Development of fast FPGA based wavefront sensor for aircraft vision

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ABSTRACT

In the age of deep penetrating missiles and star-wars fine tracking and imaging has becoming more challenging and thus the development of Electro-optical (EO) sensors has became important. An EO sensor used for defence has to counter various turbulent or turbid media which deteriorate the optical signal that reaches to the sensor. The media that causes problem to such sensors could be the turbulent atmosphere, poor visibility (due to haze or fog), boundary layer turbulences surrounding the aerial targets, and dust suspension at war scenario etc. An imaging system installed on a platform surrounded by highly disturbed environment degrades the image quality drastically. In recent years, there have been rapid advances in the field of imaging through turbulent or turbid media. EO sensors with diffraction limited performance have great potential for diverse applications of aerial systems. To study the image quality degradation and its compensation requires fast wavefront sensing mechanism. IRDE has developed a FPGA based fast wavefront sensor using Shack-Hartmann wavefront sensing technique. It consists of high speed CMOS sensor in conjunction with a lenslet array for optical sampling of the wavefront. High speed CamLink interface was used for retrieving the high speed images at FPGA board. It measures the slope variations of local portions of the wavefront passing through the imaging system. The local slope information is used for reconstructing the wavefront errors at $\geq$ 1000 Hz. Entrance pupil aperture of this sensor is 2.3mm and measurements are made for 16×16 sub-apertures. For reconstructing the wavefront Southwell reconstruction algorithm has been used. Study of MTF degradation of imaging system operating through highly turbulent atmosphere or turbid media could be possible by such fast wavefront sensor. Thus it would greatly benefit in designing of vision systems for aircraft.

Key words: Adaptive optics, Aero optics, CamLink interface, FPGA, Lenslet arrays, LVDS.

1. INTRODUCTION

Shack Hartmann wavefront sensor (SH-WS) is an evolutionary technology based on Hartmann screen test[1]. This is the simplest and elegant means of measuring the shape of wavefront in real time. The development of sensor grew out of cold war efforts in the USA. The air force had requirement of imaging satellites from ground based telescopes. In the decades of 80s there were numerous developments for the high energy laser community in SH-WS and Adaptive Optics (AO) technologies. While these are most classified, there is some published work that describes the development[2-4]. Other than imaging through turbulence or turbid media, this sensor is proving its presence in the pin point hitting of aerial targets by high power lasers, designing and testing of EO sensors for aircrafts, studying ocular aberrations, producing diffraction

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limited laser beam qualities etc. It is rare for a technology to have such a dramatic impact in the multiple fields alone, as did the SH-WS.
There are various applications for which fast wavefront sensors is mandatory. For designing vision systems for aircrafts, characterisation of dynamic aberrations caused by the turbulent aerodynamic flows is essential. This application requires a fast wavefront sensor. At IRDE, Dehradun we have developed FPGA based fast wavefront sensor. Such high end sensor has been developed first time in the country. In the foregoing paragraphs, design and development of fast SH-WS is described and in last the results of the measurement of simulated wavefront error is shown.

2. DESIGN OF FAST SH-WS

To design wavefront sensor, first its design specifications are fixed, based on the applications. The application we targeted is to measure wavefront error caused by the turbulent atmosphere. Our application demands wavefront sensor should work at ~ 1000 fps. But it could measure wavefront errors caused by events occurring at millisecond level due to any reason. Disturbances due to aero optical effects occurring at ~1 KHz could also be registered with such sensors, and thus characterised. Processing for such fast SH-WS need to be designed on FPGA plateform[5].
SH-WF sample the admitted wavefront using lenslets that leads an image as arrays of spots and is mapped on a suitable CCD placed at the image plane of the lenslet array. The acquired image data is further used to process the centroids of each spots and then its movements are tracked in real time. The algorithm and design issues are discussed in detail[6]. Spatial sampling of wavefront is carried out by lenslets arrays as 16 × 16 with resolution ~ 144 µm. Thus input aperture of the sensor is 2.3 mm. The focal length of the lenslets used is 8.2 mm. The SH-WS is designed to sense wavefront error with resolution of ~ 6 µrad and maximum tilt of ~ ± 4 mrad. For large aperture input wavefront, a de-magnifier is required. Conceptual design of the fast sensor is shown in the figure 1.

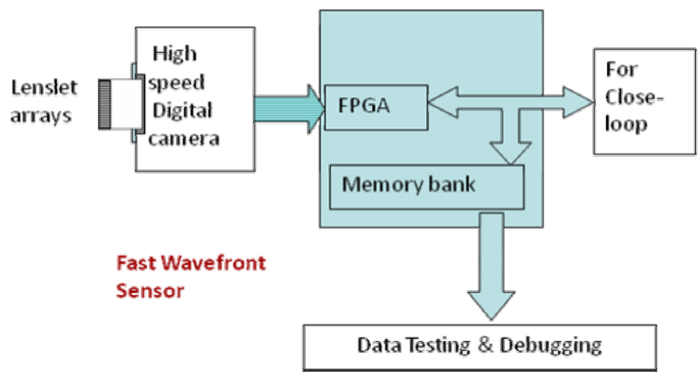

Fig. 1. Design concept of fast SH-WS

3. DEVELOPMENT OF SH-WS

The fast SH-WS consists of a 16 × 16 lenslet array interfaced to a CMOS sensor with a custom designed mounting. The SH-WS is illuminated by a collimated laser beam of 2 mm diameter. The image spots were focused onto a digital monochrome camera. High speed data transfer is achieved by CamLink interface between camera and processing board. Camera output is connected to a PCI express based processing board by 2 m long CamLink cable. Incoming image is divided into 256 equal sub images of size 14 × 14 pixels each. The algorithm used for estimation of local gradients is Center-of-Mass with thresholding and wavefront reconstruction is based on the Southwell geometry as described in our earlier work[6]. Software for calculating wavefront error is developed in VC++ as a console application. FPGA based fast SH-WS was realized employing the following components.

3.1 Optical sampler

Lenslet arrays sample the input wavefront optically in spatial domain and converts local gradients into measurable spot displacements. To obtain maximum efficiency the lenslets are contiguous and cover the entire optical aperture. Lenslet array used have focal length of 8.2 mm and pitch 144 µm with 100 % fill factor. The lenslet is having multilayer dielectric AR coating at 532 nm to attain maximum throughput. Suitable mounting (Type C-mounting) with x-y movements in two orthogonal directions in the plane of lenslet was developed and fabricated at IRDE. Mounting also has motion in z-axis for precise focusing of the array of spots.

3.2 Fast CMOS sensor

DALSA's 1M150 digital monochrome camera programmed for windowed resolution of 224 × 224 with very high frame rate of ~ 2400 frame per second at 0.01µsec. exposure time. To realize faithful generation of spot arrays sufficient light level is required that is provided with collimated He-Ne laser. With theses parameters, input data rate goes very high (224 × 224 × 8 × 2400=114 megabytes per second). Pixel size of CMOS sensor is 10.6 µm.

3.3 High speed interface

Camera Link (CamLink) is a communication interface for vision applications. A high-speed serialized cable and protocol standard, CamLink simplifies connectivity and communication and handles the incredible data rates that accompany high-speed and high-resolution applications. Data rate ~ 114 MB/s is possible with CamLink interface on camera and interfacing board. The CamLink interface extends the base technology of Channel Link to provide a specification more useful for vision applications. Channel Link consists of a driver and receiver pair. The driver accepts 28 single-ended data signals and a single-ended clock. The data is serialized 7:1, and the four data streams and a dedicated clock are driven over five LVDS pairs. The receiver accepts the four LVDS data streams and LVDS clock, and then drives the 28 bits and a clock to the board. The data transmission rates of the Channel Link chipset (up to 2.38Gbits/s) support the current trend of increasing transfer speeds.

3.4 FPGA processing

Microenable III-XXL processing board from silicon software is used which have CamLink interface for connecting camera output and Spatran FPGA to process the image data. Associated driver and SDK were utilized to develop our dedicated processing software. For generating the online graphs to display slope and wavefront map, we integrated the matlab engine[7] with C++ program.

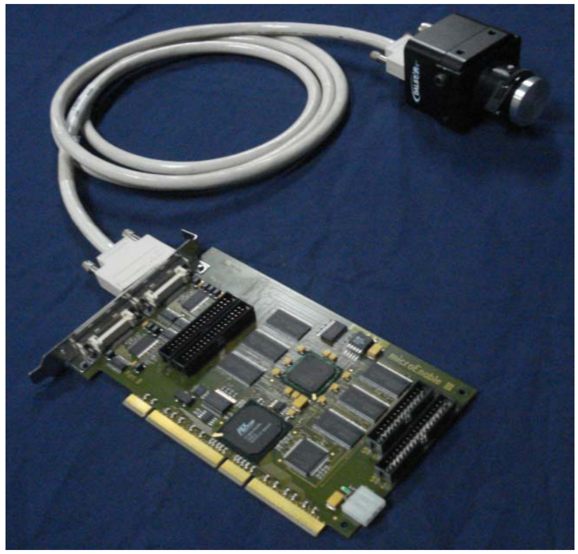

Fig. 2. Fast Shack Hartmann Wavefront Sensor

4. RESULTS AND DISCUSSION

At present we are testing and validating the system with simulated wavefront errors in laboratory. A typical defocus aberration produced in the laboratory by micro-machined deformable mirror[9] (DM) is sensed. The results are as shown in the figure 3. The sensor is designed to measure the wavefront errors with ~ 6 μrad resolution and maximum tilt range ± 4 mrad with events occurring at 1 msec. Thus, the sensor possesses high degree of dynamic range with fine resolution and sufficiently fast to develop closed loop operation ~ 100 Hz bandwidth. Sensor is using AR coated lenslets therefore its best response is at 532 nm but it could work at any wavelength within visible band of light.

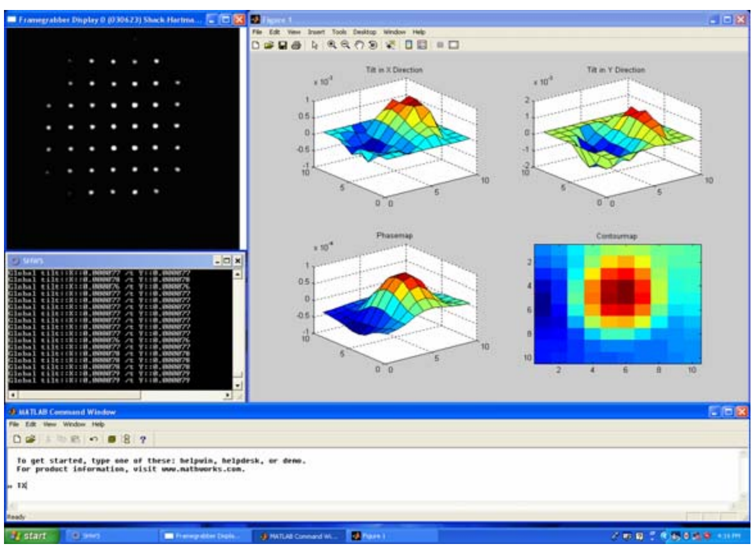

Fig. 3. Sensing of Defocus aberration by 100 V to DM

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