Sub-Pixel Registration for Super High Resolution Image Acquisition Based on Temporal Integration

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Abstract. Towards the development of super high resolution image acquisition, we present a temporal integration imaging method. The image processing algorithm for a generic temporal integration imaging method consists of the three stages: segmentation, sub-pixel registration and reconstruction. The segmentation stage and the sub-pixel registration stage are interdependent and extremely difficult to construct completely. Instead, aiming at a particular type of application where a user indicates a region of interest (ROI) on an observed image, we construct a prototypal temporal integration imaging method which does not involve the segmentation stage at all. Moreover, we develop a new quadrilateral-based sub-pixel registration algorithm, the key idea of which is to cover a ROI with deformable quadrilateral patches whose spatial fineness is automatically changed in accord with the curvature of the object's surface and then to describe an image warp between two image frames as deformation of the quadrilateral patches and finally to perform a sub-pixel registration by warping an observed image to a temporally integrated image with the recovered warping function.

1 Introduction

Some research institutes are elaborating plans to develop super high definition (SHD) image media beyond the HDTV. The SHD images should have high spatial and temporal resolutions at least equivalent to those of 35/60 mm films and/or motion pictures. Imaging is a principal problem for handling SHD images. CCD camera technology is considered promising as a high resolution imaging device. Although 1 inch CCD imagers with two million pixels have been developed for HDTV, spatial resolution should be increased further to acquire SHD images. Reducing the pixel size is the most straightforward way to increase spatial resolution, which makes a CCD imager much more sensitive to shot noise. To keep shot noise invisible on a monitor, there needs to be a limitation in the pixel size reduction. Current CCD technology has almost reached this limit. Therefore, a new approach is required to increase spatial resolution further beyond the resolution bounds qualified by shot noise physically.

One promising approach towards improving spatial resolution is to incorporate image processing techniques into the imaging process [1]. Imaging methods based on this approach can be classified into two main categories: a spatial integration imaging method and a temporal integration imaging method. As a spatial integration imaging method, recently we have presented a method for producing an improved-resolution image with sufficiently high SNR by integrating multiple images taken simultaneously with multiple different cameras [1].

This paper presents a temporal integration imaging method. A temporal integration

imaging method uses a single camera with insufficiently low spatial resolution, and produces an improved-resolution image by integrating multiple consecutive image frames taken with the camera. The principle of a generic temporal integration imaging method is that we reach an increase in the sampling rate by integrating more samples of the imaged object from an image sequence where the object appears moving.

The image processing algorithm for a generic temporal integration imaging method consists of the three stages: segmentation, sub-pixel registration and reconstruction. In the segmentation stage and the sub-pixel registration stage, while dividing a moving area into multiple small distinct patterns undergoing coherent motion with a certain motion segmentation algorithm, we make precise sub-pixel interframe correspondence between pixels that appear in given two image frames. In the reconstruction stage, an improved-resolution and/or improved-SNR moving image sequence with uniformly-spaced samples is reconstructed from a given moving image sequence by integrating the nonuniformly-accumulated samples composed of samples showing the sub-pixel interframe correspondence.

It seems that there is no unsolved problem about the reconstruction stage, and a number of algorithms are available for it [2, 3]. As described in [3], we can construct an interpolation algorithm that takes several degradation factors into account by extending the image reconstruction algorithm of projections onto convex sets (POCS). Presently, we believe that the POCS-based iterative interpolation method is fairly flexible, suited to the temporal integration imaging method.

On the other hand, the segmentation problem and the sub-pixel registration problem are highly interdependent and extremely difficult to solve completely. It seems that there is little prospect of a general solution of the highly interdependent problem in the near future and hence for the time being we cannot construct a generic temporal integration imaging method completely. To escape the predicament and then to form a prototypal temporal integration imaging method, for the present, we should relinquish a generic approach and confine its applications in a particular type of application such as surveillance, where a user indicates a region of interest (ROI) on an observed low-resolution image before applying the temporal integration technique to an observed image sequence [4].

Aiming at such a limited application, we construct a prototypal specific temporal integration imaging method which does not involve the segmentation stage at all. Moreover, we develop a new quadrilateral-based sub-pixel registration algorithm which describes an image motion within the ROI with sub-pixel accuracy as deformation of quadrilateral patches covering the ROI and then performs a sub-pixel registration by warping an observed image in accord with a temporally integrated image with the warping function recovered from the deformed quadrilateral patch. Before processing an observed image sequence, we should fix the size of quadrilateral patches properly in advance; hence it is certain that the algorithm works well for a plane surface of object, while it does not necessarily work satisfactorily for a curved surface of an object. In order to solve this problem and then to enhance the applicability of the prototypal specific temporal integration imaging method, furthermore we introduce a hierarchical patch splitting algorithm for controlling spatial fineness of quadrilateral patches in accord with the curvature of an object surface corresponding to the ROI.

2 Hierarchical Quadrilateral-Based Sub-pixel Registration

2.1 Computational Framework

Fig. 1 illustrates the computational framework of our proposed hierarchical quadrilateral-based sub-pixel registration algorithm. The key idea of the new hierarchical quadrilateral-based algorithm is to cover a ROI, indicated by a user on an observed low-resolution image frame, with deformable quadrilateral patches whose spatial fineness is automatically changed in accord with the curvature of the object's surface corresponding to the ROI and then to describe an image warp between two image frames within the ROI as deformation of the quadrilateral patches and finally to perform a sub-pixel registration by warping an observed image to a temporally integrated image with the recovered warping function.

2.2 Estimation of Grid Points' Displacement Vectors

We estimate displacement vectors of all the grid points within the ROI, describe an image warp with sub-pixel accuracy inside the ROI as deformation of the quadrilateral patches determined by the grid points shifted by an estimated sub-pixel displacement vector and thus track interframe correspondence of image points inside the ROI with sub-pixel accuracy over consecutive image frames.

The quadrilateral-based sub-pixel registration, of course, depends on accurate estimation of the grid points' displacement vectors. The displacement of each grid point is closely linked with the deformation of the patches. To determine the deformation of each quadrilateral patch, we should compute displacement vectors of all four grid points. Simultaneously, these grid points influence the deformation of four contiguous quadrilateral patches. We iteratively refine the displacement vector estimates of the grid points so that the matching errors for the four contiguous quadrilateral patches decrease after iteration. We refer to this algorithm as the iterative refinement algorithm.

2.3 Image Warping - Perspective Transformation -

In most applications, the ROI corresponds to a two-dimensional plane surface or a smoothly curved surface of an object, and a smoothly curved surface can be well approximated by a two-dimensional plane locally in the vicinity of a point within the ROI. It was shown that the mapping of an arbitrary two-dimensional plane surface of an object onto the image plane of the arbitrary moved camera is described by two-

Fig. 1. Computational framework of the hierarchical quadrilateral-based sub-pixel registration.

dimensional perspective transformations [5]. For perspective transformations, the forward mapping functions are

$$x' = T_1(x, y) = \frac{a_1 \cdot x + a_2 \cdot y + a_3}{a_7 \cdot x + a_8 \cdot y + 1} \quad (1)$$

$$y' = T_2(x, y) = \frac{a_4 \cdot x + a_5 \cdot y + a_6}{a_7 \cdot x + a_8 \cdot y + 1} \quad (2)$$

The eight mapping coefficients can be determined by establishing correspondence between four points in two images. Perspective transformations facilitate planar quadrilateral-to-quadrilateral mappings. Because of this property, we employ quadrilateral patches. When the three-dimensional structure of an object within a quadrilateral patch can be well approximated as a rigid two-dimensional plane, a good approximation of the image warp is provided.

2.4 Global Displacement Estimation

If an image warp inside the ROI is very large, we cannot obtain an accurate image warp estimate only with the iterative refinement algorithm. To cope with the problem, we use a global displacement estimation algorithm for shifting the entire ROI as a pre-process of the iterative refinement algorithm. The global displacement estimation algorithm operates on the entire ROI in the same manner as the iterative refinement algorithm.

2.5 Control of Quadrilateral Patches' Fineness

The size of deformable quadrilateral patches is an important factor. Larger quadrilateral patches are required to sufficiently constrain the solution of the problem of recovering an image warp from an observed image sequence and to provide some insensitivity to noise. The larger the quadrilateral patches are made, the less likely the local plane surface assumption about an object's local surface will be valid within each quadrilateral patch; the local plane surface assumption is that an object's local surface corresponding to a quadrilateral patch defined in the observed image is well approximated by a two-dimensional plane.

The appropriate size of quadrilateral patches depends on the curvature of an object's surface, and hence it is extremely difficult to determine the proper size of quadrilateral patches. To cope with this problem, we introduce a simple hierarchical patch splitting algorithm for controlling spatial fineness of deformable quadrilateral patches in accord with the curvature of an object's surface. We start with initial coarse quadrilateral patches, and then divide each quadrilateral patch iteratively into four finer quadrilateral patches until the size of the divided finer quadrilateral patches reaches the prescribed minimum size, typically 8×8 , if and only if the following two conditions are satisfied.

The two conditions are as follows:

(1) The first condition is that the eight mapping coefficients of the perspective transformation determined for the objective quadrilateral patch with the iterative refinement algorithm differ definitely from those determined for its contiguous

quadrilateral patches sharing a side. We define the distance between a couple of the eight mapping coefficients, on the Lie algebra associated with the Lie group of perspective transformations corresponding to all possible patterns of the eight mapping coefficients. The distance $D(\mathbf{a}, \mathbf{b})$ between two patterns of eight mapping coefficients, $\mathbf{a}=(a_1, a_2, \dots, a_7)^t$, $\mathbf{b}=(b_1, b_2, \dots, b_7)^t$, are defined by the equation:

$$D(\mathbf{a}, \mathbf{b}) = \iint_R \|\mathbf{v}(\mathbf{a}) - \mathbf{v}(\mathbf{b})\|^2 \cdot dx \cdot dy \quad (3)$$

where the vector, $\mathbf{v}(\mathbf{a})$, corresponds to the optical flow field determined by the perspective transformation with the eight mapping coefficients $\mathbf{a}$.

(2) The second condition is that the edge structure included in the objective quadrilateral patch is complex enough. If the objective quadrilateral patch satisfies the inequality,

$$\frac{1}{S(P)} \cdot \iint_P \left[\frac{\partial^2 I(x, y)}{\partial x^2} + \frac{\partial^2 I(x, y)}{\partial y^2} \right]^2 dx \cdot dy \geq Th \quad (4)$$

$$\begin{array}{ll} I(x, y) : \text{image intensity} & Th : \text{threshold value} \\ P : \text{quadrilateral patch} & S(P) : \text{area of } P \end{array}$$

then we regard the patch as a textured region containing salient local image features. On the other hand, once the objective quadrilateral patch is judged not to be a textured region, we will never divide the patch and thereafter we will exclude the patch from the region where the matching errors are computed in the iterative refinement algorithm.

3 Experimental Simulations

We conduct experimental simulations on a real test image sequence which we take with a normal 8-mm video camera for home use while moving the camera before a NESCAFE bottle. The test image sequence consists of 50 consecutive image frames. Fig. 2(a) shows the first image frame of the test image sequence, where a ROI is superimposed. We assume that the objects of interest are small characters and figures shown on a NESCAFE bottle. Both the vertical size and the horizontal size of the reconstructed improved-resolution image are made five times as large as that of the observed image frame. Fig. 2 contrasts the reconstructed improved-resolution image with the first observed image frame, but in Fig. 2(b) for ease of comparison the first observed image frame is interpolated and magnified by five times in the vertical and horizontal directions with the normal bilinear interpolation technique. As shown in Fig. 2, the hierarchical quadrilateral-based algorithm works well for a smoothly curved surface of an object, and temporal integration of pixels within the tracked ROIs enhances spatial resolution to such a degree that in the reconstructed improved-resolution image we can read small characters and figures which we can scarcely make out in the original observed image frame.

4 Conclusion

We develop a new hierarchical quadrilateral-based sub-pixel registration algorithm which is equipped with the capability of automatically controlling spatial fineness of

quadrilateral patches in accord with the curvature of an object surface, thus organizing a prototypal specific temporal integration imaging method oriented to specific applications. The experimental simulations demonstrate that the temporal integration imaging method works well when the local geometrical structure of an object's surface corresponding to a quadrilateral patch can be well approximated as a rigid two-dimensional plane. To extend the applicability of the temporal integration imaging method further, we should develop more flexible algorithms for segmentation and sub-pixel registration.

References

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(a) ROI in the 1st image frame

(b) 1st observed low-resolution image frame   (c) Reconstructed improved-resolution image (bilinear interpolation technique)

Fig. 2. The tracked regions of interest (ROIs) and spatial resolution improvements.