ROBUST SUB-PIXEL DISPARITY ESTIMATION AND ITS REFINEMENT AROUND DEPTH DISCONTINUITY AND FEATURELESS AREAS

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1. INTRODUCTION

Phase correlation feature matching method has been a popular choice in estimating the global or local translational motions between two similar images due to its remarkable accuracy and its robustness to uniform variations of illumination and signal noise in images. Recently, we proposed a robust phase correlation based sub-pixel feature matching technique to accurately extract the disparity map from a stereo image pair for DTM (Digital Terrain Model) generation [1] [2] [3]. However, its degraded performance around depth discontinuity, featureless and low correlation areas is recognized. In addition, while our robust phase correlation based disparity estimation algorithm is good at sub-pixel disparity measurement it is not capable of stereo matching for large disparity which is the usual case of conventional wide baseline stereo image pairs for DTM generation. Motivated by the strengths and limitations of phase correlation based methods for disparity estimation, this paper has been focused on further enhancing the performance of the robust phase correlation technique and solving its problems in the DTM generation.

This paper presents an enhanced robust phase correlation based sub-pixel disparity estimation technique without the ill-posed 2D phase unwrapping. A coarse-to-fine multi-resolution scheme is designed to improve the ability of phase correlation method for large disparity estimation. Noting the degraded performance of phase based methods for disparity estimation in the areas with depth discontinuity, we improved our Compound Phase Correlation (CPC) [1] technique with a “coefficient of determination” algorithm to more accurately locate and then refine the unreliable disparity estimates. Finally, the Median Shift Propagation (MSP) [4] filter technique is applied to amend the error disparity estimates in featureless and other low correlation areas. With this refinement scheme, we are able to greatly improve the accuracy of phase correlation based disparity estimation for DTM generation stereo image pairs with versatile baseline settings (from narrow to wide baseline).

2. ROBUST PHASE CORRELATION BASED FEATURE MATCHING

2.1. Enhanced robust technique for feature matching with sub-pixel accuracy

Phase correlation is based on the well-known Fourier shift property that a shift in the spatial domain between two duplicates of an image results in a linear phase difference in the frequency domain of the Fourier Transforms. The phase difference angle is simply a planar surface through the origin in u-v coordinates in frequency domain. Thus a complicated problem of complex numbers in frequency domain becomes a simple issue of finding the best 2D fitting of the phase difference angle data to a plane of phase difference in the coordinates of u and v. However, the phase difference angle is 2π wrapped, and 2D unwrapping on the phase difference angle data is often unreliable and results in failure of finding *a* and *b* correctly [5]. In our previous work [1] [2] [3], we applied a phase fringe filtering technique to reduce the noise in the periodic data of phase correlation matrix before 2D phase unwrapping. However, this technique has some limitations. First, it can not deal with the large shift resulted dense fringes due to the restriction of the smallest fringe filter size (3x3). Second, 2D unwrapping is an ill-posed problem and tends to generate error matching results [6]. Here, we propose a new algorithm for robust phase correlation based feature matching with sub-pixel accuracy, which overcomes the ill-posed problem of 2D phase unwrapping. First, we estimate the stereo correspondence with integer pixel level accuracy using a Delta function based phase correlation matching method [7]. Thus, the estimation error becomes no greater than 1 pixel for every corresponding correlation point. Second, the disparity measurement is further improved to sub-pixel accuracy for corresponding points through a highly robust estimation technique. In the sub-pixel shift estimation stage, a most robust fitting technique, Quick Maximum Density Power Estimator (QMDPE) [8], is applied to find the best fitting estimates of the phase angle data with only sub-pixel shift, which often is contaminated by the very noisy phase angle data with the sub-pixel shift information and contain multi-structure mode. Due to the corresponding correlation points have only sub-pixel shift each other, the phase unwrapping is not necessary any more before the robust fitting estimation. This new algorithm greatly improved the limitation of our previous robust phase correlation based disparity estimation technique [1] [2] [3]. The QMPDE robust fitting method repeatedly selects a random set of three points within the phase angle data and gets the plane transformation model induced by them. The plane model with the largest density power value can be obtained through a mean shift procedure, and such set of phase angle data is chosen to represent the statistical inliers. A least-squares solution finally applies to these inliers to form the final estimates of the phase angle plane. The benefit of using the QMDPE robust estimator is that the best fitting estimates can be obtained from the noisy phase angle data set. Our initial test indicates that with a window based robust phase correlation scanning processing, it can measure less than 1/50th pixel accuracy to generate dense disparity map for high quality 3D data generation.

2.2. Phase correlation quality evaluation method

Although the QMDPE technique is highly robust [8], it still has the potential flaw to produce incorrect estimates of inliers and outliers, especially when an image patch does not contain sufficient data (lack of texture) or the image data is very badly corrupted (aliasing). Thus, it is necessary to reliably assess the quality of the inliers estimates from the QMDPE robust method. Here we propose to use the "coefficient of determination" used in standard regression problem [9] as the quality assessment coefficient for the inliers derived from the robust QMDPE 2D fitting in frequency domain, which is more reliable than the method using the ratio of outliers to inliers [1].

3. MULTI-RESOLUTION ALGORITHM FOR LARGE DISPARITY ESTIMATION

In phase correlation methods for signal registration, it is assumed that in a small local area, one image is simply a shifted version of the other image [7]. In practice, the disparity between a pair of corresponding pixels is measured locally using a scanning window centered at the pixel in the master scene. The phase correlation is calculated in the windowed regions of the left and right images instead of the whole original images. The size of the window must be sufficiently larger than the expected displacement so that there is adequate information for matching. This means that the maximum ability of the disparity estimation is much smaller than the scanning window size for phase correlation. Our investigation indicated that a 32×32 scanning window size generally achieves good performance in the disparity values not greater than 10 pixels.

In order to deal with large disparity estimation, a coarse-to-fine multi-resolution scheme is designed. The new algorithm comprises: (1) a coarse-to-fine strategy using image pyramids for coarse correspondence search with integer pixel displacement accuracy and (2) a robust phase correlation based matching technique for finding a pair of corresponding window with sub-pixel accuracy. The processing is proceeded in two stages; we first find the stereo correspondence with integer pixel level accuracy using hierarchical Delta function based phase correlation matching method [7]. Thus, the estimation error becomes no larger than 1 pixel for every corresponding point in the each pyramid level. The disparity measurement is then further improved to sub-pixel accuracy for each corresponding point through the proposed enhanced robust phase correlation based disparity estimation technique at the bottom pyramid level.

4. REFINEMENT OF THE UNRELIABLE DISPARITY ESTIMATIES

The phase correlation matrix operation for estimating the feature shift is not stable for small matching blocks due to insufficient data to achieve effective correlation. As mentioned before, our experiments suggest 32×32 scanning window size for optimal performance in measuring the disparity value range within 10 pixels. However, 32×32 window size is much larger than that for most of intensity correlation based disparity estimation techniques [10]. Phase correlation based block matching is based on the assumption that in the matching blocks there is only one dominant translational shift but this is not true in the image blocks with the depth discontinuity which is characterized by at least two different translational shifts. A large matching block may cover both sides of a depth discontinuity and results in unreliable disparity estimates from phase correlation based method. Besides, the phase correlation method encounters the same problems common to most existing methods of disparity estimation, such as lacking of texture, significant spectral changes and system noise.

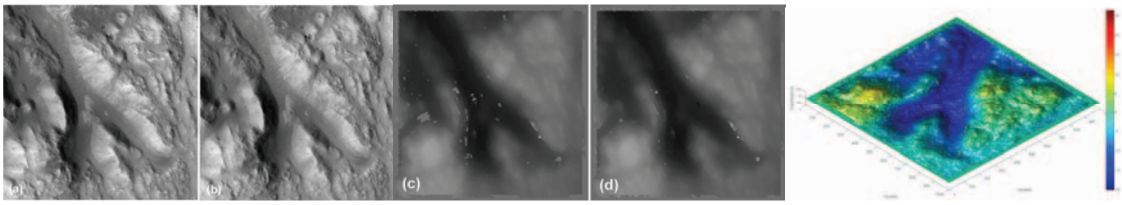
Noting the limitation of phase correlation based method for disparity estimation, we first use the QMDPE robust phase correlation based quality evaluation method to locate the unreliable disparity estimates in the areas with discontinuity, lack of texture, significant spectral changes and noise. We then developed a novel phase correlation based technique to distinguish depth discontinuities from unreliable estimates resulted from other low correlation factors. The key technical aspects of the new approach include: the application of compound phase correlation (CPC) method [1] to identify and refine disparity estimates around depth discontinuity areas, followed by median shift propagation (MSP) technique [4] to refine the low quality disparity estimates in image areas either featureless or subject to significant spectral changes where phase correlation fails.

With the robust phase correlation disparity estimation and its refinement scheme, we are able to greatly improve the accuracy of phase correlation based disparity estimation.

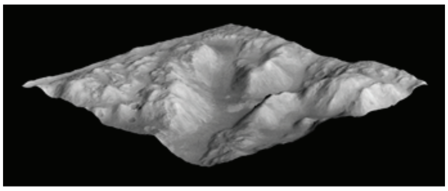
5. EXPERIMENTAL RESULTS

Based on the enhanced robust phase correlation techniques presented in this paper, we have developed a standalone C++ software package PCIAS with a friendly graphic user interface (GUI) and powerful image fusion and analysis functions such as global image registration, pixel-to-pixel image registration, and disparity mapping for DTM generation with sub-pixel accuracy. A series of images from different sensor platforms or with different spectral bands have been exploited to examine the accuracy and robustness of the proposed phase correlation based techniques. An example of the experimental results is presented here.

Figure 1 shows an example of large disparity measurement from conventional baseline Mars Columbia Hills stereo image pair, at sub-pixel accuracy using our coarse-to-fine phase correlation scheme. This conventional baseline stereo image pair Figure 1(a)-(b) has been rectified to epipolar geometry before disparity estimation processing, and its maximum disparity difference is around 15 pixels. A two-level pyramid was used in the coarse-to-fine multi-resolution algorithm. The initial calculated disparity map is shown in Figure 1(c), in which the unreliable disparity estimates around the depth discontinuity and low correlation areas have been masked off with the proposed phase correlation quality evaluation method. The refined disparity map (DTM) using the CPC method around discontinuity areas and MSP filter in low correlation areas is shown in Figure 1(d). Figure 1(e) presents the refined disparity map in 3D prospective pseudo colour view. Finally, a 3D prospective view of draping Figure 1(a) image on the DTM (d) is shown in Figure 1(f).



(e)



(f)

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