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Speckle reduction by employing two green lasers and two-dimensional vibration of lenses

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Abstract
A method of speckle reduction suitable for use in a laser projector was proposed in the paper. Speckle contrast ratio (SCR) reduction was achieved by combining wavelength diversity and angular diversity methods. First, wavelength diversity was demonstrated by the use of two green laser sources (a 520 nm laser diode (LD) and a 532 nm diode-pumped solid-state (DPSS) laser) at a power ratio of 4:1. Second, angular diversity was achieved via the vibration of two lenses in two orthogonal directions placed directly after the laser source. The vibrating lenses are small and do not require changes to the beam path of the laser source, allowing for more compact projector designs. The frequency of vibration of these lenses was optimized to minimize the SCR in the output image. A SCR of less than 4% was achieved without the use of optical diffusers, which significantly reduces optical losses. Optical transmission could be further increased with the optimization of optical coatings on the lenses. This result shows great promise for applications such as laser pico-projectors within the realm of heads-up displays (HUDs) and mobile devices.

1. Introduction
In recent years, projection display technology has played a vital role in modern life. Projectors can often be found acting as an invaluable tool for the communication of ideas within a classroom or conference room [1]. Projectors can also function as entertainment devices within home theatres [1] or cinemas [2]. Notably, the advent of the pico-projector has brought display technology into the mobile space with great potential to revolutionize heads-up display (HUD) systems [3]. Large number of projection systems is still relying on lamps [4] and light-emitting diodes (LEDs) [5] as light sources launched into the light engines. The problems that plague these display technologies can be effectively overcome with the use of laser sources, which have increased brightness, wider color gamut, longer lifetime, and increased optical efficiency [6]. The pico-projector is a miniaturized application of this laser display technology, which has generated a great deal of interest due to its reduced size and weight. Therefore, it has become highly sought after for mobile photo/video applications [7], portable personal cinemas [8], and HUD systems [9]. To date, pico-projectors commonly use LEDs as light sources rather than lasers, and therefore using lasers as a light source would provide a significant improvement to image quality and light engine efficiency (due to a reduction in etendue).

However, it must be noted that the adoption of lasers as a light source has suffered due to a phenomenon known as laser speckle caused by the high coherency of the laser source [10]. Laser speckle results in a noticeable decrease in output image quality and therefore, the success of laser display technology is dependent on the reduction of this effect. For the purposes of this paper, this effect will be referred to as speckle noise. Speckle noise can be calculated via the SCR which is defined as $SCR = \frac{\sigma}{\bar{I}}$, where $\sigma$ is the standard deviation and $\bar{I}$ is the mean of the light intensity passing through the plane of the projected image.

There are several methods of suppressing speckle noise and decreasing the SCR of the laser projection system. These methods are often divided into three categories: wavelength diversity [11], angular diversity [12], and polarization diversity [13]. The effective application of one or more of these effects can reduce the SCR to...
less than 5%, which is the limit where the speckle effect becomes invisible to the human eye [12, 14]. Due to the benefits associated with laser projection, multiple techniques have been implemented to take advantage of these speckle reduction methods. They include but are not limited to, the use of micro-electro-mechanical systems (MEMS) scanning mirrors [15, 16], deformable mirrors [17], diffractive optical elements [18], and vibrating diffusers [19]. Although these techniques effectively suppress speckle noise, they can be unattractive to manufacturers due to a high cost and/or degree of complexity, as well as reduced optical and electrical efficiency [18]. Additionally, they can be relatively bulky, which can cause problems when attempting to optimize a small form factor design, such as with pico-projectors and related applications.

In this paper, we propose an effective method of speckle reduction with a low cost and a compact size, which is especially important to pico-projectors. The method is depending on the our presented idea of using single lens vibration in one dimension (1D) to reduce laser speckle noise [20]. Two cascaded lenses were inserted into the red, green blue (RGB) laser optical path. Each lens was fixed inside an optical CD/DVD pickup actuator to create what will be referred to as a lens vibrating module (LVM). The two lenses were then vibrated in the directions perpendicular to the optical axis at optimized frequencies to achieve angular diversity. In addition to speckle noise reduction, we discuss prevention of image fluctuations (‘flickering’) by optimizing the vibration frequencies in the proposed method. To further reduce speckle, wavelength diversity was implemented via the use of a green light source comprised of two individual green wavelengths (532 nm and 520 nm). This served a dual purpose in both reducing the speckle noise and greatly enhancing the color gamut and brightness of the output image.

2. Working principle of LVM

Figure 1 shows a schematic diagram of a single LVM module, which is widely used as an optical CD/DVD pickup actuator [21]. A plano-convex lens with 4.5 mm diameter and 4 mm focal length is capable of vibration in two dimensions (i.e., along the direction of the optical axis and perpendicular to the optical axis). In our experiments, only the tracking motion (i.e., the direction perpendicular to the optical axis) was used.

The vibration of the lenses is facilitated by small voice coils and small permanent magnets on the LVM frame. Under the application of a voltage across the voice coil terminals, an electromagnetic force will act against the static magnetic field from the magnets, which then manifests as a mechanical motion of the lens. The lens was transparent (no coating) and made of acrylic (or PMMA). The measured transmission efficiency of a single lens is around 90%. No obvious degradation of the transmission efficiency with an input green DPSS laser power of 1.5 W for 1 h with no obvious degradation of the lens, which means the acrylic lens is suitable for a pico-projector system which usually has low optical power. Figure 2 shows the transmission efficiency of a single lens versus input of the green DPSS laser power. The transmission efficiency is about 90%, which is almost independent of the input green DPSS laser power.

3. Characterization of the lens vibrator module (LVM)

Figure 3 shows a schematic diagram of the experimental setup used to characterize the amplitude of each LVM and the scanning area shape. In figure 3, the laser source is a DPSS laser. The wavelength of the DPSS laser is 532 nm, with a linewidth of 0.1 nm. In this experiment, two LVMs with different dimensions were used.
(14.9 mm × 10 mm and 13 mm × 10 mm for LVM1 and LVM2, respectively). The tracking coil of LVM1 was controlled by a ±3 V square wave voltage from a multifunction generator, while the tracking coil of LVM2 was controlled by a transistor–transistor logic (TTL) signal (+3.1 V) from another signal generator. The lens of LVM1 vibrates in the Y-direction and the lens of LVM2 vibrates in the X-direction. A high-resolution charged coupled device (CCD) camera (DCU224M from Thorlabs, pixel size 5.86 μm × 5.86 μm) was used to capture the image of the screen.

Figure 4 shows images captured by the CCD camera using the test setup shown in figure 3. In figure 4(a) represents the output image as a bright point when there are no applied signals on both LVM1 and LVM2. Figure 4(b) represents the output image as a horizontal bright line when LVM1 is ‘off’ and LVM2 is ‘on’. Figure 4(c) represents the output image as a vertical bright line when LVM1 is ‘on’ and LVM2 is ‘off’. Figure 4(d) represents the output image as a bright pattern (the shape of this pattern depends on the frequency change of LVM1 and LVM2) when both LVM1 and LVM2 are ‘on’. In this context, ‘on’ and ‘off’ refers to whether the aforementioned input signal(s) are being applied. During this measurement, the amplitudes of LVM1 and LVM2 covered a frequency range of 30 to 130 Hz. Note, the fourth image was taken under the condition that the frequency of vibration of the two modules was not equal.

Figure 5 shows the relationship between the frequency of vibration and the measured amplitude on the screen. Using the distance between the LVMxy and the screen (37 cm), the real values of the amplitude from the LVMxy module can be estimated by considering the magnification of the lenses used. In figure 5, the vertical and horizontal bright lines images represent the shape of the laser beam on the screen under the effects of the vibration. The vertical and horizontal bright lines are produced by LVM1 and LVM2, respectively.
4. Theoretical background

The SCR is dependent on a speckle reduction factor $R$, which can be expressed as:

$$\text{SCR} = \frac{1}{R} = \frac{1}{R_\lambda R_{\Theta} R_s}$$

Where, $R_\lambda$, $R_{\Theta}$, and $R_s$ are the wavelength, angular, and polarization diversity, respectively. $R_s = 1$ for any screen can preserve the polarization state of laser and $R_s = \sqrt{2}$ for any depolarized screen such as the white A4 paper used in this experiment. Thus, $R_s$ is constant in all experiments and the reduction factor $R$ depends on the values of $R_\lambda$ and $R_{\Theta}$. One of the most effective method to achieve large $R_{\Theta}$ is by moving a diffuser in the path of laser beam [22]. As the lens array is considered a diffuser with low diffusion and high transmission efficiency [23], the motion of the laser beam across the lens array can increase $R_{\Theta}$.

Figure 4. Captured grayscale images from CCD camera where (a) $LVM_1$ and $LVM_2$ are off, (b) $LVM_1$ and $LVM_2$ are on and off, respectively, (c) $LVM_1$ and $LVM_2$ are on and off, respectively, and (d) $LVM_1$ and $LVM_2$ are both on with different frequencies.

Figure 5. Amplitude versus frequency for the two individual vibrating lenses.
Also, $R_\Omega$ has an upper limit according to the solid angles of the projection lens and the detector lens [13]. So, the only remaining factor can yield a further reduction of the speckle noise is $R_n$. According to Goodman's theory [13], the $R_n$ of two laser wavelengths with equal intensities, Gaussian shape and wavelength separation greater than 1 nm, is $R_n = 1/\sqrt{2}$. However, according to [24], to achieve the minimum SCR by using two lasers with two different linewidths thus the power level of each laser is not the same. As a result, the lower values of SCR can be achieved when the power level of the laser with wider linewidth must be higher than the power level of the laser with narrower linewidth. Eventually, the total speckle reduction is a combination from the aforementioned values of $R_n$, $R_\Omega$, and $R_p$.

5. Proposed laser projector layout

Figure 6 shows a proposed configuration for a laser projector layout. In figure 6, the red, blue, and green laser modules are combined using a dichroic prism to complete the RGB light source. The green laser module is comprised of a DPSS laser (532 nm) and laser diode (LD) (520 nm). The combination of the two lenses performed by using a single lens. The RGB laser light is collimated by a lens and then directed to cross two lenses (LVM_1 and LVM_2). The two lenses are vibrated in directions either perpendicular or parallel to the optical path and make up the component LVM_{xy} (as shown in figure 6). A homogenizer module will be used to homogenize the light field. A lens system (including a pair of lens arrays) is used to reshape the light field to be rectangular. A polarizing beam splitter (PBS) is used to take the footprint image from a liquid-crystal on silicon (LCoS) panel. Finally, the output image will be projected via a projection lens. The overall length of the light engine from the dichroic prism to PBS is 70 mm.

Utilizing this projection system with a laser light source shows great promise in terms of creating compact and cost-effective mini-/pico-projector systems.

6. Experiments and discussions

6.1. Speckle reduction characterization

An experiment was performed for studying laser speckles and evaluating its reduction efficiency by using the green laser source as the human eye is most sensitive to green wavelengths, compared to both red and blue [25].

Figure 7 shows the experimental setup, which was used to reduce the green laser speckle noise. The laser source consisted of a green LD (NDG7475 Nichia) at 520 nm with 2 nm linewidth and a green DPSS laser at 532 nm with 0.1 nm linewidth. The green LD and DPSS laser were attached to Peltier elements, and aluminum heat sinks to maintain an operating temperature of 25 °C. The two laser sources were then combined using a cubic beam-splitter. Half of the combined green laser (CGL) beam was collected by a power meter (LM10 from coherent Inc.) to measure the power ratio between the two green sources.

The remaining half of the CGL was then directed to pass through two vibrating lenses (LVM_1 and LVM_2) which comprise LVM_{xy}. After LVM_{xy}, a pair of micro-lens arrays (fly-eye lenses) were used to act like a laser beam homogenizer [23]. That is, they were used to transform the initially circular cross-section of the CGL into a rectangular cross-section with uniform intensity distribution. The fly-eye lens was followed by a telecentric imaging system consisting of two lenses (L_2 and L_3) to project the rectangular CGL beam into a rectangular aperture (6.60 mm × 5.23 mm). Finally, a projection lens with a focal length of 6.5 mm produced the output image on an A4 white paper screen.
It is well known that the measurement conditions have a significant impact on measuring the SCR, thus the measurement conditions used correspond to the human eye perception. In order to ensure an accurate SCR value, the parameters used in this work agree with the previously reported work in [15, 17, 19, 22, 26] to measure the SCR in a handheld laser projector such as pico-projector. The pixel size of the CCD camera is 5.2 μm × 5.2 μm with a resolution of 1280 × 1024 pixels. The F/# for the camera lens is 1.4. The integration time of CCD camera was chosen to be 20 ms as that is comparable to the integration time of the human eye. The focal length of the camera’s lens was 25 mm. The distance between the camera and the screen was 0.5 m. The CCD camera-generated an 8-bit grayscale image and was used in the linear region. All experimental data were collected under the conditions of a dark room to avoid noise generated by background light.

To evaluate the effect of speckle reduction due to the individual vibrating lens, the SCR was measured for each laser source when either LVM1 or LVM2 was turned on. Figure 8 shows the measured SCR versus vibrational frequency over a range from 0 to 130 Hz.

From figure 8 and table 1, the SCR values were 0.093 and 0.160 for the LD and DPSS laser, respectively when neither LVM1 or LVM2 were vibrating. Once the modules began to vibrate, the SCR began to decrease with increasing vibration amplitude. It can be seen from figure 8 that the minimum SCR was achieved within the range of 50 Hz to 80 Hz. With only the DPSS laser as a source, and LVM1 (or LVM2) vibrating, the minimum SCR was 0.078 (or 0.90). This can be attributed to the linewidth of the LD being much broader than the linewidth of the DPSS laser (2 nm versus 0.1 nm). This also shows that the vibration along the x- and y- direction alone cannot achieve an SCR below the human-perception limit of 5% for both the green LD and DPSS laser. Therefore, wavelength diversity is required in combination with angular diversity to further reduce the SCR.

6.2. Optimization of a green laser source

Figure 9 shows the relation between the SCR and the power ratio. That is, the ratio between the power of the LD to the total power of the two laser sources when both LVMs are OFF. The current sources output of the LD and DPSS lasers are adjusted electrically to fix the optical power at 500 mW for both lasers. The optical power of the DPSS is controlled by a half-wave plate and polarization beam splitter. The optical laser power of the DPSS is controlled by a half-wave plat and polarization beam splitter. According to Goodman’s theory [13], when blending two lasers of equal linewidths, the optimum speckle-noise reduction occurs at a power ratio of 1:1. However, when blending lasers of two separate linewidths the optimal power ratio will not be at a ratio of 1:1 [24]. From figure 9, the minimum SCR was achieved when the power of the LD was four times larger than that of the DPSS laser (P_{LD}: P_{DPSS} = 4:1). This result was expected from [24]. At this power ratio, the green point in the color gamut wheel would be shifted closer to 520 nm. This is not preferred in terms of color gamut coverage as it is far from the ideal wavelength of 532 nm as recommended by Rec.2020 [24]. Therefore, a trade-off exists between color quality and minimum SCR however it must be noted that solving this problem is not the main target of our study. Although the combination of the green LD and DPSS laser can achieve much better color gamut coverage and even lower SCR, the power ratio which yields these benefits is not the same for both. That is, the power ratio which offers increased color gamut coverage is not the same the ratio which yields the lowest SCR. Once again, optimization must be performed to obtain the best result taking into consideration the results from both effects.
Figure 8. The measured SCR for DPSS and LD source in separate as a function of the frequency of vibration of (a) LVM₁ and (b) LVM₂. The error bars -at each frequency- are given by calculating the standard deviations of the SCRs for the individual sub-images.

Table 1. The speckle reduction efficiency of the LD and DPSS laser sources for each LVM module.

<table>
<thead>
<tr>
<th>LVM</th>
<th>LVM₁</th>
<th>LVM₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Source</td>
<td>DPSS</td>
<td>LD</td>
</tr>
<tr>
<td>SCR when both LVMs OFF</td>
<td>0.160</td>
<td>0.093</td>
</tr>
<tr>
<td>Minimum SCR (Frequency of LVM₁ or LVM₂ are 70 Hz)</td>
<td>0.078</td>
<td>0.051</td>
</tr>
<tr>
<td>Reduction Efficiency: ((1 - \text{Minimum SCR}) \times 100)</td>
<td>51.25</td>
<td>43.33</td>
</tr>
</tbody>
</table>

Figure 9. Measured SCR using wavelength blending of a green LD and a green DPSS laser versus the power of the LD divided by total power, where from a power ratio of 0 to 1 both LVMs are in the ‘off’ state. The error bars -at each frequency- are given by calculating the standard deviations of the SCRs when different areas similar are selected.
6.3. Optimization of operating frequencies

After optimizing the power ration between the LD to the power of the DPSS laser to be 4:1, the operating frequencies must be optimized. Figure 10 shows the relation between the SCR versus the frequencies of LVM1 and LVM2. From figure 10, it can also be seen that the lowest SCR was achieved between a frequency of 40 and 60 Hz for vertical vibration and between a frequency of 60 and 100 Hz for horizontal vibration. It can, therefore, be shown that a minimum SCR ranging from 0.035 to 0.04 can be achieved by employing two green lasers and two-dimensional vibration of lenses. The SCR can be further reduced to be under 4% by using optical diffusers or even a combination of them [17], but this will be on the expense of the optical efficiency of the illumination system [19]. For example, in [22], the minimum SCR achieved was from 2.81% to 4.60% with optical efficiency from 34 to 43% by using pairs of high divergence angle diffusers under vibration. In any pico-projector, the brightness (optical efficiency) must be considered when creating these laser projection systems. Therefore, it is very beneficial that an SCR of less than 5% was achieved without using any diffuser. Obviously, the value of SCR can be further decreased by inserting a low divergence angle optical diffuser (e.g. <15°). Such a low divergence angle diffusers are preferred as it has no significant optical loss [27].

Figure 11 shows the measured speckle image when the frequency of LVM1 and LVM2 is 50 Hz and 90 Hz (dynamic state), respectively by the setup is shown in figure 7. The SCR was 0.084 in a static state (no vibration for both modules and the power ratio between LD and DPSS laser is 4:1) and 0.035 + 0.003 in a dynamic state. This is implying that the efficiency of speckle-noise reduction is 56.25% for wavelength diversity and angular diversity \(\left\{1 - \frac{0.035}{0.08}\right\} \times 100\%\).
In conclusion, it has been demonstrated that a SCR below the human-eye perception limit (5%) can be achieved by employing novel two-dimensional vibrating lenses coupled with the wavelength diversity techniques. Our proposed optimized method can achieve excellent output image quality with an SCR of 4% and no image flickering.

The proposed method is compact because it does not require any modification of the optical path. In our proposed method, the optical power efficiency (for green laser) was 69.62%. The optical efficiency can be further increased by at least 15.38% via the application of an anti-reflection coating to the two vibrational lenses.

The proposed projection system has the potential to significantly improve the brightness, optical-to-optical efficiency, and colour gamut coverage of laser projection systems. Therefore, reduced cost and size alongside increased efficiency makes this laser projection system ideal for practical mini- /pico-projection systems.

In the future, the proposed method will be optimized as follows: First, the use of anti-reflection coated lenses to increase the transmissivity. Second, design and manufacturing of a 2D scanning device with single aspheric lens and with high resonance frequencies. Third, using a low divergence angle diffuser (< 15 degree) to reduce the SCR. Fourth and finally, using a DPSS laser with wide linewidth in order to further optimize the blending ratio. Fifth, as known that the luminance of the output projected images from the laser projector would influence the human perception of the speckle noise. Therefore, a study of the best power ratio between the RGB lasers used has to be performed to achieve the optimum luminance.

Figure 12. Speckle images for (a) DPSS laser source with \( f_1 = f_2 = 70 \) Hz, (b) LD laser source with \( f_1 = f_2 = 70 \) Hz, and (c) CGL source with \( f_1 = f_2 = 50 \) Hz.

In the above discussion, the focus was on achieving the minimum SCR value. To fully encompass all the necessities of practical laser display applications, another important parameter must be considered which is the output image flickering. The flickering in the output light field on the output screen was noticed at some vibration frequencies. According to [28], the output Lissajous shape parameters, such as line density and repetition rate for each shape from both LVMs as well as the scanning area on the 1st lens array are related to the frequency applied to each LVM. First, the repetition rate is the main cause of the flickering which will result in decreasing the output image quality. From [29], the repetition frequency of the output can be calculated by finding the greatest common divisor (GCD \( f_1, f_2 \), where \( f_1 \) and \( f_2 \) are the frequency of LVM1 and LVM2, respectively) for the frequency of LVM1 and LVM2. The expected highest repetition frequency can be achieved at \( f_1 = f_2 \) or \( f_1 = 2f_2 \). For instance, the GCD (50 Hz, 50 Hz) = 50 Hz, and GCD (50 Hz, 100 Hz) = 50 Hz. This means that the repetition frequency of the output light field will be 50 Hz. As a result, the output light field will appear fixed without any flickering with respect to the human eye, as the repetition rate is sufficiently greater than the perception threshold of 25 Hz.

Secondly, as the scanned area increases, the time needed to complete one scanning cycle will increase as well [28, 29]. The dimensions of the scanned area corresponding to the 1st lens array depend on the amplitude of the two vibrating lenses and the distance between the second vibrating lens and the first lens array (b) (c).

Figure 12 shows the measured speckle images from the experimental setup in figure 7. In figure 12(a), the green laser source was a DPSS laser with \( f_1 = f_2 = 70 \) Hz. The SCR was 0.068. In figure 12(b), the green laser source was an LD with \( f_1 = f_2 = 70 \) Hz. The SCR was 0.05. In figure 12(c), the LD and DPSS green laser power were blended with a power ratio of 4:1 (as mentioned in section 6.2) with \( f_1 = f_2 = 50 \) Hz. The SCR was 0.04. In figure 12 the output images are free of flickering under the proposed frequencies, with 10 mm distance between the 2nd vibrating lens and the 1st vibrating lens.

7. Conclusion

In conclusion, it has been demonstrated that a SCR below the human-eye perception limit (5%) can be achieved by employing novel two-dimensional vibrating lenses coupled with the wavelength diversity techniques. Our proposed optimized method can achieve excellent output image quality with an SCR of 4% and no image flickering.

In the future, the proposed method will be optimized as follows: First, the use of anti-reflection coated lenses to increase the transmissivity. Second, design and manufacturing of a 2D scanning device with single aspheric lens and with high resonance frequencies. Third, using a low divergence angle diffuser (< 15 degree) to reduce the SCR. Fourth and finally, using a DPSS laser with wide linewidth in order to further optimize the blending ratio. Fifth, as known that the luminance of the output projected images from the laser projector would influence the human perception of the speckle noise. Therefore, a study of the best power ratio between the RGB lasers used has to be performed to achieve the optimum luminance.
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