Electro-optical sensor with spatial and spectral filtering capability

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Received 6 April 2011; revised 26 May 2011; accepted 31 May 2011;
posted 1 June 2011 (Doc. ID 145435); published 11 July 2011

We describe a new concept of an electro-optical sensor with the capability of simultaneous spatial and spectral filtering. It is based on a spatial light modulator, and in combination with the technique of wavelength multiplexing, it enables one to manipulate the spectral content of an indicated spot within the field of view of the sensor. This new concept allows the attenuation of monochromatic light of undetermined wavelengths in particular and is of worth for imaging vision systems to suppress unwanted detector overexposure. © 2011 Optical Society of America

OCIS codes: 140.3360, 230.6120, 230.7408, 280.4788.

1. Introduction

Modern electro-optic sensors are widespread devices used in many different applications, but they are vulnerable to overexposure and to optical damage. A main source that threatens optical sensors is the laser. Since its invention 50 years ago, the laser has proved to be a very valuable instrument [1] when used according to safety regulations. The consequence of the increasing availability of low priced, compact, and quite powerful laser sources is, however, the increase in misuse of such devices. These days, handheld laser pointers with emission wavelengths in the visible spectral region and with output powers up to 1 W are available on the free market [2]. In civil environments, aircraft crews particularly [3], as well as motorists [4], are considered to be candidates for dazzling attacks. In such cases the loss of the vision can lead to catastrophic accidents.

In addition, laser dazzling can also pose a severe problem not only for the human eye but also for electro-optical sensors used in autonomous or surveillance systems [5]. Adequate protection against dazzling is highly desirable. Electro-optical sensors can suffer various effects due to dazzling with intense light [6]. At low irradiation levels, just a simple saturation of single pixels occurs. With increasing irradiation, the overexposed region increases and complex dazzling structures appear due to multiple reflections of light, diffraction, and scattering effects within the optical system (e.g., lens flares). At very high irradiation levels, but still a factor of 100–1000 below the damage threshold, complete detector columns can fail due to effects influencing the image transfer electronics.

Current laser protection measures are typically realized using conventional optical filters based on absorption or interference effects. Unfortunately, these filters work for predefined wavelengths, but not beyond. Therefore, sophisticated protection concepts against dazzling and also against damage are required, which work independent of the threatening wavelength and do not influence the system performance.

In the last decades, passive optical limiting devices based on nonlinear optical effects were studied to protect both the human eye and electro-optical sensors against wavelength agile laser sources [7–9]. Because of the low magnitude of the optical nonlinearities, such kinds of devices always need to be placed in the focal plane of an optical system to increase the

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nonlinear effects. Good results were obtained concerning protection against damage [10]. However, optical limiting devices are usually not suitable as protection measures against laser dazzling due to their high activation threshold, though in a recent paper a passive dynamic sunlight filter was announced [11].

Numerous kinds of approaches based on active systems have been discussed in the literature in order to realize laser protection. Among them are shutters, frequency agile filters, and spatial light modulators. A short review on these technologies is given by Svensson *et al.* [4]. In general, active systems are useless against short laser pulses, since they suffer from the disadvantage of a finite response time. They also need a kind of laser warning sensor to detect the threatening laser light and a servo loop to react. Additionally, an electrical power supply is necessary. Nevertheless, active concepts are definitely attractive, since the proliferation of compact cw laser sources is very high and uncontrollable.

In the case of electro-optical sensors, the implementation of an active laser protection measure benefits from the already available components such as the electrical power supply and the lens. In general, the imaging optics of the sensor can be utilized to work together with the protection concept, as the protection measure (optical power limiter, shutter, etc.) will be placed in the intermediate focal plane of the imaging lens. Furthermore, the sensor to be protected may be used as a laser warning sensor at the same time and thus may take part in the servo loop.

In this paper we present a novel concept for an electro-optical sensor with the ability to filter incident radiation both spatially and spectrally within a small area of the field of view. This capability can be used particularly as a protection measure against laser dazzling, which ideally suppresses only the threatening cw laser light while not affecting the nonthreatening radiation. In order to achieve this aim, we made use of a spatial light modulator (SLM) in combination with wavelength multiplexing as the key elements of the sensor concept. Typical protection measures such as conventional laser protection filters or shutters were discarded, since they influence the complete field of view of the sensor uniformly.

2. Setup for Spatial Filtering Only

The use of SLMs as a protection measure against dazzling light sources was already described earlier by Tomilin and Danilov [12] and is also the subject of several patents [13,14], but no experimental results were given there. In order to investigate the potential of this method, we first started experiments with the setup shown in Fig. 1.

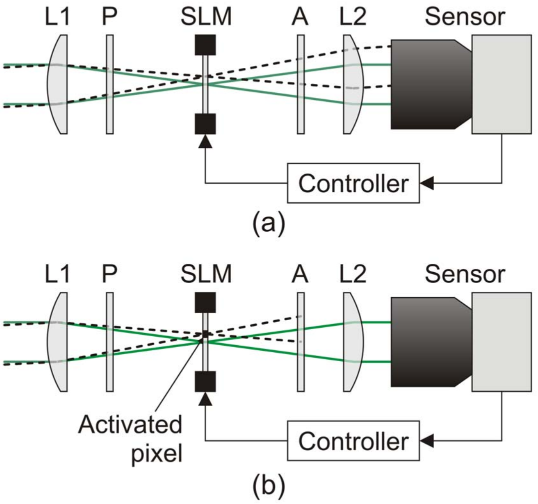

Fig. 1. (Color online) Sensor concept including a spatial light modulator. An SLM is located in the intermediate focal plane of an optical system (lenses L1, L2). By means of two polarizers (polarizer P, analyzer A), the spatial light modulator is used as an intensity modulator. (a) In the passive operating mode the transmittance of the optical arrangement is high, and the light can reach the sensor nearly undisturbed; (b) in the case where the sensor gets dazzled (shown here by the black dashed light rays), a number of pixels of the SLM corresponding to the dazzled pixels of the sensor have to be activated to reduce the transmission of the dazzling light.

In this experimental setup a transmissive SLM (Holoeye LC2002) was placed in the intermediate focal plane of a 1∶1 Keplerian telescope formed by two identical lenses (lenses L1 and L2 in Fig. 1, focal length: 80 mm). The SLM consists of a 26.6 mm × 20.0 mm twisted nematic liquid crystal display (Sony LCX016) with 832 pixels × 624 pixels with a pixel pitch of $32\,\mu$m and a fill factor of 55%. For unpolarized white light the transmittance of the SLM was measured to be around 0.4 in our setup. Since the SLM operates by rotating the polarization of incident light, two linear polarizers (denoted as P and A in Fig. 1) were placed before and after the SLM to make it work as an intensity modulator. Each polarizer has a maximum transmittance of 0.55 for linear polarized light. Thus, for both polarizers in series and irradiated with unpolarized light, a maximum transmittance of 0.15 ($0.5 \cdot 0.55^2$) results. As the electro-optical sensor to be protected, we used a color CMOS camera (VRmagic VRmC-12 PRO) equipped with a zoom lens (Schneider-Kreuznach Variogon 1.8/10–100). The SLM is driven by a controller with standard SVGA signals (800 pixels × 600 pixels). Gray values of 255 and 0 correspond to maximum and minimum light transmission, respectively.

As a start, the optical setup was operated at maximum transmission [Fig. 1(a)]. Then, for dazzling light arriving at the sensor, the controller reacts by activating just those SLM pixels corresponding to the overexposed sensor pixels [Fig. 1(b)]. As a consequence, the transmission of the dazzling light beam is reduced, while the transmission of all other light beams from the scene is left unaffected. The level of the SLM driving signal determines the attenuation of the activated SLM pixels. The maximum achieved attenuation for laser light of a wavelength of 633 nm was measured to be about 37 dB (see Fig. 2).

As demonstrated by a sequence of photographs (see Fig. 3), this approach allows the suppression of light in small areas of the field of view of the optical sensor system. The urban scene shows the roof part of a church and intensive laser light appearing from the subsidiary steeple. Since the SLM was placed in the intermediate focal plane of the optical setup, the structure of the SLM appears as a meshlike pattern in the image. Figure 3(a) may be considered as a reference photograph to give an impression the scene. In Fig. 3(b), intensive green laser light is observed, originating from a dazzle laser (cw, wavelength: 532 nm, output power: 36 mW, full angle divergence: 1 mrad). For convenience, the laser head was placed in the laboratory next to the optical setup, and its light was back reflected from a retroreflector mounted at a column of the steeple (distance: 412 m). We estimated the irradiance from the retroreflected laser beam at the entrance aperture of our optical system to be about $10\,\mu\mathrm{W/cm}^2$ (assuming Gaussian beam propagation and an atmospheric extinction coefficient of $0.2\,\mathrm{km}^{-1}$). Figure 3(c) illustrates the effect when the appropriate pixels of the SLM are activated with individual attenuation to block the laser light. The geometrical structure of the activated SLM pixels corresponded to a disk-shaped pixel pattern 15 pixels in diameter. The inner core of the disk was attenuated maximally (SLM control signal: 0), while the boundary region was less attenuated (SLM control signal: 180). It can be seen that the dazzling light vanishes nearly completely except for the peak of the irradiance profile. The scene in the remaining part of the field of view is left unaffected.

Figure 3 reveals that this approach has two main disadvantages. First of all, a distracting pixelation effect is noticed, which is caused by the patterned structure of the SLM. This effect can be reduced to some degree by slightly shifting the SLM out of the image plane of the Keplerian telescope until the structure of the SLM is no longer imaged sharply onto the detector (in our setup, approximately 0.5 mm). Second, a more or less small part of the scene has to be blocked in order to attenuate the laser radiation. This helps to reduce the laser hazard, but at the cost of useful information, which gets lost by the blocking of a part of the scene.

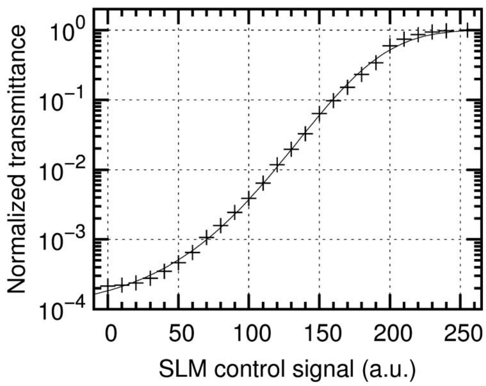

Fig. 2. Intensity modulation of the spatial light modulator Holoeye LC2002 at the wavelength 633 nm. The minimum transmittance is 2×10^{-4}.

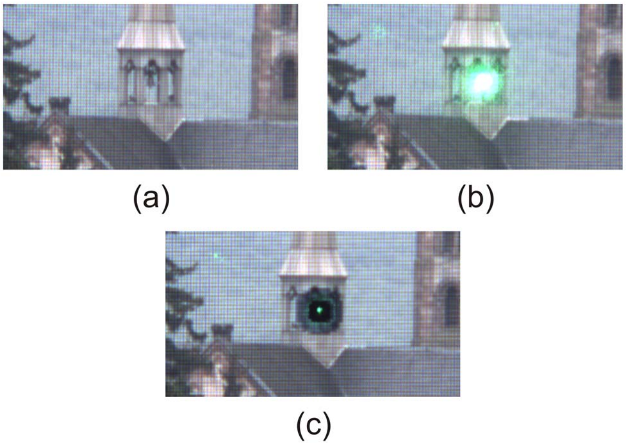

Fig. 3. (Color online) View of an urban scene with an optical system as presented in Fig. 1. The zoom lens was adjusted to 50 mm, and the exposure time of the camera was 50 ms. Because of the SLM placed in the intermediate focal plane, a meshlike structure is visible. (a) View without a dazzling laser source; (b) a dazzle laser originating from the steeple can be seen; (c) the dazzling laser radiation is attenuated nearly completely by activating the SLM. A limited area of the field of view is affected and hides useful information.

With the help of an improved optical setup comprising the concept of the SLM and wavelength multiplexing, both of the above mentioned disadvantages can be avoided. This technique will be described in Section 3.

3. Setup for Spatial and Spectral Filtering

Wavelength multiplexing is a technique that was introduced by Koester to improve the quality of the image transfer through optical fiber bundles [15]. Koester's aim was to overcome local transmission errors within the fiber bundle, e.g., by broken fibers, and to avoid annoying patterns due to the imaging of the structure of the fiber's exit facet.

The concept of wavelength multiplexing is based on transmitting the various wavelengths from a given object point through a large number of different fibers. This was realized by placing a double Amici prism (also known as direct vision prism) in front of the input optical system of a fiberscope, which imaged the object onto the entrance facet of the fiber bundle. Thus, the light from a given object point was spectrally broken down and then transmitted through the fiber bundle. A corresponding dispersing element was placed at the exit end of the fiber bundle to reverse the dispersion.

In contrast to Koester's idea, we make use of the possibility of manipulating the transmission in local areas by replacing the fiber bundle by an SLM. In combination with wavelength multiplexing, the setup now allows us to filter the scene spectrally within defined areas.

A. Setup with Direct Vision Prisms

The implementation of the wavelength multiplexing technique in our experimental setup is shown in Fig. 4. Before the objective (L1) and behind the eyepiece (L2) of the Keplerian telescope, we inserted two identical direct vision prisms (Pr1, Pr2) into the optical path. For a light beam emerging from a certain object point of the (distant) scene, the optical path is visualized. The light beam is spectrally broken down by the first prism. For each object point of the scene a wavelength spectrum is formed in the intermediate focal plane of the telescope at a slightly different position on the SLM. In order to restore the object scene, the dispersion has to be reversed by means of the second prism behind the eyepiece of the telescope. Furthermore, the imaging of the annoying SLM structure onto the sensor is prevented. As depicted in Fig. 4, the transmission of a narrow spectral range of the light beam (here represented by the blue dashed lines) can be blocked by activating the appropriate pixels of the SLM. All the remaining wavelengths can pass the optical arrangement unaffected.

A minor drawback of wavelength multiplexing is a slight color distortion in the vicinity of the activated area. This results from the fact that the spectra of light beams from different spatial directions overlap in the intermediate focal plane (see Fig. 5). Thus, the manipulation of a certain area in the intermediate focal plane influences all those light beams whose spectra overlap in this area. Each spatial direction is affected at a different wavelength.

The results achieved with such a wavelength multiplexing setup are presented in Fig. 6 for the same scene as in Fig. 3. Figures 6(a) and 6(b) show the scene without and with dazzling, respectively. When compared to Fig. 3, it is clearly recognizable that the patterned structure of the SLM has vanished in the image. By activating the appropriate pixels of the SLM, the dazzling laser light is suppressed nearly completely [see Fig. 6(c)]. As described in Section 2, again a disk-shaped pixel pattern 15 pixels in diameter was used to block the dazzling radiation (SLM control signals: 0 in the core and 128 in the boundary region). In contrast to the “simple” setup without wavelength multiplexing, now the details of the steeple in the vicinity of the laser source are left clearly visible. Only the green laser light is attenuated, whereas all other wavelengths pass nearly unaffected. Since the activated pixels of the SLM also influence neighboring light beams, a colored bar crossing the image is weakly visible. However, this color distortion has no influence on the recognizability of scene details.

A disadvantage of the optical setup with direct vision prisms is the large amount of space needed for the two prisms (30 mm × 30 mm × 106 mm). This impedes the construction of compact and lightweight systems.

B. Setup with Gratings

The overall size of the optical setup could be significantly reduced by the use of gratings instead of

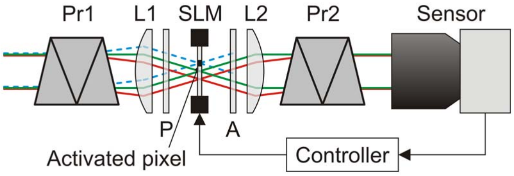

Fig. 4. (Color online) Advanced sensor concept using wavelength multiplexing by means of two direct vision prisms (Pr1/Pr2, direct vision prisms; L1/L2, lenses; SLM, spatial light modulator; P/A, polarizers). Because of the spectral dispersion, the local activation of the spatial light modulator attenuates only a narrow spectral band of the incident light beam (blue dashed lines), whereas the remaining wavelengths can pass the optical arrangement unaffected. This allows for spatial and spectral filtering of monochromatic light sources without losing useful information.

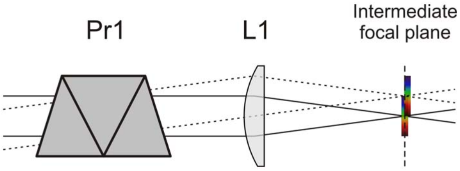

Fig. 5. (Color online) Illustration of the spectral breakdown of incoming light by a direct vision prism. To simplify matters, the exact optical paths of the dispersed light beams are not shown. For each incident light beam a spectrum is produced in the intermediate focal plane. The spatial position of the spectrum depends on the angle of incidence of the light beam. At a certain position in the intermediate focal plane all wavelengths can occur, though they belong to light beams with different angles of incidence.

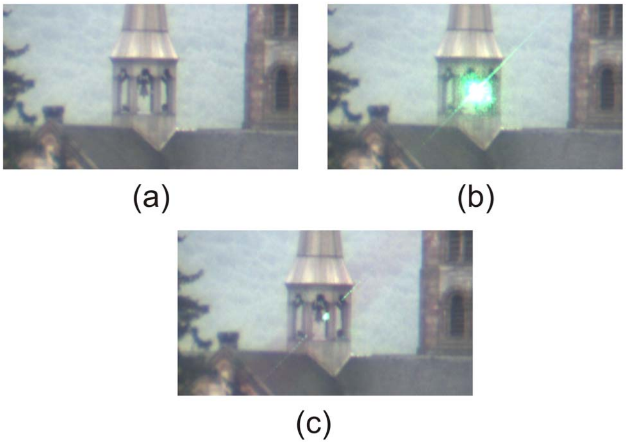

Fig. 6. (Color online) View of an urban scene with an optical system with wavelength multiplexing as presented in Fig. 4. The zoom lens was adjusted to 50 mm, and the exposure time was 50 ms. Compared to Fig. 3, the square-pattern structure of the SLM has vanished. Scene (a) without and (b) with the dazzling laser source; (c) the dazzling laser radiation is attenuated nearly completely by activating the SLM. Only a marginal area of the field of view is still affected. Compared to Fig. 3(c), all the geometrical details of the scene are now visible.

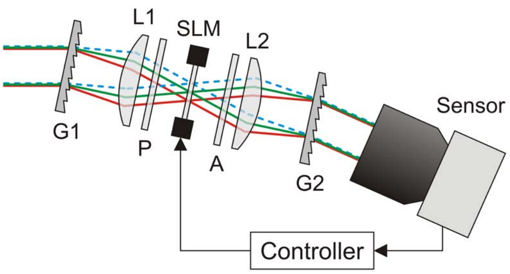

Fig. 7. (Color online) Optical setup with gratings used for the implementation of the wavelength multiplexing (G1/G2, gratings; L1/L2, lenses; SLM, spatial light modulator; P/A, polarizers). Since the diffraction orders occur at specific diffraction angles, a folded optical path results.

the direct vision prisms. A corresponding optical setup is shown in Fig. 7. Because dispersion occurs only in the first or higher diffraction orders, the use of gratings results in a folded optical path as indicated in the figure. Moreover, since the incident light is diffracted into several diffraction orders, the dispersion reversal behind the telescope by a second grating can only be provided for one diffraction order. Thus, a loss of light has to be accepted when gratings are used. In order to keep the loss of light as low as possible, blazed gratings should be employed.

For our experimental setup, we used two blazed transmission gratings with 300 grooves/mm (Thorlabs GT25-03). They offer an absolute efficiency of more than 60% for wavelengths in the range from 450 to 700 nm. The absolute efficiency is defined by the ratio of the energy diffracted into a specific order to the total incident energy.

4. Image Quality

Since each optical component influences the sensor's imaging performance, the different filter concepts (SLM only, SLM with prisms, SLM with gratings) were analyzed regarding their image quality. The individual setups were

- Setup 1: Only the camera with the objective lens
- Setup 2: The optical setup with SLM according to Fig. 1
- Setup 3: The optical setup involving wavelength multiplexing with direct vision prisms according to Fig. 4
- Setup 4: The optical setup involving wavelength multiplexing with gratings according to Fig. 7

For all the measurements concerning the image quality we used a monochrome CCD camera (Kappa DX4-285FW, pixel size: 6.45 μm) equipped with an $f = 50$ mm objective lens (Schneider-Kreuznach Xenoplan 2.8/50). To get a qualitative impression, we took images of a United States Air Force (USAF) 1951 target. Figure 8(a) shows an image taken with setup 1. This image serves as a reference image, since no filtering components were present. The optical setup with just the SLM [Fig. 8(b)] causes the worst image, as the pixelation effect annoyingly superimposes the scene. A much better image quality was achieved applying wavelength multiplexing. This improvement is clearly observable in Figs. 8(c) and 8(d) for optical setups 3 and 4, respectively. Please note that the figures just illustrate the individual image quality of each setup. They are not comparable in terms of brightness, since the overall transmittances of the four setups are all different. In each case the experimental conditions (i.e., camera exposure time, target illumination) were adapted to make full use of the camera's dynamic range. For example, Figs. 8(b)–8(d) show images taken under nearly the same illumination conditions, while the camera exposure time was adjusted to be 20, 40, and 30 ms, respectively. Figure 8(a) was taken with a much lower target illumination and an exposure time of 13 ms.

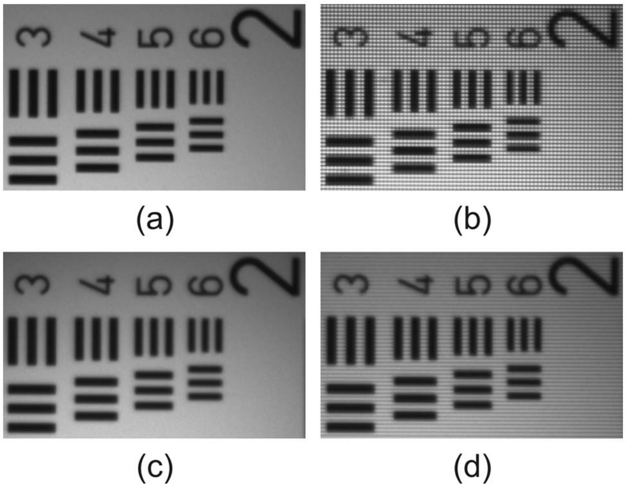

Fig. 8. Images of an USAF 1951 target taken with various optical setups: (a) optical setup without filtering component (camera with objective lens), (b) optical setup with the SLM according to Fig. 1, (c) optical setup with direct vision prisms used for the wavelength multiplexing according to Fig. 4, (d) optical setup with transmission gratings used for the wavelength multiplexing according to Fig. 7.

A more quantitative assessment of the image quality can be obtained by measuring the modulation transfer function (MTF) of the different optical setups, which characterizes the spatial frequency response of an optical system [16]. For our various optical setups the MTF was estimated by means of the knife-edge method for digital imaging devices [17]: the spatial frequency response of an imaging system is determined by analyzing the image of a slightly tilted knife edge.

Figure 9 shows the MTFs for the four different optical setups. The Nyquist frequency $f_N = 0.5/(6.45\,\mu\text{m}/50\,\text{mm}) \approx 3.9\,\text{mrad}^{-1}$ is marked in the graph. As expected, the response for the camera alone is better than for all the other setups. It is interesting to see that the MTF for setup 2 seems to be better at medium spatial frequencies (1.5 to 3 mrad)

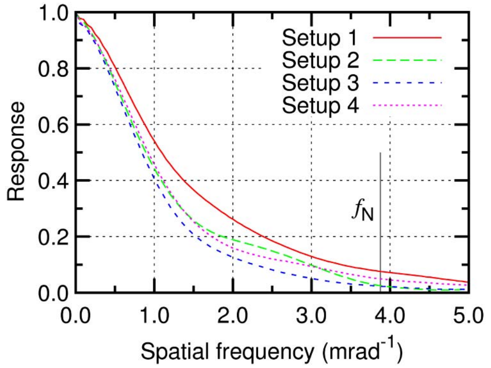

Fig. 9. (Color online) MTFs for several optical setups: (1) the camera equipped with an objective lens alone, (2) the MTF for the optical setup with SLM, and the MTFs for the optical setups with wavelength multiplexing with (3) direct vision prisms and (4) gratings. The vertical gray line indicates the Nyquist frequency.

than for setups 3 and 4, even though the subjective image impression is worse (see Fig. 8). We attribute this to the fact that the pixelation effect visible in Fig. 8(b) is mostly suppressed by the dark frame and the flat field correction procedure used to process the images taken with the CCD camera [18]. An estimation of image quality by means of measuring the minimum resolvable contrast in observer experiments [19] would probably lead to different results.

5. Conclusions

A new concept for an electro-optical sensor with spatial and spectral filtering capability was presented. It is based on an SLM combined with wavelength multiplexing. This technique can be used in particular as a protection measure for imaging sensors against laser dazzling. It allows the suppression of monochromatic laser light within its field of view, but without losing optical information from the area from which the annoying laser light occurs. This advantage will be reduced for nonmonochromatic light sources. The larger the wavelength spectrum of the light sources, the larger the amount of pixels to be blocked by the SLM, which results in a gradual decrease in optical information.

The maximum attenuation was measured to be 37 dB for laser radiation at the wavelength of 633 nm. As demonstrated by Fig. 6(c), where the sensor was dazzled with an irradiance approximately a factor of 100 below the damage threshold, this attenuation was sufficient to reduce the overexposure down to a few pixels.

The response time of the filter is in the range of several milliseconds and depends mainly on the frame rate of the imaging sensor and on the switching time of the SLM. This means that laser pulses, even arriving within the integration time frame of the sensor, are difficult to suppress. Thus, this concept is best suited to damp cw laser radiation. The attenuation of hazardous laser radiation may also help to prevent the sensor from damage, but the initially unblocked portion of the incident laser radiation could cause permanent damage to the sensor.

The optical imaging performance of the sensor concept was evaluated qualitatively on the basis of a USAF 1951 target, but also quantitatively by means of the MTF. The filter elements (SLM, polarizers, and dispersion elements) have minor impact on the image quality, but they seriously affect the transmittance of the system. Without wavelength multiplexing, the total transmittance is $T = 0.06$ (both polarizers together: 0.15, SLM: 0.4). Depending on the dispersive elements used for the wavelength multiplexing, the transmittance drops to $0.06 \cdot 0.9^2 \approx 0.05$ for the direct vision prisms or to $0.06 \cdot 0.6^2 \approx 0.02$ for the gratings.

The current experimental setup demonstrated proof of the principle, but for an operational system the transmittance is far too low. An improved concept making use of a reflective SLM that does not depend on polarized light (e.g., a digital micromirror device) can certainly overcome this insufficiency.

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