3D Surface Shape Measurement based on Fringe Projection Techniques

Zonghua Zhang* and Shujun Huang
School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, China

Optical full-field fringe-projection-based 3D measurement techniques have been widely studied in academia and applied to industrial fields such as automated inspection, reverse engineering, cosmetic surgery and so on owing to the advantages of non-contact operation, fast acquisition, high precision and automatic data processing [1-6]. One or a series of fringe patterns are projected onto the surface of measured objects. From a different viewpoint, the fringe patterns are deformed with respect to the measured shape and an imaging device captures and saves the deformed fringe patterns for post processing. The phase information modulated in the deformed fringe patterns corresponds to the depth (shape) of the measured object and can be calculated mostly by the Fourier transform [7], Wavelet transform [8] or phase stepping algorithms [9] and then unwrapped to obtain absolute phase data. The obtained phase needs to be converted into depth data by a procedure called as calibration, which builds up the relation between phase and depth [10].

Existing fringe-projection-based 3D measurement systems mostly utilize evenly spaced fringes at the projecting device which can be formed using either a Ronchi ruling, grating or computer generated fringe pattern image. Non-telescopic lenses are mostly used on both the imaging and projecting devices to provide flexibility over the object size and field of view. The non-parallel axes of the imaging device and projecting device, necessary for triangulation, create variable period fringes across a plane orthogonal to the imaging axis. Therefore, the phase to depth relation is nonlinear and dependent of x and y-coordinates of the imaging system [10]. A number of researchers have studied the relation between phase, depth, the systematic parameters and x, y-coordinates (pixel position when the imaging device is a CCD camera) [10-14].

Based on the mathematical relation of phase, depth, the systematic parameters and x, y-coordinates, one approach is to estimate the systematic parameters. This may be achieved using multi-parameter minimization or least-square methods; however, the object depth calculation depends on the x coordinate in the image. To correct for the non-linear relation, some alternative neural network approaches have been studied, using for example, radial basis functions, multi-layer perceptron, Bernstein basis functions and feed-forward back-propagation configurations [15-19]. Neural networks offer the potential to accommodate deviations from the ideal mathematical relations, e.g. due to lens distortions. However, neural networks-based methods require considerable sets of training data to be generated to define the relation between the input parameters and the desired object depth at adequate resolution.

With the advent of color CCD cameras and DMD (Digital Micromirror Device) based color DLP (Digital Light Processing) projectors [20], the fringe patterns are generated by programming in a software and sent out by a DLP projector. Therefore, the programmed fringe patterns can have variable periods in between to give evenly spaced fringes within the measurement volume with a constant period on a plane orthogonal to the imaging axis, which called as an uneven fringe projection technique [21]. The relation between phase and depth becomes a simple linear function, independent of the pixel position. This means the relation is the same at all the pixel position in principle without considering lens distortion. It is possible to calibrate the uneven fringe projection system by using several discrete points with known phase and depth data in the measurement volume.

Another application of color CCD cameras and color DLP projectors is to code fringe patterns into the red, green and blue channels of a color image to measure colorful objects [22] or reduce the acquired numbers of fringe pattern images [23,24]. By comparing the fringe modulation depth between color channels, phase information at each pixel is determined from one color channel having the maximum modulation depth value. Color information of the object surface is also calculated with high dynamic range from the same captured color fringe patterns [22]. When three fringe patterns are coded into the three color channels of a composite RGB image, they can be simultaneously projected onto the measured object surface. Therefore, the acquired numbers of images reduce to 1/3 in comparison to gray fringe projection technique [23, 24].

With the rapid development of MEMS (Micro Electro Mechanical Systems), micro fluids and the micro moldings industries, there are great demands for on-line inspection of the surface quality by using their 3D CAD design data. Another future direction is to measure shape of big manufactured parts, for example, airplane body and ship hull. Existing methods to inspect 3D discontinuous structure and surface shape need long data acquisition time and the calibration procedures are complicated. Therefore, there are many challenging unsolved problems to the digital fringe projection method for fast measuring 3D surface shape of objects with large slopes and/or discontinuities.

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*Corresponding author: Zonghua Zhang, School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, China, E-mail: hzhangtju@hotmail.com, zhzhang@hebut.edu.cn

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