3D Mesh Normalization, Quantization & Reconstruction

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GitHub Link: https://github.com/barnamdas/Mixar-Assignment

(Above link consist of all the python scripts , output meshes, visualizations and a short README, and the report is also attached in the link as well)

TASK 1: LOAD AND INSPECT THE MESH

CONCEPT OF MESH: A 3D mesh is a geometric representation of an object, consisting of vertices and faces.

Vertices are points in 3D space represented by coordinates (x, y, z).

Faces are the connections between these vertices that form the surface of the object, usually triangles or quadrilaterals.

By storing vertex positions and how they are connected, a mesh defines the overall shape of the model.

Understanding the range and distribution of vertex coordinates helps in processing, normalization, and reconstruction tasks later.

STATISTIC TABLE:

Mesh Name	Vertices Count	Min (x,y,z)	Max (x,y,x)	Mean (x,y,z)	Std (x,y,z)
girl.obj	8284	(-0.5, 0.0, -0.181)	(0.5, 0.904, 0.181)	(0.002, 0.403, 0.014)	(0.179, 0.214, 0.062)
branch.obj	2767	(-0.852, 0.0, -0.465)	(0.850, 1.9, 0.463)	(0.075, 1.087, 0.122)	(0.343, 0.457, 0.2)
cylinder.obj	192	(-1.0, -1.0, -1.0)	(1.0, 1.0, 1.0)	(0.0, 0.0, 0.0)	(0.707, 1.0, 0.707)
explosive.obj	2812	(-0.2, 0.0, -0.197)	(0.2, 1.0, 0.197)	(0.043, 0.529, -0.003)	(0.115, 0.390, 0.095)
fence.obj	1088	(-0.5, 0.0, -0.023)	(0.5, 0.843, 0.023)	(-0.004, 0.41, -0.0)	(0.346, 0.254, 0.011)
person.obj	3103	(-0.844, 0.0, -0.213)	(0.842, 1.9, 0.211)	(0.005, 1.159, -0.004)	(0.395, 0.512, 0.095)
table.obj	3148	(-0.209, 0.0, -0.5)	(0.209, 0.612, 0.5)	(-0.013, 0.386, -0.004)	(0.153, 0.192, 0.346)
talwar.obj	1668	(-0.032, 0.0, -0.117)	(0.032, 1.0, 0.117)	(0.022, 0.303, -0.004)	(0.011, 0.237, 0.047)

From the statistics, we observe that models such as person, branch, and fence have a larger spread along the vertical (y) axis, indicating tall or elongated shapes. The cylinder model shows symmetric distribution across all axes, which is reflected by uniform min and max values. The girl and talwar meshes have tighter bounding ranges and more compact geometry. Understanding these differences is important because normalization will scale these models differently, which can affect shape preservation during reconstruction.

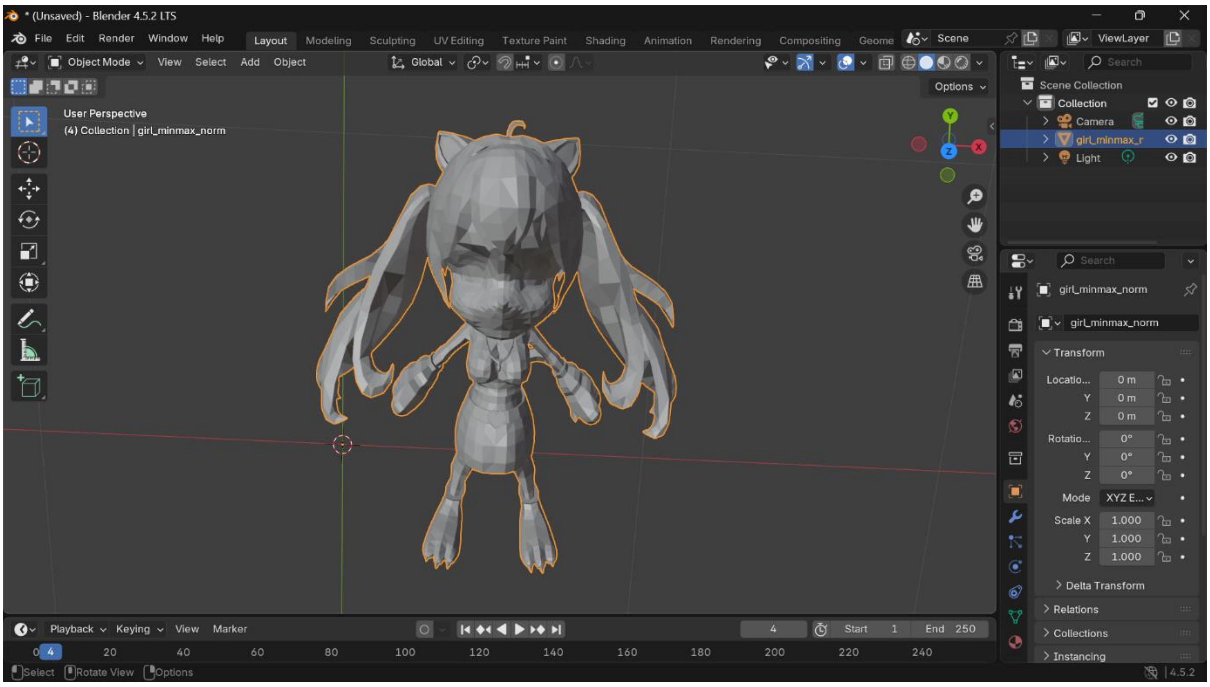
Screenshots before Normalization:

Original Mesh view of girl.obj before normalization

TASK 2: NORMALIZATION AND QUANTIZATION

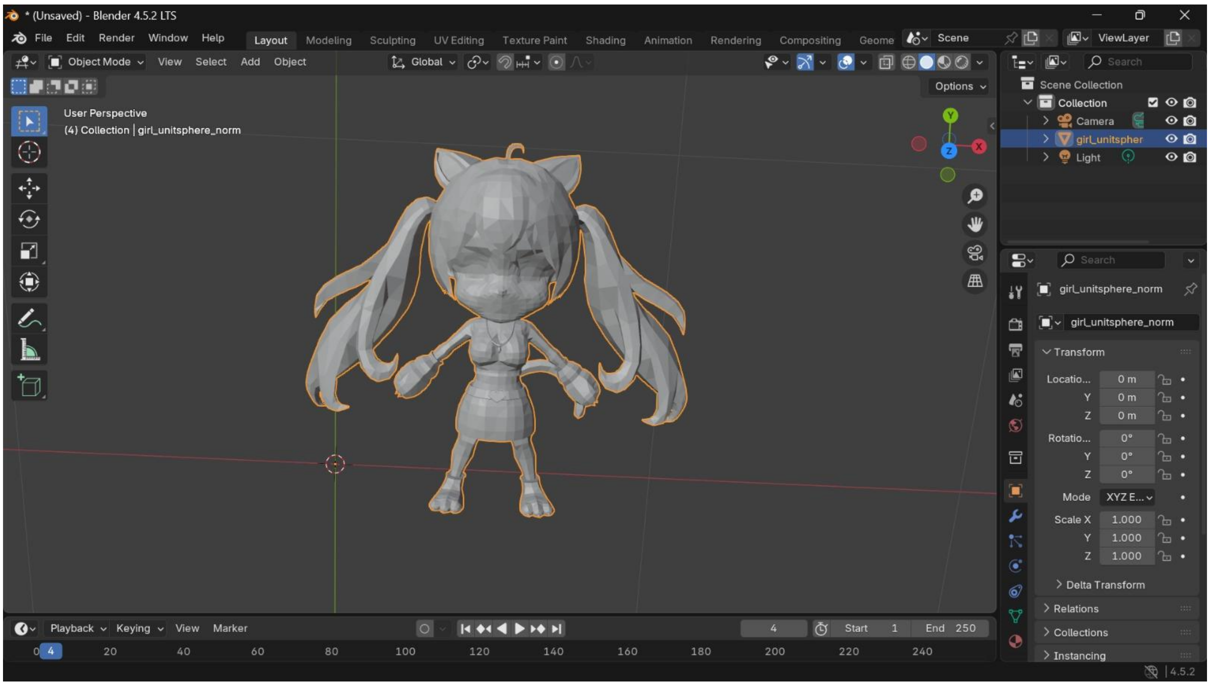
PURPOSE OF NORMALIZATION: Different mesh models in the dataset have different scales, heights, and coordinate ranges. Without normalization, comparing or processing these meshes is inconsistent. Normalization ensures that all meshes share a common coordinate range, making them easier to visualize, compress, and analyze uniformly. This step is essential before quantization and reconstruction.

MIN-MAX NORMALIZATION: Min–Max normalization scales each vertex coordinate to the range [0, 1] independently for the x, y, and z axes. This preserves the relative proportions of the mesh, because each axis is scaled based on its own minimum and maximum values.



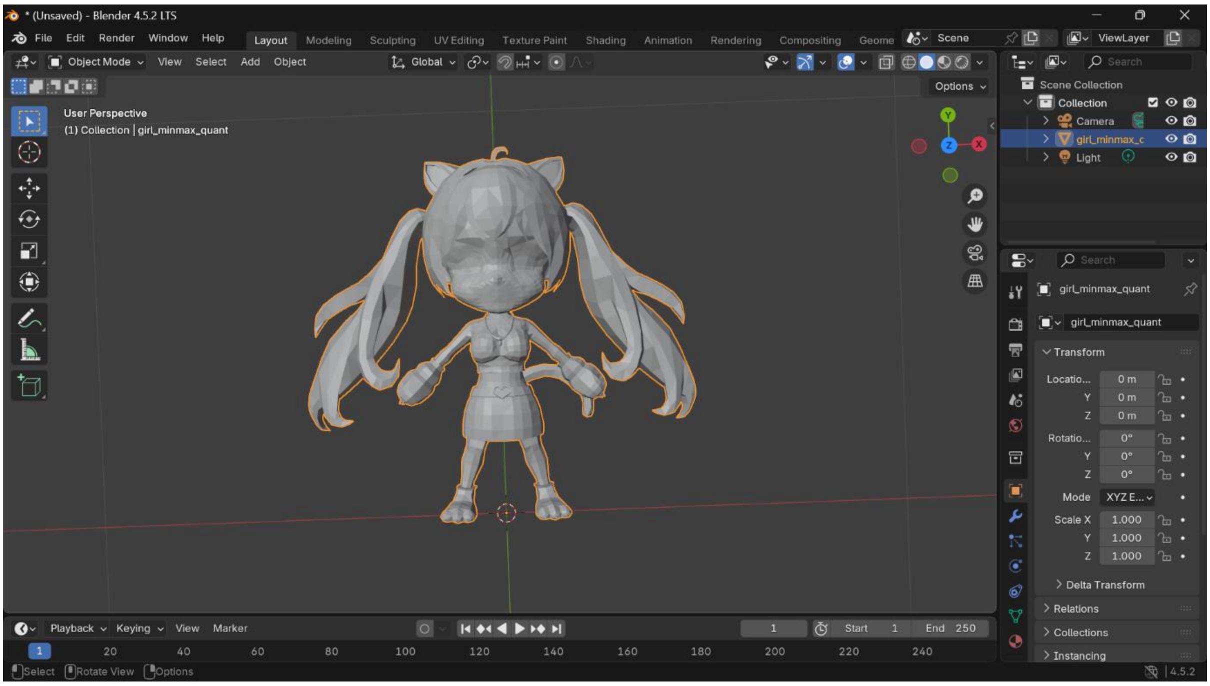
Mesh after Min-Max Normalization

UNIT SPHERE NORMALIZATION: Unit Sphere normalization scales the mesh so that it fits inside a sphere of radius 1 centered at the origin. Unlike Min–Max, this method applies uniform scaling across all axes. However, this can lead to shape distortion for elongated models.

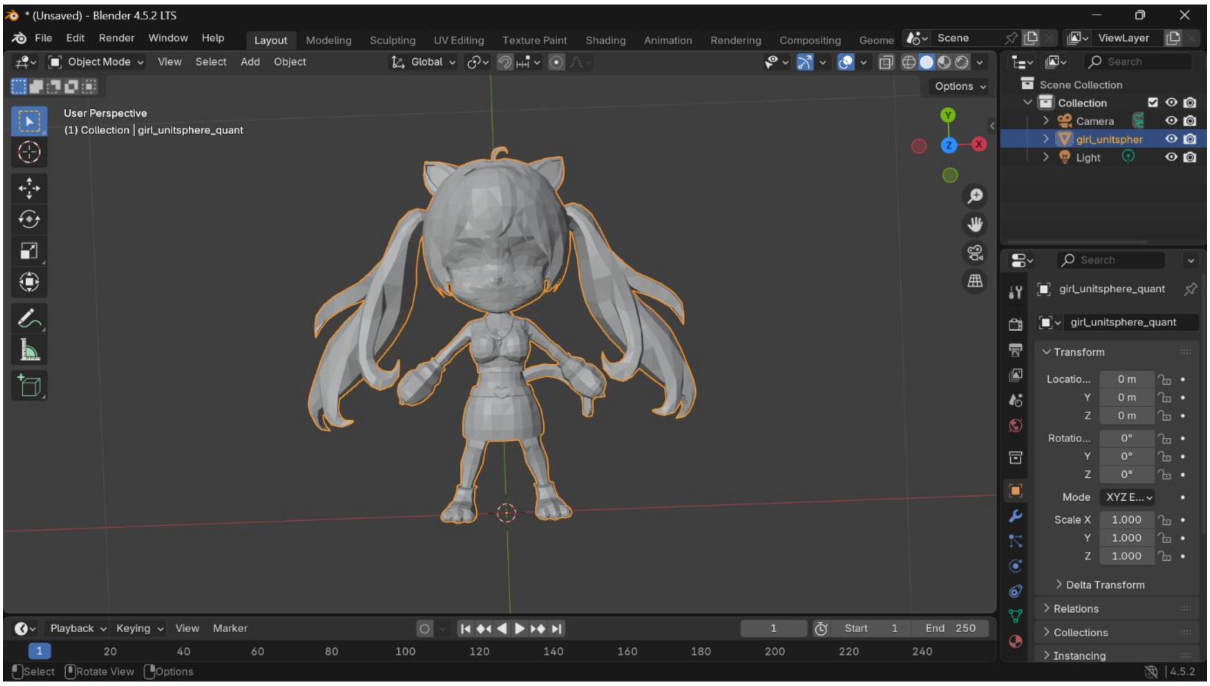


Mesh after Unit Sphere Normalization (uniform scaling applied)

<u>QUANTIZATION:</u> Normalized meshes still contain floating-point values. To reduce storage size and prepare for compression, the coordinates are converted to 1024 discrete levels through uniform quantization.



Reconstructed Mesh after Min-Max Quantization



Reconstructed Mesh after Unit Sphere Quantization

COMPARISON AMONG THEM: From the visual comparison, the Min–Max normalized meshes preserve the original proportions more accurately. The Unit Sphere normalized models show slight distortion on elongated shapes, because all coordinates are scaled uniformly. Quantization to 1024 bins introduces only minimal visible changes, confirming that this level of precision provides a good balance between compression and quality preservation.

TASK 3: RECONSTRUCTION AND ERROR ANALYSIS

PURPOSE OF RECONSTRUCTION: After quantization, the mesh coordinates are stored as integer values, which reduces precision. To evaluate how much information was lost, the quantized coordinates are dequantized and then denormalized back to the original scale. The reconstructed mesh is compared with the original mesh to measure the effect of quantization and normalization. This allows us to analyze the trade-off between compression and geometric accuracy.

DEQUANTIZATION AND DENORMALIZATION:

Step 1: Dequantization – Quantized coordinate q (0-1023) is converted back to normalized range [0,1]

Step 2: Denormalization – Depending on which normalization was originally applied (Min-Max / Unit Sphere)

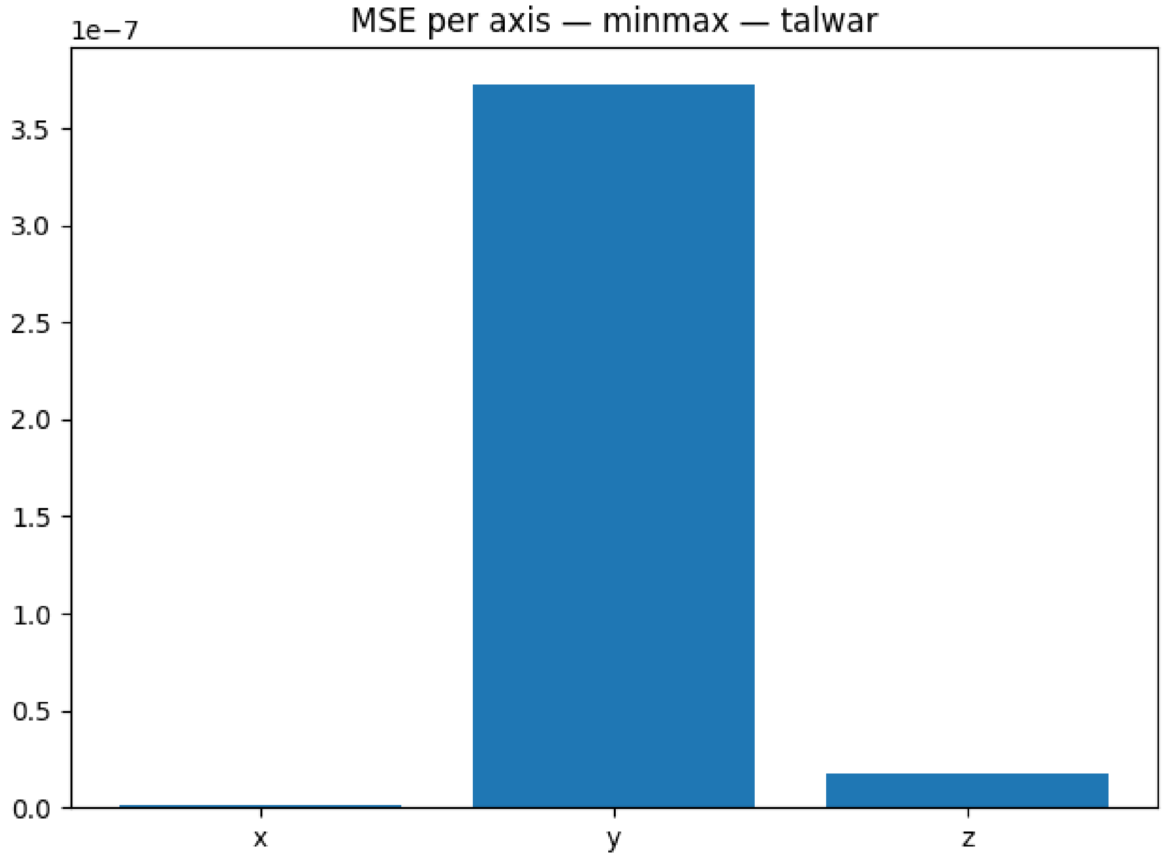
ERROR METRICS USED: To quantify the reconstruction quality, two common error metrics were used:

1) MSE (Mean Squared Error): Measures the squared difference between original and reconstructed coordinates.
2) MAE (Mean Absolute Error): Measures the average absolute difference.

Lower values indicate better reconstruction.

ERROR TABLE:

Model	Min-Max MSE	Unit Sphere MSE	Min-Max MAE	Unit Sphere MAE
Branch.obj	0.00000019	0.00000058	0.00036339	0.00065842
Cylinder.obj	0.00000015	0.00000049	0.00028206	0.00063051
Explosive.obj	0.00000003	0.00000010	0.00014386	0.00027721
Fence.obj	0.00000004	0.00000019	0.00014654	0.00039918
Girl.obj	0.00000006	0.00000010	0.00019055	0.00026885
Person.obj	0.00000017	0.00000044	0.00031062	0.00056744
Table.obj	0.00000005	0.00000012	0.00017350	0.00030960
Talwar.obj	0.00000003	0.00000015	0.00009969	0.00033330


MSE per axis — minmax — talwar
1e−7
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x
y
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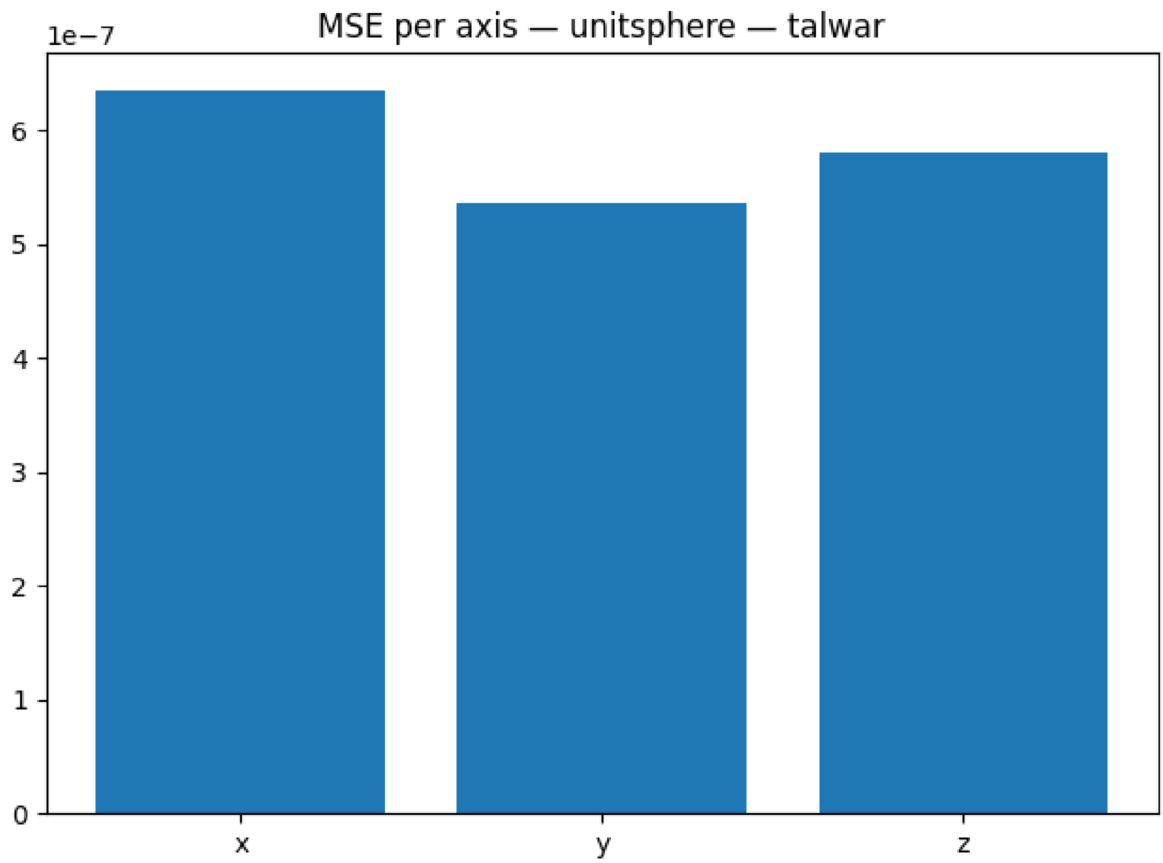
MSE per axis — unitsphere — talwar
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6
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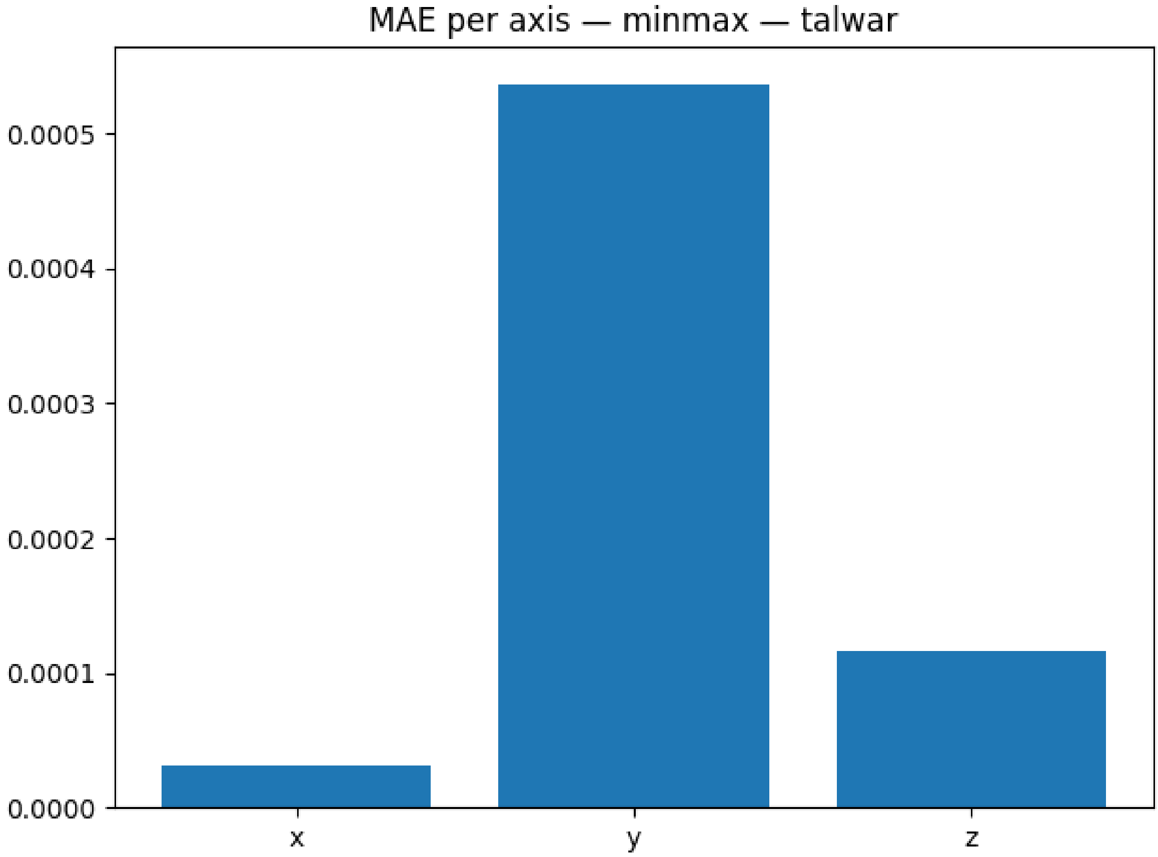
MAE per axis — minmax — talwar
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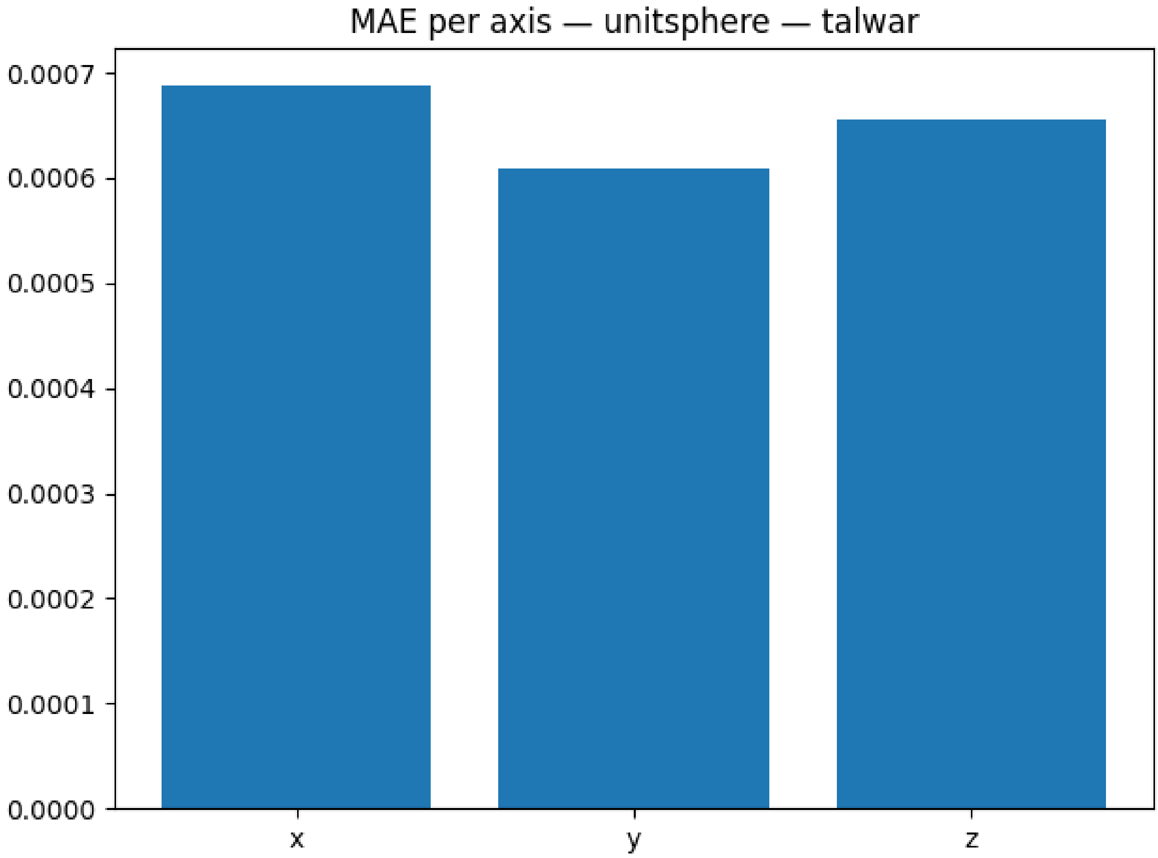
MAE per axis — unitsphere — talwar
0.0007
0.0006
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The plots compare reconstruction errors on each axis (x, y, z) after Min–Max normalization and Unit Sphere normalization.

In both MSE and MAE plots, Min–Max normalization shows lower error values, indicating more accurate preservation of the mesh's original geometry.

Unit Sphere normalization shows higher error, especially in the y-axis for the talwar model, because this model is elongated along one dimension.

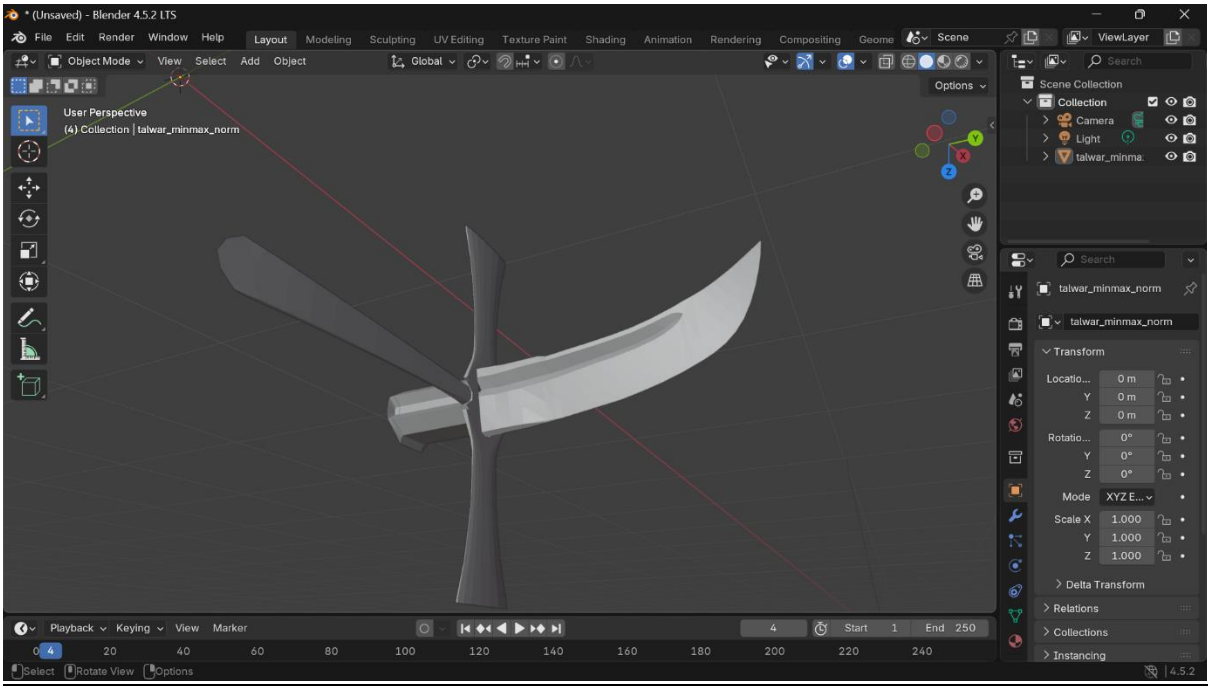
Uniform scaling forces the entire shape to fit inside a sphere, which slightly distorts long shapes.

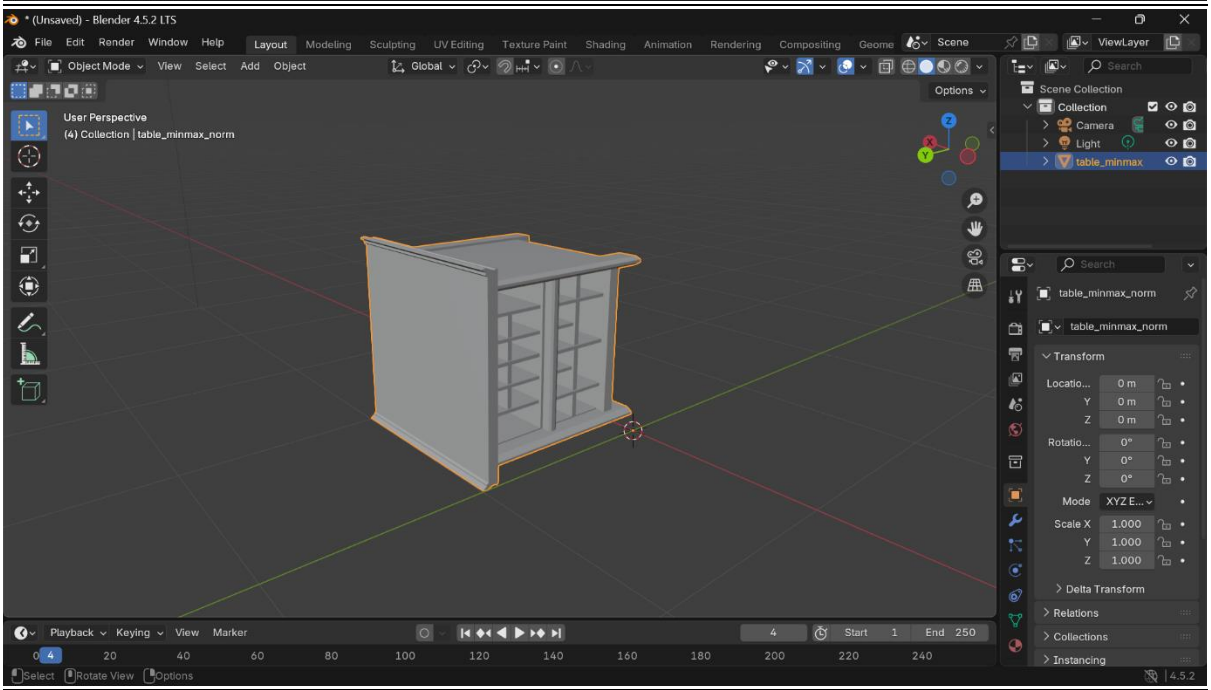
Therefore, Min–Max normalization yields better shape reconstruction, while Unit Sphere normalization introduces small but noticeable axis distortion.

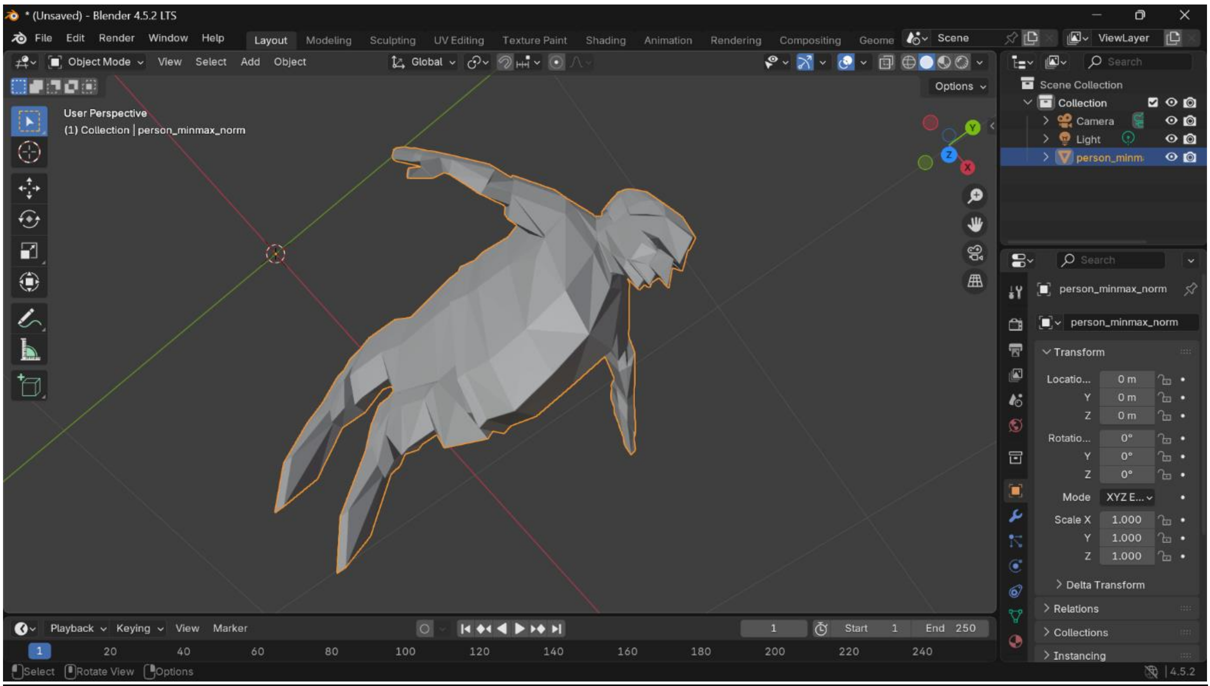
CONCLUSION:

- The assignment demonstrated the full workflow of loading, analyzing, normalizing, quantizing, and reconstructing 3D mesh models.
- Min–Max normalization preserved the mesh geometry more accurately because each axis is scaled independently based on its own min and max values.
- Unit Sphere normalization introduced slightly more distortion since it applies one uniform scaling factor for all axes, which affects elongated or uneven shapes.
- Quantization with 1024 bins resulted in very small reconstruction error, showing that geometric detail is mostly preserved even after reducing precision.
- Across all models, Min–Max normalization consistently showed lower MSE and MAE compared to Unit Sphere normalization.
- The overall reconstructed models remained visually similar to the originals, indicating that the compression approach is efficient and reliable.
- In conclusion, Min–Max normalization is better for accuracy, while Unit Sphere normalization is suitable when uniform scale comparison across models is required.

MISCELLANEOUS - PICTURES OF OTHER MESH OBJECTS IN RANDOM ORDER



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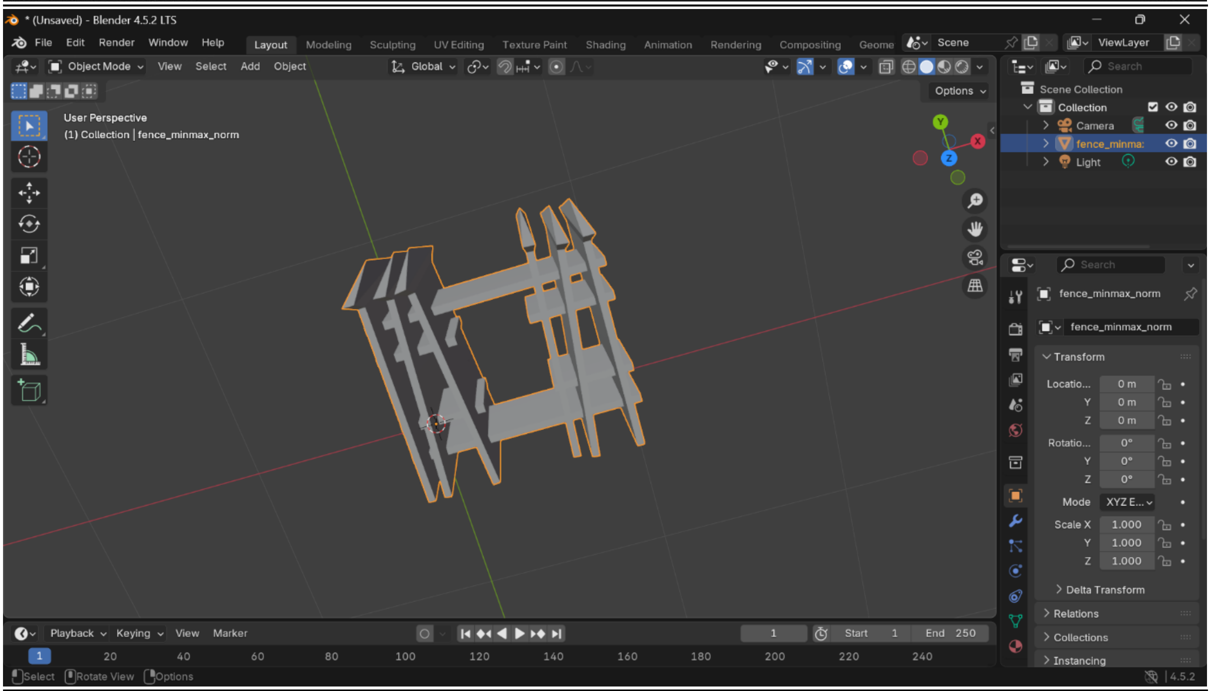
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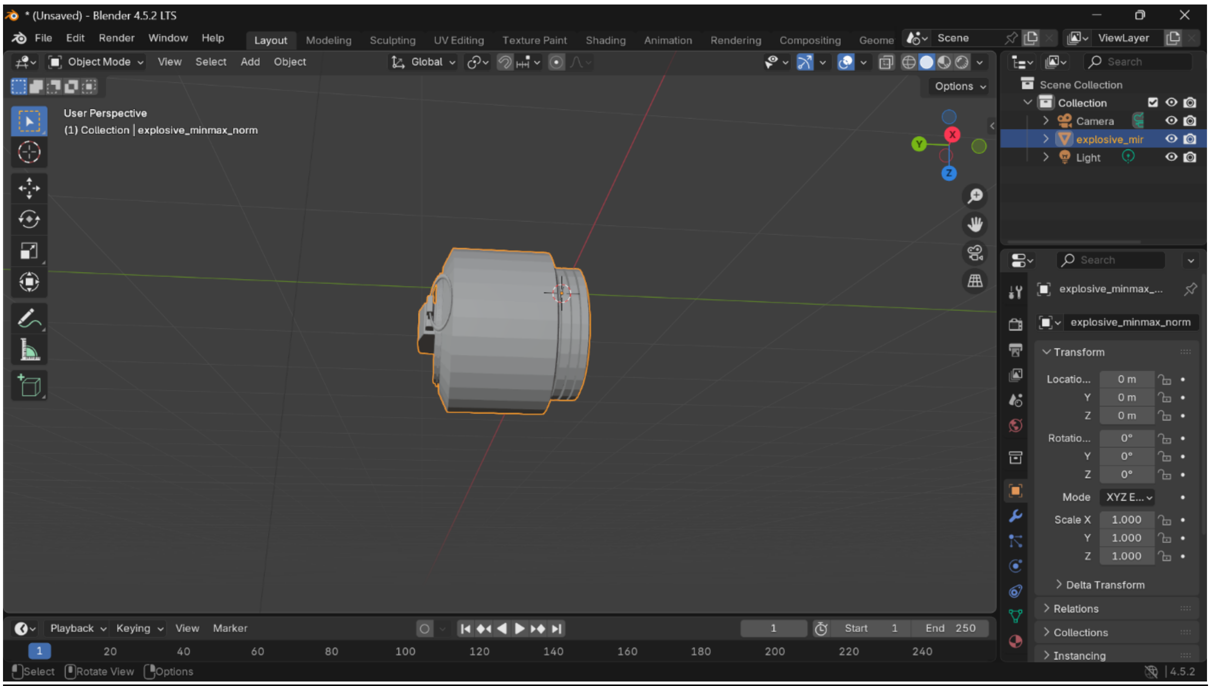
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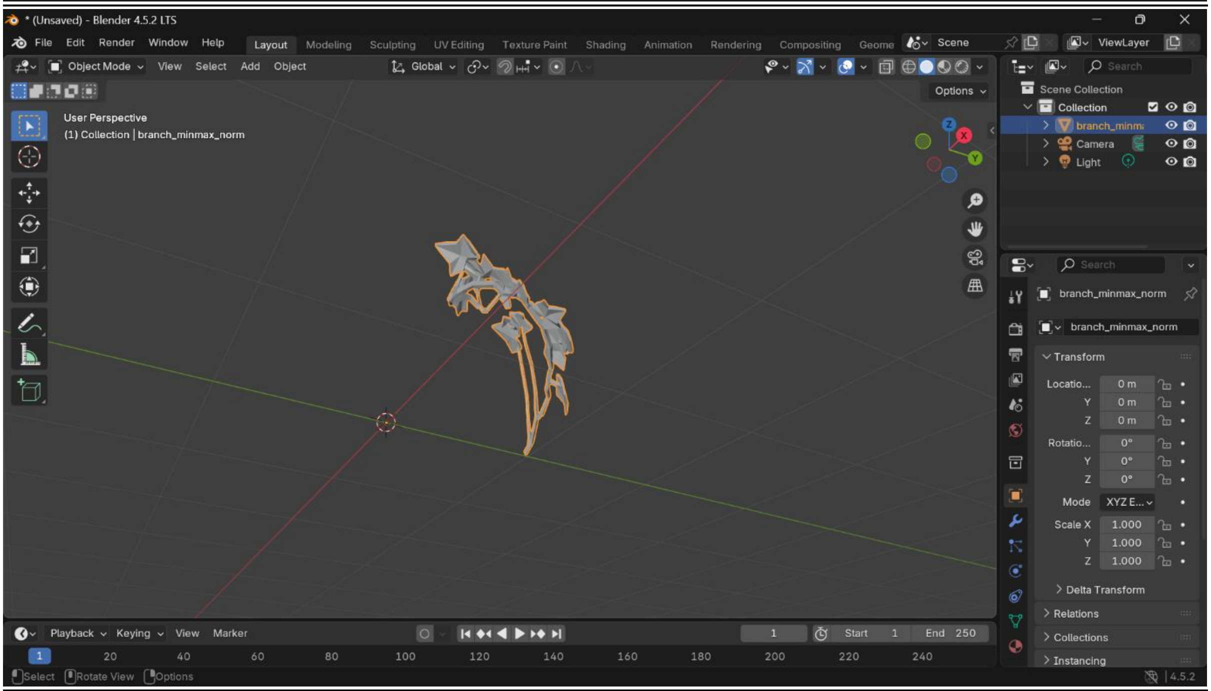
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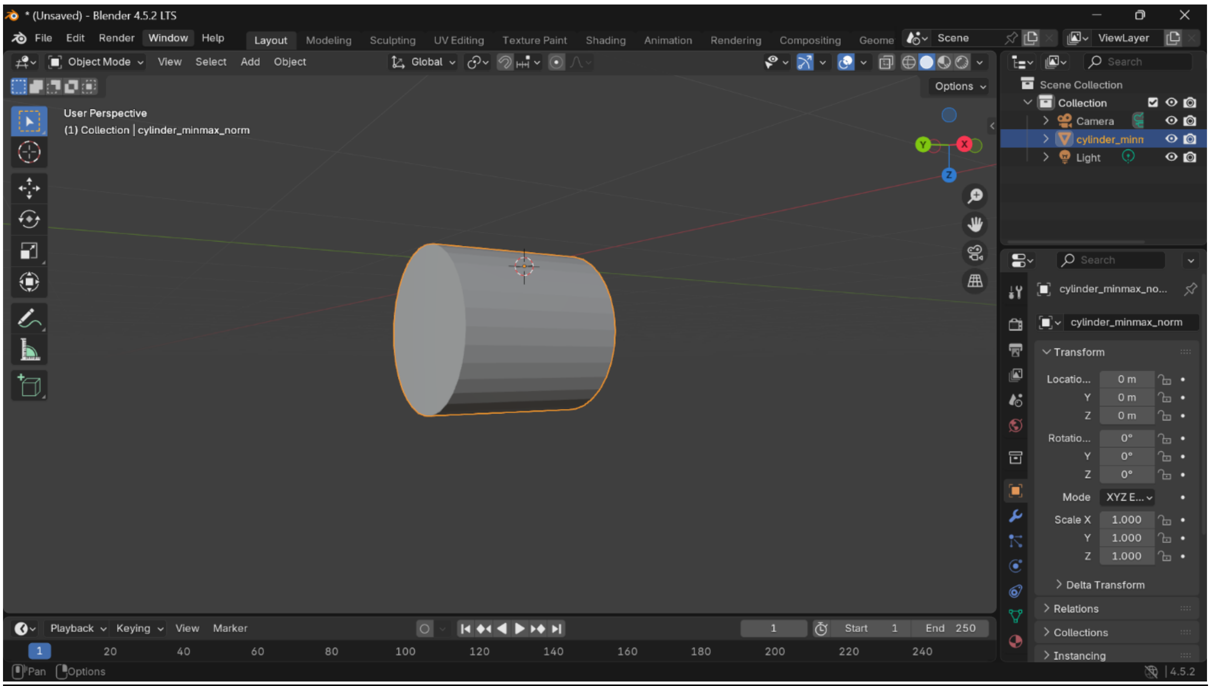
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Options
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REFERENCES:

1) Trimesh Library Documentation
Used for loading, inspecting, and processing 3D mesh data.
https://trimsh.org/

2) NumPy Scientific Computing Library
Used for numerical operations, vector math, and statistical calculations.
https://numpy.org/

3) matplotlib Visualization Library
Used for plotting reconstruction error graphs (MSE and MAE).
https://matplotlib.org/

4) Blender
Used to visualize normalized and reconstructed meshes.
https://www.blender.org/

5) Python 3.10+ Runtime Environment
Used as the primary programming language for implementing all tasks.

6) Assignment Handout & Provided Dataset
Given by the course instructor; used as the basis for performing normalization, quantization, and evaluation.