3D Mesh Retrieval System

Multimedia Retrieval
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Introduction

With the advance in modeling software and 3D scanners, the speed of 3D content creation increased rapidly. Nowadays, much 3D content has been produced, and people are still creating many more objects constantly. These kinds of contents are usually stored in so-called shape databases. But, there is a challenge to browse and find the 3D objects of interest within these numerous amounts of data.

Several techniques have already been presented for finding desired data in these shape databases. For example, searching by keyword, browsing the database along a few predefined categories, or content-based shape retrieval (CBSR). Although the first two options do not need a sample model for searching in a database, they need more effort to label or categorize these contents. On the other hand, there is content-based shape retrieval which can retrieve all the similar samples to the existing query shape.

In this project, we want to categorize the 3D objects of a database based on their shape similarity. This process will be done by normalizing all the objects and extracting some general features from them. Then, we can divide similar objects based on their similarity in their features. Also, there would be a content-based shape retrieval that can find similar 3D objects based on the feature extracted from the given query shape and compared to other objects in the database.

1 Selection and setup the work environment

In this section, four different related packages have been tested and compared. The Comparison of these packages has been done based on several features that might be useful in the future sections of this project. For example, being able to re-mesh objects, scaling them, rotating them, and moving them are the feature that can be useful in the process of normalizing the 3d objects in the database. Also, having some information about the 3d objects, like the number of vertices and faces, is necessary for understanding if these 3d objects are normalized or not. On the other hand, this package must support different formats that are usually used to store 3d objects. In this case, we narrowed down the packages that work with Python language and well-known between the community. So, we tested and analyzed "Pymesh", "PyMeshLab", "TriMesh", and "Open3D". Results can be found in the table 1.

We wanted to be able to open "PLY", "OFF", "OBJ", and "STL" formats. "PLY" and "OFF" formats were discussed in the lecture, while "OBJ" and "STL" are really common. All of them were able to open "PLY", "OFF", "OBJ", and "STL" formats, so that was not really discriminating.

We tried to compare the different re-meshing, repairing and extraction features with our current knowledge and thought that PyMeshLab and Open3D seems to be quite good. The complexity was also one of our requirements as from previous experience less complex library offers less options.

After achieving step 1 with four of those libraries, we try to find a balance between number of dependencies, options proposed for visualizing and analysis. Then we decide to choose "PyMeshLab"[1] Our project has three main dependencies. "PyMeshLab", "Polyscope", and "Numpy", and it runs with Python 3.9.

pymeshlab

Features category	Desired Fetures	PyMesh	PyMeshLab	TriMesh	Open3D
3D format supported	PLY	X	X	X	X
	OFF	X	X	X	X
	OBJ	X	X	X	X
	STL	X	X	X	X
Repairing	Isolated Vertices	X	X	X	To implement
	Duplicated Vertices	X	X	X	To implement
	Duplicated Faces	X	X	X	To implement
Remeshing	Uniform sampling	X	X	X	X
Analysis features		Simple	Rich	Sufficient	Rich
Visualisation features	Scale	0	X	X	X
	Pan	0	X	X	X
	Rotate	0	X	X	X
	Screenshot	0	X	0	X
	Multiple mesh	0	X	0	X
Language	Source code	70% C++ 20% Python 10% C	80% C++ 20%Python	100% Python	80% C++ 10% Python 10% Cuda
Number of dependencies		7	2	3	0
Interface of preview windows		None	Advanced	Minimalistic	
Visualisation interface	Shading methods	None	Flat	Flat	Flat
Installation tools	Pip or Anaconda	Docker	Pip	Pip	Pip

tab:libraries

Table 1: In-built features for different Python libraries

2 Rendering

We have two scripts for this step called "main.py" and "render.py" Where "main.py" verifies the console arguments and calls the render function from "render.py". The first argument passed through is the path of the file.

In "render.py", there is a function called "render". This function loads the mesh and displays the vertices and the mesh of the 3D object. PyMeshLab has a built-in function ".show_polyscope" that shows a mesh. While we found it more interesting to override it with polyscope functions to have more control if we need to upgrade anything. The result of the mesh visualization script can be found in Figure 1. The 3D mesh visualization windows offered many functionalities.

fig:ant-mesh

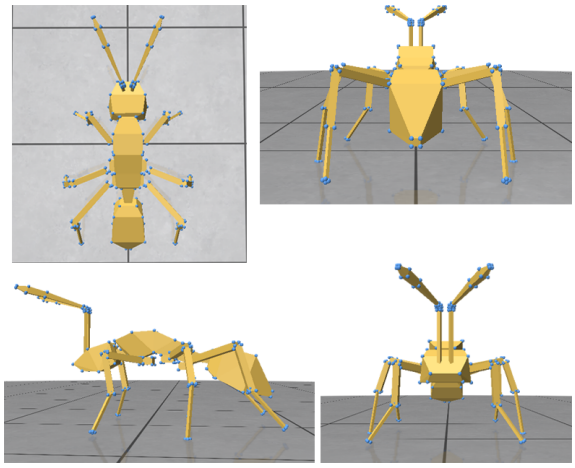


Figure 1: Visualisation of an ant mesh

3 Shape analysis

To avoid too many disparities between the properties of 3D objects in the database, we wanted to normalize some features to extract them with ease in the following step. So, we implemented some functions to extract generic information and normalize them from all 3D objects of the database. These features are the number of vertices, the position, the scale, the alignment, the orientation, the location of the barycenter, and the size of the bounding box.

Also, we had to determine an order for all the different extracting and normalizing steps, as some of them can have an impact on the following one. In general, any transformation T has to be performed before T' if T has a side effect on the properties that T' has to normalize. First of all, we began with the numbers of vertices and how they were sampled to obtain a uniform mesh from the poorly sampled ones. This action help computations, that are dependent on the number of vertices, to be computed correctly. Second, we normalized the positions

of 3D objects as it does not impact other properties. As any rotation impacts the orientation of the bounding box, we applied to scale after any rotation. Therefore in third place, we rotate the 3D object with the axis given by PCA in the next step. Then, we did the flipping in fourth place. Now, that the 3D object is aligned with its most spread axis the oriented bounding box and the bounding box coincide. It then makes sense to scale to fit in the unit cube in fourth place.

We discuss further details for each feature in the following.

3.1 Vertex numbers

:vertex numbers

3.2 Position

fig:barycenter-before

One way of normalizing the position is to translate the barycenter to the origin of the 3D space. As PyMeshLab has a built-in function for translation, we only needed the barycenters of the 3D objects to be calculated. Usually, we had to compute the average position of the center of all faces weighted by the area of that face because the vertices are non-uniformly distributed over the mesh. However, we ensured in section ?? subse that vertices spread uniformly around the mesh. With this assumption, we can just compute the average x,y, and z of all the vertices of each 3D object. Here is the formula to compute the barycenter :

$$b_i = \frac{\sum_{v \in V} v_i}{|V|}$$

fig:barycenter-after

(with i the i-th coordinate of v ($i \in \{x, y, z\}$)and V the set of vertex of the mesh.)

Once the barycenter was computed we translated each vertex by the $\overrightarrow{BO}$ vector (with B the barycenter and O the origin of the 3D reference space). After that, we compared the distance of the barycenter to the origin for each 3D object before and after normalization.

As we can see after normalization (see Fig.3), fig:barycenter-after all the 3D objects have their barycenter really close to the origin. All the distance origin-barycenter are lower than 0.0001.

3.3 Rotation

We used a PyMeshLab built-in function to compute the eigenvector of the 3D mesh and used them for alignment later on. The function computes the eigenvector from the co-variance matrix which can be described with the following formula :

$$C = \begin{pmatrix} \sigma(x,x) & \sigma(x,y) & \sigma(x,z) \\ \sigma(y,x) & \sigma(y,y) & \sigma(y,z) \\ \sigma(z,x) & \sigma(z,y) & \sigma(z,z) \end{pmatrix}$$

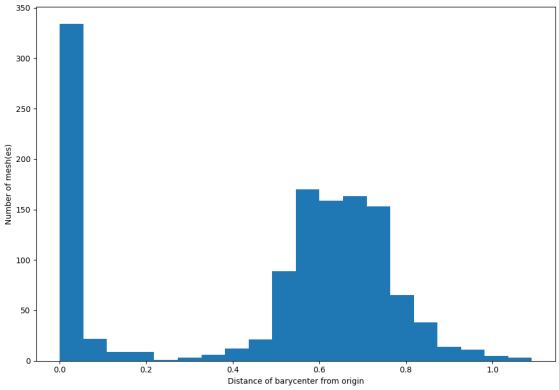


Figure 2: Distances of the barycenters of 3D objects to the origin of 3D space before normalization

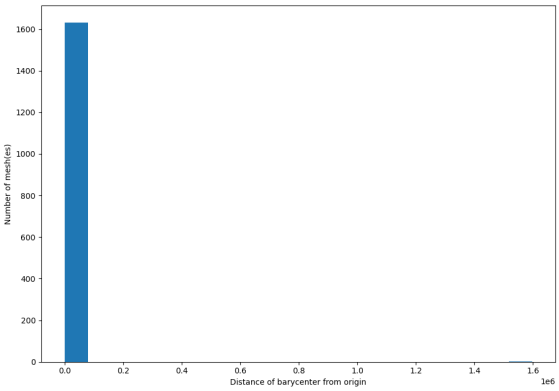


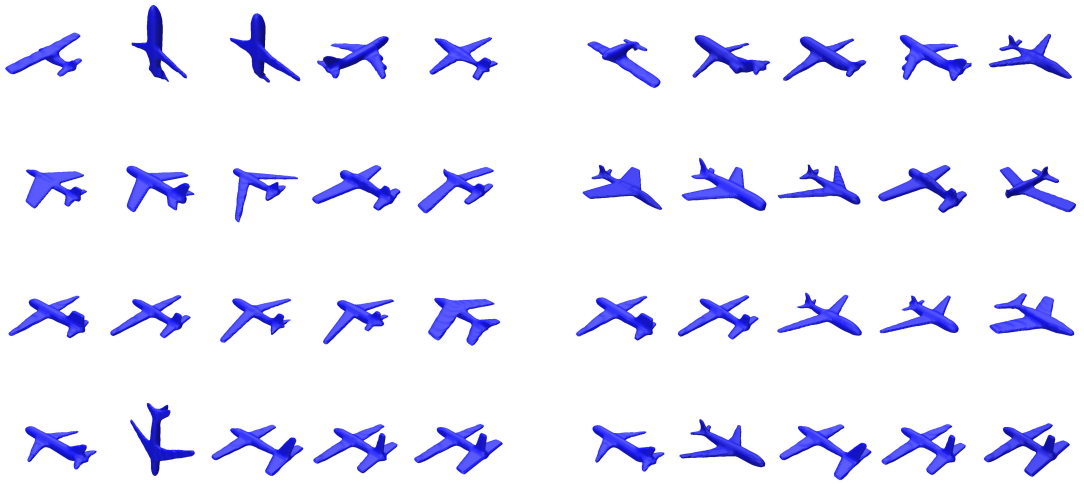
Figure 3: Distances of the barycenters of 3D objects to the origin of 3D space after normalization

where $\sigma(x,y) = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})$ the co-variance of x with respect to y

We implemented the rotation to align the 3D object with the given eigenvectors as follows. The PCA gives us 3 vectors respectively the most spread axis ($\overrightarrow{E_x}$), the second most spread axis orthogonal to the first one ($\overrightarrow{E_y}$), and the normal of the two previous one ($\overrightarrow{E_z}$) that form the new coordinate system. The new coordinates of each vertex are just the projection of this vertex on the three vectors of the new coordinate system. To rotate, we compute the coordinate $(\overrightarrow{OV}.\overrightarrow{E_x}, \overrightarrow{OV}.\overrightarrow{E_y}, \overrightarrow{OV}.\overrightarrow{E_z})$ (where O is the origin and V is the vertex that we transfer to the new coordinate). This change of coordinate align the 3D object with the three vectors given by the PCA.

The effect of rotation normalization can be seen at Figure 4. fig:PCA-alignement

We can see the orientation of a class of objects



(a) Before orientation and alignement normalisation (b) After orientation and alignement normalisation

Figure 4: View of different airplanes

before and after the normalisation. All objects are oriented in the same direction. Some objects can be seen as outliers. We analyse that this behavior is mostly caused by some features of the 3D object that result in a different rotation. For example, the size of the wings for airplanes can influence the most spread axis (see Figure 4b). If the wings are longest than the body of the airplane the most sread axis is the plane and conversly. After analysis of the same figure presented (see 4) for all different categories, we conclude that the orientation is then working correctly.

3.4 Orientation

We now need to normalize the orientation. Determine if flipping along an axis is needed based on the moment test. We compute the second-order moment of the area with respect to a given axis, if it is negative for a given the axis is flipped. The negative values become positive and vice-versa. This inverse the momentum of the object with respect to that axis.
The second-order moment of the area with respect to a given axis is computed with this given formula :

$$f_i = \sum_t sign(c_{t,i})(c_{t,i})^2$$

(with $c_{t,i}$ the i-th coordinate of center of triangle T ($i \in \{x, y, z\}$)

Using the same figure (see 4) we see that it is working. After analysing outliers, we deduct that it is mostly cause by some features of the 3D object that result in different orientation. (see 4). For example, we can see that the top left plane is upside down. After analysis, this is explain by the position of the barycenter that not balanced regarding to the height of the plane. Therefore according to the vertical axis the part with more momentum is the body that is put upward.

3.5 Scaling

The objective is to scale 3D objects to fit in a unit cube. As we wanted all axis to be scaled with a coefficient, we considered that the longest side of the bounding box has to be one, so other sides might be lower or equal to one. We compute two points that will describe the bounding box as follows:

$$min\_box = (\min_{v \in V}(v_x), \min_{v \in V}(v_y), \min_{v \in V}(v_z))$$

and

$$max\_box = (\max_{v \in V}(v_x), \max_{v \in V}(v_y), \max_{v \in V}(v_z)$$

with V the set of vertex of the mesh. We define the length of the bounding box as following:

$$|Bounding\_box| = max(\max_{v \in V}(max\_box_i) - \max_{v \in V}(max\_box_i))$$

(with i the i-th coordinate of v ($i \in \{x, y, z\}$)and V the set of vertices of a mesh.) The effect of this scale normalization can be seen in Figure 6.

In comparison with the initial database (see Figure 5), we can deduce that the size of the bounding boxes has been normalized around one.

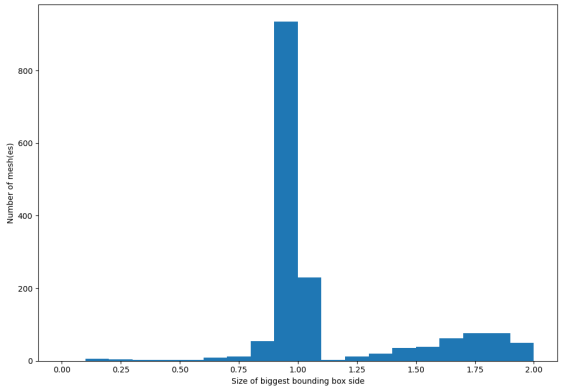


Figure 5: Size of biggest bounding box side for the initial 3D mesh database

box-size-before

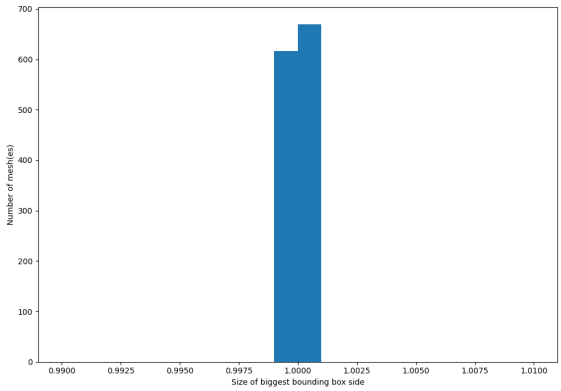


Figure 6: Size of biggest bounding box side after normalisation

:box-size-after

References

pymeshlab

[1] Alessandro Muntoni and Paolo Cignoni. *PyMeshLab*. Jan. 2021. DOI: 10.5281/zenodo.4438750.

polyscope

[2] Nicholas Sharp et al. *Polyscope*. www.polyscope.run. 2019.