A MEMS-based interactive laser scanning display with a collocated laser range finder

Sungho Jeon\textsuperscript{1a)}, Hiroyuki Fujita\textsuperscript{2}, and Hiroshi Toshiyoshi\textsuperscript{1,2}
\textsuperscript{1} Research Center for Advanced Science and Technology, The University of Tokyo,
4–6–1 Komaba, Meguro-ku, Tokyo 153–8504, Japan
\textsuperscript{2} Institute of Industrial Science, The University of Tokyo,
4–6–1 Komaba, Meguro-ku, Tokyo 153–8505, Japan
\textsuperscript{a)} jsh@iis.u-tokyo.ac.jp

Abstract: This paper presents an interactive laser scanning display (LSD) based on a microelectromechanical systems (MEMS) optical scanner that projects full-color images of lateral 720 pixels by two-dimensionally scanning a collimated laser beam. The scanner optics is also designed to function as a laser range finder (LRF) to measure the distance to the screen or an inserted object within arm’s reach of 20 cm to 60 cm. The combination of LSD and LRF constructs an interactive image display that could be remotely controlled by the viewer’s hand gestures.

Keywords: MEMS, interactive image display, laser scanning display, laser range finder, optical scanner

Classification: Micro- or nano-electromechanical systems

References

1 Introduction

Interactive display is an emerging technology to capture the viewer’s motion as a pointing device to give a feedback to the presented images. Touch-panel display is a most widely used interactive display but recent applications demand larger display areas beyond the size of hand-held devices. One of the solutions for such application is to use a video projection system combined with an image recognition algorithm. P. Khandnor et al. used a video camera to capture the location of the electronic pointing gear for visual input [1]. J. C. Lee et al. used a mobile panel equipped with light-emitting devices that could be used as a marker to locate the position and the attitude of the hand-held panel [2].

Commercial versions of such interactive displays have also been released from Microsoft Corp. [3] and Touchjet Pte Ltd. [4] They commonly use an arrayed light valve device such as a liquid crystal (LC) or a digital mirror device (DMD) for image projection along with a separate CMOS (complementary metal-oxide semiconductor) imaging chip for visual recognition. A drawback of such system is that the projection optics always needs to adjust the focusing lens to present images onto the screen; in other words, no clear image is presented when projected onto a curved screen or the surface of an arbitrary shape. Furthermore, additional light emitting devices are needed for a visual feedback purpose, thereby making the system complex. To simplify the optics of interactive displays, we have proposed a use of a microelectromechanical systems (MEMS) scanner for laser scanning display (LSD) as well as for laser ranger finder (LRF) [5]. Owing to the collimated laser beam, clear images are projected onto any type of screens without using a focusing unit. Furthermore, the beam spot scanned at a fast speed can also be used as a probe light for the LRF.

In this paper, we present the optical system of the interactive display that could recognize the position of an object inserted between the projector and the screen. We also give an analytical model for the triangulation measurement of the LRF with a MEMS scanner along with experimental verification results. As a demonstration of interactive display, we use a moving palm and a screen to range the distance to it. The hand gesture of the viewer can also be used as an input device to control the contents of the projected images.

2 Optics for interactive image display

Fig. 1 schematically shows the interactive image display, which uses the light source for image projection as well as for a laser range finder based on the triangulation measurement method [5]. When projecting an image on the screen by raster scanning the laser beam, the human visual system cannot discern the individual beam spots because its temporal resolution of recognition is no faster than 100 ms, while the image frame is refreshed in every 17 ms (60 frame per second, fps). The coordinate sensitive detectors, on the other hand, usually have time resolution in the order of a few μs, therefore it is theoretically possible to resolve more than thousands of pixels as a probe lights to perform multi-probe triangular LRF measurement while presenting images [6].
We used a MEMS optical scanner based on the piezoelectric PZT (lead zirconate titanate) drive reported elsewhere [7]. The piezoelectric strain induced by the applied voltage generates mechanical torque to twist the suspended mirror in the orthogonal directions for two-dimensional spatial modulation.

The vertical and horizontal angles of the scanner \((\theta, \phi)\) are independently controlled by the set of two voltages, \(V_\theta\) and \(V_\phi\). The horizontal scan \(\phi\) at a fast speed over 25 kHz is controlled by exciting the electromechanical resonance of the scanner. On the other hand, the vertical scan \(\theta\) is operated off the resonance at 60 Hz by quasi-statically deflecting the mirror in the orthogonal direction. The combination of two orthogonal motions thereby creates a raster scan for two-dimensional images with the synchronized modulation of the laser intensity.

The same optics can be used as an LRF to tell the distance \(r\) to the object inserted within the projected rays by means of the triangulation method. The directional vector of the probe light, \(r_p\), is known by the scanner’s angles \((\theta, \phi)\) through the drive voltages \((V_\theta, V_\phi)\), while the direction to the object seen from the LRF optics, \(r_o\), is measured by observing the scattered light on the position-sensitive detector (PSD) through a lens or a pin-hole. Provided that the distance between the scanner and the PSD is \(d\), the distance to the object \(r\) is calculated from the parallax difference between \(r_o\) and \(r_p\).

Fig. 2 shows the block diagram of the signal flows in the developed system. The controller makes the drive signals for the MEMS scanner and the laser diodes. The signals from the PSD are acquired by a personal computer (PC) through the analog-to-digital converter (ADC), and the distance \(r\) is calculated based on the triangulation with respect to the scanner’s angle \(\theta\) in the vertical motion on the screen. Depending upon the value of \(r\), the PC interactively changes the images to be projected in the subsequent frames.
The simplified waveforms of the signal voltages are shown in Fig. 3. The scanning mirror periodically deflects at a fast speed in the horizontal direction (angle $\phi$ in Fig. 1) and at a slow speed in the vertical direction (angle $\theta$ in Fig. 1); to be more specific, scanning starts from the top line of the screen and finishes in the bottom line, and it flies back to the top line again after completing a frame. The drive voltage for the vertical scan $V_\theta$ is programmed as a skewed saw-tooth wave at 60 Hz as shown in Fig. 3a.

In the horizontal direction, on the other hand, the MEMS scanner periodically deflects at a fast speed of 25 kHz or over, and therefore the scanner is operated at its mechanical resonant frequency, which is excited by the sinusoidal voltage $V'_\theta$ as shown in Fig. 3b. The scanner used in this study is designed to auto-calibrate its resonant frequency, thereby compensating the effects of the temperature and humidity in the operation environment. The resonant frequency is used as a master clock-signal to the rest of the image projection system to synchronize the intensity modulation of the lasers [7].

Fig. 3c shows the drive voltage of the green laser when displaying a white test image on the screen. The drive signal to the laser is modulated at 120 MHz, and its modulation patterns depend upon the colors and brightness of the pixels. The laser is periodically turned off whilst the MEMS scanner flies back to the top line, so that the projected images are not disturbed by the bright trajectory. The laser is also turned off near the edges of the horizontal scans, where the aspect ratio of the image is significantly distorted due to the slow turn-around speed of the scanner.

As a first test, we took the vertical position of the beam spot (i.e. the vertical scan angle $\theta$) for triangulation measurement. The PSD output $S_{PSD}$ was proportional to position of the beam spot on the screen, and it was designed to be high when the beam spot was located at the lower part of the PSD’s detecting surface. Fig. 3d shows the signal pattern of the $S_{PSD}$ when the screen was at a 40 cm distance from the PSD. The voltage rolled down linearly with the vertical position of the beam spot. The signal height of the PSD signal includes the information about the distance to the beam spot on the screen; we used the averaged signals to numerically calculate the distance by using the LabView program code. When the
laser was turned off, the PSD output was not uniquely determined but it randomly fluctuated due to the intrinsic noise of the PSD of this type. The noise level became smaller when the room light was turned on rather than turned off.

LRF system can also be constructed by measuring the time-of-flight (TOF) [8, 9] but it is not compatible with our interactive display system because the target distance is shorter than 1 m and that the TOF is as small as 3.3 ns, requiring an ultrafast electronics for signal processing. Besides, TOF measurement needs a coded light source for pattern matching but our system already used the intensity modulation of lasers for an image projection purpose; another modulation such as polarization might be used but the entire system may become complicated. Therefore we have chosen the triangulation method in our LRF rather than TOF.

3 Analytical model for triangulation

Fig. 4 illustrates the analytical model for the LRF with a MEMS optical scanner. The optical deflection angle $\theta$ is the incident angle of the beam with respect to the mirror’s normal. A bi-convex lens (LB1092-A, Thorlabs) is located at a distance $d_l$ from the laser’s axis at the rest position, and a two-dimensional PSD (S5991-01, Hamamatsu Photonics K. K.) is placed behind the lens at its focal length.
$d_2 = 15\, \text{mm}$. The PSD is intentionally displaced from the lens axis to accommodate the shift of the beam spot deflected from the lowest part on the screen.

The beam spot location on the screen measured from the center of the scanned area is $z_s = x \cot \theta$, where $x$ is the screen’s distance from the scanner. The scattered light is collected by the bi-convex lens and focused onto the PSD; the beam spot position $z$ is estimated by following the chief-ray between the scattered light on the screen and the center of the lens. Due to the similarity of the triangles $\triangle ABC$ and $\triangle CP_0 P$, we write

$$z : d_2 = d_1 - x \cot \theta : x,$$

and therefore,

$$z = (d_1/x - \cot \theta)d_2. \quad \text{(2)}$$

In this study, we set $d_1 = 42\, \text{mm}$, $d_2 = 15\, \text{mm}$, and the image is displayed when the $\theta$ varies between $81.73^\circ$ and $98.27^\circ$.

While the $z$-position on the PSD is measured, the beam spot also moves in the horizontal direction due to the fast axis of the scanner. To cover the lateral expansion of the beam spot, we used the two-dimensional PSD of relatively large detector area of $9\, \text{mm} \times 9\, \text{mm}$.

The PSD is electrically biased to $-10\, \text{V}$ to its base substrate, and it has four output terminals on the corners to deliver current outputs (as shown in Fig. 4 inset), whose magnitudes are proportional to the relative position of the beam spot on the detector area. Each output current is converted into a voltage through a resistor $R_c (= 1\, \text{k}\Omega)$ and then amplified through an inverted amplifier of a gain $G = 800$. The voltages are read by the data acquisition device (USB-6363, National Instruments Corp.) and signal-processed by a LabView program. We compared the voltages from the top corners of the PSD ($V_1 + V_3$) with those from the bottom ($V_2$ and $V_4$) and defined this signal as $S_{\text{PSD}}$.

\[ S_{\text{PSD}} = \frac{(V_2 + V_4) - (V_1 + V_3)}{V_1 + V_2 + V_3 + V_4}. \quad \text{(3)} \]

The vertical position of the beam spot $z$ on the PSD is estimated by
where the differential voltages are normalized by the sum of all the outputs and the PSD’s length is \( L(=10\text{ mm}) \). The initial offset displacement of the PSD, \( y_0 = 1.4 \text{ mm} \), is also considered as a constant.

4 Experimental results of LRF measurement

Experimental apparatus for the demonstration of interactive projection display is shown in the photograph in Fig. 5. On the LSD package, we placed the PSD and the bi-convex lens. The screen was mounted on a straight railway such that it could be displaced back and forth with respect to the LSD.

![Optical apparatus for laser range finding with the laser scan display.](image)

We set 1,000 sampling points per a frame (i.e. 16.67 ms) to obtain data \( S_{\text{PSD}} \) from the PSD. The 500-th data from the beginning was used to measure the distance to a fixed point on the screen, while displacing the screen position in a range between 20 cm to 60 cm from the LSD module, as shown in Fig. 6. When no average was used, the sampled data point had a large noise as indicated by the red dots in the figure; in this condition, the target resolution of 1 cm was not fulfilled. When 21 sampling points (from 490-th to 510-th) were taken for average, on the other hand, the error in measurement was effectively suppressed as shown by the blue dots. The measurement error was further suppressed to realize the 1-cm resolution when 101 data points (from 450-th to 550-th) were averaged. Sampling of 101 data points required a measurement time of 1.68 ms, which corresponded to 66 horizontal scan lines.

We set four zones of detection that were vertically stacked on the screen, and measured the mean distance to each zone. Fig. 7 shows the results of the measurement by using 100 sampling points. Zones 1 to 4 were placed from the top to the bottom on the screen as shown in the figure inset. We also show the theoretical curve derived from the analytical model; the simulation was found to quantitatively explain the experimental results very well.
5 Demonstration of interactive display

5.1 Real-time feedback of screen distance to projected images

With the distance recognition system developed in this work, we built an interactive projection display that controlled the output image according to the screen distance. Fig. 8(a) shows the block diagram on the LabView platform, where the sampled points from 450-th to 550-th out of the total 1,000 points were used to estimate the distance by averaging, and the results of measurement was image-projected in numbers. For demonstration, we used a viewer’s hand inserted into the projected light such that the measurement data was directly displayed on the palm, as shown in Fig. 8(b). Owing to the collimated beam of lasers, the projected image looked clear on the curved surface of the palm.
5.2 Page-flip by viewer’s hand gesture

We also developed another LabView program to demonstrate the page flipping of projected images based on the viewer’s hand gesture. In this demonstration, we split the screen into two segments that were vertically stacked, and traced the presence of the inserted object (viewer’s hand). Fig. 9(a) shows the state-transition diagram of the viewer’s swipe motion over the screen. The position of the hand was known by the drop of the PSD’s output level, and hence the system could tell the initial position of the hand. The program was coded such that the pages were flipped forwards when the hand moved in the downward direction, while pages were flipped backwards when the hand moved in the upward direction. Fig. 9(b) shows the snapshot image during the demonstration, where the page numbers were either incremented or decremented.

6 Conclusions

As an example of the simple architecture of user-interactive image display, we have proposed a combined use of the laser scanning display (LSD) and the laser range finder (LRF), in which a laser beam for creating images was also used as a probe light to detect the distance to an object. We used an LSD with a piezoelectric MEMS optical scanner to build the interactive sensing system with a position sensitive detector (PSD) based on the triangulation measurement. Distance measurement between 20 cm and 55 cm was successfully operated. Analytical model for the LRF was developed and found to quantitatively explain well the experimental results. As a demonstration of real-time interactive display, we developed a system that returned the measured distance by projecting the numbers. We also demonstrated an interactive display controlled by the viewer’s hand gesture, in which the pages were flipped in forward or backward direction according to the direction of the waved hand in front of the LSD system.
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Fig. 9. Demonstration of page flipping commanded by the viewer’s hand gesture. (a) State-transition diagram of the system to correlate the hand position to the page-flip operation. (b) Snapshot images of the demonstration, where pages were changed by the upward or downward motion of the inserted hand.