# 3D Fingerprint

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## Synonyms

3D fingerprint reconstruction, 3D fingerprint recognition, biometrics

## Definitions

A 3D fingerprint is a set of cloud points or a 3D surface reconstructed from a real finger, which records the depth information of ridges and valleys. 3D fingerprint features extracted from the 3D fingerprints are used for biometrics recognition and other applications.

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## Background

As one of the widely used and very distinctive biometrics, fingerprints have been successfully deployed in various applications, such as secure payment, electronic devices, forensics and security (Yin et al 2016; Zhu et al 2018; Yin et al 2018). Those applications are mainly based on two-dimensional (2D) fingerprints, where fingerprint collection requires physical contact between the finger and sensor's surface. Although 2D fingerprints (i.e., live-scan or wet-inked fingerprints) are easy to acquire and usually have high ridge-to-valley contrast, the physical contact during the acquisition process often introduces some problems. One of the most significant is that fingerprints tend to be easily contaminated by latent ones remaining on a scanner platen (Wang et al 2007; Zhu et al 2017). This will reduce the reliability of the features from extracted the captured fingerprints. Secondly, the collected fingerprints inevitably have different degrees of non-linear distortion caused by varying amounts of pressure against the scanner platen during the acquisition process (Yin et al 2020). Thirdly, there is a hygienic risk that pathogens such as coronaviruses may spread through the surface of the sensor. More importantly, 2D fingerprints cannot truly represent natural 3D fingerprints, because when curved 3D fingers are flattened relative to a 2D plane, they will inevitably lose 3D information. Therefore, 3D fingerprint techniques that can provide potential advantages to avoid those problems have been proposed in recent years, and have become promising research topics

## Theory

### *3D Fingerprint Reconstruction*

3D fingerprint reconstruction is an essential but challenging component of a 3D recognition system. Based on imaging techniques, 3D fingerprint reconstruction methods can be classified into three main categories: 1) stereo vision-based methods; 2) structured light scanning-based methods; and 3) photometric stereo-based methods.

Stereo vision-based 3D fingerprint reconstruction methods require capturing at least two different views of 2D images using cameras. The depth information is calculated based on triangulation according to corresponding pixels between two different views of the fingerprint images. As shown in Fig. 1, $P$ is a point of a 3D object in 3D space, $p$ and $p'$ its corresponding points in 2D images (the blue lines) captured by two cameras, $O_L$ and $O_R$ the centers of the left and right cameras, respectively, $b$ the distance between the centers of the two camera centers, and $f$ the distance between the lens and image plane. The depth $z$ of $P$ relative to the left fingerprint image is calculated by

$$z = \frac{b * f}{x_L - x_R}. \tag{1}$$

One of the most challenging problems is the establishment of the correspondence between two different views of the fingerprint images. Most of the current methods of establishing correspondences are computationally complex and time-consuming. In contrast, a ridge-valley-guided 3D fingerprint reconstruction method proposed in Yin et al (2019) obtain well-structured 3D fingerprints with the ridge/valley detail in real time.

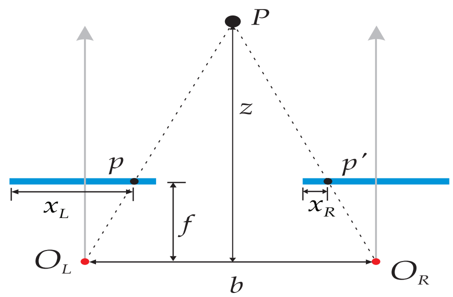


**Fig. 1** Diagram of triangulation for stereo vision.

Structured light scanning-based 3D fingerprint reconstruction methods (Huang et al 2014) require capturing multiple 2D images with structured light patterns using a digital light processing projector and a camera. Its underlying principle is also triangulation, whereby the depth information of a point is determined by the corresponding pixels between an image captured by the camera and a structured pattern used by the projector. Compared with the stereo vision methods mentioned above, such methods use a series of structured patterns to encode the correspondence relationship between the captured image and the structured patterns. The disadvantage of such methods is that their hardware systems are often expensive and bulky due to the digital light processing projector and a high-speed camera. The advantage is that such methods can reconstruct the ridge/valley details of a 3D fingerprint.

Photometric stereo-based 3D fingerprint reconstruction methods (Lin and Kumar 2018) require capturing multiple 2D images using a fixed camera under different lighting conditions. Its underlying principle is that the amount of light reflected by a surface is dependent on the orientation of the surface relative to the light source and the observer . By calculating the amount of light reflected into a camera (i.e., the intensity of captured images), the potential surface orientations can be bounded in a solution space. Let $\mathbf{y}_i \in \mathbb{R}^1$ denote the intensity of an observed point, $\mathbf{a}_i \in \mathbb{R}^3$ the direction of a light source ($\mathbf{a}_i$ is a column vector, and so is the following $\mathbf{x}$), and $\mathbf{x} \in \mathbb{R}^3$ the unknown unit surface normal of a point in the surface. $\mathbf{Y} = [\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_m]^T$ and $\mathbf{A} = [\mathbf{a}_1, \mathbf{a}_2, \cdots, \mathbf{a}_m]^T$. The problem is formulated as

$$\mathbf{Y} = \rho \mathbf{A}\mathbf{x}, \tag{2}$$

where $\rho$ is a surface albedo. The unknown surface normal $\mathbf{x}$ can be solved using least squares methods as follows

$$\rho\mathbf{x} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{Y}. \tag{3}$$

Therefore, when enough light sources are provided from different angles, the surface orientation can be determined. The advantage is that the hardware system is relatively simple; however, methods based on this hardware system are usually very time-consuming due to the large overhead of calculating the surface normal for each pixel.

In addition to the categories mentioned above, several 3D fingerprint reconstruction methods based on optical coherence tomography (OCT) and ultrasonic imaging (UI) have recently been proposed. The OCT-based methods are based on the interferometry principle, can recover accurate 3D fingerprint information, and have a potential anti-spoofing capability; but the hardware used in such methods is expensive and costs more than $7000. The UI-based methods recover 3D fingerprint information by measuring the acoustic time-of-flight. Such methods are often low-cost but time-consuming as it takes approximately 5 seconds to reconstruct a 3D fingerprint with a resolution of 1000 dpi. Also, this type of method is not completely contactless since it requires fingers to be pressed against a platen during the acquisition process.

## *3D Fingerprint Recognition*

A 3D fingerprint feature is essential for identifying 3D fingerprints; however, only a few have been developed in recent decades, and effective 3D features are still highly demanded. The feature of the surface curvature of a 3D fingerprint proposed in Liu et al (2015) is based on the curve's skeleton and overall maximum curvature of a 3D fingerprint. But, this method is of poor recognition accuracy, equal-error rates of 15% and 14.44%, respectively. A representation of 3D minutia, composed of three coordinates and two ridge orientations in 3D space, is introduced in Kumar and Kwong (2015). The disadvantage is that it is often time-consuming to align 3D minutia. To reduce computational complexity, Lin et al. (Lin and Kumar 2018) propose a Delaunay tetrahedron-based 3D minutia feature defined as a convex polyhedron consisting of four triangular faces of 3D minutiae. But the spatial topology is susceptible to spurious and missing 3D minutiae. Yin et al. (Yin et al 2019) propose an effective 3D topology polymer feature (TTP) for 3D fingerprint recognition. Firstly, multiple new 3D spaces are re-represented based on 3D minutiae extracted from the 3D fingerprint. Then, the TTP is extracted by projecting the 3D minutiae onto multiple planes and coding their corresponding 2D topologies. Its experimental results show that this method achieves highly accurate recognition and short running time.

## Open problems and Future directions

3D fingerprint reconstruction and recognition are still developing. Developing a robust 3D fingerprint reconstruction and novel 3D fingerprint features are essential to automated 3D fingerprint recognition systems. Besides, one of the most interesting future directions is the potential anti-spoofing capabilities of 3D fingerprints, which is worthy of investigating in the future. As 3D fingerprints provide the real 3D space information of real fingers, it is undoubted that they can improve the anti-spoofing capability of security systems.

## Summary

In conclusion, 3D fingerprint techniques contain two major components: 3D fingerprint reconstruction and 3D fingerprint recognition. The 3D reconstruction is essential for 3D feature extraction and the subsequent recognition.

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