part2

October 31, 2022

[16]:
```
%matplotlib inline
import os
import sys
import glob
import re
import numpy as np
import matplotlib
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D
from PIL import Image
import time
```

1 Image loading and saving

[17]:
```
def LoadFaceImages(pathname, subject_name, num_images):
    """
    Load the set of face images.
    The routine returns
        ambimage: image illuminated under the ambient lighting
        imarray: a 3-D array of images, h x w x Nimages
        lightdirs: Nimages x 3 array of light source directions
    """

    def load_image(fname):
        return np.asarray(Image.open(fname))

    def fname_to_ang(fname):
        yale_name = os.path.basename(fname)
        return int(yale_name[12:16]), int(yale_name[17:20])

    def sph2cart(az, el, r):
        rcos_theta = r * np.cos(el)
        x = rcos_theta * np.cos(az)
        y = rcos_theta * np.sin(az)
        z = r * np.sin(el)
        return x, y, z
    ambimage = load_image(
        os.path.join(pathname, subject_name + '_P00_Ambient.pgm'))
    im_list = glob.glob(os.path.join(pathname, subject_name + '_P00A*.pgm'))
    if num_images <= len(im_list):
        im_sub_list = np.random.choice(im_list, num_images, replace=False)
    else:
        print(
            'Total available images is less than specified.\nProceeding with %d␣
 ↪images.\n'
            % len(im_list))
        im_sub_list = im_list
    im_sub_list.sort()
    imarray = np.stack([load_image(fname) for fname in im_sub_list], axis=-1)
    Ang = np.array([fname_to_ang(fname) for fname in im_sub_list])

    x, y, z = sph2cart(Ang[:, 0] / 180.0 * np.pi, Ang[:, 1] / 180.0 * np.pi, 1)
    lightdirs = np.stack([y, z, x], axis=-1)
    return ambimage, imarray, lightdirs
def save_outputs(subject_name, albedo_image, surface_normals):
    im = Image.fromarray((albedo_image*255).astype(np.uint8))
    im.save("%s_albedo.jpg" % subject_name)
    im = Image.fromarray((surface_normals[:,:,0]*128+128).astype(np.uint8))
    im.save("%s_normals_x.jpg" % subject_name)
    im = Image.fromarray((surface_normals[:,:,1]*128+128).astype(np.uint8))
    im.save("%s_normals_y.jpg" % subject_name)
    im = Image.fromarray((surface_normals[:,:,2]*128+128).astype(np.uint8))
    im.save("%s_normals_z.jpg" % subject_name)
```

2 Plot the height map

[18]:

```
def set_aspect_equal_3d(ax):
    """https://stackoverflow.com/questions/13685386"""
    """Fix equal aspect bug for 3D plots."""
    xlim = ax.get_xlim3d()
    ylim = ax.get_ylim3d()
    zlim = ax.get_zlim3d()
    from numpy import mean
    xmean = mean(xlim)
    ymean = mean(ylim)
    zmean = mean(zlim)
    plot_radius = max([
        abs(lim - mean_)
        for lims, mean_ in ((xlim, xmean), (ylim, ymean), (zlim, zmean))
        for lim in lims
    ])
    ax.set_xlim3d([xmean - plot_radius, xmean + plot_radius])
    ax.set_ylim3d([ymean - plot_radius, ymean + plot_radius])
    ax.set_zlim3d([zmean - plot_radius, zmean + plot_radius])


# Add 2 params: elev, azim to change 3D viewpoint
def display_output(albedo_image, height_map, elev=20, azim=20):
    fig = plt.figure()
    plt.imshow(albedo_image, cmap='gray')
    plt.axis('off')

    fig = plt.figure(figsize=(10, 10))
    ax = fig.gca(projection='3d')
    ax.view_init(elev, azim)
    X = np.arange(albedo_image.shape[0])
    Y = np.arange(albedo_image.shape[1])
    X, Y = np.meshgrid(Y, X)
    H = np.flipud(np.fliplr(height_map))
    A = np.flipud(np.fliplr(albedo_image))
    A = np.stack([A, A, A], axis=-1)
    ax.xaxis.set_ticks([])
    ax.xaxis.set_label_text('Z')
    ax.yaxis.set_ticks([])
    ax.yaxis.set_label_text('X')
    ax.zaxis.set_ticks([])
    ax.yaxis.set_label_text('Y')
    surf = ax.plot_surface(
        H, X, Y, rcount=200, ccount=200, cmap='gray', facecolors=A,␣
 ↪linewidth=0, antialiased=False)
    set_aspect_equal_3d(ax)
```

3 Plot the surface norms.

[19]:

```
def plot_surface_normals(surface_normals):
    """
    surface_normals: h x w x 3 matrix.
    """
    fig = plt.figure()
    ax = plt.subplot(1, 3, 1)
    ax.axis('off')
    ax.set_title('X')
    im = ax.imshow(surface_normals[:,:,0])
    ax = plt.subplot(1, 3, 2)
    ax.axis('off')
    ax.set_title('Y')
    im = ax.imshow(surface_normals[:,:,1])
    ax = plt.subplot(1, 3, 3)
    ax.axis('off')
    ax.set_title('Z')
    im = ax.imshow(surface_normals[:,:,2])
```

4 Self implementation

[20]:

```
def preprocess(ambimage, imarray):

    # 1. subtract ambient_image from each image in imarray.
    processed_imarray = imarray - ambient_image[:, :, np.newaxis]
    # 2. make sure no pixel is less than zero.
    processed_imarray[processed_imarray < 0] = 0
    # 3. rescale values in imarray to be between 0 and 1.
    processed_imarray = processed_imarray / 255

    return processed_imarray
```

[21]:

```
def photometric_stereo(imarray, light_dirs):

    # imarray:  h x w x Nimages
    h = imarray.shape[0]
    w = imarray.shape[1]
    n_images = imarray.shape[2]
    n_pix = h * w

    # Reshape imarray
    imarray = imarray.reshape(n_pix, n_images).transpose()

    # light_dirs: Nimages x 3
    results = np.linalg.lstsq(light_dirs, imarray)
    g = results[0]

    # albedo_image: h x w
    albedo_image = np.linalg.norm(g, axis=0)
    surface_normals = g / albedo_image

    # surface_norms: h x w x 3
    surface_normals = surface_normals.transpose().reshape(h, w, 3)
    albedo_image = albedo_image.reshape(h, w)

    return albedo_image, surface_normals
```

[22]:

```
def get_surface(surface_normals, integration_method):
    """
    Inputs:
        surface_normals:h x w x 3
        integration_method: string in ['average', 'column', 'row', 'random']
    Outputs:
        height_map: h x w
    """
    # Partial derivative.
    fx = surface_normals[:, :, 0] / surface_normals[:, :, 2]
    fy = surface_normals[:, :, 1] / surface_normals[:, :, 2]

    row_sum_x = np.cumsum(fx, axis=1)
    col_sum_y = np.cumsum(fy, axis=0)

    # Four integration methods.
    def row():
        # First row, then column.
        return row_sum_x[0] + col_sum_y

    def column():
        # First column, then row.
        return col_sum_y[:, 0][:, np.newaxis] + row_sum_x

    def average():
        # Take average over column and row methods.
        return (column() + row())/2

    def random():

        # Initialize hight map
        h = surface_normals.shape[0]
        w = surface_normals.shape[1]
        height_map = np.zeros((h, w))

        # Configure number of random paths.
        n_paths = 25

        # Loop through each pixel.
        # Note: y is axis 0 (row), x is axis 1 (column).
        for y in range(h):
            for x in range(w):

                # Exclude the starting point (0, 0).
                if x != 0 or y != 0:

                    for path in range(n_paths):
                        # Flip coins to generate paths.
                        # Should guarantee #zeros = x, #ones = y in coins.
                        zeros = [0] * x
                        ones = [1] * y
                        coins = np.array(zeros + ones)
                        # Randomly shuffle coins (sudo-random path).
                        np.random.shuffle(coins)

                        current_x = 0
                        current_y = 0
                        step = 0
                        cumsum = 0

                        while current_x < x or current_y < y:
                            # Move right.
                            if coins[step] == 0:
                                cumsum += fx[current_y, current_x]
                                current_x += 1
                            else:
                                cumsum += fy[current_y, current_x]
                                current_y += 1

                            step += 1

                        height_map[y, x] += cumsum

                    height_map[y, x] = height_map[y, x]/n_paths
        return height_map

    method = {'row': row, 'column': column, 'average': average, 'random':␣
 ↪random}

    start = time.time()
    height_map = method[integration_method]()
    end = time.time()
    print('Method: ' + integration_method +
          '; Excution time: {} s.'.format(end-start))

    return height_map
```

5 Main function

5.1 1 Outputs for yaleB01

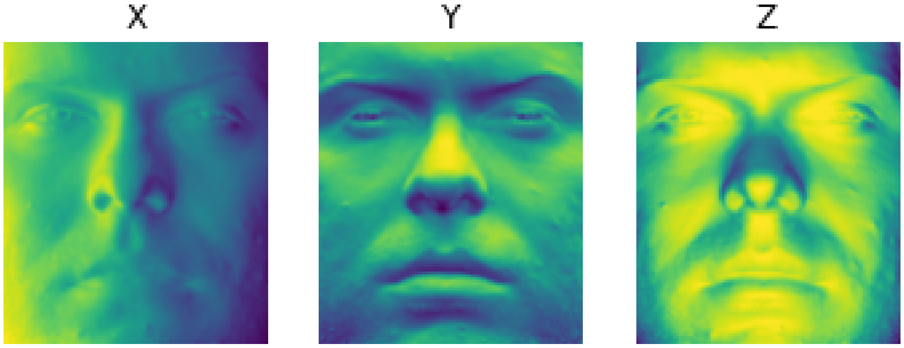
[23]:

```
save_flag = True
full_path = './croppedyale/yaleB01'
ambient_image, imarray, light_dirs = LoadFaceImages(full_path, subject_name, 64)

processed_imarray = preprocess(ambient_image, imarray)
```

```
albedo_image, surface_normals = photometric_stereo(processed_imarray,␣
 ↪light_dirs)

if save_flag:
    save_outputs(subject_name, albedo_image, surface_normals)
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/85377190.py:13:
FutureWarning: `rcond` parameter will change to the default of machine precision
times ``max(M, N)`` where M and N are the input matrix dimensions.
To use the future default and silence this warning we advise to pass
`rcond=None`, to keep using the old, explicitly pass `rcond=-1`.
  results = np.linalg.lstsq(light_dirs, imarray)
```

[24]:
```
plot_surface_normals(surface_normals)
```

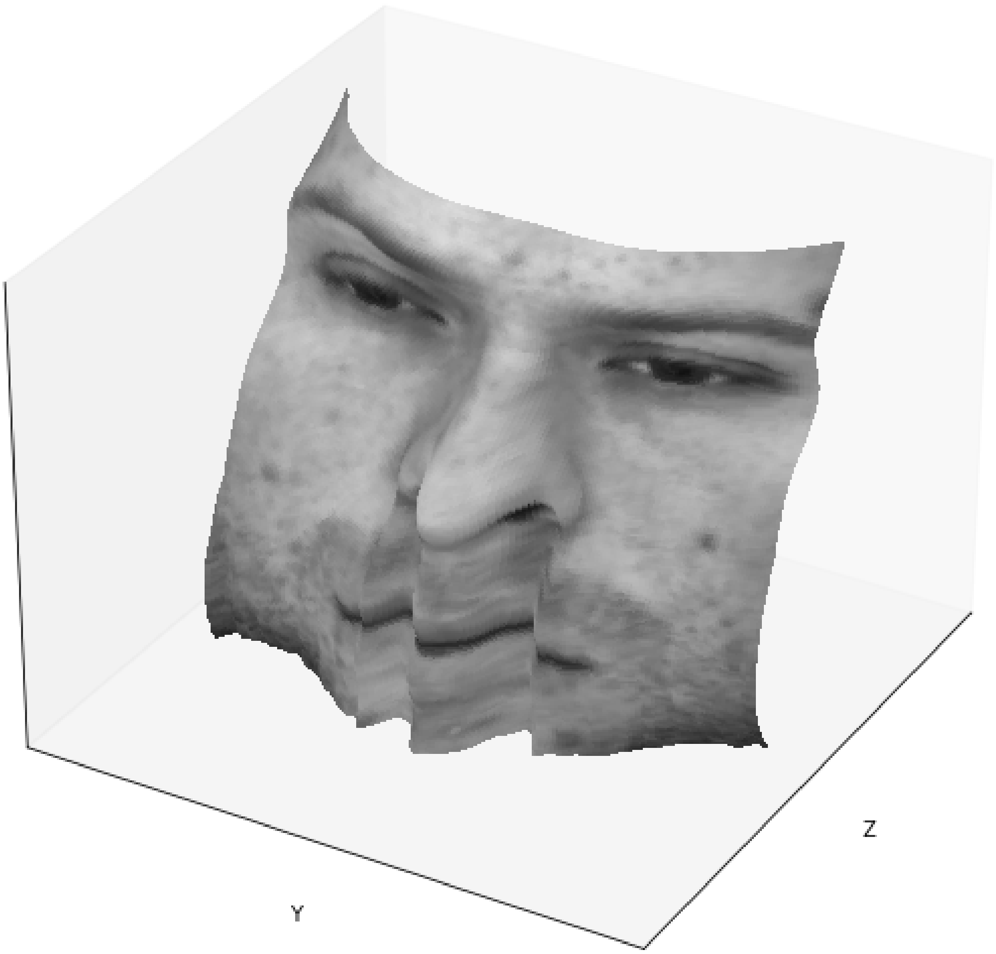


5.1.1 1.1 First row, then column

[27]:
```
integration_method = 'row'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

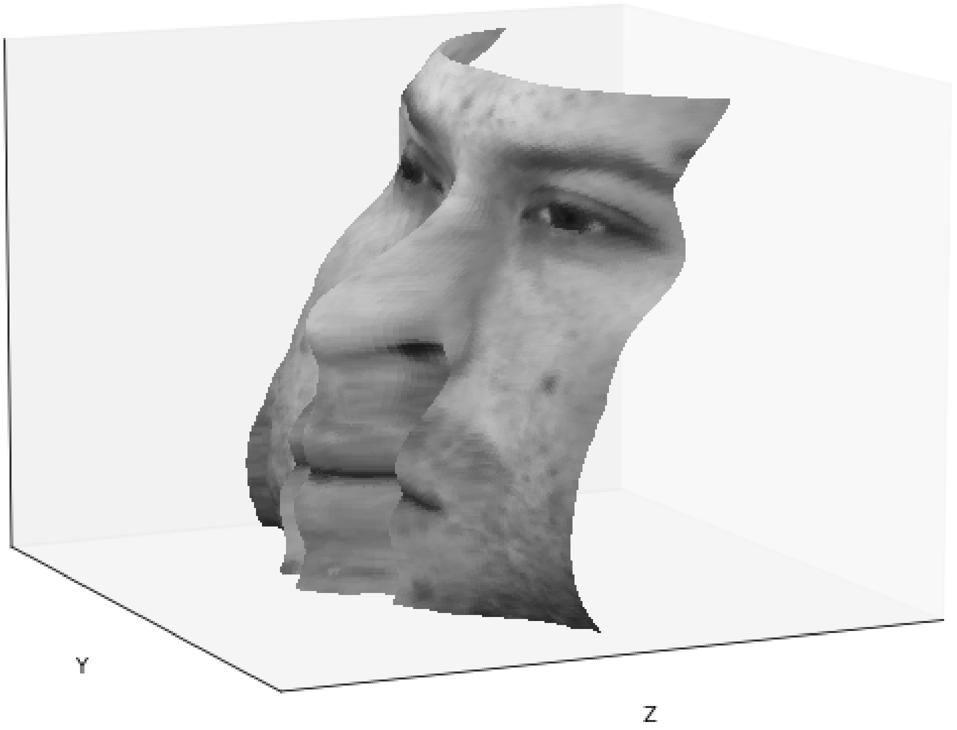
```
Method: row; Excution time: 0.00016570091247558594 s.
Viewpoint 1:
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



[28]:
```
print("Viewpoint 2:")
display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 2:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



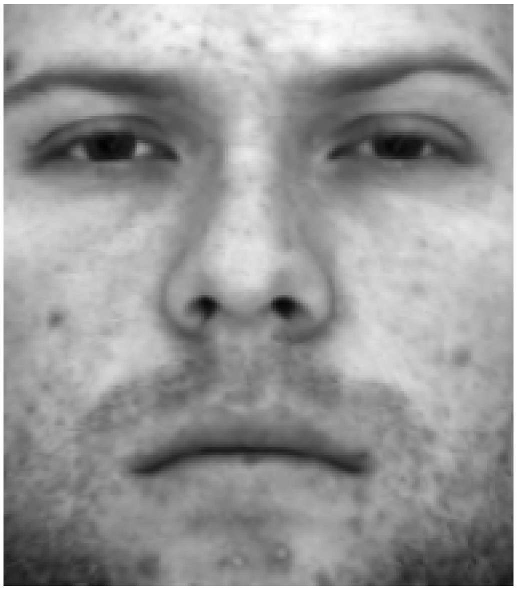
5.1.2 1.2 First column, then row

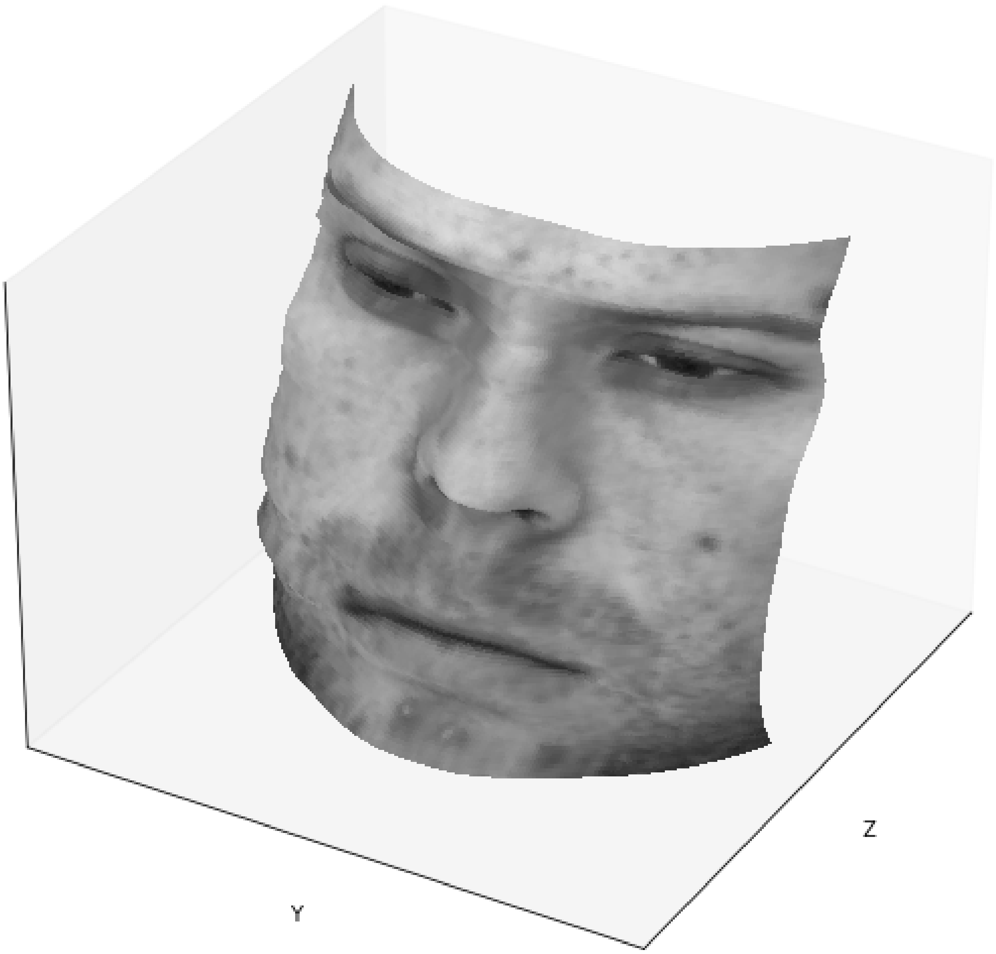
```
[29]: integration_method = 'column'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

```
Method: column; Excution time: 0.00011181831359863281 s.
Viewpoint 1:
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
```

```
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```

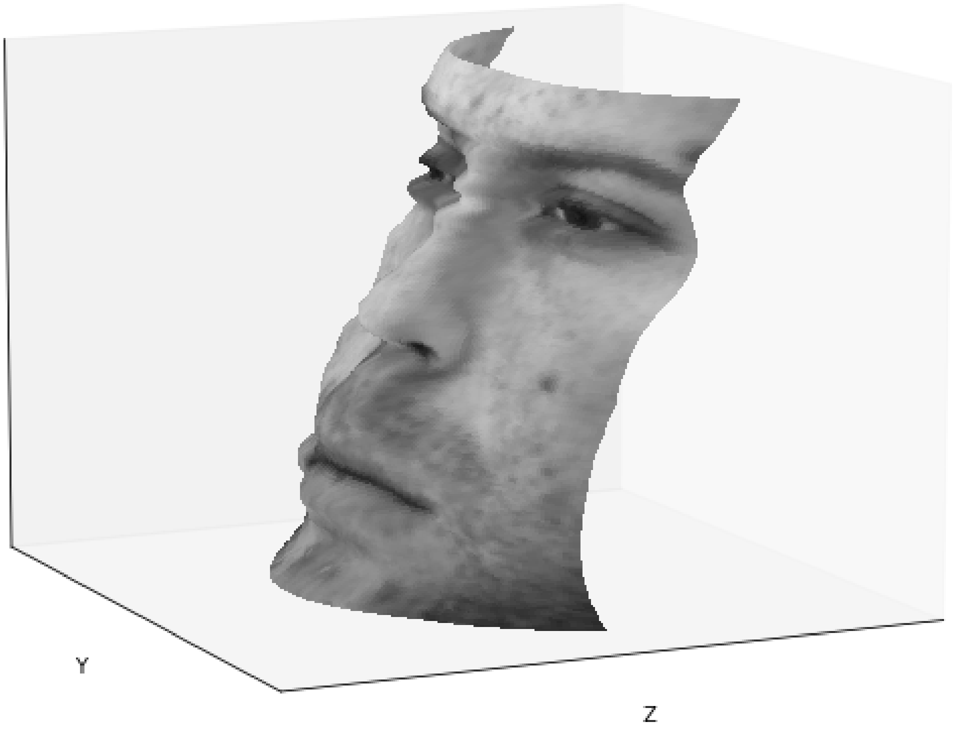




[30]:

```python
print("Viewpoint 2:")
display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 2:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



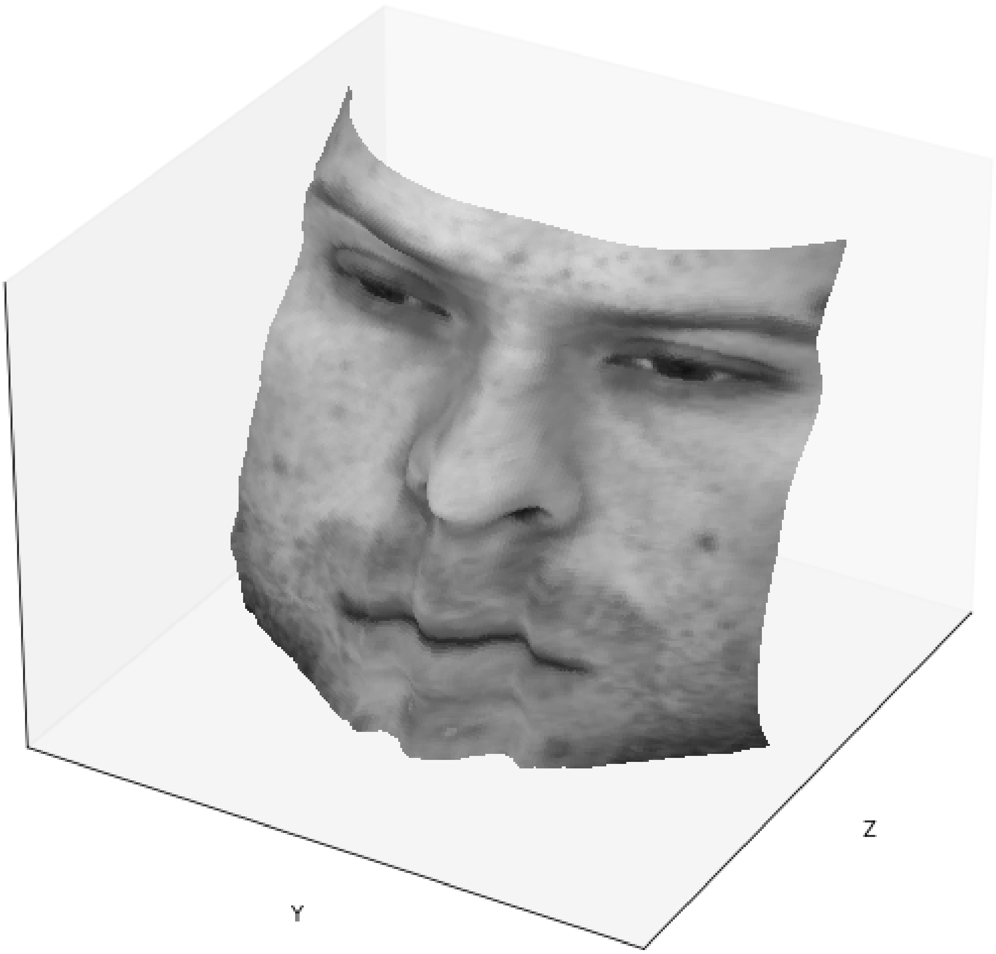
5.1.3 1.3 Surface height map of method average

[31]:
```
integration_method = 'average'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

```
Method: average; Excution time: 0.0006020069122314453 s.
Viewpoint 1:
```

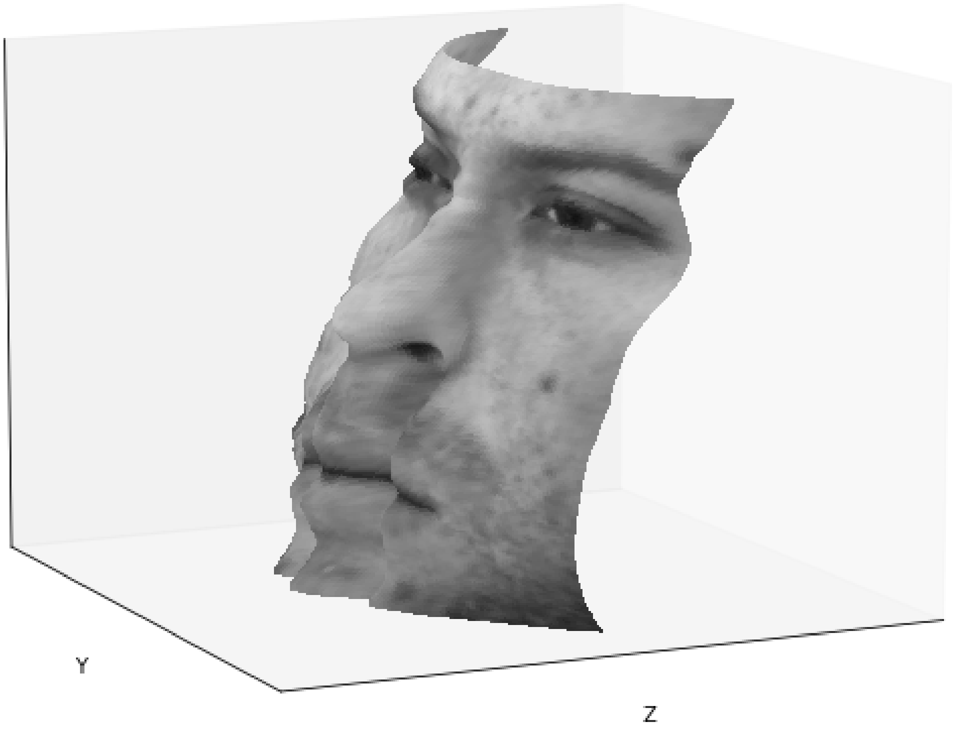
```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
```

```
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



[32]:
```
print("Viewpoint 2:")
display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 2:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



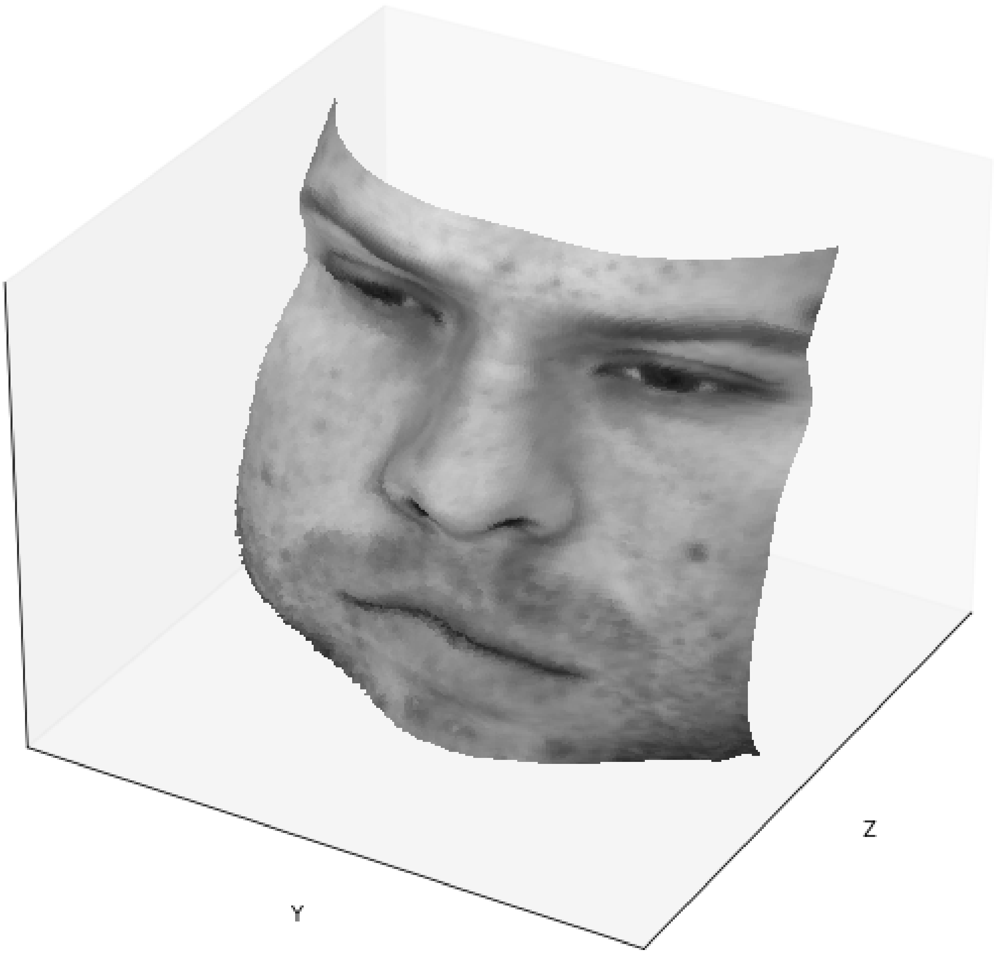
5.1.4 1.4 Surface height map of method random

```
[34]: integration_method = 'random'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

```
Method: random; Excution time: 70.55510687828064 s.
Viewpoint 1:
```

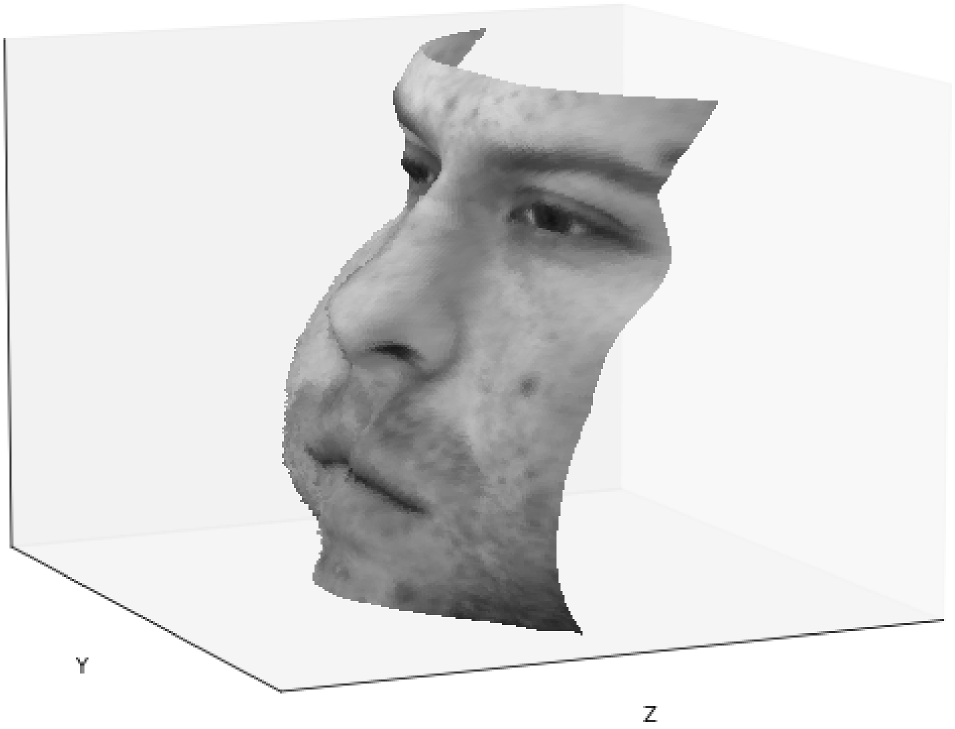
```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
```

```
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



[35]:
```
print("Viewpoint 2:")
display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 2:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



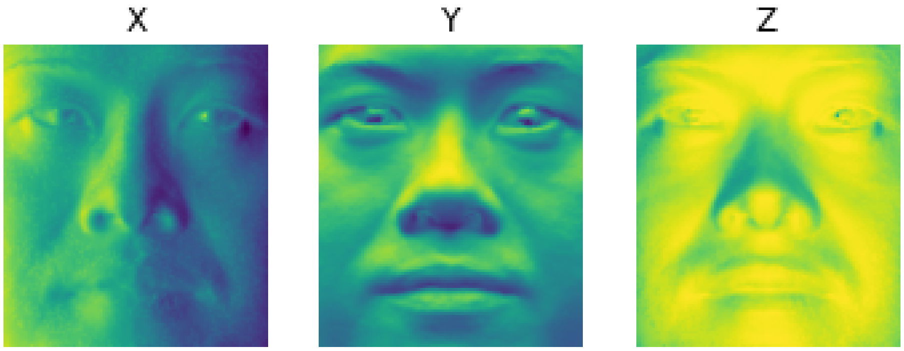
5.2 2 Outputs for yaleB02

[46]:
```
save_flag = True

full_path = './croppedyale/yaleB02'
ambient_image, imarray, light_dirs = LoadFaceImages(full_path, subject_name, 64)

processed_imarray = preprocess(ambient_image, imarray)
albedo_image, surface_normals = photometric_stereo(processed_imarray,␣
 ↪light_dirs)

if save_flag:
    save_outputs(subject_name, albedo_image, surface_normals)
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/85377190.py:13:
FutureWarning: `rcond` parameter will change to the default of machine precision
times ``max(M, N)`` where M and N are the input matrix dimensions.
To use the future default and silence this warning we advise to pass
`rcond=None`, to keep using the old, explicitly pass `rcond=-1`.
  results = np.linalg.lstsq(light_dirs, imarray)
```

[47]:

```
plot_surface_normals(surface_normals)
```



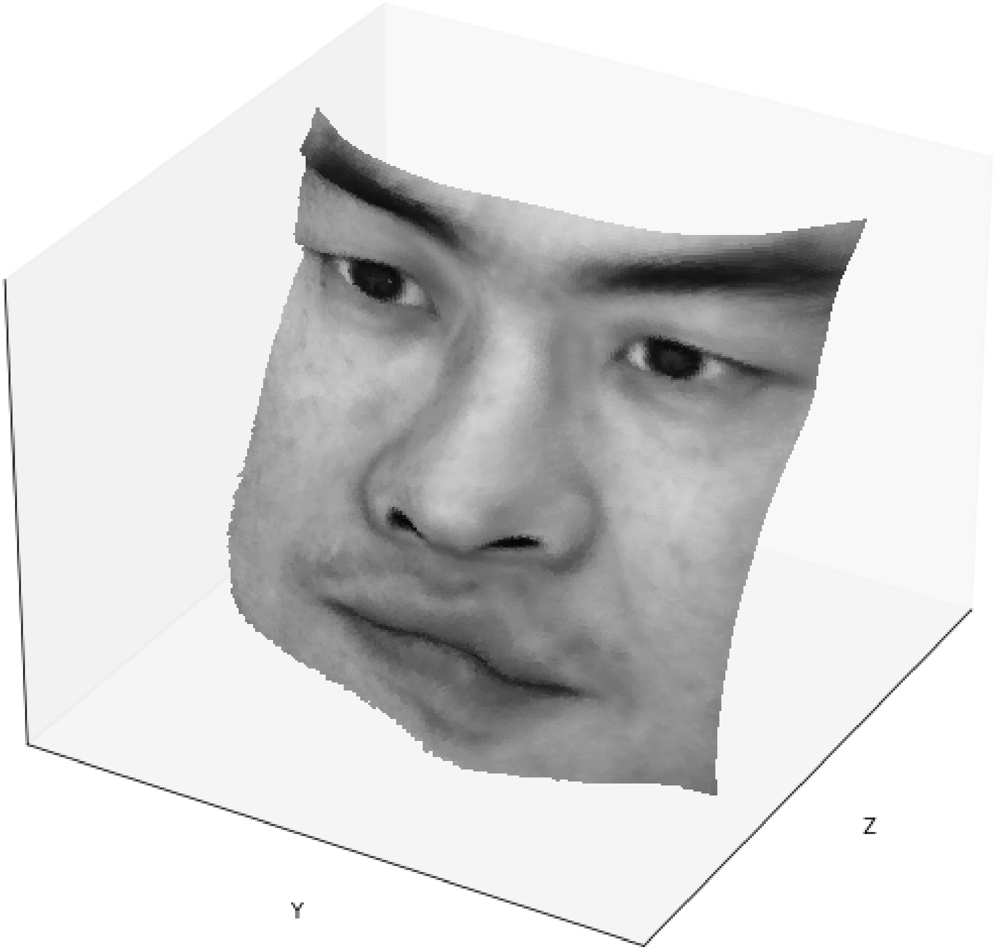
5.2.1 2.1 Best Surface height map

[48]:

```
integration_method = 'random'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

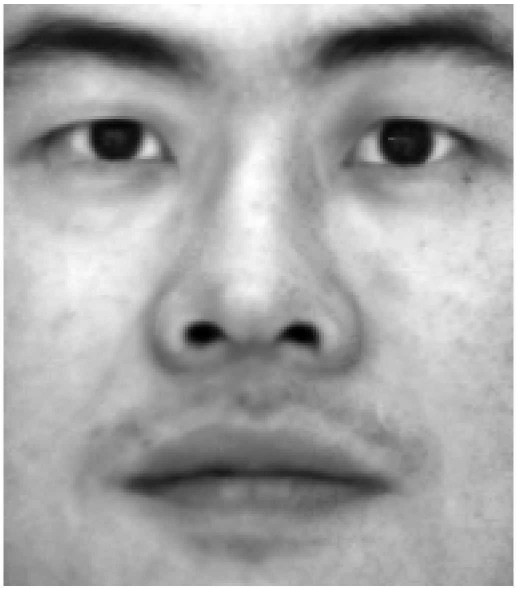
```
Method: random; Excution time: 73.09051871299744 s.
Viewpoint 1:
```

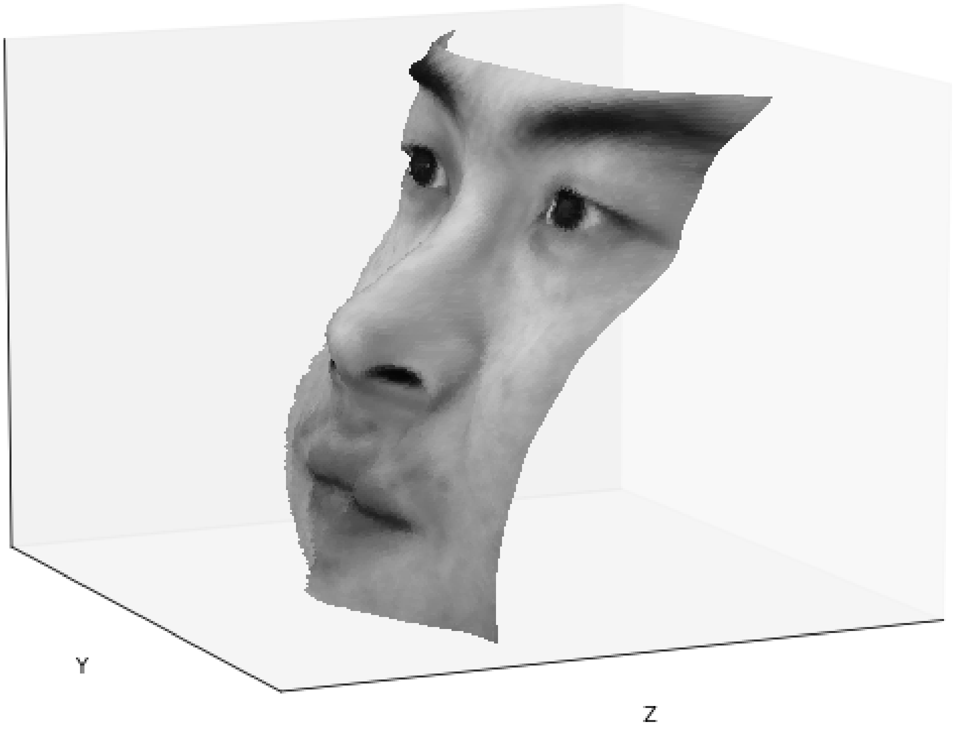
```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



```
[53]: print("Viewpoint 1:")
      display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 1:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```





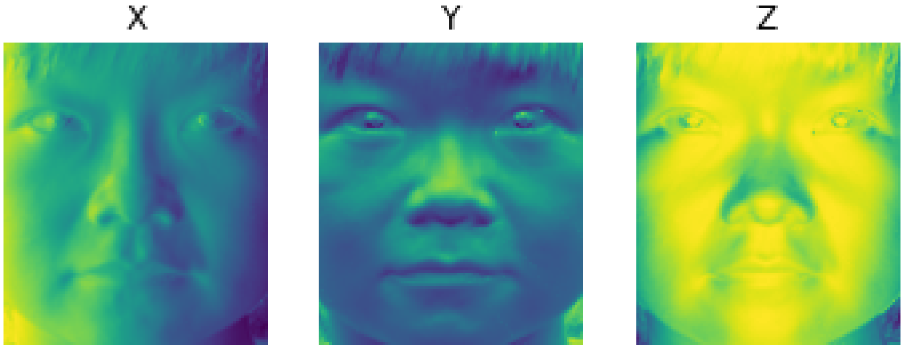
5.3 3 Outputs for yaleB05

```
[63]: save_flag = True

full_path = './croppedyale/yaleB05'
ambient_image, imarray, light_dirs = LoadFaceImages(full_path, subject_name, 64)

processed_imarray = preprocess(ambient_image, imarray)
albedo_image, surface_normals = photometric_stereo(processed_imarray,␣
 ↪light_dirs)

if save_flag:
    save_outputs(subject_name, albedo_image, surface_normals)
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/85377190.py:13:
FutureWarning: `rcond` parameter will change to the default of machine precision
times ``max(M, N)`` where M and N are the input matrix dimensions.
To use the future default and silence this warning we advise to pass
`rcond=None`, to keep using the old, explicitly pass `rcond=-1`.
  results = np.linalg.lstsq(light_dirs, imarray)
```

[64]:

```
plot_surface_normals(surface_normals)
```



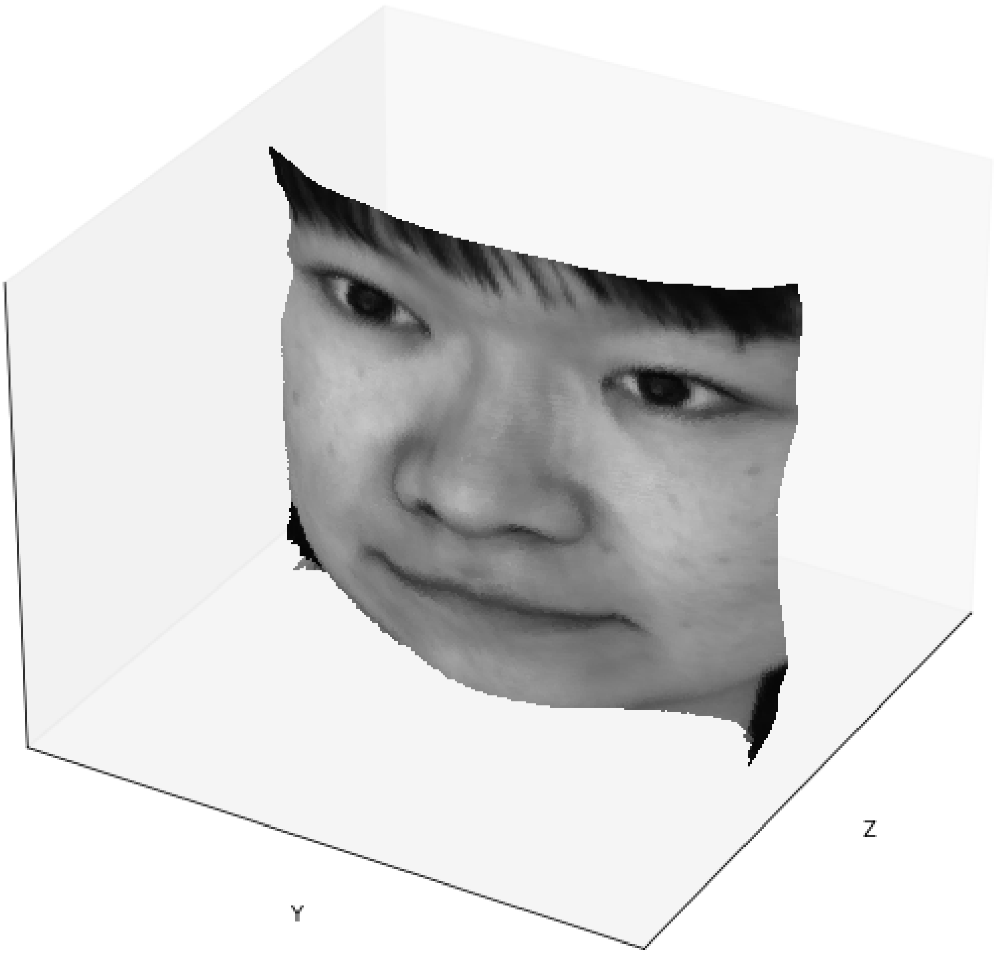
5.3.1 3.1 Best Surface height map

[65]:

```
integration_method = 'random'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

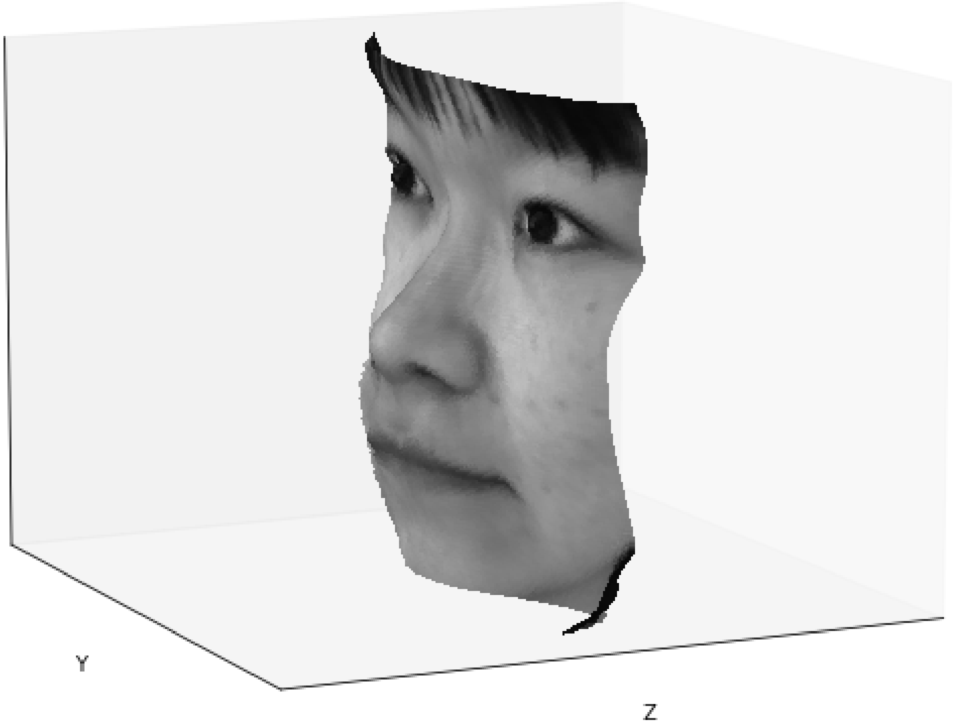
```
Method: random; Excution time: 72.14865016937256 s.
Viewpoint 1:
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



[66]:
```
print("Viewpoint 2:")
display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 2:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



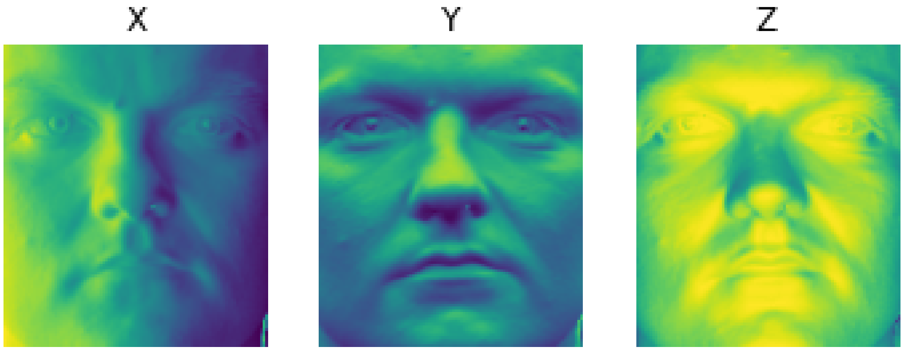
5.4 4 Outputs for yaleB07

[67]:
```
root_path = './croppedyale/'
subject_name = 'yaleB07'
save_flag = True

full_path = './croppedyale/yaleB07'
ambient_image, imarray, light_dirs = LoadFaceImages(full_path, subject_name, 64)

processed_imarray = preprocess(ambient_image, imarray)
albedo_image, surface_normals = photometric_stereo(processed_imarray,␣
 ↪light_dirs)
```

```
if save_flag:
    save_outputs(subject_name, albedo_image, surface_normals)
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/85377190.py:13:
FutureWarning: `rcond` parameter will change to the default of machine precision
times ``max(M, N)`` where M and N are the input matrix dimensions.
To use the future default and silence this warning we advise to pass
`rcond=None`, to keep using the old, explicitly pass `rcond=-1`.
  results = np.linalg.lstsq(light_dirs, imarray)
```

[68]:
```
plot_surface_normals(surface_normals)
```

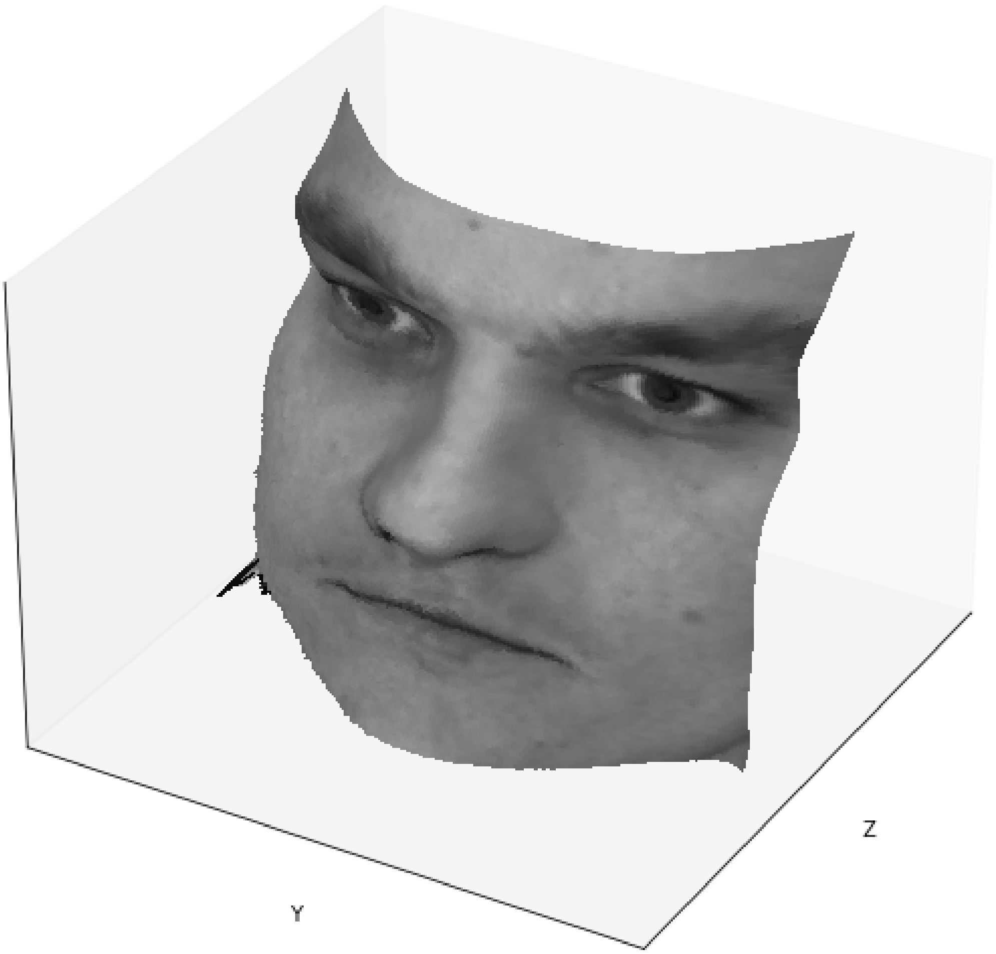


5.4.1 4.1 Best Surface height map

[70]:
```
integration_method = 'random'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

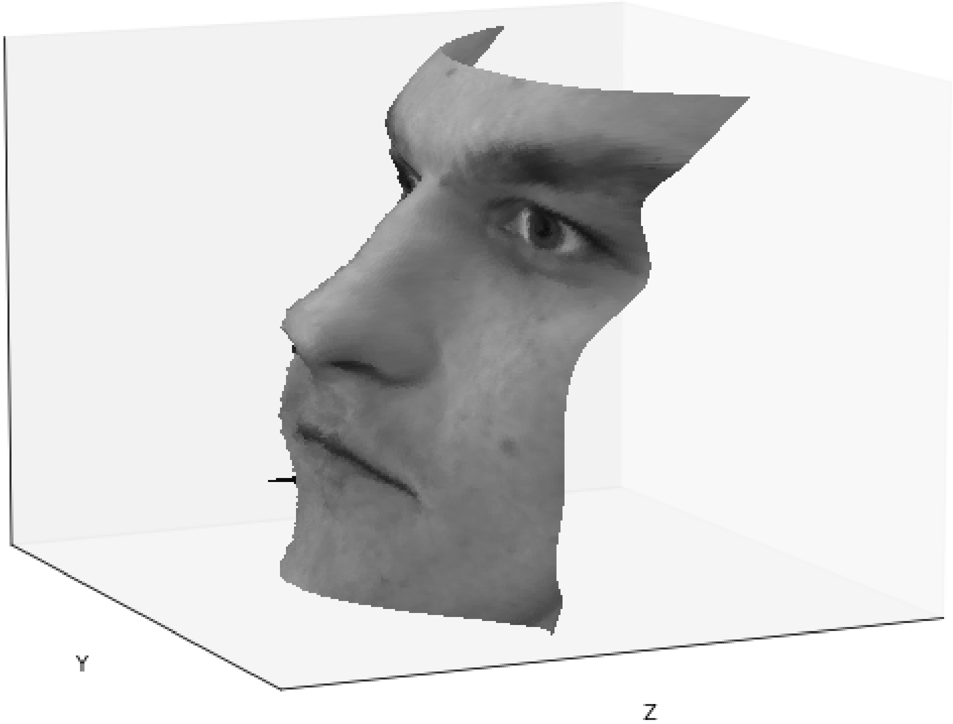
```
Method: random; Excution time: 73.47473931312561 s.
Viewpoint 1:
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



```
[71]: print("Viewpoint 2:")
      display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 2:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



5.4.2 2.2 Improvement of yaleb02

[72]:

```
def LoadFaceImages_improved(pathname, subject_name, threshold):
    def load_image(fname):
        return np.asarray(Image.open(fname))

    def fname_to_ang(fname):
        yale_name = os.path.basename(fname)
        return int(yale_name[12:16]), int(yale_name[17:20])

    def sph2cart(az, el, r):
        rcos_theta = r * np.cos(el)
        x = rcos_theta * np.cos(az)
        y = rcos_theta * np.sin(az)
        z = r * np.sin(el)
        return x, y, z

    ambimage = load_image(
        os.path.join(pathname, subject_name + '_P00_Ambient.pgm'))
    im_list = glob.glob(os.path.join(pathname, subject_name + '_P00A*.pgm'))

    # Only choose images with less shadow.
    im_sub_list = []
    for fname in im_list:
        im_arr = load_image(fname)
        num_shadow = len(np.where(im_arr < 50)[0])
        ratio = num_shadow / im_arr.size
        if ratio < threshold:
            im_sub_list.append(fname)

    im_sub_list.sort()
    imarray = np.stack([load_image(fname) for fname in im_sub_list], axis=-1)
    Ang = np.array([fname_to_ang(fname) for fname in im_sub_list])

    x, y, z = sph2cart(Ang[:, 0] / 180.0 * np.pi, Ang[:, 1] / 180.0 * np.pi, 1)
    lightdirs = np.stack([y, z, x], axis=-1)
    return ambimage, imarray, lightdirs
```

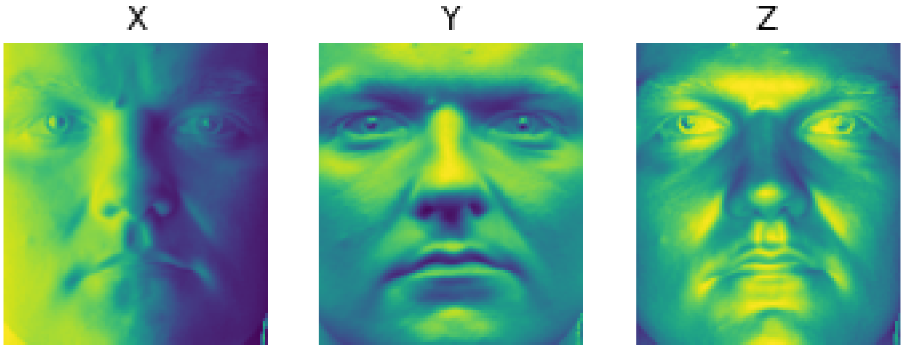
[77]:

```
save_flag = False

threshold = 0.6

full_path = './croppedyale/yaleB07'
ambient_image, imarray, light_dirs = LoadFaceImages_improved(full_path,␣
 ↪subject_name, threshold)

processed_imarray = preprocess(ambient_image, imarray)
albedo_image, surface_normals = photometric_stereo(processed_imarray,␣
 ↪light_dirs)

if save_flag:
    save_outputs(subject_name, albedo_image, surface_normals)
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/85377190.py:13:
FutureWarning: `rcond` parameter will change to the default of machine precision
times ``max(M, N)`` where M and N are the input matrix dimensions.
To use the future default and silence this warning we advise to pass
`rcond=None`, to keep using the old, explicitly pass `rcond=-1`.
  results = np.linalg.lstsq(light_dirs, imarray)
```

[78]:

```
plot_surface_normals(surface_normals)
```

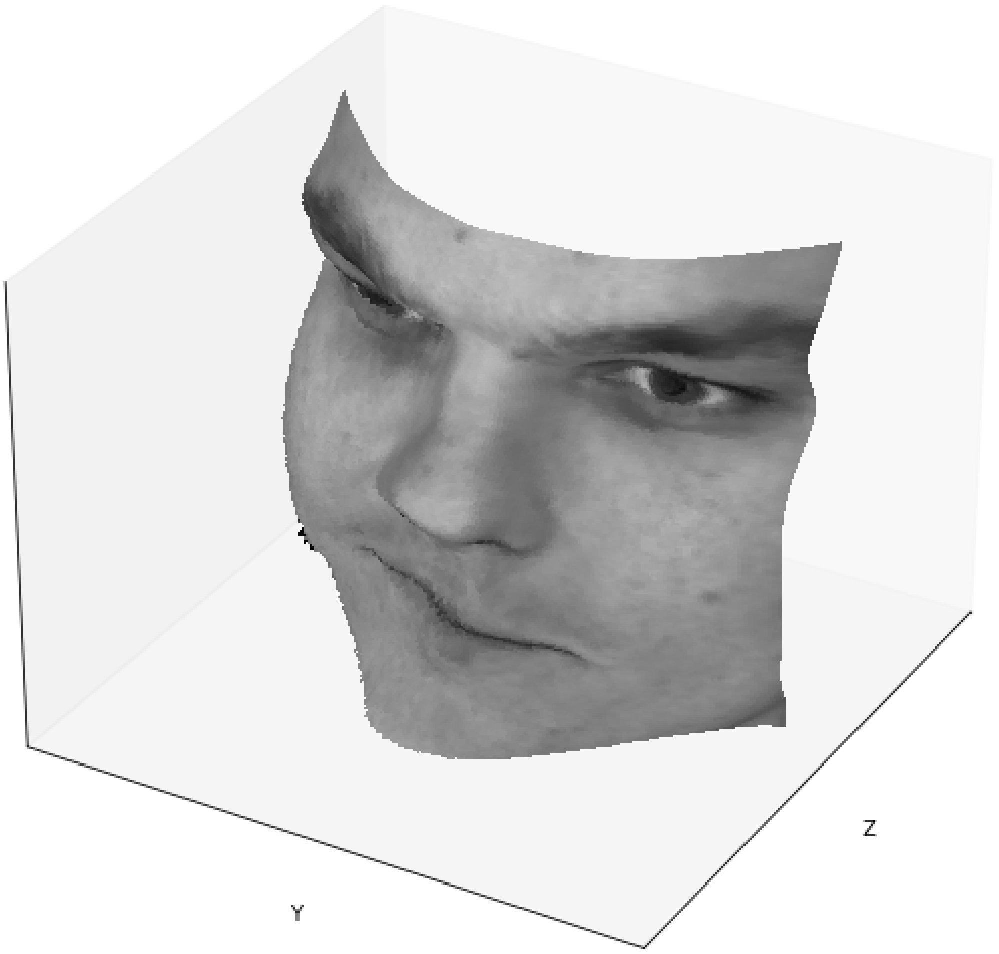


[79]:

```
integration_method = 'random'
height_map = get_surface(surface_normals, integration_method)
print("Viewpoint 1:")
display_output(albedo_image, height_map, 30, 30)
```

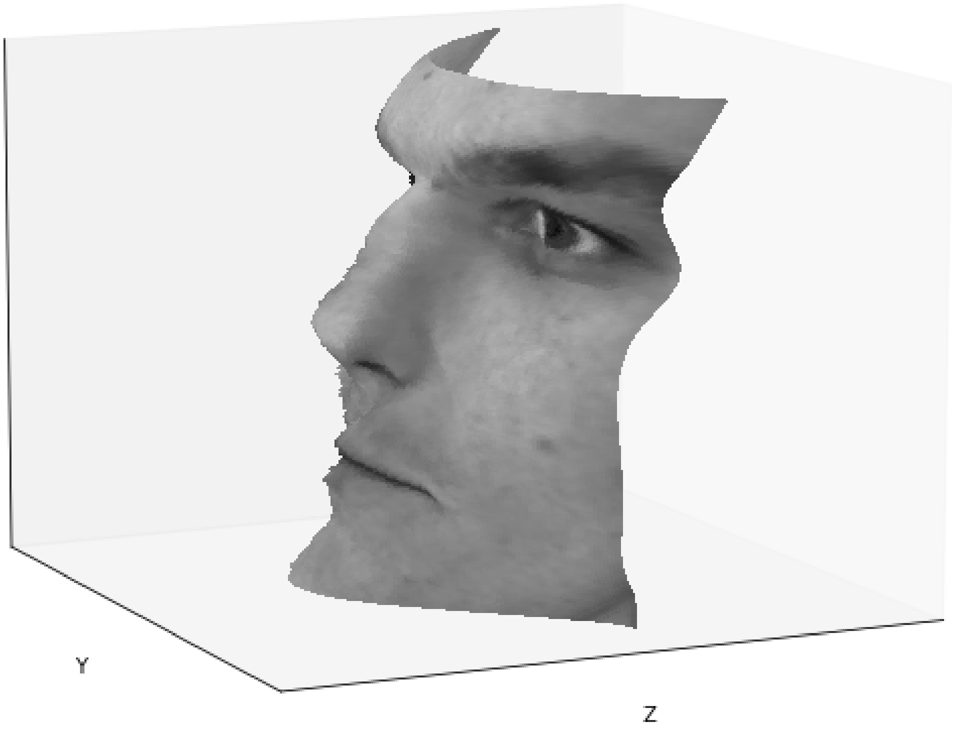
```
Method: random; Excution time: 74.08606386184692 s.
Viewpoint 1:
```

```
/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```



[80]:
```
print("Viewpoint 2:")
display_output(albedo_image, height_map, 10, 65)
```

```
Viewpoint 2:

/var/folders/gj/wh0hvr2s3lqgjbm2qyqh154c0000gn/T/ipykernel_25524/54591787.py:28:
MatplotlibDeprecationWarning: Calling gca() with keyword arguments was
deprecated in Matplotlib 3.4. Starting two minor releases later, gca() will take
no keyword arguments. The gca() function should only be used to get the current
axes, or if no axes exist, create new axes with default keyword arguments. To
create a new axes with non-default arguments, use plt.axes() or plt.subplot().
  ax = fig.gca(projection='3d')
```


Y
Z

```
[ ]:
```