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Grid-based matching for full-field large-area deformation measurement

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ABSTRACT

Grid-based measurement can facilitate metrology and inspection of flexible electronics manufacturing. Multiple fundamental difficulties, however, arise in the large-area and full-field deformation measurement of deformable grid patterns including noise, occlusions, and artifacts. This paper addresses one of the key issues in deformation measurement: the registration and matching of deformed grid patterns. The emphasis is on accurate and robust periodicity tracing registration and constellation matching algorithms for grid pattern fidelity. The registration algorithm uses deviation metrics in deformed grids to estimate global translation, rotation and scaling; the matching algorithm uses the constellation reference grid to mine buried deformed point patterns. Using synthetic data, the validity of the registration algorithm is proved by registering noisy deformed grid patterns with various distortion scales and transformations; the validity of the matching algorithm is proved by matching deformed grid point patterns with various distortion scales, extra point rates and missing point rates. Compared to established non-rigid registration and point pattern matching algorithms, our algorithms demonstrate higher speed, sub-pixel accuracy and robustness in the matching of highly-deformed and noisy grids.

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1. Introduction

Flexible electronics integrate conventionally rigid silicon-based functions into elastomeric substrates to achieve high performance. Its advantages include low cost, light weight, compact forms and favorable electronic properties [1,2] that spur its ubiquitous developments and applications in flexible displays, solar panels, radio-frequency identification tags (RFIDs), medical devices, bio-integrated sensors, microfluidic devices and a variety of computing platforms. As of recent, printing technology for flexible electronics, such as roll-to-roll (R2R) manufacturing is nearing commercial reality [3]. While good yield, high speed and low cost are envisioned for the printing process of flexible electronics, multiple fundamental difficulties arise in the metrology and inspection of the R2R manufacturing, such as full-field deformation measurement for heterogeneity detection and failure control [4].

Classical contact strain methods are unsuitable for the full field deformation measurement of large area flexible material because of difficulties in mounting large amounts of gauges on the high-resolution, thin, and vulnerable flexible electronics specimen [5,6]. An alternative approach is noncontact optical techniques that can be classified into two groups: interferometric and non-interferometric. Although interferometric techniques, such as moiré interferometry and electronic speckle interferometry [7], exist, these methods are sensitive and susceptible to environmental disturbances. Non-interferometric methods generally use a lens to image deformed patterns, such as regular rectangular grid patterns [10]. Then, the deformed patterns are matched to the known reference pattern by integrating advanced image processing and pattern recognition techniques in the optical systems. The registration between the correspondences results in a full-field displacement mapping. The differentiation of the displacement field results in the strain matrix. These non-interferometric systems are recently accessible in commercial testing extensometers that mostly employ grid registration and matching. Spot centroid and digital image correlation (DIC) [6,8,9] are among the most popular matching methods. Generally, the spot centroid method involves segmenting and labeling spots in the target image, and matching the spots in reference and target images by using spots' constellation map. This method has limited matching accuracy and robustness, because deformation, electronic effects and uneven illumination can cause missing points, outliers, and point displacements. The DIC approach scores the similarity across all the spots in two images by correlation coefficients, with paired spots having the maximum scores. The DIC-based matching has been employed to characterize large deformations undergone by flexible materials including PDMS [11], polyether polyurethane [12],

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rubber polyurethane [13], and rubbers [14]. However, DIC requires the surface of a test sample have isotropic, high contrast and random surface patterns [16] that may be inaccessible in practical imaging processes. Meanwhile, seeking an appropriate DIC threshold for matching of low signal-noise ratio (SNR) images is challenging: a lower DIC threshold will mislabel some noise while a higher threshold can miss some signals. Instead, constellation matching [15] can use prior knowledge in a reference image to strengthen the accuracy of detecting spots in the target. The constellation matching generally extracts interest points (IPs) from a target image using prior knowledge of point patterns with methods such as template DIC, and examines the positional relationship between those points using the known point constellation map. Constellation matching has shown wide applications in industry because of its effectiveness and convenience. However, conventional constellation matching algorithms are only suitable for rigid registration and matching. In addition, the aforementioned missing-point and extra-point issue remains insolvable. As deformation in a target can be described as the combination of global and local deformations, we attempt to solve the above problems in constellation matching in two steps: global registration and local matching. First, the constellation map of the deformed target is registered with respect to the reference target by measuring the global transformation between the two targets. We desire a registration algorithm that is not limited by DIC or other point pattern extraction techniques. Second, IPs are matched across the neighborhoods between the two constellation maps. We expect a matching algorithm that takes into account the local deformation, missing points and extra points in matching.

Our registration algorithm is aimed to account the deformation of target in a global transformation. In this paper we use a rectangular grid as the target for its easy duplication and control in constellation matching [10]. We assume the deformed grid is near regular under reasonable forces such that the pixel patterns remain periodic and regular within tolerance under deformation [24,25]. The periodicity and regularity of the grid allows for the calculation of registration parameters under deformation. In the literature, methods for identifying the periodicity of structural textures have been proposed based on Fourier spectral analysis (FSA) [22], DIC [26], co-occurrence matrix [20], and discrepancy norm [21]. These methods have various weaknesses: FSA is not suitable for the periodicity estimation of textures of insufficient large size which lack salient peaks in the power spectrum; Co-occurrence matrix methods are unacceptably slow for large textures and sensitive to distortion [20]; Discrepancy norm is sensitive to image contrast because it relies on the difference between pixel values [23]. FSA is a comparatively fast and robust among these methods. It expressed the Fourier spectrum of periodic or almost periodic 2-D patterns of an image in polar coordinates. For each direction angle, its 1-D spectrum function has a behavior along a radial direction from the origin. Integrating the 1-D spectrum function along all the direction angles will generate a global descriptor of spectrum-radius where the prominent peaks gives the principal direction of the texture patterns. To improve the registration accuracy, robustness and speed for noisy targets, we propose a statistical shape metric to describe the global pattern distribution of the grid. The closest work in this area is the trace transform [27] that calculates functionals of the image function along tracing lines drawn across the image. The paper proposed two sets of functionals; which were ‘invariant’, such as integral operation, or ‘sensitive’, such as image weight center, to global transformation and noise. Consequently, these properties can be used to identify the rotation, translation and scaling parameters between images to reveal the differences between them. However, changes in regularity and periodicity between transformed images were not considered. To measure the characteristics of the deformed grid for registration computation, we proposed other types of functionals using shape metrics that have additional global regularity invariant to translation, local distortion and noise, but periodicity sensitive to rotation and scaling. The proposed registration algorithm is computationally fast because it requires no image preprocessing or feature extraction.

Our matching algorithm is aimed to tackle the following matching problem: given a list of reference points, how can their correspondences be identified in the list of points that are extracted from a target image that includes a blend of distortion, missing points and outlier points. A number of point pattern matching (PPM) techniques, besides DIC, have been proposed in the literature to solve this problem. Two notable non-rigid PPM techniques are thin plate spline – robust point matching ((TPS-RPM) [17], and Gaussian mixture model (GMM) [18,19], though we have not seen their applications in full-field deformation measurement. TPS-RPM proposed one-to-many relaxations to allow fuzzy correspondences, instead of using one-to-one correspondence and nearest neighbor criterion. It combines affine transformation and soft assignment to update correspondences iteratively. The method is sensitive to parameters for optimal matching. The GMM method represented each data point by a Gaussian component in a Gaussian mixture function. The distance between the Gaussian mixture of the reference point set and parameterized spatial transformation family of the target point set defines the cost function for minimization. The GMM matching method is statistically robust and simple for implementation, but can be easily trapped in a local minimum and is sensitive to a high amount of outliers. In addition, both methods are computationally intensive and slow. We develop a constellation-based algorithm that rapidly and robustly maps the IPs in a deformed target to the IPs in a reference image. We will benchmark the proposed PPM algorithm by comparison with the recent PPM techniques above. Overall matching accuracy is expected to maintain in sub-pixel size, while the extra rate is less than 0.5 and the missing rate is less than 1. In this paper, an extra rate and missing rate are respectively defined by the ratio of outlier points to reference points, and the ratio of missing points to reference points.

We have two main contributions in this paper: 1. a simple global registration method using a statistical shape metric for a deformed grid with fast, accurate and robust performance; 2. a local matching algorithm to fit an expected constellation to a noisy and deformed observed constellation by balancing global registration and local deformation constraints.

This paper is organized into four sections. In Section 2, we propose the registration and constellation matching algorithms. In Section 3, we report the accuracy and robustness of the algorithms after testing both synthetic and real images in experiments. In Section 4, we give conclusions.

2. Method

The workflow of our algorithms lies within the frame of Fig. 1, including the registration and matching of the deformed grid for deformation mapping. In the registration algorithm, global affine transformation parameters are derived from a deformed grid for matching, including scale, rotation and translation. In the matching process, template DIC first extracts IPs from the deformed grid. Second, the IPs are morphologically cleaned and labeled. Third, the constellation matching algorithm uses the registration parameters and grid knowledge to seek the deformed point patterns. The first two steps of the matching process are already established and are not discussed in further detail.