Literature Review: Mitigation of Atmospheric Turbulence Impact on Long Distance Imaging System with Various Methods

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Abstract: ***A consequence of non-stationary random distribution of refractive index in layer of atmosphere is air turbulence. Numerous methods have been developed to mitigate the impact of turbulence on performance of imaging system. This paper is a comprehensive, critical review of atmospheric turbulence; nature, cause and impacts on imaging with distance and exposure time, We present existing restoration algorithms and MEMS/MOEMS based adaptive optics to correct geometric deformation and time-/space-varying blur with their results to get high quality image from image sequences or videos affected by turbulent flow of air in atmosphere.***

Keywords: Atmospheric Turbulence, Kolmogorov model, Image Processing Restoration Algorithms, MOEMS, Adaptive Optics

1. Introduction

Since atmosphere must be considered as transmission path of any optical system therefore its impact as perturbed wave-front by turbulent flow of air is also meaningful to performance of any long-distance (ground based and space based) imaging systems [1] [2]. In the last decade such systems have been developed to improve target identification. When a target is small and moving, its actual location becomes very difficult to estimate in the presence of atmospheric turbulence. The visual effect of atmospheric turbulence causes geometric distortion and time varying blur in images [3], [4], [5], [6], [7]. Before mitigate the impact of atmospheric turbulence in imaging systems, the first step is to characterize turbulence nature and its causes with theoretical studies and experimental measurements [8]. Then modeling of imaging process is discussed. Distorted images due to turbulent atmosphere can be restored or reconstructed by numerous methods [6], [7], [9], [10], [11], [12], [13]. Three broad classes of techniques used to correct turbulence effects have performance limitation as well as hardware and software requirements. Pure post-processing (*Image processing*) method: Restoration algorithms and Pre-processing (*MEMS based adaptive optics*) are discussed in this review paper. This paper is organized as follows: Section II describes the atmospheric turbulence with theoretical model (*Kolmogorov* theory [14], [15]) and experimental measurements of turbulence effect on optical transmission path. Image processing model of undistorted image with geometric deformation matrix, blurring matrix and additive noise is given in section III. Different Pre- and Post- processing techniques to restore undistorted image are also presented in this section. Finally we conclude and discuss the future scope of this *literature survey* in section IV and V.

2. Atmospheric Turbulence: Nature and Its Causes

Atmosphere of earth is a medium with non-homogenous distribution of temperature, density and air pressure. It emits, absorbs and refracts radiation. The presence of winds and thermal currents which continuously create eddy air currents causes atmosphere may therefore be thought of as a large number of regions of various dimensions called eddy as shown in Fig1. Each eddy is a patch of air over which the temperature and refractive index deviates from the average [8] causes turbulence with position and time. This Atmospheric turbulence has been studied by a numbers of authors [4], [16], [17], [18], [19], [20]. It is an evitable problem**.** By nature it is dynamic, random and very complex phenomenon [14]. It is caused by many different phenomena: *convection*, *wind shear* and *wind over objects* [14]. Convection leads "*seeing*" effects. Wind shear leading to a tubulent layer and wind over objects or telescope dome induces turbulence.

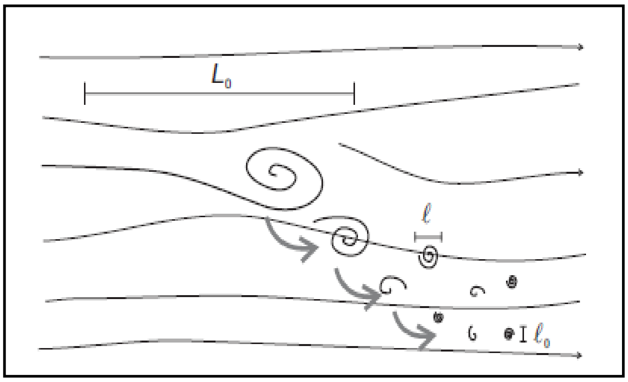


Figure 1: Illustration of the emergence of turbulence in the atmosphere [34**].** Large-scale wind flows of size L_0 turn unstable. The resulting eddies of dimension *l* sequentially disintegrate, a process that continues down to the damping scale l_0

Kolmogorov's Two-Thirds Law

Atmospheric turbulence causes effects on optical waves which have been of great interest to scientists for many years. The phase of a wave that has propagated through turbulence is a space- and time- varying random process. Although random processes are typically described by correlation functions, in atmospheric science structure functions are typically used. A structure function is the mean square difference between the two values of a random process [14]. Statistical character of refractive index is measured as refractive index function D_n [21]:

$$D_n = \langle [n(A,t) - n(B,t)]^2 \rangle$$

where n(A, t) and n(B, t) are refractive indexes in the point A, B and in time t. Refractive index structure parameter is in the relation with the distance r between points A and B, according to two-thirds power law derived by *Kolmogorov* [14], [22], [23] the refractive index structure function is

$$D_n = \begin{cases} C_n^2 \cdot r^{2/3} & l_0 \ll r \ll L_0 \\ C_n^2 \cdot l_0^{-4/3} r^2 & r \ll l_0 \end{cases},$$

where C_n is the refractive index structure constant. The refractive index fluctuations results mainly from the fluctuation from temperature in the atmosphere. The structure function of temperature in the atmosphere also follows a two-thirds law: $D_T(r) = C_T^{\,2} r^{2/3}$

where C_T is the temperature structure function constant. When wave-front passes through the atmosphere, refractive index variations of air may perturb it in both amplitude and phase. Phase variations are dependent on altitude, temperature, rate of energy per mass dissipated by viscous friction, sheer rate of wind and so on. Working with a multiparameter function is problematic and thus simplified model of optical transfer function: OTF was derived by *Hufnagel* and *Stanley* [24]. In theoretical derivations, the optical strength of turbulence is represented by C_n, refractive index structure co-efficient [14]. The majority of papers in the published literature have been primarily concerned with the development of a theory of atmospheric turbulence and its effect on the performance of optical systems. First attempts to measure the resolution through a turbulent atmosphere were made by *Riggs* et al [8], the angular deviation was determined. Using a similar technique, the experiments of *Smith* et al [8] have shown that the extent to which turbulence degrades the photographic resolution is markedly dependent upon the location of the disturbance along the optical path. Turbulence near the camera significantly reduces the mean resolution, while the same turbulence located at the target end of the optical path has little or no effect.

Degradation Due To Turbulence

Atmospheric turbulence is a well known source of distortion that can degrade the quality of images and videos acquired by camera viewing scenes from long distance so as the performance of long- distance imaging systems can strongly degraded [4], [10] over propagation distances that exceed several kilometers, it is difficult to evaluate the impact of turbulence because of terrain variability. The variation in amplitude and phase of optical beam leads to several terms: *scintillation* (brightness variations due to local fluctuations in amplitude) [8], *speckles* (multiple copies) [14], *image dancing* (beam wandering/steering) [8] and *shimmering* (apparent distortion) [8] in imaging. These terms are responsible for blurring and geometric distortion in imaging through turbulence. Degradation in imaging may occur in many other scenarios [25], for example- underwater imaging systems are subject to scattering effects and video shooting in summer suffers from hot air near the ground and so on.

Fig 2 [25] shows some examples obtained by a camera in real scenarios.

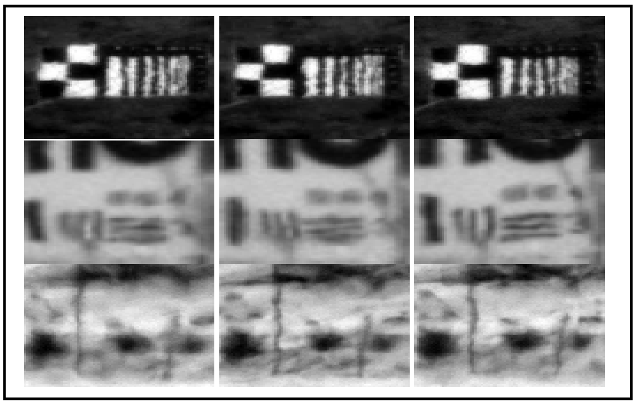


Figure 2: Sample images. Each row contains three arbitrary frames from different testing turbulence videos [25]

3. Image Processing Model And Methods To Mitigate Atmospheric Turbulence Impacts

The optical effect of turbulence arises from random in-homogeneities in the temperature distribution of the atmosphere and consequence of this is non-stationary random distribution of refractive index in atmosphere [26]. It produces geometric distortion, space- and time- varying blur and some time even more blur if the exposure time is not sufficiently short [3], [4], [5], [6],[7]. The imaging process in turbulence can be modeled as [12]

$$\mathbf{g}_k = \mathbf{B}_k \mathbf{F}_k \mathbf{z} + \varepsilon$$

where z denotes the ideal image without turbulence distortion or blur, F_k and B_k represent the deformation matrix and the blurring matrix respectively, ε denotes additive noise, and g_k is the k-th observed frame. Three broad classes of techniques used to correct turbulence impact are: (1) *Pure post-processing* (signal processing) approach, which use several specialized image processing algorithms [6], [7], [10], [11], [12], [13]; (2) *Hardware based* adaptive optics approach, which afford a mechanical means of sensing and correcting for turbulence effects [9]; (3) *Hybrid* approach, which combine the elements of image processing techniques and adaptive optics techniques. Each of the above approach has performance limitation as well as hardware and software requirements. In our literature survey due to its low cost, we firstly focus on the survey of pure post-processing methods to mitigate atmospheric turbulence effects. And later on we resent a review of adaptive optics also.

In the last two decade several algorithm have been developed to solve the problem of geometric distortion and blur [6], [10], [11] and since the information in a single frame is usually insufficient to recover high quality image, all these works are based on videos or image sequences [12]. For example, in the article [6] an experiment is provided to illustrate that the local turbulent motion has a zero-mean Gaussian distribution, and thus the geometric distortion can be removed by simply averaging the observed frames. Such averaged image, though even more blurred than the original data, can serve as a reference frame to register each observed frame. Generally, existing restoration algorithms for imaging systems to restore a single high quality image from the observed sequence or videos can be divided in to two main categories. One category is based on *multi-frame reconstruction algorithms* [6], [12]. These algorithms first requires a non rigid image registration method to register each observed frame with respect to a turbulence free grid and use the registration parameters to estimate the corresponding deformation matrix F_k [27]. Then a sharp image is reconstructed through a Bayesian reconstruction method. The main problem for multi- frame reconstruction algorithms is that in general they hardly estimate the actual point spread function (PSF), which is spatially and temporally changing.

Another class of approaches called *lucky imaging* includes lucky framing and fusion algorithms to reduce the blurring affects [7], [11], [28], [29]. The image selection technique used to find lucky frames (frames of best quality) and output image is produced by fusing these lucky frames [28], [29] hence named as lucky imaging. The problem of this approach is the very low probability of existence of a whole high- quality frame. It is favored for *isoplanatic* scenarios- a small angle that can be viewed as containing space-invariant blur [7]. For *anisoplanatic* scenarios *Vorontsov et al.* [30] proposed “lucky region” restoration algorithm where it is shown that for short-exposure images turbulence creates “mutations” in the local image quality and randomly makes some regions sharper, which are called lucky regions. Theses lucky regions then fused to produce a high quality output image [30], [31], [32] as shown in Fig 3 [30].

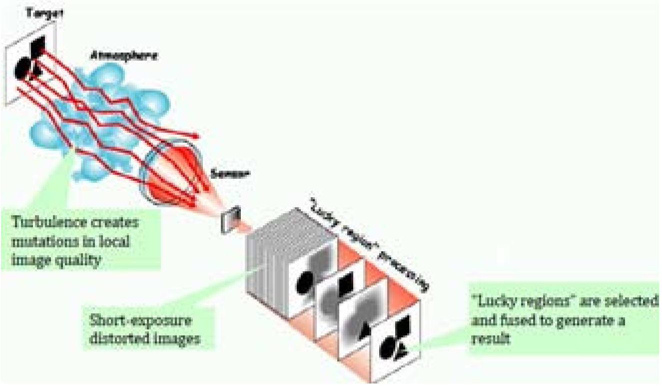
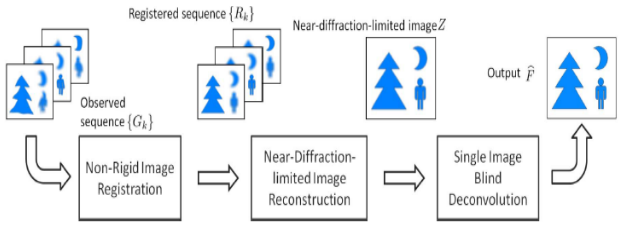
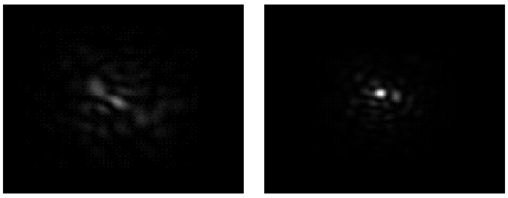


Figure 3: Lucky-region fusion approach [30]

A difficulty with this method is again the low probability of the appearance of lucky regions. Although high-quality regions happen more frequently than high-quality frames, this method generally requires a large number (usually hundreds) of frames to create one single sharp image. Another problem is that this method is applicable only for short-exposure videos, while for long-exposure videos motion blur makes the lucky regions too rare to be useful. Even though turbulence caused blur is strongly alleviated through the fusion process, the output still suffers from the blur caused by the diffraction-limited PSF as shown in fig 5. In [27], [33] *Xiang Zhu* and *Peyman Milanfar* proposed a new approach: *Removing atmospheric turbulence via space-invariant deconvolution* to correct geometric distortion and reduce space- and time- varying blur capable of restoring a single high-quality image from a given image sequence distorted by turbulence. This new framework is proposed for restoring a single image in anisoplanatic scenarios. The 3-D physical scene is assumed to be static, while the air between the scene and sensor is affected by atmospheric turbulence. This approach is designed to reduce the space and time-variant deblurring problem to a shift invariant one. It focuses on the observed regions convolved by near-diffraction-limited PSFs, which can be viewed as space and time-invariant. Fig -4 is the block diagram of their proposed approach [33]. Experiments show that this frame-work is capable of alleviating both geometric deformation and blur, and significantly improving the visual quality.





(a) (b)

Figure 4- Block diagram: Removing atmospheric turbulence by space-invariant deconvolution [33], Fig 5-PSF examples: (a) an example of PSF caused by air turbulence; (b) an example of near-diffraction-limited PSF [27]

Review of Some real video data tested to illustrate the performance of the [27], [33] proposed restoration framework by *Xiang Zhu* and *Peyman Milanfar* shown. The existing restoration algorithm of multi-frame reconstruction approach [12] and lucky imaging [30] tested data are also shown as comparison. The first set of images (410 ×380 × 80) show the Moon surface imaged from a ground based telescope (see Fig 6[27] (a). From (b) we can see that though the output image of lucky imaging looks slightly sharper than one of the observed frames, it is still quite blurry probably due to the diffraction-limit blur and the limited number of frames. Multi-frame reconstruction algorithm provides a better result but with some details (small craters) vanished (Fig. 6 (c)). The approach [33] gives a significant improvement in visual quality (Fig. 6(d)). It successfully removed blur and meanwhile recovered many small craters on the surface that can hardly be seen from either original frame or the outputs of other two methods.

The term adaptive optics-AO refers to an optical system that correct aberration introduced along the propagation path in atmosphere of imaging system. The main purpose of this pre-processed or hardware based technique- AO is to physically compensate for distortion of air turbulence, thereby improving image quality. A typical AO system (as shown in fig 7[36]) is a combination of a wave-front sensor that measures the aberrations; a control system that reads the wave-front sensor and calculates and applies correction and a corrective element that physically change the impinging light in order to remove aberrations caused by distorted wave-front.

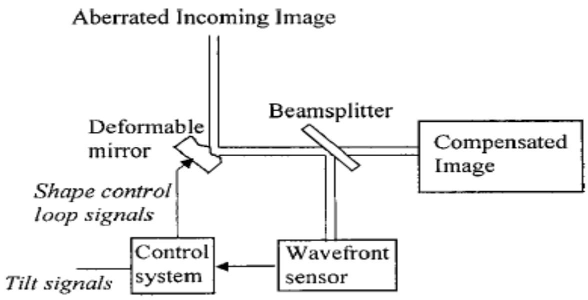


Figure 7: AO imaging system [36]

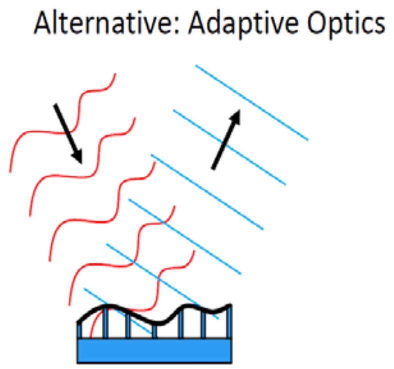


Figure 8: correcting element –DM [30]

The most common type of correcting element in adaptive optics is deformable mirror (DM) i.e. a flexible mirror with actuators, usually piezo-electric, that can deform the surface of the mirror to the phase conjugate of the aberrated wave-front, removing or greatly reducing the aberration in the reflected light as shown in fig 8 [30].

Such system while very successful in the past decades, have also proven extremely bulky, costly and complex to operate. The use of MEMS technology in optics termed as micro-opto-electro-mechanical systems-MOEMS and the DM of MOEMS technology in AO results a reduction of cost, complexity and weight. A standard AO system requires large optical benches, several racks of dedicated power supplies and computer equipment. By the use of MOEMS devices all the full functioning AO system can fit in to a single enclosure and made AO portable.

4. Discussion

In this literature survey we discuss the turbulence; its nature, causes and impacts on optical transmission path of long distance imaging systems with turbulence theory "*Kolmogorov*". The discussed impacts of atmospheric turbulence, geometric deformation and time-/space- varying blur can be reduced by three different approaches each of which has performance based and software/hardware based limitations. Like software based approach is of low cost which we discussed with restoration algorithms: multi-frame reconstruction, lucky-imaging along their shortcomings and "*Removing atmospheric turbulence via space-invariant deconvolution*" [33] which is recent one restoration algorithm is discussed with review of their experimental data. A pre-processing approach of MEMS based AO is also a part of this literature survey. In the end, we conclude that a hybrid approach of pre-processing and post-processing may effectively reduce the impact of air turbulence on imaging.

5. Future Scope

We can implement the best algorithm after pre-processing approach of MEMS-DM based AO to reduce deformation and blur caused by atmospheric turbulence (non-stationary random fluctuations in refractive index of air), recovering details of scene and significantly improve the visual quality. By the use of hybrid technique fidelity of long distance ground/space based imaging may improved. Also such approach can be implementing to remove other environmental degradations.

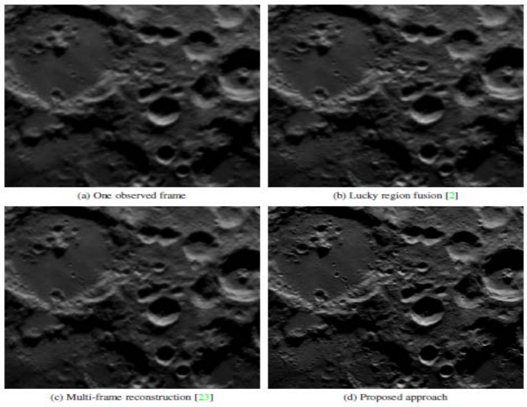


Figure 6: Image reconstruction result using 80 frames taken from the video *Moon Surface* distorted by real atmospheric turbulence [27]

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