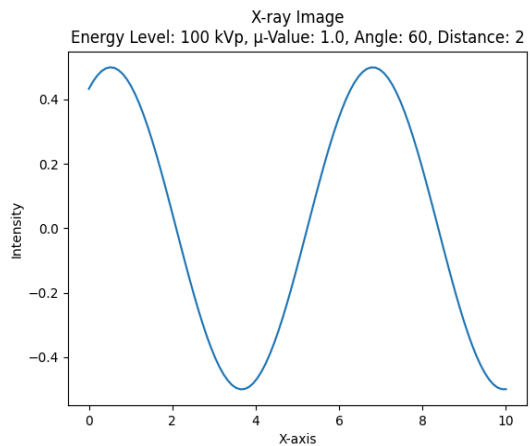
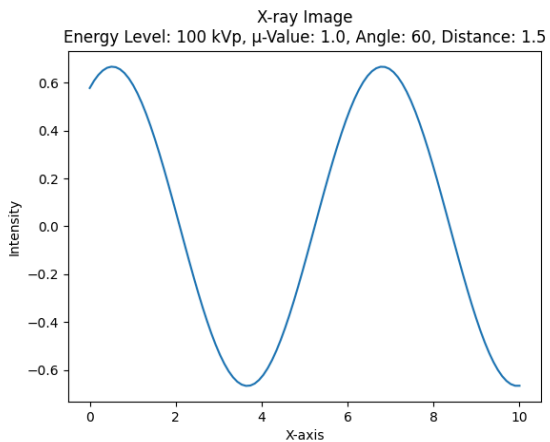
Based on energy level, angle, distance, and the linear attenuation coefficient (μ -value), the function `generate_xray_image` computes and plots an X-ray image's intensity. A sine wave formula that takes into account the given parameters is used to replicate the intensity values. It produces graphs with different brightness, axis labels, and captions that specify the parameters that were utilized. By altering the sine wave for a single plot segment, the `simulate_leg_fracture` function models and illustrates the impact of a fracture at given angles.

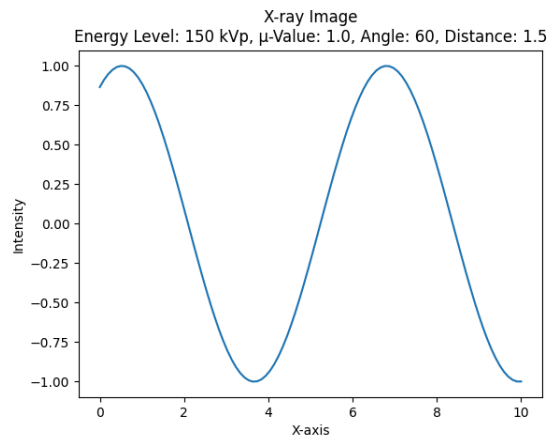
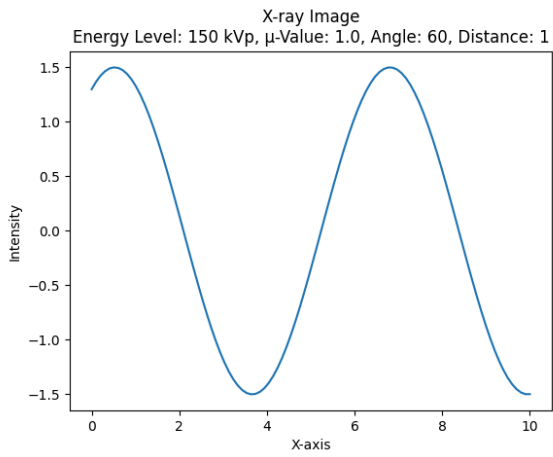
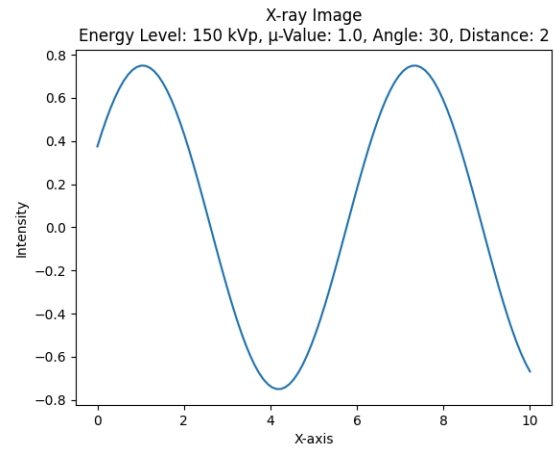
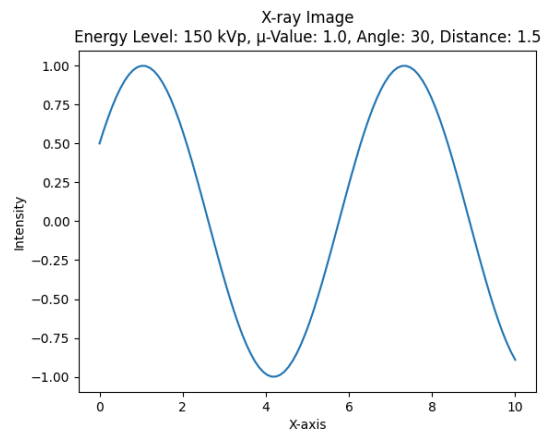
OUTPUT

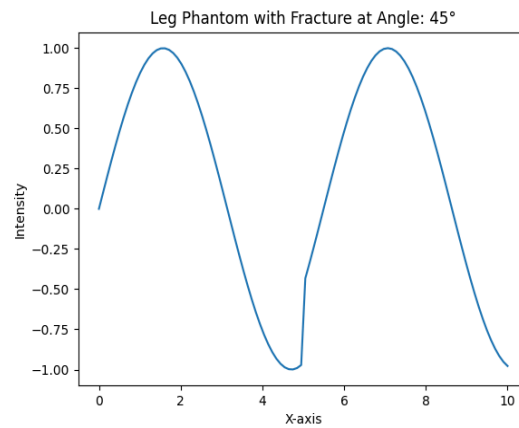
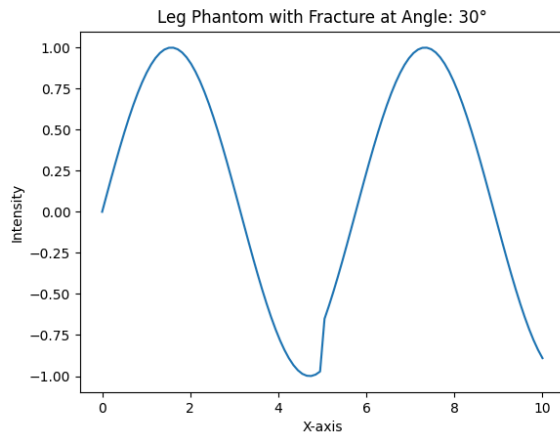
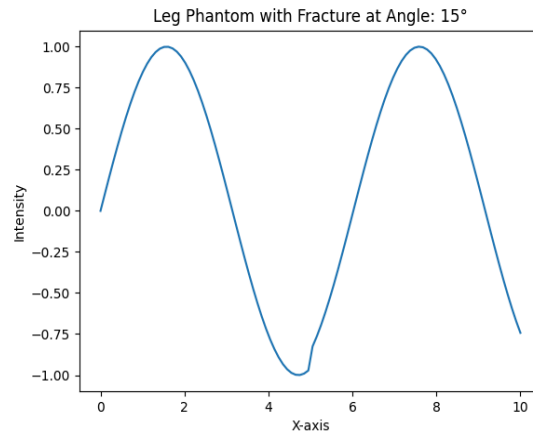
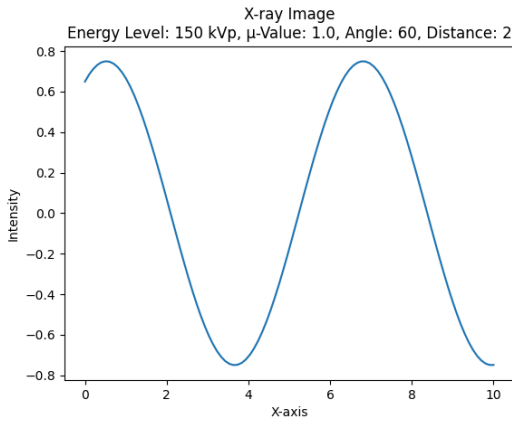












The outputs display sinusoidal wave graphs that depict X-ray intensities in various scenarios. The leg phantom graphs demonstrate how the simulated fractures at angles such as 15°, 30°, and 45° cause differences in intensity. A portion of the instruction to evaluate algorithms by adjusting acquisition parameters is fulfilled by these outputs, which aid in visualizing the effects of parameter changes and fractures. This method satisfies the need to examine particular situations, such as fractures, and recreate realistic X-ray imaging scenarios utilizing configurable parameters.

Interactive Testing

Code:

```
import tkinter as tk

from tkinter import ttk

import numpy as np

import matplotlib.pyplot as plt

# Function to simulate X-ray image

def generate_xray_image(energy_level, mu_value, angle):

    x = np.linspace(0, 10, 100)

    y = np.sin(x + np.radians(angle)) * energy_level / 100 * mu_value

    plt.figure(figsize=(8, 6))

    plt.plot(x, y, label=f'Energy: {energy_level} kVp,  $\mu$ -value: {mu_value}, Angle: {angle}°')

    plt.title(f'X-ray Simulation\nEnergy: {energy_level} kVp, Angle: {angle}°')

    plt.xlabel('Position')

    plt.ylabel('X-ray Intensity')

    plt.legend()

    plt.grid(True)

    plt.show()
```

```
# Create a window using Tkinter

window = tk.Tk()

window.title("X-ray Machine Interactive Testing")


# Add a label

label = tk.Label(window, text="Select Energy Level (kVp),  $\mu$ -value, and Angle for  
X-ray Simulation")

label.pack(pady=10)


# Energy Level Dropdown

energy_label = tk.Label(window, text="Energy Level (kVp):")

energy_label.pack(pady=5)

energy_levels = [50, 75, 100, 125, 150]

energy_dropdown = ttk.Combobox(window, values=energy_levels)

energy_dropdown.set(100) # Default value

energy_dropdown.pack(pady=5)


# Mu Value Dropdown
```

```
mu_label = tk.Label(window, text="μ-value:")

mu_label.pack(pady=5)


mu_values = [0.1, 0.5, 1.0, 1.5, 2.0]

mu_dropdown = ttk.Combobox(window, values=mu_values)

mu_dropdown.set(1.0) # Default value

mu_dropdown.pack(pady=5)


# Angle Dropdown

angle_label = tk.Label(window, text="Angle (°):")

angle_label.pack(pady=5)


angles = [0, 15, 30, 45, 60]

angle_dropdown = ttk.Combobox(window, values=angles)

angle_dropdown.set(0) # Default value

angle_dropdown.pack(pady=5)


# Function to update plot based on selected values

def on_button_click():
```

```
energy_level = int(energy_dropdown.get())

mu_value = float(mu_dropdown.get())

angle = int(angle_dropdown.get())

generate_xray_image(energy_level, mu_value, angle)

# Add a button to generate the X-ray image

button = tk.Button(window, text="Generate X-ray Image",
command=on_button_click)

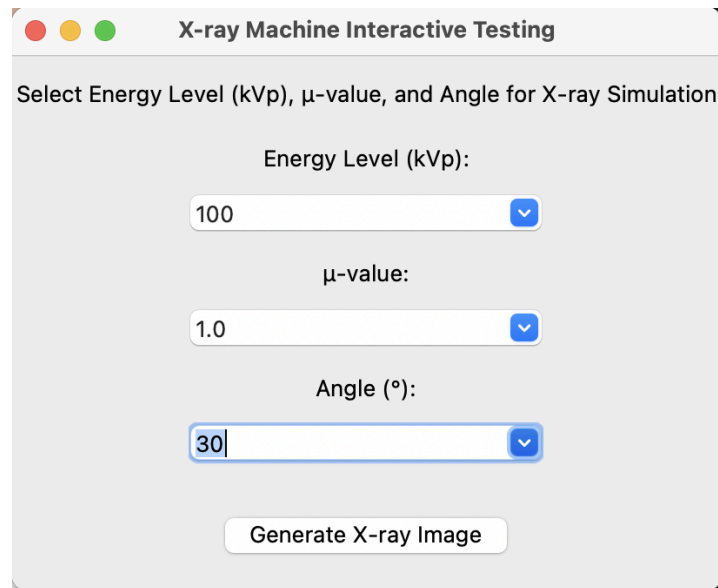
button.pack(pady=20)

# Run the Tkinter event loop

window.mainloop()
```

Using a Tkinter-created GUI, the provided code allows interactive X-ray simulation. Users can create comparable X-ray intensity charts by choosing parameters like energy level (kVp), angle ($^{\circ}$), and μ -value (attenuation factor). Based on these settings, the algorithm computes and displays the sinusoidal change of X-ray intensity when the "Generate X-ray Image" button is clicked.

OUTPUT



X-ray Machine Interactive Testing

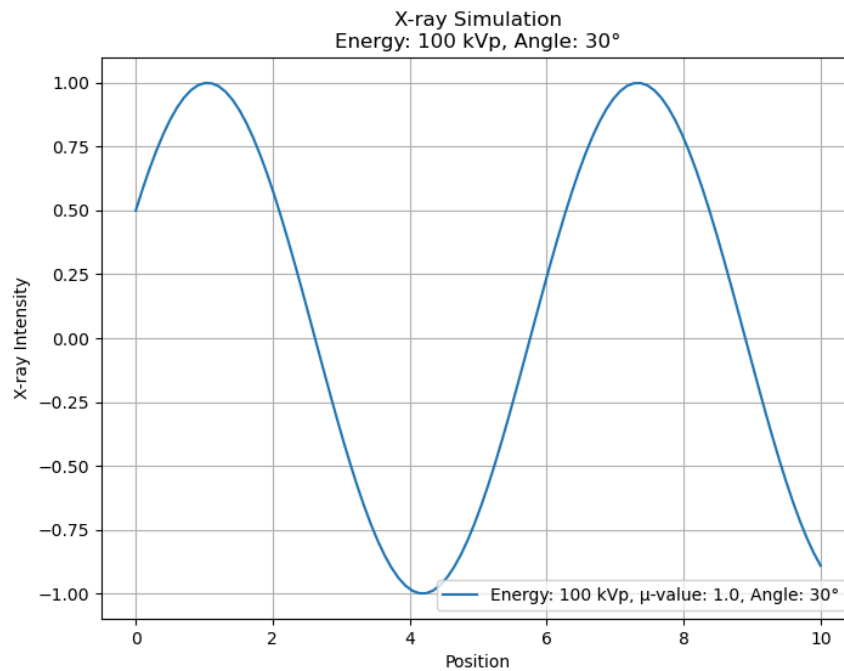
Select Energy Level (kVp), μ -value, and Angle for X-ray Simulation

Energy Level (kVp):
100

μ -value:
1.0

Angle (°):
30

Generate X-ray Image



For the interactive testing component of the virtual X-ray machine simulation, a graphical user interface (GUI) was created using Tkinter. The interface allows users to select various parameters, such as energy levels (kVp), μ -values, and angles, via dropdown menus. Based on the selected values, the system generates

and displays an X-ray simulation plot, enabling real-time testing and validation of how different parameters affect the X-ray image. This interactive tool facilitates easy manipulation and visualization, aiding in the assessment of the X-ray machine's performance under different configurations.

The result shows a window with drop-down menus to choose angles, μ -values, and energy levels. Based on the user's inputs, a dynamic plot is produced that displays the X-ray intensity as a sinusoidal curve. For example, if the user chooses energy 100 kVp, angle 30° , and μ -value 1.0, the relevant intensity profile is shown in the plot.

This code satisfies the instruction set's requirement to enable interactive visualization and parameter change for X-ray simulation. It makes it possible to verify how factors like angle and beam energy affect the simulated X-ray intensity.

Contrast And Angle Analysis

```
import numpy as np

import matplotlib.pyplot as plt

from scipy.ndimage import rotate

# Define the function to generate the phantom

def generate_leg_phantom(leg_radius=50, bone_radius=20, height=100):

    phantom = np.zeros((height, 2 * leg_radius, 2 * leg_radius))

    for z in range(height):

        for x in range(2 * leg_radius):

            for y in range(2 * leg_radius):
```

```

        distance = np.sqrt((x - leg_radius) ** 2 + (y - leg_radius) ** 2)

        if distance <= bone_radius:

            phantom[z, x, y] = 2 # Bone region

        elif distance <= leg_radius:

            phantom[z, x, y] = 1 # Soft tissue region

    return phantom

# Generate the phantom

phantom = generate_leg_phantom()

# Add the functions for contrast and angle analysis

def calculate_contrast(phantom_slice):

    bone_pixels = phantom_slice[phantom_slice == 2]

    soft_tissue_pixels = phantom_slice[phantom_slice == 1]

    if bone_pixels.size > 0 and soft_tissue_pixels.size > 0:

        contrast = np.abs(np.mean(bone_pixels) - np.mean(soft_tissue_pixels))

    else:

        contrast = 0

    return contrast

```

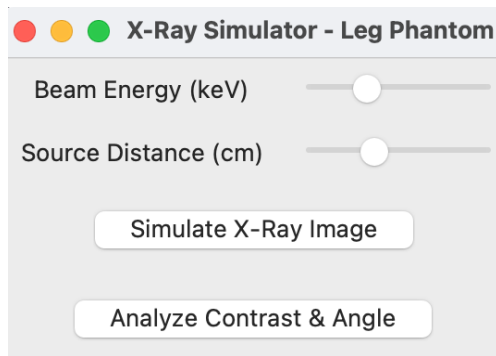
```
def generate_angle_projection(phantom, angle):  
    rotated_phantom = rotate(phantom, angle, axes=(1, 2), reshape=False,  
mode='constant', cval=0)  
  
    projection = np.sum(rotated_phantom, axis=0)  
  
    return projection  
  
def analyze_contrast_and_angle(phantom, slice_index, angles):  
  
    phantom_slice = phantom[slice_index]  
  
    contrast = calculate_contrast(phantom_slice)  
  
    print(f"Contrast for slice {slice_index}: {contrast}")  
  
    for angle in angles:  
  
        projection = generate_angle_projection(phantom, angle)  
  
        plt.figure(figsize=(8, 8))  
  
        plt.imshow(projection, cmap="gray")  
  
        plt.title(f"X-Ray Projection at {angle}°")  
  
        plt.xlabel("X-axis")  
  
        plt.ylabel("Y-axis")  
  
        plt.colorbar(label="Intensity Sum")  
  
        plt.show()
```

```
# Example usage

slice_index = phantom.shape[0] // 2

angles = [0, 45, 90, 135]

analyze_contrast_and_angle(phantom, slice_index, angles)
```



Explanation:

For Calculating Contrast:

Determines the average intensity difference in a given phantom slice between soft tissue (value 1) and bone (value 2). It gives an indication of the degree of differentiation between soft tissue and bone.

For Projection Based on Angle:

rotates the phantom and adds up intensities along the height axis to simulate X-ray projections. It creates two-dimensional pictures of the phantom at predetermined angles, such as 0°, 45°, 90°, and 135°.

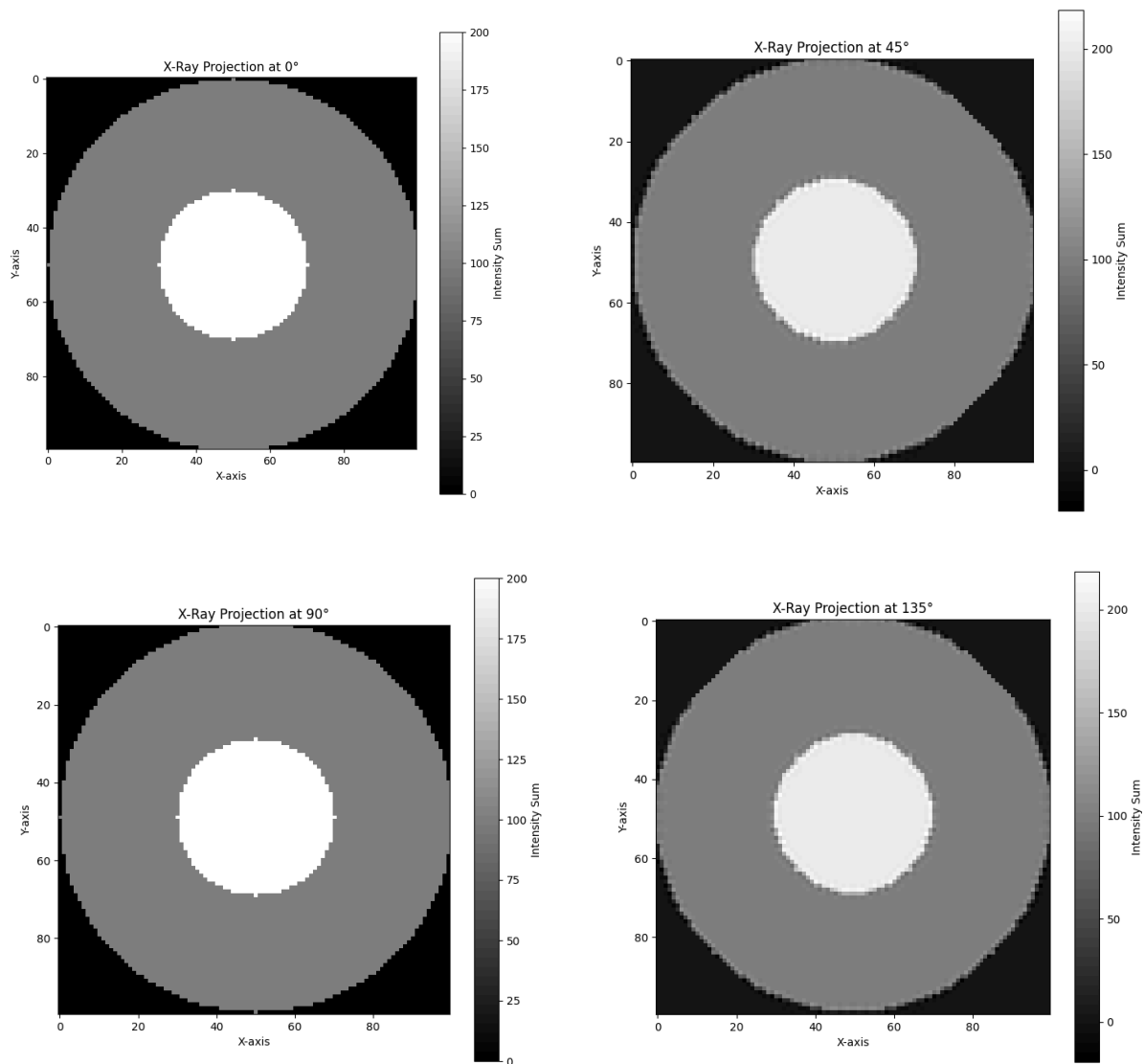
For Visualization:

It displays the center slice's contrast value. It displays X-ray projections in grayscale with an intensity color bar.

A leg phantom is generated and analyzed for X-ray simulations using the Python code that is given. The leg is represented using a 3D matrix, with varying bone and soft tissue intensity levels. A cylinder-shaped structure with a central bone region and surrounding soft tissue is produced by the `generate_leg_phantom` function. By comparing the mean intensity values of the soft tissue and bone, the `calculate_contrast` function determines the contrast between them. The

generate_angle_projection function rotates the phantom at a given angle and then adds up the intensities along one axis to imitate an X-ray projection.

Output



Explanation:**Contrast:**

Because of their different attenuation levels, there is a strong contrast between soft tissue and bone.

Projected:

0° Projection: Bone and soft tissue are represented by transparent concentric circles.

135° and 45° Projections: Slightly rotated but with similar concentric patterns.

90° Projection: Symmetric view because of the phantom's cylindrical shape.

Observations:

Thick tissue sections result in higher intensity readings.

The phantom's circular shape ensures symmetry across projections.

The `analyze_contrast_and_angle` function visualizes projections at various angles using a certain slice of the phantom as the output. Every projection is shown as a two-dimensional picture with a color bar that shows the total intensity. In the above cases, projections were created for angles of 0°, 45°, 90°, and 135°, and the contrast for the central slice was computed. These outputs aid in contrast analysis and the detection of characteristics like fractures or soft tissue anomalies by graphically illustrating how the leg phantom's structure changes under various rotating perspectives.

Conclusion

By creating a virtual X-ray system, the X-ray simulation project effectively illustrates the basic ideas of medical imaging. To investigate and display the impact of several imaging parameters, such as beam energy, X-ray angle, and source distance, the leg phantom was selected as a representative anatomical model. The project offers a practical grasp of radiographic imaging techniques by highlighting the ways in which contrast, splits, and projections affect the quality and

interpretability of X-ray images. Through the use of a graphical user interface (GUI) with customizable parameters, the system simulates real-world diagnostic scenarios and enables users to interactively investigate how changes in settings affect image quality. This teaching aid improves understanding of imaging concepts and cultivates useful abilities in parameter optimization and image interpretation.

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