State of the Art Report on Damage Prevention and Repair of Digital AV Media

DIGITAL AV MEDIA DAMAGE PREVENTION AND REPAIR

Where DAVID started from

SEVENTH FRAMEWORK PROGRAMME

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Author(s) and company: P. Schallauer (JRS), Paul Walland (ITInnov), Martin Hall May (ITInnov), Hannes Fassold (JRS), Jörg Houpert (CTI), Luis Laborelli (INA), Bailer Werner (JRS)

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1 Executive Summary

This report contains information on the state of the art in digital damage prevention and repair of audio-visual media. It has been compiled in course of the project definition of DAVID. The DAVID project addresses specific research questions for preservation and restoration of audio-visual media. An overview on the projects rationale is presented in section 2, details on the continuing project can be found at www.david-preservation.eu.

This report reflects the state of the art available at the starting time of the DAVID project. It addresses specific topics in four areas

- Understanding how damage occurs in IT based storage systems and what impact loss has on the usability of digital AV content
- Risk management for long-term quality assurance and interoperable preservation metadata for digital AV content
- Scalable tools for content based damage detection (digital dropouts), repair (digital dropouts and digital sensor noise) and quality improvement (resolution) of digital AV objects
- Standardised service-oriented interfaces (FIMS) for integrating project results applied to audiovisual collections

We hope that the state of the art information provided in these four areas is of interest to a wider research community dealing with preservation and restoration of digital audiovisual media.

2 Rationale of the DAVID project

Long term digital preservation of Europe's audiovisual content is a pressing political, economic, social and cultural challenge. 'The New Renaissance' report by the Comité des Sages[1] promotes the huge benefits of digitisation and online access to cultural content – much of which will be audiovisual content from Europe's extensive libraries and archives. The tragedy would be to slip back into a dark age because digitised or born digital content was subsequently and irretrievably lost or damaged in the digital domain.

Budgets are always limited, resources tight and there is more content to preserve than can be realistically be kept. Hard choices and trade-offs are inevitable. Building a perfect preservation system is an impossible task at anything approaching a realistic cost. The challenge is how to keep AV content usable in the face of technical obsolescence, media degradation, and failures in the very people, processes and systems engaged to keep this content safe.

Data integrity problems in large-scale IT storage are becoming increasingly well known, with the term of 'bit rot' emerging in the storage and preservation communities. But loss isn't just at the 'bit' level: corruption can be in the form of sectors, blocks, files, drives, tapes or even the failure of complete storage arrays. Causes include errors in hardware, bugs in firmware, accidental operator errors or even deliberate attacks. Storage capacity and cost continues to improve at a phenomenal rate, but improvements in reliability and error prevention and correction are failing to keep pace. The result is that data safety in IT storage is now more of a concern than ever before for AV content holders.

This is especially true for the digital preservation of AV content. It has all the challenges that other domains face of long-term storage of files using IT systems and managing the problems of application obsolescence. But it also has the challenge of digital video tape. Digital Betacam, IMX, DV, HDCAM and other digital video formats have been, and remain, the mainstay for recording in production environments for nearly two decades. The PrestoPRIME preservation status report[2] estimates the digital intake of major audiovisual collections to be about 8 million hours over the last decade, the majority is digital, but it is still non-file-based. Only now are digital video tapes being superseded by pure file-based technologies. But that leaves archives with 100,000s of digital video tapes in their storage. These are all at risk of loss: when stored, when used, when migrated, or simply because nothing is done at all to ensure their long term safe keeping.

The impact of loss on the usability of AV content varies according to the kind of loss event, the carrier, the content encoding and whether content quality control processes are followed. For example, even infrequent bit-level data corruption can have significant consequences on the usability of audiovisual assets. This is not only a problem for archive content, but it also affects the huge amount of born-digital AV content created every year by the media industry, other professional organisations, and consumers.

New tools and methods are needed to store, monitor, repair and restore audiovisual content in a way that balances long-term costs, risks of loss, and content quality both today and in the future. This comes with many specific challenges that we set out to address:

- How does damage occur in digital file and digital video tape based systems used for preservation and access?
- How can this damage be efficiently monitored and detected?
- What are the consequences of this damage on the ability to make use of audiovisual content?
- Accepting that damage will occur, how can content be repaired to enable re-use?
- Are there better ways to structure media files that make them more resilient?
- How can the technical quality of content be improved beyond the original state to satisfy requirements of new use channels and to ensure efficient storage utilisation?
- How can all this be done at scale and at speed for large audiovisual collections?
- How can effective risk management and quality assurance techniques be built into preservation systems so that the systems themselves become more robust and resilient?

[1] The New Renaissance - Report of the 'comité des sages' on bringing Europe's cultural heritage online.
http://ec.europa.eu/information_society/activities/digital_libraries/doc/refgroup/final_report_cds.pdf

[2] PrestoPRIME 2009 Audiovisual digital preservation status report,
http://www.prestocentre.org/system/files/library/resource/original_v1.01.pdf

- How can better preservation techniques be incorporated directly into the devices and systems that produce born digital content?

To give scale to the challenge this project addresses, surveys by UNESCO estimate 200M hours of AV content worldwide in the world's AV archives[3], a 2010 study by Screen Digest[4] and others reports that a total of 42.7M hours of content are held in the world's professional audiovisual archives, with PrestoSpace[5] and TAPE[6] showing 30M hours in Europe – which by now will have increased substantially due to the explosion of new digital channels and productions. Indeed, projections by Coughlin Associates are for 61,000 Petabytes of archived digital AV content by 2016[7]. But that is becoming dwarfed by consumer content, for example over 60 hours of video are uploaded every minute to YouTube, which to quote YouTube is "more in one month than the 3 major US networks created in 60 years"[8]. It is almost impossible to attach a value to this content, but it is worth noting that - according to Coughlin Associates - the storage industry for the media industry alone will be $6.4bn by 2016, with 60% of this storage by volume being for preservation and archive. The economics of long-term storage of Europe's AV content demand more cost effective, resilient and intelligent approaches. New ways are needed to ensure content is 'born robust' so it is more resilient to failures from the outset rather than somehow hoping that content will somehow survive until it makes into the safe harbour of a well-managed archive – if it ever gets there.

From a societal point of view, digital audiovisual content is pervasive. Prominent applications include professional content in the form of film, television and online material (both new born digital and from digital archives) and the personal creation and use of AV content (phones, cameras, PCs, tablets etc.). AV content is also used extensively in civil, industrial, scientific, medical and corporate environments with applications that include environmental monitoring, corporate training, surveillance and call recording. In all cases there are different requirements for retention including compliance and archive monetisation, different requirements for quality, different needs for data safety, and a multitude of approaches to storage and access. But all share a common challenge – how to keep AV content usable over time, often decades or longer.

[3] "UNESCO Takes Action to Help Safeguarding Sound and Film Heritage", http://portal.unesco.org/ci/en/ev.php-URL_ID=2034&URL_DO=DO_PRINTPAGE&URL_SECTION=201.html

[4] http://www.screendigest.com/reports/201074c/10_08_the_global_trade_in_audio_visual_archives/view.html

[5] Final report on users requirements (D2.1), 15/09/2004, http://www.prestospace.org/project/deliverables/D2-1_User_Requirements_Final_Report.pdf

[6] TAPE Survey Factsheet, http://www.tape-online.net/docs/Tape_survey_factsheet.pdf

[7] "2011 Digital Storage for Media and Entertainment Report", Coughlin Associates, 2011, http://www.tomcoughlin.com/Techpapers/2011%20M&E%20Storage%20Report%20Brochure,%20051611.pdf

[8] http://www.youtube.com/t/press_statistics

3 State of the art on damage prevention and repair

The research in DAVID focuses on the following main scientific and technological areas:

- Understanding how damage occurs and what impact it has on digital AV content
- Risk management for long-term quality assurance and interoperable preservation metadata for digital AV content
- Scalable tools for content based damage detection, repair and quality improvement of digital AV objects
- Standardised service-oriented interfaces for integrating project results applied to audiovisual collections

The state of the art in these areas is described in the following.

3.1 Understanding how damage occurs and what impact it has on digital AV content

3.1.1 IT-based storage

Many audiovisual archives are making the transition to IT storage systems as the basis for long-term retention and access to their holdings. This is driven both by the need to migrate ageing analogue archive holdings into new digital formats - and so preserve them digitally - and by new ways of working in the production process, e.g. file-based workflows where new material is shot in a digital format and then processed using computer-based systems. The result is that audiovisual archives, such as INA and ORF, are now faced with the challenge of how to preserve and manage huge file-based repositories of digital audiovisual assets, which can easily be petabytes in size.

There are many reports on the reliability (or lack of it) for storage technology and storage systems, including the types and origins of failures[9], mostly for Hard Disk Drive (HDD) based systems, which are supported by field studies and evidence of failure rates seen in practice[10] including for AV archives[11]. It is natural to think of failure modes in terms of the media or underlying physical devices used for storage, for example HDD failures as examined in the analysis by Google of their storage infrastructure[12], but data corruption can take place in all types of IT storage and at all levels, including in systems explicitly designed to prevent it, for example RAID arrays of HDD. The study done by CERN[13] highlights many issues seen in practice with large scale storage; including firmware bugs and failures in other links in the chain of getting data to and from storage, e.g. imperfect computer memory. Most worryingly, this corruption can be both silent (otherwise known as latent corruption or 'bit rot') and permanent. A good overview of latent and extant faults and their causes was provided in Baker et al.[14] in 2006. This and subsequent work has looked at how failures translate into various metrics for characterizing the 'safety of storage', for example Mean Time to Data Loss (MTTDL) , 'bit half-life' [15], Mean Latent Error Time

[9] Elerath, J.. Hard Disk Drives: The Good, the Bad and the Ugly!, Queue 5, 6, p28-37, 2007. http://doi.acm.org/10.1145/1317394.1317403

[10] Jiang, W. et al. Are Disks the Dominant Contributor for Storage Failures? A Comprehensive Study of StorageSubsystem Failure Characteristics. FAST '08. http://www.usenix.org/events/fast08/tech/jiang.html

[11] Addis, M. et al. Audiovisual Preservation Strategies, Data Models and Value-Chains. PrestoPRIME Deliverable D2.2.1, 2010, http://www.prestoprime.eu/

[12] Eduardo Pinheiro, Wolf-Dietrich Weber. Failure Trends in a Large Disk Drive Population. Google. Proceedings of the 5th USENIX Conference on File and Storage Technologies (FAST'07), February 2007

[13] Péter Kelemen. Silent Corruptions, CERN IT. LCSC 2007, Linköping, Sweden

[14] Mary Baker, Mehul Shah, DAVID S. H. Rosenthal, Mema Roussopoulos, Petros Maniatis, TJ Giuli, Prashanth Bungale. A fresh look at the reliability of long-term digital storage. Proceeding EuroSys '06 Proceedings of the 1st ACM SIGOPS/EuroSys European Conference on Computer Systems 2006

[15] Rosenthal, D. S. H. Bit preservation; a solved problem? International Journal of Digital Curation 1(5), 2010.

(MLET)[16], and Normalized Magnitude of Data Loss (NoMDL) as described in Greenan et al.[17], the latter serving to highlight the challenges involved in defining a meaningful metric and a realistic underpinning storage model.

It should be said that corruption levels both published by manufacturers and seen in practice are actually remarkably low, which is testament to the levels of engineering in these technologies. For example, a modern hard drive has a Bit Error Rate of 1 in 10^{14} with LTO data tape being lower at 1 in 10^{17}. However, with 1TB requiring approx. 10^{13} bits of storage it becomes clear that errors are inevitable at the PB storage scale seen in many large archives. The problem is that whilst the capacity of a storage system of a given cost will typically double every 18 months or so, the rate at which this system can be loaded with data and the rate at which errors will occur do not keep pace with this trend. This results in increased data integrity recovery operations (e.g. RAID array rebuild times) and increases in complexity of error protection schemes (e.g. the transition from single parity RAID5[18] to double parity RAID6[19] with triple parity already on the horizon[20].

The responses developed to cope with, or counter, failure modes and data corruption in storage are manifold. Techniques include RAID for storage arrays, ever more advanced techniques for dealing with latent errors in HDD storage as reviewed in Schroeder et. al[21], and a wide range of approaches to distributed storage, including erasure codes, e.g. as described as the basis of Redundant Array of Independent Nodes (RAIN)[22] and more recently in archive applications such as Pergamum[23] and DAWN[24]. Simple replication techniques also have a part to play, e.g. as used by Lots of Copies Keep Stuff Safe (LOCKSS)[25]. These techniques can be combined, e.g. a layered combination of replication, integrity checking, erasure coding and other techniques are now seen in advanced file systems designed to manage data integrity from the outset such as ZFS[26].

3.1.2 Impact of loss on content usability

Despite industry and academic work on the failure modes of storage, how to model them, and how to manage them, it still remains the case that storage technology is imperfect. Therefore, it is possible to reduce the level of data loss at increased cost, but not to eradicate it completely, especially for large-scale long-term data retention in archive applications.

The impact of loss on the usability of AV content varies according to the kind of loss event, the carrier and the content encoding. For example, even infrequent bit-level data corruption can have significant consequences on the usability of audiovisual assets. In effect, corruption is amplified, particularly if the

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[16] Alina Oprea, Ari Juels. A clean-slate look at disk scrubbing. FAST'10 Proceedings of the 8th USENIX conference on File and storage technologies. USENIX Association Berkeley, CA, USA, 2010.

[17] Kevin M. Greenan, James S. Plank, and Jay J. Wylie. Mean time to meaningless: MTTDL, Markov models, and storage system reliability. In Proceedings of the 2nd USENIX conference on Hot topics in storage and file systems (HotStorage'10). USENIX Association, Berkeley, CA, USA, 5-5, 2010.

[18] S. Chen and D. Towsley. The design and evaluation of RAID 5 and parity striping disk array architectures. Journal of Parallel and Distributed Computing, 17(1-2):58–74,1993

[19] A. Dholakia, E. Eleftheriou, I. Iliadis, J. Menon, and K. Rao.Analysis of a new intra-disk redundancy scheme for high-reliability RAID storage systems in the presence of unrecoverable errors. In Proceedings of the joint international conference on Measurement and modeling of computer systems, pages 373–374. ACM New York, NY, USA, 2006

[20] Adam Leventhal. . Triple-Parity RAID and Beyond. Queue 7, 11, Pages 30 (December 2009), 10 pages

[21] Bianca Schroeder, Sotirios Damouras, and Phillipa Gill. . Understanding latent sector errors and how to protect against them. Trans. Storage 6, 3, Article 9 (September 2010)

[22] Hakim Weatherspoon and John D. Kubiatowicz. Erasure Coding vs. Replication: A Quantitative Comparison.. Computer Science Division University of California, Berkeley. Proceedings of the 1st International Workshop on Peer-to-Peer Systems (IPTPS '02). http://oceanstore.cs.berkeley.edu/publications/papers/pdf/erasure_iptps.pdf

[23] M. W. Storer, K. M. Greenan, E. L. Miller, and K. Voruganti. Pergamum: Replacing tape with energy efficient, reliable, disk-based archival storage. In Proceedings of the 6th USENIX Conference on File and Storage Technologies (FAST), Feb. 2008

[24] Ian Adams and Ethan L. Miller and DAVID S.H. Rosenthal. Using Storage Class Memory for Archives with DAWN, a Durable Array of Wimpy Nodes. Technical Report. UCSC-SSRC-11-07. University of California, Santa Cruz. Oct, 2011

[25] DAVID S.H. Rosenthal. "LOCKSS: Lots Of Copies Keep Stuff Safe", presented to the NIST Digital Preservation Interoperability Framework Workshop, March 29-31, 2010

[26] Zhang, Y., Rajimwale, A., Arpaci-Dusseau, A. C., Arpaci-Dusseau, R. H.. End-to-end data integrity for file systems: a ZFS case study. In 8th Usenix Conference on File and Storage Technologies, 2010.

file is compressed, e.g. studies show[27] that a single byte corrupted in a JPEG2000 image (lossless or lossy) can result in 30% or more of the decoded pixels being affected and in many cases with major visual artefacts being visible across the whole image. In an investigation by the BBC on the effects of data corruption from IT storage technology on content usability of a video file encoded using the Dirac codec. For example, if corruption occurs in the lower frequency sub bands, then ability to use the content is completely lost. If corruption occurs in the higher frequency sub bands, then loss may be tolerable. Similar effects can be observed in non-audiovisual formats; a CERN study[28] on data corruption observed that over 99% of zip compressed files would not open as a result of bit-level corruption.

3.2 Risk management for long-term quality assurance and interoperable preservation metadata for digital AV content

3.2.1 Risk management

The historical approach to data protection in file-based storage, e.g. use of RAID in hard disk servers or ECC in DVDs, is to design a scheme that results in no data loss to files stored under normal conditions and to work in a way that is generic, i.e. independent of the type of content being stored. Recently, work has been done on storage systems where loss is accepted as likely over a preservation timescale and if it does occur then the remaining data is afforded extra protection based on its proximity to the damaged data[29]. Work has also been done on encoding schemes specific to audiovisual data where the most critical parts of the content are given more protection in storage, e.g. JPEG2000 and Dirac[30], or during transmission over a network, e.g. H.264[31].

Risks to content from IT storage technology come from many sources, as discussed in section 3.1, including storage failure modes, technical obsolescence and human factors (e.g. deliberate or accidental deletion of data, failure to budget properly, failure to follow data management processes). Short lifetimes of storage technology require frequent migration to avoid loss from technical obsolescence. For example, there is limited backwards read compatibility of LTO data tape drives with previous generations of tape meaning the effective lifetime of a data tape is approximately 6 years. For HDD systems, the lifetime is often less with 5 years being a typical service life for an individual drive. The biggest risk to content is perhaps a failure to migrate rather than data corruption. The issue becomes one of how to take a comprehensive approach to considering all the factors.

Risk management is a cyclic activity[32] of assessing and dealing with risk, including the selection and application of one or more treatments. Risk management as a methodology is ideally suited to assessing ‘whether IT systems are safe’ in the context of long-term storage and access of data assets. Not surprisingly, application of risk management techniques is widespread in critical applications, e.g. information security[33]. In the digital preservation domain, the CCSDS (producers of OAIS) have combined the efforts of TRAC[34], DRAMBORA[35], Nestor[36] and ISO 27001[37] to ISO standardize the results (Trusted Digital Repository Checklist ISO16363[38]). Work in the PrestoPRIME project by IT

[27] Heydegger, V (2009) Just One Bit in a Million: On the Effects of Data Corruption in Files. Research and Advanced Technology for Digital Libraries, ECDL 2009, LNCS 5714

[28] Panzer-Steindel, B. (2007). Data integrity. 08 April, 2007. CERN/IT http://indico.cern.ch/getFile.py/access?contribId=3&sessionId=0&resId=1&materialId=paper&confId=13797

[29] Xyratex US patent 8020047 method and apparatus for managing storage of data. http://www.freepatentsonline.com/8020047.pdf

[30] Addis, M., Wright, R. and Weerakkody, R. Digital preservation strategies for AV content. In:2010 Conference of the International Broadcasting Convention (IBC 2010), 9-14 September, 2010

[31] Xingjun Zhan, Xiaohong Peng; Fowler, S.; Dajun Wu. Robust H.264/AVC Video Transmission using Data Partitioning and Unequal Loss Protection. IEEE 10th International Conference on Computer and Information Technology (CIT), 2010

[32] Risk Management Standard: http://www.theirm.org/publications/documents/Risk_Management_Standard_030820.pdf

[33] CERT: http://www.cert.org/work/organizational_security.html

[34] TRAC: http://www.crl.edu/PDF/trac.pdf

[35] DRAMBORA: http://www.repositoryaudit.eu/

[36] Nestor: http://edoc.hu-berlin.de/series/nestor-materialien/8en/PDF/8en.pdf

[37] ISO27001: http://www.27001-online.com/

[38] ISO16363: http://public.ccsds.org/publications/archive/652x0m1.pdf

Innovation has applied a risk assessment approach[39,40] that looks at the risks and counter-measures for a wide range of storage technologies (optical, HDD, data tape, printing bits to film and others).

New approaches to loss risk reduction can be achieved by using data encoding schemes that make a particular format more resilient to corruption, including how the more significant parts of the data within a file can be given extra protection. We will build on the understanding introduced in section B1.2.1 on the sensitivity of different content encodings to errors. This requires understanding of both the content of file and the impact of data corruption, for example as developed by the BBC[41] in an archive version of their Dirac video codec that allows more protection to be given to the parts of a video file that are most sensitive to corruption, such as the header information or the lower frequency coefficients in wavelet based video compression.

Therefore, when looking at the cost and safety of long-term storage, a wide range of risks need to be considered along with the impact on the utility of content should those risks materialize. Each countermeasure employed will have a cost associated with it, and in some cases the countermeasure itself, if applied too frequently, can be counterproductive and increase the risk. Consider data scrubbing as an example. This is a common approach for HDD systems where data integrity is checked periodically using checksums. A reference checksum is computed for known good data and then at regular intervals the data being stored is physically read and a new checksum generated. A mismatch between this checksum and the reference checksum can indicate data corruption. However, the act of accessing data to generate a checksum can cause failures (e.g. increased wear, possibility of head crashes etc.). Therefore, checking data too often can be counterproductive, for example as presented by Mary Baker at MSST 2011[42]. Checking data can also increase costs, especially in archive storage systems that keep data on media that is at rest, e.g. data tapes or spun-down disks in MAID type arrays. Indeed, all countermeasures will incur costs and result residual risks after their execution. These costs need inclusion in the overall cost model of storage TCO over time. However, there is relatively little work that investigates the trade-offs that exist between cost and loss[43] by looking at the relationship between the two over time.

3.2.2 Interoperable preservation metadata

Interoperable metadata is a key prerequisite for long-term preservation and quality assurance of content. For preservation purposes, the following two types of metadata are most crucial: *Structural* metadata, i.e., metadata that is needed to correctly interpret the stored essence (header structures of containers, technical metadata about the type of encoding, etc.), and *preservation* metadata, which includes information about the fixity of the object (i.e., properties that allow checking the integrity and quality of the essence), as well as a documentation of the preservation actions applied (e.g., devices/tools used and their parameters).

While there exists an abundance of metadata standards and formats for describing multimedia content[44], this is not the case for the description of material properties, tools and processes for preservation of audiovisual content[45]. Preservation metadata is a relatively new concept, and preservation metadata models (e.g., PREMIS[46]) emerged quite recently in the digital library domain.

[39] Matthew Addis et al. Threats to data integrity from use of large-scale data management environments PrestoPRIME Deliverable ID3.2.1, 2010, http://www.prestoprime.eu/

[40] Addis, M., Wright, R. and Weerakkody, R. Digital Preservation Strategies: the cost of risk of loss. SMPTE Motion Imaging Journal, 120, 2011

[41] Addis, M., Wright, R. and Weerakkody, R. Digital preservation strategies for AV content. In: 2010 Conference of the International Broadcasting Convention (IBC 2010), 9-14 September, 2010

[42] Mary Baker, Keynote for IEEE MSST 2011: "Preserving Bread Crumbs"

[43] Wright, R; Matthew Addis; Ant Miller The Significance of Storage in the 'Cost of Risk' of Digital Preservation. Proceedings of iPRES 2008: http://www.bl.uk/ipres2008/ipres2008-proceedings.pdf

[44] Michael Hausenblas (ed.), Multimedia Vocabularies on the Semantic Web, W3C Multimedia Semantics XG, 2007, http://www.w3.org/2005/Incubator/mmsem/XGR-vocabularies/

[45] Guus Schreiber et al., Metadata Models, Interoperability Gaps, and Extensions to Preservation Metadata Standards, PrestoPRIME Deliverable 2.2.2, 2010, https://prestoprimews.ina.fr/public/deliverables/PP_WP2_D2.2.2_MetadataModels_InteroperabilityGaps_v1.50.pdf

[46] PREMIS Editorial Committee chaired by Rebecca Guenther; PREMIS Data Dictionary for Preservation Metadata; version 2.0; March 2008; http://www.loc.gov/standards/premis/v2/premis-2-0.pdf

The existing implementations[47] thus cover the significant properties and the processes involved in preserving film and video only superficially. Gaps also exist in standards from the audiovisual domain. For example, MPEG-7[48] only includes detailed description capabilities for audio impairments (part 4, AMD 1), but not for visual ones. The SMPTE metadata dictionary[49] contains a long list of properties, including many describing tools and their settings in production, but lacks comparable properties for preservation.

First steps to document the knowledge involved in preservation processes are simple databases of format properties on obsolescence (e.g., PRONOM[50], JHOVE[51]), but they do sufficiently cover the audiovisual domain. Recently, the PrestoPRIME project has started working on a registry including information about the obsolescence of audiovisual formats, which also considers the issues of container formats with different encodings inside.

Also with strong involvement of PrestoPRIME partners, MPEG has started work on multimedia preservation metadata, called Multimedia Preservation Application format (MP-AF). A first working draft is expected in May 2013.

3.3 Scalable tools for damage detection, repair and quality improvement of digital AV objects

3.3.1 Digital drop-out detection

Digital drop-outs are a major type of damage when storing digital AV content on digital video tape carriers or when transferring this content to file based environments. There is a high risk of introducing errors within the transfer process as it is not protected by any fixity information. Despite the practical importance of algorithms for the detection of drop-outs originating from digital video tapes (Digi Beta, IMX etc.), there is only very little related scientific work focusing on image based methods focusing on this kind of defect.

The closest related work is given in Sun et al[52] where an algorithm for the detection of mosaic-like defects occurring in digital video is proposed. It detects rectangular-shaped blocks with homogeneous intensity appearing in the image by a combination of intensity- and edge- based features. The detection capability of the method is questionable as no evaluation of the detector is given in the publication. The work of Kaprykowsky et. al.[53] focuses on the detection of frames heavily affected by line-wise drop-outs in analogue video. It uses local image histogram features organised in a quad-tree to localise the analogue drop-outs within an image. This approach is tailored to detect large drop-outs in analogue video, so its performance for digital video drop-outs will likely be poor.

Although the appearance of digital drop-outs differs in certain aspects from those of single-frame defects (dust, dirt, blotches) for archived film, they share also some similarities (nearly homogeneous intensity, mostly affecting a single frame). A survey of methods for the detection of single-frame defects in archived film has been done by Ren and Vlachos.[54].

The measure of the radio frequency (RF) level can be used as an important parameter to double check whether the digital video tape playback is within expected tolerances. In maintenance troubleshooting this measure is used to validate that the first parts of the signal chain are working fine. If the alignment of the tape path exceeds the tolerance, if a sufficient physical contact between video head and tape is not achieved or if the track layout of the tape is not correct then the RF level is very low, but stays more or less stable. If the overall RF level is within its tolerance but many drop-outs in the RF envelope occur, than this can be an indicator that the video tape is in bad shape. Mechanical tape cleaning often

[47] PREMIS Implementation Registry: http://www.loc.gov/standards/premis/registry/

[48] MPEG-7, Multimedia Content Description Interface, ISO/IEC 15938, 2001.

[49] Metadata Dictionary Registry of Metadata Element Descriptions. SMPTE RP210.11, 2008.

[50] http://www.nationalarchives.gov.uk/PRONOM/Default.aspx

[51] JHOVE - JSTOR/Harvard Object Validation Environment,http://hul.harvard.edu/jhove/http://hul.harvard.edu/jhove/

[52] Sun F., Han S.. Mosaic Defect Detection in Digital Video. Chinese Conference on Pattern Recognition, 2010.

[53] Kaprykowsky, H.; Mohan Liu; Ndjiki-Nya, P.; Restoration of digitized video sequences: An efficient drop-out detection and removal framework, 16th IEEE International Conference on Image Processing (ICIP), vol., no., pp.85-88, 7-10 Nov. 2009

[54] Ren J., Vlachos T. Detection of dirt impairments from archived film sequences: survey and evaluations. SPIE Optical Engineering, 2010

improves the situation. In all the maintenance cases the RF signal off tape is only measured for its envelope but not used further, as every further interpretation of the signal would need the demodulation/decoding of the RF signal. To understand the internal signal processing of professional digital tape playback machines like Digi Beta, the analyses of the first published digital video formats is essential. The first digital video format which was internationally standardised was D-1 a 4:2:2 DTV standard, “Draft Rec. AA/11 (Mod F): Encoding parameters of digital television for studios”. It was adopted by the ITU-R/CCIR Plenary Assembly in 1982 and became ITU-R Recommendation 601). The detailed specification of the signal processing chain is published. The R601[55,56] was used by Sony in order to develop the Digital Betacam (Digi Beta) format. The detailed Digi Beta format description itself remained closed source.

3.3.2 Digital drop-out repair

Similar to the topic of digital drop-out detection, related work to the repairing of digital drop-outs is mainly limited to algorithms from the restoration of single-frame defects in archived film. Commonly these methods follow an approach based on motion compensated interpolation using image content from the neighbouring non-corrupted frames[57,58] or based on spatial inpainting[59]. There is no existing literature specifically addressing the properties of digital drop-outs.

3.3.3 Digital sensor noise repair

The occurrence of digital sensor noise is an inherent characteristic of digital video and movie cameras. These cameras typically have CCD or CMOS sensors which convert the measured amount of light a certain sensor area receives in a specified time span into a discrete intensity value. Due to random fluctuations in the number of received photons during this time span and several other noise-generating sources within the camera, noise appears in the recorded digital image. Image noise has an adverse influence on efficient storage utilisation for long-term preservation, as the high-frequency noise components require a high quality encoding with a considerable bit-rate. An alternative would be to keep the bit-rate the same, causing a degradation of image quality. One can see from this that a robust and efficient digital sensor noise repair method is highly beneficial for preservation. Most algorithms for the removal of noise take advantage of the spatial and temporal redundancy of the images within a sequence. Most approaches rely on motion-compensation of several consecutive images and a subsequent filtering, either in the spatio-temporal[60] or in the transform[61,62] domain. An issue with many approaches in the literature is that they make somewhat simplistic assumptions about the nature of noise (e.g., no signal dependency). This leads to inaccurate noise models which do not reflect the actual noise characteristics of digitally born content, captured with digital video or movie cameras, precisely. For example, the assumption of signal in-dependency of noise is not correct for these digital cameras as darker regions contain usually more noise than brighter regions.

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[55] SMPTE (2003) ST 224 Television Digital Component Recording – 19-mm Type D-1 – Tape Record
SMPTE (2003) ST 225 Television Digital Component Recording – 19-mm Type D-1 – Magnetic Tape
SMPTE (1996) ST 226 Television Digital Recording – 19-mm Tape Cassettes
SMPTE (1996) ST 227 Television Digital Component Recording – 19-mm Type D-1 – Helical Data and Control Records
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3.3.4 Resolution improvement

Resolution improvement denotes increasing the video content's resolution beyond the original camera, production or archive resolution. It is an important tool as it allows keeping the mass of preserved audiovisual content, often available only in PAL or NTSC standard definition resolution, usable for current distribution channels like HD broadcast. Methods for resolution improvement of video are commonly termed super-resolution algorithms and generate a high resolution video by exploiting the redundancy in the content. Most super-resolution algorithm use a sliding window of consecutive images to determine one high-resolution image. Typically, the first step is to calculate the motion of the images within the sliding window with respect to e.g. the central image. Most approaches employ simple parametric models like translatory[63] or affine transformations[64] for this task. Then, either interpolation methods[65] or regularisation based methods[66], which model the image degradation due to blur and the sampling of the image on a regular grid and solve the regularized model iteratively, are employed. A disadvantage of many super-resolution methods is that they use simple blur models, that are not able to model the actual Point-Spread Function (PSF)[67,68], and simple motion models (which are unsuitable for video where arbitrary motion is present). On the other hand, super-resolution methods which employ more sophisticated motion estimation via optical flow methods[69,70] have processing times of several minutes for one frame in standard definition resolution, which makes them not feasible for large-scale audiovisual content.

Furthermore, no super-resolution method in the literature specifically addresses the characteristics of analogue and digital archive material (e.g. in terms of impairments typically present in archive material).

Even if the material has not been subject to damages caused by the ageing of storage media, the electronic signal processing applied during video production limit the application of known super-resolution algorithms due to linear degradations. More specifically, video is mostly available in interlaced form, and some non-linear processing like contour correction and/or noise coring has been already applied during capture or in the storage chain, beyond the traditional optical or sensor PSF considered in papers. While the technical literature on super-resolution is extremely large and still growing[71,72,73,74], few papers consider blurry interlaced input sequences resulting from analogue electronic processing. The challenge is to extend the state of the art of up-sampling methods to real imperfect historical interlaced video instead of perfect low resolution recent sequences.

3.3.5 GPU based methods for handling large volumes of AV content

A critical factor determining the practical usability of the developed methods for damage detection and repair is their runtime. This is due to the sheer size of the audiovisual collections, occurring e.g. in

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[63] Farsiu S., Elad M., Milanfar P. Multiframedemosaicing and super-resolution of color images. IEEE Transactions on Image Processing, Vol. 16, 2006

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broadcaster's archives, on which the methods will be applied. In recent years, the usage of graphics processing units (GPUs) for computationally intensive problems has become very popular as they deliver massive speedups[75] with respect to a CPU implementation when the problems are sufficiently parallelizable. At JRS several computer vision algorithms for e.g. image warping, image inpainting[76], feature point detection and tracking[77] and video breakup detection[78] have been implemented already successfully on the GPU, delivering significant speedup factors of up to an order of magnitude and allowing JRS to gain plenty of knowledge about the efficient implementation of algorithms on the GPU.

3.4 Standardised service-oriented interfaces

By looking for standardisation bodies worldwide that are developing standards in the area of IT based technologies for networked media for the motion imaging industry, there remains not much choice. The most influencing standard developing body in that domain is the Society of Motion Picture and Television Engineers (SMPTE). To shorten the time-frame in developing international standards, supportive standards preparation is needed to prepare well-defined input documents for the SMPTE. The work of the European Broadcasting Union (EBU) and the Advanced Media Workflow Association (AMWA) in this role are well established.

In December, 2009 the EBU and the AMWA joined forces and established the Framework for Interoperable Media Services (FIMS) initiative to develop open standards solutions for more efficient workflows in file-based Service Oriented Architecture production environments for the creation and delivery of content across a wide range of media. In a first time ever collaboration to drive future media standards & interoperability across digital media ecosystems the SMPTE, AMWA and the EBU announced in Nov. 2011 that they will work together to accelerate their respective efforts at driving interoperability and delivering efficient media workflows.

The first FIMS Request for Technology (RFT) was published in early 2010. By end of 2010 the industry's responses to the RFT was evaluated against the requirements and the technology inputs analysed and in early 2012 the FIMS 1.0 Final Output Documents were released. FIMS open standards are guaranteed to be usable without royalties. FIMS is now a quickly emerging open standard backed by big media industry players like AVID, IBM, Sony, with support from Harris Corporation, Harmonic, Snell and a lot of other influencing manufacturers.

Even before the final release of FIMS 1.0 there was already a strong support from large-scale media automation users like Turner Broadcasting, Red Bee Media, NBC Universal, Bloomberg and public broadcasters like BBC, RAI and the Canadian Broadcasting Corporation, and of course also by DAVID consortium members JRS and CTI. CTI is one of the 5 FIMS demonstration partners together with IBM, Sony and Avid and Cinegy, and presented FIMS technology live at the two biggest media exhibition NAB in Las Vegas and IBC in Amsterdam the previous two years.

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4 Glossary

Terms used within the DAVID project, sorted alphabetically.

AMWA	Advanced Media Workflow Association
EBU	European Broadcasting Union
FIMS	Framework for Interoperable Media Services
SMPTE	Society of Motion Picture and Television Engineers

Partner Acronyms

CTI	Cube-Tec International GmbH, GE
HSA	HS-ART Digital Service GmbH, AT
INA	Institut National de l'Audiovisuel, FR
ITInnov	University of Southampton - IT Innovation Centre, UK
JRS	JOANNEUM RESEARCH Forschungsgesellschaft mbH, AT
ORF	Österreichischer Rundfunk, AT

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