Towards a Channel Model for Microfilm

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Abstract

Technological advance causes obsolescence and unpredictable lifetimes of digital storage media and systems. We present PEVIAR, a digital archival solution based on microfilm that offers superior lifetime and independence from proprietary hardware and software technologies. Digital data is to be stored as a 2-dimensional raster image. In order to determine the technical parameters of our system, we carry out an investigation of the device setup given by a recorder, the film itself and a scanner. We measure the modulation transfer function of these components and the granularity of the film material. We also propose a 2-dimensional channel model incorporating intersymbol interference. From our examinations we conclude that a resolution of $8\mu m$ can be achieved.

1 Introduction

PEVIAR (Permanent Visual Archive) [1] is a microfilm-based technology for migration-free archiving of digital data. Microfilm can be used as a hybrid medium, containing both analog and digital data. Due to its visibility, the content is human and machine readable. In addition, microfilm is a very stable material and offers a lifetime of up to 500 years [3]. These features address a fundamental difficulty in archiving: the necessity of migration. This necessity arises for three main reasons: (a) the materials used to store the data are subject to decay, (b) the hardware technologies used to write and read the data become outdated and obsolete, and (c) the software formats and respective applications may change considerably over time. The stability of microfilm addresses the first point. The visual and hybrid nature of microfilm addresses the latter two. Apart from the digital data, we can include directly human readable information (metadata about the data, the format, the encoding process, etc.). Therefore, the storage system (hardware and software) is openly accessible even without prior knowledge of the system.

The PEVIAR project has two very important perspectives: it investigates a hybrid, general-purpose, long-term digital archiving medium, from one point of view, and a digital storage medium with a 2-dimensional layout of physical representation and encoding, from another point of view. In this paper, we will focus on the latter perspective. Specifically, we report (1) on how to measure the characteristics of microfilm as a communication (storage) channel and (2) on how to develop a channel model that will allow simulations and the development of effective encoding schemes. The goal of our investigation is an accurate prediction of the achievable data density on microfilm, and on a more general level, providing an abstract model that captures the behavior of microfilm as a communication channel.

The paper is organized as follows: in section 1, we report on our measurements of photographic properties of microfilm. In section 2, we introduce a model for simulation of 2-dimensional data representations. We will show how the properties of the microfilm relate to the modeled properties of the communication channel. In the conclusion, we will provide an accurate estimate of the achievable data density of microfilm. We will also give an outlook on future work, novel investigation directions and on the final goal and expectation of the PEVIAR project.

2 Microfilm properties

The data that is to be stored with PEVIAR is represented by a 2-dimensional barcode. A 2-dimensional barcode is a raster image in which each raster point represents a state. One raster point serves as a binary state description (maximum or minimum optical density) or as a description of a state of higher order (several density levels). In order to be written onto the medium, the original data is encoded into the barcode pattern. We will cover the relevance of an appropriate encoding scheme in the next section. In the context of the barcode, the technical parameter of highest importance is the achievable data density. It depends on two factors: on the area covered by each raster point and on the number of states represented by each raster point[1]. We can't simply maximize the two parameters, since they are interdependent. In order to find the ideal combination of the two parameters, we have conducted an examination of two important properties of the microfilm: the modulation transfer function and the granularity.

2.1 Modulation Transfer Function

Writing to and reading from microfilm involves three imaging systems: an exposure device (the recorder), the film itself and a scanner (camera and optics). All these components have a resolving power limit, and their combined resolving power delimits the achievable data density. In order to determine the minimum raster point size possible, the resolving power limit of all involved imaging systems has been measured. The relevant measurement is the modulation transfer function (MTF) according to ISO 12233 [2]. It gives information about the amount of detail an imaging system is able to reproduce[2].

In the cascading of individual components, the one with the lowest resolving power determines the performance of the entire system. When measuring based on a target exposed on film and read back by a scanner, the total system performance is measured - and not an individual component. A measurement of

[1] Color microfilm is composed of three separate layers of dye independently addressable. The storage capacity is thus tripled.

[2] The ISO 12233 standard provides a measurement of the spatial frequency response (SFR). We use the term MTF because we are applying the measurement to photographic film. The units of the measurements, however, are *cycles/mm*, and not *lp/mm*.

the individual components is possible by altering the target, which in the case of the ISO 12233 measurement is the image of a slightly slanted edge, and by making use of the knowledge that the MTF of an entire system is the result of the multiplication of the MTFs of the system components. When we capture a razor blade (it can be assumed to be infinitely sharp), the measurement provides the MTF of the scanner only. When we capture an edge that was applied to the film using vacuum deposition (here, we assume infinite sharpness of the deposition), we measure the combination of film and scanner, and since we already know the MTF of the scanner, we can divide the combined scanner/film MTF by the scanner MTF to obtain the isolated film MTF. In a third step, we capture an edge exposed onto film, and we divide the system MTF by the MTF of scanner and film to obtain the isolated MTF of the recorder.

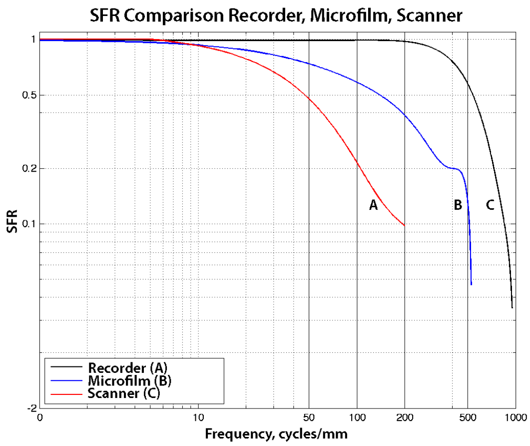

Figure 1: MTF curves for recorder (A, Fraunhofer IPM ArchiveLaser), microfilm (B, Ilford CMM) and scanner (C, Zeiss AxioCam HR mounted on Leitz Diaplan microscope (NA 0.6))).

The MTF for all three components is shown in Figure 1. Clearly, the recorder is the limiting component. What we see in the measurement is the behavior of the modulation transfer with increasing spatial frequencies. The question, of course, is: which level of modulation transfer is relevant in determining the minimum raster point size necessary for reliable representation? In a first theoretical approach, we base our modulation transfer limit on the value of $3dB$ (modulation transfer of approx. 0.7), which is the signal to noise ratio proposed by Shannon that is necessary to reliably transmit information through any given channel[3].

The table in Figure 2 shows the modulation transfer values for the recorder. We see that the response drops below the 0.7 ($3dB$) limit at around 60 cycles per millimeter. At such a spatial frequency, we could create dots with a diameter of approx. $8\mu m$. Several exposure devices were tested[4]. They supported point

[3]Using a relatively high limit, we consider ourselves to be on the safe side. In photographic applications, for example, the resolution limit is often set at a modulation transfer of only 0.1 or 0.2.

[4]Fraunhofer IPM Archive Laser and Fluck Eternity 105. The MTF measurements pub-

sizes between $9\mu m$[5] and $15\mu m$. On a 600 meter $35mm$ color film roll, 22 gigabyte of data could be stored at $15\mu m$ point size[6]. At a point size of $12\mu m$, 38 gigabyte could be stored. At $9\mu m$, approximately 70 gigabyte would fit onto the film roll. This amount of storage seems unable to compete with the amount provided by state-of-the-art storage technologies such as hard disks. But it should be kept in mind that in digital archiving, hight data density is not always a critical factor, especially when measured up against stability and longevity.

2.2 Granularity

The MTF measurements were done using a high contrast edge. This implies the use of two signaling levels and a binary code. But theoretically, the data density could be increased by representing more than two states with a single

lished above are for the Archive Laser.

[5] The measurements show that the Archive Laser allows an $8\mu m$ resolution. However, its hardware and software only allow a dot size variance in $3\mu m$ increments.

[6] One frame $35 \times 45mm$ has $((35mm*45mm)/(15\mu m*15\mu m))$ / 8 = 875.000 bytes. Color microfilm has three layers, so a 600 meter roll has (600/0.045)*3*0.875 = 35.000 megabytes. We apply a fill factor of 0.9 (not all surface area can be used for data) and an encoding redundancy loss of 0.3, which gives us approx. 22 gigabyte. The other calculations are done in the same way.

Cycles/mm	**SFR**
0.00	1.00
7.23	0.98
14.46	0.94
21.69	0.90
28.92	0.86
36.15	0.82
43.38	0.78
50.61	0.74
57.84	0.70
65.07	0.67
72.30	0.63
79.53	0.59
86.76	0.56
93.99	0.52
101.22	0.49
108.45	0.46
115.68	0.43
122.91	0.40
130.14	0.38
137.37	0.35
144.60	0.32
149.42	0.30

Figure 2: Tabular MTF report for microfilm as suggested in ISO 12233 showing the modulation response for various spatial frequencies. A spatial frequency of $60\,cycles/mm$ results in a dot diameter of approx. $8\mu m$.

raster point. If we have 4 points at two possible gray levels (black and white), we can represent 4 bit. When using 4 possible levels, we only need two points to represent the same 4 bit. However, when using multiple levels of gray on the film, the granularity of the film gains relevance. The granularity of the film gives a measure of how much variance in film density there is on a given, uniformly exposed area. Our measurement shows that at very high and very low densities - basically, when working with black and white - the granularity is relatively small. But at medium densities - different shades of gray, which would encode a higher-level alphabet - the granularity increases considerably. Figure 3 shows our results. The observed property of the granularity means that when we use multiple levels of gray, we not only decrease the density distance between the levels - we also increase the medium-inherent fluctuation of a part of our dots. Let us interpret the granularity of the film as the noise component of a communication channel, and the difference in density between the various levels as the signal strength. Then, we can say that by introducing further signaling levels, we not only decrease the signal strength, but we also and inevitably increase the level of noise on the channel.

In the RMS granularity measurement, several sections of the film surface that have been equally exposed are measured. The RMS granularity is the root mean square of the variance of the density for measurements in different areas. The size of the areas measured - the aperture - is an important factor. The variation is smaller for larger areas. The relation between the RMS granularity $\sigma(D)$ and the aperture a has been described by Selwyn [4][7]:

$$\sigma(D)\,\sqrt{a} = constant \tag{1}$$

When going from only two to more density levels, the signal strength is reduced (if we go from two to four density levels, the density difference between the levels is cut in half). This must be compensated by a respective reduction of the noise - if we only have half the signal strength, we can only support half the noise. Equation (1) shows that for a reduction of the granularity by factor n, an enlargement of the aperture by factor n^2 is required. While the Selwyn relation is not applicable to microfilm across various density levels, but only for a given density level, it does suggest that the amount of data per area necessarily decreases as we use more density levels for representation.

We do not consider this to be a proof of the impossibility of increasing data density through the use of a higher alphabet. We are confident, however, that through further studies of the properties of the microfilm, we will come up with a conclusive argument in that regard. In the meantime, we have conducted experiments that support our intuition. In order to be able to properly detect the dot pattern when using more than two density levels, we had to increase the dot size. The loss of information density due to the increased area was, in all scenarios, greater than the gain of information density due to the higher alphabet[8]. While we have not yet come to a final conclusion, our results so far suggest that microfilm is most suitable for using a binary alphabet.

[7]Selwyn showed that this relation applies to black and white film. We assume that it holds for color microfilm.

[8]We have concluded the experiment for 4, 8 and 16 density levels.

3 Channel model

For simulations and analysis of the PEVIAR storage system we need an appropriate model of the channel. Eventually, this model can serve as a framework on how to come up with both data detection and coding schemes. The latter are a crucial ingredient in communication and storage systems. Source data is encoded by adding a certain amount of redundancy in order to be able to recover errors introduced by damage and decay of the film. Of course, recovery of erroneous encoded data is only possible up to a decoding threshold. We can view the archiving on microfilm as a noisy channel in the sense of Shannon [5]. The following conception of our device setup as a channel with noise is inspired by Vasic and Kurtas [6].

3.1 Intersymbol Interference

A common impairment observed in high density recording channels is intersymbol interference (ISI). In other words, at symbol read-back the value is affected by the values of neighboring symbols. By the value of a symbol we mean the measured optical density expressed as an RGB value. The symbols are written onto film as a 2-dimensional ($2D$) raster of pixels. These pixels consist of laser dots and we will refer to the pixels as symbols.

For an isolated symbol its impulse response can be measured along one axis. We will denote the extension of the impulse response in both directions as $h(x, y)$. We can interpret the isolated impulse response as a noise-free response of a symbol that is not affected by ISI.

Figure 4 depicts the isolated impulse response of a symbol of size 2 laser dots. The isolated impulse response is measured over a black-white-black isolated film

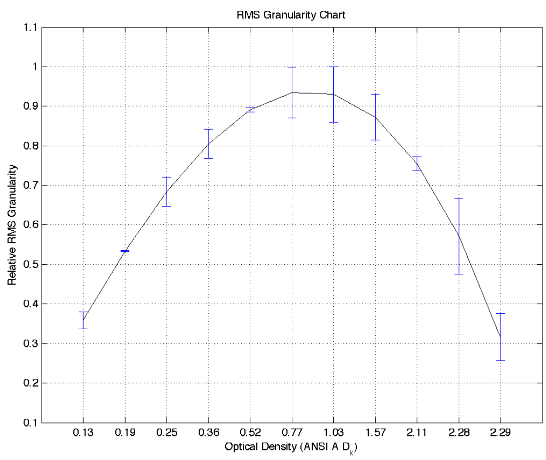

Figure 3: Relative RMS granularity for color microfilm (Ilford CMM). As expected, the granularity is considerably different from other materials, such as black and white film. It is evident that working with high and low densities results in dramatically lower granularity, or noise.

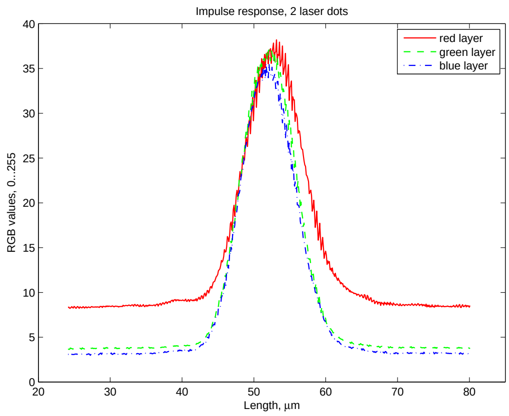

Figure 4: Impulse response for a symbol of size 2 laser dots.

sample. It can be seen that the impulse response for all layers extends to the nearest neighboring symbols. However, amplitude-wise the three layers behave in a different manner. We observe that the blue layer performs best, whereas the red layer suffers from a relatively high minimum amplitude. This is due to the composition of the film and the diffraction of light at the different layers of the film. The slight shift of the peak amplitude and the response in general ($1\mu m$ at peak) results from differing laser calibrations.

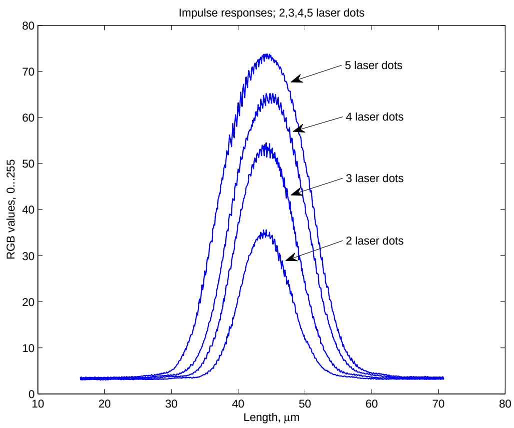

Figure 5: Impulse responses for symbols of sizes 2, 3, 4 and 5 laser dots.

Figure 5 shows the isolated impulse responses of symbols of sizes 2, 3, 4 and 5 laser dots on the blue layer. As in Figure 4 the isolated impulse responses are measured over black-white-black isolated film samples. We see that the peak amplitudes increase with the symbol sizes. Furthermore, let us suppose that the impulse width at half of the peak amplitude corresponds to the width of the symbol itself. Then, we deduce that the impulse responses of size 3, 4 and 5 laser dots still extend to the nearest neighboring symbols. But the broadening diminishes and for the symbol of size 5 laser dots it substantially contributes only up to the half of the nearest neighboring symbols. The half-peak impulse width for the symbol of size 2 laser dots is approximately 9 μm. Compared to the proposed symbol size of approx. 8 μm and the supported sizes of the laser, it makes sense to opt for a size of two laser dots.

3.2 2D model

In practice at the read-back process the data on film is captured by a still camera image. For a model, this image is interpreted as a $2D$ camera array. We assume that the read signal is a superposition of the isolated impulse responses introduced in the previous subsection. Then, the read signal can be described as

$$r(x, y) = \sum_{i,j} b_{i,j}\ h(x - iT, y - jT) + n(x, y)\,, \tag{2}$$

where the summation is over all symbols $b_{i,j}$ in the raster, i. e., i and j index rows and columns, respectively, and $h(x, y)$ is the isolated bit response. By T we denote the symbol period or symbol length. For the electronics noise in the system we account additive white Gaussian noise (AWGN) $n(x, y)$ at instances x and y.

Note that a linear model as described in Equation (2) may be insufficient. In practice, especially at high recording densities, one has to deal, amongst other difficulties, with variations of the position of a symbol. Commonly called jitter, this signal dependent noise is to be distinguished from the RMS granularity of the film. Thus, Equation (2) becomes

$$r(x, y) = \sum_{i,j} b_{i,j}\ h(x - iT + \Delta x_i, y - jT + \Delta y_j) + n(x, y)\,, \tag{3}$$

where Δx_i and Δy_j denote jitter noise in x and y directions, respectively. Provided the noisy response function $h(x - iT + \Delta x_i, y - jT + \Delta y_j)$ in Equation (3) represents a twice differentiable function, it can be expanded into a second order Taylor series

$$\begin{aligned} h(x - iT + \Delta x_i, y - jT + \Delta y_j) &= h(x - iT, y - jT) + \\ &+ \Delta x_i\ h^{(x)}(x - iT, y - jT) + \Delta y_j\ h^{(y)}(x - iT, y - jT) + \\ &+ \frac{1}{2}\Big\{ \Delta x_i^2\ h^{(x,x)}(x - iT, y - jT) + \\ &+ 2\Delta x_i \Delta y_j\ h^{(x,y)}(x - iT, y - jT) + \\ &+ \Delta y_j^2\ h^{(y,y)}(x - iT, y - jT) \Big\}\,, \end{aligned}$$

where the superscripts denote the corresponding partial derivatives.

Whether the description of the read signal in Equations (2) and (3) is appropriate will emerge through the comparison of simulated and real exposure and scanning of microfilm. Note that this comparison will require a position discrete interpretation of the position continuous model presented above. However, this is not addressed in this paper.

4 Conclusion

Measurements of microfilm and imaging components involved in a microfilm-based storage system (MTF, RMS) have led us to two conclusions. First, we have found that using state-of-the-art technology, data can be represented on film by using dots with a diameter of around $8\mu m$. This leads to a maximum data density of approximately $15kbit/mm^2$ for each of the three layers of color microfilm. Second, using a binary alphabet to represent the data on the microfilm layers will result in maximum data density.

In the second part we examined the interference of symbols written onto film and deduced that the use of symbols of size 2 laser dots is a legitimate choice. Moreover, we proposed a $2D$ position continuous channel model for PEVIAR. In a next step we will establish a position discrete channel model. It will incorporate the ISI effect and an accurate description of the symbol impulse response. This will allow us to actually detect the data. As an open problem we state the computation of channel information rates and possible encoding schemes. Also, we will explore possibilities of a combined data detection and decoding technique.

5 Acknowledgments

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