High-frame Rate Wavefront Sensor Based on Flexible Read-Out Technique for C-MOS Image Sensor

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Abstract— **In this paper, high frame-rate Shack Hartmann wavefront sensor with a C-MOS image sensor is presented. To realize high data rate wavefront sensor we adopted the flexible read out technique on C-MOS sensor, which makes it possible to reduce not only the amount of Hartmann spot but also image size. In the preliminary experiments, we have successfully obtained 10x10-Hartmann diagram with a rate of 4 kHz, leading to a high frame-rate wavefront sensor.**

Keywords—free space communication;adaptive optics; CMOS image sensor; wavefront

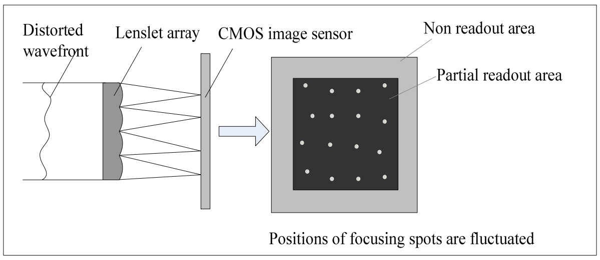
I. Introduction

In late years, the data quantity of observation sensors is significantly increasing because of requirement of higher resolution and more wide area of observation[1]. For such requirement, it is effective to apply optical telecommunication technology to free space optical communication (FSO)[2]. The advantage of FSO is not only broadband but also extremely narrow beam for high security and downsizing of the antenna, because of shorter wavelength than micro wave for conventional RF communication. FSO technology has mainly used for data link between two satellites, one is the data relay satellite in geostationary orbit (GEO), and the other is the user satellite in low Earth orbit (LEO), and space to ground data link has almost depended on RF communication. One of issue for space to ground FSO data link is wavefront distortion of laser beam caused by atmospheric turbulence[3]. The wavefront distortion in such optical wave propagation is severely impact for performance of FSO such as degradation of BER. An optical compensation method with adaptive optics technology (AO) is one of the solution for such wavefront distortion caused by atmospheric turbulence in light wave propagation. The AO is technology incorporate the wavefront sensor which measures distorted wavefornt profile caused by atmospheric turbulence and deformable mirror which compensates the wavefront profile to desired shape with high speed control bandwidth. A study of AO devices was started with application to astronomical observation using ground based telescopes. In a control bandwidth for such ground based telescope, a few hundreds to a few kilo Hz order is required. In case of FSO, more severe condition caused by fluctuated atmosphere depending on site of ground station is prospected. Therefore, the speedup of a wavefront sensor for AO devices is an important issue. Shack Hartmann wavefront sensor (SHWFS) is one of the most popular wavefront sensor because of insensitivity under environmental vibration, high sensitivity, and unnecessity of coherent light source like interferometer[4][5][6]. SHWFS has a lenslet to generate Hartmanngram (many focused spots) associated with local tilt of incidental wavefront and photo-detector to imaging. SHWFS can be used for analysis of lens system aberration, measuring laser beam quality, and AO devices. Although SHWFS with conventional imaging sensor, like CCD or CMOS imager, is used for an AO (Adaptive Optics) system, their data-rate is limited due to frame rate of the above image sensors. For suppressing atmospheric turbulence, an image sensor of SHWFS must operate with much faster framing rate than the Greenwood frequency. In case of CCDs, 4 kHz frame rate is required depending on the delay time caused by sequential process of accumulating electrons and readout. One of the solutions of fast framing is using photodiodes, like PSDs (Position Sensitive Detectors) or QDs (Quadrant Detectors). But we have not accepted the solution, because such photo-detectors have disadvantage on sensitivity with background noise, narrow dynamic range, and poor linearity of tilted wavefront. We have newly developed SHWFS with improved frame rate, which has CMOS image sensor capable of changing readout format adaptively. In this paper, the concept of design, the system design and test results of our SHWFS are discussed.

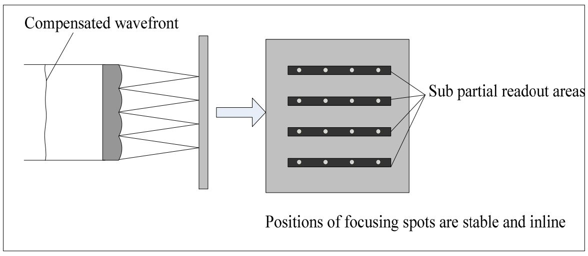
II. Concept Design

It is well known that it is effective to reduce the number of pixels for readout in order to improve frame rate. We have combined following two approaches to reduce number of pixels for readout. The first approach is simply reducing number of the sub-apertures corresponding to each focused spot on Hartmanngram. The second approach is reducing number of pixels including each focused spot. The most pixels are not used for signal processing; nevertheless they waste considerable time for readout. In case of SHWFS in AO system, focused spots are considered to exist constantly and stably on some specified pixels while the closed loop control is adequately effective, it is expected to reduce frame time applying above-mentioned idea. Based on this idea, we composed our prototype SHWFS to readout specified multiple partial areas (we call them “sub partial areas”) any of which was rectangle shape including focused spots in a line. Fig.1 shows the examples of two readout modes: (a) wide dynamic range mode and (b) high speed mode. Note that it is possible to change whether the above readout modes. (a) and (b) flexibly depending on amount of wavefront error.

III. System design



(a) Wide dynamic range mode



(b) High speed mode

Fig. 1. The concept of two readout modes for speed-up

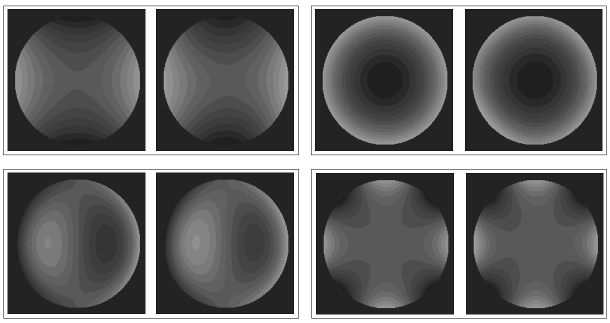
The basic specification of prototype SHWFS is shown in Table I. We specified spatial resolution of the SHWFS to the fourth order Zernike mode taking into account of the deformable mirror which we are developing. Although ideal minimal number of the sub-apertures is 8 x 8 based on sampling theory, we determined 10 x 10 considered with an alignment margin. The image sensor of the prototype SHWFS has 512 x 512 pixels, pixel pitch is 20 micro meter, and lenslet pitch is 300 micro meter. In normal condition, the footprint area of 10 x 10 sub-apertures including 152 x 150 pixels is partially readout (partial readout mode). In case of sub partial readout mode, the rate of reducing readout time, R_1 , is characteristic with the height of sub partial areas (size of shorter side) against the interval of them. We set R_1 to be 7/15 this time, so it would be expected to reduce readout time with that rate. In sight of dynamic range, when the sub partial readout adopted for AO, some focused spots might displace out of sub partial area caused by distorted shape on a deformable mirror before closed loop control. Allowing such cases, in the first step of sequence of the AO control, the SHWFS measures wavefront with wide dynamic rage mode (Fig.1 (a)) and using the result, distorted mirror surface of the deformable mirror is controlled to correspond to desired shape. When the SHWFS becomes to detect all focused spots in sub partial area, the detector of the SHWFS is changed to readout pixels with high speed mode (Fig.1 (b)). Finally, it is possible that the deformable mirror corrects wavefront error with closed loop control using measured result by SHWFS with high frame rate. Two readout modes are switchable either partial or sub partial within 10msec by using FPGA based readout frontend of the CMOS camera.

TABLE I. Specification of the test model of SHWFS

Number of sub-apertures	10 ×10
Frame rate	4kHz@sub partial readout mode
	2kHz@partial readout mode
Dynamic range	4λ@633nm@sub partial readout mode
	9λ@633nm@partial readout mode
Accuracy	<1/100λ@633nm RMS
Upper spatial resolution	to the 4th order Zernike mode
Interval of lenslets	0.3mm
focal length of lenslets	18mm
Image sensor type	C-MOS image sensor
Size of readout pixels	152 x 7 x 10@sub partial readout mode
	152 x 150@partial readout mode

IV. Test and Results

We developed experimental AO system comprising a reflection type liquid crystal spatial light modulator (SLM) and the prototype high frame rate SHWFS, and estimated a basic performance of the sensor in the system. We performed wavefront control to generate a desired Zernike mode shape. The result is shown in Fig. 2 as four pairs of desired and measured wavefronts. In the diagram, the desired wavefront patterns correspond to the measured one by SHWFS with high precision. In addition, a quantitative test result is shown in Fig.3. The diagram shows time series of measured wavefront fluctuation by the SHWFS under stable condition. The repeatability was 0.0058 lambda in 3 sigma on partial readout mode, 0.0099 lambda on sub partial readout mode. The repeatability on sub partial readout mode was more than the other mode caused by degrading SNR depended on exposure time. In any case, the wavefront error even in worse case was smaller than our target specification. Fig.3 also indicates twice faster frame rate of SHWFS in the sub partial readout



mode than in the partial readout mode.

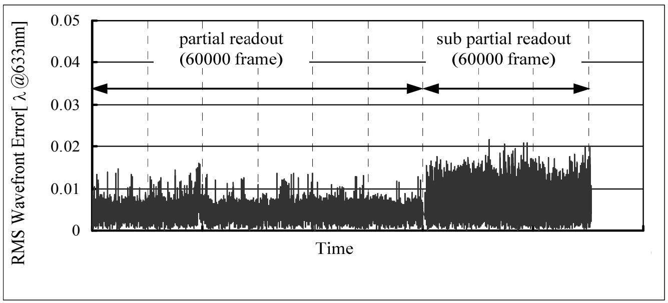


Fig. 2. Comparison of 4 pairs of desired and measured Zernike mode wavefront
Left: desired wavefront, right: measured wavefront by SHWFS

Fig. 3. Measured wavefront error of the prototype SHWFS

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