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3D Coding Techniques

TC2 Technical Report 3

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Executive Summary

Progress of research in WP9 during the last year is reported in this deliverable.

The NoE plays a worldwide leading role in multi-view video coding (MVC). Researchers from the NoE have been leading the corresponding standardization activities in MPEG and the JVT. Technology proposals from the NoE performed best within the related MPEG Call for Proposals, thus the fundament of this new standard has been developed within the NoE. Participation in MPEG and the JVT will be continued. Besides these more applied standardization activities, also basic research on MVC has been continued, resulting in various publications. A new standardization activity for multi-view video plus depth has been initiated and researchers from the NoE again play a leading role in management as well as on technical level.

Research on 3D mesh compression has been continued successfully as well. One focus was on dynamic mesh compression. The coder developed within the NoE now forms the basis of a new MPEG standard, which is a new part of the MPEG-4 Animation Framework eXtension (AFX).

The NoE performed pioneering research in the area of multiple description coding (MDC) for 3D data. So far only a few publications about MDC for 3D meshes were known. In this area research in the NoE has reached a very good standard and significant contributions have been made. In addition MDC for stereo video was first considered in the NoE. Future research will include studies of performance over real transmission channels, both wired and wireless, such as IP and DVB-H, and modification of developed techniques to reflect the real channel error patterns. Combination of MDC with other resilience techniques, such as FEC and raptor codes will be investigated as well.

Watermarking for 3D is also a pioneering research area. Contributions have been made to watermarking of 3D mesh models that has been studied to some extend outside the NoE as well. In addition watermarking of image-based rendering data has been investigated within the NoE for the first time. Such algorithms will be very important for future protection of image-based 3DTV data. Future research will continue along these lines to ensure future protection of 3D data.

In general conclusion, the research on 3D compression within the NoE reached a high level of excellence, for both scientific fundamentals and more applied development of international standards. Partners formed a strong network and benefit from each others expertise and resources.

1. Introduction

This Technical Report 3 summarizes the research results in WP9 during the last year. Research in the NoE converged more and more into joint activities, where partners benefit from collaboration and synergies. The work has been clustered into the following high priority research areas:

- Multi-view video coding,
- 3D mesh compression,
- Multiple description coding for 3D,
- Watermarking for 3D.

This list includes well established but nevertheless highly active fields like for instance 3D mesh compression as well as highly innovative topics like watermarking for 3D. In the latter for instance the NoE was doing pioneering work. Multi-view video coding is related to compression of any kind of pixel data, such as video, stereo video, multi-view video, but also associated per-pixel depth data, etc. This wide field is partially well established but partially also very innovative, and in any case highly actual. For instance MPEG is working on a new standard for multi-view video coding and partners from the NoE play a leading role in development of this standard. 3D mesh compression is related to this type of classical computer graphics representations of 3D data. Also here partners contribute to activities within MPEG. Multiple description coding is studied for the first time with focus on 3D within the NoE. Also work on watermarking of various 3D data is, besides for 3D meshes, for the first time being done within the NoE.

For all these topics groups of institutions have been formed that carry out joint research in an integrated and collaborative manner. This includes exchange of know-how, software, data, researchers and students, common usage of equipment and infrastructure, with focus on common publications. Links have also been established to other WPs along the 3D-TV chain.

Section 2 of this document gives an analysis of the results so far. These are brief summaries each related to a specific part of the annex. The annex contains all the descriptions in detail. This may be published or unpublished papers, MPEG documents or other types of reports. The analysis in section 2 is intended to extract the essence of all of this work and to put all into a concise context. The assessment is done by research topic listed above by a “summary, conclusions and plans” section for each. An overall summary and conclusions can be found in section 3.

This report summarizes 35 journal and conference papers, book chapters, PhD theses and standard input contributions that were prepared by the NoE partners in the area of 3D coding (11 for MVC, 12 for 3DMC, 4 for MDC, 1 for Watermarking, 1 general). Further, it lists more than 30 MPEG and JVT output and input documents that were created with contributions from NoE partners during the reporting period.

2. Analysis of Results

This section gives an analysis of the work and results of the NoE within the reporting period as a collection of abstracts. The more detailed descriptions of each topic can be found in the related annex. Research in WP9 has been clustered into the main subjects multi-view video coding (MVC), 3D mesh compression, multiple description coding (MDC) for 3D, and watermarking for 3D. Each of the related sub-sections in the following includes overall summary, conclusions, and plans for the related research topic as a whole.

2.1. Multi-view video coding (MVC)

Multi-view video coding (MVC) is related to compression of any kind of pixel data, such as video, stereo video, multi-view video, but also associated per-pixel depth data, etc. It is a key technology serving a wide range of applications, such as free viewpoint video (FVV) and 3DTV. More precisely, MVC is characterized by efficient methods for source and channel coding for multi-view video and related data, as disparity maps and camera parameters.

A main focus of work during this reporting period was the development of the new MPEG standard for MVC. Participants from the NoE performed Core Experiments, provided reference software, edited standards documents, and chaired working groups. Several conference publications listed below are as well related to this work. Further research was focused error concealment for stereo, object-based MVC, streaming of MVC, and coding of multi-view depth data. In the following, abstracts regarding these topics are given, followed by an analysis of results, conclusions and future plans regarding this research topic.

2.1.1. Two Novel Methods for Full Frame Loss Concealment in Stereo Video

Authors: C. Bilen, A. Aksay, G. Bozdagi Akar

Institutions: METU

Publication: Picture Coding Symposium PCS'07 , Lisboa, Portugal, Nov. 2007.

Streaming media applications often suffer from packet losses in wired or wireless IP links. In order to get reasonable degree of quality in case of packet losses, it is necessary to have error concealment tools at the decoder. Even though several research has been done on monoscopic video, very few studies are found in the literature for stereoscopic error concealment. In this paper we propose novel full frame loss concealment algorithms for stereoscopic sequences. The proposed methods use redundancy and disparity between the two views and motion information between the previously decoded frames to estimate the lost frame. The results show that, the proposed algorithms outperform the monoscopic methods when they are applied to the same view as they are simulcast coded.

2.1.2. Low Bit-Rate Object-based Multi-view Video Coding using MVC

Authors: Andreas Krutz, Michael Droese, Matthias Kunter, Mrinal Mandal, Michael Frater**, and Thomas Sikora*

*Institutions: Technische Universitaet Berlin, *University of Alberta, Canada, **University of New South Wales, Australia*

Publication: 1st 3DTV-Conference 2007, Kos Island, Greece, 07 May 2007 - 09 May 2007.

Work is currently underway to develop a new multi-view video coding (MVC) standard, based on the recent H.264/AVC standard. Recent work has shown, however, that object-based video coding can provide higher performance than H.264, especially at low bit rates and in sequences containing rotating camera motion and moving objects in the foreground. In this paper, we propose an object-based extension to MVC, in which sequences are segmented into foreground and background objects, with each object coded using H.264/AVC for single-view sequences and MVC for multi-view sequences. Experimental results show that the object-based approach significantly outperforms the basic MVC at low bit rates.

2.1.3. Object-based Multiple Sprite Coding of Unsegmented Videos Using H.264/AVC

Authors: Matthias Kunter, Andreas Krutz, Michael Droese, Michael Frater, and Thomas Sikora*

*Institutions: Technische Universitaet Berlin, *University of New South Wales, Australia*

Publication: IEEE 14th International Conference on Image Processing (ICIP'07), San Antonio, Texas, USA, 16.-19. September, 2007

In spite of recent progress in the development of hybrid block-based video codecs, it has been shown that for low-bitrate scenarios there is still coding gain applying object-based techniques. We present a sprite-based codec, based on latest H.264 features using an in-built segmentation approach for scenes recorded by a rotating camera. The segmentation itself is built up on reliable background estimation from the sprite and short-term image registration. Moreover, we generate multiple sprites based on physical camera parameter estimation that overcome three of the main drawbacks of sprite coding techniques. First, the coding cost for the sprite image is minimized. Second, multiple sprites allow temporal background refresh and finally, registration error accumulation is kept very small. Experimental results show that this coding approach significantly outperforms latest H.264 extensions applying hierarchical B pictures.

2.1.4. Client-driven selective streaming of multi-view video for interactive 3DTV

Authors: E. Kurutepe, R. Civanlar, and A. M. Tekalp

Institutions: Koc University, Technische Universitaet Berlin

Publication: IEEE Trans. on Circ. and Syst. for Video Technology, vol. 17, no. 11, Nov. 2007

In spite of recent progress in the development of hybrid block-based video codecs, it has been shown that for low-bitrate scenarios there is still coding gain applying object-based techniques. We present a sprite-based codec, based on latest H.264 features using an in-built segmentation approach for scenes recorded by a rotating camera. The segmentation itself is built up on reliable background estimation from the sprite and short-term image registration. Moreover, we generate multiple sprites based on physical camera parameter estimation that overcome three of the main drawbacks of sprite coding techniques. First, the coding cost for the sprite image is minimized. Second, multiple sprites allow temporal background refresh and finally, registration error accumulation is kept very small. Experimental results show that this coding approach significantly outperforms latest H.264 extensions applying hierarchical B pictures.

2.1.5. Adaptive streaming of scalable stereoscopic video over DCCP

Authors: N. Ozbek, B. Gorkemli, A. M. Tekalp, and E. T. Tunali

Institutions: Koc University, Ege University

Publication: Proc. IEEE Int. Conf. Image Processing, San Antonio, Texas, Sept. 2007

We propose a new adaptive streaming model that utilizes DCCP in order to efficiently stream stereoscopic video over the Internet for 3DTV transport. The model allocates the available channel bandwidth, which is calculated by the DCCP, among the views according to the suppression theory of human vision. The video rate is adapted to the DCCP rate for each group of pictures (GoP) by adaptive extraction of layers from a scalable multi-view bitstream. The objective of the streaming model is to maximize perceived quality of the received 3D video while minimizing the number of possible display interrupts. Experimental results successfully demonstrate stereo video streaming over DCCP on wide area network.

2.1.6. Efficient Prediction Structures for Multiview Video Coding

Authors: P. Merkle, A. Smolic, K. Mueller, and T. Wiegand

Institutions: Fraunhofer HHI

Publication: Invited Paper, IEEE Transactions on Circuits and Systems for Video Technology, Special Issue on Multiview Video Coding and 3DTV, Vol. 17, No. 11, November 2007

An experimental analysis of multi-view video coding for various temporal and inter-view prediction structures is presented. The compression method is based on the multiple reference picture technique in the H.264/AVC video coding standard. The idea is to exploit the statistical dependencies from both temporal and inter-view reference pictures for motion-compensated prediction. The effectiveness of this approach is demonstrated by an experimental analysis of temporal versus inter-view prediction in terms of the Lagrange cost

function. The results show that most at the time prediction with temporal reference pictures is very efficient, but for 20% of a picture's blocks on average prediction with reference pictures from adjacent views is more efficient. Hierarchical B pictures are used as basic structure for temporal prediction. Their advantages are combined with inter-view prediction for different temporal hierarchy levels, starting from simulcast coding with no inter-view prediction up to full level inter-view prediction. When using inter-view prediction at key picture temporal level average gains of 1.4 dB PSNR are reported, while additionally using inter-view prediction at non-key picture temporal levels average gains of 1.6 dB PSNR are reported. For some cases gains of more than 3 dB, corresponding to bit-rate savings of up to 50%, are obtained.

2.1.7. Coding Efficiency and complexity analysis of MVC prediction Structures

Authors: P. Merkle, A. Smolic, K. Mueller, and T. Wiegand

Institutions: Fraunhofer HHI

Publication: Proc. EUSIPCO 2007, Poznan, Poland, European Signal Processing Conference, Poznan, Poland, September 3, 2007

Based on the idea to exploit the statistical dependencies from both temporal and inter-view reference pictures for motion compensated prediction, this paper presents a systematic evaluation of multi-view video coding with optimized prediction structures. The compression method is based on the multiple reference picture technique in the H.264/AVC video coding standard. The advantages of hierarchical B pictures for temporal prediction are combined with inter-view prediction for different temporal hierarchy levels, starting from simulcast coding with no inter-view prediction up to full level inter-view prediction. When using inter-view prediction at key picture temporal level average gains of 1.4 dB PSNR are reported, while additionally using inter-view prediction at non-key picture temporal levels average gains of 1.6 dB PSNR are reported. For some cases gains of more than 3 dB, corresponding to bit rate savings of up to 50%, are obtained.

2.1.8. Efficient Compression of Multi-view Depth Data Based on MVC

Authors: P. Merkle, A. Smolic, K. Mueller, and T. Wiegand

Institutions: Fraunhofer HHI

Publication: Proc. 3DTV-CON 2007, Kos Island, Greece, May 2007

This paper presents a method for efficient compression of multi-view depth data based on our multi-view video coding approach for color data. The idea is to exploit statistical dependencies from both temporal and inter-view reference pictures for prediction. For this purpose a multi-view video data set including color and depth information is analyzed in terms of coding efficiency. Coding experiments using prediction structures with and without inter-view reference pictures are performed with multi-view depth data and compared to

multi-view video coding. The results show that additionally applying inter-view prediction to temporal prediction with hierarchical B pictures improves coding efficiency for depth as well as color, reporting average gains in PSNR-Y of 0.5 dB for depth and 0.3 dB for color.

2.1.9. Compression of multi-view video and associated data

Authors: A. Smolic, P. Merkle, K. Muller, C. Fehn, P. Kauff, and T. Wiegand

Institutions: Fraunhofer HHI

Publication: In "Three-Dimensional Television: Capture, Transmission, and Display", Editors: Haldun M. Ozaktas and Levent Onural, Springer, Heidelberg, 2007

This chapter for the edited book gives an overview of the state-of-the-art in compression of multi-view video and associated data. 3DTV and FVV applications and systems are generally outlined. 3D scene representations suitable for this purpose are introduced. The main focus is then on compression of classical stereo video, video plus depth and multi-view video, explaining basic algorithms and results.

2.1.10. Multi-view video plus depth (MVD) format for advanced 3D video systems

Authors: A. Smolic, K. Mueller, P. Merkle, N. Atzpadin, C. Fehn, M. Mueller, O. Schreer, R. Tanger, P. Kauff, T. Wiegand, T. Balogh, Z. Megyesi, A. Barsi

Institutions: Fraunhofer HHI, Holografika

Publication: JVT-W100, San Jose, CA, USA, March 2007

The contribution proposes to initiate a study on how to support multi-view video plus depth (MVD) data efficiently by a coding standard. It illustrates advanced 3D video and free viewpoint video systems, and argues that these are not efficiently supported by available and emerging specifications, such as MPEG-C Part 3 and MVC. The central requirement of such technology is said to be an input data format that allows rendering a wide range continuum of views at the decoder. MVD is introduced and illustrated in some detail, being multi-view video with multiple associated per sample depth maps. It is claimed that MVD fulfills the above requirement and is therefore a suitable candidate for a basic format for advanced future 3DV and FVV systems. Finally, an initial work plan for the proposed investigation is presented.

2.1.11. MVC: Experiments on Coding of Multi-view Video plus Depth

Authors: P. Merkle, A. Smolic, K. Mueller, T. Wiegand

Institutions: Fraunhofer HHI

Publication: JVT-X064, Geneva, Switzerland, July 2007.

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A study on the video plus depth representation for multi-view video sequences is presented. Such a 3D representation enables functionalities like 3D television and free viewpoint video. Compression is based on algorithms for multi-view video coding, which exploit statistical dependencies from both temporal and inter-view reference pictures for prediction of both color and depth data. Coding efficiency of prediction structures with and without inter-view reference pictures is analyzed for multi-view video plus depth data, reporting gains in luma PSNR of up to 0.5 dB for depth and 0.3 dB for color. The main benefit from using a multi-view video plus depth representation is that intermediate views can be easily rendered. Therefore the impact on image quality of rendered arbitrary intermediate views is investigated and analyzed in a second part, comparing compressed multi-view video plus depth data at different bit rates with the uncompressed original.

2.1.12. Development of MPEG Standard for Multi-view Video plus Depth

Authors: MPEG, including Aljoscha Smolic, Karsten Müller, and others

Institutions: MPEG, including Fraunhofer HHI, and others

Publication:

San José, March 2007
N8944 FTV Model and Requirements

Lausanne, July 2007
N9168 Preliminary FTV Model and Requirements

Shenzhen, October 2007
N9466 Applications and Requirements of FTV
N9467 FTV Test Cases and Evaluation
N9468 Call for Contributions on FTV Test Sequences

These are working documents of MPEG for the development of a new standard to support multi-view video plus depth (MVD). This includes specifications of requirements, overall system architecture, test data and evaluation procedures. They have been prepared under the lead of and with strong influence from researchers of the NoE. The purpose is development an extended standard to support advanced 3DTV and FTV systems. The coding part may become an extension of MVC. The documents are not included in the annex.

2.1.13. Development of MPEG/VCEG Standard for Multiview Video Coding

Authors: JVT of ISO-MPEG and ITU-VCEG, including Aljoscha Smolić and others

Institutions: JVT of ISO-MPEG and ITU-VCEG, including Fraunhofer HHI and others

Publication:

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San Jose April 2007
JVT-W013 AHG Report: JMVM & JD text editing
JVT-W014 AHG Report: MVC exper. framework & test cond
N8966 Working Draft 3 of ISO/IEC 14496-10:2005/Amd.4 Multiview Video Coding
N8967 Joint Multiview Video Model (JMVM) 4
N8968 JMVM 4 Software

Geneva & Lausanne July 2007
JVT-X008 AHG Report: JMVM & JD text & software
JVT-X009 AHG Report: MVC exper. framework & test cond
N9163 Multiview Video Coding Requirements
N9213 Text of ISO/IEC 14496-10:200X / PDAM 1 Multiview Video Coding
N9214 Joint Multiview Video Model (JMVM) 5
N9215 JMVM 5 Software

Shenzen October 2007
JVT-Y007 AHG Report: JMVM & JD text & software
JVT-Y008 AHG Report: MVC exper. framework & test cond
N9445 Study Text of ISO/IEC 14496-10:200X/PDAM 1 Multiview Video Coding
N9446 Joint Multiview Video Model (JMVM) 6
N9447 JMVM 6 Software

Antalya, January 2008
N9596 Description of Exploration Experiments in 3D Video
N9595 Call for Contributions on 3D Video Test Material (Update)

These are working documents of MPEG and the JVT for the development of the MVC standard. This includes specifications (Working Draft, PDAM, JMVM), reference software, ad-hoc group reports, and requirements. They have been prepared under the lead of and with strong influence from researchers of the NoE. The work has been moved to the JVT of MPEG and VCEG, and the final standard is scheduled to be available in 2008. The documents are not included in the annex.

2.1.14. Analysis, conclusions, plans

The worldwide leading role of the NoE in the area of MVC was maintained and strengthened, both on the academic side as well as in standardization.

A researcher from the NoE is among the editors of the MVC standard, responsible for formulation of the standard text (PDAM, JMVM). He is also among the chairs of the related working groups. Leadership in the management of development of the MVC standard is continuing within the JVT of MPEG and VCEG. Algorithms for MVC developed and optimized in the NoE define the state-of-the-art and have been published for instance in an invited paper for IEEE Trans. on CSVT.

Proposals from other institutions outside the NoE have been evaluated in core experiments and partially integrated. There is a strong participation of companies and academic institutions especially from Asia but also from the US within this process, only few Europeans are active.

Technical work is focused on high-level syntax elements (e.g. for improved random access, buffer management, parallel processing), as well as on new coding tools (e.g. view interpolation prediction, illumination compensation, disparity vector prediction, MV direct mode).

In order to support advanced 3DTV and FTV systems more efficiently, a new activity was initiated in MPEG under leadership and strong influence from the NoE. The goal is to create a standard for compression of multi-view video plus depth (MVD) data. Basic pioneering research on compression of MVD has been done by partners, published at conferences and contributed to MPEG and the JVT.

One main focus of research in WP9 during the last year will therefore be compression of MVD data and maybe also layered depth video (LDV). LDV is an alternative to MVD to provide advanced 3DTV and FTV functionality, which is favored for instance by Philips.

Since MVC technology is maturating streaming is coming increasingly into focus. Institutions from the NoE performed groundbreaking research in this area that was published for instance in IEEE Trans. on CSVT. Error concealment for transmission over error prone channels has been investigated successfully as well.

Finally, ideas from object-based video coding have been extended successfully to multi-view, i.e. different parts of images are coded with specific algorithms such as sprites. To our knowledge such research was performed for the 1st time worldwide within the NoE. Object-based approaches have an immense potential to further increase coding efficiency compared to frame-based algorithms, however, applicability may be restricted. This will be investigated further in more detail.

Regarding a roadmap for future R&D, 3 main areas can be identified, MVC, MVD for automultiscopic displays and MVD for free viewpoint video. Those relate roughly to short-, mid- and long-term research, although optimization and improvement will be possible in all areas. Each of them includes development of algorithms, standardization and implementation in products and services.

The following table gives a roadmap for MVC. The 1st version of the standard will be available most probably in July 2008, which will be based on combined inter-view/temporal prediction as developed in the NoE. Implementation of products and services is on the way already. Further optimization and development of MVC algorithms is on the way and may continue. Some coding tools known to be under development are listed below. However, a 2nd version of the standard is currently not planned.

Roadmap: Multi-view Video Coding (MVC)

1st standard • Combined inter-view/temporal prediction	July 2008
Development and optimization of algorithms, coding tools • Illumination compensation • View interpolation prediction	continuing

• Disparity compensation • Motion skip • Mixed resolution stereo coding • Background sprites	
2nd version of standard	not planned
Implementation in products and services	from July 2008

A roadmap for MVD coding for automultiscopic displays enabling advanced 3DTV systems is given in the following table. Development and optimization of algorithms such as depth estimation, coding of depth and color video, depth image based rendering (DIBR) is on the way. First mature results are expected by the end of 2008. Standardization is expected to start with a "Call for Proposals" of MPEG in early 2009. such a standard may be finalized in a 1st version in 2011. Implementation in products and services may start at the same time.

Roadmap: MVD coding for automultiscopic displays

Development and optimization of algorithms • Depth estimation • Depth and color video coding • Depth image based rendering (DIBR)	1st version until end 2008 continuing after
Starting standardization, "Call for Proposals" in MPEG	early 2009
1st standard	2011
Implementation in products and services	from 2011

A roadmap for the most visionary topic being free viewpoint video is shown in the next table. In this case all dates are shifted further into the future.

Roadmap: MVD coding for free viewpoint video

Development and optimization of algorithms • Depth estimation • Depth and color video coding • Depth image based rendering (DIBR)	1st version until end 2010 continuing after
Starting standardization, "Call for Proposals" in MPEG	early 2011
1st standard	2013
Implementation in products and services	from 2013

2.2. 3D mesh compression

This research group is dealing with aspects of compression of static and dynamic 3D meshes. 3D meshes are a common form of representation for 3D objects. They are used in scene description languages like VRML97, X3D or MPEG-4 BIFS and their rendering and texturing is supported by a lot of multimedia hardware. Recently, even mobile devices like smartphones are equipped with graphics chips which support rendering of 3D meshes. Such developments further the dissemination of static and dynamic 3D content. Developments like this stimulate not only a permanent improvement of existing applications, but they facilitate the development of new applications, like 3DTV. Compression of static and dynamic 3D content gets crucial importance in this context.

Research in dynamic 3D mesh compression was continued during the third period. The main focus was now on the

- Optimization of the predictive coder for dynamic meshes developed in the previous two research periods in order to improve its compression efficiency and to support temporal and spatial scalability.

- Development of a second predictive coder based on PCA.

The first coder was successfully proposed within MPEG for a standard on compression of dynamic 3D meshes. Researchers form this NoE made proposals in MPEG, performed core experiments, provided reference software and conformance bit streams, and edited standards documents. A great part of this forthcoming standard, which will be referred to as MPEG-4, Part 16, Amendment 2, is contributed by NoE partners.

All together the following prospective topics were covered during the third period:

- Extension of the first coder in order to support temporal and spatial scalability (support of hierarchical B-frames and spatial layers)

- Improvement of the compression performance of the first coder using CABAC

- Active contribution in the standardization within MPEG in the area of compression of dynamic 3D meshes

- Development and evaluation of the second (PCA-based) coding approach.

All the work performed in the third research period is reflected in the following documents.

2.2.1. Layered Coding of Time-Consistent Dynamic 3D Meshes Using a Non-Linear Predictor

Authors: Nikolce Stefanoski, Patrick Klie, Xiaoliang Liu, Jörn Ostermann,

Institutions: Leibniz Universität Hannover

Publication: ICIP '07 - IEEE International Conference on Image Processing, San Antonio, September 2007

We present a layered predictive compression approach for time-consistent dynamic 3D meshes. The algorithm decomposes each frame of a dynamic 3D mesh in layers employing patch-based mesh simplification techniques. This layered decomposition is consistent in time. Following the predictive coding paradigm, local temporal and spatial dependencies between layers and frames are exploited for compression. Prediction is performed vertex-wise from coarse to fine layers exploiting local linear and non-linear dependencies between vertex locations for compression. It is shown that a non-linear predictive exploitation of the proposed layered configuration of vertices can improve the compression performance upon other state-of the-art approaches by more than 15% in domains relevant for applications.

2.2.2. CoDDyAC: Connectivity Driven Dynamic Mesh Compression

Authors: Libor Vasa and Vaclav Skala

Institutions: University of West Bohemia

Publication: 3DTV Conference Proceedings, 2007.

In this paper we present an improved approach for dynamic mesh compression based on known techniques, such as principal component analysis (PCA) and EdgeBreaker, which allows efficient encoding of highly detailed dynamic meshes, exploiting both spatial and temporal coherence. We present the results of our method compared with similar approaches described in literature, showing that using our approach we can achieve better performance in terms of rate/distortion ratio.

2.2.3. STAR: Dynamic Mesh Compression

Authors: K. Mamou, N. Stefanoski, L. Vasa, T. Zaharia, F. Prêteux, J. Ostermann, V. Skala

Institutions:
Institut National des Télécommunications, France,
Leibniz Universität Hannover, Germany,
University of West Bohemia, Czech Republic.

Publication: submitted to Eurographics 2008, Crete, Greece, 2008

This STAR we will provide an overview of the state-of-the-art techniques recently developed within the emerging field of dynamic mesh compression. Four families of approaches, including local spatio-temporal predictive techniques, wavelet-based schemes, PCA-based approaches, and clustering-based representations are considered, presented, analyzed, and objectively compared. Comparison is carried out in terms of compression efficiency, algorithmic and computational aspects, field of applicability, and offered functionalities (streaming, progressive transmission, scalable rendering...). A special attention will be given to the current situation in the standardization of the dynamic mesh compression, which is conducted by the ISO/MPEG group.

2.2.4. Frame-Based Compression of Animated Meshes in MPEG-4

Authors: K. Mamou, N. Stefanoski, T. Zaharia, J. Ostermann, F. Prêteux,

Institutions:
Institut National des Télécommunications, France,
Leibniz Universität Hannover, Germany,

Publication: submitted to ICME 2008, Hannover, Germany, 2008

This paper presents a new compression technique for 3D dynamic meshes, referred to as FAMC - Frame-based Animated Mesh Compression, recently promoted within the MPEG-4 standard as Amendement 2 of part 16 AFX (Animation Framework eXtension).

The FAMC approach combines a model-based motion compensation strategy, with transform/predictive coding of residual errors. First, a skinning model is automatically computed from a frame-based representation and then encoded within the bitstream in order to be exploited for motion compensation. Subsequently, either 1) DCT/lifting wavelets or 2) layer-based predictive coding is employed to exploit remaining spatio-temporal correlations.

The proposed encoder offers high compression performances (gains in bitrate of 60% with respect to the previous MPEG-4 technique and of 20 to 40% with respect to state-of-the-art approaches) and is well suited for compressing both geometric and photometric (normal vectors, colors...) attributes. In addition, the FAMC method supports a rich set of functionalities including streaming, scalability (spatial, temporal and quality) and progressive transmission.

2.2.5. Scalable Compression of Dynamic 3D Meshes

Authors: Nikolce Stefanoski, Jörn Ostermann,

Institutions: Leibniz Universität Hannover

Publication: ISO/IEC JTC1/SC29/WG11, Doc M14363, San Jose, USA, 2007

In this document we propose a method for predictive compression of time-consistent 3D mesh sequences supporting and exploiting scalability. The applied method decomposes each frame of a mesh sequence in layers, which provides a time-consistent multi-resolution representation. Following the predictive coding paradigm, local temporal and spatial dependencies between layers and frames are exploited for compression. Prediction is performed vertex-wise from coarse to fine layers exploiting the motion of already encoded neighboring vertices for prediction of the current vertex location. It is shown that a predictive exploitation of the proposed layered configuration of vertices can improve the compression performance in domains relevant for applications.

2.2.6. Frame-based Animated Mesh Compression: integration of the CABAC arithmetic encoder

Authors: K. Mamou, D. Marpe, K. Müller, T. Zaharia, F. Prêteux

Institutions: Fraunhofer HHI, INT France

Publication: ISO/IEC JTC1/SC29/WG11, MPEG07/M14493, San Jose, CA, USA, March 2007

This proposal describes an approach of integrating CABAC into the FAMC technology. As will be shown by experimental results, this proposed enhancement of FAMC results in average bit-rate savings of around 16% when compared to the current WD. At the same time, by replacing the N-ary adaptive arithmetic coder in the current WD by the fast multiplication-free M coder, as being an integral part of CABAC, computational complexity will be reduced.

2.2.7. Proposed Modifications to Residual Coding Part of Frame-based Animated Mesh Compression

Authors: H. Kirchhoffer, D. Marpe, K. Mamou, K. Müller, T. Wiegand

Institutions: Fraunhofer HHI, INT France

Publication: ISO/IEC JTC1/SC29/WG11, MPEG07/M14697, Lausanne, Switzerland, July 2007.

In this document, we propose a set of modifications to improve the current Working Draft of Frame-based Animated Compression (FAMC). The objectives of our investigations are aligned with those of CE 1, where potential improvements on the recently adopted integration of CABAC into FAMC were discussed.

Our present study is focused on the DCT-based encoding/decoding part for coordinate residual errors only. We propose a set of normative changes related to the following issues:

- Representation and coding of predictors
- Representation and coding of significance maps
- Binarization schemes for absolute values of transform coefficients

In addition, we propose an improved non-normative encoding method for selecting the best predictor in a rate-minimizing sense.

2.2.8. FAMC Decoder Conformance

Authors: K. Mamou, H. Kirchhoffer, N. Stefanoski, D. Marpe, K. Müller, J. Ostermann, T. Zaharia, F. Prêteux

Institutions: INT France, Fraunhofer HHI, Universität Hannover

Publication: ISO/IEC JTC1/SC29/WG11, MPEG07/M14936, Shenzhen, China, Oct. 2007

This contribution presents the conformance tests for the FAMC decoder.

2.2.9. FAMC Decoder Software Description

Authors: K. Mamou, H. Kirchhoffer, N. Stefanoski, D. Marpe, K. Müller, J. Ostermann, T. Zaharia, F. Prêteux

Institutions: INT France, Fraunhofer HHI, Universität Hannover

Publication: ISO/IEC JTC1/SC29/WG11, MPEG07/M14934, Shenzhen, China, Oct. 2007

This contribution presents the FAMC decoder software with the list of source files and description of corresponding classes.

2.2.10. A survey on coding of static and dynamic 3D meshes

Authors: A. Smolic, R. Sondershaus, N. Stefanoski, L. Vasa, K. Mueller, J. Ostermann, and T. Wiegand

Institutions: Fraunhofer HHI, University of Tuebingen, Universität Hannover, Plzen University

Publication: In "Three-Dimensional Television: Capture, Transmission, and Display". Editors: Haldun M. Ozaktas and Levent Onural, Springer, Heidelberg, 2007

In this chapter we survey recent developments in the area of compression of static and dynamic 3D meshes. In an introductory section we give a definition of meshes and define terms and notations related to meshes. Furthermore, we give an overview to coding techniques in general and describe the principles of mesh compression algorithms at a very informative level. The following two sections give an overview on single rate and progressive coding techniques for static and dynamic meshes, explaining them in more detail pointing out the main ideas of each encoding approach. We conclude each section with a discussion providing an overall picture of developments in the mesh coding area, highlighting advantages and disadvantages of presented approaches, and pointing out directions for feature research.

2.2.11. Connectivity-Guided Adaptive Wavelet Transform For Image-Like Compression of Meshes

Authors: Kivanc Kose, A. Enis Cetin, Ugur Gudukbay, Levent Onural

Institutions: Bilkent University

Publication: 3DTV Conference 2007

We propose a new connectivity-guided adaptive wavelet transform based mesh compression framework. The 3D mesh is first transformed to 2D images on a regular grid structure by

performing orthogonal projections onto the image plane. Then, this image-like representation is wavelet transformed using a lifting structure employing an adaptive predictor that takes advantage of the connectivity information of mesh vertices. Then the wavelet domain data is encoded using "Set Partitioning In Hierarchical Trees" (SPIHT) method or JPEG2000. The SPIHT approach is progressive because the resolution of the reconstructed mesh can be changed by varying the length of the 1D data stream created by the algorithm. In JPEG2000 based approach, quantization of the coefficients determines the quality of the reconstruction. The results of the SPIHT based algorithm is observed to be superior to JPEG200 based mesh coder and MPEG-3DGC in rate-distortion.

2.2.12. 3D Model Compression using Connectivity-guided Adaptive Lifting Transform

Authors: Kivanc Kose, A. Enis Cetin, Ugur Gudukbay, Levent Onural

Institutions: Department of Electrical and Electronics Engineering, Bilkent University, Department of Computer Engineering, Bilkent University

Publication: Signal Processing and Communications Applications 2007, SIU 2007, IEEE 15th

Two compression frameworks that are based on a Set Partitioning In Hierarchical Trees (SPIHT) and JPEG2000 methods are proposed. The 3D mesh is first transformed to 2D images on a regular grid structure. Then, this image-like representation is wavelet transformed employing an adaptive predictor that takes advantage of the connectivity information of mesh vertices. Then SPIHT or JPEG2000 is applied on the wavelet domain data. The SPIHT based method is progressive because the resolution of the reconstructed mesh can be changed by varying the length of the one-dimensional data stream created by SPIHT algorithm. The results of the SPIHT based algorith is observed to be superior to JPEG200 based mesh coder and MPEG-3DGC in rate-distortion.

2.2.13. Development of MPEG Standard for Frame Based Animated Mesh Compression (FAMC)

Authors: MPEG, including Nikolce Stefanoski, Jörn Ostermann, Karsten Müller and others

Institutions: MPEG, Leibniz Universität Hannover, Frauenhofer HHI and others

Publication:

San Jose, April 2007
M14363 Scalable Compression of Dynamic 3D Meshes
M14493 Frame-based Animated Mesh Compression: integration of the CABAC arithmetic encoder
N9138 3D Graphics Core Experiments Description

Lausanne, July 2007
M14652 FAMC's layer-based scalable extension

M14653 FAMC: bitstream description for the layer-based scalable extension
M14654 FAMC with progressive transmission and scalable rendering functionalities
M14697 Proposed Modifications to Residual Coding Part of Frame-based Animated Mesh Compression
N9259 Request for Amendment of ISO/IEC 14496-4:2004 (FAMC Conformance)
N9264 Request for Amendment of ISO/IEC 14496-5:2001 (FAMC RefSoft)
N9266 Text of ISO/IEC 14496-16:2006/PDAM2 (Frame-based Animated Mesh Compression)

Shenzhen, October 2007
M14891 Proposed corrections and changes to ISO/IEC 14496-16:2006/PDAM2 (FAMC)
M14934 FAMC decoder software description
M14936 FAMC decoder conformance
M15028 German National Body comments on ISO/IEC 14496-16:2006/PDAM2 (FAMC)
N9494 AHG on 3DG documents, experiments and software maintenance
N9528 PDAM of ISO/IEC 14496-4:2004 AMD32 (FAMC Conformance)
N9532 PDAM of ISO/IEC 14496-5:2001 AMD21 (FAMC RefSoft)
N9535 Study on Text of ISO/IEC 14496-16:2006/PDAM2 (Frame-based Animated Mesh Compression)

These are working documents of MPEG for the development of a standard for compression of dynamic meshes. Within MPEG this standard is referred to as “Frame-Based Animated Mesh Compression”. The documents listed above include description of core experiments, specifications (Working Draft, PDAM), reference software, conformance bit streams, ad-hoc group reports as well as other reports and documents. They have been prepared under the lead of and with strong influence from researchers of the NoE. The final standard is scheduled to be available in July 2008. The documents are not included in the annex. The final standard will be referred to as ISO/IEC 14496-16, Amendment 2, Frame-Based Animated Mesh Compression.

2.2.14. Analysis, conclusions, plans

In these documents techniques were investigated with the aim to improve the existing predictive coder developed in the previous two research periods. A second coder was developed, too, in order to examine the compression efficiency of PCA-based compression approaches for dynamic 3D meshes.

During the third research period the first coder was extended in order to support temporal scalability (additionally to spatial scalability, which was introduced during the second research period). For this hierarchical B-frames were employed, which allow to exploit dependencies of the current frame to two other already encoded reference frames. This extension of the coder with hierarchical B-frames allows an increase in compression performance because of more accurate prediction. On other hand it provides temporal scalability, due to the hierarchical ordering of B-frames during encoding. This work is reflected in document 2.2.1.

Researchers from this NoE had strong influence in the development of a forthcoming standard on compression of dynamic 3D meshes in MPEG. UHANN proposed a predictive coder for standardization in MPEG, which was developed within this NoE. This coder is described in

documents 2.2.1, 2.2.4, and 2.2.5. HHI proposed in MPEG an optimization of the residual coding part of the coder based on CABAC, which is described in documents 2.2.7 and 2.2.6. Both proposals were accepted after an evaluation process by performing core experiments. UHANN and HHI contributed with their proposals in great part to the development of the forthcoming standard, which will be an amendment to MPEG-4 AFX standard referred to as ISO/IEC 14496-16:2006/Amd.2, Frame-based Animated Mesh Compression. In the standardization process, which is not yet finished, are participating companies and academic institutions from Europe, USA, and Asia. The finalization of the standard is scheduled for July 2008. In the standardization process researches from this NoE contributed also in writing of the reference software (2.2.9), producing of conformance bit streams (2.2.8), refining the text of the standard, and editing several other documents. The complete development chain in the standardization process until now, with contributions of researches from this NoE, is shown in 2.2.13.

During an exchange of researches in collaboration between Pilzen and UHANN ideas were developed for a predictive coder performing prediction on PCA coefficients. During the third research period the corresponding coder was developed and examined. Results of this work are presented in document 2.2.2.

In future we plan to optimize the first encoder in order to exploit the full syntax of the standard for more efficient compression of dynamic meshes. For instance, the standard supports the encoding of simplification operations, which is not yet exploited in the encoder of the reference software in order to increase the compression performance. During the forth research period we intend to develop an encoder, which encodes simplification operations in manner, which enables smoother spatial scalability and an increase in compression performance. Furthermore, the applicability of the developed coder for compression of depth maps (as they are used in Multi-View Video + Depth coding) will be examined. Researches from this NoE will continue to actively contribute in the preparation of the standard in MPEG until its finalization.

Roadmaps for coding of static and dynamic 3D meshes are shown below. The AFX amendment for dynamic mesh coding will be ready in October 2008. In future it will be evaluated if mesh based compression approaches are applicable for compression of depth video. Furthermore, the encoder for compression of dynamic meshes will be further improved and extended so support compression of textured dynamic meshes.

Roadmap: Coding of Dynamic 3D Meshes

Finalization of the amendment to MPEG-4 AFX for compression of dynamic meshes	October 2008
Evaluation of the applicability of mesh based coding techniques for compression of depth video.	2009 - ?
Development and optimization of algorithms for • More efficient compression of dynamic meshes • Compression of textured dynamic meshes • Compression of multiple texture coordinates	continuing

• Mesh based compression of depth video (opt.)	
Implementation in products and services	from 2011

Work on a new standard for low-complexity static mesh coding is just starting. Implementation in products such as mobile phones is on the way.

Roadmap: Coding of Static 3D Meshes

Call for low-complexity static mesh coding (for mobile devices) in MPEG	January 2008
Implementation of Graphics player on mobile devices (starting with Nokia N93 and Nokia N95)	from January 2008
1st standard on low-complexity static mesh coding	2009
Implementation in products and services	from 2010

2.3. Multiple description coding (MDC) for 3D

When the compressed 3D data content is to be transmitted over error-prone channels, error resilience tools has to be applied in order to ensure robust transmission. In general, error resilience methods rely on adding some controlled amount of redundancy to the effectively compressed data in order to make it more robust to channel errors.

During the third year of joint research activities, the research team continued to study multiple description coding (MDC) as a promising error resilience approach for 3D data. Recall some of the plans sketched after the second period: '*to consider more advanced channel model and packetization strategies which better emulate the behavior of a real network and further investigate tree grouping strategies*'. Following this direction, the techniques for error-resilient transmission of 3D compressed meshes, suggested during the second period, were further developed and improved. The previously developed MDC of 3D geometry with error correction codes, evolved to an FEC scheme employing Reed-Solomon codes for specific transmission channels. Its study put the transmission channels in focus, thus making a bridge between the research problems addressed by WP9 and WP10.

In addition, all previously developed MDC techniques were put together in a book chapter to emphasize their relevance to 3DTV.

2.3.1. Packet loss resilient transmission of 3D models

Authors: Mehmet Oguz Bici, Andrey Norkin, Gozde Bozdagi Akar.

Institutions: Middle East Technical University, Tampere University of Technology

Publication: in Proc. IEEE Int. Conf. Image Processing (ICIP) 2007, San Antonio, USA, Sept. 2007.

This paper presents an efficient joint source-channel coding scheme based on forward error correction (FEC) for three dimensional (3D) models. The system employs a wavelet based zero-tree 3D mesh coder based on Progressive Geometry Compression (PGC). Reed-Solomon (RS) codes are applied to the embedded output bitstream to add resiliency to packet losses. Two-state Markov channel model is employed to model packet losses. The proposed method applies approximately optimal and unequal FEC across packets. Therefore the scheme is scalable to varying network bandwidth and packet loss rates (PLR). In addition, Distortion-Rate (D-R) curve is modeled to decrease the computational complexity. Experimental results show that the proposed method achieves considerably better expected quality compared to previous packet-loss resilient schemes.

2.3.2. An efficient joint source-channel coding system for 3D models

Authors: Mehmet Oguz Bici, Andrey Norkin, Gozde Bozdagi Akar.

Institutions: Middle East Technical University, Tampere University of Technology

Publication: Submitted to Image and Vision Computing

This paper presents an efficient joint source-channel coding system for three dimensional (3D) models. The system is based on unequal protection of embedded bitstream with FEC codes. To produce the embedded bitstream, the system employs a subdivision based zero-tree 3D mesh coder utilizing Progressive Geometry Compression. A two-state Markov channel model is employed to model packet losses. The proposed method applies approximately optimal and unequal FEC across packets. Therefore the scheme is scalable to varying network bandwidth and packet loss rates (PLR). Experimental results show that the proposed method achieves significantly higher quality compared to the previous packet-loss resilient schemes based on Compressed Progressive Meshes.

2.3.3. Multiple description coding and its relevance to 3DTV

Authors: Andrey Norkin, Mehmet Oguz Bici, Anil Aksay, Cagdas Bilen, Atanas Gotchev, Gozde Bozdagi Akar, Karen Egiazarian, Jaakko Astola.

Institutions: Tampere University of Technology, Middle East Technical University

Publication: chapter in edited book "Three-Dimensional Television: Capture, Transmission, and Display", Editors: H. M. Ozaktas and L. Onural, Springer, Heidelberg, 2007.

This chapter discusses multiple description coding and its relevance to 3DTV. The motivation for using multiple description coding in 3DTV arises from vulnerability of the compressed bitstream in case of channel errors and erasures and the increasing amount of data when transmitting compressed stereoscopic and multi-view video over error-prone channels. As a prominent error resilience approach, multiple description coding developed from an information-theoretic problem to practical coding techniques for various compressed data.

The book chapter has been structured in a way to acknowledge this development. Section 1 addresses the MDC information-theoretic basics. Namely, it reviews the studies on the rate distortion region for multiple descriptions. The knowledge of such region for different information sources can be used to evaluate the performance of MDC designs. Section 2 and Section 3 survey MDC approaches for images and video, which can be successfully applied to 3DTV as well. In particular, Section 2 addresses the problem of adding controllable redundancy to the compressed image. Such redundancy can be added at any of the typical stages of the image coding chain, namely, the transform stage, quantization stage, or even at the preprocessing stage or the channel coding stage. Section 3 addressed the MDC of video, as an inherently more complicated problem than MDC for images. Two general groups of video coders and related problems are distinguished: motion-compensated (MC) coders, and coders based on 3D transforms. A number of works on both groups is reviewed and analyzed.

MDC approaches for images and video can be applied directly or in a modified form to multi-view or 3D-mesh data. In addition, MDC of multi-view video and 3D-meshes exploit the '3D-type' of redundancy inherently present in these data. Section 4 introduces MDC of stereoscopic video and relates it with single-view video approaches. It is identified that approaches based on temporal subsampling are readily applicable to MDC of stereoscopic and multi-view video. Two techniques of MDC of stereoscopic video are discussed in details. They both produce balanced descriptions and provide drift-free stereoscopic reconstruction with acceptable quality in the case of one channel failure for the price of moderate, in the range of 10-50%, redundancy.

In Section 5, three MDC techniques for 3D geometry coding are discussed and compared. The so-called TM-MDC and MDSQ-based methods use the *progressive geometry compression* approach, thus achieving high compression ratios for highly detailed 3D meshes. The Partitioning Vertex Geometry method is expected to perform competitively for 3D meshes with small number of vertices. The advantage of the TM-MDC method is in its ability to create more than two descriptions. This method can also be flexibly adapted to varying channel bandwidth and channel error rate. The rate-distortion curve modeling used in TM-MDC significantly decreases the number of computations, making it possible to efficiently exploit this method in practical applications.

2.3.4. Multiple Description Coding of Visual Information

Authors: Andrey Norkin

Institutions: Tampere University of Technology

Publication: PhD Thesis, 2007

Nowadays, image and video compression are well developed fields of signal processing. Modern state-of-the-art coders allow better compression with better quality. A new field in signal processing is representation of 3D scenes. 3D visual scenes may be captured by stereoscopic or multi-view camera settings. The captured multi-view video can be compressed directly or converted to more abstract 3D data representations such as 3D dynamic meshes (mesh sequences) and efficiently compressed. In any case, efficiently compressed visual data has to be transmitted over communication channels, such as wireless channels or best-effort

networks. This raises the problem of error protection, since most of these channels are error-prone.

A common approach to error protection is to consider it as a pure channel problem, separate from the source compression problem. This approach is based on Shannon's work, which states that in principle source and channel coding tasks can be carried out independently with no loss of efficiency. However, this cannot be achieved in practice due to delay requirements and other problems. As an alternative, one can tolerate channel losses. Assuming that not all the data sent has reached the decoder, one can concentrate on ensuring efficient decoding of the correctly received data only. One way to achieve this is to use multiple description coding (MDC). The source is encoded into several descriptions, which are sent to the decoder independently over different channels. The decoder can reconstruct the source with lower yet acceptable quality from any description received. Better reconstruction quality is obtained from more descriptions.

This thesis investigates MDC of images, video, stereoscopic video, and 3D meshes thus validating MDC as an error resilience tool for various types of multimedia data. The thesis consists of four main chapters.

Chapter 2 deals with MDC of images. It introduces an MDC algorithm based on a 2-stage compression scheme employing B-spline-based image resizing which is used to split the image into the coarse and residual parts. The coarse part is included in both descriptions while the residual part is split into two parts. A bit allocation algorithm optimizes the scheme for a given bit budget and probability of description loss.

Chapter 3 addresses MDC of video. It presents a 3D-transform-based MD video coder targeted for mobile devices. The encoder has low computational complexity and the compressed video is robust to transmission errors. The chapter estimates the scheme's encoding complexity and introduces an optimization procedure which minimizes the expected reconstruction distortion subject to the packet loss rate.

In Chapter 4, MDC of stereoscopic video is addressed. Two MDC schemes are introduced, one based on spatial scaling and another based on temporal subsampling. A switching criterion makes it possible to decide, which scheme is more advantageous for the sequence being encoded.

Chapter 5 discusses MDC of 3D meshes. It introduces two MDC approaches for coding highly detailed 3D meshes. The schemes are able to produce multiple descriptions and are easily adaptable to changing packet loss rate and bit budget. The proposed D-R curve modeling significantly decreases computational load at the preparatory stage.

2.3.5. Analysis, conclusions, plans

In contrast to the first and the second periods of research, when rather general schemes were developed, during the third period more specific solutions have been targeted. The previously developed MD-FEC scheme for 3D meshes, employing wavelet/SPIHT progressive geometry compression, has been improved and adapted to the transmission over packet networks. The packet losses have been modeled by two-state Markov model. The core of the new scheme is

an unequal FEC, where stronger FEC is allocated to the beginning of the SPIHT stream, while less or no FEC bits are allocated to the end of the bit-stream. Scalability with respect to both channel bandwidth and packet loss rate has been achieved. The experimental results have shown significantly better performance of the proposed method compared to previous packet-loss resilient schemes. The method has been also tested for the mismatch scenarios when the "real" packet loss rate is different from the one the encoder had been optimized for. The simulation results indicate the necessity of more robust bitstream protection when the packet loss conditions are varying or uncertain.

A book chapter has summarized the research about how MDC approaches can provide error robustness to 3D visual data. Theoretical aspects of MDC, such as the rate-distortion bounds, have been considered first, in order to emphasize the trade-off between coding efficiency and error-resilience. MDC approaches for images and video have been described within the context of their adaptivity to 3D data protection. The book-chapter has also presented two novel approaches for MDC of stereo-video and three approaches for MDC of 3D meshes. Some of the proposed approaches are based on adapted MDC approaches for image and video while others, such as TM-MDC, have exploited 3D-genuine types of redundancy.

During the third research period, the study of MDC for stereo and multi-view video has been somehow disregarded due to the reached general maturity of such methods and because of engaging the available resources in mesh-related research. However, the developed methods for stereo and multi-view video should be studied for their performance while applied to real transmission channels. Packetization strategies adaptable to the behavior of real networks should be studied as well. Future research on error-resilient transmission of 3D meshes shall include over-complete frame expansions. A roadmap for MDC for 3D is shown in the next table.

Roadmap: MDC for stereo and MVC

• Generalization of MDC for stereo video to MVC;	September 2008
• Optimization of algorithms related with visual perception;	Second half of 2009

Roadmap: MDC for meshes

• Optimization of index assignments in MDSQ	June 2008
• Optimization of MDC and FEC; • Stude the relevance of Raptor codes to MDC	continuing

2.4. Watermarking for 3D

The utilization of 3D information for the modeling and representation of a real world scene brings copyright problems by itself for the content providers. 3D watermarking is proposed as

a solution to the copyright problems of 3D information by means of embedding a secret imperceptible signal, called watermark, into the main components of a 3-D representation and extracting the watermark from the resulting components of a scene after any applications.

Considering the dimensions of the main components of scene representations and the resulting components after the application of the algorithm, the watermarking methods can be classified into three groups, which we denote as 3D/3D, 3D/2D, and 2D/2D. The first pair of symbols identifies whether the watermark is embedded in the 3D model or a 2D rendering of it, and similarly the second pair of symbols identifies whether the watermark is detected in the 3D model or a 2D rendering.

3D/3D Watermarking

The first group, 3D/3D watermarking, mostly focuses on protection of the intellectual property rights of the 3D geometrical structure. The watermark is embedded into the 3-D geometric structure of an object used in a scene and tried to be extracted from the 3-D geometry after any attacks on the geometry

3D/2D Watermarking

The second group, 3D/2D watermarking, aims to extract the watermark that was originally hidden in the 3D object, from the resulting images or videos (obtained after projection of 3D object into 2D image planes), thus protecting any visual representation of the object. The watermark can be both embedded to the geometry or the texture of the object

2D/2D Watermarking

The final group, 2D/2D watermarking, try to protect the image-based representation of a 3D scene. While the first two groups try to protect the intellectual property rights for the two important components of a traditional representation of a 3D scene, geometry and texture, the third group approaches to this problem, by watermarking sequences of images, which represent the 2D projections of the same 3D scene, and extracting the watermark from any 2D rendered image, generated for an arbitrary angle of the scene via these sequences. An application of this category should be expected in the copyright protection of multiview video content in emerging new technologies such as free view televisions (FTV) where the TV-viewers freely select the viewing position and angle for the transmitted multiview video.

In this context and since 3D watermarking can still be accepted to be immature (although the great number of applications in which 3D content is utilized and consumed), the 3DTV NoE research group on 3D watermarking worked together examining and presenting new 3D watermarking techniques: First, a PhD Thesis has been written on the watermarking techniques for different 3D representations. Several methods are proposed and evaluated in 3D/3D and 3D/2D watermarking while the thesis is focused on the watermarking problem for the emerging free-view televisions (FTV). A book chapter is also edited with a rigorous literature survey on 3D watermarking techniques. Finally several papers were presented dealing with important issues in 3D watermarking such as: watermarking for free-view television, watermarking for image-based rendering via homography-based virtual camera location estimation and best watermarking selection for free-view point television.

2.4.1. PhD Thesis: Watermarking For 3D Representations

Authors: Alper Koz

Institutions: Middle East Technical University

Publication: PhD Thesis

In this thesis, a number of novel watermarking techniques for different 3D representations are presented. A novel watermarking method is proposed for the monoview video, which might be interpreted as the basic implicit representation of 3D scenes. The proposed method solves the common flickering problem in the existing video watermarking schemes by means of adjusting the watermark strength with respect to temporal contrast thresholds of human visual system (HVS), which define the maximum invisible distortions in the temporal direction. The experimental results indicate that the proposed method gives better results in both objective and subjective measures, compared to some recognized methods in the literature.

The watermarking techniques for the geometry and image based representations of 3D scenes, denoted as 3D watermarking, are examined and classified into three groups, as 3D-3D, 3D-2D and 2D-2D watermarking, in which the pair of symbols identifies whether the watermark is embedded-detected in a 3D model or a 2D projection of it. A detailed literature survey on 3D-3D watermarking is presented that mainly focuses on protection of the intellectual property rights of the 3D geometrical representations. This analysis points out the specific problems in 3D-3D geometry watermarking , such as the lack of a unique 3D scene representation, standardization for the coding schemes and benchmarking tools on 3D geometry watermarking.

For 2D-2D watermarking category, the copyright problem for the emerging free-view televisions (FTV) is introduced. The proposed watermarking method for this original problem embeds watermarks into each view of the multi-view video by utilizing the spatial sensitivity of HVS. The hidden signal in a selected virtual view is detected by computing the normalized correlation between the selected view and a generated pattern, namely rendered watermark, which is obtained by applying the same rendering operations which has occurred on the selected view to the original watermark. An algorithm for the estimation of the virtual camera position and rotation is also developed based on the projective planar relations between image planes. The simulation results show the applicability of the method to the FTV systems.

Finally, the thesis also presents a novel 3D-2D watermarking method, in which a watermark is embedded into 3-D representation of the object and detected from a 2-D projection (image) of the same model. A novel solution based on projective invariants is proposed which modifies the cross ratio of the five coplanar points on the 3D model according to the watermark bit and extracts the embedded bit from the 2D projections of the model by computing the cross-ratio. After presenting the applicability of the algorithm via simulations, the future directions for this novel problem for 3D watermarking are addressed.

2.4.2. 3D Watermarking: Techniques and Directions

Authors: Alper Koz, George Triantafyllidis and A. Aydin Alatan

Institutions: Middle East Technical University, ITI-CERTH

Publication: book chapter in in Three-Dimensional Television: Capture, Transmission, and Display, Editors: Haldun M. Ozaktas and Levent Onural, Springer, Heidelberg, 2007.

In this chapter, a rigorous literature survey on 3D watermarking techniques is presented. The chapter categorizes the 3D watermarking techniques according to the main components of the major representation techniques, as geometry-, texture- and image-based watermarking. The requirements and problems in each branch of 3D watermarking are briefly reviewed in the manuscript.

A detailed literature survey on the state-of-the-art 3D watermarking methods forms the core of the chapter. It is realized that the existing 3D scene watermarking methods mainly focus on the watermarking of 3D geometry data, which are mostly represented with mesh structures. These methods are classified, as spatial domain methods, where the watermark is embedded into the geometric values of the geometric primitives, such as the coordinates of the points, length of a line, area of a polygon, volume of a polyhedron, and transform domain methods, where the watermark is embedded into the resulted coefficients, after a 3D geometry-based transformation is applied to the 3D geometry data. Pros and cons of each category are summarized. Briefly, transform domain methods should be more appropriate for determining the significant portions of the 3D object, hence more robust to the compression and noise attacks. On the other hand, spatial domain approaches are easier to implement and robust against the geometrical attacks, such as cropping.

The proposed solutions in the literature to the main attacks in geometry watermarking are examined separately, in order to give a more concise evaluation on 3D geometry watermarking. The robustness of the methods against main attacks is also compared. Although it is difficult to state the superiority of a method against another, due to the lack of a unique 3D scene representation, coding scheme and a benchmarking on 3D geometry watermarking, some methods are found out to be more promising, based on their robustness against possible common attacks on 3D geometry.

2.4.3. Watermarking Tests for Free-View Point Television

Authors: Evlambios E. Apostolidis, Alper Koz and George Triantafyllidis

Institutions: Middle East Technical University, ITI-CERTH

Publication: 3D TV Conference, Kos Island, Greece, 7-9 May 2007.

The recent advances in Image Based Rendering (IBR) has pioneered a new technology, free view point television, in which TV-viewers select freely the viewing position and angle by the application of IBR on the transmitted multi-view video. In this paper, exhaustive tests were carried out to conclude to the best possible non-blind watermarking for free-view television. The watermark should not only be resistant to common video processing and multi-view video processing operations, it should also be extracted from a generated video for an arbitrary view.

2.4.4. Best Watermarking Selection For Free-View Point Television

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Institutions: Middle East Technical University, ITI-CERTH

Publication: 14th International Conference on systems, Signals and Image Processing IWSSIP 2007 and 6th EURASIP Conference Focused on Speech and Image Processing, Multimedia Communications and Services EC-SIPMCS 2007, Maribor, Slovenia, June 2007.

In free view point video, the user might record a personal video for an arbitrarily selected view and misuse the content, so it is apparent that copyright protection problems should be solved for free-view TV. In this paper we employed several distributions as watermark sequences and we tested them in terms of robustness and imperceptibility using a blind detection scheme

2.4.5. Watermarking for Light Field Rendering

Authors: Alper Koz, Cevahir Cigla, A. Aydin Alatan

Institutions: Middle East Technical University,

Publication: EURASIP European Signal Processing Conference, Poznan, Poland, September 3-7, 2007.

The recent advances in Image Based Rendering (IBR) have pioneered freely determining the viewing position and angle in a scene from multi-view video. Remembering that a person could also record a personal video for this arbitrarily selected view and misuse this content, it is apparent that copyright and copy protection problems also exist and should be solved for IBR applications, as well. In our recent work, we propose a watermarking method, which embeds the watermark pattern into every frame of multi-view video and extracts this watermark from a rendered image, generated by the nearest-interpolation based light-field rendering (LFR) and watermark detection is achieved for the cases in which the virtual camera could be arbitrarily located on the camera plane only. This paper presents an extension to the previous formulation for the rendered images where the location of the virtual camera could be completely arbitrary in this new formulation. The results show that the watermark could be extracted successfully for LFR via nearest neighbourhood interpolation for any imagery camera location and rotation, as long as the visual quality of the rendered image is preserved.In free vie Analysis, conclusions, plans

2.4.6. Free View Watermarking for Free-View Television

Authors: Alper Koz, Cevahir Cigla, A. Aydin Alatan

Institutions: Middle East Technical University,

Publication: to be submitted in IEEE Transactions on Image Processing.

With the advances in Image Based Rendering (IBR) in recent years, generation of a realistic arbitrary view of a scene from a number of original views has become easier and faster. One of the main applications of this progress has emerged as free-view TV, where TV-viewers select freely the viewing position and angle by the usage of IBR on the transmitted multi-view video. Noting that the TV-viewer might also record a personal video for this arbitrarily selected view and misuse this content, it is apparent that copyright and copy protection problems also exist and should be solved for free-view TV. In this paper, we focus on this problem by proposing a watermarking method for free-view video. The watermark is embedded into every frame of multiple views by exploiting the spatial masking properties of the Human Visual System (HVS). Assuming that the position and rotation of the virtual camera is known, the proposed method extracts the watermark successfully from an arbitrarily generated image. In order to extend the method for the case of an unknown virtual camera position and rotation, the transformations on the watermark pattern due to image based rendering operations are analyzed. Based on this analysis, camera position and homography estimation methods are proposed for the virtual camera. The encouraging simulation results promise not only a novel method, but also a new direction for the watermarking research.

2.4.7. Watermarking for Image-Based Rendering via Homography-Based Virtual Camera Location Estimation

Authors: Alper Koz, Cevahir Cigla, A. Aydin Alatan

Institutions: Middle East Technical University,

Publication: to be submitted ICIP 2008.

The recent advances in Image Based Rendering (IBR) have pioneered freely determining the viewing position and angle in a scene from multi-view video. Remembering that a person could also record a personal video for this arbitrarily selected view and misuse this content, it is apparent that copyright and copy protection problems also exist and should be solved for IBR applications, as well. In our recent work [1], we propose a watermarking method, which embeds the watermark pattern into every frame of multi-view video and extracts this watermark from a rendered image, generated by the nearest-interpolation based light-field rendering (LFR) and watermark detection is achieved for the cases in which the virtual camera could be arbitrarily located on the camera plane only. This paper presents an extension to the previous formulation for the rendered images, which are generated by using bilinear interpolation, namely the most attractive and promising interpolation method in LFR¬-based applications. Moreover, the location of the virtual camera could be completely arbitrary in this new formulation. The results show that the watermark could be extracted successfully for LFR via bilinear interpolation for any imagery camera location and rotation, as long as the visual quality of the rendered image is preserved.

2.4.8. Analysis, conclusions, plans

There is indeed a strong necessity for developing techniques, which protect the ownership rights of the original 3D data, as well as prevent unauthorized duplication or tampering. A detailed literature survey on the state-of-the-art 3D watermarking methods and new effective techniques for watermarking 3D content, form the core of this joint effort.

It is realized that the existing 3D scene watermarking methods mainly focus on the watermarking of 3D geometry data, which are mostly represented with mesh structures. These methods can be classified, as spatial domain methods, where the watermark is embedded into the geometric values of the geometric primitives, such as the coordinates of the points, length of a line, area of a polygon, volume of a polyhedron, and transform domain methods, where the watermark is embedded into the resulted coefficients, after a 3D geometry-based transformation is applied to the 3D geometry data. The pros and cons of each method were stated: Briefly, transform domain methods should be more appropriate for determining the significant portions of the 3D object, hence more robust to the compression and noise attacks. On the other hand, spatial domain approaches are easier to implement and robust against the geometrical attacks, such as cropping. In this context, future plans include efforts of improving 3D geometry data watermarking techniques by taking into the aforementioned analysis.

Some alternative representation techniques for 3D scenes, such as image based modeling and rendering (IBR) have been rapidly developed in the recent years. By capturing a set of images from different viewpoints of a scene, these techniques are designed to reproduce the scene correctly at an arbitrary view point. Compared to the geometry-based models, this approach is more advantageous, since images are easier to obtain, simpler to handle and more realistic to render Noting that the users could record a personal video for their arbitrarily selected views and misuse this content, this technology makes the copyright problem for the image based represented scenes more apparent. Fortunately, there are pioneering works in this new area of 3D watermarking and among them, the work from the 3DTV NoE team.

To conclude, it can be said that most of the techniques in the literature belong to 3D/3D watermarking group. On the other hand, 3D/2D and 2D/2D watermarking receives less attention. However, once a 3D model is used in synthetic video within applications, such as computer generated animations, virtual/augmented reality or any kind of simulators, the projection of the 3D model has more importance compared to the 3D model itself. In addition, considering the increased research and progress in the virtual view synthesis and its applications, such as free-view TV and 3D TV in the recent years, the scenarios of 3D/2D and 2D/2D watermarking will become more significant for the copy right protection of 3-D representations.

The following table gives a roadmap for 3D/3D watermarking: The watermark is embedded into the 3D geometric structure of an object used in a scene and tried to be extracted from the 3D geometry after any attacks on the geometry.

Roadmap: 3D/3D watermarking

Development and optimization of algorithms	continuing
1st standard	2011
Implementation in products and services	from 2011

A roadmap for the 3D/2D watermarking is shown in the next table. 3D/2D watermarking, aims to extract the watermark that was originally hidden in the 3-D object, from the resulting

images or videos obtained after projection of 3-D object into 2-D image planes. The watermark can be both embedded to the geometry or the texture of the object

Roadmap: 3D/2D watermarking

Development and optimization of algorithms	continuing

The following table gives a roadmap for 2D/2D watermarking which tries to protect the image-based representation of a 3-D scene by watermarking sequences of images, which represent the 2-D projections of the same 3-D scene, and extracting the watermark from any 2-D rendered image, generated for an arbitrary angle of the scene via these sequences.

Roadmap: 2**D/2D watermarking**

First techniques reported	from 2006
Development and optimization of algorithms	2009

2.5. Survey of coding algorithms for 3DTV

A survey paper on coding algorithms for 3DTV was prepared as contribution to the Special Issue on MVC and 3DTV of the IEEE Transactions on Circuits and Systems for Video Technology. This paper gives an overview of the whole scientific area outside and inside the NoE.

2.5.1. Coding Algorithms for 3DTV - A Survey

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Publication: Invited Paper, IEEE Transactions on Circuits and Systems for Video Technology, Special Issue on Multiview Video Coding and 3DTV, Vol. 17, No. 11, November 2007

Research efforts on 3DTV technology have been strengthened worldwide recently, covering the whole media processing chain from capture to display. Different 3DTV systems rely on different 3D scene representations that integrate various types of data. Efficient coding of these data is crucial for the success of 3DTV. Compression of pixel-type data including stereo video, multi-view video, and associated depth or disparity maps extends available principles of classical video coding. Powerful algorithms and open international standards for multi-view video coding and coding of video plus depth data are available and under development, which will provide the basis for introduction of various 3DTV systems and services in the near future. Compression of 3D mesh models has also reached a high level of maturity. For

static geometry, a variety of powerful algorithms are available to efficiently compress vertices and connectivity. Compression of dynamic 3D geometry is currently a more active field of research. Temporal prediction is an important mechanism to remove redundancy from animated 3D mesh sequences. Error resilience is important for transmission of data over error prone channels, and multiple description coding is a suitable way to protect data. Multiple description coding of still images and 2D video has already been widely studied, whereas multi-view video and 3D meshes have been addressed only recently. Intellectual property protection of 3D data by watermarking is a pioneering research area as well. The 3D watermarking methods in the literature are classified into three groups, considering the dimensions of the main components of scene representations and the resulting components after applying the algorithm. In general, 3DTV coding technology is maturating. Systems and services may enter the market in the near future. However, the research area is relatively young compared to coding of other types of media. Therefore, there is still a lot of room for improvement and new development of algorithms.

3. General Summary and Conclusions

Technical work on 3D compression is progressing very successfully. The partners' individual research converges more and more into real joint and integrated activities, taking benefit of each others expertise and resources. The work covers all areas identified to be important for 3D compression.

In the highly actual and important area of multi-view video coding the NoE plays a worldwide leading role, both in basic research as well as in standards activities. The latter includes management as well as technical work. It can be foreseen that this work will have a significant impact on future economy and society in a global sense. This work will of course be continued with maximum effort, including both the scientific fundamentals and the exploration in MPEG. New activities for better support of automultiscopic displays and FTV have just been initiated.

The interest in efficient compression techniques for dynamic 3D meshes is rapidly growing. This is mainly due to the increased spread of animated 3D content in the world of digital multimedia today. Researches from this NoE contributed significantly and are still contributing in the development of a MPEG standard on compression of dynamic 3D meshes. They are playing a leading role in the standardization in this domain making research results obtained within the NoE visible to a broad public. Joint activities among NoE partners in research and standardization will continue also in future with maximal effort.

During the second research period partners within the NoE developed first MDC schemes for stereo and multi-view video. During the same period, MDC methods for 3D meshes have been suggested as well. The latter have been successfully improved during the third period of research (being summarized by this TR3). The topic of error-resilient transmission of 3D meshes was favoured during the reporting period for a number of reasons. First, the general topic of compression of 3D meshes has gotten a renewed attention worldwide, and breakthroughs by NoE partners have been achieved including MPEG standardization. Second, error resilience methods for 3D meshes were developed outside the NoE and the NoE partners have been challenged to compete with them. Third, the general methods needed to be related with real networks, which turned to be more challenging for the case of 3D meshes. In overall, the research on error resilience for both multi-view video and 3D geometry has a clear horizon and will be continued.

Watermarking of 3D data has been studied to some extend for the case of 3D meshes so far. Watermarking for other types of 3D data such as free-view point TV is being studied for the first time within the NoE. Also here the future work will benefit from close collaboration between the partners.

In general conclusion, the research on 3D compression within the NoE reached a high level of excellence, for both scientific fundamentals and more applied development of international standards. Partners formed a strong network and benefit from each others expertise and resources. The following table gives an overview of established collaborations within the different research areas. In each of these areas one researcher/student exchange was done

during the reporting period. As well one researcher/student exchange is planned in each high-priority research area for the following months.

AREA	**Collaborating Partners**
MVC	TUB, KU, METU, HHI
3D Mesh compression	Hannover, Plzen, HHI, Bilkent
Multiple Description Coding for 3D	TUT, METU
Watermarking for 3D	ITI-CERTH, METU

4. Annex

4.1. Multi-view video coding (MVC)

4.1.1. Two Novel Methods for Full Frame Loss Concealment in Stereo Video

4.1.2. Low Bit-Rate Object-based Multi-view Video Coding using MVC

4.1.3. Object-based Multiple Sprite Coding of Unsegmented Videos Using H.264/AVC

4.1.4. Client-driven selective streaming of multi-view video for interactive 3DTV

4.1.5. Adaptive streaming of scalable stereoscopic video over DCCP

4.1.6. Efficient Prediction Structures for Multiview Video Coding

4.1.7. Coding Efficiency and complexity analysis of MVC prediction Structures

4.1.8. Efficient Compression of Multi-view Depth Data Based on MVC

4.1.9. Compression of multi-view video and associated data

4.1.10. Multi-view video plus depth (MVD) format for advanced 3D video systems

4.1.11. MVC: Experiments on Coding of Multi-view Video plus Depth

4.2. 3D mesh compression

4.2.1. Layered Coding of Time-Consistent Dynamic 3D Meshes Using a Non-Linear Predictor

4.2.2. CoDDyAC: Connectivity Driven Dynamic Mesh Compression

4.2.3. STAR: Dynamic Mesh Compression

4.2.4. Frame-Based Compression of Animated Meshes in MPEG-4

4.2.5. Scalable Compression of Dynamic 3D Meshes

4.2.6. Frame-based Animated Mesh Compression: integration of the CABAC arithmetic encoder

4.2.7. Proposed Modifications to Residual Coding Part of Frame-based Animated Mesh Compression

4.2.8. FAMC Decoder Conformance

4.2.9. FAMC Decoder Software Description

4.2.10. A survey on coding of static and dynamic 3D meshes

4.2.11. Connectivity-Guided Adaptive Wavelet Transform For Image-Like Compression of Meshes

4.2.12. 3D Model Compression using Connectivity-guided Adaptive Lifting Transform

4.3. Multiple description coding (MDC) for 3D

4.3.1. Packet loss resilient transmission of 3D models

4.3.2. An efficient joint source-channel coding system for 3D models

4.3.3. Multiple description coding and its relevance to 3DTV

4.3.4. Multiple Description Coding of Visual Information

4.4. Watermarking for 3D

4.4.1. PhD Thesis: Watermarking For 3D Representations

4.4.2. 3D Watermarking: Techniques and Directions

4.4.3. Watermarking Tests for Free-View Point Television

4.4.4. Best Watermarking Selection For Free-View Point Television

4.4.5. Watermarking for Light Field Rendering

4.4.6. Free View Watermarking for Free-View Television

4.4.7. Watermarking for Image-Based Rendering via Homography-Based Virtual Camera Location Estimation

4.5. Survey of coding algorithms for 3DTV

4.5.1. Coding Algorithms for 3DTV - A Survey