Development of a Focal Point Positioning System for Laser Sensing Instruments using Galvano Mirrors and Tunable Lens

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Abstract— We developed a focal positioning system for laser sensing instruments. The positioning system consists of x- and y-axis galvano mirrors and a high-speed response tunable lens. It allows for quick adjustment of the measuring position with high resolution and repeatability afforded by the galvano mirrors, which enable the plotting of 10,000 focal points per second, and the tunable lens, which allows adjustment of the focal length within 2.5 ms (10%-90% step). For laser measurements, the location information of the laser spot on the sample is the key parameter to determine the quantitative difference in chemical compositions at different locations. Furthermore, if the sample changes location systematically with some temporal variation, quick correction before changing the default position is required to prevent missing the target. The laser spot positioning system we present here can play an important role in obtaining multi-plot measurements for complicated surface topologies and dynamic micro-samples.

Keywords: laser; galvano mirror; tunable lens; laser projector

I. INTRODUCTION

We have developed a micro-drop sampling sub-system to obtain quantitative measurements using laser-induced breakdown spectroscopy (LIBS) [1–4]. Since the droplet size is smaller than the size of the laser beam spot, the entire volume of the droplet can be confined within the laser beam spot and good quantitative data can be obtained by fixing the measuring volume. However, the method is technically difficult to implement because it requires strict coincidence in location and synchronization between the sample and pulsed laser beam spot. The deviation from juxtaposition point is due to aging variation caused by external factors such as temperature, humidity, and pressure changes or internal factors such as change in concentration, viscosity of the liquid sample, and decrease in water shedding quality on the surface of the micro-droop ejection nozzle. These factors can be eliminated using various methods. One such method is installing the equipment in an experimental chamber with regulated air conditions. However, this requires sample treatment and bulky instruments in the laboratory, thus reducing the flexibility of LIBS measurements. Another method employs a real-time adjusting system that can maintain the juxtaposition point while laser shots are used to make measurements. The laser spot positioning system presented here facilitates readjustment after every interruption in measurement and improves the efficiency of the measuring process. LIBS measurements have been used for chemical compositions analysis on the surface of the stones and soil [5, 6]. For LIBS measurements conducted outdoors, if the sample treatment is not conducted, information for each spot the laser hits should be recorded instead of only classifying each sample. For example, in LIBS measurements intended for chemical analysis of rock surfaces, it is often found that the chemical compositions even for nearby locations on the surface are extremely different. Thus, employing the laser scanning system to fix the measuring positions and recording each location’s information is useful for proper analysis of materials with inhomogeneously distributed compositions. In literature, several combinations of LIBS systems with other optical observation systems have been reported such as LIBS system installed with a microscope called micro LIBS technique [7, 8] and LIBS system combined with a remote micro-imager [9–11]. If the laser-scanning device is employed with these combination LIBS systems, integration of multi-point measurements on one image can be achieved. The advantage of multi-point measurements is that composition differences between points can be identified and the selection of points for detailed analysis can be narrowed at an early stage in the measuring process. The laser spot positioning system should be regarded as a key device to enhance the simple, quick, non-contact, and remote sensing capabilities of the LIBS system.

II. DEVELOPMENT OF THE LASER SCANNER

Figure 1 shows the layout of our laser scanning system. A D-subminiature connector (DB-25) was used to connect the laser scanner to the PC and the interface between them conformed to the International Laser Display Association (ILDA) standard in order to use versatile software that facilitated the use of the laser projector. The scanner can draw complex illustrations and animations using the ILDA-compliant interface. However, the color signal and effector used in drawing geometric patterns were not mounted on the system because these are optional extensions for the imaging system. In exchange for these artistic attachments, optical devices for laser measurements—a condenser lens, tunable lens, cold mirror, and highly durable galvano mirrors—were additionally installed on the system. These optical parts supported LIBS measurements with the near infrared high-power laser.
A. Optical Parts

- Laser: Diode pumped solid-state (DPSS) laser was used as a reference light source to adjust the optical system on our scanning system. The rated specifications for the laser were a wavelength of 532 nm, output power of 5 mW, and a DC voltage of 3V. Note, the applied input voltage and power were higher than the rating in order to obtain greater intensity of the laser irradiation. The laser was covered with brass plates to increase heat radiation performance and for long-term stability.

- Half mirror: To be coincident with the optical axes of the DPSS laser and Nd:YAG laser, a half mirror was located between the galvano mirrors and tunable lens. The half mirror used on the system is called a cold mirror, and has the special characteristic that it transmits light in the infrared range (transmission: 95% at 1064 nm, for incident angle = 45°) and reflects light in the visible range (reflectivity: 95% in the range 450 nm–680 nm, for incident angle = 45°). It is easy to efficiently separate the optical path of the two lasers, which have different wavelengths, using this characteristic of the cold mirror.

- Galvano mirrors: Actuators and driver boards to scan x and y directions were applied from the commercial components (Dragon Tiger DT30). The maximum scanning speed was 30,000 points per second in the original condition. To use the mirrors with the high-power infrared Nd:YAG laser, the original mirrors (size: 5×10×0.8 mm, reflectivity: 95% in the range 400 nm–700 nm) were replaced with highly durable new mirrors made from Cr-Au coated synthetic quartz glasses (size: 7×10×1.9 mm, reflectivity: 75% at 530 nm, 95% in the range 700 nm–1100 nm). The new mirrors were attached to the actuators using specially made joints.

- Condenser Lens: Unlike typical laser projectors, our system employed a condenser lens. The lens was coated with anti-reflection coating for a near infrared laser. Its diameter was 25 mm and focal length was 50 mm.

- Tunable Lens: A tunable lens (EL-10-30-C-NIR-LD, manufactured by Optotune) was used for fine adjustment of the focal length of the Nd:YAG laser. One of the reasons for employing the tunable lens was that it reduces the risk of damage to the galvano mirrors by making the beam diverge by use of an additional lens. Another reason is that the breakdown point is coincident with the focal point of the reference laser. The breakdown point where the plasma is generated was located short of the focal point because the energy threshold for generating the plasma was overcome at this point. The operational principle of the tunable lens is that the shape of an optical fluid sealed within an elastic polymer membrane can be changed by controlling the electrical current. This method yields focal lengths in the range 210 mm–80 mm for current values in the range at 0 mA–300 mA and allows adjustment of focal length with high response time (2.5 ms in a 10%–90% step).

B. Interface

The pin layout for input signal processing on the system is shown in Figure 2. D-subminiature connector (DB-25) was used for interconnection between the laser scanner and PC. Some parts of the pin layout corresponded to the ILDA standard. Details of the ILDA signal compliance and adoption for our system are listed in Table I.
TABLE I. ILDA STANDARD FOR LASER PROJECTORS

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>DB-25 Connector pin layouts</th>
<th>Signal name</th>
<th>Used or not on the laser scanning system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>X +</td>
<td>Used</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Y +</td>
<td>Used</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Intensity +</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Interlock A</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>R +</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>G +</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>B +</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>User-defined signal 1 +</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>User-defined signal 2 +</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>User-defined signal 3 +</td>
<td>No</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>User-defined signal 4 +</td>
<td>No</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Projector return signal</td>
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</tr>
<tr>
<td>13</td>
<td></td>
<td>Shutter</td>
<td>No</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>X -</td>
<td>Used</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Y -</td>
<td>Used</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Intensity -</td>
<td>No</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>Interlock B</td>
<td>No</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>R -</td>
<td>No</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>G -</td>
<td>No</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>B -</td>
<td>No</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>User-defined signal 1 -</td>
<td>No</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>User-defined signal 2 -</td>
<td>No</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>User-defined signal 3 -</td>
<td>No</td>
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</tr>
<tr>
<td>25</td>
<td></td>
<td>Ground</td>
<td>Used</td>
</tr>
</tbody>
</table>

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In this work, the feasibility of the laser sensing system was investigated. Since only monochrome and pulse operated lasers were used, several pins remained free. We plan to use the remaining free pins in a future work employing a shutter signal (pin 13/pin 3 and 16) for the use of continuum laser blanking signal and some user-defined signals for tunable lenses in order to achieve focal depth control. The laser scanning system has vast development potential in addition to its intended use for laser measurements.

III. EXPERIMENTS AND RESULTS

For confirmation test of the galvano scanner, several drawing tests were conducted by selecting scan speeds of 10,000 points per second (10K), 20,000 points per second (20K), and 30,000 points per second (30K). The drawing workload level depends on the momentum of the galvano mirrors and the torque capacity of the motors. Thus, the accuracy of the drawing images is related to multiple factors such as number of total points, distance between points, and plot order to be drawn. Sample results shown as follows are dot drawing, line drawing, unicursal drawing, letter drawing, and ILDA test pattern. Figure 3 shows a photograph of the front view of the laser scanning system that was set up for the experiments.

In the following experiments, left-right reversed signal (horizontal flipped image) and back shot photography were applied in order to take pictures perpendicular to the propagation axis. A semi-translucent screen was put in front of the condenser lens at a distance of 25 mm from the lens surface. The drawing size was approximately 20 mm × 20 mm at the imaging location on the screen.

A. Dot drawing

Figure 4. Comparison between photographs of the dot drawing images: (a) original, (b) 10,000 points per second scanning speed, (c) 20,000 points per second scanning speed, (d) 30,000 points per second scanning speed.
B. Line drawing

(a). original  
(b). 10 K

(c). 20 K  
(d). 30 K

Figure 5. Comparison between photographs of line drawing images: (a). original, (b). 10,000 points per second scanning speed, (c). 20,000 points per second scanning speed, (d). 30,000 points per second scanning speed.

C. Letter drawing

(a). original  
(b). 10 K

(c). 20 K  
(d). 30 K

Figure 6. Comparison between photographs of letter drawing images: (a). original, (b). 10,000 points per second scanning speed, (c). 20,000 points per second scanning speed, (d). 30,000 points per second scanning speed.

D. Unicursally drawing (straight line)

(a). original  
(b). 10 K

(c). 20 K  
(d). 30 K

Figure 7. Comparison between photographs of unicursally drawn images: (a). original, (b). 10,000 points per second scanning speed, (c). 20,000 points per second scanning speed, (d). 30,000 points per second scanning speed

E. Unicursally drawing (curve line)

(a). original  
(b). 10 K

(c). 20 K  
(d). 30 K

Figure 8. Comparison between photographs of the unicursally drawn images: (a). original, (b). 10,000 points per second scanning speed, (c). 20,000 points per second scanning speed, (d). 30,000 points per second scanning speed.

F. ILDA test pattern

(a). original  
(b). 10 K

(c). 20 K  
(d). 30 K

Figure 9. Comparison between photographs of the ILDA test pattern images: (a). original, (b). 10,000 points per second scanning speed, (c). 20,000 points per second scanning speed, (d). 30,000 points per second scanning speed.

The photographs shown above were shot with a typical compact digital still-camera in “film speed” mode at International Organization for Standard (ISO) 100. These settings required that the shutter speed be set to slow although these images were drawn in high speed. However, these settings are not suitable for the high contrast exposure of bright laser drawing images in a darkroom. These images showed drag lines because a blanking/shutter device was not installed. The diagonal shift in the images are caused by the misalignment of levelness between the laser scanning system and camera. Geometric distortion was caused by the condenser lens. We used the software “Lasershows Designer Quickshow” produced by “Pangolin Laser Systems, Inc.” to convert images to coordinate values for the output signals.

There is only a slight difference between images for the simple designs shown in Figures 4 and 5. However, it is evident that for increasingly complex images (Figures 6–9), operations
at higher scan speed result in greater distortion as compared with slow scan images. These results indicate that while the galvano scanning system allows scan speeds as high as 30,000 points per second, effective scan speed, within the safety margin, is under 10,000 points per second for accurate laser spot positioning.

G. Test operation for LIBS measurement

Figure 10 shows the design image and results of the laser scan for the image "Emu" bound in the software. Figures 10.(b) and 10.(c) are output drawings using DPSS laser, while Figure 10.(d) is drawn by a laser plasma spot mark on a black paper using Nd:YAG laser and tunable lens used in our LIBS combination system.

![Figure 10](image)

Figure 10. Comparison between photographs of "Emu" images: (a). original, (b). 10 K, (c). 30 K, (d). LIBS at 30 K

In the operation test for LIBS measurement, the spatial resolution between spot marks on a black paper was less than 0.1 mm. For typical use of LIBS measurements, the pulse frequency of the Nd:YAG laser was chosen to be 1 Hz, 2 Hz, 5 Hz, 10 Hz, and 20 Hz corresponding to the internal trigger default specification. Even if we use an external trigger, the maximum frequency is approximately 50 Hz. Thus, the scan speed of the galvano mirror is sufficient to conduct laser spot alignment with high precision for LIBS measurements.

IV. Conclusion

The development of a focal point positioning system for laser sensing instruments and demonstration of confirmation experiments is reported in this paper. From the results of these experiments, it is evident that the galvano scanner can operate at speeds between 30,000 points per second and 10,000 points per second for accurate drawing. We found that if a continuum laser was used for the laser measurements, the system had to be operated at 10,000 points per second or less with blanking/shutter operation. Further, if a pulsed operated high power laser was used, the scan speed was sufficient to set focal point positions. The galvano scanner mirrors were replaced with thicker, Au-Cr coated mirrors to assure high durability when used with an Nd:YAG laser. However, the mirrors were damaged during experiments for testing LIBS operation. The damage was not related to the durability of the mirrors but was due to particle deposition and contamination on the mirrors. We found that the galvano mirrors need to be improved to prevent deposition of dust particles in the air. New materials must be investigated as substitute for the mirrors. Additionally, the condenser lens we used causes geometrical distortion. We plan to employ another kind of lens, such as an F-theta lens, as a condenser lens in future works. Moreover, we found that the relationship between the electrical current and focal length for the tunable lens was slightly affected by the temperature of the surroundings. We plan to conduct careful quantitative analysis and evaluation in the next stage.

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