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Signal Processing Issues in Diffraction and Holography

TC4 Technical Report 3

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Contents

1 EXECUTIVE SUMMARY

Technical Committee 4 (TC4) of the 3DTV Network of Excellence (NoE) has been conducting joint research activities on signal processing issues in diffraction and holography. In the first year of the project a detailed survey on issues related to Workpackage 11 (WP11) was delivered. Then, on the seventh month and on the nineteenth month of the project, the first and second Technical Reports (TR1 and TR2) were delivered, respectively. In this third Technical Report (TR3), two book chapters, four journal papers, nine conference papers, and two internal reports are reported and discussed under four categories (Table 1).

Number of Journal Papers: 4	Number of Conference Papers: 9	Number of Internal Reports: 2	Number of Book Chapters: 2
Ref. no: [5, 7, 10, 17]	Ref. no: [2, 3, 6, 8, 11, 12, 14–16]	Ref. no: [4, 13]	Ref. no: [1, 9]

Table 1: Numbers for types of publications

One book chapter and two papers are listed under "Research in Diffraction Field Computation." The book chapter "Holographic Displays Using Spatial Light Modulators" [1] involves issues related to both WP11 and WP12, and deals with three high priority tasks in WP11: Theory and algorithms for diffraction calculations from arbitrary surfaces, "multicolor holography (3 parallel recordings)" and "reconstruction with three colors". These WP11 related issues mainly focus on the performances of three different hologram computation methods in both numerical and optical reconstructions. Also, holograms of colored objects are computed, and numerical and optical reconstructions are presented. The paper "Performance Assessment Of A Diffraction Field Computation Method Based On Source Model" [2] presents the performance of a diffraction field computation method which is based on superposition over given object samples. Defined performance criteria are subjective quality of reconstructed images and computational complexity under different distributions of given samples. In an other paper entitled "Wavefield Reconstruction and Design as Discrete Inverse Problems" [3], a new diffraction field computation method which is based on the Rayleigh-Sommerfeld diffraction integral is proposed. The novel contribution of this paper is the utilization of a holographic display during the reconstruction step that has a pixelated structure. This method allows computation of diffraction fields due to a planar object on a pixelated holographic display.

"Fast computation of holograms" is another high priority task of the committee. There are two papers on this subject; one of them is an internal report, "Accelerated Optical Field Computation for Hologram Synthesis Using FPGA" [4], and the other one is a submitted journal paper, "Hologram Synthesis for Photorealistic Reconstruction" [5]. To achieve fast computation of holograms, computer graphics methods and the computation power of GPU are used. Synthetically generated objects are sampled accordingly, and then diffraction patterns and holograms are computed using computer graphics methods. Implementations on a single CPU, multiple CPU (parallel computation) and GPU platforms are realized and compared. Both numerical and optical experiments give good results.

A third priority research topic is "Phase Retrieval Based Approaches to Holography," with two subsections. In the first, three papers deal with the problem of phase unwrapping from noisy measurements. The first entitled "Noisy Phase Unwrap for Fringe Techniques: Adaptive Local Polynomial Approximations" [6] proposes a novel approach for phase unwrap filtering of noisy holographic data. That technique is further improved in the second paper named "Phase Local Approximation (PhaseLa) Technique For Phase Unwrap From Noisy Data" [7]. Yet a third paper, "Adaptive Local Phase Approximations And Global Unwrapping" [8] considers further modifications on the algorithms proposed in the first two works. The second subsection deals with phase-shifting profilometry, which is a powerful non-contact technique for measuring the shapes of 3D objects. There are three papers and one book chapter listed under this subsection. The book chapter entitled "Pattern projection profilometry for 3D coordinates measurement of dynamic scenes" [9] discusses phase-measuring methods in pattern projection profilometry for shape measurement and elaborates on the application of these methods for capturing of time-varying scenes within 3D display. In "Pattern Projection with a Sinusoidal Phase Grating" [10] the incorporation of a sinusoidal phase grating as a pattern projection element in a multi-source and multi-camera profilometric system is proposed. Another paper, "3D Scene Capture by Multi-Wavelength Pattern Projection at Divergent Illumination of a Sinusoidal Phase Grating" [11] investigates the performance of a phase-shifting profilometric system with a sinusoidal phase grating as a projection element under simultaneous multi-wavelength projection of four phase-shifted patterns at divergent illumination and simultaneous multi-camera registration.

Besides the signal processing problems that arise in the context of holographic displays, we have also investigated certain signal processing problems that arise in stereoscopic displays, in accordance with the fact that one of our high priority research tasks is entitled “Correction filters for autostereoscopic displays.” The main goal is to use signal processing to enhance the visual quality of multi-view stereoscopic displays and remove certain visual artifacts. The achievements along this research line are discussed under the section “Research in Signal Processing for Stereoscopic Displays”, and here we have four papers and an internal report. In “Crosstalk Measurement Methodology for Auto-Stereoscopic Screens” [12], inter-view crosstalk is identified as the reason for annoying artifacts hindering 3D perception, and a method is proposed for its measurement. The process causing the crosstalk is explained in depth in the internal report “Practical measurements of optical characteristics of a slanted parallax-barrier multi-view display” [13]. Two GPU-based algorithms for rendering a 2D-plus-Z stream on multi-view displays are proposed in “GPU-based algorithms for optimized visualization and crosstalk mitigation on a multi-view display” [14]. Yet, another approach in visual optimization for multi-view displays is presented in “OpenGL-Based Control of Semi-Active 3D Display” [15]. Finally, the paper “Optimized Single-Viewer Mode of Multi-view Autostereoscopic Display” [16] studies further the concept of visual optimization for a single observer.

The paper entitled “A Survey of Signal Processing Problems and Tools in Holographic Three-Dimensional Television” [17] summarizes the literature in diffraction theory and holography from a signal processing perspective. The authors emphasize the importance of utilizing results and techniques from signal processing in holographic three-dimensional television. They analyze the three-dimensional visualization methods and the related signal processing problems. Also, they focus on the signal processing problems that emerge within the context of holography and holographic 3DTV Displays.

2 Introduction

2.1 Scope of Technical Committee 4 (TC4)

The scope of Technical Committee 4 (TC4) is defined as Signal Processing Issues in Diffraction and Holography. The topics we conduct research on involve both optics and signal processing and are of great interest to both the optics and signal processing communities. The problems we try to address are quite challenging, since 3DTV requires both that we be able to operate in real time and that we achieve high resolution, both of which are very challenging targets in imaging technology. Thus we believe any advances we make will meet with interest from the related communities and that such advances will represent significant contributions to both optics and signal processing. While the problems are theoretical and numerical in nature, they are inspired by the demands of 3DTV and so have the potential to find immediate applications in holographic 3DTV displays.

During the early collaboration phases, we identified two fundamental research problems related to holographic 3DTV according to which we aligned our research work: computation of the 3D light field scattered by a given 3D scene, and determination of the optimum configuration for a specific physical display device given a desired 3D light field. We call these two problems the forward and the inverse problems, respectively. As we progressed, we also decided to deal with signal processing problems associated with stereoscopic displays, in which our aim was to apply proper signal processing to increase the visual quality of these displays.

In order to progress towards a complete 3DTV system, we also collaborate with the other Technical Committees of the 3DTV project and try to provide solutions for end-to-end 3DTV operation.

Achieving a complete three-dimensional television (3DTV) system is a timely, but challenging problem. There are several functional components that are vital for a successful end-to-end system: the capture of 3D moving scenes, abstract representation of captured data, formation and transmission of 3DTV signals, and the 3DTV display. As seen, the technological basis is highly multidisciplinary. Apart from the problems within each functional component, there are other problems related to proper interfacing of the basic functional blocks in harmony.

Conversion of abstract 3D moving scene information into signals driving the 3DTV display is one of the most important problems. Several candidate technologies exist for the 3DTV display: stereoscopic techniques, their extensions involving lenticular microlens technology, and techniques such as integral imaging, which seem to be relatively easier to implement; and holography based techniques, which seem to be more difficult, but probably more desirable. Regardless of the used technology, the solution of the interface problem, in which the optimum display configuration is determined from the given 3D scene information, requires exhaustive resorting to signal processing tools. While there are many classical signal processing tools and algorithms from which this problem can benefit, still they are beneficial to a certain extent and they suffer from many inadequacies that need to be addressed. The goal to achieve real-time 3DTV operation is another complicating factor that makes the efficiency and speed of the associated algorithms a major concern.

Though the research on the forward and inverse problems stated above has been conducted for about thirty years, still most techniques are not systematic and the solutions are not elegant. Moreover, many of the proposed methods are not compatible with real time operation. One of the main reasons for this state is that most researchers in this field, instead of systematically concentrating on the fundamental theoretical aspects of the problems and trying to deal with the inadequacies in basic tools, conduct a method/technique development based approach. For instance, the information theoretical aspects of these problems have rarely been considered seriously up to this time. Also, rarely have these problems been formulated as well-defined signal processing problems, so that the applicability and relevance of existing tools and solutions could not be recognized. Many researchers with a strong optics background lacked a sufficient understanding of signal processing, and vice versa. This situation prevented the development of fruitful results. We believe that our technical committee consists of researchers with a broad vision on both topics and therefore we are one of the most promising research groups in the world in the sense of fusing the achievements within both optics and signal processing in the most efficient manner, towards providing systematic and satisfactory solutions to these problems.

2.2 Research activities of TC4

After clarifying its scope and having completed an extensive survey, the committee had outlined its preliminary high-priority research tasks as:

- Information theory and signal processing based approaches to optical propagation, diffraction, and holography (general unifying theory of discretization, quantization, and interpolation in optics)
- Theory and algorithms for diffraction calculations from arbitrary surfaces
  - Non-orthogonal decompositions for forward problems
  - Fresnel transforms in arbitrary bases
- Phase-retrieval based approaches to holography
  - Phase shifting digital holography and its relation to problems in interpolation
  - Phase retrieval from multiple images distributed in space or time
- Other topics
  - Multicolor (3 parallel recordings)
  - Reconstruction of 3 colors simultaneously
  - Synthetic aperture techniques in 3DTV

The research activities during the first 17 months of the project resulted in a collection of papers and presentations that collectively made up *TC4 Technical Report I.* Following this, the committee further refined its list of high-priority research tasks:

- Information theory and signal processing based approaches to optical propagation, diffraction, and holography (general unifying theory of discretization, quantization, and interpolation in optics)
  - Device specific wavefield reconstruction
- Theory and algorithms for diffraction calculations from arbitrary surfaces
  - Non-orthogonal decompositions for forward problems
  - Fresnel transforms in arbitrary bases
- Phase-retrieval based approaches to holography
  - Phase shifting digital holography and its relation to problems in interpolation
  - Phase retrieval from multiple images distributed in space or time
  - Self-referencing techniques
- Other topics
  - Multicolor (3 parallel recordings)
  - Reconstruction of 3 colors simultaneously
  - Synthetic aperture techniques in 3DTV
  - Fast computation of holograms by employing computer graphics methods
  - Correction filters for autostereoscopic displays
  - Superresolution techniques applied to fringe pattern capture.

These high-priority research tasks guided the committee during the consecutive phases of operations. The results have been presented in *TC4 Technical Report II* and the present *TC4 Technical Report III.*

3 Analysis of Research Results

3.1 Research in Diffraction Field Computation

Holography is a visualization technique that retains all the depth cues, because it is based on physically duplicating the light waves originally emanating from the object. These waves carry the necessary information related to the 3D scene. Therefore, computation of diffraction fields is an important issue in holographic 3DTV. Indeed, one of the high priority tasks in our list is “Theory and Algorithms for diffraction calculations from arbitrary surfaces”.

The recently published edited 3DTV book has a chapter entitled “Holographic Displays Using Spatial Light Modulators” [1], which focuses on both the numerical and optical performances of three hologram computation methods. The chapter covers three high priority tasks in WP11: theory and algorithms for diffraction calculation, multi-color holography, and reconstruction of colored objects. The chapter also overlaps with some high priority topics in WP12. To achieve a true 3D display unit, integration of hardware and software is essential. Therefore, it is crucial to tailor the software according to the capabilities of the display devices. Therefore, a thorough survey on liquid crystal (LC) spatial light modulators (SLMs) is presented in this chapter. LC SLMs are mostly used to achieve holographic videos as dynamic displays. Their structures and characteristics are explained in detail. Performances of three hologram computation methods are evaluated by numerical and optical experiments. Evaluation is based on both numerically and optically reconstructed objects by these methods. These methods depend on the widely used Rayleigh-Sommerfeld diffraction integral, Fresnel-Kirchhoff diffraction, and bipolar intensity method. Optical experiments are conducted by two different SLMs: LC in transmissions mode and LCoS in reflection mode. The first two methods are used to calculate diffraction field due to the object, so it is possible to compute both off-axis and in-line holograms by using these methods. However, the last method can only be used to compute off-axis holograms. Another appealing part of this chapter is the color holography generation and reconstruction. Color holograms are obtained by combining monochromatic components for each of the R, G, B channels. Then, the reconstructed color object is formed by the inverse of this operation. In optical experiments, a LC SLM is used and the presented results are found to be satisfactory.

In the paper, “Performance Assessment Of A Diffraction Field Computation Method Based On Source Model” [2], there is a discussion of the sufficiency of the reconstructed fields which have been obtained based on the widely used source model under the distribution of the given field samples. In the source model, the diffraction field is computed by superposition over the given field samples. Ignoring the interactions and redundancies between the given samples in the reconstruction process may cause important deviations from the initial field. Notwithstanding, there are some distributions of the given samples over space that lead to acceptable reconstructed fields by using the source model.

In the paper “Wavefield Reconstruction and Design as Discrete Inverse Problems” [3], the complex wavefield reconstruction and design is addressed and considered as a discrete inverse problem. A novel discrete diffraction transform (DDT) as a frequency-domain discrete model for wavefield propagation is proposed. It is derived from the first Rayleigh-Sommerfeld integral and is exact for pixel-wise-constant wavefield distributions, i.e. for distributions which are constant on pixel-size rectangular elements of a digital sensor.

This approach is of importance for many 3DTV problems; in particular, for holographic 3DTV based on SLMs. There, the DDT is a tool for design of wavefield distributions implemented by digitally controlled SLMs.

3.2 Research in Fast Computation of Holograms

Computation of holograms is a numerically demanding process. Fast computation of these patterns can be achieved by the integration of appropriate algorithms and implementing them using optimized software on specific hardware platforms. To achieve real-time holographic 3DTV operation, several algorithms exploiting the computation power of GPUs are proposed. Even if GPUs provide highly efficient computational power, they are actually designed for graphics operations. Also, the computation power is still not enough to achieve real-time 3DTV operations for complex large 3D objects. To have faster computation, utilization of more diffraction field oriented processing unit seems promising. One way to have this kind of processing unit is to use FPGA-based hardware. The internal report “Accelerated Optical Field Computation for

Hologram Synthesis Using FPGA" [4] presents a hologram computation method which is run on FPGA. Furthermore, the computation method allows parallelization and scalability. As a result of this, it has incontrovertible potential to outperform the CPU and CPU/GPU based methods.

In the paper, "Hologram Synthesis for Photorealistic Reconstruction" [5], holograms of synthetically generated complex 3D objects or scenes are computed. To have more appealing results, each object has a realistic light reflectivity and a complex texture. The proposed algorithm can be implemented on different platforms like commercially available GPU's or parallel computers, in addition to single CPU based architectures. The rendering algorithms utilized in the proposed algorithm are suited to employ the source model. Even if, in the strict mathematical sense, the proposed algorithm does not give the exact reconstruction of the field, both optical and numerical experiments provide satisfactory results.

3.3 Research in Phase-Retrieval Based Approaches to Holography

One of the high priority research tasks of TC4 is "Phase Retrieval Based Approaches to Holography". Phase-retrieval can be used to determine the shape of an object from the reflected wave field. Thus, it is an important problem in 3D holographic imaging and has important applications in 3DTV. Common to these applications is that the observations are periodic functions, defined on the interval $[-\pi, \pi)$, of the true phase, the so-called absolute phase. If the true phase is outside this interval, its observed value is wrapped into it, corresponding to an addition or subtraction of an integer number of 2π. General approaches to absolute phase estimation follow a two-step procedure: in the first step, the wrapped phase is inferred from noisy wrapped observations; in the second step, the absolute phase is inferred from the wrapped estimates. The latter procedure is known as phase unwrapping. The high levels of observation noise, typical of many holographic imaging modalities, introduce further difficulties in the phase reconstruction, as the phase unwrapping methods developed for noiseless data are very sensitive to noise. One of the first and natural ideas is to pre-filter the noisy wrapped data and then to use the filtered output for further processing, in particular for phase unwrapping. However, a phase fringe pattern is a very delicate object with crucial details easily damaged by inaccurate pre-filtering. If the noise level is small, any reasonable filtering is acceptable. However, in the large noisy case, the standard approaches often damage data in such a way that further unwrapping becomes impossible.

3.3.1 Research in Phase Unwrapping in Noisy Environments

In the paper "Noisy Phase Unwrap for Fringe Techniques: Adaptive Local Polynomial Approximations" [6], a novel approach for phase unwrap filtering for noisy holographic data is proposed. It is based on two independent ideas: local approximation for design of nonlinear filters (estimators) and adaptation of these filters to unknown smoothness of the varying phase. Two powerful, flexible and universal tools have been used, namely local polynomial approximation (LPA) for approximation, and intersection of confidence intervals (ICI) for adaptation. Simulation results show that the technique achieves high phase reconstruction accuracy. In particular, a comparison between the suggested algorithm and the so-called $Z\pi M$ algorithm—considered state-of-the-art in the area—demonstrates better performance of the proposed method. The approach of [6] has been further elaborated in "Phase Local Approximation (PhaseLa) Technique For Phase Unwrap From Noisy Data" [7] where a theoretical analysis for the accuracy of the point-wise estimates has justified the use of the ICI algorithm for spatial adaptation. A third paper, "Adaptive Local Phase Approximations And Global Unwrapping" [8], suggests a different approach based however on the same two ingredients (LPA and ICI). The zero and first order approximations of the phase are calculated in sliding windows of varying size. The former is used for pointwise adaptive window size selection, while the latter is used for filtering the phase in the obtained windows. For unwrapping, the denoised wrapped phase obtained by the proposed approach is fed as an input to the PUMA unwrapping algorithm. Simulations show that this hybrid technique yields strong noise attenuation yet preserves image details. Further development of the proposed technique is targeted for 3D imaging of originally noisy data.

3.3.2 Research in Phase-Shifting Profilometry

Projection of a light pattern with a regular structure is a highly sensitive non-contact technique for measuring three-dimensional parameters of an object. A widely used approach is known as phase measuring profilometry in which the parameter being measured is encoded in the phase of a two-dimensional fringe pattern. A popular phase demodulation method is that known as sinusoidal fringe projection based phase-shifting profilometry. Using spatial light modulators, it is possible to obtain robust profilometric systems that offer flexibility in choosing fringe profile and spacing and enable fast and accurate phase shifting. But such systems suffer from artifacts due to luminance non-linearity and higher harmonic content of the fringes. Such systematic errors can be suppressed by digital signal processing. Yet, as the algorithms developed so far became more efficient in suppressing these systematic errors, they became more vulnerable to random error sources. This inadequacy forced us to seek for ways of obtaining higher quality projected fringes so as to obtain high accuracy profilometric measurements with a sinusoidal fringe projection. In the four papers described under this subsection, we carried out some analysis in the fields of diffractive optics and phase retrieval to achieve that goal.

In the book chapter entitled "Pattern projection profilometry for 3D coordinates measurement of dynamic scenes" [9], we considered phase-measuring methods in pattern projection profilometry as a perspective branch of structured light methods for shape measurement and emphasized the possibility of applying these methods for time-varying scene capture in dynamic 3D displays. First, we discuss the basic principles of phase measuring profilometry, describe the means of generating sinusoidal fringe patterns, formulate the tasks of phase demodulation in a profilometric system and point out the typical error sources influencing the measurement. Second, we discuss phase-retrieval methods, which are divided in two groups—multiple-frame and single-frame methods or temporal and spatial methods. In particular, we discuss the the phase-shifting approach along with its pros and cons, various error-compensating algorithms and generalized phase-shifting techniques. The details of the Fourier transform method are explained. The generic limitations, important accuracy issues, and different approaches for carrier removal are clarified. Space-frequency representations such as wavelets and windowed Fourier transforms for phase demodulation are also considered. Other point-wise strategies for demodulation from a single frame such as quadrature filters, phase-locked loops, and regularized phase tracking are briefly presented. The problem of phase unwrapping, essential for many of the phase retrieval algorithms, is explained with classification of the existing phase-unwrapping techniques. This chapter also includes the experimental set-ups developed by CLOSPI-BAS as well as the technical solutions of problems associated with measurement of the absolute 3D coordinates of the objects and the loss of information due to shadowing effect. In the end, we discuss the phase demodulation techniques from the point of view of observation of fast dynamic processes and the current development of real-time measurements in phase measuring profilometry.

We previously proposed a single-shot pattern projection profilometric system with simultaneous projection and recording of four phase-shifted fringe patterns which are generated at four different wavelengths. The system included a pattern projection module with four projection elements irradiated by four near-infrared diode lasers and a registration module with four CCD cameras. As candidates for a projection element, we identified a sinusoidal phase grating and a holographic optical element which reconstructs two point sources. Technical simplicity of a set-up, easy manufacturing and reproducibility of the desired modulation and spacing, high efficiency, minimization of the phase-shifting error, and independence of the spatial period of the diffraction pattern on the wavelength advocated strongly for the choice of the phase grating. In the paper entitled "Pattern Projection with a Sinusoidal Phase Grating" [10], we now propose incorporation of a sinusoidal phase grating as a pattern projection element in a multi-source and multi-camera profilometric system. Two challenges that are connected to inherent limitations of the phase-shifting algorithm should be overcome for successful operation of such a system—the requirements for a sinusoidal fringe profile and for equal background and contrast of fringes in the recorded fringe patterns. As a first task, we analyze the frequency content of the projected fringes in the Fresnel diffraction zone at different grating parameters and wavelengths. As a second task, we evaluate the systematical errors due to higher harmonics and multi-wavelength illumination. The results of test measurements are also presented.

The paper "3D Scene Capture by Multi-Wavelength Pattern Projection at Divergent Illumination of a Sinusoidal Phase Grating" [11] focuses on the performance of a phase-shifting profilometric system with a sinusoidal phase grating as a projection element under simultaneous multi-wavelength projection of four phase-shifted patterns at divergent illumination and simultaneous multi-camera registration. The quality of the projected fringes is evaluated by calculation of the Fresnel diffraction integral for a spherical wave illumination at paraxial approximation. It is shown that the frequency content and contrast of the fringes depends on the wavelength. We simulated reconstruction of a 3D surface of a dome in the case of the multi-wavelength profilometric system described in [10] which represents a conventional cross-axes optical arrangement. The simulation includes registration of four fringe patterns which are deformed by the object and four fringe patterns of the reference plane without the object. The experimental verification included evaluation of the fringe spectral content and contrast at increasing distance from the grating as well as 3D surface measurement of a test object. The optical scheme consisted of a diode laser, a beam expander, a grating, a projective and a CCD camera. We demonstrate that the intensity of higher harmonics is much lower in comparison with the first order of diffraction. The experiment suggests that the optimal distance between the projective and the grating is about 9–12 cm at the chosen interval of the wavelengths. The uncertainty of 3D reconstruction is about 0.1 mm. A good phase measuring profilometric system should provide good contrast of fringes in a large depth range and it should be built from a small number of low-cost components to ensure its portability and reliability. The frequency content of the projected fringes in the Fresnel diffraction zone are analyzed, accompanied by simulations of pattern projection with a sinusoidal phase grating at a given wavelength and results of test measurements of relative 3D coordinates. Moreover, the usage of Talbot self-imaging under coherent divergent illumination of an amplitude sinusoidal grating for profilometry of 3D diffuse objects is discussed.

3.4 Research in Signal Processing for Stereoscopic Displays

Though the main task of TC4 is to deal with signal processing problems encountered in the context of holographic displays, we have also investigated certain signal processing problems that arise in stereoscopic displays. Indeed, one of our high priority research tasks is entitled "correction filters for autostereoscopic displays." Within this research line, we tried to enhance the visual quality of multi-view stereoscopic displays and remove certain visual artifacts through appropriate signal processing.

Multi-view 3D displays produce specific artifacts which affect the perception of a 3D scene. The problem of measurement and mitigation of such artifacts by signal processing means has been addressed in a series of papers. The paper "Crosstalk Measurement Methodology for Auto-Stereoscopic Screens" identifies inter-view crosstalk as the reason for annoying artifacts hindering 3D perception, and proposes methodology for measuring it [12]. By introducing a methodology for crosstalk measurement of an arbitrary multi-view display, the paper aims to help content creators by optimizing a 3D scene for a given monitor. In a follow-up study, "Practical measurements of optical characteristics of a slanted parallax-barrier multi-view display" the process causing the crosstalk is explained in depth, being a consequence of certain design parameters of displays utilizing slanted optical layer [13]. The measurement methodology is extended to allow assessing the amount of light radiated by a given sub-pixel, and could be adapted to a wide range of multi-view displays. The ways for adapting the measurement approach for practical purposes such as finding the interdigitation map for a multi-view screen with unknown view topology or correcting the map for various observation distances have been shown. Three other papers propose various ways to optimize a 3D scene following measurements of a given 3D display. In the paper "GPU-based algorithms for optimized visualization and crosstalk mitigation on a multi-view display," two GPU-based algorithms for rendering a 2D-plus-Z stream on such displays are proposed [14]. Two alternative approaches—using pre-filtering and using extra observations—are compared. Both deliver perceptually optimized image with mitigated crosstalk artifacts, one is optimized for speed, while the other one is applicable to a wider range of graphical accelerators. Another approach in visual optimization for multi-view displays, following the methodology from [13] is presented in "OpenGL-Based Control of Semi-Active 3D Display" [15]. The paper presents a system for 3D visualization, which combines a "user-tracking" approach, used by displays with steerable optics, with generation of multiple views, typical for displays with a fixed optical filter. The outcome is an algorithm which can optimize the image based on the number of the observers—it provides continuous head parallax for a single user by using computationally non-intensive head tracking, and satisfactory 3D visualization for multiple observers. The concept of visual optimization for a single observer is further studied in "Optimized Single-Viewer Mode of Multi-view Autostereoscopic Display" [16]. This paper proposes an algorithm, which uses the input from a pair of inexpensive video-cameras and employs fast and robust face and facial feature detection algorithms to provide features for stereo matching and subsequent eye position detection. By utilizing display characteristics, measured with the methodology proposed in [13], the algorithm delivers continuous head parallax, cross-talk mitigation, brightness enhancement and distance-related image compensation related for a single observer.

3.5 Survey on Signal Processing Problems in Holographic Three-Dimensional Television

The paper "A Survey of Signal Processing Problems and Tools in Holographic Three-Dimensional Television" [17] provides an extensive survey of previously conducted work in the literature that falls within the scope of TC4. The authors discuss the general 3D visualization problem and present three common methods to achieve 3D visualization: holography, stereoscopy, and integral imaging. Then, they focus on problems and recent advancements in holography and holographic 3DTV displays from a signal processing perspective. They also discuss signal processing tools that find use in processing holographic signals.

4 Comparison of the Conducted Work and the State-of-the-Art

Here, we give a review of the most notable accomplishments of researchers outside our NoE on topics that are in line with those of TC4. This review is an incremental one in the sense that it covers the research that is not reported in the TC4 survey delivered in 2005. We also provide a comparison between their work and our work whenever such a comparison is possible.

Holographic displays are used to modulate the incident light in a manner so as to construct the desired pattern at a specific location in space. There are some commercial display devices that have the ability to steer light to arbitrary directions, such as those given in the papers "A scalable hardware and software system for the holographic display of interactive graphics applications" [18] and "A large scale interactive holographic display" [19]. These types of devices are put forward as possible candidates for 3DTV displays.

Integral imaging is one of the promising visualization techniques to achieve a 3D display. It uses a microlens array to capture a 3D scene and the captured information is encoded as a planar intensity distribution. To reconstruct the captured 3D scene, reversing the direction of the incident optical rays is needed. The paper "Full parallax viewing-angle enhanced computer generated holographic 3-D display system using integral lens array" [20] deals with integral imaging systems from a ray optics perspective and the papers "Multifacet structure of observed reconstructed integral images" [21] and "New characteristic equation of three-dimensional integral imaging system and its applications" [22] explain integral imaging systems by using diffractive optics principles. The paper "Multidimensional optical sensor and imaging system" [23] provides improvements in related computational techniques such as taking into consideration the sub-pixel structures. Integral imaging suffers from low resolution of the reconstructed images, but the method presented in the paper "Very large-scale integral imaging (VLSII) for 3-D display" [24] proposes a solution to overcome this bottleneck. There are other uses of integral imaging as well. It can be applied to solve different problems such as the visualization of partially occluded objects: "Three-dimensional visualization of partially occluded objects using integral imaging" [25], and to calculate holograms from captured elemental images "Calculation of holograms from elemental images captured by integral holography" [26].

Calculation of scalar optical diffraction is one of the central tasks of TC4. Moreover, it is a subject receiving renewed interest, as a result of 3DTV efforts. Thus, many of new algorithms and systems based on combinations of hardware and software are presented.

Firstly, we point out algorithm based advancements. Then, we present systems exploiting both the computational power of GPUs and the effectiveness of computer graphics algorithms.

The Rayleigh-Sommerfeld diffraction integral is one of the well known methods to compute the scalar optical diffraction field between two planar surfaces and it gives the correct diffraction field relationship between these surfaces. Another widely used method to calculate the diffraction field is the angular spectrum approach, which is also known as the plane wave decomposition method. Both of the methods give the same result: the former method expresses the relationship in the spatial domain and the latter method specifies it in the frequency domain. Some approximations can be applied to these methods to have simpler expressions. One of them is the paraxial approximation, which leads to the Fresnel diffraction integral.

The paper "Diffraction transfer function and its calculation of classic diffraction formula" [27] discusses the performances of three diffraction field computation methods which are implemented by utilizing fast Fourier transform. It is seen that plane wave decomposition is more effective than the other methods for the same calculation problem. Effectiveness arises from necessary number of samples and calculation time. This work has several common features with the paper "Holographic Displays Using Spatial Light Modulators," [1] but the latter work takes up a more general perspective, starting by discussing the structure of liquid crystal SLMs and their effects on the reconstructed images. Moreover, among the three algorithms considered, one of them is the same, but the other two are different.

The diffraction computation method proposed in "Numerical Techniques for Fresnel Diffraction in Computational Holography" [28] overcomes the limitations on sampling imposed by Fourier based algorithms by a fast shifted Fresnel transform. This transform utilizes a tiling approach to hologram construction and reconstruction between parallel planes.

Generally, monochromatic light is employed in hologram writing. However, the method proposed in "Digital spatially incoherent Fresnel holography" [29] uses incoherent illumination to compute complex-valued Fresnel holograms. Their method blends three sequentially recorded holograms, each for a different phase factor, to obtain a Fresnel hologram.

The Rayleigh-Sommerfeld diffraction integral gives the most generally valid solution for the diffraction field calculation problem. However, its use requires care since its kernel exhibits highly oscillatory behavior. Thus, this behavior may causes errors in calculations. Veerman et al. propose a method that utilizes the slow-varying nature of the envelope of the highly oscillatory quadratic-phase function in "Calculation of the Rayleigh-Sommerfeld diffraction integral by exact integration of the fast oscillating factor" [30]. However, the algorithmic complexity of this method is not as low as the methods that are based on plane wave decomposition or Fresnel approximation. In "Fast-Fourier transform based numerical integration method for the Rayleigh-Sommerfeld diffraction formula" [31], the Rayleigh-Sommerfeld diffraction integral is computed by exploiting FFT based on direct integration and angular spectrum methods. To improve the calculation accuracy Simpson's rule is employed.

Lucke took a closer look to the difference between the Fresnel-Kirchhoff and Rayleigh-Sommerfeld diffraction integrals in "Rayleigh-Sommerfeld diffraction and Poisson's spot" [32]. He used Poisson's spot experiment to show the difference between two methods and he concludes that Fresnel-Kirchhoff diffraction integral gives unacceptable results and Rayleigh-Sommerfeld diffraction integral provides an accurate description.

Plane-wave decomposition with rotational transformations is one of the common ways to calculate diffraction fields between tilted planes. The paper "Performance of the polygon-source method for creating computer-generated holograms of surface objects" [33] presents an algorithm that uses the mentioned computation strategy to compute full-parallax hologram due to an object, by superposing the diffraction fields emitted by each planar patch of the object. A similar algorithm is employed in "Computer-generated holograms for three-dimensional surface objects with shade and texture" [34] to compute diffraction field of an object whose planar patches exhibit brightness following Lambert's law. Moreover, the object is warped by a texture. Optical reconstructions due to the calculated holograms show that the proposed algorithms works well. The performance of the explained methods are good when there is only one object. There are some scenarios where there are multiple objects in the scene and one of them can occlude the others. The optimized algorithm given in "Exact hidden-surface removal in digitally synthetic full-parallax holograms" [35] is proposed as a solution to the occlusion problem. In the paper "Formulation of the rotational transformation of wave fields and their application to digital holography" [36], it is shown that plane-wave decomposition with rotational transformation formula satisfies the Helmholtz equation. Thus the method can be used to compute an exact spatial solution of the wave equation. Another method presented in "Pixel-size-maintained image reconstruction of digital holograms on arbitrarily tilted planes by the angular spectrum method" [37] uses similar algorithms as in the previous papers, but the given algorithm in this paper employs pixel by pixel operations to decrease the total error on the computed diffraction field. In "Mathematical modeling of triangle mesh-modeled three-dimensional surface objects for digital holography" [38], analytic spectrum representation of the light field emitted from an object formed by triangular patches is derived. Therefore, an exact angular spectrum representation is obtained without interpolated remapping. Occlusion is also overcome by this method.

The scalar diffraction field relation between input and output wave fields can be expressed as a quadratic-phase system under the Fresnel approximation. This relationship can be expressed or modeled in the form of a fractional Fourier transform or linear canonical transform. In the paper "Fast numerical algorithm for the linear canonical transform" [39], the derivation of a fast linear canonical transform is provided after the presentation of the theory of discrete linear canonical transforms. The paper "Generalizing, optimizing, and inventing numerical algorithms for the fractional Fourier, Fresnel, and linear canonical transforms" [40] provides a comparison of the accuracy of the diffraction field computation methods which are based on fast Fourier transform and fractional Fourier transform methods, as a function of the propagation distance. The authors point out that the fractional Fourier transform provides better results then the others. The algorithms proposed in "Efficient computation of quadratic-phase integrals in optics" [41] and "Digital computation of linear canonical transforms" [42] which is based on the fractional Fourier transform, provides an optimal solution valid in the Fresnel regime.

The diffraction field computation methods mentioned above, when applied to a 3D object constructed by planar patches, are based on superposition of the diffraction fields emitted from each planar patch. However, the assumption of omitting the mutual coupling between the patches may lead to unacceptable reconstructed objects. The paper "Performance Assessment of A Diffraction Field Computation Method Based On Source Model" [2] clarifies the situations that will provide acceptable results when superposition is employed.

Optical reconstruction in holography is the crucial test to determine performance of an employed algorithm and SLM. In [1] a thorough survey on the latest liquid crystal displays is presented. Moreover, three widely used algorithms are tested by these SLMs both numerically and optically. Also, polychromatic diffraction patterns are computed. Then reconstruction from the computed color holograms is shown in this document. Due to comprising all these three major topics, this book chapter fills an important gap in holography.

Reference [3] focuses on an innovative representation of diffraction field computation which takes into consideration the pixelated structure of the SLM and the capture device. By using the proposed method, better SNR values for the reconstructed objects can be obtained compared to state-of-the-art methods.

Various signal processing tools are heavily used in diffraction field computations to achieve faster and more accurate calculations. In the paper "Improved-resolution digital holography using the generalized sampling theorem for locally band-limited fields" [43], space-frequency analysis of typical transforms that are used to represent scalar optical diffraction are given. It is shown that there are some conditions on the recording that pave the way to reconstruct the initial optical signal even when the Nyquist rate is violated.

Diffraction field computations are expensive processes; thus a myriad of methods have been proposed to decrease its algorithmic complexity. These methods employ several assumptions which are based on the shape of a 3D object or the diffraction field computation method. Even in those cases, it is hard to achieve real-time computations. Therefore, the computational power of GPUs and efficiency of computer graphics methods are needed to have faster algorithms. In "A framework for holographic scene representation and image synthesis" [44] an efficient hologram computation method based on computer graphics algorithms and the power of GPUs is proposed. The presented results are impressive. A similar method that exploits computer graphics algorithms and GPUs is given in "Computer generated holography using a graphics processing unit" [45]. However, they can deal with simple objects which are constructed by 100 voxels and the calculated hologram resolution has to be smaller than 1024×1024.

Reference [46] describes a holographic video display system. The Emphasis of this paper is on fast computation of the holograms. While in rainbow-holography the vertical parallax is omitted, here image holograms are chosen which reproduce full parallax. A further advantage of image holograms is the closeness of the object to the hologram; therefore for calculation of each hologram pixel only a few points in the close vicinity have to be engaged, contrary to Fresnel holography where for each hologram pixel all object points have to be taken into account. This choice significantly reduced the computational effort. The spatial light modulators used are three LCoS in a conventional video projector, one for each of three colours, thus producing full-colour reconstructions. Obviously the scenes to be displayed are not recorded in the real world, but are synthetic artificial objects calculated in computer.

Using computer graphics approaches and readily available computer graphics hardware, like the GPU, for fast computation of diffraction and holography related problems is getting popular [5, 44]. The method proposed in [5] presents a novel approach to represent diffraction signal formation from a photorealistic object using space-frequency techniques in signal processing. Furthermore, it proposes a different sampling scheme on the object surface; the proposed scheme makes the implementation of the algorithm more suitable for parallel processing environments. It is quite feasible to compute diffraction patterns from large size mesh-based structures with a realistic surface properties using the proposed method. Moreover, in [44] a correct physical modeling of a camera that includes optical elements, such as lens and aperture are also investigated. On the other hand, the former method overcomes the occlusion problem and also it is presented in a more descriptive mathematical groundwork.

The system presented in [4] uses more operation-specific oriented hardware in hologram calculation. Using optimized hardware for a specific operation brings advantage during computation. FPGA-based systems can pave the way to benefiting from the integration of operation-specific hardware and optimized software, to achieve faster computations than GPU-based systems. This is discussed in [45].

Phase retrieval is an important and well-studied area in image processing. It has a myriad of applications such as magnetic resonance imaging, adaptive optics and reconstruction of the shape of 3D objects. Usually the L^p norm is used as a minimization criterion and this leads to computationally demanding algorithms. To overcome this bottleneck, a novel energy criterion with an iterative binary optimization scheme is proposed in "Phase Unwrapping via Graph Cuts" [47]. Another novel method is given in "Unwrapping of MR Phase Images Using a Markov Random Field Model" [48] that utilizes smoothness of the true phase of an MR image. This method also handles abrupt phase changes. Moreover, experimental results shows that the method works fine with noisy data as well. The method based on the "PhaseLa" technique, given in "Phase local approximation (PhaseLa) technique for phase unwrap from noisy data" [7], surpasses the state-of-the-art methods such as those presented in [47] and [48]. Comparison of the methods are given as charts in [7].

In the paper "Adaptive Local Phase Approximations and Global Unwrapping" [8], adaptive window size for the phase unwrap is used instead of the fixed window size used in [7]. The method given in "Noisy Phase Unwrap for Fringe Techniques: Adaptive Local Polynomial Approximations" [6] focuses on filtering of the wrapped phase as the prefiltering procedure for the forthcoming unwrapping, and provides an improvement over the method in [7].

Pattern projection profilometry is a high resolution structured light technique for capturing 3D scenes. With its high accuracy and large dynamic range, phase-shifting with projection of several patterns constitute a popular and simple technique for 3D scene capture. The phase-shifting algorithm implies a sinusoidal fringe profile and equal background and contrast of fringes in the recorded patterns. But this algorithm has mostly been applied off-line, with successive recording of the phase-shifted fringe patterns in time. Recently, [49] proposed a slight modification which enables real-time operation with high resolution. Additionally, [50] proposes a real-time method based on single-shot measurement of object parameters through simultaneous projection of three color patterns (red, green and blue) on the object at different angles and recording by a single CCD camera. [51] develops a phase-shifting method for objects moving at a constant speed by projection of a sinusoidal pattern and continuous intensity acquisition by three phase-shifted linear array sensors. Several advanced signal processing tools have also recently been used in analysis of projected patterns. [52, 53] develop approaches based on space-frequency representations for phase retrieval from a single pattern. Another recent development is the spatial analysis methods devised for phase retrieval from a single pattern. [54] proposes a fitting-error modified spatial fringe modulation, [55, 56] propose phase demodulation based on fringe skeletonizing when an extreme map is introduced by locating the fringes minima and maxima, and [57] proposes phase-stepping recovery of objects by numerical generation of multiple frames from a single recorded frame. Another recent popular method for generating sinusoidal fringes is by using a defocused Ronchi grating. Reference [58] investigates this case and points out that higher harmonics are unavoidable in the created fringe profiles. The book chapter that we wrote [9], can be consulted for an up-to-date comprehensive review of the subject.

One of the most vital components of a pattern projection profilometry system is the projection element. It should be selected such that it has a sinusoidal fringe profile and provides sufficient contrast of fringes in the recorded patterns. Above we listed a number of candidates for this projection element, but most of them suffer from problems such as being difficult to manufacture, the fact that reproduction of desired modulation and spacing is hard, the fact that the spatial period of the diffraction pattern depends strongly on the illumination wavelength, etc. To overcome these drawbacks, in [10], we propose and analyze the usage of a sinusoidal phase grating as a projection element. Here, to our knowledge for the first time, the diffractive properties of a sinusoidal phase grating for incorporation as a pattern projection element in a multi-source and multi-camera profilometric system are studied. We also analyzed the frequency content of the projected fringes in the Fresnel diffraction zone for parallel and divergent light illumination at different grating parameters and wavelengths. We also evaluated the systematical errors due to higher harmonics and multi-wavelength illumination. In another paper [11], we investigate the performance of a phase-shifting profilometric system with a sinusoidal phase grating as a projection element under simultaneous multi-wavelength projection of four phase-shifted patterns at divergent illumination and simultaneous multi-camera registration. Both simulations and experiments verify that the choice of a sinusoidal phase grating as the projection element is a good approach and many of the problems that arise for other projection elements are solved to a significant extent. Through the systems we developed, we are able to record and reconstruct 3D objects in real time, which, despite the presence of other research groups having achieved real-time operation with other techniques, remains a great challenge in the field.

One of the main problems addressed in this TC is the synthesis of three-dimensional light fields in space, so that observers interacting with these fields perceive a 3D view of the scenes that are intended to be displayed. One of the well-known techniques for this task is computer generated holography (CGH), in which one tries to find the optimum configuration of a display device under certain constraints (for instance, binary amplitude SLMs or binary phase SLMs), such that the information about the desired light field is encoded in the device with the greatest fidelity possible. In the context of dynamic displays, we need fast algorithms compatible with real-time operation to compute these optimum configurations. Ideally, we would like to have SLMs that perform full complex modulation of light fields, but it is difficult to realize SLMs which can provide the desired complex phase and amplitude at the same time. Most SLMs provide either amplitude or phase modulation. Reference [59] proposes a fast and accurate method to encode the information in complex wavefronts into amplitude-only SLMs. Making the best use of the SLM characteristics is crucial for the quality of the optical reconstruction of digital holograms. Reference [60] provides a comparison of the optical reconstruction of phase and amplitude holograms by different modulators in terms of diffraction efficiency and reconstruction quality. Hardware and look-up table based computations are proposed in [61]. Real color fractional Fourier transform holography along with its implementation on SLMs is proposed in [62]. References [63] and [64] propose usage of multiple holograms or SLMs so that reconstruction quality is enhanced. There are also methods based on phase-shifting digital holography, which enable the encoding of the information in 3D fields only to the phase of a wavefront [65, 66]. Apart from these CGH generation techniques, researchers have also concentrated on related fundamental issues, such as sampling and quantization. Most notably, [67] stresses the fact that it is possible to reconstruct objects from hologram samples obtained below the Nyquist rate; and analyzes real-life applications where one can take a finite number of samples through a capturing CCD device with pixels of finite (non-impulsive) area. Sampling under noisy conditions is also analyzed. Another important study, which deals with quantization issues, is presented in [68]. This paper examines nonuniform quantization through companding of complex numbers by employing nonuniform grid patterns over the complex plane and shows that this method is efficient for digital holograms with a reconstruction quality comparable to that obtained by quantization by the k-means algorithm. A new quality factor of an incident beam on the reconstruction performance of a computer generated hologram is proposed in "Investigation of m2 factor influence for paraxial computer generated hologram reconstruction using a statistical method" [69]. The mentioned quality factor takes into account several parameters such as diffraction efficiency, root mean-square error, illumination uniformity, and correlation coefficient calculated in the numerical reconstruction.

Stereoscopy is based on the principle of invoking a 3D-perception in the human observer by exposing each eye of the observer to a slightly different perspective of the 3D scene. Conventional systems require special equipment such as glasses to be used by the observers, whereas auto-stereoscopy eliminates that requirement through intelligent use of lenticular covered screens or similar methods [70]. Reference [71] provides a nice assessment of the visual quality of displays making use of lenticular screens. Multiview display systems may offer additional advantages. Some of these multiview displays track the observer's eyes and beam different images towards each eye, whereas others work by showing a set of images simultaneously, where each image is from a particular viewing angle along the horizontal direction. Most multiview displays of the second kind employ slanted lenticular sheets [72] or slanted parallax barrier [73], and they use TFT screens for image formation [74]. Reference [75] also implements a multiview system of the second kind by means of an optical filter whose purpose is to alter the propagation direction for the displayed image. Some vendors also felt the need to broaden the observation angle of a pixel so as to achieve a more uniform view [74]. In such multiview displays, only a part of the screen is seen from each particular observation angle. However, for some scenes, double images are seen from almost any observation angle. One way to get rid of such artifacts is sub-sampling followed by anti-alias filtering. References [76, 77] develop such signal processing methods for conventional multiview displays whose views are ordered in the horizontal direction. References [76, 77] propose resampling a view on a non-rectangular grid and emphasize that this requires specially designed anti-aliasing filters. Reference [77] develops algorithms to enhance the visual quality of displays whose views are ordered in a matrix arrangement. Another related task in stereoscopic displays is the computation of 2D observations of a 3D scene described in abstract computer graphics terms for a number of observation angles. Reference [78] proposes an OpenGL implementation to tackle this problem, which computes the disparity corresponding to different depth levels given a number of observation angles, displaces the pixels in the 2D image horizontally according to the calculated disparity, and finally recovers the pixels which belong to previously hidden parts of the image. Another recent method is depth-of-field rendering, which works by decomposing the scene into sub-images with different depth levels, applying different blur filters, and then blending the sub-images together [79]. GPU-based implementations to handle signal processing issues related to other various artifacts in a fast manner are proposed in [80, 81].

Though the state-of-the-art on stereoscopic and especially multiview displays is promising, still there are many issues to be considered, and in our work, we attempted to address these issues. For instance, by design, multiview 3D displays utilizing slanted lenticular sheets have an intrinsic drawback—subpixels which belong to a certain view are partly visible in the neighboring views. It is possible to model this effect as inter-view crosstalk, and the presence of this effect introduces annoying scene-dependent artifacts, hindering the visual quality of the display. Moreover, in most cases, the parameters characterizing this crosstalk are not available to the end user. In our paper [12], we introduce a methodology for crosstalk measurement of an arbitrary multi-view display, through which we aim to help content creators and end users in optimizing 3D scenes for a given monitor. In order to mitigate the effects of crosstalk even better, we will continue this study by investigating adaptive filtration of multi-view image sets. Similarly, in another work [13], we point out the problem that interdigitation algorithms, whose main aim is to broaden the observation angles of the sub-pixels of multiview displays in order to create interspersed viewing angles, but which usually do not take into account the complexity of the light distribution, produce images with visible and annoying "lattice" and "ghosting" artifacts. Then, we develop measurement techniques to predict the amount of light radiated by a given sub-pixel towards a range of observation locations with an aim to assist signal processing algorithms aimed at improving the visual quality of multi-view displays. Another paper of ours [14] also identifies crosstalk as a quality degrading factor, and proposes texture pre-filtering and usage of extra observations as methods for handling it. In this paper, we develop a GPU-based perceptually optimized rendering of 2D+Z video frames and show that both of our algorithms improve the depth perception of rendered content substantially over what has been done elsewhere.

As discussed above, a significant improvement in stereoscopy technology is the development of autostereoscopic systems. However, these are not without certain significant difficulties. Basically, there are two types of techniques: passive techniques achieve auto-stereoscopy through physical modifications on the display such as covering the screen with lenticular sheets, whereas active techniques such as eye tracking optimize the content depending on the location of the observer. While passive techniques are simple to implement, they do not provide a high visual quality compared to active techniques, but active techniques are computationally very demanding. In one of our papers [15], we propose a semi-active, GPU-based 3D visualization approach which combines active tracking with a passive multi-view 3D display. Here, instead of the eyes, we track the head, and in this way we obtain a wide range of viewing angle without increasing the computational complexity severely. Moreover, we observe that our system delivers a seamless experience to the end user. In [16], we make our system even more perfect by embedding fast and robust face and facial feature detection algorithms to provide features for stereo matching and sub-sequent eye position detection. In this way, we achieved, to our belief, a very successful system that optimizes the visual quality of a multiview display for a single viewer.

5 Abstracts of Publications

5.1 Holographic Displays Using Spatial Light Modulators [1]

Authors: M. Kovachev, R. Ilieva, P. Benzie, G. B. Esmer, L. Onural, J. Watson and T. Reyhan
Publication: *Appeared as a Chapter in* Three Dimensional Television: Capture, Transmission, Display. Editors: H. M. Ozaktas and L. Onural

The display is the most important component of a holographic 3DTV system. Quality of the reconstructed 3D scene highly depends on the characteristics of the display unit. The profound survey and analysis on liquid crystal panels show that these devices can be used as holographic display units. Modulation characteristics of commercially available liquid crystal panels are known. Thus, the responses of the panels under coherent light illumination at 543nm and 633nm are fully understood. Incorporating these characteristics of the panels into our hologram computation procedure enabled us to obtain better quality reconstructed 3D scenes. Three hologram computation methods, based on Rayleigh-Sommerfeld diffraction integral, Fresnel-Kirchhoff diffraction integral and bipolar intensity method, are discussed. Their performances are evaluated based on numerical and optical experiments. The algorithms utilizing Rayleigh-Sommerfeld and Fresnel-Kirchhoff diffraction integrals provide similar reconstructed patterns in both optical and numerical experiments when the distance along the optical axis is around 0.8m. Moreover, color holograms are computed by digitally combining the R, G and B channels. Numerical and optical experiments for color hologram are presented. From the optical experiments, it is seen that liquid crystal spatial light modulators can be used as a holographic display to reconstruct the color holograms.

5.2 Performance Assessment of A Diffraction Field Computation Method Based On Source Model [2]

Authors: G. B. Esmer, L. Onural, H. M. Ozaktas, V. Uzunov and A. Gotchev
Publication: *Appeared in* IEEE Proceedings on 3DTV Conference 2008

Efficient computation of scalar optical diffraction field due to an object is an essential issue in holographic 3D television systems. The first step in the computation process is to construct an object. As a solution for this step, we assume that an object can be represented by a set of distributed data points over a space. The second step is to determine which algorithm provides better performance. The source model whose performance is investigated is based on superposition of the diffraction fields emanated from the hypothetical light sources located at the given sample points. Its performance is evaluated according to visual quality of the reconstructed field and its algorithmic complexity. Source model provides acceptable reconstructed patterns when the region in which the samples are given has a narrow depth along the longitudinal direction and a wide extent along the transversal directions. Also, the source model gives good results when the cumulative field at the location of each point due to all other sources tends to be independent of that location.

5.3 Wavefield Reconstruction and Design as Discrete Inverse Problems [3]

Authors: V. Katkovnik, J. Astola and K. Egiazarian
Publication: *Appeared in* IEEE Proceedings on 3DTV Conference 2008

We consider a wavefield reconstruction in two conjugate settings. First, the object wavefield is reconstructed from data recorded by a finite size sensor located in the image plane. Second, the 3D object wavefield has to be designed in such a way that the desired 3D wavefield distribution is obtained in the image area. For wavefield propagation we use a novel frequency domain discrete model derived from the first Rayleigh-Sommerfeld integral. This model is precise for piece-wise (pixel-wise) constant wavefield distributions.

5.4 Accelerated Optical Field Computation for Hologram Synthesis Using FPGA [4]

Authors: I. Hanak, P. Zemcik, M. Zadnik, A. Herout and V. Skala
Publication: Internal Report

Hologram and/or optical field synthesis is one of the challenging tasks of contemporary computer graphics. While the principle is known, a solution for an effective or fast optical field synthesis remains an issue. This paper addresses primarily large optical field computation that is essential and the most computationally expensive part of hologram synthesis. This paper introduces a solution suitable for speeding up of the optical field computation through usage of programmable hardware (Field Programmable Gate Array FPGA) as the computational core. The solution offers very high potential for parallelization and scalability and due to the nature of the task also potential to outperform CPU-based and/or CPU/GPU-based solutions. The paper contains a brief overview of methods for optical field computation and hologram synthesis, which have features similar to the presented solution. It also contains a description of the FPGA core and discussion of performance issues.

5.5 Hologram Synthesis for Photorealistic Reconstruction [5]

Authors: I. Hanak, M. Janda and L. Onural
Publication: *Submitted to* Journal Of Optical Society of America A

Computation of diffraction patterns, and thus holograms, of scenes with photorealistic properties is a highly complicated and demanding process. An algorithm, based primarily on computer graphics methods, for computing full- parallax diffraction patterns of complicated surfaces with realistic texture and reflectivity properties is proposed and tested. The algorithm is implemented in single CPU, multiple CPU and GPU platforms. An alternative algorithm, which implements reduced occlusion diffraction patterns for much faster but somewhat lower quality results, is also developed and tested. The algorithms allow GPU aided calculations and easy parallelization. Both numerical and optical reconstructions are conducted. The results indicate that the presented algorithms compute diffraction patterns that provide successful photorealistic reconstructions; the computation times are reasonable especially on GPU implementations.

5.6 Noisy Phase Unwrap for Fringe Techniques: Adaptive Local Polynomial Approximations [6]

Authors: V. Katkovnik, J. Astola and K. Egiazarian
Publication: *Appeared in* IEEE Proceedings on 3DTV Conference 2007

Many imaging systems deal with phase measurements using coherent radiation in order to illuminate objects. The reflected scattered return carries information on physical and geometrical properties of illuminated objects. It can be information on shape, deformation, movement and structure of the object's surface. We propose a novel phase unwrap filtering for noisy holographic data. Based on the window size adaptive local polynomial approximation it allows dramatically reduce level of noise and in the same time preserve phase variation features. Simulation shows that the technique enables an advanced accuracy for phase reconstruction from wrapped noisy observations.

5.7 Phase Local Approximation (PhaseLa) Technique For Phase Unwrap From Noisy Data [7]

Authors: V. Katkovnik, J. Astola and K. Egiazarian
Publication: *Will Appear in* IEEE Transactions on Image Processing

The local polynomial approximation (LPA) is a nonparametric regression technique with pointwise estimation in a sliding window. We apply the LPA of the argument of cos and sin in order to estimate the absolute phase from noisy wrapped phase data. Using the intersection of confidence interval (ICI) algorithm the window size is selected as adaptive pointwise varying. This adaptation gives the phase estimate with the accuracy close to optimal in the mean squared sense. For calculations we use a Gauss-Newton recursive procedure initiated by the phase estimates obtained for the neighboring points. It enables tracking properties of the algorithm and its ability to go beyond the principal interval $[-\pi, \pi)$ and to reconstruct the absolute phase from wrapped phase observations even when the magnitude of the phase difference takes quite large values. The algorithm demonstrates a very good accuracy of the phase reconstruction which on many occasion overcomes the accuracy of the state-of-the-art algorithms developed for noisy phase unwrap. The theoretical analysis produced for the accuracy of the pointwise estimates is used for justification of the ICI adaptation algorithm.

5.8 Adaptive Local Phase Approximations And Global Unwrapping [8]

Authors: J. Bioucas-Dias, V. Katkovnik, J. Astola and K. Egiazarian
Publication: *Appeared in* IEEE Proceedings on 3DTV Conference 2008

The paper introduces a new modulo-2π phase denoising algorithm based on local polynomial approximations. The zero and first order approximations of the phase are calculated in sliding windows of varying size. The former is used for Pointwise adaptive window size selection, while the latter is used for filtering the phase in the obtained windows. For unwrapping, we input the PUMA unwrapping algorithm with the denoised wrapped phase obtained with the proposed approach. Simulation shows that this technique enables strong noise attenuation while preserving image details.

5.9 Pattern projection profilometry for 3D coordinates measurement of dynamic scenes [9]

Authors: E. Stoykova, J. Harizanova and V. Sainov
Publication: *Appeared as a Chapter in* Three Dimensional Television: Capture, Transmission, Display. Editors: H. M. Ozaktas and L. Onural

Recently there has been a growing interest in the development of various optical techniques for precise measurement of 3D coordinates. In this chapter, we consider phase-measuring methods in pattern projection profilometry as a perspective branch of structured light methods for shape measurement and discuss the application of these methods for time-varying scene capturing in the dynamic 3D display. We start by explaining the basic principles of phase measuring profilometry and describing the means for generation of sinusoidal fringe patterns. Here we see that the accuracy of the measurement crucially depends on correct determination of the stripe orders of the reflected patterns and on their proper connection to the corresponding orders in the projected patterns. Then we formulate the tasks of phase demodulation in a profilometric system and point out the typical error sources influencing the measurement. We show that these errors lead to random variations of the background and fringe visibility, and that measurement accuracy can be improved by taking special precautions. Next, we summarize the phase-retrieval methods and outline the phase shifting approach with its pros and cons. Special attention is given to error-compensating algorithms and generalized phase-shifting techniques. The Fourier transform method is discussed in detail. The generic limitations, important accuracy issues and different approaches for carrier removal are enlightened. Space-frequency representations such as the wavelet and windowed Fourier transforms for phase demodulation are also considered. Other pointwise strategies for demodulation from a single frame as quadrature filters, phase-locked loop and regularized phase tracking are briefly presented. The problem of phase unwrapping which is essential for many of the phase retrieval algorithms is explained with classification of the existing phase-unwrapping approaches. We discuss the phase demodulation techniques from the point of view of observation of fast dynamic processes and the current development of real-time measurements in the phase measuring profilometry. Finally, we talk about the developed by CLOSPI-BAS experimental set-ups as well as the technical solutions of problems associated with measurement of the absolute 3D coordinates of the objects and the loss of information due to shadowing effect. We see that with our system, the projected fringe pattern is practically identical with a sinusoidal profile for the chosen spectral region, implying that we managed to overcome the degrading effect of the higher frequency components. We conclude that usage of sinusoidal phase gratings is very promising for realization of real time operation for 3D coordinate measurement of dynamic scenes.

5.10 Pattern Projection with a Sinusoidal Phase Grating [10]

Authors: E. Stoykova, J. Harizanova and V. Sainov
Publication: *Will Appear in* EURASIP Journal on Advances in Signal Processing - Special Issue on 3DTV: Capture, Transmission and Display of 3D Video

The aim of this work is study the diffractive properties of a sinusoidal phase grating for incorporation as a pattern projection element in a multi-source and multi-camera phase-shifting profilometric system. Two challenges should be overcome for successful operation of such a system that are connected to inherent limitations of the phase-shifting algorithm - the requirements for a sinusoidal fringe profile and for equal background and contrast of fringes in the recorded patterns. As a first task, we analyze the frequency content of the projected fringes in the Fresnel diffraction zone for parallel and divergent light illumination at different grating parameters and wavelengths. As a second task, we evaluate the systematical errors due to higher harmonics and multi-wavelength illumination. Finally, operation of the four-wavelength profilometric system is simulated and the error of the profilometric measurement evaluated. The results of test measurements are also presented.

5.11 3D Scene Capture by Multi-Wavelength Pattern Projection at Divergent Illumination of a Sinusoidal Phase Grating [11]

Authors: E. Stoykova, V. Sainov and G. Minchev
Publication: *Appeared in* IEEE Proceedings on 3DTV Conference 2008

The paper focuses on the performance of a phase-shifting profilometric system with a sinusoidal phase grating as a projection element under simultaneous multi-wavelength projection of four phase-shifted patterns at divergent illumination and simultaneous multi-camera registration. The quality of the projected fringes is evaluated by calculation of the Fresnel diffraction integral for a spherical wave illumination at paraxial approximation as well as by measurement of the contrast and the spectral content of the fringes as a function of the distance from the grating. The good quality of fringes is proved by simulation of the four-wavelength profilometric measurement. An accurate restoration of a 3D test object (dome) from experimental data is presented.

5.12 Crosstalk Measurement Methodology for Auto-Stereoscopic Screens [12]

Authors: A. Boev, A. Gotchev and K. Egiazarian
Publication: *Appeared in* IEEE Proceedings on 3DTV Conference 2007

Autostereoscopic displays utilizing slanted lenticular sheets produce specific artifacts. These artifacts affect the perception of a 3D scene, and are caused by a process which can be modelled as inter-channel crosstalk. We propose methodology for measuring such a crosstalk for arbitrary multi-view 3D display. The measured data might be used for optimizing multi-view image sets for a given display.

5.13 Practical measurements of optical characteristics of a slanted parallax-barrier multi-view display [13]

Authors: A. Boev, A. Gotchev and K. Egiazarian
Publication: Internal Report

Modern multiview 3D displays which utilize slanted lenticular sheet or slanted parallax barrier are designed to have interspersed viewing regions. This is done in order to provide continuous parallax and remove the picket fence effect. However, such design produces ghosting artefacts which hinder the perception of binocular depth cues, and lattice artefacts which affect the 2D resolution. In this paper, we propose to model the process which produces these artefacts as inter-channel crosstalk with two components. The first component is large-scale crosstalk, which causes ghosting and diminishes the 3D quality of the display. The second component is small-scale crosstalk, which causes brightness fluctuations and lattice artefacts, and affects the 2D quality. We develop methodology for measuring the two components separately, which can be applied to arbitrary multiview display. As a case study, we provide measurement results for a display with eight views. Such measurements data can be used for optimizing multiview image sets for a given display.

5.14 GPU-based algorithms for optimized visualization and crosstalk mitigation on a multi-view display [14]

Authors: A. Boev, K. Raunio, A. Gotchev and K. Egiazarian
Publication: *Appeared in* Proceedings of SPIE on Electronic Imaging Symposium 2008

In this contribution, we present two GPU-optimized algorithms for displaying the frames of 2D-plus-Z stream on a multi-view 3D display. We aim at mitigating the cross-talk artifacts, which are inherent for such displays. In our approach, a 3D mesh is generated using the given depth map, then textured by the given 2D scene and properly inter-digitized on the screen. We make use of the GPU built-in libraries to perform these operations in a fast manner. To reduce the global crosstalk presence, we investigate two approaches. In the first approach, the 2D image is appropriately smoothed before texturing. The smoothing is done in horizontal direction by a 1-D filter bank driven by the given depth map. Such smoothing provides the needed anti-aliasing at the same filtering step. In the second approach, we introduce a higher number of properly blended virtual views than the display views supported and demonstrate that this is equivalent to a smoothing operation. We provide experimental results and discuss the performance and computational complexity of the two approaches. While the first approach is more appropriate for higher-resolution displays equipped with newer graphical accelerators, the latter approach is more general and suitable for lower-resolution displays and wider range of graphic accelerators.

5.15 OpenGL-Based Control of Semi-Active 3D Display [15]

Authors: A. Boev, K. Raunio, M. Georgiev, A. Gotchev and K. Egiazarian
Publication: *Appeared in* IEEE Proceedings on 3DTV Conference 2008

We present a system for 3D visualization, which combines "user-tracking" approach, used by displays with steerable optics, with generation of multiple views, typical for displays with fixed optical filter. Instead of eye-tracking, typical for the "user-tracking" approach, we propose a less computationally demanding head tracking, based on face detection. We investigate if the precise delivery of different images to each eye of the observer can be handled by the fixed optics of a multi-view 3D display, and if continuous head parallax can be achieved.

5.16 Optimized Single-Viewer Mode of Multi-view Autostereoscopic Display [16]

Authors: A. Boev, M. Georgiev, A. Gotchev and K. Egiazarian
Publication: *Submitted to* EUSIPCO 2008, Lausanne - Switzerland, September 2008

We propose an approach for optimizing the visual quality of a multi-view 3D display for a single viewer. The approach combines eye-position tracking system with on-the-fly visual optimization of multi-view image content. The tracking algorithm uses the video input from a pair of off-the-shelf web-cameras and employs fast and robust face and facial feature detection algorithms to provide features for the subsequent stereo matching and distance estimation.

Based on display measurements and having user's eyes position, the following visual improvements are achieved: continuous head parallax for wide range of observation angles, cross-talk mitigation and brightness enhancement for a single viewer, and multi-view image compensation related to the distance of the observer.

5.17 A Survey of Signal Processing Problems and Tools in Holographic Three-Dimensional Television [17]

Authors: L. Onural, A. Gotchev, H. M. Ozaktas and E. Stoykova
Publication: *Appeared in* IEEE Transactions on Circuits and Systems for Video Technology, Special Issue on MVC, Volume 17, 2007

Diffraction and holography are fertile areas for application of signal theory and processing. Recent work on 3DTV displays has posed particularly challenging signal processing problems. Various procedures to compute RayleighSommerfeld, Fresnel and Fraunhofer diffraction exist in the literature. Diffraction between parallel planes and tilted planes can be efficiently computed. Discretization and quantization of diffraction fields yield interesting theoretical and practical results, and allow efficient schemes compared to commonly used Nyquist sampling. The literature on computer-generated holography provides a good resource for holographic 3DTV related issues. Fast algorithms to compute Fourier, WalshHadamard, fractional Fourier, linear canonical, Fresnel, and wavelet transforms, as well as optimization- based techniques such as best orthogonal basis, matching pursuit, basis pursuit etc., are especially relevant signal processing techniques for wave propagation, diffraction, holography, and related problems. Atomic decompositions, multiresolution techniques, Gabor functions, and Wigner distributions are among the signal processing techniques which have or may be applied to problems in optics. Research aimed at solving such problems at the intersection of wave optics and signal processing promises not only to facilitate the development of 3DTV systems, but also to contribute to fundamental advances in optics and signal processing theory.

6 Roadmap

Roadmaps are useful in many industrial and technological development contexts, especially so that multiple researchers and companies can coordinate their actions and make human resources and capital investment decisions, for monitoring progress, identifying bottlenecks and enabling technologies, and enabling collaboration.

The present technical committee has its mission of furthering the theory and algorithms that will bridge the work of the other committees. This technical committee does not aim at producing a visible end product, but rather making possible the end products which are the main interest of the other technical committees. Therefore, the usefulness of a roadmap dedicated to this committee is limited; in essence the roadmaps for other committees, such as TC5, indirectly incorporate some of the developments being studied under the present committee.

Despite its limited usefulness, in what follows we will try to apply the roadmap concept to understand the precedence relationships between expected results and developments. This may help future efforts to be focused on problems that are most likely to hinder further progress if not satisfactorily solved, and help us better appreciate the linkage between the various efforts.

One of our high-priority research areas is "Information theory and signal processing based approaches to optical propagation, diffraction, and holography" and another one is "Theory and algorithms for diffraction calculations from arbitrary surfaces". While these physical phenomena are rather well understood, they are not normally formulated with a mathematical sophistication necessary to tackle the kind of complex processing tasks confronting us here. More sophisticated understanding and formulations are essential. Since progress in solving such theoretical problems is relatively erratic, it is difficult to provide a timeline. However, we may state an order of precedence that is necessary to be followed. There are basically three approaches to making progress in this area, each of which will be taken up in the following paragraphs.

The first approach is an information theoretical one in which the problem of estimating optical wavefields, be they created as the result of holographic processes or diffraction, is formulated as an information-theoretical measurement problem. This in turn has two aspects, the metrical problem which deals with quantization and noise sensitivity issues and the structural problem which deals with sampling and resolution issues. Theoretical results have been produced with regards to the metrical problem. However the results are not in a form to be applicable to real time problems. Whether the algorithms can be made fast enough to support real time application should be clear in 2-3 years, and if positive, such algorithms can be realized in about 3-4 years. These would allow theoretically efficient solutions of several of the inverse problems discussed elsewhere in this report. With regards to the structural problem, results are in a more preliminary state. Within 2-3 years we may expect them to be comparable to the state of the art of the metrical problem now, and within 3-5 years we may expect efficient algorithms to appear, if indeed possible. Unified and optimized treatment of both the metrical and structural problems may take longer, perhaps 7-8 years to appear. If not feasible, this would probably be evident by 3-4 years.

The second approach is numerical experimentation. Much of the work we have undertaken in this NoE under TC4 has been of this nature. We have collected considerable evidence on the behavior of several inverse problems, and their dependencies on various parameters. Different algorithms have been compared. This includes the subtopic "Device specific wavefield reconstruction" under our high-priority research areas. We expect this work to reach a maturity with the completion of student theses in 1-2 years. However, this will not solve all problems of real-time implementation. Such may take 5-7 years to appear as other graduate students take up this challenge. Actually, these numerical approaches will certainly be influenced by the information theoretic approach discussed in the previous paragraph and in fact the two approaches may merge in the context of producing real-time algorithms. Overall, if successful, in about 10 years such algorithms may be ready to take their place in holographic 3DTV systems.

The final approach involves linear algebraic approaches to tackling the inverse problems that arise. This is also a theoretical approach, that much like the information theoretic approach, could influence and merge with the numerical approach at the stage of algorithm development. However, little work has been done until now in this area. Therefore we do not know if useful results will yet emerge. If they do, they will probable emerge around 2-3 years from now and become practically applicable after 5 years.

It is important to underline that while all of the approaches above influence each other and may provide insights for the development of others, none of them is a prerequisite for the other. The development of neither is dependent on the other, and indeed a satisfactory solution using any one approach would be sufficient for the purpose. A multiplicity of approaches is taken since no single one has a guarantee of producing the desired fast real-time algorithms.

The subtopics "Non-orthogonal decompositions for forward problems" and "Fresnel transforms in arbitrary bases" are more specific theoretical avenues. These represent approaches that have the potential of enabling fast computations. While the vision associated with these is clear, unfortunately progress has been slow. It is difficult to put a time frame on these, since a breakthrough could lead to immediate development of fast algorithms; otherwise concrete results may not be available for 5 years or more.

Our third high-priority topic is "Phase-retrieval based approaches to holography", under which we have the subtopics "Phase shifting digital holography", "Phase retrieval from multiple images distributed in space or time", and "Self-referencing techniques". The subject matter of the subtopics are relatively concrete, with results already produced both within and external to the NoE. Further results are expected to continue to appear in the next 5 years. The umbrella topic involves a synthesis of such approaches, and would ideally culminate in a systematic method of choosing and applying such methods to digital holography. Such a unification would probably take 6-8 years.

All of the above efforts are either components or alternative avenues towards the goal of solving forward and inverse problems in the pre-display stage of 3DTV systems. Very roughly, we may say that the period from now to 5 years from now is expected to constitute the period of theoretical consolidation, the period from 5 years to 10 years is the period of realistic algorithm implementation, and in the period beyond 10 years we would hopefully see implementation quality refinement of the methods.

We conclude with a few comments on the time frames expected regarding the high priority area "Multicolor (three parallel) holographic recordings". We may expect near-term results in this area as high-resolution electronic color cameras (4K pixels or more) are now available. As the research in multi-sensor holographic recording and reconstruction is under way, more work in this field with visible results within 2-3 years is expected. As for the reconstruction of three color holograms simultaneously, research is progressing at a good pace, and we have already demonstrated two-color LED-based reconstructions in the lab. The field could mature in a couple of years.

As programmable electronic display devices like the graphics processing units in computers are getting more powerful and sophisticated, and the fundamental research in computer graphics rendering algorithms is producing novel results, the area "Fast computation of holograms by employing computer graphics methods" is also advancing. There are a few research groups with already published results. It is reasonable to expect an expansion during the next few years with useful end products in 3-4 years.

There is no doubt that near-term (3-5 years) 3DTV systems will be primarily based on multi-view video techniques. Commercial companies already have quite good auto-multi-view display devices. Thus the area "Correction filters for autostereoscopic displays" is already a prime topic for commercial display producers, and therefore the research with end products are already in place.

Needless to say, these estimates are based on current human efforts we see being put into the problem. It is reasonable to expect accelerated time-lines in our estimates as the interest of the research community expands in these topics and thus more researchers are involved. There is also a risk that despite best efforts, the desired solution may not be possible, or proves too difficult to develop. That is why a multiplicity of approaches and paths of development are being considered at this time. A chart that summarizes the mentioned roadmap can be seen in Figure 1.

7 Conclusions and Future Directions

This Technical Committee of 3DTV Project is relatively small compared to other Technical Committees. Furthermore, other TCs have advantage of dealing with more concentrated and established research areas with a greater degree of self-containedness. Even if, TC4 related research literature is scattered and non-uniform, we believe that one of the achievements of our NoE work is to emphasize and bring to the attention of researchers the relevance and the importance of these tasks within different contexts. TC4 related tasks are essential to achieve holographic 3DTV, but further progress in processing optical signals is needed. In Sec. 2.2, we listed the high priority topics that the TC found worthwhile to investigate and conducted research on.

Research areas related to TC4 are interdisciplinary; for example, the high priority task "Research in Diffraction Field Computation" is related to signal processing, optics and numerical methods. There are two conference papers and a book chapter related to this task which are discussed in Sec. 3.1. Due to existing fertile areas, the established collaborations between institutions are decided to be continued in the future.

In the high priority task "Research in Fast Computation of Holograms", performances of software and hardware are improved by utilizing computer graphics methods and specialized hardware for the implemented algorithms. There are one journal paper in preparation and one internal report related to this high priority task, discussed in Sec. 3.2.

The reconstruction of the shape of the object from wavefront measurement is investigated under the high priority task "Research on Phase-Retrieval Based Approaches to Holography". Here we conducted research on two different research lines, "Phase Unwrapping in Noisy Environments" and "Phase Shifting Profilometry". Three papers are listed in the former task and discussed in Sec. 3.3.1, while three papers are listed under the latter topic and discussed in Sec. 3.3.2. Proposed methods have several applications,

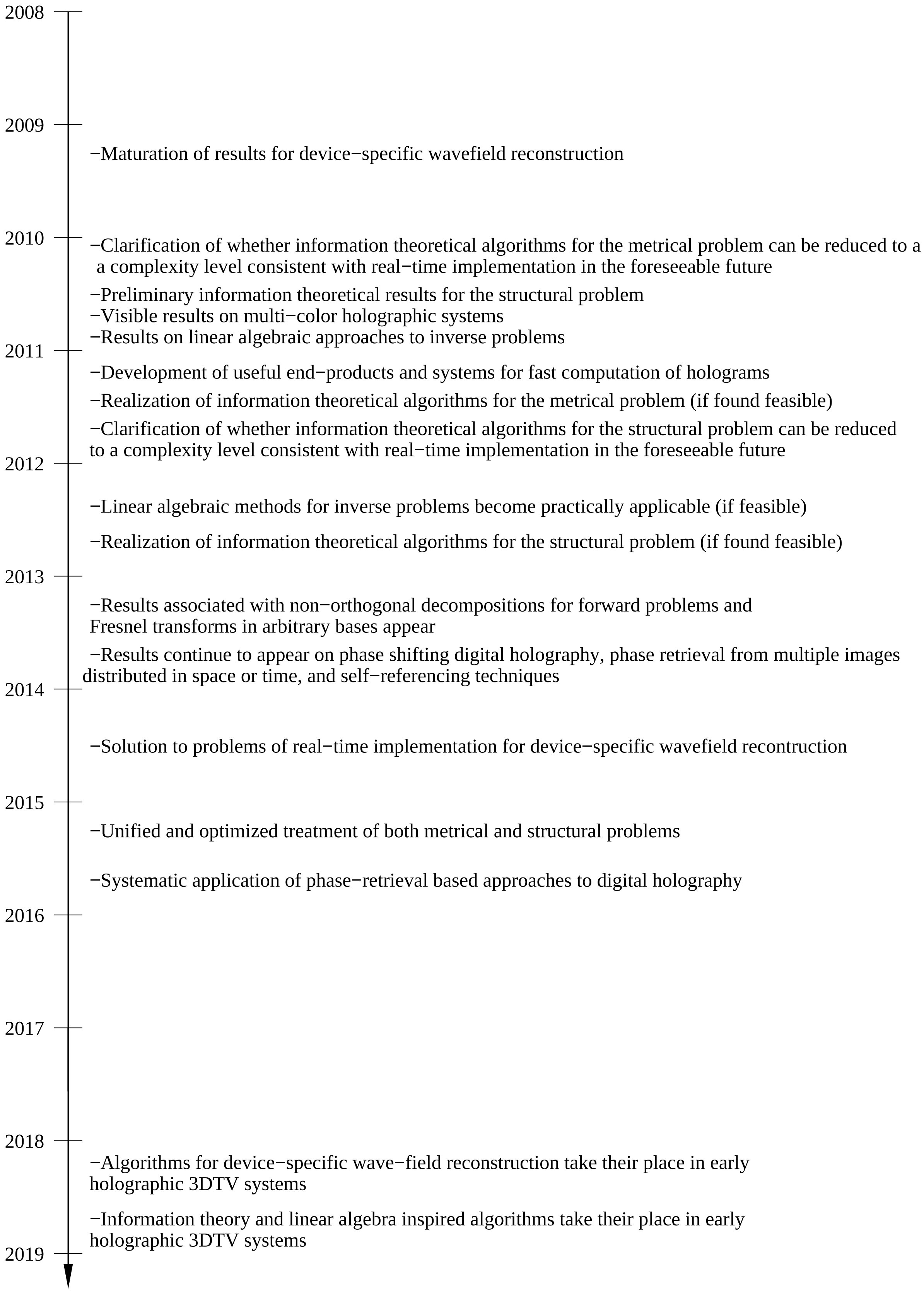

Figure 1: Roadmap chart

such as interferometric aperture radar and sonar, magnetic resonance imaging, adaptive optics, diffraction tomography, nondestructive testing of components, deformation and vibration measurements.

Our TC also investigated methods for increasing the visual quality of stereoscopic displays. Our accomplishments are discussed under Sec. 3.4, where we list four papers and one internal report.

A survey paper, discussed in sec. 3.5 summarizes the state-of-the-art developments on the topics within the scope of the Technical Committee. The achievements up to now are briefly presented and the future direction of the committee is painted.

In Sec. 4, we provide a brief marginal survey of the research work that is conducted outside the NoE and relevant to our research interests. Here, we also make a comparison between our achievements and the state-of-the-art and highlight the innovative aspects of our work.

The research results analyzed and reported in Sec. 3 basically summarize our achievements so far on the high priority research topics listed in Sec. 2.2. However, there remains uncompleted work or unsolved problems in virtually all the topics listed under this list and we plan to continue our research on them in the future. For instance, on the topic "Theory and algorithms for diffraction calculations from arbitrary surfaces", we plan to extend our results to cover the case of diffraction between continuously specified surfaces. About the topic "Device specific wavefield reconstruction", we will try to make our algorithms faster so that we get closer to real-time operation and we will try to devise algorithms for devices that are not considered until now. Regarding the topic "Phase-retrieval based approaches to holography", we will try to develop real-time systems for recording and reconstruction of 3D scenes in the light of our results that justify the usage of our techniques. Also, we will concentrate on methods for improving the performance and decreasing the computational complexity of the algorithms we proposed for phase unwrapping. This also applies to our work that appears under the category "Fast computation of holograms by employing computer graphics methods". Our research on the topic "Correction filters for autostereoscopic displays" will continue as well, in which we will continue to employ signal processing techniques to fight the artifacts that create visual disturbance.

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