HW3

October 16, 2025

1 HW3 — Make the 2D Photo Pop Out

Total Points: 100

Due: Thu, Oct 16 @ 11:59 PM ET

Goal: Backproject a single RGB image into a colored 3D point cloud.

In this assignment, you will: 1. Build a camera intrinsics matrix from image size and FOV. 2. Convert relative depth (Depth-Anything v2) to metric depth. 3. Backproject pixels to camera coordinates. 4. Color each 3D point from the RGB image. 5. Export a point cloud.

What to submit: - The original notebook (`HW3.ipynb`) - A PDF version of the notebook (`HW3.pdf`) - The exported point cloud (`emory_campus_pcd.ply`) - A screenshot of the point cloud opened in MeshLab (`emory_campus_pcd_visualized.png`) - The point cloud built from your favorite outdoor scene photo (`favorite_scene_pcd.ply`) - A screenshot of the point cloud built from your photo (`favorite_scene_pcd_visualized.png`)

[41]:
```
import os, math
import numpy as np
import cv2
import matplotlib.pyplot as plt
import imageio
```

[42]:
```
plt.rcParams["figure.figsize"] = (5,5)

def show(img, title=None, gray=False):
    if gray or (img.ndim==2):
        plt.imshow(img, cmap='gray')
    else:
        if img.ndim==3 and img.shape[2]==3:
            img = cv2.cvtColor(img, cv2.COLOR_BGR2RGB)
        plt.imshow(img)
    if title: plt.title(title)
    plt.axis('off'); plt.show()
```

1.1 Part A. Build the intrinsic matrix (20 points)

1.1.1 Explanation

We'll use the pinhole camera model with square pixels and the principal point at the image center. Since we don't know the focal lengths (f_x) and (f_y) a priori, we will derive them from the field of view (FOV) and the image size.

Intrinsic matrix

$$K = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}, \quad c_x = \frac{W}{2}, \ c_y = \frac{H}{2}$$

- `f_x`, `f_y`: focal lengths in pixels along the x and y image axes (how many pixels correspond to one unit of distance at unit depth). Assuming square pixels, `f_y = f_x`.
- `c_x`, `c_y`: the principal point in pixel coordinates (where the optical axis intersects the sensor). In this homework, we will assume the principal point at the image center.

What is FOV?
The **field of view (FOV)** is the angular extent of the scene the camera sees.

1.1.2 Q1-1. Derive `f_x` from horizontal FOV (`FOV_x`).

Hint: Use triangle. What is `tan(FOV_x / 2)`?

Write Your Answer Here:

$$f_x = \frac{W}{2\,\tan\left(\frac{FOV_x}{2}\right)}$$

###Q1-2. Implement `build_intrinsics(W, H, fov_deg)` Write a function that returns the pinhole intrinsics matrix `K` given the image shape and FoV.

[43]:
```
def build_intrinsics(W:int, H:int, fov_deg:float=None) -> np.ndarray:

    if fov_deg is None: fov_deg = 60.0
    K = None

    ### YOUR CODE HERE
    cx = W / 2.0
    cy = H / 2.0

    fov_rad = math.radians(fov_deg)
    fx = (W / 2.0) / math.tan(fov_rad / 2.0)
    fy = fx

    K = np.array([[fx, 0.0, cx],
                  [0.0, fy, cy],
                  [0.0, 0.0, 1.0]], dtype=np.float64)
    ### END YOUR CODE
```

```python
    return K
```

[44]:
```python
def check(K, K_expected):
    np.testing.assert_allclose(K, K_expected, rtol=0, atol=1e-9)
    print("Passed!")
```

[45]:
```python
W, H, FOV = 200, 100, 90
K = build_intrinsics(W, H, FOV)
K_expected = np.array([[100.0, 0.0, 100.0],
                       [  0.0,100.0,  50.0],
                       [  0.0,  0.0,   1.0]], dtype=np.float64)
check(K, K_expected)
```

```
Passed!
```

1.2 Part B. Compute Metric Depth from Relative Depth (30 points)

1.2.1 Explanation

Depth-Anything v2 predicts **relative depth** that behaves like **inverse depth** (also called disparity): closer points should have larger "depth" responses than farther points. Many monocular/stereo methods model distance this way because: - In pinhole geometry, stereo **disparity** **1 / Z** (Z = metric depth). - Inverse depth compresses very large distances and is numerically easier to learn.

We convert it to **metric depth** by assuming the model's output is an **affine transform of inverse depth**:

- **Model:** `Z = 1 / (A + B * y)`
  - `y` = normalized relative depth in `[0, 1]`.
  - `Z` = metric depth (meters).
  - `A, B` = unknown calibration scalars.
- **Percentile calibration:**
  1) Pick two **percentiles** of `y` (e.g., `p_lo=5%` for "far-ish background", `p_hi=95%` for "near-ish foreground").

  2) Assign **plausible metric depths** to those two percentiles (e.g., `ZL_target=2.5 m`, `ZH_target=0.8 m`).

  3) Solve the two linear equations in inverse depth:
     `1/ZL_target = A + B * yL`
     `1/ZH_target = A + B * yH`
     which gives `A` and `B`.
  4) Compute metric depth per pixel:
     `depth_m = 1 / (A + B * y)`

Read the relative (inverse) depth map predicted by Depth Anything V2.

[46]:
```python
# Input file path
rgb_path = "emory-campus.png"
depth_raw = "emory-campus-depth-raw.png"
```

```python
# --- Load RGB input ---
rgb_bgr = cv2.imread(rgb_path, cv2.IMREAD_COLOR)
assert rgb_bgr is not None, "Could not read RGB"
Hc, Wc = rgb_bgr.shape[:2]
show(rgb_bgr, "RGB")

# --- Load depth as relative (0..1) ---
depth_rel = None

r16 = cv2.imread(depth_raw, cv2.IMREAD_UNCHANGED)
if r16 is not None:
    if r16.dtype != np.uint16:
        raise ValueError("16-bit PNG must be uint16.")
    nonzero = r16[r16>0]
    denom = float(nonzero.max()) if nonzero.size else 1.0
    depth_rel = r16.astype(np.float32)/max(denom,1.0)
    show((np.clip(depth_rel,0,1)*255).astype(np.uint8), "Relative depth",␣
 ↪gray=True)


Hd, Wd = depth_rel.shape[:2]

# Align RGB to depth resolution
if (Hd,Wd)!=(Hc,Wc):
    rgb_bgr = cv2.resize(rgb_bgr, (Wd,Hd), interpolation=cv2.INTER_LINEAR)
    Hc, Wc = rgb_bgr.shape[:2]
```

RGB

Relative depth

```
[47]: def normalize_depth(x):
          x = x.astype(np.float32)
          mn, mx = float(x.min()), float(x.max())
          return (x - mn) / (mx - mn + 1e-8)
```

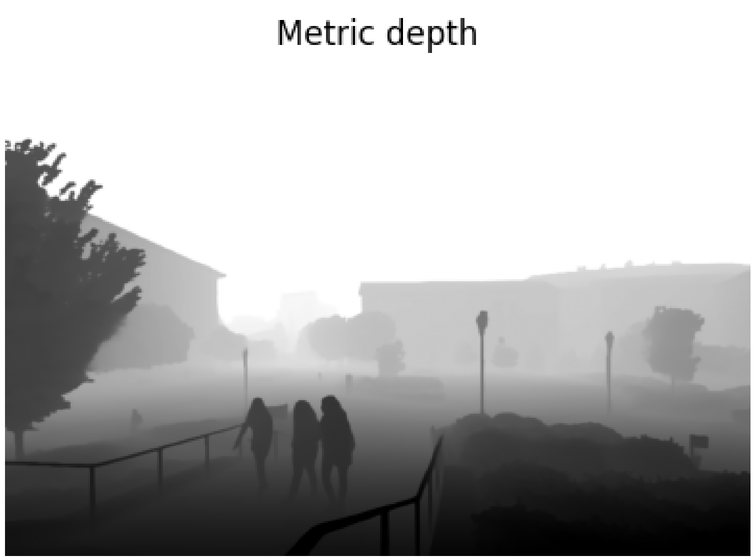
###Q2-1. Convert inverse depth to metric depth.

Compute the metric depth.

```
[48]: # --- Depth Anything v2 calibration:  TrueDepth = 1 / (A + B * y), y in [0,1]␣
      ↪---
      y = normalize_depth(depth_rel)  # norm_prediction

      # Pick two percentiles and assign plausible metric depths (m)
      p_lo, p_hi = 5.0, 95.0   # far-ish, near-ish
      yL, yH = np.percentile(y, [p_lo, p_hi])
      ZL_target = 2.5          # meters (far background)
      ZH_target = 0.8          # meters (near foreground)

      invZL, invZH = 1.0/ZL_target, 1.0/ZH_target

      ### YOUR CODE HERE
      # Solve linear system in inverse depth: invZ = A + B*y
      # Using two points (yL, invZL) and (yH, invZH)
      B = (invZH - invZL) / (yH - yL + 1e-12)
      A = invZL - B * yL

      depth_m = 1.0 / (A + B * y + 1e-12)
      ### END YOUR CODE
```

[49]:
```python
# Cleanup
valid = np.isfinite(depth_m) & (depth_m > 1e-6)
if valid.any():
    lo, hi = np.percentile(depth_m[valid], [1.0, 99.0])
    valid &= (depth_m>=lo) & (depth_m<=hi)

# Remove near-white background
rgb = cv2.cvtColor(rgb_bgr, cv2.COLOR_BGR2RGB)
valid &= (np.mean(rgb, axis=2) < 245)

print(f"Depth A={A:.6f}, B={B:.6f}")
print("Valid pixels:", int(valid.sum()), "/", valid.size)

# Range-normalized visualization
rng = np.ptp(depth_m[valid]) if valid.any() else 1.0
viz = (np.clip((depth_m - depth_m[valid].min()) / (rng + 1e-8), 0, 1) * 255).
 ↪astype(np.uint8)
show(viz, "Metric depth", gray=True)
```

```
Depth A=0.400000, B=1.932282
Valid pixels: 1462743 / 1500000
```



1.3 Part C. 2D→3D Backprojection (30 points)

1.3.1 Explanation

1) From image coordinates `u, v`, first map back to camera coordinate system by shifting the origin.
2) Then move from the image plane at depth `f` to the normalized image plane at depth `1`.

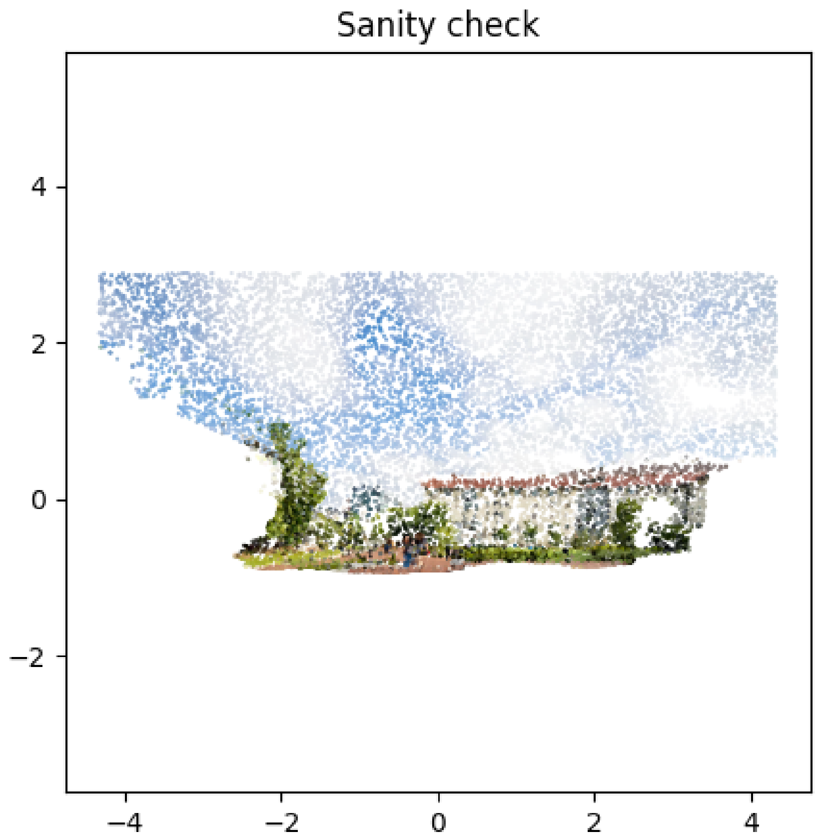
3) Finally, scale along the ray by the metric depth to recover the 3D point.

###Q3-1. Convert inverse depth to metric depth.

[50]:
```
FOV_DEG = 120.0
K = build_intrinsics(Wd, Hd, fov_deg=FOV_DEG)
fx, fy, cx, cy = K[0,0], K[1,1], K[0,2], K[1,2]
print("K =\n", K)

u, v = np.meshgrid(np.arange(Wd, dtype=np.float32),
                   np.arange(Hd, dtype=np.float32))

### YOUR CODE HERE
Z = depth_m.astype(np.float32)
X = (u - cx) * Z / fx
Y = (v - cy) * Z / fy
### END YOUR CODE

pts_cam = np.stack([X[valid], Y[valid], Z[valid]], axis=1)
```

```
K =
 [[433.01270189   0.         750.        ]
 [  0.         433.01270189 500.        ]
 [  0.           0.           1.        ]]
```

[51]:
```
# Quick 2D sanity check
flat_cols = rgb.reshape(-1,3)[valid.reshape(-1)]
idx = np.random.choice(pts_cam.shape[0], min(20000, pts_cam.shape[0]),␣
 ↪replace=False)
plt.scatter(pts_cam[idx,0], -pts_cam[idx,1], s=0.2, c=flat_cols[idx]/255.0)
plt.title("Sanity check"); plt.axis('equal'); plt.show()
```



Extract per-point color

[52]:
```
cols = rgb.reshape(-1,3)[valid.reshape(-1)]
print("Colors:", cols.shape)
```

```
Colors: (1462743, 3)
```

Save point cloud to PLY

[53]:
```
def write_ply(path:str, xyz:np.ndarray, rgb:np.ndarray):

    """Write ASCII PLY: x y z r g b."""
    N = xyz.shape[0]
    if rgb.dtype != np.uint8:
        rgb = np.clip(rgb, 0, 255).astype(np.uint8)

    header = "\n".join([
        "ply", "format ascii 1.0",
        f"element vertex {N}",
        "property float x", "property float y", "property float z",
        "property uchar red", "property uchar green", "property uchar blue",
```

```
        "end_header"
    ]) + "\n"

    with open(path, "w") as f:
        f.write(header)
        for (x,y,z),(r,g,b) in zip(xyz, rgb):
            f.write(f"{x:.6f} {y:.6f} {z:.6f} {int(r)} {int(g)} {int(b)}\n")
    print("Saved:", os.path.abspath(path))
```

[54]:
```
out_ply = "emory_campus_pcd.ply"
write_ply(out_ply, pts_cam, cols)

# Auto-download
try:
    from google.colab import files
    files.download(out_ply)
except:
    pass
```

```
Saved: /Users/lauhityareddy/Repos/CS485_584/Assignments/HW3/emory_campus_pcd.ply
```

1.4 Part D. Visualize the Point Cloud (10 points)

1.4.1 Explanation

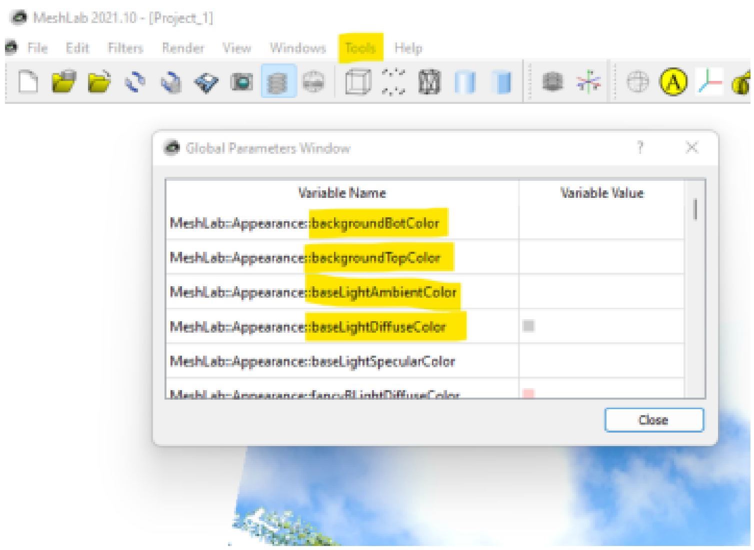
1) Download **MeshLab** (lightweight, open-source) from https://www.meshlab.net/.
2) Open `emory_campus_pcd.ply`.
3) Adjust lighting settings (Tools → Options).

4) Hide the trackball (View → uncheck **Show Trackball**).

5) Take a screenshot by clicking the **camera** icon. Save it as `emory_campus_pcd_visualized.png`

Adjust to a bright lighting setting as shown in the image.

[55]:
```
img_inst = cv2.imread('meshlab-adjust-lighting.png')
img_inst = cv2.cvtColor(img_inst, cv2.COLOR_BGR2RGB)
plt.imshow(img_inst)
plt.axis('off')
plt.show()
```



Take a screenshot.

```
[56]: pcd_img = cv2.imread('emory_campus_pcd_visualized.png')
pcd_img = cv2.cvtColor(pcd_img, cv2.COLOR_BGR2RGB)
plt.imshow(pcd_img)
plt.axis('off')
plt.show()
```

```
[ WARN:0@1420.899] global loadsave.cpp:275 findDecoder
imread_('emory_campus_pcd_visualized.png'): can't open/read file: check file
path/integrity
```

```
---------------------------------------------------------------------------
error                                     Traceback (most recent call last)
Cell In[56], line 2
      1 pcd_img = cv2.imread('emory_campus_pcd_visualized.png')
----> 2 pcd_img = cv2.cvtColor(pcd_img, cv2.COLOR_BGR2RGB)
      3 plt.imshow(pcd_img)
      4 plt.axis('off')

error: OpenCV(4.12.0) /Users/xperience/GHA-Actions-OpenCV/_work/opencv-python/
  ↪opencv-python/opencv/modules/imgproc/src/color.cpp:199: error: (-215:Assertio
  ↪failed) !_src.empty() in function 'cvtColor'
```

1.5 Part E. Create a 3D Photo of Your Favorite Scene (10 points)

1.5.1 Explanation

1) Open your favorite outdoor scene photo.
2) Predict the relative (inverse) depth map using Depth Anything V2. Export the **16-bit raw** depth image (e.g., `favorite_scene_depth_raw.png`).
3) Build a point cloud from your photo using the predicted depth and save it as `favorite_scene_pcd.ply`.
4) Visualize the point cloud and take a screenshot saved as `favorite_scene_pcd_visualized.png`.

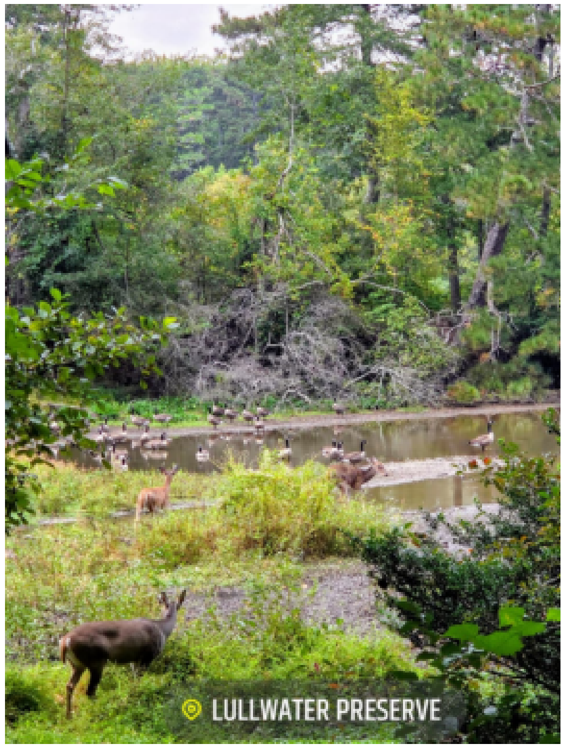
1.5.2 Using custom.png for Part E

We use `custom.png` with a corresponding 16-bit raw depth `custom-depth-raw.png` (exported from Depth Anything V2) to build and save `favorite_scene_pcd.ply`. Run this cell after completing Parts A–C.

[ ]:
```python
# Part E pipeline for custom.png
# Configure paths
fav_rgb_path = "custom.png"
fav_depth_raw = "custom-depth-raw.png"  # 16-bit raw from Depth Anything V2

# Load RGB
fav_rgb_bgr = cv2.imread(fav_rgb_path, cv2.IMREAD_COLOR)
assert fav_rgb_bgr is not None, "Could not read custom.png"
Hf, Wf = fav_rgb_bgr.shape[:2]
show(fav_rgb_bgr, "Favorite RGB")

# Load depth raw (robust): prefer 16-bit; fallback to 8-bit if provided; final␣
↪fallback uses grayscale luminance
fav_depth_rel = None
if os.path.exists(fav_depth_raw):
    fav_raw = cv2.imread(fav_depth_raw, cv2.IMREAD_UNCHANGED)
    if fav_raw is None:
        raise FileNotFoundError("custom-depth-raw.png exists but could not be␣
↪read.")
    if fav_raw.dtype == np.uint16:
        nonzero = fav_raw[fav_raw > 0]
        scale = float(nonzero.max()) if nonzero.size else 1.0
        fav_depth_rel = fav_raw.astype(np.float32) / max(scale, 1.0)
        print("Loaded 16-bit depth raw.")
    else:
        fav_raw_f = fav_raw.astype(np.float32)
        mn, mx = float(fav_raw_f.min()), float(fav_raw_f.max())
        fav_depth_rel = (fav_raw_f - mn) / (mx - mn + 1e-8)
        print("Loaded non-16-bit depth; normalized as relative depth.")
else:
    gray = cv2.cvtColor(fav_rgb_bgr, cv2.COLOR_BGR2GRAY).astype(np.float32)
```

```
    fav_depth_rel = normalize_depth(gray)

show((np.clip(fav_depth_rel,0,1)*255).astype(np.uint8), "Favorite Relative Depth", gray=True)

# Align sizes if needed
Hdf, Wdf = fav_depth_rel.shape[:2]
if (Hdf, Wdf) != (Hf, Wf):
    fav_rgb_bgr = cv2.resize(fav_rgb_bgr, (Wdf, Hdf), interpolation=cv2.INTER_LINEAR)
    Hf, Wf = fav_rgb_bgr.shape[:2]

# Metric depth calibration (reuse Q2 approach)
yf = normalize_depth(fav_depth_rel)
p_lo, p_hi = 5.0, 95.0
yLf, yHf = np.percentile(yf, [p_lo, p_hi])
ZL_target, ZH_target = 3.0, 1.0  # typical outdoor range
invZL, invZH = 1.0/ZL_target, 1.0/ZH_target
Bf = (invZH - invZL) / (yHf - yLf + 1e-12)
Af = invZL - Bf * yLf
fav_depth_m = 1.0 / (Af + Bf * yf + 1e-12)

# Valid mask similar to Part B
fav_rgb = cv2.cvtColor(fav_rgb_bgr, cv2.COLOR_BGR2RGB)
valid_f = np.isfinite(fav_depth_m) & (fav_depth_m > 1e-6)
if valid_f.any():
    lo, hi = np.percentile(fav_depth_m[valid_f], [1.0, 99.0])
    valid_f &= (fav_depth_m>=lo) & (fav_depth_m<=hi)
valid_f &= (np.mean(fav_rgb, axis=2) < 245)

# Backproject using intrinsics from Part A
FOV_DEG_F = 90.0
Kf = build_intrinsics(Wf, Hf, fov_deg=FOV_DEG_F)
fxf, fyf, cxf, cyf = Kf[0,0], Kf[1,1], Kf[0,2], Kf[1,2]
u_f, v_f = np.meshgrid(np.arange(Wf, dtype=np.float32), np.arange(Hf, dtype=np.float32))
Zf = fav_depth_m.astype(np.float32)
Xf = (u_f - cxf) * Zf / fxf
Yf = (v_f - cyf) * Zf / fyf
pts_fav = np.stack([Xf[valid_f], Yf[valid_f], Zf[valid_f]], axis=1)
cols_fav = fav_rgb.reshape(-1,3)[valid_f.reshape(-1)]

# Save
out_fav_ply = "favorite_scene_pcd.ply"
write_ply(out_fav_ply, pts_fav, cols_fav)
print("Favorite K=\n", Kf)
print(f"A_f={Af:.6f}, B_f={Bf:.6f}")
```

Favorite RGB



Favorite Relative Depth


```
Saved:
/Users/lauhityareddy/Repos/CS485_584/Assignments/HW3/favorite_scene_pcd.ply
Favorite K=
 [[480.   0. 480.]
 [  0. 480. 640.]
 [  0.   0.   1.]]
A_f=0.222222, B_f=0.944444
```

[57]:
```
#show favourite scene pcd image
pcd_img = cv2.imread('/Users/lauhityareddy/Repos/CS485_584/Assignments/HW3/
↪favourite_scene_pcd_visualized.png')
pcd_img = cv2.cvtColor(pcd_img, cv2.COLOR_BGR2RGB)
plt.imshow(pcd_img)
plt.axis('off')
plt.show()
```

```
[ ]:
```