Classifying Surface Points Based on Developability Using Machine Learning

Vahide Bulut

Izmir Katip Çelebi University, Department of Engineering Sciences, İzmir, Turkey, (ORCID: 0000-0002-0786-8860), vahide.bulut@ikcu.edu.tr

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Abstract

The classifiers K-nearest neighbor (KNN), Multiclass support vector machine (MSVM), Decision Tree (DT), Discriminate Analysis (DA), Naive Bayes (NB), Random Forest (RF), and Ensemble Tree (ET) are the most well-known methods in machine learning. They are used in many fields like pattern recognition, medical disease analysis, user smartphone classification, text classification, etc. This paper presents a new framework for 3D surface point type classification using the most known classification methods in machine learning and the principal curvatures, the binormal vector, the cosine value of the angle between the normal vector and binormal vectors. The purpose of this study is to classify data points according to their developability. Also, the comparison between these methods is given to measure developability based on the accuracy and the processing time using several 3D surface examples.

Keywords: Machine learning, classification, principal curvatures, binormal vector.

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1. Introduction

Surface normals, principal directions, and principal curvatures are utilized in 3D computer vision to find solutions for some basic tasks, such as segmentation, surface classification, surface reconstruction, and registration Krsek et al. (1998). We can use the principal curvatures to determine the characterization of a surface due to the principal curvatures’ invariant properties at a surface point. Many researchers studied the Gaussian and the mean curvatures on several kinds of surfaces such as faces and human bodies.

Shape recognition from range data is studied in terms of the principal curvatures in Vemuri et al. (1986). On the other hand, the principal curvatures are utilized for object recognition in Deng et al. (2007). Darveau et al. expressed the effect of the principal curvatures 3D rendering of relatively noisy ultrasound angiograms without degrading the spatial resolution Darveau et al. (2018). Shape similarity is measured in Wang et al. (2018) in terms of the principal curvatures.

A 3D object classification method is presented based on the numerical surface point signatures on interest points of 3D objects point cloud Rinkus et al.(2014). A 3D surface object classification method based on shape description and suitable pattern classification techniques is proposed in Shen et al. (2004). They used normalization and the spherical harmonic parameterization techniques to define a surface shape and derive a dual high dimensional landmark representation. Zheng et al. presented a new deep learning method to classify surface materials according to the acceleration signal and a corresponding surface texture image using Fully Convolutional Network (FCN) Zheng, et al. (2016).

This paper provides a new perspective for 3D surface point type classification regarding developability using the most utilized classification methods in machine learning and the principal curvatures, the binormal vector of S. Frenet frame, and the angle between the surface normal, and the binormal vectors. Additionally, we compare these methods to determine the developability of surface data points in terms of accuracy and the processing time using different 3D surface examples.

The rest of the paper is given in this manner: Section 2 provides basic information about a surface and the most popular machine learning classification methods. The proposed method is given in Section 3, while Section 4 presents several experimental studies and their results. Finally, Section 5 concludes the study.

2. Preliminaries

This section briefly describes the curvatures of a surface and classification methods in machine learning.

2.1. Curvature of a Surface

A surface is a subset of \( \mathbb{R}^3 \) and looks like a piece of \( \mathbb{R}^2 \) in the vicinity of any given point. The following definitions describe the notion of a surface in \( \mathbb{R}^3 \).

**Definition 1:** If a surface patch \( \text{SP}: U \to \mathbb{R}^3 \) is smooth, and the vectors \( \text{SP}_u \) and \( \text{SP}_v \) are linearly independent at all points \((u, v) \in U\), this surface is called a regular surface.

A normal unit vector is defined at a point \( P \) on this surface as

\[
\mathbf{n}_{\text{SP}} = \frac{\text{SP}_u \times \text{SP}_v}{\|\text{SP}_u \times \text{SP}_v\|}
\]

**Definition 2:** Suppose that \( \text{SP}(u, v) \) is a surface patch of a surface \( \text{S} \) and \( \mathbf{r}(t) = \text{SP}(\mathbf{u}(t), \mathbf{v}(t)) \) is a unit speed curve in \( \text{SP} \). The normal curvature of this curve is expressed with the following equation:

\[
\kappa_n = Lu'^2 + 2Mu'v' + Nv'^2
\]

in which \( L, M \) and \( N \) are coefficients of the second fundamental form and defined by

\[
L = \text{SP}_{uu} \cdot \mathbf{n}, \quad M = \text{SP}_{uv} \cdot \mathbf{n}, \quad \text{and} \quad N = \text{SP}_{vv} \cdot \mathbf{n}.
\]

**Proposition 1:** The principal curvatures \( \kappa_{n1} \) and \( \kappa_{n2} \) are the maximum and minimum of the normal curvature in (2) at the point \( P \). The principal curvatures can be written in the mean and Gaussian curvatures by Pressley, A. (2010).

\[
K = \kappa_{n1} \cdot \kappa_{n2} \quad \text{and} \quad H = \frac{\kappa_{n1} + \kappa_{n2}}{2},
\]

or in a quadratic equation form

\[
\kappa_n^2 - 2HK_n + K = 0,
\]

which has solutions as

\[
\begin{cases}
\kappa_{n1} = H + \sqrt{H^2 - K} \\
\kappa_{n2} = H - \sqrt{H^2 - K}.
\end{cases}
\]

The principal and Gaussian curvatures \( \kappa_{n1}, \kappa_{n2} \) and \( K \) have great importance in determining the shape of the surface. The classification of points on a surface in terms of the principal curvatures is presented in Table 1.

**Table 1:** Classification of surface points based on principal curvatures.

| \( \kappa_{n1} \) | \( \kappa_{n2} < 0 \) | \( \kappa_{n1} = 0 \) | \( \kappa_{n2} > 0 \) |
|----------------|------------------|------------------|------------------|
| \( \kappa_{n1} \) | Concave Ellipsoid | Concave Cylinder | Hyperboloid Surface |
| \( \kappa_{n2} = 0 \) | Concave Cylinder | Plane | Convex Cylinder |
| \( \kappa_{n2} > 0 \) | Hyperboloid Surface | Convex Cylinder | Convex Ellipsoid |

**Definition 3:** Let \( \mathbf{r}(t) \) be a non-uniform speed curve. S. Frenet frame of this curve is:

\[
\frac{\mathbf{r}'(t)}{\|\mathbf{r}'(t)\|} = T, \quad \frac{\mathbf{r}''(t)}{\|\mathbf{r}''(t)\|} \times T = N \quad \text{and} \quad \frac{\mathbf{r}'(t) \times \mathbf{r}''(t)}{\|\mathbf{r}'(t) \times \mathbf{r}''(t)\|} = B
\]

in which \( T, N, \) and \( B \) are the unit tangent vector, principal normal vector, and binormal vector, respectively Kreyszig, E. (1959).
2.2 Classification Methods in Machine Learning

Machine learning is a branch of computer science and tries to obtain meaning from data. We describe objects around us according to their features (or attributes). Intuitively, a featured class is composed of similar objects. A training process is to state the connection between the output and the input features Patil and Kulkarni, (2019). Features can be determined in the form of names, categories, types of entities, etc. On the other hand, non-numerical features can be converted to numerical values. There are some basic classification methods in machine learning.

The k-nearest neighbor classifier (k-NN) is used widely since it is theoretically elegant and simple to use Duda et al. (2001). This method classifies an input in data by retrieving the k nearest prototypes from the labeled reference set.

The decision tree algorithm classifies the given data by containing the minimum number of nodes Sulaiman, M. A. (2020). It is related to knowledge of relationships that include nodes and connections Priyanka and Kumar, (2020).

An SVM model is applied to binary classification by dividing data elements either in 1 or 0. However, the same principle MSVM is utilized, and the multiclass problem is broken down into multiple binary classification cases Ahuja and Yadav, (2012).

For the discriminant analysis method, it generates classes based on the Gaussian distributions. The fitting function calculates the parameters for each class, and the trained classifier seeks the class for new data according to the smallest misclassification cost Tharwat, A. (2016).

A Naive Bayes classifier method is based on applying Bayes’ theorem, so it is a simple probabilistic classifier. It assumes any class feature as independent from any other feature Berrar, D. (2018).

Like the KNN and the decision tree methods, a random forest method is also a tree-based method, and this method is based on a random vector’s sampled values for each tree independently with the same distribution Breiman, L. (2001).

On the other hand, ensemble methods construct a classifier set and classify new data points by taking their predictions’ vote Dietterich T.G. (2000).

Algorithm 1: The proposed method

3. Proposed Method

The principal curvatures have been used for object recognition. Therefore this study constructs a bridge between the object recognition and surface points types based on machine learning.

Assume that data points belonging to a surface are given. First, the binormal vectors, the normal vectors, and the angles between these vectors are estimated. Next, the principal curvatures are calculated at each point in the data. Moreover, some well-known classification algorithms in machine learning are used to state the best method that classifies the points without knowing the principal curvatures. The Gaussian curvature is utilized to determine the points which have developability properties. Because a surface that has zero Gaussian curvature is called a developable surface. Finally, we apply machine learning classification methods K-nearest neighbor (KNN), Multiclass support vector machine (MSVM), Decision Tree (DT), Discriminate Analysis (DA), Naive Bayes (NB), Random Forest (RF), and Ensemble Tree (ET), and obtain accuracy with the computational cost for each one, respectively. The proposed algorithm is presented in Algorithm 1.
4. Experimental Study and Results

In this section, as shown in Table 2, five surface examples are considered to apply the most known classification methods in machine learning. Next, the comparison between these methods is presented in Table 3 regarding the accuracy and processing time (s).

Table 2. Example Surfaces

| Example Surface | Data Points Number | Example Surface | Data Points Number |
|-----------------|--------------------|-----------------|--------------------|
| ![Surface 1](image1.png) | 2400 | ![Surface 2](image2.png) | 1296 |
| ![Surface 3](image3.png) | 44100 | ![Surface 4](image4.png) | 48400 |
| ![Surface 5](image5.png) | 8709 | | |

![Graph 1](image6.png)

![Graph 2](image7.png)

![Graph 3](image8.png)
As seen in Table 3, the random forest (RF) method is the most accurate one among the applied methods. The RF method makes classification providing almost 100% accuracy for general 3D surfaces #1 and #3, while providing accuracies in the range 65%-80% for the surfaces with specific shapes. However, the processing time for the RF is the second most taking time to calculate the proper classes. On the other hand, the Ensemble Tree (ET) method is the one that has the most spending time even though it cannot find the accuracy with high percentages.

### 5. Conclusion

In this study, we utilized the most-known machine learning classification methods K-nearest neighbor (KNN), Multiclass support vector machine (MSVM), Decision Tree (DT), Discriminate Analysis (DA), Naive Bayes (NB), Random Forest (RF), and Ensemble Tree (ET) to classify 3D surface points in terms of developability. The classification is made according to the principal curvatures, binormal vector, and the angle between the normal and binormal vector features. We compared the mentioned methods using several 3D examples in terms of accuracy and computational time. Table 2 expresses that the RF method is the best classifier for surface point developability even if it takes some time to process. Also, we realized that it is more accurate for general 3D surfaces such as #1 and #3 than object surfaces.

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