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A novel feature representation for automatic 3D object recognition in cluttered scenes

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ABSTRACT

We present a novel local surface description technique for automatic three dimensional (3D) object recognition. In the proposed approach, highly repeatable keypoints are first detected by computing the divergence of the vector field at each point of the surface. Being a differential invariant of curves and surfaces, the divergence captures significant information about the surface variations at each point. The detected keypoints are pruned to only retain the keypoints which are associated with high divergence values. A keypoint saliency measure is proposed to rank these keypoints and select the best ones. A novel integral invariant local surface descriptor, called 3D-Vor, is built around each keypoint by exploiting the vorticity of the vector field at each point of the local surface. The proposed descriptor combines the strengths of signature-based methods and integral invariants to provide robust local surface description. The performance of the proposed fully automatic 3D object recognition technique was rigorously tested on three publicly available datasets. Our proposed technique is shown to exhibit superior performance compared to state-of-the-art techniques. Our keypoint detector and descriptor based algorithm achieves recognition rates of 100%, 99.35% and 96.2% respectively, when tested on the Bologna, UWA and Ca' Foscari Venezia datasets.

1. Introduction

Feature representation is of critical significance to many pattern recognition applications and systems involving detection [1], recognition [2–8], registration [9], reconstruction [10–12] and classification [13–15]. Among these applications, object recognition in complex real environments in the presence of occlusion and clutter is a challenging task [16]. The aim of object recognition is to correctly identify objects in a scene and recover their poses (i.e. position and orientation) [17,18]. A popular approach to tackle these challenging conditions is to detect 3D keypoints and capture the local geometric information around each detected keypoint, in the form of a local feature descriptor [19]. Local feature based algorithms have been shown to be robust to occlusion and clutter [19].

In this paper, we propose to exploit the divergence and vorticity of the vector field to respectively detect 3D keypoints, and build a local feature descriptor around each of these detected keypoints. The motivation behind the introduction of the proposed technique is to convert the vector field information into a more discriminating local representation that can improve 3D object recognition. A vector field is a vector associated with every point of the 3D surface [20]. This can be visualized as a collection of arrows with a given magnitude and direction each attached to a point of the surface as shown in Fig. 1(a) and (b). Vector fields are often used to model, for example, the strength and direction of some force, such as the magnetic or gravitational force, as it changes from point to point.

The elements of differential and integral calculus extend to vector fields in a natural way. When a vector field represents a force, the line integral of a vector field represents the work done by a force moving along a path, and under this interpretation conservation of energy is exhibited as a special case of the fundamental theorem of calculus. Vector fields can usefully be thought of as representing the velocity of a moving flow in space, and this physical analogy leads to notions such as the divergence and vorticity [21]. The physical significance of the divergence stems from the fact that it captures the amount of local expansion taking place in the vector field. It can be noted that for a volume with an enclosed surface, an outward or inward vector field flow through the surface respectively indicates the presence of a source, or a sink in the vector field [22], as can be seen in Fig. 1(a) and (b). Divergence is a signed scalar that measures the magnitude of a 3D vector field's source (i.e. positive divergence) or sink (i.e. negative

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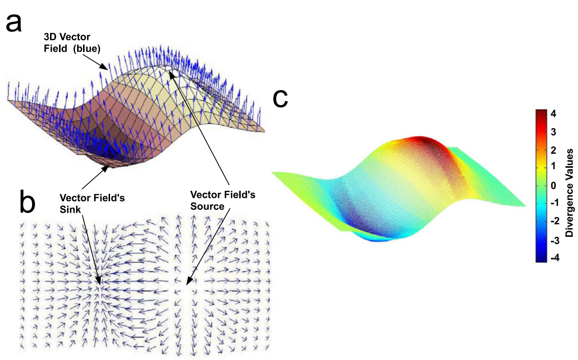

Fig. 1. Illustration of divergence computation. (a) Vector field on a 3D surface. (b) Top view of the vector field. (c) Divergence values computed at each point of the 3D surface. Divergence has high positive values at area of high surface variations and vice versa.

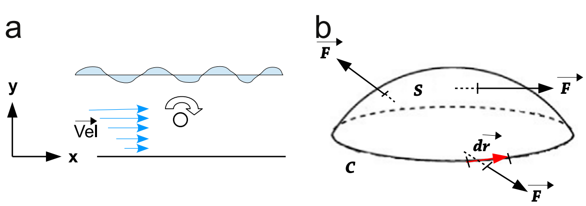

Fig. 2. Illustration of the concept of vorticity (a) in the case of a velocity vector field $\overrightarrow{Vel}$ and (b) a vector field $\overrightarrow{F}$ across a 3D surface.

divergence) at each point of the surface as illustrated in Fig. 1(c). We are particularly interested in 3D points which indicate sources in the vector field i.e. positive divergence values, as the neighborhood of these keypoints can be used to derive descriptive local features. These points are considered to be the potential keypoints in this work, and are ranked based on the saliency measure for their final selection as 3D keypoints.

Once keypoints have been detected, the local neighborhood of the keypoints is captured to derive the proposed descriptor 3D-Vor (*Vor*ticity). 3D-Vor exploits the vector field's vorticity at each point of the local surface, around the keypoint, to capture the predominant information of the underlying surface. Vorticity is the measure of the local spin around the axis perpendicular to the plane of the vector field.

To provide an intuitive interpretation of the concept of vector field's vorticity, consider the example of a vector field describing the velocity field of a fluid flow in a channel, with a paddle wheel placed in the liquid (Fig. 2(a)). The small solid arrows represent the velocity vectors of the fluid $\overrightarrow{Vel}$, being zero at the boundary and increasing upward. The top of the paddle wheel will have a greater force on it than the bottom due to the different fluid velocities. This will cause a torque on the paddle wheel, which is regarded as a vector along the paddle wheel axis [23]. This torque is normal to the velocity vector, and in this case is directed (using the right-hand rule) into the page. The velocity vector field is said to have vorticity, which is represented by the torque normal to the vector field.

This concept of fluid mechanics theory is also applicable to 3D surfaces. Suppose we have a closed-line path C that is the contour of the surface S (Fig. 2(b)). Also, assume that there is a vector field $\overrightarrow{F}$ which passes through the surface. Let $d\overrightarrow{r}$ be an increment of the contour (C). Then according to Stokes' theorem, the vorticity of the vector field $\overrightarrow{F}$ can be represented by:

$$vorticity = \lim_{r \to 0} \frac{1}{|A|} \oint_C \overrightarrow{F} . d\overrightarrow{r} \qquad (1)$$

In Eq. (1), $\oint_C \overrightarrow{F} \cdot d\overrightarrow{r}$ represents the circulation[1] of the vector field. This line integral, derived from Stoke's theorem, is a generic expression which can be applied to non-rigid (e.g., fluids) or rigid (e.g., surfaces) objects for the analysis of fields in various domains. For example, $\overrightarrow{F}$ in the integral part of Eq. (1) could represent the velocity vector for the analysis of fluid flow, wind force in the case of wind analysis, electric field force in the case of a charged body or vector field in the case of 3D surfaces. The concept of vorticity is therefore not restricted to fluid mechanics only, but it can be equally applied to rigid objects.

The vorticity of the vector field has also been shown to relate to 3D surfaces, by Longuet-Higgins [25]. For a concave surface, the curvature is negative. The circulation of the vector field is in the counter clockwise direction and resulting vorticity over the surface is positive, while the opposite applies in the case of convex surfaces. Based on the explanation of vorticity given by Longuet-Higgins, vorticity can capture the intrinsic curvature at a given point on the surface. We exploit these facts to capture the local surface information. We extract the local surface patch around each detected feature point. We next compute the vector field at each point of the local surface patch and calculate the vorticity of the vector field, using Eq. (1). The locally tangent circulation of the vector field results in a high signal-to-noise ratio and thus robust features. In addition, the integration operation carried out in the computation of vorticity has a smoothing effect, providing increased robustness to noise.

The vorticity is a point function,[2] with different values, at different points in the vector field [24,21]. The vorticity at a given point is positive, if the circulation is in the counter clock-wise direction (using the right-hand rule) and vice versa. The vorticity values computed at each point of the local surface are concatenated to construct the proposed 3D-Vor descriptor (see Section 5 for details). The robustness to mesh resolution is therefore achieved by using all the points of the 3D local surface. The vorticity (Eq. (1)) turns out to have a geometric meaning and provides a significant information about the surface variations [25–27]. Integration, which is an essential constituent in the definition of vorticity (Eq. (1)), has a smoothing effect [27] that provides the desired robustness to noise without the need for any preprocessing. In addition, vorticity is derived from the vector field's circulation, which is locally tangent to the surface contours [24]. The signal to noise ratio is thus higher for a tangent based scheme than for other feature representations relying on high order derivatives. Therefore, from a practical viewpoint, the proposed approach constitutes a more reliable surface representation for the purpose of accurate 3D object recognition.

1.1. *Paper contributions*

The contributions of this paper can be summarized as follows:

- A novel 3D keypoint detector exploiting the divergence of the vector field to detect highly repeatable 3D keypoints at a fixed scale.
- A novel saliency measure for ranking the detected keypoints.
- A novel local surface descriptor, 3D-Vor, capturing vorticity at each point of the local surface to provide a highly discriminative surface representation.

[1] Circulation about a closed contour in a field is defined as the line integral evaluated along the contour of the component of the velocity vector field that is locally tangent to the contour [24].

[2] A point function $k = f(P)$ is a function that assigns some number or value k to each point P of some region R_o of space.