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Image Restoration of Images Obtained by Near-Horizontal Imaging through the Atmosphere

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Abstract

Continuing experiments in restoring images obtained by telescope looking in a near horizontal direction close to the ground are discussed. The input data are from a time-sequence of short exposure image frames of a scene that are registered to a prototype to determine the warping as a function of the image coordinates. The prototype is initially an average of the whole sequence, being a motion-blurred but geometrically correct result. Each frame is then dewarped according to its derived warping function to remove apparent internal motion, and the new sequence is averaged to produce a new prototype having reduced motion blur.

Registration is carried out by cross correlation within a hierarchy of reducing windows or apertures in the prototype and the image frame to be registered. The effect is to "zoom in" on the relative motion at every pixel position within the image, obtaining x-shift and y-shift maps. The shift maps are used to dewarp the corresponding image frame. The resulting time-sequence of x-shift and y-shift maps also provides useful visualisations of the local directional tip and tilt behavior of the causal turbulence.

This paper discusses development of the algorithms in MATLAB, and commissioning of new telescopes and imaging equipment.

1. Introduction

Recently, we described a method of motion-blur restoration of images degraded by random, internal warping due to the effects of atmospheric turbulence [1-5]. The input data are from a time-sequence of short exposure image frames of a scene. Each is registered to a prototype to determine the warping as a function of the image coordinates. The prototype is initially an average of the whole sequence, being a motion-blurred but geometrically correct result. Each frame is then dewarped according to its derived warping function to remove apparent internal motion, and the new sequence is averaged to produce a new prototype having reduced motion blur. The registration and dewarping sequence is repeated again, based on the new prototype, producing a third prototype with less motion blur. The iterations may be continued, but we have found that, after the third iteration, there is usually little gain in quality.

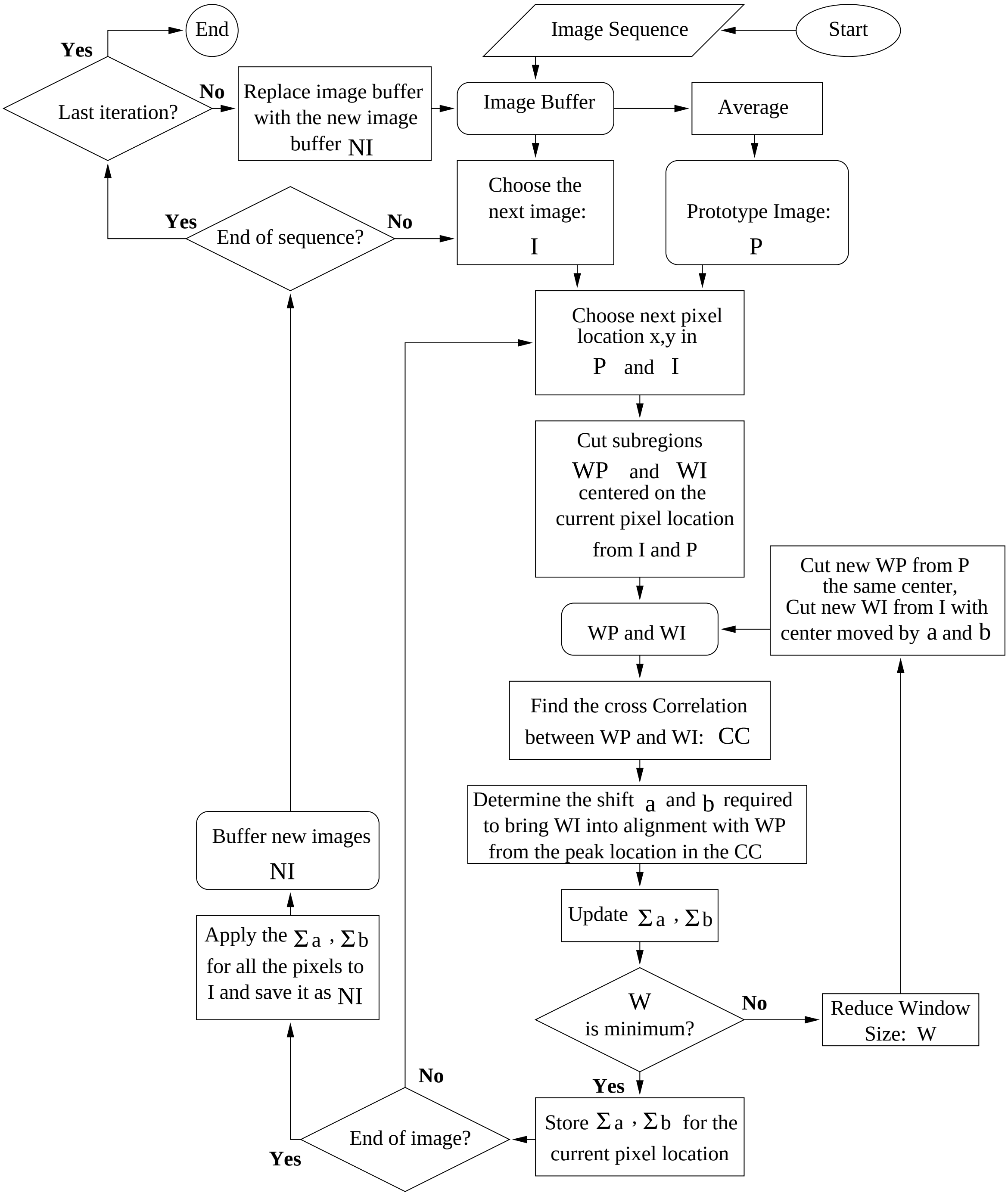
In our previous work, data are cross-correlated within a hierarchy of reducing windows or apertures in the prototype and the image frame to be registered. The effect is to "zoom in" on the relative motion at every pixel position within the image, obtaining x-shift and y-shift maps. The shift maps are used to dewarp the corresponding image frame. Interestingly, the resulting time-sequence of x-shift and y-shift maps also provides a useful visualization of the local directional tip and tilt behavior of the causal turbulence. We are also currently investigating other methods of registration (e.g., [1]).

In this paper we detail the algorithm, as it is coded for implementation in Matlab[6] data analysis software. This transfer of previous code from experimental Fortran base to the more commonly distributed Matlab code, makes the results more easily repeated and expanded upon by colleagues and other researchers, and allows us to investigate the relationship between data and ideal windowing functions, while making use of the other toolboxes that Matlab provides for data analysis. Since the processing effort on each frame is still well in excess of the inter-frame time, we are not yet concerned with optimisations for specific hardware, although with increases in computation capacity of modern computer hardware, the algorithm may soon be applicable in the realms of real-time post processing operation.

We also indicate the equipment, with which we obtained our horizontal imaging sequences, and bring readers up-to-date with our current work and equipment to improve on this acquisition phase. It is expected that new sequences with higher fidelity than those shown here, will have been acquired and analysed using this algorithm and its future modifications, by the time of presentation.

2. Algorithm

This method of motion-blur restoration that we describe in detail is illustrated in the following flow chart.



To process the acquired image sequence, whose individual images are distorted by different position dependent point spread functions, and are low in signal to noise ratio, we must first form a prototype image to register against. This process may be recursive, updating the prototype as each new image arrives, or it may be static in that the entire image sequence is averaged to form the prototype. In fact, one could recursively update the evolving or predetermined prototype with each corrected estimate of the correct image.

Note the averaging process is usually a Shift and Add algorithm [7] where the global shift is removed from each image before accumulating it on the prototype. A prototype for subsequent iterations might be formed using the corrected estimates as the input sequence, and averaging over these. The prototype then is a best estimate, with higher signal to noise ratio than the individual images, assuming the noise is zero mean, and the distortion holds to the central limit theorem. These are the only assumptions that are enforced in this algorithm.

The process of hierarchically correlating smaller and smaller windows of the current image with similarly decreasing regions of the prototype is then carried out. We use various types of Fourier based correlation algorithms to determine the shift, including Phase Correlation. These shifts at each stage may in fact be sub-pixelar, so interpolation using Fourier methods is usually employed. Of course, as size is reduced there is more chance of erroneous correlation, so a rule-based system must be employed to analyse the quality and correctness of the peaks. There are also some occasions where no feature information is present, i.e. the region is constant brightness, or linear in slope, so the quality of the peaks is an important rule for discarding a shift. We are researching many ways for characterising this quality, e.g. [11].

A natural way to drive the success of the correlation is to address the shape of the window function that defines the decreasing region. This also is necessary to remove errors introduced through spectral leakage. We have found in many studies that this management of the windows is data dependent, and the rate of reduction of these window sizes with respect to the iteration is important. It also may be necessary to shape the frequency domain representation of each image. The quantification of this is a matter of current studies.

The determination of the cumulative shift of each pixel in the image results in a shift vector for each pixel, which may then be used to inverse map the pixel to its estimated true location. However, this shift vector, may also be used to visualise the disturbance, and its evolution over time, such as is evidenced by the vectors overlaid on Fig 1. This may in fact prove to be a very useful application of this technology.

A final comment is necessary on the computation time of this post-processing algorithm. Clearly, such an algorithm lends itself too much optimisation. The rule-based system that terminates the iteration for window reduction based on quality of the peaks is crucial to increasing the speed of the process. Our Matlab code, presented online at http://www.ee.adfa.edu.au/widearea, is minimally optimised, so serves as a framework for investigation into the process, rather than fast execution of the final application. As computer hardware speeds increase, it will not be far in the future when a real-time implementation of this algorithm can be expected. Previous work undertaken on the first Apple PowerPC Macintosh computers took several hours for each image estimate. Currently, the entire 15 frame sequence can be processed in a similar time.

3. Experimental Equipment

The experimental work, which is the base of our research, is all conducted in our Electrical Engineering School. We have an observatory on the roof of our School and recently it has been upgraded to allow horizontal imaging as well as astronomical imaging. Our observatory dome contains a computer-controlled equatorial mount that can handle either a 0.4 m diameter, f8 Cassegrain telescope or a 0.4 m diameter, f4 Newtonian telescope. For our field work, we have a smaller Cassegrain telescope (14 cm diameter, f14) that DSTO has lent us. We have equipped this telescope with motorised drives on a portable tripod mount, so as to be able to use this in the field We are using two Pulnix megapixel (1024 x 1024 pixels) monochrome full-frame CCD cameras which use a progressive scan interline transfer CCD. They allow us to capture up to 15 frames per second with an exposure time of as low as a few microseconds, for a limiting sensitivity of approximately 1 lux. Generally, we use exposure times on order of 5 ms, such that atmospheric turbulence effects are frozen.

There is an overall project redevelopment for this equipment in order to create a more integrated system for real time capturing and analysis of the captured frames. We are developing a 500 frame per second, megapixel CMOS camera, to quantify the time interval over which the turbulent atmosphere is effectively frozen, and to aid in the acquisition of faster sequences. This time interval is generally accepted as approximately 10 ms for the less turbulent astronomical observations, but is most likely to be different in the daytime, horizontal imaging scenario. By the time of the presentation in January, we expect to have new data and new results to discuss.

4. Previous horizontal imaging results

The images in Fig. 1 and Fig. 2 were obtained with the Newtonian astronomical telescope mounted nearly horizontal. The original sequence was taken, using a

Pulnix 1001 digital camera over a field of view of 500 arc sec for the selected patch of 256 x 256 pixels. Exposure time for each frame was 5 ms, and the images were obtained through a red filter (Parkes No. 25). The object in view is a hut on a hillside about 6 km away, with the telescope pointing in a virtually horizontal direction, and with the optical path about 50 m above most of the intervening ground plane.

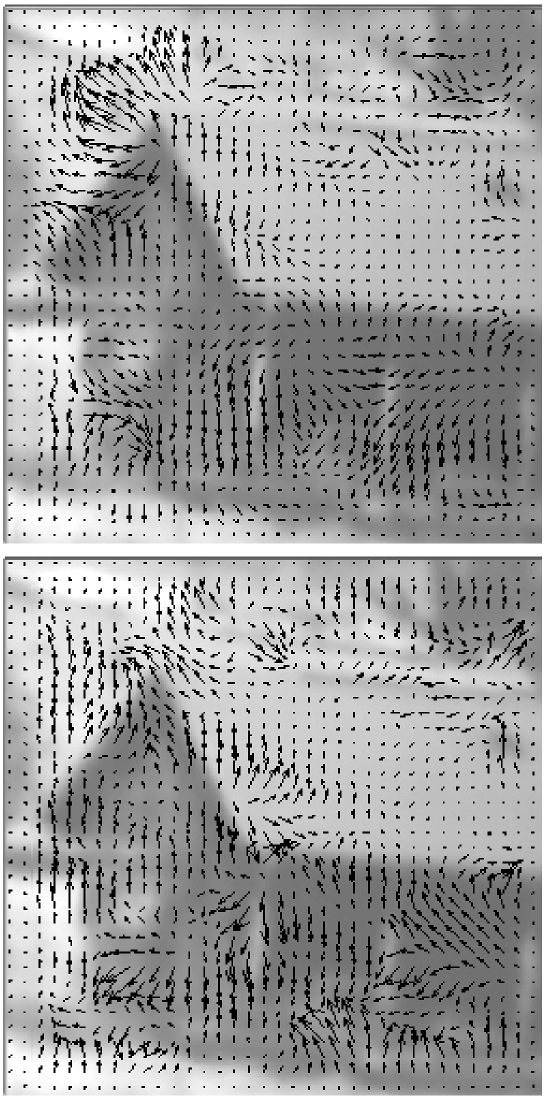


Figure 1. Two frames from a daytime image time sequence, showing derived shift motion vectors. The field of view is 500 arc sec; the hut is 6 km from the telescope while both are about 50 m above the intervening ground plane.

Figure 2. Top: A single frame from the same daytime image time sequence as in Fig. 1. Bottom: The motion-blur restored result (after further deconvolution by an average instantaneous point spread function).

The images in Fig. 1 have the hut image as background with shift vectors superimposed. The shift vectors were derived by registration of two frames of the time sequence to the iterated, best average prototype.

Figure 3. Single frame from a recent telescopic sequence obtained over a horizontal distance of 10 km. Frames from the sequence are to be processed by the method discussed.

A typical raw frame of the hut sequence is shown at left in Fig. 2. Observation of the sequence as a movie highlights the typical geometric distortion introduced by the atmosphere between the camera and target, but unfortunately this cannot be easily illustrated on paper. A restored result based on the complete image sequence is shown in Fig. 2, on the right. It is interesting to note that cars parked beside the hut are almost indistinguishable in the raw image, but are so clear in the restored result that any car enthusiast could probably tell their make and model. Also, there appear to be ladders or scaffolding on the left wall of the hut that are simply a blur in the raw frame. It is also a tribute to the human eye-brain combination that one can imagine this information in the distorted sequence during playback, particularly with the restored image as a-priori information. Clearly, though this information is not discernable in each snapshot, even with this assumed knowledge.

To obtain the restored result, the frames of the sequence were used to create a motion-blur compensated result, by the iterative registration method discussed in the section 3. One consequence of this process is that any residual non-motion blur, e.g., due to the directionally varying higher order curvatures of the wavefront, changes from being position variant in an individual frame, to being position invariant in the composite. An iterative, blind deconvolution method was used to further restore the image to the result on the right of Fig. 2.

5. Conclusions

Restoration of images obtained through atmospheric turbulence has been of great interest for several years (e.g., [7-10]). The registration and dewarping method, which we have described here in terms of Matlab code, works well for certain atmospherically degraded images. These are those that show mainly a random, internal warping (or motion in a movie sequence) due to the direction dependent tip and tilt of the wavefront following its passage through different regions of turbulence. Since the method relies on pattern matching for registration, it will have difficulty when there is little pattern information present, and in fact analysing this difficulty proves to be the success or failure of the algorithm. Analysis of the quality and correctness of the correlation peaks is paramount to the success [11]. Incidentally, the method will fail in parts of the image if the turbulence is so bad that the resulting warp causes cross-over and consequent scrambling of image data.

Preliminary results also suggest that multi-path scintillation can cause problems, particularly by introducing two or more strong peaks in the correlation process, and hence a one-to-many mapping by the distortion. In horizontal imaging this situation often occurs with glint off metallic objects such as tail edges on aircraft, for example. This however, confines itself through natural processes to bright, small regions of the image.

The method described herein only restores internal motion blur. It does have the effect of making an otherwise position varying instantaneous point spread function due to higher order wavefront distortion into a position invariant, average point spread function, which allows a subsequent deconvolution restoration to be applied, if the average PSF can be estimated (as shown by the right image of Fig. 2).

It is expected that new data and new results, using more efficient and better registration methods will be available by the time of the presentation in January. In the future, we also plan to look at the possibility of some form of adaptive optics being used in this type of imaging. Because of the position dependent nature of the PSF, adaptive optics and wavefront estimation will be somewhat different from that applied to current systems.

10. References

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