Image Stabilization Using Motion Estimation and Micro-mechanical Compensation

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Abstract

Airborne and space-borne imaging systems are often limited in resolution by image degradation resulting from mechanical vibrations during image exposures. A new image stabilization method using digital motion estimation and micro-mechanical compensation is presented. Motion estimation is accomplished by an auxiliary high-speed camera using modified real-time digital image stabilization (DIS) algorithm. Then the image motions during exposure of the primary imaging system are eliminated by micro-mechanical compensation on the focal plane assembly with detected motion vectors to achieve high precision positioning. An imaging system model based on the proposed concept is built with commonly used facilities. Theoretical analysis and experimental result show that the performance of the proposed concept is convincing.

1. Introduction

Airborne and space-borne imaging systems often suffer from unwanted motion disturbances during image exposures which limit the imagery resolution. High resolution imaging systems are especially sensitive to such degradations of the modulation transfer function (MTF) and geometrical distortions of the obtained images caused by focal plane attitude instability [1].

One common approach to overcome this problem is to minimize the vibrations produced by platform mechanics and to improve the positioning stability. Some Remote sensing satellites benefit this concept, but their costs are significantly increased [2], [3]. Another method is to stabilize the focal plane or optical axis during disturbances. Janschek et al. [1], [4] use an auxiliary matrix image sensor and an onboard joint transform optical correlation processor (JTOC) to measure real-time 2D image motion, and then image motion of the focal plane is stabilized by a 2-axis piezo-drive assembly [4].

An alternative way to measure 2D image motion is the digital image stabilization (DIS) technology which can be implemented with a small circuit [5] or VLSI [6]. Traditional DIS technology refers to measuring 2D inter-frame image motion and stabilizing the image sequences, without improving the imagery quality. Many DIS algorithms, such as traditional block matching algorithm (BMA) [7], bit-plane matching algorithm (BPM) [8], projection algorithm (PA) [9], feature tracking algorithm (FTA) [9], [10], optical flow based algorithms [11], et al. have been proposed. PA uses only one-dimensional waveforms in correlation, so it is of less computational complexity than standard frame-by-frame cross-correlation methods (BMA, BPM, etc), feature tracking methods and differential methods, and allows for real-time implementation [9]. Noise problem and low-luminance can be critical for remote imaging systems. Study has been made to evaluate the PA performance against noise and under-exposed imagery. The result indicates that PA is feasible with $1/2^5$ under-exposed images with certain random noises, so it is suitable for aerial photography and remote sensing. Furthermore, measuring accuracy can be improved dramatically to about 0.1 pixels with sub-pixel correction while standard PA only has integer pixel-level accuracy [12].

The paper presents a new image stabilization method by digital image motion estimation and micro-mechanical compensation to achieve stabilized focal plane attitude. Image motion is measured by the modified projection algorithm with sub-pixel correction and compensated by accurate piezo-electric actuated micro-displacement stage. Experimental results indicate that the proposed method is feasible for real-time image motion estimation and high-resolution image acquisition.

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2. The Proposed System Configuration

Fig.1 shows the configuration of the proposed image stabilization system. It mainly includes a motion estimation module and a motion compensation module. The motion estimation module includes an auxiliary high-speed matrix camera, a motion estimation unit and a processing unit. The motion compensation module includes a piezo-electric actuated micro-displacement stage, a micro-displacement driver and a control unit.

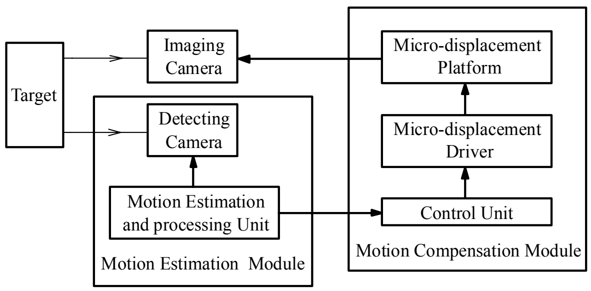


Figure 1. Image stabilization system

The concept combines the advantages of digital image stabilization technology with micro-mechanical compensation method. Low resolution images are obtained by the auxiliary high-speed matrix camera and 2D focal plane image motions are measured by the modified gray-scale projection algorithm with sub-pixel correction. Then the focal plane is moved in the reverse directions by the micro-displacement stage, in order to remove the unwanted motion. Thus, the disturbances caused by the platform instability can be stabilized.

3. Modified PA with sub-pixel correction

Projection algorithm is an accurate real-time motion estimation method [9]. Each incoming image is mapped into one-dimensional horizontal and vertical waveforms. Eq (1) is used to compute column projections. Row projections are computed in a similar manner.

$$Col_k(j) = \sum_i Cur_k(i,j) \qquad (1)$$

Here, $Col_k(j)$ represents the projection of the k^{th} image, j^{th} column; $Cur_k(i,j)$ is the $(i,j)^{th}$ pixel of the k^{th} input image.

Sum of absolute difference (SAD) is used to perform the correlation process where pixel-level image displacement is measured. SAD is of low computational complexity due to its simple form and multiplication free. Thus it is very suitable for parallel processing. SAD of two column projections can be calculated by

$$D_k(w) = \sum_{i=0}^{NC-1} \left| Col_k(i+w) - Col_{ref}(i+m) \right| \qquad (2)$$

Where $0 \le w < 2m+1$

Here, $D_k(w)$ is the SAD of the current column projection $Col_k(i)$ of the k^{th} image and the column projection $Col_{ref}(i)$ of the reference image; NC is the number of columns; the size of the search window is $[-m,+m]$; w is the shift variable. Integer pixel-level horizontal image motion can be obtained at minimum SAD value $D_k(w_{\min})$ by

$$\Delta x = m - w_{\min} \qquad (3)$$

Vertical image motion can be obtained in a similar way.

Parabola fitting over three correlation values is used to increase measuring resolution.

$$D_k(x) = a(x-m)^2 + b(x-m) + c \qquad (4)$$

Here, $D_k(x)$ is the correlation result of PA; m is the integer pixel-level estimate. The sub-pixel estimate achieved where the parabola fitting has its minimum. That is

$$\frac{\mathrm{d}D_k(x)}{\mathrm{d}x} = 0 \qquad (5)$$

From Eq (4) and (5), with three values around integer minimum ($D_k(m-1)$, $D_k(m)$, $D_k(m+1)$), sub-pixel estimate can be calculated

$$x = m - \frac{D_k(m+1) - D_k(m-1)}{2[D_k(m+1) + D_k(m-1)] - 4D_k(m)} \qquad (6)$$

x is the refined horizontal sub-pixel displacement between the current image and the reference image.

4. System assembly

To prove the feasibility of the proposed system, a hardware model has been built with common facilities (Fig.2). It includes an auxiliary matrix camera, a primary imaging camera assembly, a control circuit and a control center to record and process the image data. The key part of the system is the primary imaging camera assembly, including lens, an imaging CCD, a piezo-electric ceramics, a micro-displacement platform and a dark chamber (Fig.3).

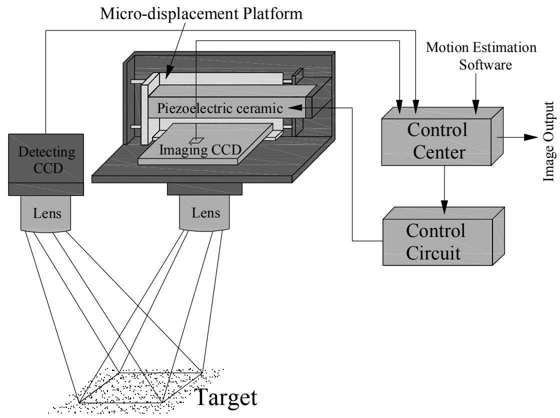


Figure 2. Hardware model of the Image Stabilization System

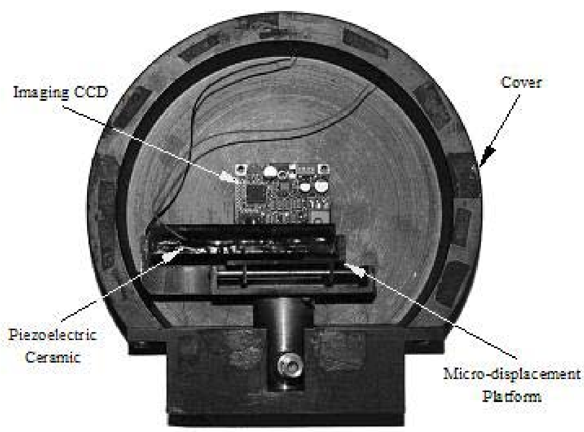


Figure 3. Model of the imaging CCD part

4.1. Motion estimation

The image stabilization model is depicted in Fig.4. During operation, the primary imaging CCD captures one frame (B1) while the auxiliary matrix CCD gets e.g. four frames (A1、A2、A3、A4). So, during one exposure of the primary imaging CCD, the auxiliary matrix CCD can perform motion estimation for three times. Motion vectors are calculated real-time by modified PA with sub-pixel correction. Meanwhile, real-time compensation using piezo-electric ceramics is applied. Thus, we can get high resolution image frames from the primary imaging CCD with stabilized focal plane attitude.

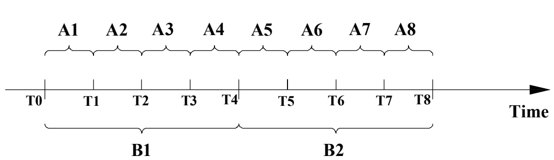


Figure 4. Image stabilization model

4.2. Micro-mechanical compensation

Piezo-electric ceramics [13] is an effective micro-displacement device. Converse piezo-electric effect and electrostriction effect occur when external electrical field is added. Compared with other micro-displacement devices, piezo-electric ceramics has many advantages. It does not need any transmission agent, and is very accurate and fast.

In the experiment, after the image motion vector is measured, piezo-electric ceramics is given a proper voltage based on the motion vector and the installation. Reversed micro-displacement is produced in order to compensate the focal plane image motion.

5. Experimental results and image quality evaluation

Experiment has been taken to prove the feasibility of the proposed image stabilization method using the proposed hardware model. Experimental results and image quality evaluation are presented below.

5.1. Experiment and test results

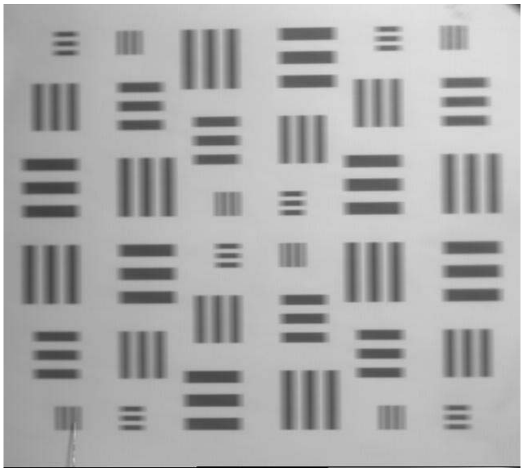
Tests had been performed on an optical table. Two 30mm zoom lenses were used for primary and auxiliary cameras. The frame rate of each camera was 24frames/s. The object distance was 1m. The maximum displacement of piezo-electric ceramics was 80μm.

In the test, only horizontal motion was compensated because of the limitation of the current structure (the vertical motion could be compensated in a similar manner).

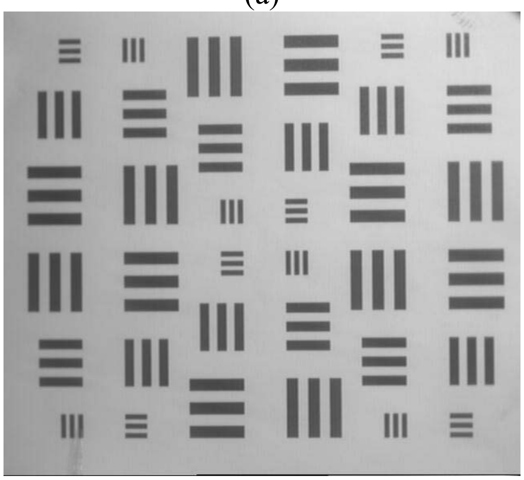
Object (a reprinted image) was set up on a motion platform providing user-defined motions. Two cameras were installed relatively static and parallel, and were calibrated.

During operation, the auxiliary matrix camera collected image sequences for motion estimation, in order to provide motion vectors for the piezo-electric ceramics. In the experiment (about 3 seconds), 70 frames were collected by the auxiliary camera and were added together and weighted averaged to get a motion blurred image without image motion compensation. Then, another 70 frames which were obtained by the primary camera were added together and weighted averaged to get a sharp image while image motion compensation was applied.

The motion of the target in the experiment was as follows. The amplitude of vibration was 1.5 mm (about 45μm on the CCD focal plane). The motion frequency was 3Hz. An example of the experimental results is presented in Fig.5.



(a)



(b)

Figure 5. Example of image stabilization on base of motion estimation and optical-mechanical compensation

5.2. Image quality evaluation

Firstly, we use subjective evaluation methods to evaluate the experimental results. Comparing the images in Fig.5, we could easily find out that the quality of the motion compensated image is better than that without motion compensation. In order to show the image motion more clearly, we add a reference object in the experiment. From Fig.5, we could see a needle at the bottom of each image. The needle keeps still during the experiment. The distorted image shown in Fig.5 (a) was captured without compensation. The focal plane of the primary camera kept still, so we could get a clear image of the needle while the target image is blurred. In Fig.5 (b), image motion was compensated, so the focal plane moved along with the object. On the focal plane, the image of the needle moved correspondingly. So we could get a clear image of the target, however, the image of the needle became blurred.

Secondly, the fidelity of the image stabilization technique is evaluated by the gradient function [14], which reflects tiny detail contrast, texture change and articulation of an image. The function is usually used to pick up edge information. The gradient function in common use is defined as

$$T(f) = \frac{1}{(M-1)\times(N-1)}\sum_{x=1}^{M-1}\sum_{y=1}^{N-1}\sqrt{(\Delta I_x^2 + \Delta I_y^2)/2} \qquad (7)$$

Where $\begin{cases} \Delta I_x = f(x+1, y) - f(x, y) \\ \Delta I_y = f(x, y+1) - f(x, y) \end{cases}$

Sharp images have a large number of sharp edge information, and the value of gradient function will be large. The gradient function value of the image in Fig.5 (a) was 4.9486. In Fig.5 (b), after applying the image stabilization method using digital motion estimation and micro-mechanical compensation to the imaging process a value of 7.8014 is produced. Image quality is significantly improved by using the proposed image stabilization method.

6. Conclusions

In this paper we have proposed a high resolution image acquisition method using digital motion estimation and micro-mechanical compensation. Using an auxiliary high-speed matrix camera and a primary imaging camera can we carry out real-time focal plane attitude position stabilization during image exposure. Experimental results on a hardware model prove the feasibility of the proposed method and it is suitable for airborne and space-borne imaging systems.

Further work will be focused on available very high-speed auxiliary cameras for image acquisition and accurate motion estimation. High-speed and precise micro-mechanical motion compensation models will also be studied and detailed system tolerance (noise, low luminance, etc) and performance (accuracy, system time delay, etc) will be examined.

7. Acknowledgment

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