https://doi.org/10.2352/ISSN.2470-1173.2020.4.MWSF-219

High-Entropy Optically Variable Device Characterization – Facilitating Multimodal Authentication and Capture of Deep Learning Data

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Abstract

A previously presented multidimensional high-fidelity optical instrument is able to characterize the perceptually significant features of Optically Variable Devices (OVDs). This high-entropy digital information source facilitates the adoption of algorithmic-based communication protocol, and principally new services of which a few will be presented.

This detailed characterization is significant for a forensic or reference tool but overly redundant for most authentication applications. Thereby, the high-entropy full characterization ability may reside at the trusted forensic authority. Distributed in a potential hostile environment are authentication devices of desirably lower characterization capabilities optimized for authentication and operational capabilities, and low cost. This protocol resembles well with the information security principle admitting information access on a need-to-know basis. Such devices may be vital improving the OVD ratio of inspection.

In a high-security application, the redundant OVD characterization facilitates challenge-response authentication, including single-use codes, prohibiting eavesdropping reply-attacks. More significantly, an intertwined multimodal (electro-optical) communication protocol is described, in which OVD-assisted authentication cooperates with cryptographic algorithms improving e.g. the sensitive access control of electronic machine-readable travel documents, eMRTD.

The characterization method, focusing only on overt (first-line inspection accessible) OVD features, facilitates inspection method monitoring, promoting this other example of multimodal (human-instrument) services, e.g. indicating possible first-line or instrument inspection shortcomings.

A combination of high-entropy and low cost instruments may be essential capturing necessary high quality, representative and large volume data for robust response deep learning algorithms, a challenge in part due to the variation of circulation caused degradation of OVD optical performance.

These services illustrate how OVD inherent capabilities may be better captured and exploited, facilitated by the described high-entropy characterization tool.

Introduction

Optically Variable Devices (OVDs) applied in the optical document security industry are in general of high optical performance including high contrast as well in spatial as in angular dimension, also spanning a wide color gamut (wide dynamic range or highly vivid colors). Instrumentally based characterization able to capture the perceptually significant features of such OVDs, including a high enough spatial and angular resolution is a challenge met by a prototype method [1] introduced by the author at the 2008 Optical Document Security conference (ODS). This method is also described [2] and referred to as “gonioLabs' DOVID Reader” (GDR) by the late authority van Renesse. Note however, the characterization is not limited to diffractive optically image device (DOVID) OVDs only, as e.g. the physical principles on which the diffusely scattering moiré magnifier and products such as “Motion”®, Crane Inc. (USA), are based, are also within the characterization capabilities of the method. In fact, any OVD effective under common condition for perceptual evaluation (such as stationary relative positions of illuminator and inspector, changing the inclination of the OVD relative to the illuminator/inspector etc.) is within the characterization capabilities of the GDR.

Applications based on this prototype characterization method, and suggested by the industry, was presented [3] at the 2010 ODS. As a side note, although the GDR is designed to capture and characterize ideally every aspect that significantly influence a result of a human-based visual inspection, one such aspect not implemented in the GDR is a stereoscopic twin-camera measurement and characterization. A trial mock-up of a previous version of the system restricted to monochromatic gloss measurement and visualization, including algorithmically based merging of stereoscopic sensor characterization and visualization [4], shows however the potential for including also stereoscopic characterization in the GDR.

Imaging at a high signal-to-noise ratio (SNR) is a challenge irrespective of image sensor technology, in part as every physical sensor show pixel-to-pixel correlation or “interpixel correlation” (IC), where nearby pixels interfere, hence deteriorating the SNR of the result image. Avoiding this sensor IC effect entirely is normally not possible or at least not desirable, as sensor designed for pixel crosstalk minimization comes at a cost (e.g. reduced sensor well capacity, read-out performance etc.), and will thus cause negative side-effects of dependent other sensor characteristics. Strategies instead include both sensor IC reduction and software based (post-exposure) IC reduction. This is an engineering and measurement challenge of growing importance for a significant range of imaging sensors and applications, including massive-volume mobile phone imaging sensors where the miniaturization and increasing number of pixels, individually and in combination lead to reduced pixel pitch and thereby a tendency of increasing IC [5, 6]. In the other end of the performance range: for the most sophisticated high-end scientific-grade sensors, with applications e.g. for the weak gravitational lensing effect characterization (gravitation characterization) and imaging elementary particle crashes in cyclotrons like the Tevatron and LHC [7], efforts are likewise spent in better understanding and reducing the IC. Generally, including also non-scientific grade sensors, applications having motifs of high dynamic range and high-contrast are especially susceptible to IC SNR deterioration effects. To summarize, high-contrast OVD imaging applications aiming for high SNR, stress the need for an IC reduction strategy. This subject is treated in depth by the author in a review paper [8] and a research paper [9] presenting an algorithm for a commonly used color mosaic (Bayer) sensor camera. Note, the term IC is introduced by the author to include the sensor distortion effects (optical or charge-caused diffusion, interpixel capacitance, the brighter-fatter effect, blooming and smear) increasing the pixel-to-pixel correlation and relating to different commonly used sensor technologies (CCD, CMOS, hybrids), to facilitate a generic and holistic treatment of the subject [8].

As it may be relevant for the Media Watermarking, Security, and Forensics community, the essence of the algorithm for a color mosaic sensor camera will be described in brief also in this paper.

Interpixel Correlation Characterization and Reduction

An innovative approach to characterize and reduce the IC for a color filter array (CFA) so called Bayer type of sensor is described and implemented [9] by the author and summarized here in brief. The algorithm adopts a deliberately simplistic high dynamic range (HDR) imaging method [10] where each result HDR-image is an aggregate of a sequence of low (sensor native) dynamic range (LDR) images of varying exposures. The work presents and implements a calibration method that facilitates the detection, characterization, and reduction of IC in the affected neighborhood of saturated pixels in the LDR CFA sensor images, thus improving the LDR signal-to-noise ratio (SNR) and, consequently, also the HDR reconstruction SNR. The calibration method is novel and attractive as no special setup is needed, facilitated utilizing the sensor native CFA as a matched filter for IC detection, further described in the following. The enhanced SNR and contrast capability achieved by this method is especially valuable in applications of wide dynamic range and high-contrast imaging, such as characterization of OVD for ODS applications.

Sensor Native CFA—an IC Matched Filter

The undesired IC causes a higher intensity donor pixel to contribute, optically, in electrical charge and in electrical current, to surrounding lower intensity recipient pixel values, in effect a low pass filtering and a reduced SNR. This effect decreases with pixel distance from the donor. In color filter array sensors of Bayer type configuration: given arbitrary pixel (omitting sensor border pixels), the nearest neighbors (4-connectivity) pixels are all of another color than this given arbitrary pixel. This causes the dominant effect of the donor-to-recipient pixels value transition to not only decrease the value in one color but also increase the values in other color(s). This color distortion twin-effect may be described as a matched filter as it will be highly responsive, resulting a distortion color tint already for minute IC that facilitates the detection (visually or by mathematical data analysis) and characterization of the IC effect.

Exclusion Neighborhood Optimization

The described detection and characterization approach is utilized in an sensor calibration procedure (performed once), selecting the most favorable pixel neighborhood to exclude for each saturated pixel in the low dynamic range (LDR) exposures, to achieve the highest HDR reconstruction SNR. In general, no exclusion or too small neighborhood exclusion causes unfavorably IC affected pixels of the LDR to influence and deteriorate the result HDR reconstruction SNR. Too large neighborhood exclusion is suboptimal as LDR pixel values are unnecessarily wasted (pixels having negligible IC improve HDR reconstruction SNR), causing the HDR-algorithm to operate a smaller data set and a HDR result image of lower SNR. The IC effect decreases as stated with pixel distance for arbitrary direction, however the decrease may not be circular symmetric, due e.g. to sensor circuitry configuration dependent error propagation. Therefore, not only the neighborhood extension but also the neighborhood outlay should be considered in the optimization procedure. In this optimization procedure, candidate exclusion neighborhoods are evaluated with respect to the result HDR reconstruction color tint, imaging a calibrating physical neutrally graded gray test surface.

The optimization criterion is the minimization of the mean square color distortion in RGB space after HDR reconstruction, as evaluated for each of the tested candidate exclusion neighborhood regions. The distortion is measured as the orthogonal distance from the achromatic line, i.e. the ideal reproduction of the neutral gray test surface. The achromatic line, in turn, is characterized by linear regression analysis, using singular value decomposition (SVD) to determine the principal component (largest variance). The optimization procedure identifies the optimal neighborhood to exclude analyzing every saturated pixel, and given the set of candidate neighborhoods evaluated for the imaging system calibrated. The optimum for the optical system analyzed was a 5 × 5 squared exclusion region, having the saturated (donor) pixel centered. Of course, the result optimal neighborhood is individual for each imaging systems, however the IC analysis and minimization method may be applied to arbitrary imaging system, calibrating and optimizing the optical contrast (SNR) performance.

Result IC Reduction

The calculations, in the previous section only mentioned in brief, are detailed in the referred to paper [9]. The base-line (without IC reduction) is illustrated in Figure 1and the improvement (with IC reduction) in Figure 2.

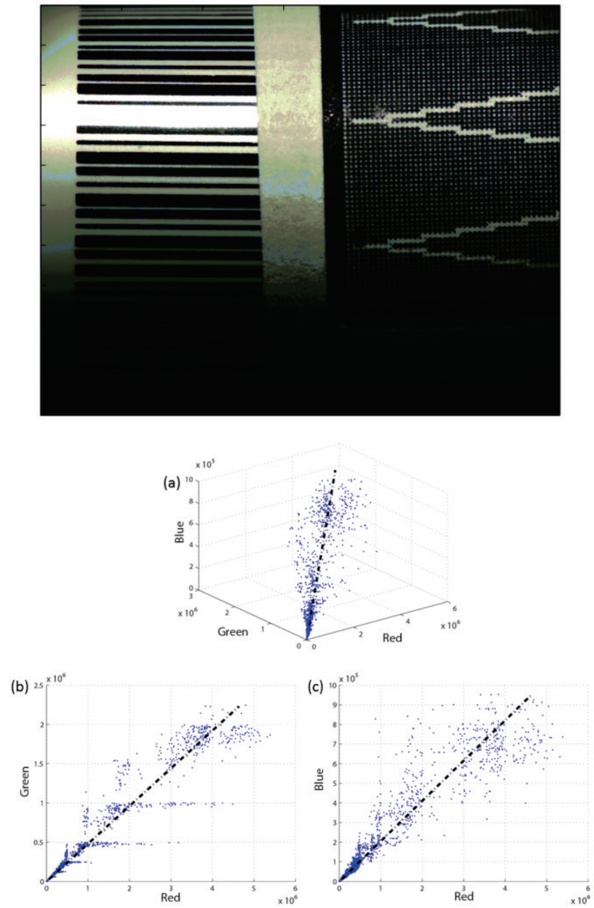

Figure 1. *TOP: Image of the white areas of the test targets, mounted on a cylinder which results in a specular highlight requiring HDRI. The measurement is performed with no IC reduction. Lefthalf of TOP image: Glossy plastic label. Righthalf of TOP image: Matte office paper. Image width 21.8 mm, pixel pitch 17 µm. BOTTOM: Plot of the reconstructed HDR RGB intensities of the white sample areas of TOP image, without IC reduction. The dashed–dotted line is the principal component (largest variance) of a principal component analysis derived by singular value decomposition, (a) 3D plot of RGB intensities. (b) Projection to R,G only (omitting the blue channel) (c) Projection to R,B.*

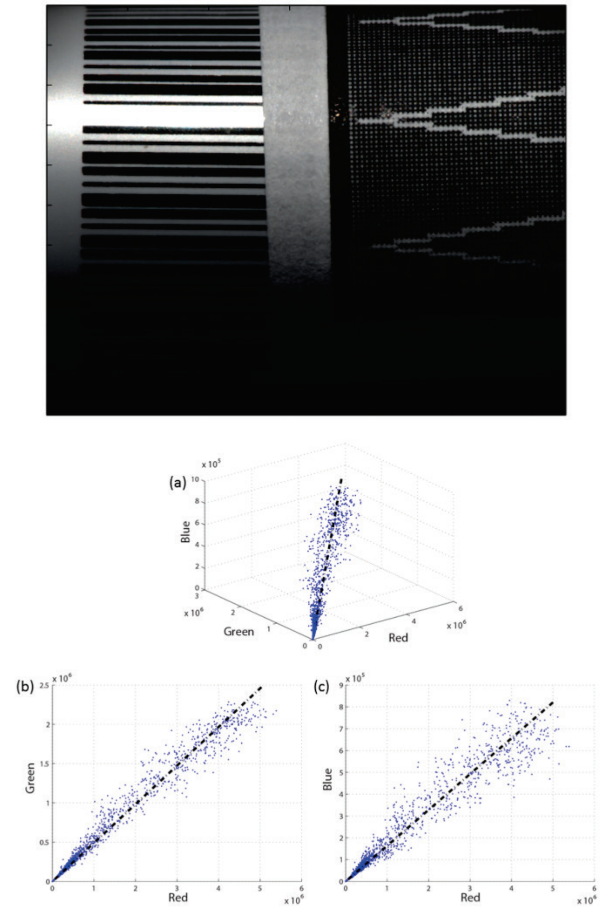

Figure 2. *TOP: HDR image reconstructed with IC reduction, otherwise identical to Figure 1 TOP. Note: the image is in color (albeit the motif is in black, white and gray tones). BOTTOM: Plot of the RGB intensities for HDR reconstruction with IC reduction, otherwise identical to Figure 1 BOTTOM.*

The relative sensitivity of the imaging color channels are compensated for, in both Figure 1 LEFT and Figure 2 LEFT. Note that Figure 2 RIGHT shows essentially a range of achromatic intensities plus noise, that is, data points clustered around the achromatic straight line in the 3D color space. This is in contrast to Figure 1 RIGHT where streaks, gaps and irregularities are clearly visible in the point cloud. The two plain white areas on the left and right hand side of the barcode in Figure 2 LEFT, show smooth achromatic gradients across the curved samples. This is in contrast to the banding and color tints apparent in Figure 1 LEFT.

Entropy – the Information Content

In 1948 Claude Shannon formalized the foundation of modern communication theory, based on a general communication system accompanied with mathematical formulae [11, 12]. The capability and generality of a deceptively simple basis of the theory can hardly be overrated. The referred work defines a (the) measurement of information content, *entropy*, based on probability, a measurement of the transmitter capability, *channel capacity* that together forms the basis for the general theory relating the measurement, characterization and analysis of a general communication system.

Characterized Reflectance Volume – a High-Entropy Source

Although without mathematical formalism, the concept of entropy is used by the author to conceptualize the potential information content of an OVD [13]. More specifically, characterizing an OVD with the “gonioLabs’ DOVID Reader” (GDR) generate a so-called RGB Reflectance Volume (RV), an information volume of reflectance data, having a Cartesian spatial image plane and an angle dimension, i.e. a 3D representation. Each volume element, voxel, in this 3D representation holds the RGB reflectance information for the spatially-angular-coordinate.

Using the characterization specifications [1] of the GDR, a basis for the potential (upper limit) information content of a characterization of an OVD of size e.g. 22 × 22 mm:

1. spatial resolution 34 μm, i.e. (22/(34×10-3))2 ≈ 0.42×106 pixels,
2. angular resolution 0.13 degrees over [-54, 54] degrees, i.e. (54-(-54))/0.13 ≈ 830 angular increments,
3. reflectance (optical) resolution for each color channel 21 bits, i.e. 221 ≈ 2.1×106 reflectance levels, and
4. number of color channels = 3.

In total (1-4): $0.42\times10^6 \times 830 \times 2.1\times10^6 \times 3 \approx 2.2 \times10^{15}$ or approximately 51 bits ($2^{51} \approx 2.25\times10^{15}$). In total (a-d): $0.42\times10^6 \times 830 \times 2.1\times10^6 \times 3 \approx 2.2 \times10^{15}$ or approximately 51 bits ($2^{51} \approx 2.25\times10^{15}$).

Of course this is, as stated, a basis for an upper bound, neglecting noise and distortion e.g. from interpixel correlation, spatial and angular inaccuracies etc. Also covering all relevant aspects of the communication system would include first the OVD production limitations, including message transmitter limitation set by laws of physics in e.g. interference features, resolution of origination equipment, and separating the OVD into a (lower-entropy) motif features optimized for conspicuousness and a (higher-entropy) information features optimized for randomness etc.). Second, the OVD characterization limitations (message receiver limitations set by sensor spatial and optical accuracy, sample positioning accuracy etc.). However, as no established procedure is defined on how to detail the information capabilities of a OVD-system, the author has instead given numerous examples of the characterization method capabilities, focusing on the separate measurement dimensions in terms of resolution, accuracy and reproducibility [1, 3]. In this work instead given as an aggregated indicative basis for entropy upper limit for the given GDR configuration, as a basis for a further treatment of the subject.

Already the given indicative characterization capabilities are essential benefits of the GDR, relying on spatial, angular and optical software controlled calibration routines and the briefly described interpixel correlation (IC) reduction algorithm. Also, the instrument configuration having a cylindrical shaped sample holder promotes a OVD snug fit, an exact rotational based positioning of the OVD and high image sharpness (part-images out-of-focus un-sharpness is in general a challenge of other more obvious angle-varying measurement configurations). All these desired measurement characteristics at the cost of a slightly more intricate imaging spatial re-transformation, however calculated, calibrated and verified only once. To summarize, much effort have been spent on promoting the accuracy and reproducibility of the GDR based characterization, all in order to best utilize the above indicated high-fidelity potential information content of an OVD, in essence a high-entropy source.

Information Redundancy – Means for New Services

Given first, the assumption that different instances of genuine OVDs are more alike than a counterfeit and a genuine OVD are alike. Second, the GDR characterized RVs is able to capture and illustrate a range of significant feature differences of different instances of genuine OVDs [13], indicates the exploratory capacity also beyond authentication applications only. Such more demanding applications include:

- facilitating unambiguous communication between forensic laboratories [2],
- facilitating the clear presentation of facts in court [2],
- counterfeit pedigree analysis, interconnecting a production unit and counterfeits in circulation [14],
- reference characterization during OVD product development,
- reference characterization procurement processes, verifying product characteristics with strict tolerances.

For applications of authentication, it may appear that the RV is overly detailed. As a basis for conventional authentication, verifying the product as genuine only, the RV is likely in the general case overly redundant. However, this information redundancy may be of high significance, opening for principally new and desired services of the RV. In the following sections, examples of such services will be described.

Increasing the Ratio of Inspections

One of the challenges of OVD’s ability to contribute to document security is inspection ignorance – the security potential of OVDs is not utilized. Therefore improving the ratio of OVD inspections is important to motivate future investments in OVD-based applications. Increasing the in general low ratio of inspections performed by human inspectors has proven difficult. Instrument-based devices for inspection are either of few-instances reference types or challenging to design algorithmically, based on mid-to-low-cost equipment, struggling to achieve the necessary high evaluation performance and robustness. Tools that facilitate this optimization, i.e. the design of OVD authentication protocols that most efficiently handle a lower-fidelity inspection device, e.g. based on a mobile phone camera (or other low-cost, hence a large-volume potential), are therefore needed. Such design choices are simplified if high fidelity and detailed OVD characterization is available, e.g. to give extensive information on the expected variation of optical feature response of a typical set of OVDs. This optimization is more effective based on high-resolution RV information than based on the target lower-fidelity inspection device generated information only. A high fidelity reference instrument is useful not only for optimal condition of e.g. fresh (not circulated) OVDs but critically important for the robustness of an authentication protocol is also to have high fidelity information on the degeneration of optical response for circulated OVDs. The potential of the GDR in this context has been treated in 2008 ODS [1].

To summarize: an effective and robust authentication protocol for a low-cost potentially large volume authentication device is facilitated if based on high fidelity high-entropy RV information generated by the GDR.

Capturing large volume, representative deep learning data

Artificial Intelligence (AI) based algorithms have obvious potential within described field of applications, including areas of monitoring (e.g. the level of optical degeneration of OVD due to circulation – is it fit for further circulation?; cross-examining performance and attention of first line inspection personnel – is retraining needed?) and authentication (detection of potential counterfeits). Irrespective if the prime application focus is e.g. on evaluation performance, or on decision explanatory capabilities (that may currently correspond to AI subfields of convolutional neural networks and decision trees, respectively) a lack of representative and adequate volume data is a general challenge for non-trivial AI applications. In fact, the significance of a well-designed protocol for capturing adequate training data is of the highest importance in order to achieve an AI-based system having a robust and desirable evaluation response in field operation and its inevitable challenging variety of OVD characteristics.

The described OVD characterization method may facilitate the capturing of adequately large volume representative deep (or other AI) learning data. If required, this can be achieved by using a combination of trusted site reference equipment generating high-entropy data, and widely distributed low-cost bulk equipment. Such aggregate of data-capturing equipment may be especially desirable e.g. for demanding authentication including also heavily circulated OVDs of inferior optical performance, that stresses the need for the described large volume representative data.

The access of to the high-entropy reflectance volume (RV) may also facilitate the challenging AI verification process to better understand which types of OVD imperfections are evaluated as desired and which may cause problems. Such information is vital valuing whether the algorithm may go in production, i.e. has achieved a desired level of performance *and* robustness, or if further training (or possibly a change of algorithm) is motivated.

OVD authentication without revealing sensitive information

The described high-entropy redundant authentication information further facilitates a tamper resilient communication infrastructure. As already a small well-selected fraction of the total RV is sufficient to distinguish a genuine from a counterfeit, a challenge-response protocol is possible. Such protocol may in its simplest form, represent a set of spatial and angular coordinates in the RV, with a corresponding set of RGB-value responses. As a side note: it may be advisable, as a security promotion heuristic, to restrict the selection of such sets of coordinates not to be random or pseudo-random, in order to avoid occasional clustered sets. In other phrasing: in the set of selected challenges and for each dimension, to enforce a minimal variation for each such challenge. If not, the response may represent a higher level of data intra-dependence, hence lower entropy and lower degree of security. This, precaution is a consequence of the OVD being a physical entity under production limitation and restricted modulation transfer functions – therefore restricting a clustering of challenges will promote the level of randomness and hence security.

In essence, the exhaustive and fully characterizing RV need not be transmitted and exposed over a possible unsecured communication channel in order to perform the authentication, only a fraction and disposable (to be used only once) challenge-response set of pairs is used. Thereby, even illicit eavesdropping does not challenge the security, as challenges are never reused, i.e. a so-called replay-attack is not possible.

OVD Assisted Cryptography – Intertwined Multimodal Authentication

The RV can, as described, be regarded as a digital source, hence general and established digital channel communication algorithms may be adopted and co-operate with other established digital algorithms including cryptography-based algorithms, to achieve principally new OVD-assisted services. This may be desired for high-security applications such as travel documents (passports, VISAs) equipped with cryptography facilitated electronics (electronic Machine Readable Travel Documents eMRTD [15, 16]). Applications include general security enhancing multimodal authentication, improving the authentication security by enforcing more than one authentication requirement, ideally further based on separate technology platforms, such as a) OVD, optically based challenge-response authentication and b) Chip, cryptography-based authentication.

A separate security challenge of high relevance in this context is the *access control* to an eMRTD, in general to limit the risk illicit repeatable and exhaustive access-denials to finally gaining unauthorized access, but especially important regarding the more sensitive personal data (including e.g. finger, iris and face info) [16]. Introducing an OVD-assisted multimodal authentication protocol, to the indicated but optional electronic based cryptographic access control, of eMRTD for such personal data, may be a niche application of significant importance.

The OVD-assisted contribution to the multimodal algorithm may be either more basic, relying on typical (group or mean) characteristics for the given type of OVD, generally of lower level of entropy, or more refined, an individualized OVD characterization, generally of high-entropy. The latter may achieve a higher potential security at the cost of being more demanding in terms of tolerances on calibration routines, acceptable optical substrate degeneration due to circulation etc. to achieve a specified robustness of functionality.

Discussion

As described in Sec. 3.2, the GDR characterized RVs captures a range of significant feature differences even for different instances of genuine OVDs [13]. That is, despite resourceful excellent producers and their efforts to achieve identical OVDs, comparing the corresponding RVs give significant feature differences. By “significant” in this context, we mean not merely a sub-millimeter OVD motif translation but feature difference both easy to detect analyzing the RVs by algorithms (even inspecting them visually), and robust, distinctively above noise-floor levels. The high information content (entropy) of RVs and the described OVD production limitations in combination opens for OVD based novel applications of “physically unclonable functions” (PUF). In recent years, the PUF has grown rapidly in importance for information technology applications. Citing Maes [17]:

“...PUFs are innovative physical security primitives which produce unclonable and inherent instance-specific measurements of physical objects; PUFs are in many ways the inanimate equivalent of biometrics for human beings. Since they are able to securely generate and store secrets, PUFs allow us to bootstrap the physical implementation of an information security system.”

Irrespective of physical principle involved, the applications of PUF generally rely on a sequence of fundamental inequalities of characteristics. The construction of PUF may be controllable down to a certain level of characterizing detail but (a) not beyond this level at which the construction introduces uncontrollable characterizing detail. The PUF verification function is able to verify characterizing detail beyond the described resolution limit (a) and – ideally – giving the characteristic features beyond said resolution limit (a) an appropriate higher level of significance, as the features up to (a) are controllable, potentially cloned and would otherwise cause the verification process to be less selective.

This potential of the OVD characterization performance surpassing the production performance is of significance, as it would generalize the established applications for OVDs to facilitate not only multimodal authentication described in this work, but also to PUF-based multimodal authentication. The potential of OVD-based PUFs is treated by the author [13] and the interested reader may consult literature on unified security models for PUFs [18] and in-depth treatment on evaluation procedures [19]. The two latter works do not include OVD-based PUFs but provides generic analyses of PUFs. In addition, an ISO working draft (IEC NP 20897) is also of relevance.

Conclusions

We have described a novel sensor interpixel analysis and reduction algorithm for color mosaic imaging sensors. The enhanced signal-to-noise ratio and contrast capabilities achieved by this method is especially valuable in applications of wide dynamic range and high-contrast imaging, such as characterization of OVD for ODS applications.

The reflectance volume (RV), generated by the “gonioLabs DOVID reader” (GDR), potentially holds a massive information set well motivated for demanding work with strict tolerances such as forensic inspection and procurement related measurements. However, being overly redundant for most conventional authentication applications opens for the described potential novel services:

- optimization procedure for the development of effective and robust authentication algorithm for low-cost and potentially large number inspection devices, hence means to increase the ratio of OVD inspection;
- authentication algorithms based on the established challenge-response dialog where the exhaustive and fully characterizing RV need not be transmitted and exposed over a possible unsecured communication channel in order to achieve the authentication, only a fraction and disposable (to be used only once) challenge-response set of pairs. Thereby, even illicit eavesdropping does not challenge the security, as challenges are never reused, i.e. a so-called replay-attack is not possible;
- capture of large volume representative deep learning data, if necessary based on an aggregate of trusted site reference equipment generating high-entropy data, and widely distributed low-cost bulk equipment. Such large volume representative data may prove vital for algorithm training but also for verification, valuing whether the algorithm may go in production, i.e. has achieved a desired level of performance *and* robustness, or if further training (or possibly a change of algorithm) is motivated.
- high-security application based on intertwined multimodal (electro-optical) communication protocol, in which OVD-assisted authentication cooperates with cryptographic algorithms improving e.g. the sensitive access control of electronic machine readable travel documents, eMRTD.

These services illustrate how OVD inherent capabilities may be better captured and exploited, facilitated by the GDR high-entropy characterization tool.

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