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Recognition of feature curves on 3D shapes using an algebraic approach to Hough transforms

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ABSTRACT

Feature curves are largely adopted to highlight shape features, such as sharp lines, or to divide surfaces into meaningful segments, like convex or concave regions. Extracting these curves is not sufficient to convey prominent and meaningful information about a shape. We have first to separate the curves belonging to features from those caused by noise and then to select the lines, which describe non-trivial portions of a surface. The automatic detection of such features is crucial for the identification and/or annotation of relevant parts of a given shape. To do this, the Hough transform (HT) is a feature extraction technique widely used in image analysis, computer vision and digital image processing, while, for 3D shapes, the extraction of salient feature curves is still an open problem.

Thanks to algebraic geometry concepts, the HT technique has been recently extended to include a vast class of algebraic curves, thus proving to be a competitive tool for yielding an explicit representation of the diverse feature lines equations. In the paper, for the first time we apply this novel extension of the HT technique to the realm of 3D shapes in order to identify and localize semantic features like patterns, decorations or anatomical details on 3D objects (both complete and fragments), even in the case of features partially damaged or incomplete. The method recognizes various features, possibly compound, and it selects the most suitable feature profiles among families of algebraic curves.

1. Introduction

Due to the intuitiveness and meaningful information conveyed in human line drawings, feature curves have been largely investigated in shape modelling and analysis to support several processes, ranging from non-photorealistic rendering to simplification, segmentation and sketching of graphical information [1–4].

These curves can be represented as curve segments identified by a set of vertices, splines interpolating the feature points [5], L^1 medial skeletons [6] or approximated with known curves, like spirals [7,8].

Traditional methods proposed for identifying feature curves on 3D models can be divided into view dependent and view independent methods. The first ones extract feature curves from a projection of the 3D model onto a plane perpendicular to the view direction, while view independent techniques extract feature points by computing curvatures or other differential properties of the model surface.

View independent feature curves assume various names according to the criteria used for their characterization (ridge/valleys, crest lines, sharp lines, demarcating curves, etc.). Furthermore, they are possibly organized into curve networks [3,4] and filtered to omit short and non-salient curves [9].

However, extracting feature curves is not sufficient to convey prominent and meaningful information about a shape. We have first to separate the curves belonging to features from those caused by noise and then, among the remaining curves, to select the lines which describe non-trivial portions of a surface. These salient curves usually correspond to high level features that characterize a portion of a shape. They can be represented by a multitude of similar occurrences of similar simple curves (like the set of suction cups of an octopus tentacle), or by the composition of different simple curves (like the eye and pupil contours). In addition, for some applications, it is necessary to develop methods applicable also in the case of curves partially damaged or incomplete, as in the case of archaeological artefacts.

To the best of our knowledge, the literature has not yet fully addressed the problem of identifying on surfaces similar occurrences of high level feature curves, of different size and orientation, and in the case they are degraded. This is not true for 2D feature curves, where the Hough Transform (HT) is commonly used for detecting

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lines as well as parametrized curves or 2D shapes in images. Our attempt is then to study an HT-based approach suitable for extracting feature curves on 3D shapes. We have found the novel generalization of the HT introduced in [10] convenient for the detection of curves on 3D shapes. Using this technique we can identify suitable algebraic curves exploiting computations in the parameters space, thus providing an explicit representation of the equation of the feature curves. Moreover, we recognize which curves of the family are on the shape and how many occurrences of the same curve are there (see Section 5 for various illustrative examples). Applying this framework to curves in the 3D space is not a trivial task: spatial algebraic curves can be represented as the intersection of two surfaces and theoretical foundations for their detection via HT has already been laid using Gröbner bases theory (see [10]). Nevertheless, the atlas of known algebraic surfaces is not as wide as that of algebraic plane curves, therefore working directly with curves could end with some limitations. Further, similarly to [2,7,8,11] our point of view is local since we are interested to the problem of the extraction of features contours that can be locally flattened onto a plane without any overlap.

Contribution. In this paper we describe a new method to identify and localize feature curves, which characterize semantic features like patterns, decorations, reliefs or anatomical features on the digital models of 3D objects, even if the features are partially damaged or incomplete. The focus is on the extraction of feature curves from a set of potentially significant points using the cited generalization of the HT [10]. This technique takes advantage of a rich family of primitive curves that are flexible to meet the user needs. The method recognizes various features, possibly compound, and selects the most suitable profile among families of algebraic curves. Deriving from the HT, our method inherits the robustness to noise and the capability of dealing with data incompleteness as for the degraded and broken 3D artefacts on which we realized our first experiments [12]. Our main contributions can be summarized as follows:

- To the best of our knowledge this is the first attempt to systematically apply the HT to the recognition of curves on 3D shapes.
- The method is independent of how the feature points are detected, e.g. variations of curvature, colour, or both; in general, we admit a multi-modal characterization of the feature lines to be identified, see Section 3.1.
- The method is independent of the model representation, we tested it on point clouds and triangle meshes but the same framework applies to other representations like quad meshes. Details on the algorithms are given in Section 3 and in the Appendix.
- A vast catalogue of functions is adopted, which is richer than previous ones, and it is shown how to modify the parameters to include families of curves instead of a single curve, details are in Section 4.
- The set of curves is open and it can be enriched with new ones provided that they have an algebraic representation.
- We introduce the use of curves represented also in polar coordinates, like the Archimedean spiral.
- Our framework includes also compound curves, see Section 4.1.
- As a proof of concept, we apply this method to real 3D scans, see Section 5.

If compared to the previous methods, we think that our approach, conceived under the framework of the Hough Transform technique, can be used and tuned for a larger collection of curves. Indeed, we will show how spirals, geometric petals and other algebraic curves can be gathered using our recognition technique.

2. Related work

The literature on the extraction of feature curves and the Hough transform is vast and we cannot do justice to it here. In this section we limit our references only to the methods relevant to our approach, focusing on HT-based curve detection and feature curve characterization.

Hough transform. We devote this section to a brief introduction to the HT technique, while we refer to recent surveys (for instance [13,14]) for a detailed overview.

HT is a standard pattern recognition technique originally used to detect straight lines in images, [15,16]. Since its original conception, HT has been extensively used and many generalizations have been proposed for identifying instances of arbitrary shapes over images [17], more commonly circles or ellipses. The first very popular extension concerning the detection of any parametric analytic curve is usually referred to as the Standard Hough Transform (SHT). In spite of the robustness of SHT to discontinuity or missing data on the curve, its use has been limited by a number of drawbacks, like the need of a parametric expression, or the dependence of the computation time and the memory requirements on the number of curve parameters, or even the need of finer parameters quantization for a higher accuracy of results.

To overcome some of these limitations, other variants have been proposed, one of the most popular being the Generalized Hough Transform (GHT) by Ballard [17]. Since its conception, it proved to be very useful for detecting and locating translated two-dimensional objects, without requiring a parametric analytic expression. Thus, GHT is more general than SHT, as it is able to detect a larger class of rigid objects, still retaining the robustness of SHT. Nevertheless, GHT often requires brute force to enumerate all the possible orientations and scales of the input shape, thus the number of parameters needs to be increased in its process. Further, GHT cannot adequately handle shapes that are more flexible, as in the case of different instances of the same shape, which are similar but not identical, e.g. petals and leaves.

Recently, thanks to algebraic geometry concepts, theoretical foundations have been laid to extend the HT technique to the detection of algebraic objects of codimension greater than one (for instance algebraic space curves) taking advantage of various families of algebraic plane curves (see [10,18]). Being so general, such a method allows to deal with different shapes, possibly compound, and to get the most suitable approximating profile among a large vocabulary of curves.

In 3D, other variants of HT have been introduced and used but as far as we know none of them exploits the huge variety of algebraic plane curves (for this we refer again to the surveys [13,14]). For instance, in [19] the HT has been employed to identify recurring straight line elements on the walls of buildings. In that application, the HT is applied only to planar point sets and line elements are clustered according to their angle with respect to a main wall direction; in this sense, the Hough aggregator is used to select the feature line directions (horizontal, vertical, slanting) one at a time.

Feature characterization. Overviews on methods for extracting feature points are provided in [1,20]. In the realm of feature characterization it is possible to distinguish between features that are view-dependent, like silhouettes, suggestive contours and principal highlights [21], mainly useful for rendering purposes [22], or those that are independent of the spatial embedding and, therefore, more suitable for feature recognition and classification processes. In the following we sketch some of the methods that are relevant for our approach, i.e., characterizations that do not depend on the spatial embedding of the surface.