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Background light suppression lock-in method for multispectral measurements with near-infrared LED spotlight illumination

Abstract

The paper deals with illumination issues in multispectral imaging and presents the lock-in approach for background light suppression. There is comparison shown between the results obtained with differential approach and lock-in approach without sweep and with sweep. Obtained results prove the good performance of background suppression with the proposed lock-in approach.

Keywords: multispectral, imaging, near infrared.

1. Introduction to multispectral imaging

The idea behind multispectral imaging is to acquire, in the same time, plurality of images of the same scene but in different spectral channels. Each channel comprises different range of wavelengths and typically channels are not overlapping each other. In multispectral systems the number of channels is limited and typically does not exceed 10 [1]. Systems with more channels are referred to as hyperspectral ones. There are different approaches to multispectral imaging described in literature. The simplest one is a multi-camera system, where each camera (channel) has different spectral sensitivity range [1]. This approach is used when it is impossible to cover the desired whole broad spectral range with one detector. Good example is simultaneous imaging in visible range (VIS, (400-700) nm), near-infrared (NIR, (700-1000) nm), short wavelength infrared (SWIR, (1-3) μm), mid wavelength infrared (MWIR, (3-5) μm) and long-wavelength infrared (LWIR, (7-14) μm) [1]. While for VIS and NIR it is sufficient to use relatively cheap CCD or CMOS array based on silicon, this material becomes transparent for longer wavelengths. Hence moving to SWIR requires using e.g. InGaAs. Cameras operating in MWIR range (most often cooled ones) typically use MCT or InSb and for LWIR one may apply uncooled aSi or VOx microbolometers. Such multi-camera system may be used e.g. for FeO content estimation in steel slag during metallurgical processes in steelworks [1].

There is a different solution for multispectral imaging, which may be applied when all channels cover the spectral sensitivity of one detector. In this case a filter wheel may be used, which is more cost-effective than multiple cameras [1]. The disadvantage of this technique may be found in possible reflections of the detector in filter's surface. This is especially visible with MWIR cameras (Narcissius effect) where a detector is cooled to about 77 K and filter is in a room temperature (referred to as warm or hot filter) [2].

Another well-known solution described in literature is based on illuminating the scene with certain wavelengths (channels) [3]. It does not require filters but it is advised to remove any background light sources, so that the camera acquires only the response of the investigated object to the certain illumination. Due to the Planck's law, in room temperature the thermal radiation of objects starts to appear in MWIR and increases significantly towards longer wavelengths (LWIR) [1]. Hence this technique is typically used in darkrooms with illumination in VIS and NIR ranges, where thermal radiation is negligible for objects in room temperature. This paper shows the technique, which enables suppression of the background light, eliminating the need for a darkroom. It may be advantageous in case of large inspected objects.

1.1. Imaging techniques

For imaging purposes typically CCD or CMOS focal plane arrays are used. They comprise plurality of single detectors forming a matrix. To enable color imaging, pixels in an array have to be sensitive to different wavelengths. While the most commonly applied pattern uses three primary colours (RGB - red, green and blue), there are also different combinations used, such as RGBW (incorporating additional white pixel). In practical applications the most commonly used arrangement of pixels is RGGB Bayer array. In this solution the number of green pixels is two times the number of red or blue ones, improving the sensitivity to green light, which is coherent with human eye behavior. The spectral sensitivity of a pixel in an array is shaped by a filter - red, green or blue one. This solution, however, has a disadvantage that a single pixel is sensitive to one color (spectral channel) only. To solve this problem, the signal values for two lacking colors for this pixel are interpolated from neighbor pixels. While this solution is commonly used in practice, it can lead to lower image sharpness compared to monochrome imaging, where no pixel filtering is applied [4].

Nevertheless, all pixels are sensitive also to near-infrared, what could make the colors look different than seen by human eye. Therefore typically there is a NIR-cut filter installed in cameras, which blocks near infrared light from reaching the sensor. In addition UV filter may be installed in the optical path of the camera. To enable measurements in the full available sensor spectral range, it is necessary to use camera without these filters or to remove it mechanically. There are security cameras available without NIR-cut filter as they benefit from NIR scene illumination to improve night vision [5].

There are more benefits from imaging in NIR than only the enhanced night vision [6]. Let us take an example of an electronic device (remote access card), which is enclosed in a plastic case. This plastic is opaque for VIS light, but becomes transparent for NIR - radiation in the wavelength range is well transmitted through this material. By illuminating the inspected object with 960 nm NIR, it is possible to image it through the plastic case, as if it was almost transparent (Fig. 1b) contrary to VIS illumination (Fig. 1a).

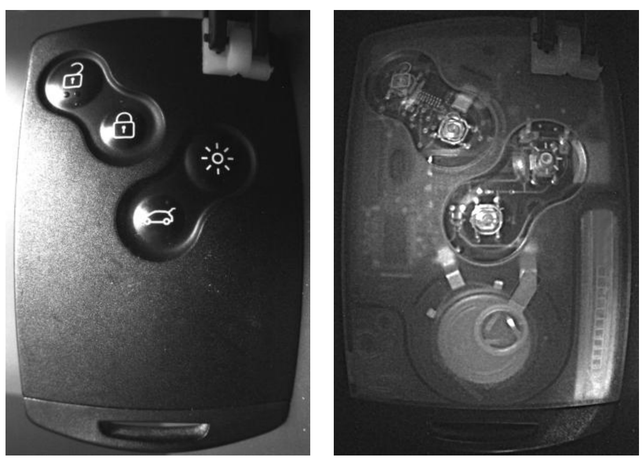

Fig. 1. Image of a remote access card acquired with PointGrey® Flea camera using LEDs for a) VIS illumination, b) 960 nm NIR illumination in a darkroom – plastic is partially transparent for this wavelength and card interior is visible

2. Methods for background light suppression

Multispectral imaging with LED illumination (narrowband) requires any background light (broadband) to be eliminated. It may be done by using a chamber (darkroom), which isolates the measured sample and camera from any external background light. In practice, however, it may be impractical with larger objects. What is more, it may be also difficult to evenly illuminate such large objects with a single LED source, especially spotlight type (with narrow beam). It may lead to creating big measurement rigs [7]. The lock-in method presented in this paper deals with above mentioned problems.

2.1. Differential method

Let us assume that an inspected object is illuminated both with broadband background light and narrowband spotlight LED. The technical requirement is that the power of LED illumination is adjusted so that it does not create over-exposure in the image, being well visible at the same time. If only one frame is acquired, in general case one cannot suppress the background. It can be possible if another frame is acquired, but without LED illumination. Then a difference of these images may be calculated to suppress the background. This solution may seem simple, but in practice one may find high level of noise in the differential image. This is the case especially if camera gain (sensitivity) is set to high, to reduce the exposure time, as in the example of a banknote shown in Fig. 2. It is illuminated with broadband VIS light only and captured with PointGrey® Flea camera.

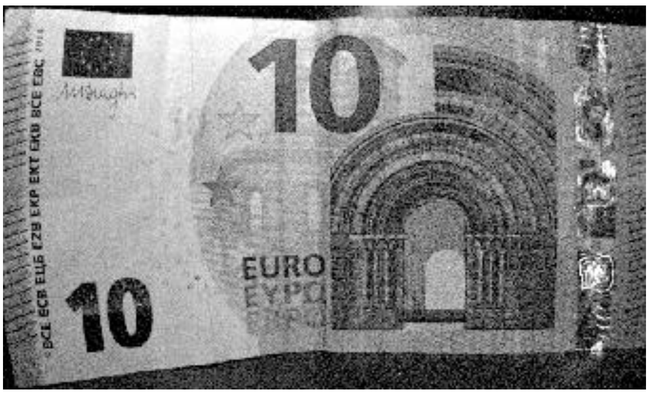

Fig. 2. Banknote illuminated with VIS broadband light

Next, the 960 nm NIR LED illuminator is turned on, showing a circular glow in the center of a banknote surface, as seen in Fig. 3.

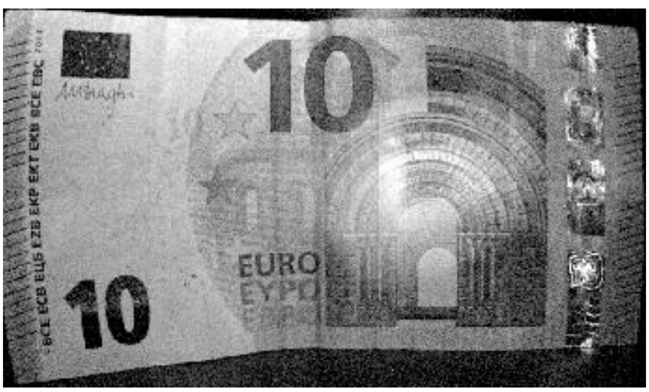

Fig. 3. Banknote illuminated with VIS broadband light and simultaneously with 960 nm NIR LED illuminator (spot type) – glow visible in the centre

If the difference of images is calculated, as mentioned before, one may find a high level of noise and considerable loss of detail in the resulting image, as shown in Fig 4.

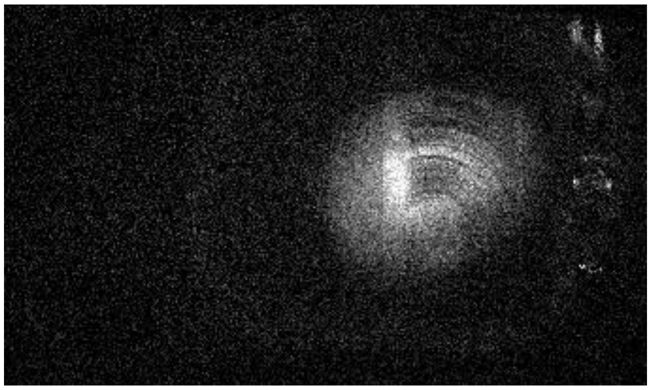

Fig. 4. Differential image of a banknote (difference of Fig. 3 and 2) – note the high level of noise and the lack of detail, only the spotlight is clearly visible

2.2. Proposed lock-in method (FFT based)

The solution, which is proposed, requires a sequence of images to be acquired. During this acquisition, one needs to illuminate the inspected object with LED(s) driven by a frequency generator. It has to be set to a particular frequency, which fulfills the Kotielnikov-Shannon theorem, according to the camera frame rate. It means that for a typical frame rate of 25 frames per second, the Nyquist frequency is 12.5 Hz, and the illumination frequency cannot be higher to avoid aliasing problem.

What is more, when spotlight illumination is used and it does not cover full object area, it should sweep the object surface within the acquisition time. The sweep rate should allow for illuminating certain areas with at least few periods resulting from the generator frequency. This way, after the processing, one can obtain one image with full sweep area visible and with removed background illumination. The proposed measurement rig scheme is shown in Fig. 5.

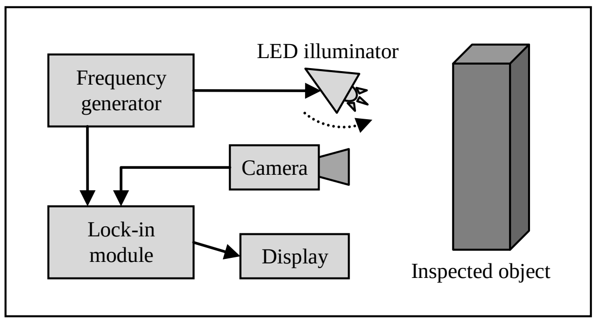

Fig. 5. Measurement rig configuration

The sequence of frames acquired in the time domain needs to be processed with the proposed lock-in method. The approach for processing is similar as in case of non-destructive testing with lock-in thermal wave method [8-11]. It should be underlined, however, that the proposed method is a reflective lock-in one in contrast to the thermal lock-in. The idea of reflective NIR measurements (without lock-in approach) in the domain of art conservation is described in e.g. [12]. The novelty of this paper is the extension of this well-known approach of reflective NIR measurements by adding a lock-in processing – a signal for a pixel in position (x, y) from the sequence is treated as a series of values in time domain and converted to the frequency domain with FFT algorithm. This way one obtains amplitude signal for pixel in position (x, y) for different frequencies. Assuming that pixels in all positions undergo this algorithm, one obtains the series of amplitude images corresponding to different frequencies, as shown in Fig. 6. At this stage it is necessary to select one particular image, which corresponds to the frequency of generator driving the LED illuminator. This is the amplitude image showing the illuminated areas only without the background.

Lock-in by definition is synchronization. It means that the frame acquisition should be synchronized with the frequency generator driving the NIR LED illuminator. In the ideal case, the acquisition time should cover the integer number of illumination periods. The advantage of synchronization is presented in [13]. In practice, however, one can use the described approach without synchronization. In this case it is recommended to reduce the leakage of spectrum by using time-windows (also known as an apodization function or tapering function [14]) - e.g. triangle, Hamming, Kaiser or Lanczos. The results presented in this paper are obtained with rectangular window, which is both the worst and the simplest case. Nonetheless, its quality meets the expectations, as presented in chapter 3.

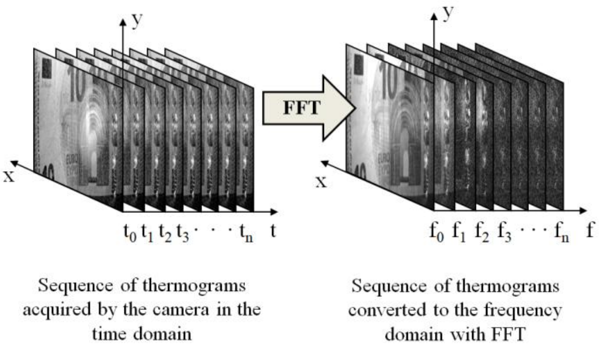

Fig. 6. The lock-in processing scheme of acquired frames

3. Verification

To verify the proposed approach, a NIR LED spotlight illuminator is set to 4 Hz frequency. This value is not critical and can be changed, observing the following precautions. The lower is this frequency (keeping the same camera frame rate), the longer the acquisition needs to last and the sweeping (described in section 3.1) should be slower. It may lead to unnecessarily high number of acquired frames, what slows down the further FFT processing. Contrarily, it has a positive impact on the noise level and is desired while high camera gain/sensitivity is used. On the other hand, increasing this frequency enables faster sweeping but one may expect weaker noise suppression. What is more, without synchronization increasing frequency reduces aliasing problems. Nonetheless, one should take care not to exceed the Nyquist frequency and limit the sweep rate as described in section 2.2.

During the described verification procedure, the NIR LED illuminates only a part of the banknote, similarly as shown in Fig. 4, but a five seconds long sequence is acquired with PointGrey® Flea camera without moving the illuminator. It is worth noting that the lens attached to the camera is designed to work both with VIS and NIR spectral ranges, i.e. it provides high transmission and correction of aberration for both these ranges.

After the proposed lock-in approach is applied to the acquired sequence (which takes about one minute with modern PC computer) and a resulting amplitude image corresponding to 4 Hz frequency is selected (Fig. 7), it can be compared to Fig. 4. One can clearly notice that the proposed approach resulted in vastly reduced level of noise comparing to the differential approach.

Thanks to the negligible level of noise, one can also assess the quality of background broadband light suppression in Fig. 7 by comparing it to Fig. 2. In NIR (Fig. 7), part of the arch construction (left side) totally disappears, while it is normally visible in Fig. 2 (VIS broadband illumination). It is a banknote protection mechanism [15] and it proves the good quality of background light suppression achieved with the proposed approach. If one would like to examine a single banknote from both sides simultaneously, it is possible to use two mirrors configured similarly as in [16].

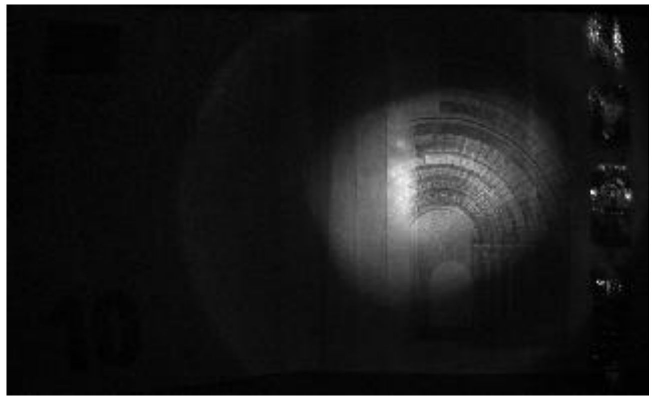

Fig. 7. Result of processing the sequence of images with the proposed lock-in approach without illuminator sweeping the object surface

3.1. Illumination sweep

As previously stated, while the images are acquired, one can sweep the surface of the inspected object (banknote) with the illuminator, to compensate for spotlight not covering its full area. In this case the sweep movement, as previously stated, cannot be too fast regarding the illumination frequency. Alternatively, one can use fast changing between few illuminator positions, in which it remains stationary for a certain period of time. The processing algorithm remains unchanged, and an example of obtained result is shown in Fig. 8, where larger area is illuminated comparing to Fig. 7, while the same LED light source was used for sweep.

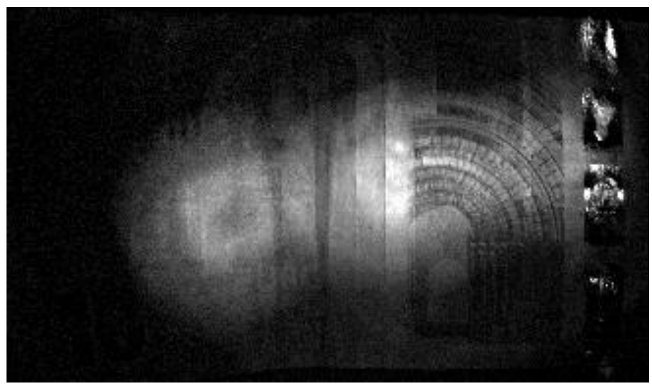

Fig. 8. Result of processing the sequence of images with the proposed lock-in approach with illuminator sweeping the object surface

3.2. Possible improvements

The possible improvement to the proposed approach is by implementing the synchronization, as stated in the section 2.2. What is more, in practice different luminance level can reach the inspected surface, depending on the LEDs type, quantity and power. In cases where it is low, the camera may need to automatically lower the framerate to increase the exposure time. To be protected against exceeding the Nyquist frequency of illumination in this case, it may be desirable to set the generated frequency dynamically, in dependence on the current frame rate, however constant within one acquired sequence. The sweeping mechanism may be automated (similarly as in e.g. [17]) and the sweep rate may be automatically set depending on the generated illumination frequency and camera framerate.

The proposed approach may be attractive for imaging through rotating elements (e.g. fans) by synchronizing the illumination frequency with the frequency of rotations. This way illumination can be provided always for the same fan position, enabling clear imaging of scene areas uncovered by the fan, similarly as in stroboscopic imaging [18].

4. Conclusions

The proposed lock-in background suppression method is similar to the approach used in non-destructive testing with thermal imaging cameras. In this case it is applied for NIR scene illumination and obtained results prove its good performance in this field. In addition it enables using spotlight not covering the full object area to illuminate it entirely by sweeping.

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