Smartphone 3D Laser & LED Beam Profiling

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***Abstract*—This paper presents a smart beam profiling system capable of measuring the 3D spatial profile of laser and other collimated and non-collimated sources. The system utilizes an ESP32 camera module for portable imaging of laser beams and online computer program for collecting the images, processing and 3D plotting of the profiles. A customized smartphone app is developed for real-time monitoring the results and controlling the systems remotely thus allowing the system deployable into a large-scale profile measurements such as required for industry and hospital laser based diagnostic and surgery systems where precise and reliable profiles are maintained. The 3D profiles of a red laser diode and blue LED are characterized and beam diameter, divergence and propagation parameter are measured.**

***Keywords*—Laser, LED, laser diode, beam profiler, smartphone, lab-in-a-phone, beam diameter, beam divergence.**

I. INTRODUCTION

Many recent advances in automated manufacturing, machining of materials and medical diagnostics and surgery have relied on improved, reliable lasers and laser based measurements. These measurements normally are of high scientific and technological complexity: their application requires specified beam characteristics with little variation and often involve sophisticated electronics to ensure critical thresholds that can generate serious problems, both economic and potentially life-threatening, are not exceeded. As a result, continuous or routine and accurate monitoring of beam quality is required. Accurate beam profile monitoring ensures the output energy density and its spatial distribution in three-dimensional (3D) space. Other important parameters such as diameter, divergence and mode propagation can also be determined [1].

A number of techniques are available for profiling laser beams and their quality matrices. These involve both electronic and non-electronic methods [2]. The most traditional non-electronic method is projecting the laser beam on the surface of a wall. The reflection from the wall is used to collect information about the beam quality. This is by far the simplest and least expensive method of observing or measuring a laser beam profile. The problem with this method is that the human eye is highly non-linear, and can see many orders of magnitude difference in light irradiance. Other simple and quick non-electronic methods involve the use of burn paper, polaroid film, steel plates and fluorescent papers that also require the use of human eye to interpret information [2]. In addition to the manual observation techniques, a number of electromechanical methods such as knife-edge [3], spinning wire [4], a translating slit [5] and a pinhole [6] use precisely controlled scanning and shading of the emitted laser profile, recording the corresponding intensity profile. Figures of merit are derived directly from this aperture scanning technique. However, the most widely used instrumental method to date is the direct projection of the laser beam onto a two-dimensional (2D) array of photosensitive pixels, such as a photodiode array or a charged-coupled device (CCD) chip working at the laser emission wavelength [7-9]. Beam analyzing software is typically run from a desktop computer to process the digital signal from the detector [10]. However, these approaches tend to be expensive and are not always feasible for quick on-site and routine measurements of laser beam characteristics in many applications, requiring some manual effort. They also have restricted use within many remote and resource limited settings particularly medical based where surgery is required or for routine manufacture. Therefore, a simple portable device that would allow on-site and accurate measurement of laser beam profile is desirable [11].

State-of-art technology complementary metal-oxide semiconductor (CMOS) detectors are integrated as increasingly sensitive cameras in many popular consumer devices such as smartphone, tablets, Google Glass, smart watch and so on. Smartphones have already been deployed in many lab-in-a-phone imaging devices, workable mostly in the visible region of electromagnetic spectrum [12-17], potentially in the near IR if the standard near IR filter is removed or phone's IR sensors is used [18]. The CMOS chip of smartphone is competitive against equivalent components in many commercial instruments but bring the benefit of low cost driven by the massive consumer communications and social media market. We have recently took these attributes of smartphone to develop and demonstrate the world first smart laser beam profiler by utilizing its CMOS image sensor and a phosphor converter [19, 20]. This smartphone beam profiler successfully produces 2D spatial profile and determine its parameters such as beam diameter, divergence, beam quality matrix (M^2 parameter) and output power. It was able to operate as an instrument on its own because the advances in edge computing power of the smartphone device.

Examined more closely, the 2D profiles of laser beams are produce by line scanning of the CMOS image of the beam cross section in the horizontal (x-axis) and vertical (y-axis) direction, having in common many of the methods used in traditional beam profiling, such as edge scanning, but all done on a single chip. Although it produces the average intensity profiles of the beams, the actual intensity distribution can be obtained by visual inspection of the 3D profile. Therefore, the 3D profiling of a laser beam is critically important to visualize

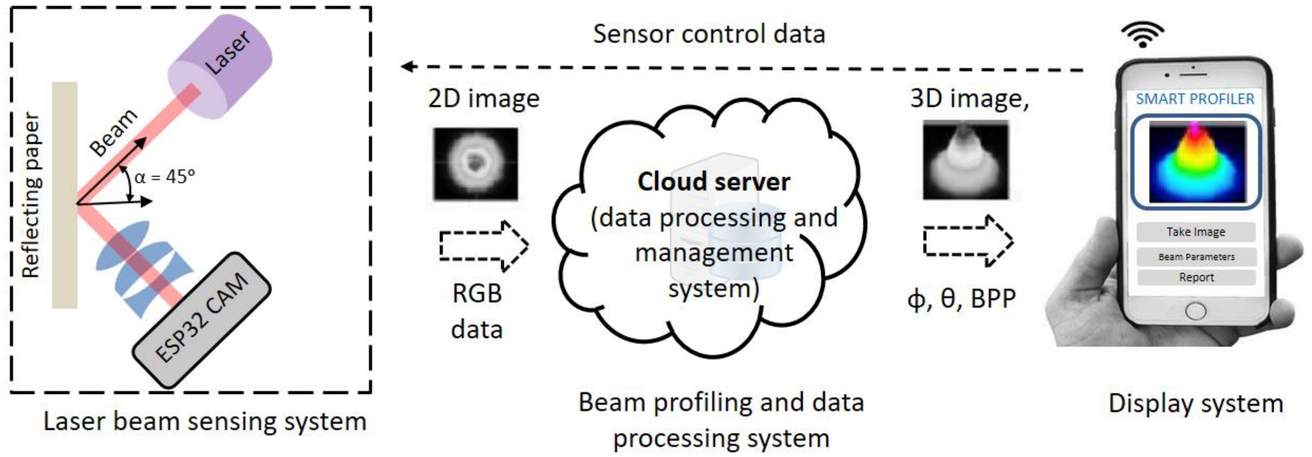

Fig. 1. Smart beam profiling system. Beam image is captured, sent to a online database for profiling and processing. The results are displayed on a smartphone app.

the actual energy distribution more clearly and determine these parameters more accurately in resource limited settings outside of a laboratory. However, 3D profiling of laser beams requires considerable computational resources, needed for research, regulation, and operation. Additional challenges include polynomial regression using complex numerical algorithms, which is often limited by the processing capability of a current generation smartphone. Finally, in an automated environmental setting, the ability to remotely monitor and interconnect devices across, for example, a manufacturing site requires connectivity and ease of data transfer and processing that is common amongst all instruments. For this reason, some computational aspects are ultimately preferred centrally through the cloud rather than at the network edge. This work aims to integrate the smartphone laser beam profiler by utilizing cloud computing capabilities with the smartphone network and allowing it to perform the computationally intensive tasks required to produce a 3D profile centrally. The beam profile is collected with a stand-alone CMOS chip to reflect specific requirements in an industrial setting, including permanent fixed sensor cameras as part of a sensor network. This technology can also be directly integrated to be part of all commercial laser systems advancing a next generation of lasers. Cloud computing has been already utilized in cellular network for computational [21] and is considered as a promising solution for the next generation IoT devices [22]. Importantly, for industrial and medical IoT applications, remote and automated monitoring and analysis, for both control and diagnostics, along with sharing between many instruments is central and part of a new generation of IoT enabled “super instruments” that will bring a statistical power to analysis not currently feasible with laboratory stand-alone instruments.

II. MATERIALS AND METHOD

The smart beam profiling system is described in the following three interconnected subsections, summarised in Fig. 1. These are the beam sensing, cloud processing and the smartphone reporting subsystems.

A. *2D Beam Imaging*

The beam spot sensing system mainly consists of an ESP-32 CAM module (802.11b/g/n Wi-Fi BT/BLE, 5V, 2A, dual-core 32-bit CPU, 240 MHz) connected with a 2 mega-pixels Si-based CMOS camera. The module is mounted on a commercial x-y translational stage continuously scans the laser beam spot using its CMOS camera sensor and send it to a remote cloud server. The laser beam is also attached to an x-y axis roller to focus the beam spot on the surface of a plain cellulose paper and reflects back on the camera surface located on the same side of the reflecting paper. The captured beam images are uploaded and beam parameters are calculated over the cloud program and the result is stored on the program log. The ESP32 CAM module upload the RGB image to the online server via its 32-bits Wi-Fi transmitter after a time intervals, $\delta t = 5$ seconds.

B. *Cloud Data Processing*

The data processing and reporting system is actually a MATLAB program run by a central computer that receives the RGB images, processes and stores them in a local memory drive. The image collection is done through the Wi-Fi connectivity that ensures data receiving at > 20 Mbps. Once received an image, it is stored in the local drive as a JPEG format with a file name that contains the identity, location and time of the beam capture. In the next stage, the program calls the stored 2D RGB image of the beam spots and convert it to 2D monochrome image. Then the values of the pixel numbers along width (w) and height (h) of the image and their corresponding intensity values are stored in a 3×1 matrix (I). When we plot this data taking the pixel numbers as x and y axis values and intensity measures as z axis values all we got is a point cloud in 3D space. However, a point cloud consisting of discrete points does not effectively visualize the energy distribution within the beam spot. To do so, a 3D continuous curve needs to be fitted. In case of fitting a 3D surface to a set of discrete data, interpolation methods have been applied. Given the energy distribution in a laser or LED beam spot are nonlinear and can be quite different, we have chosen a bicubic which is a special case of cubic interpolation technique that allows a degree of flexibility with varying non-linear distributions compared to other contemporary techniques. Finally, the 2D monochrome image is converted into a 3D spatial image where the x- and y-axis indicate the spatial distances and z-axis represents the intensity distribution. In order to make the intensity profile directly visual to the operator, a 3D color map with sufficient increment resolution is applied along the intensity (z-axis) plot. Beam parameters are calculated from the 3D plot by using the formulas given in Table. I. Finally, the 3D plot is archived as a JPEG image and interactive fig format into a Google drive space with the same identity information of the beam.

C. Smartphone Reporting and Analysis

A smartphone application (app) is developed to visualize display the results as numerical values for the determined beam parameters and 3D graphical image representation of the energy distribution of the beam spot. The app uses a call function to retrieve the 3D images from the Google drive folder and display it on an interactive canvas where the operator can rotate the 3D .fig image, select a specific axis, point of interest and focus. The app also allows the operator to compare the beam quality with standard beam types and potentially share this with other users in other locations on their phones. Upon diagnosis of a laser beam degradation the app also allows the operator to identify the sources and suggest solutions. Connectivity with others allows additional real-time expert advice as well as archiving. The app overall offers an online platform for networking that can also be integrated with other sensor devices.

D. Calibrations

The measurements controlled with the smartphone are validated by calibrating the smartphone app with respect to the beam dimension obtained from the calibrated pixel dimension of the mobile screen. In this work, a SONY IMX586 (camera: 48 Mega-pixels as 8000×6000) camera sensor has been used. A lower-cost camera with lower resolution can also be used. The 650 nm laser diode beam spot was measured on the both ESP32 module and the standard Sony camera module and a calibration factor was achieved to determine the actual beam dimension on the ESP32 camera calculation. In order to have accurate measurements, a linear response of the CMOS camera with the beam intensity is desirable. The ESP32 uses silicon-based CMOS camera that offers a wide range of linearity and used in laser beam profiling [23].

III. EXPERIMENTAL RESUTLS AND DISCUSSION

To evaluate the performance, the technique is applied to profile the beams of a 650 nm, 5 mW cw laser diode and 470 nm narrow-band blue light emitting diode (LED) source. For both of these sources, beam parameters are calculated automatically using the cloud program stored in the computer. The measured beam parameters include beam diameter (φ), beam divergence (θ) and beam propagation parameter (*BPP*). Multiple data collection is done to measure statistic validity of the experiment. The 3D visualization of the beam helps the users to realize actual energy distribution beam in 3D space.

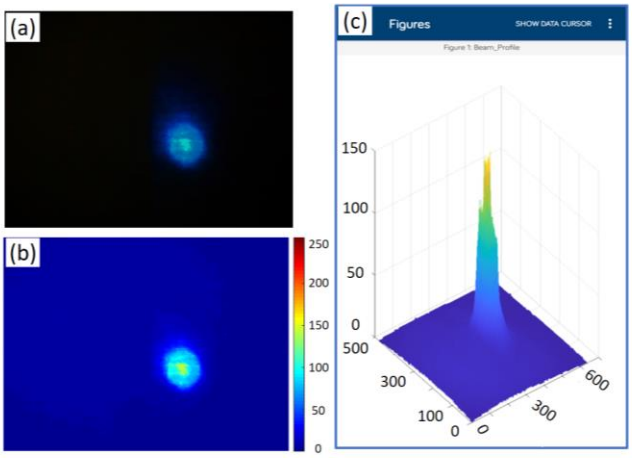

Fig. 2. LED beam profile measurments. (a) 2D image of the beam captured on the ESP32 module; (b) 2D colour mapping of beam intensity profile and (c) 3D profile collected and display on smartphone screen.

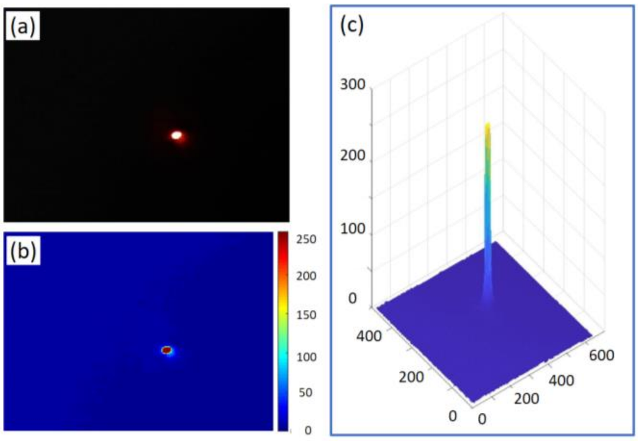

Fig. 3. Laser beam profile measurments. (a) 2D image of the beam captured on the ESP32 module; (b) 2D colour mapping of beam intensity profile and (c) 3D profile collected and display on smartphone screen.

TABLE I. BEAM MEASURMENS DATA OF LED AND LASER DIODE

Para-meters	**Gaussian beam measurements of LED and laser diode**				
	Equations	***LED***		***Laser diode***	
		x-axis	***y-axis***	***x-axis***	***y-axis***
φ (mm)	$\phi_0 = (x_2 - x_1)\frac{I_{peak}}{e^2}$	24.35 ± 0.21	20.92 ± 0.21	2.28 ± 0.02	2.31 ± 0.02
θ (mrad)	$\theta = \tan^{-1}\frac{\emptyset - \phi_0}{l_2 - l_1}$	1.57	1.57	1.51	1.52
BPP (mm mrad)	$BPP = \phi_0 \times \theta$	38.18	32.82	3.44	3.52

For the LED measurements as shown in Fig. 2 (a)-(c), the 3D profile shows a Lambertian profile of the LED where multiple so-called lateral modes exist in the direction parallel to the propagation axis. The measured profile shows large diameter, $\varphi_x = 24.45 \pm 0.21$ mm and $\varphi_y = 20.92 \pm 0.21$ mm, with large divergence angle, $\theta_x = \theta_x = 1.57$ mrad. In addition to the lateral modes, the LED sources show large divergence angle compared to lasers and other collimated optics. This divergence is the result of diffraction in the cavity and a short cavity length. Divergence in two different axes can also be measured from the 3D profile which allows for a measure of astigmatism, i.e. unequal divergence in orthogonal directions. Existence of astigmatism can make collimation of a source difficult. In contrast, the laser diode measurements in Fig. 3 (a)-(c), show comparatively narrow linewidth having beam diameter $\varphi_x = 2.28 \pm 0.02$ mm and $\varphi_y = 2.31 \pm 0.02$ mm and divergence angle, $\theta_x = 1.51$ and θ_y

= 1.52 mrad. The measured profile also shows a comparatively coherent beam because of the coherent nature of the photons.

IV. CONCLUSION

This paper presents a smartphone-based 3D laser beam profiling system, from an edge sensor to smartphone, through to cloud computing and back to edge display on a smartphone. An independent camera sensor which can be placed anywhere in a production or medical environment facilitates automated industrial and medical application and offers remote connectivity and servicing. For example, routine laser diagnostics in a laser production facility is possible but so too is direct embedding into a laser system product greatly expanding a laser manufacturers services to customers beyond point of sale. As a proof of concept, the technique has been used to 3D profile and analyse both a laser diode and LED. There is considerable room for increasing the detection range by changing the lens, filters, or the sensor module. For example, an infrared-to-visible converter can be used to characterize infrared lasers. Resolution can be improved with some better versions of ESP32 camera on the market today that have improved resolution of the CMOS chip and phone's display pixels.

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