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Multi-beam and single-chip LIDAR with discrete beam steering by Digital Micromirror Device

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ABSTRACT

A novel Digital Micromirror Device (DMD) based beam steering enables a single chip Light Detection and Ranging (LIDAR) system for discrete scanning points. We present increasing number of scanning point by using multiple laser diodes for Multi-beam and Single-chip DMD-based LIDAR.

Keywords: optics, photonics, lasers, MEMS, DMD, LIDAR

1. INTRODUCTION

Laser beam steering is essential component in Light Detection and Ranging (LIDAR) systems. Along with mechanical and completely non-mechanical beam steering. Mechanical scanning including gimbals, fast-steering mirrors, Risley prisms, rotating polygon mirrors and gratings have been used for wide wavelength ranges.¹ Although mechanical beam scanning modalities are widely adopted, having fewer or no moving parts and smaller component inertia is more desirable for fast and compact beam steering devices so that size, weight, cost, and power consumption can be reduced.^{2, 3} These qualities are especially required for autonomous vehicle and robotics applications. In contrast, completely non-mechanical scanning such as programmable spatial light modulators, modulo 2π optical phased arrays, solid state phase arrays, and liquid crystal electro-optic scanners are emerging, and are now actively researched.^{2, 4-7}

In terms of small component inertia, Micro-Electro-Mechanical Systems (MEMS) are promising due to their small size and weight, low production cost, high energy efficiency, and applicability to wide wavelength ranges. These MEMS devices include single resonant mirrors and shifting lenslet arrays.^{2, 8, 9} However, in LIDAR applications for autonomous vehicles, a large steering angle as well as large beam size are needed to cover a large angle of scanning and minimize beam divergence due to diffraction. Unfortunately, resonant mirrors and shifting lenslet arrays are limited in angular range and maximum accommodated beam size. Current high-end resonant mirror MEMS scanning systems have moderate fields of view at 36° and scan rates of 21 kHz.^{2, 10} However, a resonant mirror's maximum beam diameter is only increased at the expense of decreasing the maximum scan rate.⁹ An optical amplification of the steering angle by an inverse telescope design has been reported; however, this design requires a reduced beam diameter to conserve the Lagrange invariant, which would limit the effective delivery of light over large distances due to beam spreading by diffraction.^{11, 12}

As previously demonstrated by our group, beam steering by Digital Micromirror Device (DMD) with a short pulsed laser is not only possible, but can be implemented in scanning LIDAR systems.¹³ This beam steering technique has a high beam steering efficiency (close to 100% in theory), a larger beam size (~same as DMD area), a wide field of view (48 degrees), and a high scan rate (tens of KHz) while minimizing the number of moving parts. The limitation of the approach, however, is maximum number of scanning point is limited by number of diffraction orders available, and is about 5 to 9 points for wavelength range of 0.5 to 1 μm , with commercially available DMD. We now propose and demonstrate increasing the angular resolution of the LIDAR system by implementing multiple laser diodes.

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2. MULTI-BEAM AND DISCRETE BEAM STEERING BY DMD

In Fig. 1(a) the Digital Micromirror Device (DMD) is schematically depicted. This beam steering setup utilizes a 608x684 (horizontal by vertical) DMD chip (DLP3000, Texas Instruments). The micromirrors are positioned in a diamond configuration with a corner to corner period of $10.8\mu\text{m}$ as shown in Fig. 1(a). On this DMD, an array of micromirrors flip between an on and off state, shown in Fig. 1(b)-(d), by rotating $\pm 12^\circ$ about an axis defined by the diagonal of the mirror. Thus, a DMD is designed for binary spatial light modulation and is not intended to be used for angular beam steering.

The DMD mirrors move continuously between the on or off states with a typical transition time in the order of micro seconds.¹⁴ This unused transitional state of the DMD is utilized with a short pulsed laser with a pulse duration much shorter than the transition time of the mirrors. For a particular steered beam angle, there is a corresponding delay between laser diode activation and DMD mirror flipping. The micromirror movement is frozen at an angle between the stationary on and off states with the pulsed laser. Thus, it is feasible to form a programmable and highly efficient blazed diffraction grating to discretely steer the laser beam.

Figure 1. Representation of the (a) DMD diamond pixel layout (Top View); (b) a mirror in the on position at $+12^\circ$ (c) a mirror in the parked position at 0° when the DMD is powered down; (d) a mirror in the off position at -12° (Side View).

The number of scanning points N is given by $2m+1$ where m is the number of allowable diffraction orders for a blazed reflection. m has to satisfy following grating equations,

$$\sin(\theta_i) + \sin(\theta_r) = \frac{m\lambda}{a} \quad (1)$$

$$\theta_i + \theta_r = 2\gamma \quad (2)$$

,where θ_i and θ_r are angle of incidence and diffraction measured from normal of blazed grating surface, λ is a wavelength, m is diffraction order, a is pitch of blazed grating and γ is slope of grating facet. For example, at $\lambda=905\text{nm}$, with pitch of mirrors of DLP3000, maximum number of scanning point N is limited up to 5.

To increase the number of scanning points, multiple laser diodes were employed in the system as depicted in Fig. 2. In Fig. 2(a) single laser diode configuration is depicted. A pulsed light from a 905nm and 8ns pulsed laser module (LS9-220-8-S10-00, Laser Components, Germany) is collimated by a 20x and NA 0.4 microscope objective lens and it illuminates DMD. The timing of tilt of DMD mirror is synchronously controlled with the laser pulse by Arduino micro controller with DS1023 delay IC chip. By adjusting the time delay, each of pulses are diffracted into one among 5 discrete diffraction orders with high diffraction efficiency, theoretically close to 100%. The number of scanning points are increased by multiple laser sources as depicted in Fig. 2(b). Two additional laser modules are added with 3.3 degrees of incident angle deviated from the central laser path. This configuration allows quasi-evenly spaced angular spacing. Figure 3 is a simulated intensity distribution over the 50 degree field of view by Huygen-Fresnel integral. Each mirror was modeled as a series of point sources with an associated phase and optical path length (OPL) induced by the tilt of mirror while taking into account the angle of incidence of the incoming beam. The field contributions from each points source are added together to calculate the diffraction pattern in far field.

Figure 2. Schematic of setup utilizing (a) a single laser diode and (b) 3 laser diodes.

Figure 3. Simulated intensity profile at far-field from three laser diodes. Intensity is normalized to peak intensity of 0th order beam from the central laser module

3. EXPERIMENTAL RESULTS

3.1 Beam Steering

The timing of pulse from the 3 laser diodes module is synchronized to transition of micro mirrors between on and off state by Arduino micro controller. Figure 4 shows a picture of 15 beam spots. A screen was placed at a distance of 50cm from the DMD, and scanned spot is captures as a movie, then video frames corresponding to each of the scanning spots is cropped. At the bottom of the picture, long exposure to show all the 15 scanning spots are depicted.

Figure 4. Total of 15 scanning spots from top to bottom, scanning point +7 to -7 depicted in Fig. 2(c) are captured. At the bottom of the picture, long exposure to show all the 15 scanning spots are depicted.

3.2 Range Finding

To make time of flight measurements for the LIDAR application, an avalanche photodiode (APD) (C12702, Hamamatsu) and a fold mirror were added to the single LD optical setup as illustrated in Fig. 2(b). In this experiment, multiple laser diodes were added to the system to demonstrate a pathway to increase the number of diffraction orders in such a system. The configuration shown in Fig. 2(b) involves three 905 nm laser diode module (LS9-220-8-S10-00, Laser Components, Germany) directed towards the DMD with a $\pm 3.3^\circ$ incident angle separation from the central beam to ensure that the points are equally spaced. The $\pm 3.3^\circ$ incident angle separation generates equal spacing because diffraction orders are spaced approximately 10° apart when using 905 nm light. To save space, fold mirrors were used to physically offset the three laser diodes. In Fig. 5, a photograph of Multi-beam Single-chip DMD LIDAR is shown.

Figure 5. System layout of Multi-beam Single-chip DMD LIDAR. The transmitting path is schematically shown as dotted allows.

In Fig.6, distance measurement result at 4 different distances for all the 15 scanning points is depicted. As an object, we used a one piece of curved cardboard so that object is placed at the same distance for all the 15 scanning points. The point denoted as +7 in Fig. 6 corresponds to the beam denoted as +7 in fig. 2(b). Reported distances are plotted as points whereas, actual distance is plotted as a solid line.

Figure 6. Distance measurement result at 15 discrete points. Object, a piece of curved cardboard is used so that all the 15 scanning points measures object at the same distance.

4. DISCUSSIONS

With the current DMD, five diffraction orders are usable when using a single 905 nm laser at a 30° incidence angle. The number of scanning angles can be increased by employing a larger DMD micromirror pitch and/or a shorter wavelength.¹³ The limitations of two commercially available DMDs under ideal conditions for certain wavelengths of light are shown in Table 1. In the Table it is we estimated that 175 m with a higher scanning rate of up to (256 lines/s) x 90 (points/line) = 23k points/sec and a field of view over 60° with 0.65° angular resolution is feasible by employing 18 lasers, with commercially available high power lasers, and high sensitivity detectors.

Table 1. Performance summary for two DMD types and two wavelengths of light.¹³

DMD Model	Wavelength (nm)	Range	N_{LD}	N_{order}	Total Number of Scan Angles	FOV (°)	Resolution (°)	Scan Rate (lines/s)
DLP3000	905	55	5	5	25	49	1.9	160
DLP3000	1550	55	8	3	24	50	2.1	167
DLP9500	905	175	11	7	77	48	0.62	299
DLP9500	1550	175	18	5	90	60	0.65	256

Currently, angular spacing among multiple laser diodes is limited by size of housing of laser diode modules, and/or optics to collimate laser beam, thus it is not possible to accommodate 18 lasers. Through possible array of laser chips mounted on a common substrate with a single collimating lens solves the problem. Scanning speed is limited by the refresh rate of DMD since a single pulse is launched per single rotation of mirror. Thus to scan 15 points, 15 times of flipping DMD mirror is required. However, the requirement is not a hard one. For even faster scan rate, multiple pulses can be launched per single rotation of DMD mirror that increase scanning speed by factor of total number of diffraction orders.

5. CONCLUSIONS

Multi-beam Single-chip DMD LIDAR provides a unique pathway to long distance range finding by leveraging commercially available Digital Micromirror Device. As a proof of concept, 15 points of range finding is demonstrated by using three 905nm pulsed laser diode modules. With chip-mounted array of laser diodes, state of the art detectors, we estimated that the system provides a solution for long range, high speed and high angular resolution distance measurement without bulky scanning/receiving optics.

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