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Signal Processing Issues in Diffraction and Holography TC4 Technical Report 2

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1 EXECUTIVE SUMMARY

Technical Committee 4 (TC4) has been active in conducting joint research within Workpackage 11 (WP11) of the 3DTV NoE. The group is concentrating on signal processing issues in diffraction and holography. A survey had been completed within the first year of the project; in addition, the first Technical Report was delivered on the seventeenth project month.

This second Technical Report (TR2), consists of 24 papers presented in seven different groups. Presentation slides associated with one of the short papers are also included since the slides contain helpful additional information.

The four papers in the first group are related to research results in basic signal processing tools. Several issues associated with signal processing aspects of diffraction and holography have not been sufficiently treated in the literature. Therefore, the researchers frequently find themselves in a position where they have to develop the needed basic signal processing tools. Furthermore, novel interpretations of some existing signal processing tools paves the way for better understanding of the basics of diffraction and holography. For example, a well known signal processing tool, the projection-slice theorem, is revisited in one of the papers, and then applied to describe the diffraction between parallel planes in a totally novel fashion. In another work, the effects of sampling of the diffraction field to the reconstructed image is analyzed using signal processing tools to provide an exact result together with its interpretations. The two other papers are overview papers emphasizing the strong link between various optics problems and associated signal processing approaches.

Research work on device-specific wave-field reconstruction coincides with one of the high-priority research topics that the group has identified. A preliminary work, related to the reconstruction of a specified coherent field by a deflectable mirror-array device is reported.

Six papers are listed under the "Diffraction Field Computation" topic. A group of papers under this heading deal with computation of the volume diffraction patterns from arbitrarily located limited numbers of known data points in space. Three methods based on direct matrix inversion, projections onto convex sets and conjugate gradient approaches are developed and their performances and computational complexities are compared. It is confirmed that the methods all yield the correct answer when the number of distributed data points are sufficient. Another paper in this group proposes a formulation based on the observation that the optical field is a superposition of plane waves propagating in different directions with the same spatial frequency due to the monochromaticity restriction. Therefore, a computationally efficient reduced dimensional solution based on Bessel functions is proposed and the associated results are given. Finally, physical reconstructions from computer generated holograms based on different computational techniques are compared.

"Fast Computation of Holograms" is another topic that the group considers among the high-priority tasks. Five papers presented under this topic present methods and results for hologram computation using state-of-the-art commercial computer graphics hardware using appropriate algorithms. Several simplifying approximations are investigated. In one of the papers, holograms with only horizontal-parallax are considered and the associated savings in computational complexity is reported. In another study, pre-computed and stored holographic pattern patches are fetched and modified in a simplified manner to construct the desired larger holographic pattern.

Four papers collected under "Phase-Retrieval Based Approaches to Holography" present novel techniques based on fringe pattern projection on the objects for the purpose of 3D shape measurements. Extraction of missing phase information from multiple intensity measurements is the key feature of the methods presented in this group.

One possible approach to overcome the technology imposed inadequate array sizes is to design systems using a multiple set of these arrays. A paper listed under synthetic-aperture techniques in holography proposes and analyzes such a case: two arrays, instead of one, is used for capturing and displaying larger size holograms.

Finally, two overview papers describing the scope and the tasks of the Committee are given in the report.

The Committee is continuing its work along the directions outlined above; based on the outlined intermediate research results, the group continuously revisits and assesses its technical scope, and modifies its research direction as needed.

2 Introduction

2.1 Scope of the Technical Committee 4

The scope of Technical Committee 4 (TC4) of the 3DTV Project is defined as "Signal Processing Issues in Diffraction and Holography". Therefore the scope lies within the intersection of the optics and signal processing fields. The topic is quite difficult, yet intriguing, and research in this area is expected to extend the theory in both the optics and signal processing areas significantly. The results are quite likely to find immediate application in holographic 3DTV displays.

The Technical Committee has identified two fundamental problems during its early collaboration phases and aligned most of its research work accordingly: given a 3D scene, compute the 3D variation of the associated optical field; and, given a desired 3D optical field, find the driving signals for a specific physical display device which is capable of generating optical fields (with some constraints). We call these two problems the "forward" and the "reverse" problems, respectively.

The Committee has also considered other topics. For example, a recently added topic targets the improvement of autostereoscopic displays by employing proper digital signal processing techniques.

The Committee interacts with the other Technical Committees of the 3DTV project, and provides solutions which, together with the results of other technical committees, paves to way to an end-to-end 3DTV operation.

Three-dimensional television (3DTV), with all its functional components, is a timely, but challenging problem. The functional components include the capture of 3D moving scenes, abstract representation of the captured data, forming and transmission of 3DTV signals, and the 3DTV display. Naturally, the technological basis is highly multidisciplinary. All functional components listed above are critically important for the proper functioning of the end-to-end system. Furthermore, there are other problems associated with proper interfacing of the basic functional blocks listed above.

One of the important issues is the conversion of abstract 3D moving scene information into signals which drive the display. There are several candidate technologies for the display of 3DTV signals. Among these, stereoscopic techniques, and their extensions involving lenticular microlens technology, and techniques such as integral imaging, seem to be rather easier to achieve. A more difficult, but probably more desirable alternative is the holographic technique. Naturally, signal processing plays a central role in solving the interface problem where 3D scene information is translated into signals which drive the display, no matter what the technology is. An associated, difficult but highly important problem is to find the optical wave fields in a 3D volume resulting from 3D objects; while such topics can be treated to a certain extent with classical methods, there are plenty of open problems. Obviously, for real-time TV operation, the efficiency and speed of the associated algorithms are a major concern.

Holography is the science of recording and recreating physical electromagnetic fields (mostly optical waves) propagating from a source. As the degree of success in duplicating the original fields in the absence of the original objects gets better, the quality of the 3D image seen by the observer also gets closer to the original. In the ideal case of perfect duplication, there is no way to discriminate the image from the original by optical means. Analysis of the underlying diffraction problems date back to the seventeenth century. The principles of holography have been known for about 60 years, and practical holograms have been made since the 1960s. Applications of digital technology to the recording of and reconstruction from holograms have been quite popular. Recently maturing technologies indicate that continuously moving 3D images can be generated by refreshed holograms. Furthermore, advances in electronic technologies, optics, computer science, signal processing, and telecommunications, seem to create an exciting synergy towards achieving fully digital 3DTV.

Diffraction from coherently illuminated sources is well formulated in classical texts. Various approximation techniques, each with its own benefits and limitations, are also well developed and frequently applied to diffraction problems. However, fast and elegant solutions to fundamental problems associated with holographic 3DTV are not available yet. For example, a challenging problem is to find the 3D optical field generated by a given 3D scene; real-time TV operation requires fast implementations of these solutions, and this is another severe problem. Physical display devices that will eventually generate the desired 3D optical fields have their own properties and constraints. To drive these physical devices to eventually generate the desired 3D optical fields requires the computation of the appropriate driving signals; this is another challenging problem, especially for real-time TV operations.

Stereoscopic 3DTV displays rely on sending slightly different pictures to each eye of the human observer: each picture is a conventional picture, but the angle of observation between them is slightly different to match the horizontal separation of the two eyes. Recently developed displays based on stereoscopic principles are rather sophisticated; for example, they can track the observers' head, and then electronically generate the two views to match the observation coordinates. Furthermore, the required pictures, representing an arbitrary viewing angle, are computationally generated from a given sparse sample of such pictures, or directly from 3D scene information. In the technique known as integral imaging, instead of just a pair of views, many pictures at different angles are recorded and then properly displayed to yield 3D perception.

2.2 Summary of Survey Results

The preliminary task of TC4 during the first year of the 3DTV Project was to complete an extensive survey on topics within its scope. The survey is 133 pages, and highlights the state-of-the-art in this field by carefully assessing 819 related references in 15 sections grouped into four main parts. While updating the researchers background in the field, the survey also paved the way for finalizing the research plans by helping to identify high-priority research tasks.

Upon completion of the survey, it was concluded that appropriate mathematical tools needed to solve the problems outlined in subsection 2.1 are of special interest. Some of these tools are rather well developed, but it seems that the fundamental problems outlined in subsection 2.1 have the potential to be a driving force for further development of some primary signal processing techniques as well. Discretization and quantization issues in diffraction problems, as well as sampling and interpolation, are found to be primarily important topics. Issues associated with digital capturing of holographic signals and generating purely computational diffraction masks to achieve desired results are also of prime interest. A rather new technique called "phase-shifting digital holography" is found to be quite interesting. Space-frequency techniques, which attracted a lot of interest in signal processing, provide a rich collection of various tools to solve the fundamental problems outlined in subsection 2.1. These include plane wave decompositions, which are just Fourier transforms, and atomic decompositions, wavelets, and related issues, all of which exhibit great potential for applications to 3DTV. Existing optimization techniques deserve attention for their potential applicability. Another closely related and well developed signal processing topic is the fractional Fourier transform.

Since the observers of 3DTV are going to be human beings, a good understanding of the human visual system is essential. Algorithms which exploit the nature of the human visual system are found to be important.

2.3 Research activities of TC4

Equipped with the scientific scope, and the completed survey, the committee 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

Research activities in these fields during the first 17 months of the project resulted in a collection of papers and presentations that collectively made up *TC4 Technical Report I.*

Based on its first phase of research activities, the Committee further narrowed the scope of its high-priority research tasks. With these modifications, the current high-priority tasks are:

- 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.

Guided by these high-priority research tasks, the Committee conducted research during its second-phase of operations. Results of these research activities are published, and these publications are presented in this report as a collection of 24 papers.

3 Analysis of Research Results

3.1 Research in Basic Tools

The complexity and the richness of the problems that fall into the scope of this research group occasionally reveals the inadequacies of existing mathematical or signal processing tools. This triggers interest in research to further develop such fundamental tools, which in turn facilitates the solution of the problems described in section 2. The paper "Projection-Slice Theorem as a Tool for Mathematical Representation of Diffraction" is a good example of such work [1]. The monochromaticity restriction in diffraction results in a concentration of signal energy, associated with the 3D diffraction pattern, along a spherical curve in the 3D Fourier domain. That observation leads to utilization of impulse functions over curves and surfaces. The basic definitions of such functions were already revised with the purpose of effectively utilizing them in the problems we are interested in, in an earlier paper [25]. Here in this paper, the projection-slice theorem is revisited using the impulse functions over surfaces, and thus, a fundamental signal processing tool is given a novel interpretation. Furthermore, it is shown that this novel interpretation yields a better insight into the classical diffraction problem. The problem of monochromatic diffraction between two parallel planes is solved, once more, using this tool.

Another paper, "Exact Analysis of the Effects of Sampling of the Scalar Diffraction Field", solves the reconstruction from the sampled Rayleigh-Sommerfeld diffraction pattern [2]. Periodic sampling, and its effects, of higher-dimensional signals is well known in signal processing, and the associated tools are well developed. These tools were previously applied to Fresnel diffraction, and interesting results, which indicated huge reductions in sampling rate requirements without sacrificing full recoverability, were obtained. Now, here in this work, these results are extended to the Rayleigh-Sommerfeld case, which gives the exact solution to the scalar diffraction problem. The dispersion of the resultant replicas (the diffraction orders) are presented through rigorous mathematical analysis. The differences compared to the Fresnel case, which is an approximation, are presented and justified. Thus a clear understanding of sampling issues in diffraction is achieved. Such an understanding is essential for digital processing of diffraction related signals since the first step in digitization of continuous signals involves sampling.

The paper, "Some Signal Processing Issues in Diffraction and Holographic 3DTV" is a paper which clarifies the links between some well developed signal processing tools and diffraction [3]. Thus emphasizes the importance of signal processing in holographic 3DTV related problems. Even though the individual tools have been used for many years, the paper is useful since it provides a good collection of seemingly diverse signal processing tools together with their importance in diffraction. In addition to well known 2D system model for the computation of diffraction between parallel planes, the paper also revisits the fractional Fourier transform and its relation to diffraction. Furthermore, a concise signal processing procedure is outlined for the computation of diffraction between tilted planes. The paper then outlines the fundamental problems within the scope of the research group as also given here in Section 2. The importance of the sampling issues in diffraction is further emphasized and some interesting results are provided. The paper is a very good source of information for those who wish to start research in this field.

Another paper "A Survey on Sampling and Quantization in Diffraction and Holography" is also a good source for those who would like to start research in this field [4]. The paper outlines sampling theory, starting from classical Shannon's theorem, and continuing into more modern approaches based on shift-invariant spaces. The work then extends to sampling and reconstruction in wavelet spaces, non-uniform sampling and reconstruction. After the fundamentals of sampling are covered, the specific issue of sampling in optics, diffraction and holography is discussed. Useful results which yield very efficient sampling strategies for finite extent optical signals are outlined by pointing out related references. Wavelet inspired sampling of optical signals are examined in depth by pointing out interesting research topics. Quantization issues are also included.

The four papers above are fundamental in linking signal processing tools to diffraction problems. In addition, it is clearly shown that the application of fundamental signal processing techniques to diffraction related problems yields interesting and useful novel results. Therefore, these papers are rather basic in the sense that they provide a sound basis for further research in the field. Furthermore, these papers provide a much better insight into the physical problems that the group is dealing with.

3.2 Research on Device-Specific Wave Field Reconstruction

Among many possible forms of potential holographic 3DTV display devices, a possibility is to use deflectable mirror array devices (DMAD). Currently, one of the most widely used DMADs is the digital micromirror device (DMD) which is commercially available. It is interesting to investigate the capabilities of such devices as holographic 3DTV displays. The paper entitled "Three-dimensional Monochromatic Light Field Synthesis with a Deflectable Mirror Array Device" explores such potential by deriving the analytical expressions for coherent monochromatic light fields generated by such devices [5]. Furthermore, the problem is posed as a constrained iterative algorithm, and attempts are made to find out the discrete mirror positions to achieve the best possible approximation to a given 3D light field.

3.3 Research in Diffraction Field Computation

Computation of the scalar optical diffraction field due to an object has attracted the attention of researchers for decades even if the fundamentals of diffraction goes back to the 1600s. The richness of the topic in the application side and its complexity contribute to its attractiveness. The major goal in this problem is to model the computation of the continuous diffraction field due to an object defined in a continuous 3D space, as accurately as possible. The models in the literature are based on several approximations, such as starting with a discrete space and having simplified versions of the diffraction field relationships.

Here we analyze certain intermediate results obtained by TC4 researchers working on this task. These results are published in a number of papers which are presented in the Appendix. The first five papers deal essentially with the same problem: computation of the complete discrete field over space from a given field data over only a much smaller set of points. Initially, an algebraic solution is formulated without much emphasis on the computational efficiency. This formed a firm basis for quantitative assessment of other future solutions based on other techniques. Then, faster solutions based on Projections onto Convex Sets (POCS) and Conjugate Gradient (CG) methods, together with their performances, are presented in subsequent papers. Furthermore, the initial 2D field computation case is then extended to the 3D case. The last paper in the group simplifies the model and reduces the computational burden by converting the problem to polar coordinates; it deals with a mathematical model based on the circularly symmetric nature of the diffraction kernels using Bessel functions. Digital computation is followed by optical reconstruction in another work; thus links to real physical cases are also established. Further details of each paper are discussed below.

The paper "Signal Processing Problems and Algorithms in Display Side of 3DTV" gives an overview of the two closely related problems [6]. The first of these problems is about the simultaneous calculation of the diffraction field from an object which is described by distributed discrete sample points over 2D space by brute force computation techniques. This is done to form a reference basis for comparing other methods; therefore, the heavy computational burden associated with the matrix inversions was not a concern. The second problem is the computation of the driving signal of a deflectable mirror-array device (DMAD) used as a reflection type SLM. It is shown that both problems can be posed as optimization problems; the problem formulations are presented, together with some related simulations.

The idea of simultaneous computation of the diffraction field due to data points given at arbitrary locations in 2D space is the focus of the paper "Diffraction Field Computation from Arbitrarily Distributed Data Points in Space" [7]. For simplicity, the authors chose to work on ia 2D space. The proposed method is based on the projection onto convex sets (POCS) algorithm. Then, to understand the effectiveness of the proposed algorithm, its results are compared to the results of the direct matrix inversion method. The POCS method outperforms the direct matrix inversion method in both computation time and memory allocation criteria, as expected. These methods yields correct solutions over the space if the necessary conditions are satisfied. These conditions are having an enough number of samples and consistent data. The first one is associated with the general sampling issue; what is sampled is the 2D diffraction field, and if there are enough samples, the overall 2D diffraction field can be fully reconstructed from the available samples. The second condition is associated with the fact that the 2D diffraction pattern is not an arbitrary pattern, but is a result of a propagating 1D wave. The imposed constraint, therefore, is the mathematical model of propagation based on the underlying physics; this in turn requires that the data must be consistent with this requirement.

The paper "Non-uniform Sampling and Reconstruction of Diffraction Field" advances the results obtained in the previous papers [8]. In this paper, the problem is generalized to a non-uniformly sampled space. The presented method is based on the conjugate gradient (CG) algorithm which is known as a powerful tool for matrix inversion. The CG algorithm provides quite accurate results and fast computation.

Another paper entitled "Reconstruction of Scalar Diffraction Field from Distributed Data Points over 3D Space", extends the problem to 3D space [9]. The performances of the algorithms are evaluated according to the memory allocation and the number of complex multiplications which are needed to implement the algorithm. The POCS outperforms the CG if the given points are placed on a uniform grid.

The last paper in the group of five, entitled "Bessel Functions Based Reconstruction of Non-uniformly Sampled Diffraction Fields" provides a formulation to the diffraction problem by converting the models utilized in the previous papers to polar coordinates [10] . This brings Bessel functions into the solution. The monochromaticity of the light restricts the spatial frequencies of the plane wave components onto the Ewald sphere; therefore, a polar representation is essentially one dimensional (angular direction). Further restriction to only discrete propagation angles yields a simple discrete formulation. Determination of the unknown amplitudes of the propagating waves in different discrete directions from the available partial data over some discrete points in the space again becomes a similar problem as in the previous papers. The conjugate gradient method provides a quick and correct result.

The paper "Reconstruction of Computer Generated Holograms by Spatial Light Modulators" discusses three different in-line hologram computation methods [11]. These methods are based on bipolar intensity, the Fresnel diffraction integral and the Rayleigh-Sommerfeld diffraction. All of them assume that an initial field is defined on a plane and the computed in-line hologram is on another plane which is parallel to the previous one. The goal is to check the real-life performances of these methods when the computer generated holograms are transferred to a spatial light modulator (SLM), and illuminated by coherent light. Therefore, the reconstructions are conducted optically. The diffracted field emanated from the illuminated SLM gave the reconstructed field. The results were satisfactory.

3.4 Research in Fast Computation of Holograms

For real-time holographic 3DTV operations, we have to find fast methods to compute holograms, and this is a challenging problem. The needed improvement in speed can be achieved by finding more efficient algorithms. Naturally, fast algorithms should be optimized for the hardware architectures that they are running on. Efficiency of algorithms improve software-only implementations. But for real speed up, full-custom hardware design is the ultimate solution. However, full-custom hardware design is also a complicated and demanding process. A compromise is to use rather more standard programmable hardware like common graphics processing units. The five papers presented below fall into this final category. Fast hologram computation related algorithms using graphical processing units are developed and tested.

The paper "Scanline Rendering of Digital Hologram and Hologram Numerical Reconstruction" describes a method that uses rapidness of computer graphics techniques and computing power of Graphical Processing Unit (GPU) [12]. Objects are modelled as triangular meshes. Diffused illumination and simple constant shading are used to improve the visibility of the object. To improve the speed, the square root operation is avoided and replaced by proper numerical methods. Numerical reconstruction methods are used for visual evaluation of the results.

Another paper "Digital HPO Hologram Rendering Pipeline" deals with computation of digital horizontal parallax only (HPO) holograms of 3D objects [13]. The method given in this paper generalizes the illumination models used in the previous paper. Furthermore, the object is warped by a texture. To compute the HPO hologram due to the samples obtained after angular sampling of the object, the bipolar intensity method is used. Results are evaluated by numerical reconstruction methods.

The papers "Computer Generated Holograms of Triangular Meshes Using a Graphical Processing Unit" and "Full-parallax Hologram Synthesis of Triangular Meshes Using a Graphical Processing Unit" present another method based on the processing power of GPU [14,15]. In this method, pre-computed patterns are used to compute the diffraction pattern. Again, the angular sampling strategy is followed. Visual quality of the numerically reconstructed objects are satisfactory, but the computation time is rather long.

The paper "Computer Generated Holography Using Parallel Commodity Graphics Hardware" describes another novel method taking advantage of the GPU and computer graphics technics such as GPU shaders and blending [16]. Hence, a 10 frames per second performance for an object composed of 1000 points is achieved. However, the method is not robust against numerical errors. The algorithm to generate the hologram is based on bipolar intensity method. Optical reconstructions are conducted using SLMs.

3.5 Research on Phase-Retrieval Based Approaches to Holography

If there are enough measurements, it is possible to find out the complex-valued light distribution in space from intensity-only measurements. We call such methods collectively as "phase-retrieval based" approaches. The phase-retrieval task comprises several obligatory or optional steps as phase demodulation, including phase unwrapping when necessary, removal of non-informative phase terms, extraction of information about the object and denoising which could be applied during each of these steps.

The paper "Optical Methods for Contouring and Shape Measurement" gives an overview of phase-retrieval algorithms in fringe projection techniques for shape measurement, including phase-shifting with equal (conventional case) or arbitrary (generalized case) constant phase shifts, Fourier transform, regularized phase-tracking, and wavelet based approaches [17]. Even though the primary focus of this paper is in shape measurement, and thus falls into the scope of another Technical Committee of 3DTV NoE, the developed and presented signal processing techniques are directly applicable to the outlined phase-retrieval based approaches within the scope of our work.

Another paper entitled "Pattern Projection with a Sinusoidal Phase Grating" focuses on a sinusoidal phase grating as a pattern projection element in a phase-shifting system [18]. Usage of the phase grating for fringe pattern generation under coherent illumination proposes several advantages as technical simplicity, high efficiency, minimization of phase-shifting error, large focal depth and independence of the fringe pattern spatial period on the wavelength. The contribution of this study is to show the possibility of generating simultaneously four sinusoidal patterns of equal intensity, contrast and spacing that are phase-shifted at $\pi/2$ by using four identical phase gratings and diode lasers that emit in the NIR spectral region at wavelengths 790 nm, 810 nm, 850 nm and 910 nm. This technical solution overcomes the main drawback of the temporal phase-shifting profilometry method in which the pattern acquisition is made successively in time.

Yet another paper in this group, "Technique for Reconstructing a Surface Shape for Measuring Coordinates" further investigates the fringe projection methods for the measurement of 3D shapes [19, 20]. The paper presents the projection of two-period interference patterns. Two different projection methods are investigated: one of the methods is based on a Mach-Zender interferometer, and the other one is a micromirror projector with digital synthesis of fringes. Experimental results are presented. The paper also presents some comments on the general phase-retrieval approaches from multiple intensity measurements, and the link between holography and such techniques. This is a simultaneous publication of the Russian original and its English translation.

Measurement of the surface profile using phase-stepping techniques while projecting fringes is the topic of the paper "Real Time Phase Stepping Pattern Projection Profilometry" [21]. A single-shot measurement operation based on simultaneous projection of four phase-shifted sinusoidal fringe patterns at four different wavelengths is presented.

3.6 Synthetic Aperture Techniques in 3DTV

One of the major problems in digital holography is the inadequate resolution of the related digital devices. The number of pixels of the commonly used CCD arrays is still too small for capturing holograms with sufficient quality. Similarly, the number of elements of spatial light modulators used for holographic displays are far from adequate. Even though the resolution is increasing quickly as the technology develops, other alternatives to overcome this problem are also needed. One obvious alternative is to use many such devices simultaneously, or in a time multiplexed manner. The paper "Resolution Enhancement by Aperture Synthesis in Digital Holography" investigates such an alternative [24]. Double aperture digital holography is introduced and analyzed. Two identical CCD arrays are used to capture a higher resolution hologram. The reconstruction is performed from a single larger hologram obtained by positioning the two holograms in their respective locations. Both the analysis and the experimental results indicate that this method is feasible.

3.7 Overview Papers

The paper outlined here in this subsection, "An Overview of the Holographic Display Related Tasks within European 3DTV Project", is an overview paper to give readers a comprehensive outline of the historical developments and the state of the art in some topics within the scope of our committee [22]. After a brief introduction to the 3DTV project, and the scope of our Technical Committee as outlined in Sec. 2.1, the paper gives an overview of signal processing tasks as indicated in our high-priority list, and an account of signal processing tools readily applicable to solve these problems.

Another brief paper, "Current Issues in Holographic 3DTV" and the associated presentation gives the reader a general overview of the 3DTV Project and then presents an overview of 3D display techniques [23]. Following this, holographic displays are emphasized and an introduction to signal processing techniques that this committee is focusing on is presented.

4 Abstracts of Publications

4.1 Projection-Slice Theorem as a Tool for Mathematical Representation of Diffraction [1]

Authors: L. Onural (Bilkent)
Publication: *Appeared in* IEEE Signal Processing Letters, Volume 14, 2007

Although the impulse (Dirac delta) function has been widely used as a tool in signal processing, its more complicated counterpart, the impulse function over higher dimensional manifolds in $\mathbf{R^N}$ did not get such a widespread utilization. Based on carefully made definitions of such functions, it is shown that many higher dimensional signal processing problems can be better formulated with more insight and flexibility using these tools. The well known projection-slice theorem is revisited using these impulse functions. As a demonstration of the utility of the projection-slice formulation using impulse functions over hyperplanes, the scalar optical diffraction is reformulated in a more general context.

4.2 Exact Analysis of the Effects of Sampling of the Scalar Diffraction Field [2]

Authors: L. Onural (Bilkent)
Publication: *Appeared in* Journal of the Optical Society of America A, Volume 24, 2007

If the sampled diffraction pattern due to a planar object is used to reconstruct the object pattern by back propagation, the obtained pattern is no longer be the same as the original. The effect of such sampling to the reconstruction is analyzed. The formulation uses the plane-wave expansion, and therefore, the provided solution is exact for wave propagation in media where scalar wave propagation is valid. Contrary to the sampling effects under Fresnel approximation, the exact solution indicates that there are no modulated replicas of the original object in the reconstruction pattern. Rather, the distortion is in the form of modulated, translated and dispersed versions of the original.

4.3 Some Signal Processing Issues in Diffraction and Holographic 3DTV [3]

Authors: L. Onural and H. M. Ozaktas (Bilkent)
Publication: *Accepted for publication in* Signal Processing: Image Communication, 3DTV Special Issue

Image capture and image display will most likely be decoupled in future 3DTV systems. For this reason, as well as the need to convert abstract representations of 3D images to display driver signals, and the need to explicitly consider optical diffraction and propagation effects, it is expected that signal processing issues will be of fundamental importance in 3DTV systems. Since diffraction between two parallel planes can be represented as a 2D linear shift-invariant system, various signal processing techniques naturally play an important role. Diffraction between tilted planes can also be modelled as a relatively simple system, leading to efficient discrete computations. Two fundamental problems are digital computation of the optical field arising from a 3D object, and finding the driver signals for a given optical display device so as to generate a desired optical field in space. The discretization of optical signals leads to several interesting issues; for example, it is possible to violate the Nyquist rate while sampling, but still achieve full reconstruction. The fractional Fourier transform is another signal processing tool which finds applications in optical wave propagation.

4.4 A Survey on Sampling and Quantization in Diffraction and Holography [4]

Authors: A. Gotchev (TUT) and L. Onural(Bilkent)
Publication: *Appeared in* Workshop on Spectral Methods and Multirate Signal Processing, September 2006, Florence, Italy

We present a survey on the sampling and quantization issues arising in holography and diffraction. We comment on the importance of these issues for emerging applications such as 3D and holographic TV and video communications and emphasize the role of signal processing for designing proper drivers for future holographic displays. Our paper starts with a review of the classical sampling theory from Caushy, Whittaker, Shannon and Kotelnikov to the most recent advances based on frame theory. Then, the most influential works in the area of optics, diffraction and holography related with sampling and quantization are reviewed. We aim to provoke signal processing people to view the very known sampling theory from a new, i.e. diffraction-based point of view.

4.5 Three-Dimensional Monochromatic Light Field Synthesis with a Deflectable Mirror Array Device [5]

Authors: E. Ulusoy, L. Onural, H. M. Ozaktas (Bilkent) and V. Uzunov, A. Gotchev (TUT)
Publication: *Appeared in* Proceedings of SPIE on Photon Management II, April 2006, Strasbourg, France

We investigated the problem of complex scalar monochromatic light field synthesis with a deflectable mirror array device (DMAD). First, an analysis of the diffraction field produced by the device upon certain configurations is given assuming Fresnel diffraction. Specifically, we derived expressions for the diffraction field given the parameters of the illumination wave and the tilt angles of the mirrors. The results of the analysis are used in later stages of the work to compute the samples of light fields produced by mirrors at certain points in space. Second, the light field synthesis problem is formulated as a linear constrained optimization problem assuming that mirrors of the DMAD can be tilted among a finite number of different tilt angles. The formulation is initially developed in the analog domain. Transformation to digital domain is carried out assuming that desired fields are originating from spatially bounded objects. In particular, we arrived at a Dp = b type of problem with some constraints on p, where D and b are known, and p will be solved for and will determine the configuration of the device. This final form is directly amenable to digital processing. Finally, we adapt and apply matching pursuit and simulated annealing algorithms to this digital problem. Simulations are carried out to illustrate the results. Simulated annealing performs successful synthesis when supplied with good initial conditions. However, we should come up with systematic approaches for providing good initial conditions to the algorithm. We do not have an appropriate strategy currently. Our results also suggest that simulated annealing achieves better results than MP. However, if only a part of the mirrors can be used, and the rest can be turned off, the performance of MP is acceptable and it turns out to be stable for different types of fields.

4.6 Signal Processing Problems and Algorithms in Display Side of 3DTV [6]

Authors: E. Ulusoy, L. Onural, H. M. Ozaktas (Bilkent) and V. Uzunov, A. Gotchev (TUT)
Publication: *Appeared in* IEEE Conference Proceedings on ICIP2006, October 2006, Atlanta, USA

Two important signal processing problems in the display side of a holographic 3DTV are the computation of the diffraction field of a 3D object from its abstract representation, and determination of the best display configuration to synthesize some intended light distribution. To solve the former problem, we worked on the computation of 1D diffraction patterns from discrete data distributed over 2D space. The problem is solved using matrix pseudo-inversion which dominates the computational complexity. Then, the light field synthesis problem by a deflectable mirror array device (DMAD) is posed as a constrained linear optimization problem. The formulation makes direct application of common optimization algorithms quite easy. The simulations indicate that developed methods are promising.

4.7 Diffraction Field Computation From Arbitrarily Distributed Data Points in Space [7]

Authors: G. B. Esmer, L. Onural, H. M. Ozaktas (Bilkent) and V. Uzunov, A. Gotchev (TUT)
Publication: *Accepted for publication in* Signal Processing: Image Communication, 3DTV Special Issue

Computation of the diffraction field from a given set of arbitrarily distributed data points in space is an important signal processing problem arising in digital holographic 3D displays. The field arising from such distributed data points has to be solved simultaneously by considering all mutual couplings to get correct results. In our approach, the discrete form of the plane wave decomposition is used to calculate the diffraction field. Two approaches, based on matrix inversion and on projections on convex sets (POCS), are studied. Both approaches are able to obtain the desired field when the number of given data points is larger than the number of data points on a transverse cross-section of the space. The POCS based algorithm outperforms the matrix-inversion based algorithm when the number of known data points is large.

4.8 Non-Uniform Sampling and Reconstruction of Diffraction Field [8]

Authors: V. Uzunov, A. Gotchev (TUT) and G. B. Esmer, L. Onural, H. M. Ozaktas (Bilkent)
Publication: *Appeared in* Workshop on Spectral Methods and Multirate Signal Processing, September 2006, Florence, Italy

Reconstruction of the diffraction field from non-uniformly sampled data points is an important signal processing problem in 3D display of a scene. The plane wave decomposition approach is traditionally used to calculate the diffraction between two parallel planes. Here, we use its discrete form to create a finite dimensional model of continuous diffraction fields. The model is used to state the problem of field reconstruction as matrix inversion. When the analysis is carried out in frequency domain, a symmetric reconstruction matrix can be formed. Its inversion is simplified by fast iterative approach, based on the conjugate gradient (CG) method. Numerical experiments demonstrate the applicability and accuracy of the chosen approach. The CG method converges in a small number of iterations and requires much less computational costs compared to direct matrix inversion.

4.9 Reconstruction of Scalar Diffraction Field From Distributed Data Points Over 3D Space [9]

Authors: G. B. Esmer, L. Onural, H. M. Ozaktas (Bilkent) and V. Uzunov, A. Gotchev (TUT)
Publication: *Accepted for publication in* 3DTV-CON, May 2007, Kos Island, Greece

Diffraction field computation is an important task in signal conversion stage of the holographic 3DTV. We use plane wave decomposition which gives the same results with the Rayleigh - Sommerfeld diffraction integral, thus there is no need to have Fresnel or Fraunhofer approximations. One of the easiest way to represent a 3D scene is to use distributed data points over 3D space. Computation of diffraction field due to these points has to be done simultaneously. We proposed two methods: projection onto convex sets and conjugate gradient. The normalized error and the computational complexity are the two criteria used to evaluate the performances of the algorithms. Both of them provides the given field on the reference plane if the number of given samples is larger than the number of samples on a transversal plane. Projection onto convex sets outperforms conjugate gradient in the sense of efficient memory allocation and computation time.

4.10 Bessel Functions - Based Reconstruction of Non-Uniformly Sampled Diffraction Fields [10]

Authors: V. Uzunov, A. Gotchev (TUT) and G. B. Esmer, L. Onural, H. M. Ozaktas (Bilkent)
Publication: *Accepted for publication in* 3DTV-CON, May 2007, Kos Island, Greece

A discrete computational model for the diffraction process is essential in forward problems related to holographic TV. The model must be as general as possible, since the shape of the displayed objects does not bear any restrictions. We derive a discrete diffraction model which suits the problem of reconstruction of diffraction fields from a set of non-uniformly distributed samples. The only restriction of the model is the wave nature of the field. The derivation takes advantage of changing the spatial and frequency coordinates to polar form and ends up with a model stated in terms of Bessel functions. The model proves to be a separable orthogonal basis. It shows rapid convergence when evaluated in the framework of the non-uniform sampling problem.

4.11 Reconstruction of Computer Generated Holograms by Spatial Light Modulators [11]

Authors: M. Kovachev, R. Ilieva, L. Onural, G. B. Esmer, T. Reyhan (Bilkent) and J. Watson, P. Benzie (Aberdeen)
Publication: *Appeared in* International Workshop on Multimedia Content Representation, Classification and Security, September 2006, Istanbul, Turkey

Computer generated holograms (CGHs) are one possible technique for 3D (3-dimensional) imaging. In holography the a *priori* information of a 3D object is stored as an interference pattern. A hologram contains high spatial frequencies. Various methods, such as compression of fringe patterns, generation of horizontal-parallax only (HPO) holograms and computation of binary holograms, have been proposed to reduce the bandwidth requirements. A spatial light modulator (SLM) with high resolution and a small pixel pitch is required to optically reconstruct a dynamic CGH. For a good match between the recorded object wavefront and the reconstructed wavefront, it is necessary to generate holograms suitable to the SLMs parameters (for instance pixel pitch, pixel count, pixel geometry) and reconstruction wavelength. SLMs may be electronically written by CGHs or holograms captured directly from a digital camera. Recently, digital holography has seen renewed interest, with the development of mega pixel (MP) SLMs as well as MP charge-coupled devices (CCDs) with high spatial resolution and dynamic range.

4.12 Scanline Rendering of Digital Hologram and Hologram Numerical Reconstruction [12]

Authors: M. Janda, I. Hanak and V. Skala (Plzen)
Publication: *Appeared in* Spring Conference on Computer Graphics, April 2006, Casta-Papiernicka, Slovak Republic

This paper presents a fast and complete rendering method that can be used for creating digital holograms of a scene consisting of triangle mesh objects. This method solves visibility and occlusion problems and is capable to work with triangles as the basic primitive instead of the usually used points. It is fast because it avoids the direct distance computation using the square root operation. Advanced numerical reconstruction techniques are used for presenting the results of the rendering method.

4.13 Digital HPO Hologram Rendering Pipeline [13]

Authors: M. Janda, I. Hanak and V. Skala (Plzen)
Publication: *Appeared in* Eurographics 2006, September 2006, Vienna, Austria

This paper describes a rendering pipeline for digital hologram synthesis. The pipeline is capable of handling triangle meshes, directional light sources, texture coordinates and advanced illumination models. Due to the huge computational requirements of hologram synthesis only the HPO holograms are considered.

4.14 Computer Generated Holograms of Triangular Meshes Using a Graphical Processing Unit [14]

Authors: I. Hanak, M. Janda and V. Skala (Plzen)
Publication: *Unpublished paper*

Computer generated holography requires a computational power that is not available for a common computer today. Graphical processing unit provides a computational power greater than the CPU. This paper presents an approach that combines the digital holography, the GPU, and the computer graphics with the aim on the visual quality of the output. The goal is to render complex triangular scenes with shading and materials efficiently in times that are reasonable.

4.15 Full-Parallax Hologram Synthesis of Triangular Meshes Using a Graphical Processing Unit [15]

Authors: I. Hanak, M. Janda and V. Skala (Plzen)
Publication: *Accepted for publication in* 3DTV-CON, May 2007, Kos Island, Greece

Application of the GPU to the computer generated holography is a topic of research for some time. While the majority of authors aim on performance, we aim on visual aspects. We present a new approach that is capable to synthesize a hologram of a scene described by triangles using the GPU and it is capable to respect a local intensity variation on a surface caused by textures and solve occlusion at the same time.

4.16 Computer Generated Holography Using Parallel Commodity Graphics Hardware [16]

Authors: L. Ahrenberg, M. Magnor (MPG) and P. Benzie, J. Watson (Aberdeen)
Publication: *Appeared in* Optics Express

This paper presents a novel method for using programmable graphics hardware to generate fringe patterns for SLM-based holographic displays. The algorithm is designed to take the programming constraints imposed by the graphics hardware pipeline model into consideration, and scales linearly with the number of object points. In contrast to previous methods we do not have to use the Fresnel approximation. The technique can also be used on several graphics processors in parallel for further optimization. We achieve real-time frame rates for objects consisting of a few hundred points at a resolution of 960×600 pixels and over 10 frames per second for 1000 points.

4.17 Optical Methods for Contouring and Shape Measurement [17]

Authors: V. Sainov, E. Stoykova and J. Harizanova (CLOSPI-BAS)
Publication: *Appeared in* Proceedings of ICO Topical Meeting on Optoinformatics and Information Photonics, September 2006, St. Petersburg, Russia

An overview of phase-retrieval methods from a periodical fringe pattern in digital holography and pattern projection profilometry which provide information for three-dimensional imaging is presented. From a signal processing viewpoint, phase retrieval from a fringe pattern recorded by a CCD requires solution of a non-linear inverse problem based on fringe analysis in the presence of additive and multiplicative noises. All obligatory or optional steps comprising by the phase retrieval task as phase demodulation, including phase unwrapping when necessary, removal of non-informative phase terms, extraction of information about the complex amplitude or 3D coordinates are briefly described. The existing methods are divided in two groups . multiple frame and single frame methods or temporal and spatial methods. Following this division, first the phase-shifting approach is outlined with its pros and cons. Special attention is dedicated to error-compensating algorithms and generalized phase shifting techniques. Among special methods, 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 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. The experimental results of relative and absolute 3D coordinates measurement as well as of wavefront reconstruction in observation of biological microobjects made in CLOSPI-BAS are used for illustration.

4.18 Pattern Projection with a Sinusoidal Phase Grating [18]

Authors: E. Stoykova, J. Harizanova and V. Sainov (CLOSPI-BAS)
Publication: *Accepted for publication in* 3DTV-CON, May 2007, Kos Island, Greece

The present work focuses on a sinusoidal phase grating as a pattern projection element in a phase-shifting profilometric system. Usage of the phase grating for fringe pattern generation under coherent illumination proposes several advantages as technical simplicity, high efficiency, minimization of the phase-shifting error, large focal depth and independence of the fringe pattern spatial period on the wavelength. The work considers the frequency content of the projected fringes in the Fresnel diffraction zone and gives the results of test measurements of relative 3D coordinates by means of a pattern projection system with a phase grating that is interferometrically recorded on a holographic plate. Implementation of sinusoidal phase gratings in a four-wavelength profilometric system with parallel recording of the phase-shifted patterns by a multi-camera system for real-time measurements of 3D coordinates of objects and scenes is discussed.

4.19 Technique for reconstructing a surface shape for measuring coordinates [19, 20]

Authors: V. Sainov, J. Harizanova, E. Stoykova (CLOSPI-BAS) and H. M. Ozaktas, L. Onural (Bilkent)
Publication: *Appeared in* Journal of Optical Technology and in Opticheskiĭ Zhurnal (Simultaneous publication of Russian original and its English translation)

This paper describes a method of projecting interference fringes as one of the most accessible techniques for measuring the coordinates of objects and scenes that can be used when solving inverse problems in dynamic holographic display, where the coordinates need to be measured in order to compute diffraction structures when reconstructing three-dimensional images. A comparative analysis is presented of the experimental results obtained with successive projections of interference patterns with two different periods, using a Mach VZehnder interferometer in coherent light and a micromirror projector with digital generation of fringes in white light. The use of the method is limited by the size of the objects and scenes. The possibilities of using more refined methods, including the holographic approach to phase reconstruction, are discussed.

4.20 Real Time Phase Stepping Pattern Projection Profilometry [21]

Authors: V. Sainov, E. Stoykova and J. Harizanova (CLOSPI-BAS)
Publication: *Appeared in* The International Conference Speckle06, September 2006, Nimes, France

A single-shot fringe projection profilometry system based on simultaneous projection of four phase-shifted sinusoidal fringe patterns generated at four different wavelengths is described. The system includes a fringe pattern generation module containing four blocks with four near-infrared diode lasers and a registration module with four CCD cameras. In order to simplify the technical solution and to avoid the stringent requirement for stability in the case of interferometric fringe generation, we study both theoretically and experimentally realization of the proposed system by using of a phase grating as well as a holographic optical element for reconstruction of two point sources. The results of the measurement of the relative and absolute coordinates of test objects for both types of diffraction gratings are presented.

4.21 An Overview of the Holographic Display Related Tasks within the European 3DTV Project [22]

Authors: L. Onural, H. M. Ozaktas (Bilkent); E. Stoykova (CLOSPI-BAS); A. Gotchev (TUT) and J. Watson (Aberdeen)
Publication: *Appeared in* Proceedings of SPIE on Photon Management II, April 2006, Strasbourg, France

A European consortium has been working since September 2004 on all video-based technical aspects of three-dimensional television. The group has structured its technical activities under five technical committees focusing on capturing 3D live scenes, converting the captured scenes to an abstract 3D representations, transmitting the 3D visual information, displaying the 3D video, and processing of signals for the conversion of the abstract 3D video to signals needed to drive the display. The display of 3D video signals by holographic means is highly desirable. Synthesis of high-resolution computer generated holograms with high spatial frequency content, using fast algorithms, is crucial. Fresnel approximation with its fast implementations, fast superposition of zone-lens terms, look-up tables using pre-computed holoprimitives are reported in the literature. Phase-retrieval methods are also under investigation. Successful solutions to this problem will benefit from proper utilization and adaptation of signal processing tools like wavelets, fresnelets, chirplets, and atomic decompositions and various optimization algorithms like matching pursuit or simulated annealing.

4.22 Current Issues in Holographic 3DTV [23]

Authors: L. Onural (Bilkent)
Publication: *Appeared in* Proceedings of ICO Topical Meeting on Optoinformatics and Information Photonics, September 2006, St. Petersburg, Russia

A consortium of 19 institutions have been working on all technical aspects of 3DTV since September 2004. The technical issues associated with the multidisciplinary and broad 3DTV topic are covered by five technical committees. Within the displays area, all candidate technologies, including holographic 3DTV displays, are investigated. Deflectable mirror array devices and spatial light modulators are among the devices investigated for holographic 3DTV. Computation of the driving signals of a specific display device to achieve a holographic reconstruction is a challenging problem whose solutions require sophisticated signal processing techniques.

4.23 Resolution Enhancement by Aperture Synthesis in Digital Holography [24]

Authors: T. Kreis and K. Schluter (BIAS)
Publication: *Accepted for publication in* Optical Engineering

The resolution of digital holography as an optical imaging system is described by the point spread function of the system. Here the point spread function of double aperture digital holography is determined. It promises the possibility of a resolution increase by the concept of synthetic apertures, where we combine the digital holograms of two CCD-arrays in one large hologram and reconstruct or we superpose coherently the two reconstructed wavefields after a proper shift. An experimental method for the determination of this shift with subpixel accuracy is given. Furthermore experimental results of numerically reconstructed wave fields from synthetic holograms stemming from two mutually shifted digital holograms of the same scene are presented.

5 Conclusions and Future Directions

This Technical Committee of the 3DTV Project is unique in several ways. The other Technical Committees correspond to relatively established and better recognized research areas with a greater degree of self-containedness. In contrast, the present Technical Committee does not correspond to a well-recognized area of investigation and is even more interdisciplinary than the other Committees. Fewer researchers worldwide would identify their research focus as "signal processing issues in diffraction and holography", even including those who are undertaking relevant research efforts. The relevant research literature is scattered and non-uniform and it is one of the missions of this Technical Committee to consolidate relevant results and fill missing gaps. The existence of this Committee owes to the realization that while the other relatively self-contained research areas may show considerable progress, the realization of especially holographic approaches to 3DTV, that represent the ultimate aim in this area, will require considerable advances in processing optical signals in ways that have not attracted sufficient interest until now. The importance of these issues stems from two observations: (i) Especially holographic approaches to 3DTV will inherently require the consideration of optical diffraction; (ii) Future media technologies will be primarily digital in nature. These two observations also imply a third: Processing, conversion, and transmission of the signals in question will require considerable computational manipulation.

Due to these observations, our purpose in this Technical Committee has been to first make sure that we see the forest, before concentrating on the trees. To this end, we have first broadly defined the problem of interest as an information-theoretic understanding of optical waves, with focus on the effects of sampling and quantization which are the essence of digital processing. The high-priority research item "Information theory and signal processing based approaches to optical propagation, diffraction, and holography (general unifying theory of discretization, quantization, and interpolation in optics)" is a rather broad research program in itself. Since several TC4 members are likely to have a long-term interest in this area beyond the NoE, and since the collaborations initiated are likely to continue beyond the NoE, we hope to make major contributions to this area, which some years later may culminate in a book consolidating the uncovered knowledge. Progress so far has identified and progressed along four main avenues. The first is to develop novel mathematical tools and formulations for analyzing and representing diffraction phenomena, as well as to consolidate existing knowledge in the area. Here, in addition to our preset goals, we occasionally stumble upon gaps or insufficiencies in mathematical or signal analysis techniques in working towards our main goals, and this results in the need to fill these gaps in order to progress. This effort has resulted in many publications [1–4, 22, 25]. The second is to use traditional information and communication theory which represents the most analytical approach. The third approach is to use linear algebraic concepts to explore the resulting linear relationships between the field values in different regions of space. The fourth is to employ numerical experimentation and comparisons towards the same end. The latter two approaches have been carried out with a high-degree of collaboration between TUT and Bilkent with several conference and journal publications already achieved or under preparation [6–9]. (These tasks overlap and have been treated in the same publications as the item "Theory and algorithms for diffraction calculations from arbitrary surfaces" discussed below.)

As noted, this very broad approach to signal processing issues in diffraction and holography is an effort that is progressing steadily and will continue beyond the NoE. At the same time, as this broad research effort continues, our attention is being focused on more specific problems as well. These represent specific approaches or solutions which attract our attention as having potential technological impact. Among these we may mention several efforts. One of these is "Device-specific wavefield reconstruction", which has until now dealt with schemes to reconstruct desired optical wavefields (which would carry the 3D image) by appropriately driving DMD devices. Publications include [5, 6].

A broader effort in this context is represented by the high-priority item "Theory and algorithms for diffraction calculations from arbitrary surfaces". Several conference and journal publications have been made in this area, discussing different approaches and algorithms [6–11]. The related yet distinct focus on fast computation of holograms has also yielded several publications [12–16].

The high-priority item "Phase-retrieval based approaches to holography" focuses on certain computational approaches which are considered especially suitable to digital holography, as well as techniques such as "Phase-shifting digital holography", "Phase retrieval from multiple images", and "Self-referencing techniques". Publications have emerged from these latter techniques [17–21].

To summarize, efforts in this Technical Committee are progressing both along fundamental lines, as well as focusing on technologically promising approaches which are illuminated by the fundamental efforts. Several conference and/or journal publications have been made in all high-priority areas. Although good progress is being made in all areas, we might note a few areas where it is slower. While our progress on fundamental information theory approaches to sampling and quantization has been quite good, the breadth and depth of the problem means that consolidated results may emerge only after several years. Work on determining the best computational approaches to forward diffraction problems from arbitrary distributions is progressing slower than desirable, although concrete achievements have already been documented.

More generally, while the fundamental efforts have a long vision, the more specific technological efforts may be revised and redirected as results emerge. Therefore, the technological solutions we are studying and pursuing may change within a year or two, and other approaches may occupy us more in future periods.

Future work will involve furthering the steady progress along the fundamental avenues, and refining and revising targets along the more technologically oriented goals.

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