Electro-optical sensor with automatic suppression of laser dazzling

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ABSTRACT

The progress in laser technology leads to very compact but nevertheless powerful laser sources. In the visible and near infrared spectral region, lasers of any wavelength can be purchased. Especially continuous wave laser sources pose a serious threat to the human eye and electro-optical sensors due to their high proliferation and easy availability. The manifold of wavelengths cannot be encountered by conventional safety measures like absorption or interference filters.

We present a protection concept for electro-optical sensors to suppress dazzling in the visible spectral region. The key element of the concept is the use of a digital micromirror device (DMD) in combination with wavelength multiplexing. This approach allows selective spectral filtering in defined regions of interest in the scene. The system offers the possibility of automatic attenuation of dazzling laser radiation. An anti-dazzle algorithm comprises the analysis of the laser wavelength and the subsequent activation of the appropriate micromirrors of the DMD.

Keywords: Sensor protection, laser dazzling, digital micromirror device, wavelength multiplexing

1. INTRODUCTION

Electro-optical sensors are wide spread devices, used in many different applications, but they are susceptible to overexposure and to optical damage. A main source that threatens optical sensors is the laser. Due to the increasing availability of low priced, compact and quite powerful laser sources, there is an increase in misuse of such devices. These days, compact laser sources with emission wavelengths in the entire visible and near-infrared spectral region and with output powers up to several watts are available. In civil environments, particularly aircraft crews as well as motorists are considered to be candidates for dazzling attacks^{1,2}. In such cases, the loss of vision can lead to fatal accidents. Besides the human eye, laser dazzling can also pose a severe problem to electro-optical sensors used in autonomous or surveillance systems³. An adequate protection against dazzling is highly desirable.

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

Numerous kinds of approaches were discussed in literature regarding realization concepts for laser protection². Among them are active systems like shutters, frequency agile filters or spatial light modulators. In general, such 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 continuous wave laser sources is very high and uncontrollable.

TOMILIN and DANILOV, for example, described the use of spatial light modulators as a protection measure against dazzling light sources⁴. The advantage of spatial light modulator technology is the possibility to build a protection measure, which can attenuate light coming from a specific direction within the field of view. At the same time, light coming from all other directions is not influenced. In order to realize such an operating principle, it is necessary to place the spatial light modulator in the intermediate focal plane of an optical system. Therefore, this method is primarily useful to protect electro-optical sensors against laser radiation.

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With the implementation of *wavelength multiplexing*, we were able to improve the concept of TOMILIN and DANILOV significantly. Now, this new concept allows simultaneously spatial and spectral filtering of monochromatic light^{5,6}.

2. OPERATING PRINCIPLE

Wavelength multiplexing is a technique, which KOESTER introduced to keep the quality of images when transferred through optical fiber bundles⁷. The idea was to transmit the information from a single object point through a number of different fibers. It was realized by placing a *double Amici prism* (or *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 divided and then transmitted through the fiber bundle. A corresponding dispersing element placed at the exit end of the fiber bundle reversed the dispersion. Therefore, annoying image transmission errors of the fiber bundle, for example by broken fibers or the facet structure, were reduced.

Figure 1 shows a schematic view of our protection concept combining a spatial light modulator with the technique of wavelength multiplexing. Light beams entering the optical setup are spectrally divided by a first dispersive optical element Pr1. A lens L1 focuses the beams onto the spatial light modulator. Here, we use a *digital micromirror device* (DMD) as spatial light modulator⁸. Since the DMD works in reflection, a folded beam path arises. A second lens L2, identical to lens L1, collimates the reflected light. A second dispersive optical element Pr2 reverses the dispersion of light by the first dispersive optical element Pr1. Finally, the light is imaged onto a camera sensor.



Figure 1. Schematic view of a protection concept combining a spatial light modulator (DMD) with the wavelength multiplexing technique: (a) Operation mode for regular imaging: all micromirrors of the DMD are tilted towards the sensor. (b) Operation mode with high attenuation for dazzling light: the micromirrors which are exposed to dazzling laser light (here: the green rays) are tilted away from the sensor. Thus, the dazzling light will be strongly attenuated in the regular imaging path.

Usually, the optical setup would be operated in such a way that all light is directed towards the sensor by tilting all micromirrors to the $+\theta$ -state (Figure 1a). If the sensor is dazzled by a laser (here: the green rays in the figure), the controller toggles just these micromirrors to the $-\theta$ -state which are exposed to dazzling light (Figure 1b). Thus, the dazzling light is reflected out of the beam path. The non-dazzling light coming from the same direction as the dazzling light, but with wavelengths different from the laser wavelength, will be still imaged onto the camera sensor (here: the red and blue rays in the figure).

Such a setup suppresses only the threatening laser light, while not affecting the remaining non-threatening radiation of the scene. This concept using a DMD was described in detail in a previous publication⁹. In this publication, will we focus on our efforts to compact the system, to increase the field of view of the sensor and to improve the automatic suppression algorithm.

3. EXPERIMENTAL SETUP

Figure 2 shows the optical layout of the latest experimental setup. Please note that blazed gratings (300 grooves/mm) realize the dispersive elements depicted as direct vision prisms in Figure 1. The use of gratings instead of prisms allows to build a more compact setup, but on the cost of light transmittance. The gratings offer a diffraction efficiency of more than 60% for wavelengths in the range from 450 nm to 700 nm. The absolute efficiency is defined by the ratio of the power diffracted into the preferred order to the total incident power. As can be seen in Figure 2, the gratings were aligned so that the spectral wavelength separation takes place in a plane perpendicular to the plane of reflection at the DMD.

The DMD is placed at the position of the intermediate focal plane of the telescope formed by two achromatic lenses, each with a focal length of 50 mm (Achromatic lens 1 and 2). The light is reflected by the DMD with an angle of 24° to the normal of the DMD surface. A third lens (Achromatic lens 3) with a focal length of 35 mm forms the final image. The focal plane of the achromatic lens 2 and the plane of the DMD do not coincide. As a consequence, the image plane is tilted with regard to the optical axis. In our setup, we used a CMOS camera VRmC-12 Pro from VRmagic GmbH, which was aligned according to the SCHEIMPFLUG principle.

As DMD, we chose the DLP Discovery 4100 kit from Texas Instruments comprising a 0.7" XGA DMD. This DMD offers 1024×768 micromirrors with a pitch of 13.68 µm. Each mirror can be toggled from a +12° to a -12° state; the axis of rotation is oriented at an angle of 45° with respect to the edges of the array. The DMD efficiency for wavelengths between 420 nm and 700 nm is specified to be 68%, which includes the transmission of the protection window (~ 97%), the fill factor (~ 92.5%), the mirror reflectivity (~ 88%) and the diffraction efficiency (~ 86%). This value is defined as the amount of light that is reflected specularly by the array.



Figure 2. Optical layout of an electro-optical sensor with automatic suppression of laser dazzling: A digital micromirror device (DMD) is located in the intermediate focal plane of a Keplerian telescope (Achromatic lens 1 and 2). Wavelength multiplexing is implemented by the use of two diffraction gratings (Grating 1 and 2). Grating 1 was aligned so that the spectral separation takes place in a plane perpendicular to the plane of reflection at the DMD.

In general, the requirements for a sensor are compactness, high sensitivity and an adequate field of view. The systems described in our previous publications^{5,6,9} acted as a proof-of-principle and their footprints were quite large. To reduce the system size one can use lenses with shorter focal lengths. When the sensitivity shall be improved at the same time, which means reducing the f-number, care has to be taken to keep a high image quality. The best f-number achievable is limited by lens aberrations.

In our current system the focal length of the achromatic lenses 1 and 2 is 50 mm (previously 75 mm) and the focal length of the achromatic lens 3 is 35 mm (previously 50 mm). We obtained a good image quality while retaining the diameter of the entrance aperture (5 mm). In Figure 3 two images taken with the new setup give an impression of the image quality (a) using the example of an USAF 1951 target and (b) showing a real scene. Please note that we used off-the-shelf components for the achromatic lenses and gratings. In future, the image quality could be further improved by using customized lenses instead. Table 1 presents the main parameters of the system.



Figure 3. Two example images taken with the sensor: (a) USAF 1951 Target. (b) Real scene.

Footprint	$25 \text{ cm} \times 20 \text{ cm}$
Field of view	$7.9^{\circ} \times 5.0^{\circ}$
Transmission	24%
Mean attenuation of laser light (480 nm – 680 nm)	41.7 dB

Table 1. Parameters of the system.

4. **RESULTS**

The maximum attenuation of laser light for the system was measured as a function of wavelength. For this purpose, we used a coherent white light source (Koheras SuperK Extreme) equipped with an acousto-optical tunable filter (AOTF). The AOTF was used to produce narrow-band radiation adjustable in the spectral range from 480 nm to 700 nm. The attenuation of the system was measured for various wavelengths by comparing the attenuation of the DMD with the attenuation of a set of calibrated neutral density filters.

The graph in Figure 4 shows the results of these measurements. The location of the data points and the horizontal error bars correspond to the wavelength and FWHM linewidth as measured with a spectrometer (RGB Lasersystems Qwave). For wavelengths up to 680 nm, the attenuation is mostly above 40 dB (mean attenuation 41.7 dB). A decrease in the attenuation can be observed for wavelengths higher than 680 nm.

Figure 5 shows the results of a field trial obtained with the new setup. The urban scene shows the roof part of a church, where a retroreflector was mounted at a column of the small steeple (distance: 412 m). Two different cw lasers (wavelength: 532 nm / 656 nm, output power: 36 mW / 50 mW, full angle divergence: ~ 1 mrad), placed next to the system in the laboratory, served as dazzling light source.

Overexposure of the sensor at the wavelength 656 nm can be seen in Figure 5a. This disturbance was filtered out after toggling the appropriate micromirrors of the DMD as shown in Figure 5b. Only a slight vertical color distortion occurs because a narrow range of wavelengths is absent in the image. Figure 5c presents a quite similar situation; the wavelength 532 nm was used to disturb the sensor. Also in this case, a color distortion is recognizable in the image once the laser light is suppressed (Figure 5d). The color distortion appears different compared to Figure 5b because a different range of wavelengths is removed. In Figure 5e the situation is shown when both wavelengths, 532 nm and 656 nm, are suppressed. The geometrical details of the steeple are still observable.



Figure 4. Plot of the attenuation of the system as a function of wavelength. The mean attenuation in the wavelength range from 480 nm up to 680 nm is 41.7 dB



Figure 5. Results of a field trial: (a) Dazzling by a laser with a wavelength of 656 nm. (b) Laser dazzling suppressed; wavelength 656 nm. (c) Dazzling by a laser with a wavelength of 532 nm. (d) Laser dazzling suppressed; wavelength 532 nm. (e) Laser dazzling suppressed; both wavelength 532 nm and 656 nm.

5. AUTOMATIC SUPPRESSION ALGORITHM

The task of the controller indicated in Figure 1 is to analyze steadily the camera images for dazzling and to drive the DMD automatically according to the actual situation. In case of dazzling laser light, the controller has to toggle the appropriate micromirrors of the DMD in order to suppress the overexposure. The activation of the correct micromirrors depends (1) on the direction from where dazzling originates and (2) on the wavelength of the dazzling laser.

The direction from where the dazzling originates is delivered directly from the camera image. However, the wavelength of the dazzling laser is a priori not known. This means that the exact location where the dazzling light is focused onto the DMD is not known. In the first instance, only information on the appropriate columns of micromirrors is given since the dispersion of light due to the grating takes place in a vertical direction.

For the case of a color camera to be protected, the information on the dazzling wavelength can be deduced directly from the color information contained in the camera images. The overexposed regions on the detector are surrounded by not overexposed pixels, which contain the necessary information about the searched wavelength. For instance, in the situations shown in Figure 5a and Figure 5c, an observer could immediately say that some red and green laser light affects the sensor. A good estimation of the dazzling wavelength can be derived by an analysis of the color values of the non-saturated contour pixels surrounding the overexposed area. In order to implement an algorithm for the automatic suppression of dazzling laser light based on this idea two steps are necessary: (1) The detection of dazzling and determination of the color of the laser light. (2) The estimation of the laser wavelength on the basis of its color in the camera image.

Figure 6 depicts a flowchart of the procedure for the analysis of the camera images. In order to decide whether dazzling has occurred or not, a first step is to detect the overexposed pixels in each camera image. This is done by a simple thresholding operation (threshold value: 254) in all three RGB bands. A pixel with a value above threshold within at least one of the RGB bands is considered as overexposed. The result of the thresholding operation applied to Image 1 of Figure 6 is shown in Image 2 of Figure 6. Since saturated pixels contain no useful RGB information, the neighboring pixels forming a contour line around the overexposed area will be extracted and used for further analysis (see Image 3 of Figure 6).

At this point, one has to take into account that the background light influences the result of the analysis of the RGB values and has to be removed for exact wavelength estimation. For this purpose, we make use of the camera frame preceding the dazzled frame (see Image 4 of Figure 6). This is appropriate as long as there are only moderate changes in the illumination conditions between the acquisitions of two subsequent camera images. The according contour line in the preceding image is shown in Image 5 of Figure 6. As a last step, the background corrected pixel values of the contour line are subsequently averaged and the resulting triple (R, G, B) is analyzed to estimate the laser wavelength

The use of a color camera in order to estimate the laser wavelength was presented elsewhere in detail⁹. Briefly, the pixel values *R*, *G*, and *B* originating from laser illumination of the color camera can be compared with the camera's color response curves plotted in Figure 7. First, the intensity independent chromaticity values r = R/(R+G+B), g = G/(R+G+B), b = B/(R+G+B) are calculated. Then, each value *r*, *g*, *b* is compared with its corresponding response curve $r_{cam}(\lambda)$, $g_{cam}(\lambda)$ and $b_{cam}(\lambda)$. By including an additional uncertainty Δ for the measured chromaticity values, a set of possible wavelengths for each color component is derived. The intersection of all three sets provides a range of wavelengths, which most likely contains the laser wavelength. As an example for b = 0.3, this procedure is illustrated in Figure 7 for the blue chromaticity interval $[b-\Delta, b+\Delta]$ and the camera response curve $b_{cam}(\lambda)$ for blue light.



Figure 6. Flowchart of the image analysis procedure for the estimation of the dazzling wavelength. The color of the contour line (Image 3) is ready to be analyzed after the subtraction of the background (Image 5). The frame preceding a dazzled frame (Image 4) is used to determine the background light.



Figure 7. Color response curves of the camera used in the optical setup (VRmagic VRmC-12 Pro). The dots in the plot show measured chromaticity values for monochromatic light. The solid curves are fit curves to the measurement data.

6. SUMMARY

We presented a concept for an electro-optical sensor with automatic suppression of laser dazzling. The concept is based on the combination of a spatial light modulator with the wavelength multiplexing technique. An experimental realization by making use of a digital micromirror device was presented. An automatic algorithm is able to detect overexposure in parts of the sensor image caused by laser radiation. In that case, the wavelength of the laser is estimated by means of image analysis. With this information, the algorithm activates the digital micromirror in an appropriate way to suppress the disturbing laser light. The attenuation of the laser light is greater than four orders of magnitude for wavelengths between 480 nm and 680 nm.

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