3D Measurement of High-Reflective Surfaces

Subjects: Robotics
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The reflection phenomenon exhibited by highly reflective surfaces considerably affects the quality of captured images, thereby rendering the task of structured light (SL) 3D reconstruction.

Keywords: high reflection ; structured light ; polarization

1. Introduction

As a crucial component of computer vision, 3D reconstruction technology has been rapidly developed and has gained widespread applications in various fields, such as intelligent terminal, biomedical, mechanical manufacturing, and virtual reality [1][2]. Among vision-based 3D reconstruction methods, the typical time-coded SL system consists of a projector and a camera. The projector projects a pre-coded fringe pattern onto the surface of object, and the camera captures a series of images with pattern illuminations [3][4]. The feature points of camera and projector were matched by decoding method, and the 3D information of the object's surface is calculated by triangulation based on the calibration results [5][6]. The time-multiplexing SL method is capable of attaining both high accuracy and dense point clouds, therefore, it has a high application value in industrial inspections due to its high precision and high reconstruction density [7].

In industrial manufacturing, there are a large number of samples with highly reflective surfaces such as metal workpieces, and the highly reflective phenomenon caused by the projected light will make the projected stripes blur in the camera field of view, which will seriously affect the accuracy of 3D reconstruction and lead to irreversible loss of measurement information. Therefore, finding ways to suppress and eliminate the highly reflective phenomenon becomes a difficult problem that needs to be addressed in SL 3D reconstruction.

For the problem of highlight in SL method, the existing solutions mainly include adaptive projection intensity, multiple exposures, multi-view method, and the use of optical filters [8][9][10][11][12]. These methods can alleviate the reconstruction issue caused by high-reflective surfaces to some extent. However, the adaptive projection intensity, multiple exposure, and multi-view methods all require multiple acquisitions under different conditions, which are time-consuming and have complex algorithms. In contrast, using an optical filter such as a polarizer, which suppresses highlight areas from an optical imaging perspective, can avoid multiple scans of highly reflective surfaces.

An SL 3D reconstruction method of high reflectance surface using polarized light technique is proposed. The SL system employed in this study comprises a DLP fitted with a fixed-angle linear polarizer and a four-channel polarizing camera. The striped images of the four polarization channels with brightness differences are acquired by the SL scanning. Then, a binary code time-multiplexing SL method is adopted to obtain four distinct point clouds. The weight map is generated based on the four texture maps and depth maps to guide the point cloud fusion, and the best points are selected from the four point clouds to smooth the missing parts by the point cloud smoothing and noise reduction strategy. Finally, a precise and complete point cloud is obtained with a single scan, which has advantages in terms of time and precision.

2. 3D Measurement of High-Reflective Surfaces

In SL scanning, a pre-designed fringe pattern is actively projected onto the target surface, and the camera captures the image with the corresponding fringe information for 3D reconstruction. The commonly used sinusoidal coded stripes and gray code combined with phase-shift encoded stripes are all based on the projection intensity [13]. However, the periodic change in illumination intensity caused by these stripes results in blurred fringe information when the surface reflectance is uneven. To address this issue, a binary fringe based on Gray code combined with line shift coding has been proposed [14], which is independent of fringe intensity and shows better robustness against uneven surface reflectance. Nonetheless, highly reflective surfaces can cause overexposure in the camera image, leading to the loss of fringe information.

There are many solutions for the problem of SL scanning on surfaces with high reflectivity. In [8], a method based on camera response function, which adaptively adjusts the pixel-level intensity of projected fringe pattern according to the reflectivity of object surface, is proposed to deal with the highlight surface.This method can effectively improve the image quality of fringe, but it takes a lot of time to extract the reflectance information of object surface and calculate the projection intensity. In [9], the binary line shift fringe pattern is projected multiple times under different exposure times, and the fringe images at different exposure times are fused into well-exposed fringe images with the high dynamic range (HDR) image fusion technology for three-dimensional reconstruction. This method can also reconstruct a relatively complete point cloud, but the selection of multiple exposure times is based on experience, and multiple exposure increases the scanning time. In [10], a binocular SL system is proposed to process highly reflective surface, different angles of cameras on both sides are used to avoid specular reflection on the same surface, and highlight areas are detected separately, therefore, two point clouds can be reconstructed for splicing and fusion. Although this method can improve the reconstruction effect of the point cloud, it does not directly solve the highlight problem, and the outcome is not good for some free-form high-reflectance surfaces. In [11], a transparent screen is placed in front of the camera and the intensity of its corresponding screen pixels is adjusted according to the camera response function, which can improve the dynamic range of the camera and weaken the influence of highlights in structural light scanning. This method is equivalent to adding an optical filter to deal with the problem of high reflection. In [12], the difference in sensitivity efficiency of monochromatic laser under the RGB channel of color sensor is used to obtain images with different brightness values, which are fused to obtain images with high dynamic range for reconstruction. This method utilizes optical filters on the color sensor and HDR technology to accomplish high-dynamic-range 3D reconstruction.

Polarized light technology has been widely used in computer vision. This technology is to filter random vibration light signals into light signals that vibrate regularly along the polarization direction through polarization devices, eliminate the impact of stray reflected light on camera imaging, and achieve the removal of highly reflective areas [15]. In [16], a method is proposed to project sinusoidal encoded fringes and collect four groups of fringe images by a four-channel polarization camera. Through traversing the pixels of the four channel images, the appropriate channels were selected to enhance the fringe and then three-dimensional reconstruction was performed. However, the channel selection method is random and noise is easy to be introduced during reconstruction. In [17], a method of three-dimensional measurement of the dynamic objects by using the circularly polarized light and polarizing camera is proposed. The method also adopts sinusoidal coding, and speckle will be produced because laser is used as the light source, which will affect the measurement accuracy. In [18], a polarization-based method is proposed to remove image highlight and a normalized weighted algorithm is used to recover the surface information of the highlight region. This method can restore fringe information to complete reconstruction by adjusting the angle of polarizer and multiple exposures. However, the method of manually adjusting polarizer for measurement is difficult to adapt to complex and varied industrial scenes. In [19], a method is proposed to estimate the interval optimal projection intensity according to the camera response function under the polarization system and obtain the optimal fringe image by image fusion method, based on which 3D reconstruction is performed. Although the polarizer is not adjusted in the reconstruction process, the projection intensity is estimated according to the images acquired by multiple projections, which requires a certain preparation time.

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