Mosaic active imaging: direct physical modelling and image reconstruction

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Abstract: This paper presents a new active imaging sytem. Its performances are evaluated with an end-to-end simulator realistic in terms of turbulence effects. It performs a sequence of synthetic images. Reconstruction methods restore the scene from sequence of images.

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1. Introduction

Active imaging can be used for surveillance or target identification at long range and low visibility conditions. Its principle is based on the illumination of a scene with a pulsed laser which is then back-scattered to the sensor. When compared to passive imaging, the signal to noise ratio and contrast of the object over the background are increased. Even though, range and Field of View (FOV) are limited for a given peak laser power. In order to overcome these limitations, a new concept of active imaging system has been developed at Onera. It is based on the acquisition of the entire scene with a high-speed scanning laser illumination on a limited region to increase the irradiance, whereas at each scan the full frame active image is acquired. The whole image is then reconstructed by mosaicking from composite image of all these successive images (Fig. 1). In order to assess the performance of this new active imaging method compared with the conventional one's, a better knowledge of the propagation through the atmosphere of low divergence laser beam and a prior work to restore the whole image from such a mosaic are required. This paper gives an overview on the status of this work. A first evaluation of the performance of this system is conducted by using

Fig. 1. Left to right: the mosaic laser imaging process, the ideal image we want to estimate, a reduced part of the field of view with a single laser flash, the image composed from all laser shots where each pixel is assigned with its maximum intensity over all of them.

an end-to-end simulator. It includes the forward chain: modeling of the source, transmission through the atmosphere, interaction with a synthetic scene and then the transmission of corresponding simulated signal to the sensor. The inverse chain is then described to retrieve the total scene. A restoration processing that fall within the Maximum A Posteriori (MAP) framework, is described to overcome the artefacts introduce by the mosaic active imaging concept. Finally, the results are then compared to the performance of a full scene active imaging system.

2. Mosaic active imaging

2.1. Forward Physical Modelling

The end-to-end model presented here is based on a initial work on the flash laser imaging system published in [1]. It includes all the physical components: the laser, the deflection laser, the target, the outbound and inbound atmospheric paths and the camera. The model simulates the principal phenomena: the scintillation, the beam spreading, the beam wander, the beam jitter, the speckle, the interaction with the target and the camera noises. It is based on an approach for laser beam propagation simulation through turbulence that is simpler and faster than the commonly used numerical end-to-end model. The approach adopted to simulate images from a mosaic active imaging system is showned in

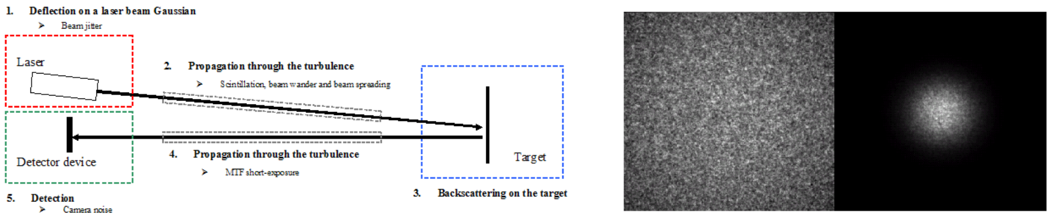

Fig. 2. On left : Approach adopted to study a mosaic active imaging system. On right: Results beam profiles generated by simulation: beam divergent (left), beam slightly divergent (right). The images were taken at measured C_n^2 value of $1.10^{-14}m^{-2/3}$. $L = 1km, \lambda = 1,57\mu m$

figure 2: 1- The source emits a laser beam which is assumed to be gaussian. 2- During its propagation through the atmosphere, the non uniformity of the laser beam intensity distribution is induced by atmospheric turbulence effects. To simulate this instantaneous turbulence effects on the propagated laser beam, we have developed a method based on the dissociation of scintillation from beam spreading and beam wander which appears to be justified in weak perturbation regime [2]. 3- The reflected intensity is obtained by multiplying the laser map with the target image appropriately selected and scaled. 4- The reflected laser beam propagation is retrieved by applying of the short-exposure Modulation Transfer Function (MTF). 5- Then, we apply the detector MTF and we add different camera noises. The output image is re-sampled in order to have the same dimensions as the camera array. Examples of the instantaneous beam profiles generated by our simplifed model are shown in Figure 2. The validity of this model was checked by comparing the results to those obtained with a numerical end-to-end propagation model called Pilot (Propagation and Imaging, Laser and Optical through Turbulence) based on a split step algorithm and developed at Onera [3]. A first validation by comparison of the mean amplitude, the Power Spectral Density (PSD) and the probability distribution with Pilot has been presented in [2]. In the case of spherical wave in the weak perturbation regime, a good accordance between both methods is presented. A second validation by comparaison of the beam radii and the scintillation index with Pilot is being published.
The work allowed us to estimate the difficulties of total scene restoration and qualitatively pre-evaluate the influence of physical parameters on the final results.

2.2. *Images reconstruction*

The restoration of the whole image from k acquired images with this new active imaging system is an inverse problem. The observed image v_k of the ideal image u (i.e. the one that would have been obtained with a non gaussian) at the focal plane of the detector is given by:

$$v_k = M_k u + n \tag{1}$$

where n is a corruptive noise process and M_k an operator. Note that the operator M_k needs to be estimated, $\forall k \in \{1,\ldots,K\}$, because all the acquisition parameters are not essentially the same as soon as there are some atmospheric perturbations. The restoration algorithm consists in alternatively estimating of these acquisition parameters and the image. The estimation of the whole image relies on the minimization (or maximization) of a criterion. To solve this problem, we first have considered an additive Gaussian white noise. We assume a Gaussian prior on the acquisition parameters and a Total Variation (TV) prior on the distribution of images [5]. Based on these assumptions and given a number k of acquired images v_k, the MAP estimation is calculated by minimizing the criterion $J_1(u)$ defined as follows:

$$J_1(u) = \frac{\|v - M_k u\|^2}{2\sigma^2} + \lambda TV^2(u) \tag{2}$$

where σ is the noise variance and λ is a regularization parameter. The criterion of Eq.(2) is minimized numerically to obtain the joint MAP estimate for the ideal image u. The minimization is performed by a standard gradient descent algorithm. This work allowed us to give a first solution to this problem. In the second instance, a fine noise model that accounts for both photonic and detector noises is considered. The photon noise follows Poisson statistics and the detector noise follows Gaussian, and approximately stationary, statistics. Here we change the quadratic regularization term which is the Total Variation by a quadratic-linear prior recently applied to imaging through turbulence [5]. The MAP estimate is calculated by minimizing the criterion $J_2(u)$ defined as follows:

$$J_2(u) = \sum_{l,m} \frac{\|v - M_k u\|^2}{2\sigma^2(l,m)} + \mu\delta^2 \sum_{l,m} \phi(\nabla u(l,m)/\delta) \tag{3}$$

where $\phi(x) = |x| - ln(1+|x|)$ and $\sigma^2(l,m)$ is the sum of the photon noise and the detector noise variances. The global factor μ and the threshold δ are adjusted according to the noise level and the structure of the object. Here the minimization is performed by a conjugate-gradient method, which is usually recognized to be faster.

3. Simulation results

The modeled mosaic active imaging system has the following parameters: an $800\mu J$ energy per pulse at $\lambda = 1,57\mu m$, an $0,8mrad$ divergence of the laser beam, an $33\mu rad$ FOV camera. In figure 3, we illustrate the results given by the restoration algorithms. For each image of size 256×256, we generate $k = 64$ images. The object of interest typically has metric dimensions and lies between $1km$ and $10km$ from the imaging system. The performance of this

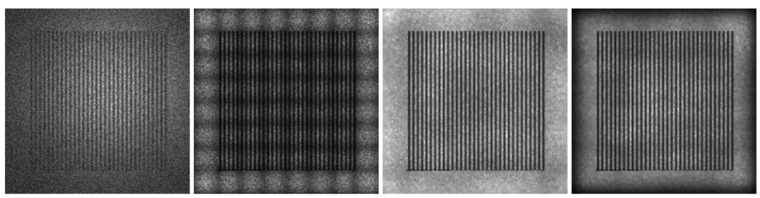

Fig. 3. Left to right: Image with conventional flash system; Resulting image of scan system, where each pixel assigned with its maximum intensity of scanned images; Reconstruction with the first algorithm using gradient descent; Reconstruction with the second algorithm using conjugate-gradient. The images were taken at measured C_n^2 value of $1.10^{-15}m^{-2/3}$. $L = 1km, \lambda = 1,57\mu m$

new concept is compared to those of a conventional flash active imaging camera by using usual metrics and will be presented. For each sequence, we measure the Signal to Noise Ratio (SNR), the Power Spectral Density (PSD) and the image histogram. We studied the influence of the different physical parameters on the quality of the image. Then, we quantified a gain in terms of range and field of view of this new concept for various mean laser powers.

4. Conclusion

An approach to model the a mosaic active imaging system has been proposed. It allows to provide good instantaneous laser illuminations with limited computational resources. Two methods to restore the observed scene are proposed and compared. Quantifying gains expected in terms of range and field of view of this new concept for various mean laser powers are currently investigated. Future work on full validation of the gains of the new system will required by checking model results with experiments results from an active imaging system.

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