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On the Potential of Film as a Digital Storage Medium

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Abstract

During the last couple of years, photographic film has gained significant attention as a medium for long-term storage of digital data. Intensive research has been performed on this topic and now the question arises whether this medium has the potential to be a serious alternative to conventional data storage systems. Aim of this paper is to this answer this question by providing a state-of-the-art technology review.

Introduction

About a decade ago, a new discussion on film as a digital storage medium has started (cf., e.g., [1, 2]). The fundamental idea to store digital data on film already dates back to many decades ago (see, e.g., [3, 4]) and digital data patterns are also used to store sound information on cinematographic films (see, e.g., [5, 6]). However, advances to digital film recording technologies (cf., e.g., [7–9]) have allowed entirely new possibilities in this context. Specifically the high lifetime of certain films as well as the vast amount of experience with photographic films are ideal preconditions for long-term archiving applications. Since then, intensive research has been performed for data storage on film. Descriptions of this technology (which is generally referred to as "Bits on Film" today) including literature reviews are provided, e.g., in [10–14].[1] Detailed research has been carried out on important aspects, such as channel modeling (e.g., [15, 16]), error correction (e.g., [12, 17, 18]), as well as signal and information processing (e.g., [19]). Besides microfilm, also cinematographic film has been investigated (e.g., [20–23]). Moreover, storage of audio data on film is described in [24]. A significant part of the research has been carried out in projects, such as Millenium (e.g., [19, 25]), Peviar (e.g., [26]), CineSave (e.g., [20–23]), and Archivator (e.g., [27]).

The workflow for data storage on film basically comprises the medium film itself, writing and reading devices as well as software and algorithms. Data points serve to store the actual digital information. It has turned out that major advantages of the medium film include (cf., e.g., [10–13, 22, 23]):

- a high estimated storage lifetime of up to 500 years depending on the employed film and the storage conditions (see, e.g., [28]),
- the ability to store analog and digital data on the same medium (referred to as hybrid storage) – this allows storing a human-readable description on how to retrieve the data in future (self-contained data storage),
- WORM (Write Once Read Many) storage which is very proof against forgery and data manipulation (due to the required chemical processing),
- only a minimum amount of costs, effort, and energy to maintain the digital archive.

Obviously, using "Bits on Film" would avoid several problems which can typically occur for many conventional digital storage media.

Despite modern storage technologies, such as flash memory, optical discs, or cloud storage, "traditional" photographic film (such as microfilm and cinematographic film) is still a very important medium. As an example, the federal republic of Germany keeps copies of important documents on analog microfilm in a central refuge (the "Barbarastollen" – an old silver mine near Freiburg in the Black Forest). This strategy is referred to as the "Bundessicherungsverfilmung", and currently microfilms with a total length of about $30,000$ km are safely kept there in air-proof steel containers (see, e.g., [29, 30]).

Basically, there is no limitation which type of data can be stored by means of "Bits on Film". Hybrid approaches may be attractive for cinematographic applications to combine the principle of a separation master (i.e., archiving of three analog color separations on black-and-white film) with "Bits on Film" to store multichannel digital audio data as well as metadata (see, e.g., [13, 20, 22, 23]).

The next section is about suitable film materials including a brief discussion of their properties. It is followed by sections on writing and reading devices, as well as software and algorithms. Finally, storage capacities are discussed and the paper ends with a detailed set of conclusions.

Film Materials

In principle, there are three major types of base materials, which can be encountered for photographic films: Cellulose nitrate, cellulose acetate, as well as polyester. Films with a nitrate base (commonly referred to as nitrate films) are highly-flammable and thus not manufactured anymore. This serious issue has been solved by using cellulose acetate as a film base material instead, although these acetate films are still not considered to be ideal archiving films, e.g., due to the so-called vinegar syndrome. For archiving applications, polyester film bases are commonly used today due to their high stability. The Life Expectancy (LE) of photographic films is frequently employed in the field of archiving (see, e.g., [31]). Its value is, e.g., strongly dependent on so-called dark fading which can be estimated by means of experiments in combination with predictions based on the Arrhenius equation (see, e.g., [32]). Of course, the specified storage conditions, such as temperature and relative humidity, for the films have to be regarded and harmful influences

[1] The author's doctoral thesis [13], which has recently been published, deals with data storage on film in detail and also provides an extensive literature review. Since further in-depth information on large parts of this paper can be found in this thesis, it is not explicitly referenced in the following, except for certain occasions.

have to be avoided.[2]

Photographic films are frequently used as microfilms and cinematographic films today. While microfilms are usually unperforated, cinematographic films normally feature perforation holes for the film transport mechanisms of projectors, cameras, recording devices etc. Commonly-used film widths are 16 mm and 35 mm for both microfilms and cinematographic films, 8 mm for cinematographic films, as well as 105 mm for microfilms (especially for so-called microfiches).

Basically, all conventional types of film can also be used for "Bits on Film", and the decision which type of film to use may depend on the specific application and situation. For archiving applications, black-and-white films based on silver halides are definitely interesting because the final image consists of metallic silver and is thus relatively stable. Furthermore, as a stable color film material, silver-dye-bleach film can be employed. A detailed analysis of data storage on such a film is provided in [13, 37]. As a summary, it can be stated that the investigated type of film indeed allows higher storage capacities compared to black-and-white films with a similar optical resolution. However, it turns out that due to spectral overlap of the dyes and the different quality of each resulting color channel, it is unrealistic to assume a factor of three. Accordingly, it should be weighted if such a color film is the right choice for data storage on film. On the other hand, using color film for "Bits on Film" can be attractive for certain scenarios, such as hybrid data storage.

Writing and Reading Devices

The data points which serve to store the information for "Bits on Film" can be written by means of a film recording device. For instance, such devices can be used to expose digital image data as analog images on cinematographic film after digital postproduction. For microfilm, so-called Computer Output Microfilm (COM) devices[3] are available to record analog images on film. Furthermore, there are devices which are capable of recording color microfilm (e.g., [7, 38]).[4]

A fundamental parameter of a film recording device is the distance between adjacent *exposure points*, referred to as the *system grid space*. Note that the actual size of the exposure points may depend on several factors, such as the recording device as well as the employed film material. For recording analog photographic images there may be an (intended) overlap of the exposure points to allow smooth resulting images. However, such overlaps are certainly not desirable when storing *data points*. The system grid space of analog exposure devices can often only be chosen from a set of predefined values by the user. To still achieve well-separated data points, it is possible to choose the *grid space* of the data points as an integer multiple of the system grid space.[5] To allow further intermediate values, a diagonal grid can be employed (see, e.g., [13, 20]).

For reading the data points, basically a high resolution film scanner is required. An interesting approach has been adopted by the CineSave project where a reading device for "Bits on Film" has been constructed by using standard optical and mechanical components as well as a digital Single-Lens Reflex (SLR) camera (see, e.g., [13, 20, 22, 23]). Accordingly, it seems reasonable to assume that film scanners with a suitable resolution are either available in future or can at least be constucted with acceptable effort (cf., e.g., [13, 20, 22, 23]).

Software and Algorithms

Besides the actual films as well as the writing and reading devices, software is required to deal with important tasks, such as error correction, signal and image processing, as well as data organization. For all software components and algorithms, a detailed documentation is desirable when dealing with long-term data storage (and is required for self-contained data storage). To avoid (or at least reduce) time-consuming and costly experiments, simulations can be used in many cases. Such simulations can be based on the channel model described in [13, 16], which is specifically capable of modelling the non-linear, amplitude-dependent, and non-Gaussian behavior of photographic films.

Synchronization is needed to exactly locate the data point positions when reading the data. This can be achieved by means of dedicated synchronization patterns (see , e.g., [13, 19]). Error correction allows to correct a limited amount of errors by adding redundancy during the writing process, which is employed during the reading process for correcting errors (cf., e.g., [12, 13, 17, 18]). This concept is generally referred to as Forward Error Correction (FEC) and widely employed in communications and data storage systems (see, e.g., [39]). In [13] the use of Low Density Parity Check (LDPC) codes is analyzed for data storage on film by means of simulations. The specific LDPC codes investigated in [13] have been chosen since they are also used for satellite-based digital television as standardized in [40] and are thus extensively documented.

Besides dust, dirt, and scratches, also Intersymbol Interference (ISI), i.e., the overlap of adjacent data points, can lead to bit errors. To reduce the amount of ISI, equalization techniques can be employed which allow closer data points and thus higher storage capacities. In [13, 41] several equalization techniques for data storage on film are analyzed, which are able to significantly reduce the impact of ISI in terms of the bit error rate.

Of course, the data to be stored cannot simply be written as a single bitstream on film without any data organization concepts. Especially for a long-term archiving system, the efficient use of metadata is very important as well. To allow self-contained data storage, the employed structures should be effective but also easy to understand and not too difficult to be implemented. Film exposure devices normally expose frames of exposure points (or data points, respectively) and it seems reasonable to divide such large frames into several subframes.[6] A low-level file system can then serve to store vital file system information. An additional high-level file system can be utilized to store additional file information and metadata, e.g., based on the Extensible Markup Language (XML).[7]

Storage Capacity

The storage capacity is certainly an important property of a "Bits on Film" system. Although it may not be as important as for

[2] Detailed treatments on photographic films and their stability can be found, e.g., in [33–36].

[3] The meaning of the abbreviation COM may slightly differ (see, e.g., [13]).

[4] Note that film recording devices intended for perforated cinematographic film are normally not suitable for microfilm (and vice versa).

[5] See [13] for a detailed definition of the terms exposure points, data points, system grid space, and grid space.

[6] As an example, the Arche laser recorder (formerly known as Archivelaser®) can expose frames with 15000×10666 data points and a size of 45 mm × 32 mm (see, e.g., [7]).

[7] See, e.g., [13, 19] for more information on subframes as well as the low-level and high-level file systems.

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many consumer storage devices, the costs of a data storage solution are of course strongly influenced by this parameter. Furthermore, specific applications may have certain minimum specifications regarding the storage capacity, especially for those fields, where the amount of data to be stored is relatively high.

In this context, it has to be distinguished between *gross storage capacity* and *net storage capacity*. As opposed to the gross storage capacity, which is defined by the number of data points per area as well as the number of amplitude levels per data point, the net storage capacity also takes into account further overhead, such as synchronization patterns, file system information, or redundancy for FEC. Both net and gross storage capacity are strongly influenced by the grid space while the impact of the number of amplitude levels is comparatively low.[8] Accordingly, it seems reasonable to employ binary modulation in combination with the smallest possible grid space to achieve a high storage capacity (cf., e.g., [12, 13, 18]). A detailed analysis based on simulations[9] has recently been published in [13], whereby the net storage capacities have been estimated to achieve values of up to $1.362\,\mathrm{Gbit/m}$.[10]

Conclusions

Aim of this paper has been to point out the potential of film a digital storage medium. Therefore, a state-of-the-art technology review has been provided and important components, such as writing and reading devices, error correction, and data organization have been addressed. Also, a brief comparison of different film types has been provided.

Due to the high estimated lifetime of certain photographic films, a "Bits on Film" storage solution can definitely be an attractive alternative to conventional storage media with relatively limited lifetimes. The consumption of electrical energy is a further important argument and because film-based data storage offers Write Once Read Many (WORM) characteristics on a physical level, it is very poof against forgery and data manipulation. Hybrid data storage is also an interesting feature, which even allows self-contained data storage by adding a human-readable description on how to read and interpret the digital data which has been stored on a film.

Successful examples from the field of analog archiving, such as separation masters for cinematographic films or the "Bundessicherungsverfilmung", show that film already *is* an important medium for long-term archiving of valuable materials. Developments such as digital cameras and digital cinema have significantly reduced the market share of photographic films, which may thus appear to be outdated today. However, due to the fact that photographic films have already been used for more than a century, there is a vast amount of experience with this medium including the field of long-term archiving. Of course, data storage on film is not intended to compete with consumer-grade storage media in terms of costs and storage capacity. On the other hand, when talking about the "digital black hole" [42] or the "digital dilemma" [43, 44] it becomes clear that the number of serious alternatives for reliable digital long-term archiving is obviously quite limited. As a solution, it seems to be straightforward to employ the well-proven medium film with its excellent long-term archiving properties also for digital data by using the technology "Bits on Film", which certainly has the potential to safely preserve valuable cultural and economic goods for future generations.

[8] See, e.g., [12, 13, 18] for detailed discussions on the storage capacity for data storage on film.

[9] Using the channel model described in [13, 16]. The parameters for these simulations have been obtained by means of real film samples.

[10] See [13] for a detailed description of the investigated data sets, specific assumptions and parameters, as well as further information.

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