Beam tracking and image steering by Texas Instruments Phase Light Modulator based on camera input for lidar and AR applications.

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ABSTRACT

Micro Electro Mechanical System (MEMS) spatial light modulators enables adaptive and fast beam and image steering. For lidar applications, Texas Instruments Phase Light Modulator (TI-PLM) is paired with real-time calculation and display of Computer Generated Holograms (CGH) by CUDA-OpenGL interoperability assisted by YOLOv4-tiny network model for object detection and recognition. The real-time object recognition, CGH calculation, and display framework replaces conventional raster scanning with camera-input based and foveated beam steering while having a beam scan rate beyond the frame rate of TI-PLM. For Augmented Reality (AR) application, the same framework is used for image steering based on gaze information of eye. With Texas Instruments Digital Micromirror Device (TI-DMD), image is steered into a part of field of view by following movement of eye. The diffractive image steering enabled by TI-DMD increases FOV while not sacrificing resolution of the image displayed.

Keywords: lidar, AR display, beam steering, image steering, phase light modulator, MEMS, spatial light modulator

1. INTRODUCTION

Lidar (Light Detection and Ranging) technology has become increasingly important in various applications such as autonomous vehicles, robotics, and 3D mapping[1, 2]. One of the key components in lidar systems is the beam steering mechanism, which directs the laser beam to specific point. As another emerging application of such steering of laser, Augmented Reality (AR) device gathers attention. Optical image projection engines employing laser beam steering can be found in several commercial devices since a laser beam steering (LBS) projector engine benefits high image brightness with a small form factor [3]. In LBS point-by-point laser scanning, or raster scanning are commonly employed in lidar and AR display engines. In the raster scanning frame rate is primarily limited by speed of scanning modalities, for example Galvo mirror for lidar and MEMS (Micro Electro Mechanical System) resonant mirror for LBS-based AR projection engine.

Phase Spatial Light Modulators (SLMs) are alternative method for LBS having unique functions that are not realizable with raster scanning devices. With a Computer Generated Hologram (CGH) displayed on a phase SLM, it is feasible to steer laser beam in random manner as well as simultaneously steer beams into multiple regions of interests (ROI), and even simultaneous raster scanning within the ROIs [4]. Moreover, with a phase SLM in lidar system, it is also possible to equalize signal strength retuning from far and near targets by pre-adjusting intensities of laser beam based on object recognition by camera. The equalization of signal enables an efficient usage of detector's dynamic range so that even closer objects is detected without sacrificing the longest detectable range in lidar system.

In a similar manner to lidar, AR projection engine benefits from Phase SLM by adaptively steering images to specific region of a field of view (FOV). Let's consider a wide FOV display system. In most cases for AR devices, information is displayed over a specific part of FOV, not over the entire region of the FOV. Nonetheless, for those no-information regions within the FOV, display pixels have to be allocated. Suppose a part of FOV is selectively displayed by image steering in a time multiplexed manner, the number of pixels required for micro display is decreased, consequently, the form factor of display AR engine reduces.

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Emerging Digital Micromirror Device Based Systems and Applications XV, edited by John Ehmke, Benjamin L. Lee,
Proc. of SPIE Vol. 12435, 124350E · © 2023 SPIE
0277-786X · doi: 10.1117/12.2651414

In this paper, we overview use cases of such adaptive laser and image steering by MEMS spatial light modulators, Texas Instruments Phase Light Modulator (TI-PLM) for lidar and Digital Micromirror Device (DMD) for AR display. For both lidar and display system, camera captures the object (i.e., cars for lidar, and direction of gaze for display), with YOLOv4-tiny network model for object detection and recognition. Based on the position and extent of the ROI around objects detected, CGHs are determined so that multiple beams simultaneously scans ROIs. For AR display, the YOLOv4-tiny network model detects pupil position of human eye followed by steering images to a part of the FOV as the user's eye moves.

2. SINGLE AND MULTI POINT LASER BEAM STEERING

Figure 1 schematically depicts the optical setup of adaptive beam steering. A 532nm CW laser with a Gaussian beam profile is expanded by beam expander. The expanded and collimated beam illuminated a 0.47-inch TI-PLM. The plane wave diffracted by PLM is focused at the back focal plane through a positive lens with focal length of 300mm. By displaying blazed grating phase hologram to PLM with its periodicity and diffraction orientation modulated, the focus spot shifts relative to the zero order on the image plane. For the camera-based adaptive single and multi-beam tracking a USB camera is connected to the laptop to capture the image of the objects followed by processing the image in real time to define ROIs where beam(s) are directed.

CGH is displayed via HDMI interface with frame rate of 60 Hz. With a RGB encoding of CGH, frame rate is increased from 60 Hz to 180 Hz [5]. For a point-by-point raster scanning, frame rate is equal to beam steering rate defined as beams/second since single point is steered at each of the frames.

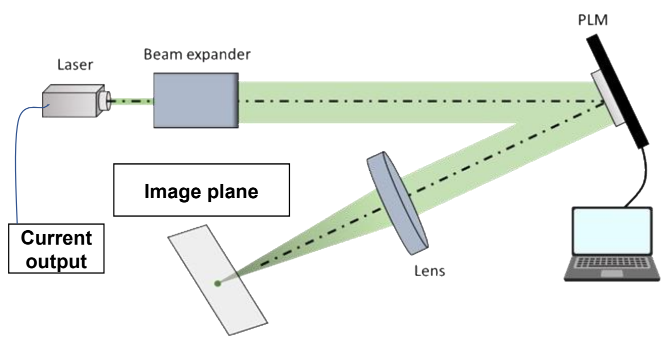


Figure 1. The experiment setup for PLM beam steering and camera-based adaptive beam tracking.

Figure 2 schematically depicts beam steering by PLM. PLM modulates incident plane wave at a normal incidence to linear phase tilt in the diffracted wave.to calculate CGH to steer beam into single beam location (i.e., point Q1 depicted in Fig. 2), at pixel location (x, y), phase value of SLM is given by,

$$\phi(x, y, \Delta x, \Delta y) = \left[\frac{2\pi}{\lambda f}(x\Delta x + y\Delta y)\right] mod\ 2\pi \quad (1)$$

, where Δx and Δy is the lateral displacement from the 0th order in x and y direction, observed at back focal plane of a lens with focal length f. $mod\ 2\pi$ stands for modulo 2π operation to wrap the phase since the maximum phase modulation value of TI-PLM is limited to 2π at wavelength of 633nm [5].

To calculate CGH to steer beam into multiple beam locations, (i.e., point Q1 and Q2 depicted in Fig. 2) at the back focal plane of the lens, the phase at the PLM plane is the argument of the complex superposition of the tilted and weighted plane wave, and is given by,

$$\theta(\mathrm{x}, \mathrm{y}, \Delta x_1, \Delta y_1, \dots, \Delta x_n, \Delta y_n) = arg\left[\sum_{k=1}^{n} \mathrm{A}_k e^{j\phi_k}\right]. \quad (2)$$

This calculation process is equivalently modified as follows,

$$\theta(\mathrm{x},\mathrm{y},\Delta x_1,\Delta y_1,\dots,\Delta x_n,\Delta y_n) = \tan^{-1}\left(\frac{\sum_{k=1}^{n} A_k \sin(\phi_k)}{\sum_{k=1}^{n} A_k \cos(\phi_k)}\right) \quad (3)$$

, where *k* represents location of beam at the back focal place of the lens, A_k is a weighting factor that represents amplitude of diffracted wave for illumination wave of amplitude of 1. The (x,y) represents the pixel location on the phase light modulator, with a lateral displacement of $(\Delta x_n, \Delta y_n)$ from the 0_{th} order, in the x and y direction. These coordinates are determined based on external inputs, such as the location and size of the desired region of interest.

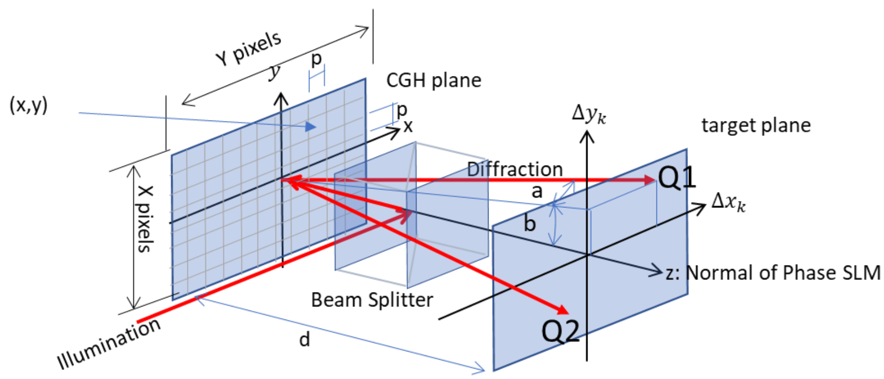
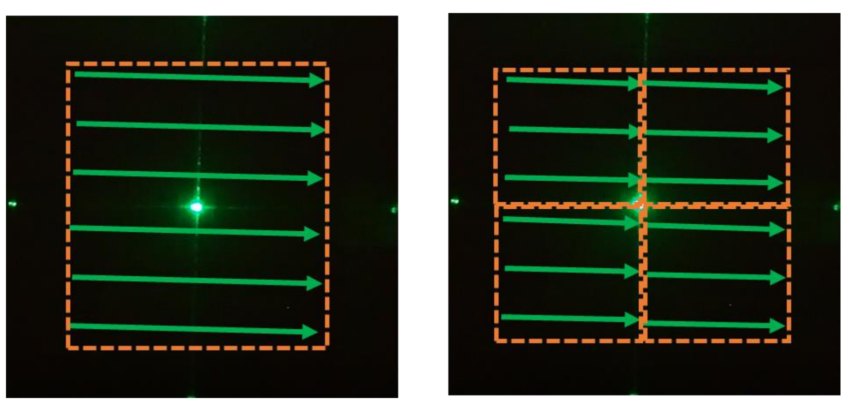


Figure 2. Schematic diagram of PLM based beam steering.

We conducted bench marking of number of scanning points/s for single and multi-beam steering experiments. In the experiment 31x31 (= 961) points are scanned within a square area of ROI depicted in Fig. 3. For single beam steering the square area is sequentially scanned with 180 fps of frame rate. For multi-beam steering, the square region is divided into multiple sub areas (i.e., 4 areas depicted in Fig. 3b) or ROIs. Each sub-ROIs is scanned from top-left to bottom-right.



(a) (b)

Figure 3. (a) Single beam laser scanning over the square region depicted as orange dotted line (ROI: Region of Interest). Beam scans the ROI from top-left to bottom-right. (b) Muti-beam laser scanning over 4 sub-ROIs with 4 beams. Each sub-ROIs is scanned from top-left to bottom-right.

Table 1 tabulates the benchmark results for single and multi-beam steering. The results indicate that as the number of sub-ROIs increases from 1 to 5, the frame rate of the TI-PLM remains at its upper limit of 180 fps, and the number of scanning points/s linearly increases. When the number of sub-ROIs exceeds 5, the frame rate slightly decreases from 180 fps due to the increased overhead to calculated CGHs with $k > 5$, in Eqn. (3), but the overall number of scanning points/s is still improving. The results demonstrate that implementing a multi-beam steering algorithm can significantly enhance beam steering speed when compared to traditional single beam scanning methods.

Table 1: Multi/single beam steering speed performance with PLM connected.

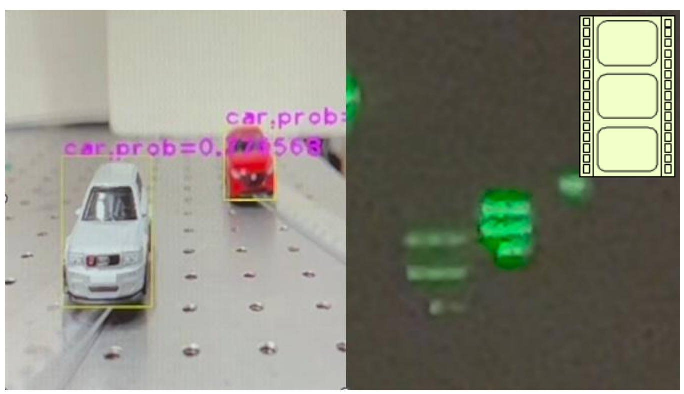
Beam #	PLM FPS	# pts / s
1	180	180
2	180	360
3	180	540
4	180	720
5	180	900
6	174	1044
7	159	1113

3. CAMERA-BASED ADAPTIVE BEAM AND IMAGE STEERING

3.1 Adaptive beam steering for lidar

A camera-based adaptive beam steering for lidar is demonstrated and pictured in video 1. A USB camera captures two miniature toy cars which move at different distances from the camera. The camera input is used to control a multi-beam scanning system, which scans over the square.

The key component of this demo is a deep learning model, YOLOv4-tiny [6] which identifies types, location and extent of the objects (i.e., cars, pedestrians) from a live camera image to perform object detection and recognition in realtime. Rectangular ROI frames the detected objects as sub-ROIs with their labels. CGH calculations are then performed using Eqn. (3) with CUDA based on the position and size of these sub-ROIs. The CGH calculation process corporates with OpenGL to display the CGH in real-time, achieving a maximum speed of 180 fps using the current generation of Texas Instruments PLM.

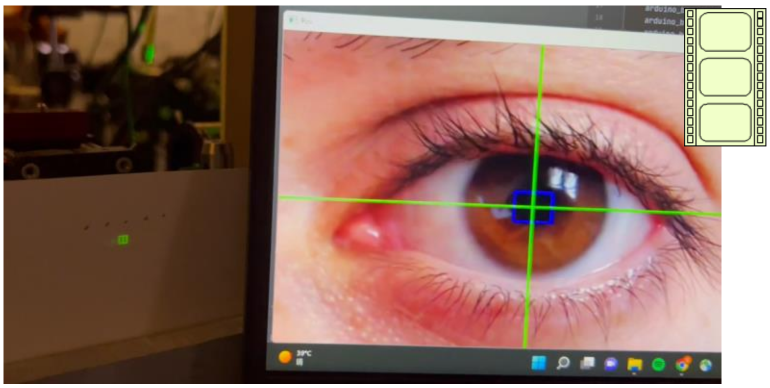


Video 1: Adaptive multi-beam variable beam ratio beam tracking demonstration, where two miniature toy cars are moved back and forth intentionally.
http://dx.doi.org/10.1117/12.2651414.1

3.2 Adaptive image steering for AR display

The adaptive beam steering for lidar is applied for image steering for augmented reality (AR) applications. DMD (Digital Micromirror Device) replaced PLM in Fig. 1, and steers image (not a beam) by diffractive image steering [7,8] . Video 2 demonstrates a gaze-input based image steering. A USB camera captures video image of eye. Center of the cornea by OpenCV package [9]. Gaussian blur (image smoothing), binary thresholding segmentation, and contour finder was used to locate the pupil region. Arduino micro controller to triggers and synchronizes DMD to 100ns DPSS pulsed laser based on gaze information. This system uses the DMD as an image generator and beam steering device to steer 5 different images to the specific diffraction order based on user's gaze information.

The adaptive image steering maintains its native resolution while expanding the field of view. The DMD-gaze tracking system also enables a more engaging and interactive experience, as the image or beam is directed to where the user is looking, rather than a fixed location. This technology has potential applications in areas such as virtual and augmented reality, as well as in industrial and medical settings.



Video 2: DMD-gaze beam tracking demonstration. 5 different image is steered determined by the gaze position. http://dx.doi.org/10.1117/12.2651414.2

4. CONCLUSIONS

This paper presents a framework for beam steering for lidar using Texas Instruments Phase Light Modulator (TI-PLM) to steer beam adaptively to multiple objects, while controlling beam intensity in real time. With CUDA-OpenGL interoperability, CGHs are calculated and displayed on TI-PLM based on camera input that provides location, and extent of the object. The multipoint beam steering replaces raster scanning with 10x higher beam scan rate that exceeds frame rate of TI-PLM. The framework is applied for display application with image steering. With Texas Instruments Digital Micromirror Device (TI-DMD) image is adaptively steered into a part of FOV based on gaze information captured by camera. The adaptive beam and image steering based on camera input has the potential to improve the scanning speed of lidar systems for various applications such as autonomous vehicles, robotics, and 3D mapping. Additionally, it also has potential in providing small factor and portable AR devices with low power consumption by steering images only to the desired position within FOV, thus increasing FOV without sacrificing resolution of images in AR applications.

5. ACKNOWLEDGEMENT

We acknowledge generous support by Semiconductor Research Corporation, Texas Instruments, Mitsubishi Electric, and Tech Launch Arizona on this study.

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