Digital Holography for Security Applications

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Abstract. A survey of Digital Holography (DH) and its employment in different application fields is provided. This paper reviews the main principles of the DH focusing on the optical techniques for security purposes. Recording and processing of three dimensional data, secured storage data, the use of Multimedia Sensor Network (MSN) for encrypted data transmission, and thus remote reconstruction of 3D images, are relevant examples in which DH represents an attractive solution. In this work, the state of art and major research challenges for this type of applications are shown and at the end fundamental open issue are discussed in order to outline the future research trends in this topic.

Keywords: Digital Holography, Interference, Diffraction, optoelectronics, Wireless Multimedia Sensor Network.

1 Introduction

Carefully attention has been shown in information security during the last decade. Optical information-processing techniques have proved to be a real alternative to purely electronic-processing in security, encryption, and pattern-recognition applications. This is partially due to recent advances in optoelectronic devices and components, such as detectors, modulators, optical memories, and displays. Now, in general, it is easy to transfer information from electronic to optical domains and vice versa at high speeds. In this way, it is possible to combine the advantages of both approaches to develop more efficient security applications. This fact is especially relevant when securing information codified in the form of two-dimensional (2D) or three-dimensional (3-D) images because, in these cases, optical systems are unavoidable. More deeply, with the coming of high-quality megapixel digital cameras, the creation of digital holograms of real-world objects has become viable today. They permit to reconstruct 3D images without optical equipment (e.g. eyeglasses to combine separate images, or special screen), such as stereoscopy technique, in which 3D of an objects is obtained by the "*illusion of depth*" due to the two offset images of the left and right eye of the viewer.

On the other hand a hologram is an optical element or an image that can record all information, both amplitude and phase information, present in a wave front needed to reconstruct the real 3 dimension image of an object [1].

Specifically a holographically storage image or *hologram* represents the recorded interference pattern between a wave field scattered from the object,

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named *wave object*, and a coherent background named *reference wave*. It is usually recorded on a flat surface, but contains the information about the entire three dimensional wave field. The process of making hologram is known as "*Holography*" and a sub area of holography is the "*Digital Holography* (DH)", that enables, thanks to the development of *Charged Coupled Devices* (CCDs), full digital recording and processing of holograms, without any photographic recording as intermediate step.

Hence the growing interest in the digital holography permits to consider new optical technique for security applications never proposed in the past, such as the secure storage of 3D data, or the pioneer remote reconstruction of 3-D image. Actually to obtain a reliable system further investigations are needed. For this scope, in this work we provide an overview of the state of art, which is the starting point for our research field. In the next future we will set up a laboratory[1] ito design a new system able to encrypt and secure transmit 3-D sensible data by using Digital Holography.

This paper is organized as follows: in Section 2, we provide a brief overview of the traditional holography, in Section 3 the main principles of the digital holography are carried out, in Section 4 we show the main holographic scenarios, while in Section 5 we pay attention to a particular type of scenarios: security scenarios takeing into account the main advantages reachable by using this technique not reachable with other technologies. Finally, in Section 6 we draw the main conclusions.

2 Holography

A hologram is the photographic record of the interference figure between the radiation scattered from an object and a coherent reference wave. Light with sufficient coherence length illuminates an object. It is scattered at the object surface and reflected to the recording medium. A second light beam, known as the reference beam, also illuminates the recording medium, so that interference occurs between the two beams. The resulting light field generates a seemingly random pattern of varying intensity which is recorded in the hologram.

2.1 Hologram Theory

Interference and diffraction effects are the theoretic concepts of the holography. Recording of the image is possible thanks to the interference effect, while reconstructing of the data is possible thanks to the diffraction effect. The holographic process is described mathematically using the description of the light propagation by the wave equation, following Maxwell formalism, in which electrical field is a vector quantity, which could vibrate in any direction, perpendicular to light propagation.

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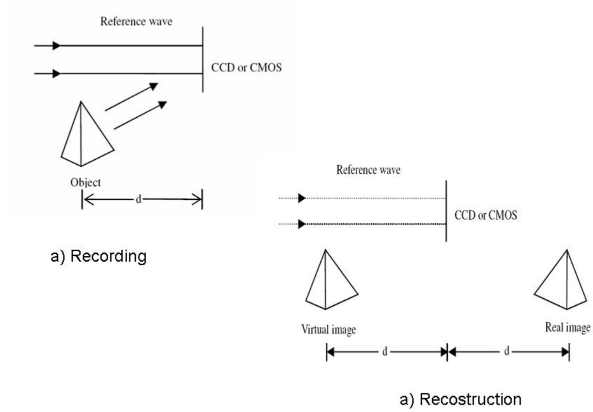

Fig. 1. Off-axis DH technique: a) Hologram recording, b) Hologram reconstruction

The superposition of two or more waves in the space is named *interference*. If we consider two monochromatic waves with equal frequencies and wavelengths the resulting intensity is the sum of the individual intensities I_1, and I_2 plus the interference term, which is:

$$2\sqrt{I_1 I_2} \cdot cos(\Delta\varphi) \tag{1}$$

this term depends on the phase difference between the waves.

The intensity distribution observed on the recording medium is the *interference figure*, and it is composed by a succession of light and dark band named *interference fringes.*

After, to reconstruct the image, diffraction effect needs to take into account. This phenomenon can be described by the Huygens' principle and mathematically analyzed by the Fresnel-Kirchhoff integral [3].

Finally, it is important to mention some drawback in the holography, for recording (*Speckles*), and reconstructing (*image distortion*) phase respectively:

- *Speckles*- This effect appears when a rough surface is illuminated with coherent light. In this situation observer sees a grainy image. The intensity of the light scattered by the surface fluctuates randomly in space, dark and bright spots appear. These spots are named *speckles.*
- *image distortion*- In the hologram reconstruction the obtained field has composed of three terms: the first term is the un-diffracted reference wave passing the hologram (*zero diffraction order*); the second term is the reconstructed object wave, forming the virtual image; and the third term generates a distorted image of the object. For off-axis holography the virtual image, the real image, and the un-diffracted wave are spatially separated.

The speckles problem can be solved by using rough surface with height variations less than the wavelength of the light, while an undistorted real image can be produced by using the conjugate reference beam for reconstruction.

3 Digital Theory

Digital holography is the technology of acquiring and processing holographic measurement data, typically via a CCD camera or a similar device. In particular, this includes the numerical reconstruction of object data from the recorded measurement data, in distinction to an optical reconstruction which reproduces an aspect of the object. Digital holography typically delivers three-dimensional surface or optical thickness data. There are different techniques available in practice, depending on the intended purpose. Among of all, in the following we report a brief description of the more extensive technique adopted:

- *Off-axis configuration* - This process was proposed for the first time in [2] where a small angle between the reference and the object beams is used. In this configuration, a single recorded digital hologram is sufficient to reconstruct the information defining the shape of the surface, allowing real-time imaging.
- *Phase-shifting holograms* - This technique uses a phase shifting algorithm to calculate the initial phase and thus the complex amplitude in any plane, e.g. the image plane. Hence with the initial complex amplitude distribution in one plane, the wave field in any other plane can be calculated by using the Fresnel-Kirchoff formulation of diffraction [4].

3.1 General Principles

In this section an overview of the theoretic principles of the DH is drawn. First of all simple evaluation of the spatial frequency requirements to obtain suitable 3-D reconstruction is provided. After two main DH techniques are taken into account in order to highlight the basic analytical concepts of both schemes.

Spatial Frequency Requirements. A CCD used to record must resolve the interference pattern resulting from superposition of the reference wave with the waves scattered from the different object points. The maximum spatial frequency to be resolved is determined by the maximum angle $\theta_m ax$ between these waves, and the wavelength λ, according to:

$$f_{max} = \frac{2}{\lambda} \cdot \frac{\theta_{max}}{2} \tag{2}$$

The distance between the neighboring pixels of a high resolution CCD is only in the order of $\Delta x \approx 5\mu m$, thus the corresponding maximum resolvable spatial frequency can be calculated by:

$$f_{max} = \frac{1}{2\Delta x} \tag{3}$$

Hence resolutions will be in the range of 100 line pairs per millimeter (Lp/mm). Combining the above equations we obtained that:

$$\theta_{max} \approx \frac{\lambda}{2\Delta x} \tag{4}$$

where the approximation is valid for small angles. The distance between neighboring pixels is therefore the quantity, which limits the maximum angle between reference and object wave.

By formula it is possible to calculate the minimum distance d_{min} between object and CCD [2]. It is shown that the minimum distance linearly increases with both the dimension of the object and the CCD pixel number, while decreases with the wavelength. It means that the maximum spatial frequency has to be adapted very carefully to the resolution of the CCD.

Off-Axis Holography. The concept of digital hologram recording is illustrated in Fig.1(part a). A plane reference wave and the wave reflected from a three dimensional object placed at a distance d from a CCD or CMOS are interfering at the same surface. The resulting hologram is electronically recorded and stored. In optical reconstruction as shown in Fig.1(part b), a virtual image appears at the position of the original object and the real image is also formed at a distance d , but in the opposite side from the CCD or CMOS.

The diffraction of a light wave at CCD or CMOS is described by the Fresnel-Kirchoff integral:

$$\Gamma(\xi', \eta') = \frac{1}{\lambda} \int \int h(x,y) R(x,y) \frac{exp(-i\frac{2\pi}{\lambda})\rho'}{\rho'} dxdy \tag{5}$$

with

$$\rho' = \sqrt{(x-\xi')^2 + (y-\eta')^2 + d^2} \tag{6}$$

where $R(x,y)$ is the plane reference wave, $h(x,y)$ is the hologram function and ρ' is the distance between a point in the hologram plane and a point in the reconstruction plane. An undistorted real image can be produced by using the conjugate reference beam for reconstruction, i.e. to consider the conjugate plane reference wave R^* instead of R in the above equation.

In addition, it is possible to consider digitized version of the equation 5 for numerical reconstruction. Generally the numerical version of the equation can be obtain by two different approaches: reconstruction by the discrete Fresnel transformation or the Fourier Transform (FT) method; reconstruction by the convolution method (CV). For the interest reader the analytical description of both methods are in [3].

Phase-Shifting Holography. The principal arrangement for phase shifting DH is shown in Fig.2. The object wave and the reference wave are interfering at the surface of a CCD. The reference wave is guided via a mirror mounted on a *piezo-electrict transducer* (PZT). Whit this PZT the phase of the reference wave can be shifted stepwise. Several (at least three) interferograms with mutual phase shifts are recorded. Afterwards the object phase ϕ_0 is calculated from these phase shifted interferograms. The real amplitude $a_0(x, y)$ of the object wave can be measured from the intensity by blocking the reference wave.

As a result, the complex amplitude:

$$E_0(x, y) = a_0(x, y) \exp(+i\phi_0(x, y)) \tag{7}$$

of the object wave is determined in the recording (x, y) plane. By using the Fresnel-Kirchoff integral is possible to calculate the complex amplitude in any other plane [5].

The advantage of phase shifting DH is a reconstructed image of the object without the zero order term and the conjugate image. The price for this achievement is the higher technical effort: phase shifted interferograms have to be generated, restricting the method to slowly varying phenomena with constant phase during the record cycle.

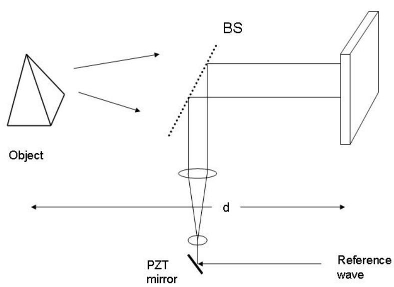

Fig. 2. Phase shifting DH, set-up

3.2 Open Issues

Holography is a 3D imaging process that instantaneously captures the volumetric information of a test object. For this purpose DH looks very promising in making holography an easy-to-use technique thanks to recent developments in megapixel CCD or CMOS cameras and the fast, efficient reconstruction algorithm by which it is now possible to record digital holograms in real time. Furthermore the use of fast computers in numerical reconstruction makes DH more flexible in terms of hologram processing.

Hence the ability of numerical evaluation of both amplitude and phase information is its main advantage over other optical imaging methods. Anyway, the limited pixel size of the commercially available digital detectors restricts the angle between the object and reference beams to a few degrees for hologram recording. Various digital methods have been proposed to solve this issue. For instance, an alternative could be perform instantaneous 3-D measurement of particle distribution as in [7], or including stereoscopic particle tracking as proposed in [8]. Actually these techniques have limitations either with volume size or particle density or the need for multiple exposures. However, in recent years Digital Holography has incurred enhancement. In addition numerical reconstruction process of particles holograms in different planes based on the Fourier transform (FT) and convolution (CV) schemes have been proposed in literature [9], to provide schemes enable the use of complex amplitude information that is inaccessible in optical reconstruction.

Future efforts in this field will be the capacity of to extraction and tracking of particles from the reconstructed images. This will permit a more deep applicability if the DH in encrypted data storage for security scenarios.

4 Digital Holography Applications

Holography can be put to a variety of uses other than recording images. In this work we are particularly interested into security applications. Anyway the application of DH can be seen in different areas:

- *Holographic Interferometry*- Holographic interferometry (HI) is a technique which enables static and dynamic displacements of objects with optically rough surfaces to be measured to optical interferometric precision (i.e. to fractions of a wavelength of light).
- *Security applications* - Holograms are used for security purposes, especially in the anti-counterfeiting field, and for optical data processing for encryption technique, hence we can distinguish:
  - *Secure Data Storage* - Holographic data storage is a technique that can store high density of information, up to become the next generation of popular storage media;
  - *Encrypted Data* - The Digital Holography permits to encrypt and decrypt 3D data, enabling a more deep secured data transmission;
  - *Secure ID Tags* - Security holograms are very difficult to forge because they are replicated from a master hologram which requires expensive, specialized and technologically advanced equipment.
  - *CCD Image Sensors*- A revolutionary application could be the employment of DH for sensors for different purposes, especially for security: sensors will be able to perform measurements and react accordingly. In this scenario the hologram is made with a modified material that interacts with certain molecules generating a change in the fringe periodicity or refractive index, therefore, the color of the holographic reflection.
- *Dynamic Holography* - In static holography, recording, developing and reconstructing occur sequentially and a permanent hologram is produced. There also exist holographic materials which do not need the developing process and can record a hologram in a very short time. This allows one to use holography to perform some simple operations in an all-optical way (e.g. optical cache memories, image processing, optical computing).

Among of all, in this work we investigated how the DH is a suitable solution for security, and how it is possible to obtain challenger solutions not yet investigated.

5 Optical Technique for Information Security

As already mentioned DH can be applied in security field. Specifically in this section we described how it can be employed in the security field, and which advantages can be reached.

5.1 Optical Encryption and Decryption of Three Dimensional Objects

Digital Holography permits to encrypt data in 3D. The existing algorithms for encryption are based on 1D, or 2D data. Usually the 2D data are often considered as mutually orthogonal, and thus a simplification of the data processing is always justified. On the other hand, by 3D data, this approach is no more valid, and then developing of more complex algorithms are required. Consequently coding these new powerful algorithms is not trivial.

During the last decade, researchers investigated in the encryption definition field and different solutions have been provided. One of the approaches to securing information by optical means consists in the use of random phase-encoding techniques. In these methods, images or holograms are transformed, by using random phase masks, into noise distributions. Therefore, the original information remains encrypted and be recovered only by means of a random phase mask acting as the key. However, in general, the resulting encrypted data contain both phase and amplitude and, thus, must be recorded and stored holographically.

Digital holography as already mentioned is a useful technique for recording the fully complex field of a wave front. Encrypted data are stored in digital format, so that is possible to transmit, and decrypt the encrypted data digitally. For instance, in Fig.3 a secure image/video-storage/transmission system that uses a combination of double-random phase encryption and a digital holographic technique is shown.

The data are encrypted optically by the double-random phase encryption technique and recorded as a digital hologram. The optical key, that is, the Fourier phase mask, can also be recorded as a digital hologram. The encrypted data can be decrypted digitally with the hologram of the optical key.

An alternative technique for optical encryption of three-dimensional (3D) information could be the use of the Computer Generated Holograms (CGH) principle [12]. Specifically the principle of off-axis digital holography is used with single and multiple phases encoding to encrypt the 3D object. Authors showed that Multiple-Phase encoding is very secure than Single-Phase encoding but it will add a noise in case of gray-scale image compared with Black-White image, and thus more investigation are needed in that direction, in order to obtain a good level of encryption without complexity addition.

In conclusion, the 3D data encryption is possible using DH, but it requires complex processing, more than other existing technologies. On the other hand, the reliability level reachable is very high with respect to other solutions, thanks to the nature of the encrypted data: 3D data cannot be considered as the

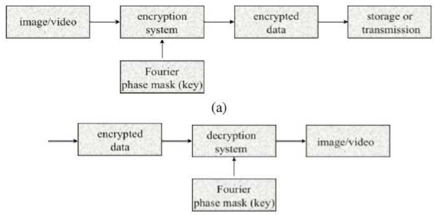

Fig. 3. Secure image/video-storage/transmission system that uses a combination of double-random phase encryption and a digital holographic technique: (a) an encryption/transmission system and (b) a receiving/decryption system.

composition of 1D data mutually orthogonal information. Consequently the developed algorithms to describe the information become complex, and not trivial to implement and simulate.

5.2 Secure Data Storage Based on Digital Holography

Digital Holography is a promising candidates for next generation of secured data elaboration. Holographic storage enables storage densities that can surpass those of traditional recording because it goes beyond the two-dimensional approaches of conventional storage technologies to write data in three dimensions. The underlying principles of holographic storage and the development of high-performance holographic recording materials are described in [10]. In addition possible solutions to obtain an encrypted optical memory system by using two 3-D keys are still open issues. Solutions are proposed in literature [11], even if more investigation are needed to obtain efficient scheme.

5.3 Wireless Multimedia Sensor Networks

Wireless Sensor Networks (WSN) have received a deep interest in research and industrial community due to many applications where they can be employed. Originally WSNs have been intended to measure physical phenomena and thus for low-bandwidth, and delay-tolerant data streams [6]. Recently, the focus is shifting toward research aimed at revisiting the sensor network paradigm even to enable delivery of multimedia content. This attitude leads to the consideration of a new sensor network concept, in which the integration of low-power wireless networking technologies with inexpensive hardware such as CMOS or CCD cameras and microphones will permit the development of a new concept of sensor networks: the *Wireless Multimedia Sensor Networks* (WMSNs). These networks are based on wireless, interconnected smart devices that enable retrieving video and audio streams, still images, and scalar sensor data [13]. A typical multimedia sensor network is shown in Fig.4. New applications are possible by using this type of networks. Among of all we remind: *Multimedia Surveillance Sensor Networks.* where sensors can be used to enhance and complement existing surveillance systems to prevent crime and terrorist attacks; or *Environmental and Structural Monitoring*, where an arrays of video sensors already are used by oceanographers can be used to determine the evolution of sandbars using image processing techniques.

To design this new sensor networks concept new paradigms are needed, among of all:

1. A real-time streaming application is more demanding than data sensing applications in wireless sensor networks primarily due to its extensive requirements for video/audio encoding. The limitations of the sensor nodes require video coding/compression that has low complexity, produces a low output bandwidth, tolerates loss, and consumes as little power as possible.
2. The area where multimedia streaming applications are different from other applications in wireless sensor networks is in the usability of encryption techniques to ensure confidentiality. We remind that in a wireless sensor network, the public key cryptography schemes are not suitable because of their high power and computation requirements. On the other hand, standard symmetric encryption schemes, such as DES and AES, are commonly used. However, these schemes are unsuitable for multimedia data. Multimedia data is generally larger in size and use of these symmetric encryption schemes has memory and computation requirements that are unsupportable by the sensor nodes.
3. To supporting multimedia traffic, a new concept of the transport layer is required, because in the traditional WSN for data transmission, the notion of end-to-end packet delivery reliability is in most cases unnecessary.

The use of holographic technique permits to solve the issues related to the multimedia transmission than the other solutions. For instance image/video encoding and transmission by DH, as described in the previous sections, will support less resource demanding than other technique. Hence DH can be used in this type of networks by considering the transmission of secure digital hologram trough the network. The CCD sensors will be connected into the distributed network for the transmission encrypted data. In contrast to Radio Frequency (RF), optical devices are smaller and consume less power; reflection, diffraction, and scattering from aerosols help distribute signal over large areas; and optical wireless provides freedom from interference and eavesdropping within an opaque enclosure. Optics can accommodate high-bandwidth transmission of multimedia without meet harmful effect due to interference of radio propagation. These motivate use of optical wireless as a mode of communication in sensor networks, and the capability of delivering high level of data due to the optical data storage not reachable with other technologies. In conclusion future researches will require to define solutions able to joint power optimization and efficient channel coding to design a new wireless sensor network for multimedia application. Actually due to the lack of comprehensive comparison studies and test-bed implementations, at the moment it is no possible to provide quantitative comparisons.

In addition, with DH it will be possible to reconstruct image remotely, without optics equipment (e.g. lens, screen) because each pixel, compounding the image, have got both amplitude and phase information needed to reconstruct the original object image. In this context, Optical Holography permits to reconstruct image in the laboratory, while by using DH it is possible to reconstruct the image remotely through a complex opto-electronic system composed by fibers, and electro-optics devices. In this way, collected images by Wireless Multimedia Sensor Networks, will be available and correctly reconstructed for instance $1000Km$ far away. Actually the system will require high costs due to both complex opto-electric devices, and powerful computers to carry out data processing. This is the pioneer system that we intend to investigate in the next years. For this scope we will set up a laboratory in the next future to perform measurements in this field. Specifically our aim is to define the guidelines of the system with restricted costs, as low as possible, in order to consider the system feasibility.

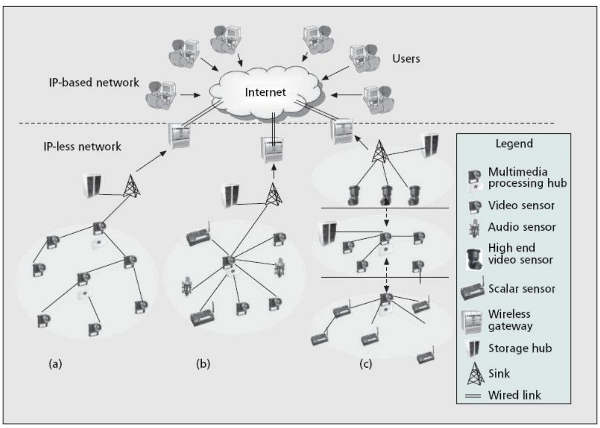

Fig. 4. Wireless Multimedia sensor Network: an architecture

6 Conclusions

In this work we discussed the state of art of research on Digital Holography, paying carefully attention in the possible application fields. Among of all, security applications have been taken into account due to the peculiarities of the Digital Holography which permit to obtain solutions not reachable with other technologies.

Indeed three main security applications have been discussed: *Secure Data Storage*, *Encryption Data*, and *Wireless Multimedia Sensor Networks*. By using DH is possible to storage big size of data in secure way, encrypt 3D data in more efficient manner, and finally record and transmit 3D measurements by using multimedia sensor network. The latter application is a new challenge in digital 3D transmission information, because it is based on new opt-electronic system enable to record data and to reconstruct 3D image remotely. It will permit to define a system never proposed in the past, and thus transmit sensible complex 3D data in secured manner.

References

1. Gabor, D.: A new microscopic principle. Nature 161, 777–778
2. Leith, E.N., Upatnieks, J.: Reconstructed wavefronts and communication theory. Journ. Opt. Soc Amer 54, 1295–1301
3. Schnars, U., Jueptner, W.: Digital Holography. Springer Edition (2005)
4. Skarman, B., Becker, J., Wozniak, K.: Simultaneous 3D-PIV and temperature measurements using a new CCD-based holographic interferometer. Flow Meas. Instrum. 7(1), 1–6
5. Seebacher, S.: Anwendung der digitalen Holografie bei der 3D-Form- und Verformungsmessung an Komponenten der Mikrosystemtechnik. Univeristy Bremen publishing house, Bremen (2001)
6. Akyildiz, I.F., et al.: A Survey on Sensor Networks. IEEE Communication Magazine (August 2002)
7. Fournier, C., Ducottet, C., Fournel, T.: Digital holographic particle image velocimetry: 3D velocity field extraction using correlation. Journal of Flow Visualization and Image Processing 11, 1–20
8. Virant, M., Dracos, T.: 3D PTV and its application on Lagrangian motion. Measurement Science and Technology 8, 1539–1552 (1997)
9. Ohmi1, K., Panday, S.P., Joshi, B.: Digital Holography Based Particle Tracking Velocimetry. In: FLUCOME 2009 (2009)
10. Dhar, L., Hortelano, E.: The Next Generation of Optical Data Storage: Holography, RADTECH Report (November, December 2007)
11. Matoba, et al.: Optical Techniques for Information Security. Proceedings of the IEEE 97(6) (June 2009)
12. Kishk, S., et al.: Optical Encryption and Decryption of Three Dimensional Objects by Computer Generated Holograms, ???
13. Akyildz, I.F., Melodia, T., Chowdury, K.R.: Wireless Multimedia Sensor Networks: A Survey. IEEE Wireless Communications (December 2007)