Superimposing Dynamic Range

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Abstract

Replacing a uniform illumination by a high-frequent illumination enhances the contrast of observed and captured images. We modulate spatially and temporally multiplexed (projected) light with reflective or transmissive matter to achieve high dynamic range visualizations of radiological images on printed paper or ePaper, and to boost the optical contrast of images viewed or imaged with light microscopes.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [COMPUTER GRAPHICS]: Picture/Image GenerationDisplay algorithms; I.4.0 [IMAGE PROCESSING AND COMPUTER VISION]: GeneralImage displays; I.4.1 [IMAGE PROCESSING AND COMPUTER VISION]: Digitization and Image Capture;

1. Motivation and Basic Principle

The basic principle of our approach is visualized in figure 1. Instead of using uniform (low-frequent) light for illumination, we apply high-frequent (projected) light. This allows a controlled spatial and temporal modulation with reflective or transmissive matter. Since we measure the modulation behaviour of the matter initially or on the fly, we can project a carefully computed illumination image which is contrast modulated by the matter itself. The formed image can then exceed the contrast that is possible with a uniform illumination alone by several orders of magnitude. Therefore, this principle superimposes dynamic range, and allows high contrast visualizations with existing surfaces or matter, such as paper, soft and hard tissue, or microscopic specimens. It can be applied in radiology, microscopy, endoscopy, and other areas that currently suffer from (optical or digital) low contrast images that are formed by a uniform illumination. We refrain from explaining technical details on optics, registration, scanning and visualisation at this point. The interested reader is referred to [BI08] for this information. Instead, we explain different application examples and initial results.

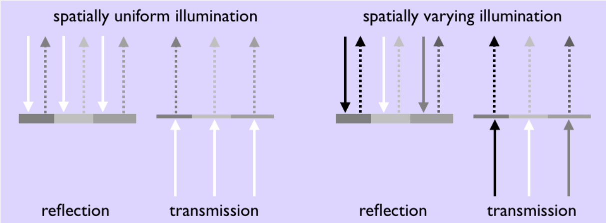

Figure 1: *Basic principle of contrast enhancement.*

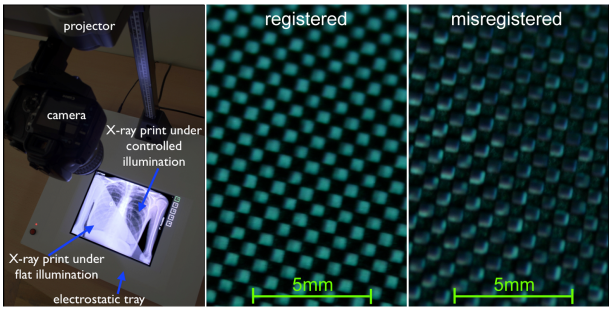

Figure 2: *HDR X-ray prints and device registration.*

2. High Dynamic Rrange X-Ray Prints

Specialized printing technologies, sometimes referred to as X-ray printers, are being used in the medical field for exchanging radiological images on paper prints, called X-ray

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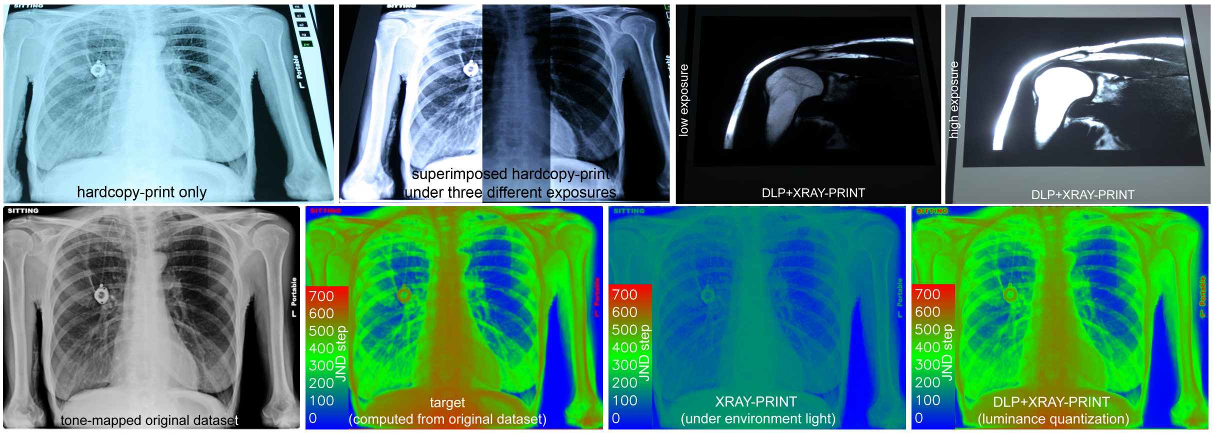

Figure 3: *Top row: X-Ray print under ordinary environment light, and contrast enhanced under projected light. Bottom row from left to right: original data tone-mapped and JND color-coded, JND color-coded when printed and viewed under environment light, and JND color-coded when viewed under projected light. While under environment light only 34% of the 738 encoded intensities that are stored in the original data set can be perceived, approx. 84% can be made visible under projected light.*

prints. Compared to conventional hardcopy media, such as X-ray film, they offer significant cost reductions, longer durability (they are less sensitive to light) and colored visualization usage. However, paper prints do not provide the diagnostic quality of X-ray film when viewed under environment light. Under normal lighting conditions, paper prints provide a contrast that is far less than 100:1 at a reflected peak luminance less of than 100 cd/m^2. The contrast of X-ray film with an optical density of D=4 is in the order of 10,000:1 while conventional light boxes provide a peak luminance of around 1,000 cd/m^2. A high contrast, contrast frequency and spatial image resolution, as well as the reproduction of a large number of perceivable tonal values and, therefore, a high peak luminance are critically important for radiological visualizations, such as in mammography. These are requirements that cannot be met fully by most interactive HDR or LDR displays. The application of a spatially controlled illumination, however, has the potential to achieve diagnostic quality with superimposed paper prints at a fraction of the cost of X-ray film development. Our approach represents a cost-efficient add-on for such print technologies that allows exceeding the contrast of X-ray film by up to a factor of 6. It also outperforms the contrast possible with X-ray paper prints viewed under environment light by up to a factor 600. Figure 1 illustrates a projector-camera system that offers an automatic registration on X-ray prints with less than 0.3 mm registration error, and physical contrast ratios of 45,000-60,000:1 with a peak luminance of more than 2,750 cd/m^2 – using consumer hardware. Figure 3 displays examples that are visualized with this system. Thereby, a novel luminance quantization technique [BI08] maximizes the number of perceived tonal values while considering the discrete nature of the applied modulation devices, such as projector and printer. As illustrated in figure 3, this allows to technically reproduce more than 620 perceptually distinguishable tonal values on paper, when using the mapping function described in [MKMS04]. We presented our system together with radiological datasets (one thorax CR scan, and one thorax CT scan with four different density settings and cutting planes – all monochrome) to ten professional radiologists. The images were visualized with our luminance quantization technique, as explained in [BI08]. The radiologists were employed by different German hospitals and institutions, and were questioned independently. With their experience, we asked them to compare the image quality of our approach to the image quality of X-ray film and high contrast medical monitors. As shown in Figure 4, the subjective impression of the professionals indicates that our approach performs significantly better in all categories. The chart presents the average scores and the ranges of variation. This early subjective feedback, together with our quantitative measurements gives an indication of the image quality that can be achieved with our approach. However, a formal clinical study has to be carried out in future.

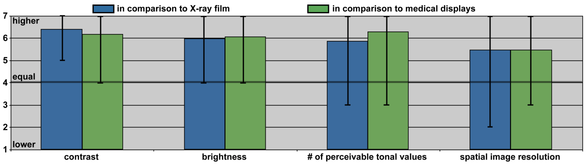

Figure 4: *Questionnaire results from ten radiologists.*

3. High Contrast Electronic Paper Displays

The same technique that is used for printed paper is, in principle, also applicable in combination with transmissive

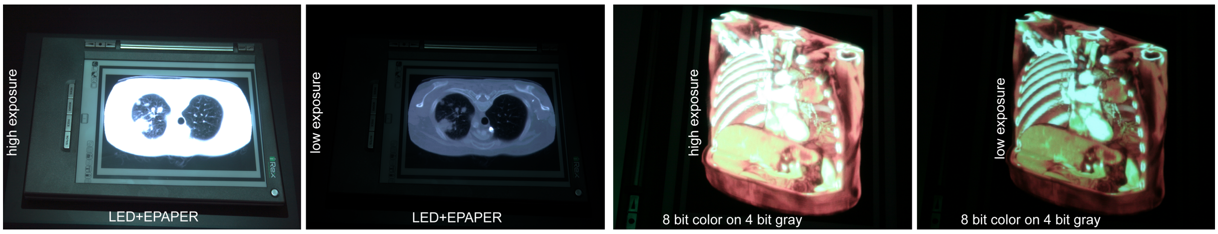

Figure 5: *Contrast enhanced ePaper (captured with different exposures and color modulated).*

(e.g., LCD) and reflective (e.g., LCOS or electronic paper) display technology. For approaches that apply a projected back-illumination together with LCD panels for double modulating the transmitted light to an HDR image, such as in [SHS*04], one of the two modulation images is of low-resolution and blurred in order to avoid artifacts such as moiré patterns that are due to the misalignment of two raster modulators (i.e., projector and LCD panel). When using printed paper or electronic paper, we benefit from the high raster resolution of printers and ePaper displays. Since it is much higher (up to a factor of 30) than the spatial resolution of projectors, the Nyquist-Shannon theorem is always satisfied, and visible moiré patterns are not produced in our case. Consequently, a high contrast frequency is achieved, and neither the projected nor the printed (or ePaper displayed) image has to be blurred. In addition, a high spatial image resolution of currently up to 300 lpi (= approx. 6 LP/mm) is supported by state-of-the-art printing technology. This approaches the spatial image resolution that is required for diagnostics in a variety of domains. Thus we benefit from the modulation of two high-frequency images. Commercial ePaper devices are 4-bit displays (usually with XGA spatial resolution). Their low tonal resolution, however, leads to image artefacts, such as banding and intensity errors that appear due to slight mis-registration. Our luminance quantization technique finds an optimal solution for the modulation of projected light with display devices that offer only a low tonal resolution, such as ePaper. We achieve this by selecting the corresponding response values of both devices within the possible luminance space that is actually covered by both devices. The luminance space is measured during calibration. We select the corresponding response values in such a way that they maximize the number of displayable JND steps while minimizing image artefacts – even in cases of slight projector mis-allingmets. Examples are shown in figure 5. Under regular environment light, the 4-bit ePaper display reaches a maximal contrast of 10:1 and 16 JNDs at a peak luminance of 34 cd/m^2. Together with projected light, we reach contrast ratios of 6,500:1-8,500:1 and up to 330 JNDs at a peak luminance of up to 1,400 cd/m^2.

4. Projected Light Microscopy

Our illumination method also enables a novel contrast enhancement technique for light microscopy which is complementary to classical contrast techniques, such as phase contrast, modulation contrast, (differential) interference contrast or fluorescence. Once structures are detectable (e.g., by a sensor, not necessarily by the human eye), they can be boosted in contrast optically via a temporally and spatially controlled illumination. Domains that utilize light microscopy, like surgery with operation microscopes, forensic analysis, and others usually suffer from too low contrast images when making observations directly through the oculars (in particular for reflection illumination). Furthermore, the acquisition of low contrast photon limited images is problematic for many digital microscopy applications that rely on robust image analysis. All of these applications can benefit from an optical contrast enhancement that is enabled by our approach. This is possible for (but not limited to) light microscopes with reflection illumination and transmission illumination. As illustrated in figure 6, we replace the spatially uniform –halogen, LED, or HBO (for fluorescence microscopy)– illumination of a light microscope with a spatially and temporally modulated illumination (i.e. projected light). By synchronizing camera and projector optically and

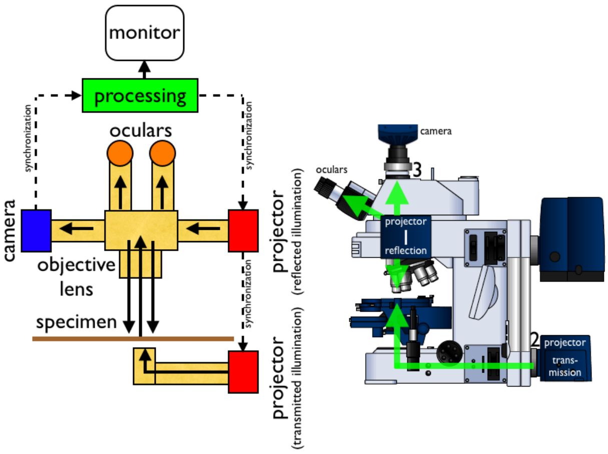

Figure 6: *Projected Light Microscope (PLM) concept.*

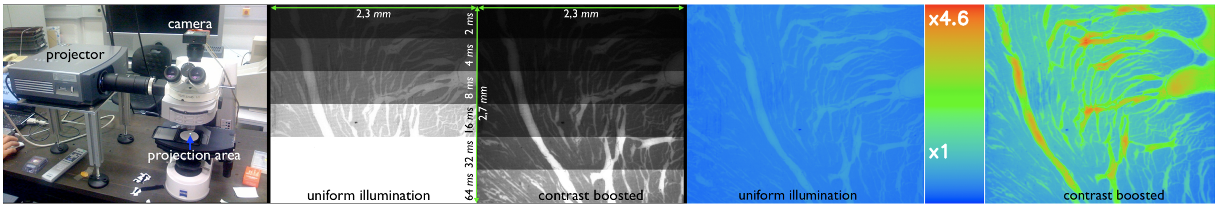

Figure 7: *PLM prototype and observed tissue sample (captured at different exposures). In this example, contrast and SNR are increased by a factors of 4.6 and 2.75, respectively (compared to a uniform illumination). The color coding illustrates the increase in local contrast (relative to the minimum luminance), where x1 is the maximum contrast under uniform illumination.*

electronically, the reflection and transmission properties of the observed specimen can be captured and analyzed. It can then be used for locally adapting the illumination, and changing it over time. For reflection illumination, the existing (infinity) camera path deflection channels are used for optical output (via camera) and for input (via projector). For transmitted illumination, we can attach the projector in a similar way to the adequate illumination port that is used for transmitted light applications. Figure 7 shows a projected light microscope prototype and early results. Since projector, camera and oculars are axis-alligned and share the same optical channel, displayed, captured and observed images remain always registered – regardless of the microscope's focus or magnification. Through a 5x objective, for instance, the size of the imaged / displayed XGA pixels on the focal plane is 2.1 μm / 2.7 μm. They become smaller with a larger objective magnification. XGA projector pixels appear with 135 μm through a 10x ocular, while UXGA projector pixels through a 5x ocular already fall below the resolution of the human eye. Especially for photon limited situations, where photon noise is the major source of noise (which applies to most situations in light microscopy) the signal-to-noise ratio (SNR) can be increased by boosting the contrast optically. A high SNR is essential for the robustness of image analysis techniques, such as segmentation. Depending on the specimen, we currently achieve contrast enhancements of up to a factor of 5, and an increase in SNR of up to a factor of 3.

5. Summary and Outlook

We explained the fundamentals of superimposing dynamic range on existing (transmissive or reflective) matter. It is achieved through the modulation of spatially and temporally multiplexed (projected) light with the matter itself. Applications and results in radiology and microscopy have been presented. In combination with X-ray printing technology, our illumination approach can reach contrast ratios that are currently up to 6 times higher than possible with X-ray film, and up to 600 times higher than possible when viewing X-ray prints under environment light. Yet, the principle advantages of X-ray prints over X-ray film are retained. With the same technique, electronic paper displays enable interactive HDR visualizations which currently achieve contrast ratios that are approximately 6-8 times higher than those of common medical diagnostic monitors. At present, contrast enhancements in the order of up to a factor of 5 are achieved when applying our technique to light microscopes. This improves the image quality when observing the samples directly through the oculars, or when capturing them with an imaging device. Domains that use light microscopes, either for direct view applications like surgery (i.e., operation microscopes) or forensic analysis; or for image analysis in digital microscopy can benefit from an optical contrast enhancement and an increased signal-to-noise ratio (momentarily of up to a factor of 3). Furthermore, a controlled illumination allows reducing specular highlights on samples that are covered by liquids, or sub-surface scattering caused by thick translucent samples.

In all explained application variants, a high light efficiency, a high spatial image resolution as well as a high contrast frequency becomes possible with our approach. Contrast enhancements through double modulation are achieved directly with elements that are not part of a display or lighting system per se. Therefore, the general principle of superimposing dynamic range is flexible and holds additional application potentials in other fields, such as endoscopy. These are all fundamental advantages over existing HDR displays as well as over conventional illumination techniques.

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