European Community's Seventh Framework Programme

Grant agreement no. 216105

Real 3D – Digital holography for 3D and 4D real-world objects' capture, processing, and display

Deliverable 5.1
Report on the physical nature of holographic data, and on an analysis of its compatibilities with the data associated with the principal non-digital holographic 3D image acquisition and display techniques – synthesis of work from tasks 5.2-5.4, 5.7

Project information

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<th>Grant Agreement number</th>
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<td>Project acronym</td>
<td>Real 3D</td>
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<tr>
<td>Project title</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Call</td>
<td>FP7-ICT-2007-1</td>
</tr>
<tr>
<td>Funding scheme</td>
<td>Collaborative Project: small or medium-scale focused research action (STREP)</td>
</tr>
<tr>
<td>Project website</td>
<td><a href="http://www.digitalholography.eu">www.digitalholography.eu</a></td>
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<tr>
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<td>Due delivery date from Annex I</td>
<td>M23</td>
</tr>
<tr>
<td>Real 3D Board approval date</td>
<td></td>
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1. Executive summary (Public)

The first objective of WP5 is to set a state-of-the-art of the way the three dimensional property of the real world is treated in a context as wide as possible: scientific and industrial imaging, everyday life images acquisition, professional and large public display. The listed techniques are compared. As a second objective, physical nature of the data coming from different techniques is investigated and particular studies are carried out in the infrared. Finally, compatibilities between techniques are investigated. The need of combinations of techniques or wavelength diversity for certain applications is highlighted.

In more details, the following points are addressed.

By collecting full information on digital holographic and non-digital holographic techniques for 3D imaging and display, and by performing comparisons of their performances and evaluation of their compatibility or complementarities, WP5 clarifies the role of currently maturing 3D digital holographic techniques in the context of existing technologies.

The intrinsic nature of holographic data, that includes the phase of the wave from which 3D information can be extracted, must be fully taken into consideration. In order to better understand and use the information coming from the interaction between light and matter, depending on the object material and the wavelength, a study on the physical nature of data is carried out. In particular, experiments have been carried out with infrared light, showing very promising applications of digital holography with non-visible wavelengths in the industry.

To go beyond the current state-of-the-art, compatibilities and complementarities between techniques are investigated and new possibilities are opened for digital holography.

WP5 also includes a study about holograms coding and compression for movies storage and network exchange not described in this report.

Work Package 5 brings bibliographic bases and justifications of the project’s goals by showing the gaps that are still to be filled in the field of 3D acquisition and display, and by highlighting the role of digital holography in this context.

Some of the techniques studied in other work packages, like depth-of-focus extension in WP6, are taken into account in the state-of-the-art. As technologies dedicated to digital holographic displays are fully described in the framework of WP8, the present report directly refers to deliverable 8.1.

On the other hand, experimental developments with infrared light carried out in WP5 will go on in WP6 to find suited processing for 3D information extraction. WP5 may also serve in WP9 as one of the starting points to define societal implications of the project.

In the demonstrator-oriented aspect of the project, WP5 contributes to each demonstrator in the quality of a state-of-the-art basis and compatibilities analysis. Finally, task 5.3 is a major part of demonstrator 4 whose aim is to show the advantages of infrared digital holography, in particular its ability to investigate silicon microdevices (wavelength around 1.5 μm) and to image large scenes (wavelength around 10 μm). Potential industrial applications are described.

2. Public section (Public)

The public sections of this Deliverable are marked as such. All other sections are confidential. A draft of this Deliverable without the confidential sections will be posted on the Real 3D public website (http://www.digitalholography.eu).
3. Results and critical analysis

3.1. Digital holographic and non-digital holographic techniques (Public)

A general survey of 3D-oriented acquisition and display techniques is presented. In each case, the techniques that are specific to or compatible with digital holography are described in a separate section in order to highlight their particular role in the field of 3D imaging.

More than 1000 publications about digital holography have been collected and organized in a database containing full PDF article and with access through endnote reference manager.

3.1.1. Acquisition techniques

Two main approaches have to be considered: 2.5D and true 3D. The techniques which only give access to the heights of an object from a single direction of observation, for example telemetric information for each visible point of the object, are referred to as 2.5D. When information is available from all parts of the object, that is to say all directions of observation, including features that would possibly be hidden by others in a unique view, we talk about true 3D measurement. True 3D can be rendered with a full impression of the three dimensions, in particular parallax.

a. Non-digital holographic approaches

i. Macroscopic techniques

At present there are many techniques for acquiring 3D data (Table 1). With the development of more efficient computers and higher resolution digital cameras, optical measurement methods are becoming more accurate, producing more measurement points in less time. Optical methods of shape acquisition can be divided into two categories:

- Active.
- Passive.
Passive methods rely on natural lighting of the scanned object. It is measured registering several images of the object form at least two different positions. In comparison in the active methods the scanned object is illuminated with specially formed light. This could either be a point, line or a raster.

In the case of range scanners, the distance is calculated by measuring the time of flight or phase comparison between the outgoing and returning signal. For distances up to about 100 meters, range scanners show the same accuracy for any range. However under a certain range, the accuracy is too low compared to the measured distance. Therefore these scanners are suitable for large objects. Laser triangulation and structured light scanners determine the measured range by calculating a triangle formed by the light emitter (laser or projector), point on the objects surface and the detector (camera, PSD: Position Sensitive Detector or other). Compared to range scanners the accuracy of distance diminishes with the distance between the scanner and the object [1].

Optical scanners are subject to edge effects. Even a well focused light spot will have a certain size. When the spot hits an object edge, only some part of the light will be reflected off it. The rest of the light might be reflected off an adjacent surface or a surface behind it. These points are inevitable since the light cannot be focused to point size. Active scanners rely on light reflected back from the object to the detector. The strength of the returning signal is influenced by such factors as distance, atmospheric conditions, incident angle and the reflective abilities of the measured surface. The amount of light reflected off a surface of a certain color depends on the spectral characteristic of the source of light. Shiny, highly reflective surfaces are usually not easy to measure. The accuracy measurement depends on the reflectiveness of the measured surface. Therefore special coating is used to reduce this effect. Spectral filters are used to reduce the influence of light from other sources that could disrupt measurements.
**Photogrammetry**

Photogrammetry is a technology based on standard photography and projective geometry and was originally used to digitize large objects. The principle behind photogrammetry is to appoint highly informative points in the multiple images of objects. These common points are manually or automatically correlated in each image \[2\]. Based on their relevant positions of these points in subsequent images spatial coordinates of these points are calculated (Figure 1). A line of sight (or ray) can be constructed from the camera location to the point on the object. It is the intersection of these rays that determines the three-dimensional location of the point. Photogrammetry is often used with other 3D scanning technology to provide full surface measurements of parts and to retain tight tolerances over large areas.

![Figure 1: Principles of photogrammetry.](image)

These are two ways of establishing highly informative points. These can either be calculated based only on the shapes of the objects in the images (stereometry), they can also be manually attached to the scanned object in the form of special markers or are appointed manually. The problem in this method is the determination of these points and identifying the same point in different images. Sometimes this is not possible due to the fact that these points are nonexistent. They may be hidden behind different parts of the scanned object or scenery. To counter this and simultaneously increase the accuracy of the whole system images are taken from more than two positions.

The advantages of photogrammetric systems are:
- Simple construction (minimum requirements are two cameras),
- Short measurement time (suitable for moving objects),
- Scalability (the same system can be easily modified for more/less cameras or measurement volume).

The downsides are:
- Complicated image analysis, necessity to determine highly informative points (stereometry) and to match the same point in subsequent images,
- Number of measurement points significantly lower than the number of pixels in the images.

One of the applications of passive photogrammetry is to reconstruct objects, sculptures or buildings which have been damaged or destroyed. This is possible if we have sufficient...
photographic material of them. This was the case with the statue of Buddha in Bamiyan [3]. It had been digitally reconstructed from several high quality photographs made in the 1970's (Figure 2). The relevant position of the camera had to be established for all images and the images themselves had to be scaled. As the result a 3D cloud of points had been created (Figure 3).

![Figure 2: Images used for reconstruction.](image)

![Figure 3: Calculated 3D data.](image)

An application for active photogrammetry is motion capture. The movements of actors or objects are sampled many times per second to acquire realistic animation. By using markers on the object we limit the number of points being analyzed that can be easily identified in the acquired images simplifying analysis process (Figure 4 b). Optical systems utilize data captured from image sensors to triangulate the 3D position of a subject between one or more cameras calibrated to provide overlapping projections. This method is fast enough to scan rapidly moving objects. Based on the coordinates of the markers a skeleton (Figure 4 a) is formed which is mapped onto a 3D model so that the model performs the same actions as the actor.
Figure 4: Example of motion capture results. a: Skeleton made from linking measured points. b: Visualization process from measured points to rendered image.

Data acquisition is traditionally implemented using special markers attached to an actor; however, more recent systems are able to generate accurate data by tracking surface features identified dynamically for each particular subject. Tracking a large number of performers or expanding the capture area is accomplished by the addition of more cameras. These systems produce data with 3 degrees of freedom for each marker, and rotational information must be inferred from the relative orientation of three or more markers.

Passive optical system use markers coated with a Retro reflective material to reflect light back that is generated near the cameras lens. The camera’s threshold can be adjusted so only the bright reflective markers will be sampled, ignoring skin and fabric. Active optical systems triangulate positions by illuminating one LED at a time very quickly or multiple LEDs with software to identify them by their relative positions. Rather than reflecting light back that is generated externally, the markers themselves are powered to emit their own light.

**Time-of-flight**

The time of flight (TOF) is an active method used to measure the time that it takes a pulse of light reach the measure object and be reflected back to the detector [4][5] while traveling over a known distance (Figure 5).

![Figure 5: Principles of the time-of-flight method.](image)

The resulting reflection is detected with a sensor and the time that elapses between emission and detection yields the distance to the object since the speed of the laser light is precisely known. At the heart of this type of scanner is a time-of-flight laser rangefinder [6]. This method is widely used by terrestrial scanning systems (Figure 6 b). The laser rangefinder only detects the distance of a single point. Thus, the scanner scans its entire
field of view one point at a time by changing its’ view direction. These systems have a very large scanning volume (up to several kilometers). The view direction can be changed by either by rotating the scanner itself, by using a system of rotating mirrors or both. The last method is commonly used because mirrors are much lighter and can thus be rotated much faster and with greater accuracy but to achieve a full 360° field of view, the laser rangefinder has also to be rotated. Scanners using the time-of-flight method measure longer distances but are relatively slow (1000 -10000 points per second) compared to the phase difference scanners. The accuracy of a time-of-flight 3D laser scanner depends on how precisely we can measure the time. 3.3 picoseconds (approx.) is the time taken for light to travel 1 millimeter. Usually it is hard to achieve such precision therefore this method is mostly suitable for large objects such as room or buildings (Figure 6 a, c), because the time measurement error when measuring short distances is significant compared to the length value. The number of measurement points is only restricted by the angular resolution of the rotating mirror.

![Figure 6: a,c: Results obtained by the Leica ScanStation (b) time-of-flight laser scanner.](image)

Deliverable 5.1, version 2010.04.12
It is also possible to use non-scanning laser sensing systems for 3D macroscopic imaging. A pulse of high energy illuminates a scene and a time-gated sensor with high temporal resolution, synchronized on the laser pulse with an adjustable delay, detects the photons scattered from a single slice of the scene. The thickness of this slice (typically 20 cm nowadays) is determined by the duration the detector remains open. With several successive pulses, the entire scene can be reconstructed until distances of several kilometres, the lateral resolution depending of the optical system and of the camera.

The time-gated system has the advantage of collecting only the photons coming from the region of interest, even if a high scattering medium like fog is present on the path to the object. The most spread technology is a focal plane based on avalanche photodiodes which are directly used for the gating. These kinds of systems can be terrestrial or carried into a plane and are generally devoted to military applications. Due to the risk of eye damage for human beings potentially present on the path of the laser beam for such long-range applications, only wavelengths higher than 1.5 μm with controlled energy can be used in natural areas.

The advantages of time of flight systems are:
- Simple construction,
- Many measurement points,
- Large measurement volume,
- Large view angle.

The downsides are:
- Point measurement (not suitable for moving objects),
- Includes moving parts (such as rotating mirrors),
- Not suitable for small objects (minimum measuring distance).

<table>
<thead>
<tr>
<th>Type</th>
<th>Accuracy</th>
<th>scanning speed</th>
<th>Measurement distance</th>
<th>View angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trimble GX</td>
<td>12mm/100m</td>
<td>≤ 5000pts/s</td>
<td>200m</td>
<td>360° x 60°</td>
</tr>
<tr>
<td>Leica ScanStation</td>
<td>6mm/50m</td>
<td>≤ 4000pts/s</td>
<td>300m</td>
<td>360° x 270°</td>
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Table 2: Parameters of time-of-flight scanners.

**Phase shift**

Phase shift laser scanners work by comparing the phase shift in the reflected laser light to a standard phase, which is also captured for comparison (Figure 7 c) [4]. This is similar to time of flight detection except that the phase of the reflected laser light further refines the distance detection, similar to the vernier scale on a caliper. In general it can be stated that phase difference method is fast, but signal to noise ratio depends on distance range and lighting conditions. This method is also used by terrestrial scanning systems (Figure 7 a) or scanning large volume objects (Figure 7 b).
The advantages of phase shift systems are:
- Simple construction,
- Many measurement points,
- Large measurement volume,
- High measurement speed,
- Large view angle.

The downsides are:
- Point measurement (not suitable for moving objects),
- Includes moving parts (such as rotating mirrors),
- Only possible to measure range differences between points,
- Not suitable for small objects (minimum measuring distance).

<table>
<thead>
<tr>
<th>Type</th>
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<th>Measurement distance</th>
<th>View angle</th>
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</thead>
<tbody>
<tr>
<td>FARO LS 880 HE</td>
<td>3mm/25m</td>
<td>$\leq 120\ 000\ \text{pts/s}$</td>
<td>1 – 80 m</td>
<td>360° x 320°</td>
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<tr>
<td>Zoller &amp; Fröhlich IMAGER 5006</td>
<td>1mm/50m</td>
<td>$\leq 500\ 000\ \text{pts/s}$</td>
<td>1 - 79m</td>
<td>360° x 310°</td>
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</table>

Table 3: Parameters of phase shift scanners.
**Laser triangulation**
Laser triangulation is a very common 3D data acquisition technique [2]. It is an active method which uses laser light to probe the environment. It exploits the ability of a laser beam to propagate in a well-collimated form over large distances.

In a typical case, the laser beam illuminates a point of the scanned object. The distance of this point from the laser scanner is measured (Figure 8). The laser is essentially used as a pointer. Diffuse or specular reflections from that point are monitored with a detector which is mounted in some distance from the axis of the laser. A lens focuses the reflected light onto a CCD/CMOS camera or a PSD. The position of the dot of the laser on the chip reveals the direction of the incoming light, from which the distance can be calculated. Since the focal length of the camera lens is known, the analysis of the resulting image can determine the angle of the scattered light. The angle is also known since it is the projection angle of the laser beam. By using simple trigonometry the 3D spatial (XYZ) coordinates of a surface point can be determined. The position of the laser dot on the chip can be calculated with sub-pixel accuracy. The high detection speed makes it possible to monitor the position of a moving or vibrating part e.g. of some machinery. The accuracy obtained may typically be one-thousandth of the measured distance in the order of tens of micrometers. They are used for high precision scanning or production process control.

There are several variations of laser triangulation scanners. The detector can be a one-dimensional (1D) or two-dimensional (2D) array of sensors. The object can be illuminated by a single point (Figure 9 d), line (Figure 9 b) or a raster. Either the scanning head is mobile (Figure 9 c) or the measured object is moved relative the scanner (Figure 9 a). This technique can also be applied to microscopic objects.
The advantages of laser triangulation systems are:
- Simple construction (many possible configurations from point to raster projection),
- High measurement speed (suitable for moving objects).

The downsides are:
- May include moving parts (measurement head positioning, object positioning),
- Not suitable for large objects (requires combining results from many measurements).

<table>
<thead>
<tr>
<th>Type</th>
<th>Accuracy</th>
<th>Scanning speed</th>
<th>Measurement distance</th>
<th>View angle</th>
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</thead>
<tbody>
<tr>
<td>G-Scan RX2</td>
<td>0.12 mm</td>
<td>≤ 19 200 pts/s</td>
<td>~0.3 m</td>
<td>60°</td>
</tr>
<tr>
<td>HANDYSCAN 3D</td>
<td>0.05 mm</td>
<td>≤ 18 000 pts/s</td>
<td>~0.5 m</td>
<td>60°</td>
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<tr>
<td>MICROTRAK II – SA LTC-025-02-SA</td>
<td>0.12 μm</td>
<td>≤ 20 000 pts/s</td>
<td>~0.025 m</td>
<td>45°</td>
</tr>
<tr>
<td>MICROTRAK II – SA LTC-300-200-SA</td>
<td>20 μm</td>
<td>≤ 20 000 pts/s</td>
<td>~0.3 m</td>
<td>8°</td>
</tr>
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Table 4: Parameters of laser triangulation scanners.

**Structured light**
Structured light scanners are composed of a wide range of 3D scanning devices (Figure 10) [7]. The principle is to project a known pattern of light (white or multi colored) and use sensors (typically CCD cameras) to capture images of the object with the patterns projected on it from a certain angle (Figure 10 d). The deformation of the observed pattern is dependent on the shape of the object; the observed distortions in the line can be translated into height variations (Figure 11). The camera looks at the shape of the pattern and uses a technique similar to triangulation to calculate the distance of every point of the object. Multiple patterns and/or multiple sensors can be used. If multiple patterns are projected, the software uses referencing and the change in shape of the known pattern to interpret 3D measurements. If multiple sensors are used the transformation matrix is created to merge the results.

Figure 10: Structured light scanners. a: SmartTech Scanbright. b: Steinbitchler COMET 5 11M. c: SPATIUM FMM 4MP 3D digitizer. d: Principles of structured light.

The advantage of structured light 3D scanners is speed. Instead of scanning one point at a time, they scan multiple points or the entire field of view at once. This reduces or eliminates the problem of distortion from motion. Some existing systems are capable of scanning moving objects in real-time. The only problem in this method is the visibility of the pattern on scanned object. Reflective or transparent surfaces have to be covered with an anti-reflective coating.

Structured lighting can be used to determine the shape of an object in machine vision and multimedia applications [8], it can also help recognize and locate an object in an environment. Structured light scanners are also used for the immortalization precious or
delicate cultural heritage artifacts [8]. There have been many research projects undertook the scanning of historical sites and artifacts both for documentation and analysis purposes. Structured lighting very useful in assembly lines and it’s used for process or quality control.

![Structured light scanning example.](image)

Figure 11: Structured light scanning example.

A variation of fringe projection is a method that projects a series of different color stripes (Fig. 12) [9]. Analysis is performed by finding the boundaries between the colored stripes. The boundaries are identified by establishing the colors of the stripes which form the boundary. The increase of measurement quality is done be projecting a series of stripes perpendicular to the edges. This way we experience densification of edges. This method is well suited for measurement of static objects (increasing the number of acquired images increases the accuracy of measurement) as well as dynamic ones. The only drawback of this method is that it cannot be used to scan multicolored objects. This could lead to misinterpretation of boundary areas and therefore produce measurement errors.

![Structured light using different coloured stripes.](image)

Figure 12: Structured light using different coloured stripes.

The advantages of structured light systems are:
- Simple construction (no moving parts),
- Full field measurement (measuring distance of all points in the field of view)
- Many measurement points (up to the number of pixels in the detector)
- High measurement speed (suitable for moving objects).

The downsides are:
- May produce errors around discontinuities,
- Results are dependent on measured surface color.

<table>
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<th>scanning speed</th>
<th>Measurement volume</th>
</tr>
</thead>
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<tr>
<td>Smarttech Scanbright</td>
<td>0,05mm</td>
<td>≤ 700 000 pts/s</td>
<td>&gt; 1,5m x 1,3m x 0,5m</td>
</tr>
<tr>
<td>SPATIUM FMM 4MP 3D Digitizer</td>
<td>0,09mm</td>
<td>≤ 1 000 000 pts/s</td>
<td>&gt; 1,2m x 0,9m x 1,6m</td>
</tr>
</tbody>
</table>

Table 5: Parameters of structured light scanners.
Moiré techniques are a kind of fringe projection. They make use of two gratings, a master grating projected onto the object under study or imaged through a reflection on it. It is superposed with a reference grating. This produces contour fringes that can be resolved by a CCD camera, even if the gratings themselves are not resolved. In the shadow Moiré technique, the master grating is the shadow of the reference one, projected on the object. The Moiré pattern is the superposition of the reference grating and the master grating observed through it. Commercial LCD panels can be used for this purpose [10]. To decrease the noise, increase the acquisition speed and use phase shifting methods for fringes processing, multiple views Moiré techniques have been developed: two or more Moiré patterns with different phase shifts are simultaneously acquired using, for example, several cameras.

The typical ranges measurable with Moiré techniques are from 1 mm to 0.5 m, with a resolution from 1/10 to 1/100 of a fringe.

Deflectometry
This technique consists in displaying a structured light represented by periodic fringes on a screen. A high resolution camera observes the reflected or refracted light onto the measured surface. The difference with fringes projection techniques is that the pattern is not projected onto the surface but it is observed through or from the object.

In reflection, light rays are reflected on the surface and a local slope variation modifies their path. By means of a phase shifting of the pattern, the local slope map is computed and the local curvature is derived. The fields of application are wide (Figure 13), from macroscopic to microscopic objects: control of shape in car body manufacturing, surface quality in microelectronics [11]...

In transmission, the fringe pattern is observed through the transparent object and defaults lead to disturbances in its shape. Again, the local slope map is deduced from a phase shifting process. It is used in particular to control the optical power of lenses [12].

![Figure 13: Local slope measurement by deflectometry. a: Contact lens optical power measurement by Lambda-X. b: Paint quality control on a car by Visuol Technologies, using illumination of the car body by a fringe pattern.](image)

The technique is fast: a few seconds are needed to measure a macroscopic surface and the resolution can be down to a few microns.
Shearography
In this technique, the (opaque) object under test is illuminated with a laser, which usually produces a speckle pattern. A shearing element, as a prism, is introduced in half the beam on its path to the detector, so that two slightly shifted images are formed and interfere on the camera (Figure 14). It leads to a fringe pattern that characterizes the shape of the object. In a second step, a load which can be for example thermal variation or pressure decrease is applied to the object and a new sheared interferogram is recorded. By comparison with the previous one recorded without load, the derivative of the deformation is found and defects or internal holes become visible because they induce non-uniform deformation under load. The method of phase-shifting is used to perform quantitative measurements of the defects location.
Shearography is nearly insensitive to vibrations thanks to the double image produced by a unique arm, without external reference. Consequently, it is mostly used in industrial environments to measure the quality of pieces. It can detect under-micron defects.
In this framework, shearography is not strictly speaking a quantitative 3D imaging method because it permits to compute the surface deformation but neither the absolute depths of the surface points nor the 3D precise localization of the defects.

Summary of macroscopic techniques
The advantage of time-of-flight range finders is that they are capable of operating over very long distances, making them suitable for scanning large structures like buildings, bridges or tunnels. The main disadvantage of time-of-flight methods is their accuracy. Due to the high speed of light, measuring the time it takes light to reach the object and return to the detector is difficult and the accuracy of the distance measurement is relatively low, on the order of millimeters when measuring distances around 100 m. Systems using laser triangulation have a limited range of some meters, but their accuracy is relatively high. The accuracy of triangulation range finders is on the order of tens of micrometers. Phase shift laser scanners are significantly faster than time of light methods, but signal to noise ratio highly depends on distance range and lighting conditions. These systems produce information which is made of the coordinates of the measured points \((x,y,z)\) called clouds of points. Such measurement results can be converted to other data formats (triangle mesh, solids) and visualized in almost any graphic computer software. It is also possible to print 3D object using stereolithography or digital presses.

Triangulation, deflectometry and shearography can be used also for small objects of order of 1 cm. Deflectometry has the advantage of being fast and simple in its principle, without expensive setups, but the illuminating and measuring device has to be adapted to each size of objects to be measured. Shearography is an interferometric method which shows very few sensitivity to vibrations but which measures deformations, not shapes for static objects. However, it is useful to detect defects inside solid opaque parts.
As most of these techniques make use of reflected or scattered light, their performances depend on the reflective properties of materials. Table 6 summarizes the main characteristics of the cited techniques.

<table>
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<tr>
<th>Technique</th>
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<th>Scanning speed</th>
<th>Measurement distance</th>
<th>Field of view</th>
<th>Surface properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion Capture</td>
<td>~1mm</td>
<td>20 – 500Hz</td>
<td>1 - 10m</td>
<td>All round</td>
<td>All (use markers)</td>
</tr>
<tr>
<td>Laser triangulation</td>
<td>~ 10^{-2} mm</td>
<td>~ 10^3 pts/s</td>
<td>~ 10m</td>
<td>~ 10^6 - 90^o</td>
<td>Partially reflective</td>
</tr>
<tr>
<td>Time of flight</td>
<td>~10mm/100 m</td>
<td>~ 10^4 pts/s</td>
<td>~ 1000m</td>
<td>≤ 360^o</td>
<td>Partially reflective</td>
</tr>
<tr>
<td>Phase difference</td>
<td>~10mm/100 m</td>
<td>~ 10^5 pts/s</td>
<td>≤ 100m</td>
<td>≤ 360^o</td>
<td>Partially reflective</td>
</tr>
<tr>
<td>Structured light</td>
<td>~ 10^{-2} mm</td>
<td>~ 10^5 pts/s</td>
<td>≤ 2m</td>
<td>~ 30^o</td>
<td>Scattering</td>
</tr>
<tr>
<td>Deflectometry</td>
<td>~1 mm - 1 μm</td>
<td>No scan, acquisition/ process. ~ 5 s</td>
<td>~10 cm</td>
<td>1 cm^2 – 1 m^2</td>
<td>Specular or transparent</td>
</tr>
<tr>
<td>Shearography</td>
<td>&lt;1 μm for deformations</td>
<td>No scan, control of ~1000m^2/h</td>
<td>Deformation device in contact</td>
<td>~10 cm^2</td>
<td>Partially reflective</td>
</tr>
</tbody>
</table>

Table 6: Comparison of different macroscopic techniques.

ii. Microscopic techniques

**Speckle interferometry**

Speckle interferometry has been widely used in a large field of applications in experimental mechanics on scattering surfaces. Indeed, when a rough surface is illuminated with coherent light, interference between all the randomly dephased wavelets produce at each point of observation a specific value of intensity. The resulting pattern is made of bright grains surrounded by dark regions. The interference of this pattern with, for example, a plane wave or another speckle pattern is again a speckle pattern. This interference permits to measure small displacements or deformations.
Figure 15: Diagram of the three categories of optical setups for speckle interferometry [13]: (A) in-line reference beam and single illumination-observation; (B) two illumination beams; (C) two observation beams.

The output of the laser can be divided in order to form, on the one hand, a single illumination/observation of the object surface and, on the other hand, a reference beam, recombined in-line with the observation wave in front of the detector (Figure 15 A). This recombination is said to be in-line because the angle between the object and the reference waves should be kept small enough so that the resulting fringe pattern has a carrier frequency that can be resolved by the photo-detector. The phase of the object speckle wave is changed according to the object deformation. The reference wave can be a smooth wave, an arbitrary speckle wave or even a speckle wave arising from a macroscopically identical object for direct comparison purposes; the reference wave can be modified or not in the final state, leading to adaptive or comparative versions of the method; when the object stays at rest, small changes in the wavelength, the illumination angle, the refractive index of the medium surrounding the object, all small enough not to destroy the correlation conditions, give rise to interference phase changes related to the shape of the object. Moreover, speckle statistics can lead to statistical roughness measurement. Figure 16 presents different points of view on speckle interferometry techniques, as proposed by Jacquot [13].
Resolutions attained in speckle interferometry are of a fraction of a wavelength, as in other interferometric techniques.

**Optical coherence tomography**

Invented in 1991 by derivation of the low-coherence reflectometry technique, optical coherence tomography (OCT) was first developed for medical imaging and especially for ophthalmology because of its high imaging ability in turbid media [14]. It is now present in a large number of fields in biology and elsewhere.

The principle is to make use of the low coherence of the source (a few microns), a superluminescent diode for example, to get 2D slice images of the medium in transmission with an interferometric technique. According to Figure 17, the object is fixed in one arm of a Michelson interferometer whereas a mirror mounted on a translation stage is placed on the reference arm. Depending of the position of the mirror, the reference path length fits the optical path length corresponding to one slice of the object in the object arm. This part of the object produces interferences with the reference, and due to the low coherence length, the slice thickness is of order of a few microns. By scanning the mirror longitudinal position, the whole object can be imaged slice by slice. A Doppler shift is introduced by the scanning in the reference arm together with a frequency shift by piezo-electric transducer in the object arm and a heterodyne detection is achieved.
OCT has recently been modified into spectral-domain OCT to lead to a better signal-to-noise ratio and a higher speed. The source is either broadband or spectrally tunable, and a spectral analyze of the interferogram is achieved. According to the Wiener-Khintchine theorem, the spectral power density is related to the signal autocorrelation by Fourier transform, thus the interference envelope can be computed very rapidly.

Current resolution is about 1 micron in depth and real-time video is possible (Figure 18).

![Diagram of first optical coherence tomographic device](image17)

**Figure 17:** Principle of the first optical coherence tomographic device [14]. SLD: superluminescent diode. 50/50: coupler. PZT: piezo-electric transducer. AD: analog to digital converter (the detector used to be a photodiode and is now replaced with a CCD camera).

![OCT images of in-vivo human skin](image18)

**Figure 18:** OCT images of in-vivo human skin recorded and displayed at 17 frames per second [15].

**Confocal microscopy**

A confocal microscope generally uses a laser source to scan the object. As can be seen on Figure 19 a, a pinhole is placed in a focal plane conjugated with the objective focal plane so that only the photons coming from this focal plane are focused and cross the pinhole to form the image on the detector. The light originating from other planes is stopped. By varying the longitudinal position of the pinhole, a slicing of the object is achieved.

A confocal microscope can use the directly reflected light or fluorescence. The resolution in depth is of order of 600 nm, with a scan of ~1 to 100 frames/s for images of 512x512 pixels.

This simple principle has open a large field in biological imaging, where confocal microscopes are now very widely used (see Figure 19 b for an example of biological image).
Figure 19: a: Principle of the confocal microscope. b: An example of an image taken with the LSM 700 confocal microscope. Human lymphocytes transmitting the HIV virus from cell to cell. (www.zeiss.de).

**Floating lens**

The principle of focusing at various distances in order to get three-dimensional information on objects is going to widely benefit from the recent invention of liquid lenses.

These small devices include two non-miscible liquids and two electrodes, as presented on Figure 20. One of the liquids is electrically conducting; the other one is an isolator. By applying a tension between the electrodes, the interfacial tension between the two liquids is changed and results in an electric field across the insulator, which effectively lowers the interfacial tension between the conductive liquid and the insulator [16]. Thus the focal length of the lens made of the liquids varies.

Figure 20: (a) Schematic cross section of a liquid-based variable lens in a cylindrical glass housing. (b) When a voltage is applied, charges accumulate in the wall electrode and opposite charges collect near the solid/liquid interface in the conductive liquid. The resulting electrostatic force effectively lowers the solid–liquid interfacial tension and with that the contact angle $\theta$ [16].
These lenses of electrically-controlled focal length with low consumption are well-suited for devices in which it is not possible to introduce a zoom with mechanical movement of optics (like in cameras for mobile phones...). Their temporal response to a change of voltage is typically about 100 ms [17]. They also permit to enhance several kinds of 3D imaging techniques like telemetry, optical coherence tomography or Shack-Hartmann wavefront sensors [18]. Nevertheless, they are not only intended to microscopic applications but also to applications like zooming in micro-cameras, etc.

**Structured illumination microscopy**

The concept of structured light has also been developed in the field of fluorescence microscopy, firstly to enhance the spatial resolution. Following Gustafsson [19], the demagnified image of a grating is projected onto the sample with partially coherent light, with line spacing close to the diffraction limit of the microscope objective (Figure 21 a, b). The second pattern is the unknown structure of the sample itself. Its high spatial frequencies are then encoded in larger stripes in the Moiré pattern and become resolvable. Deconvolution is performed to get the information of interest. As explained on Figure 21 e, a gain of a factor of two is obtained in the image resolution when several orientations of the grating stripes or several phases of the pattern are used. Unlike confocal microscopy, in which the improvement in image quality is due to blocking the unfocused light, high spatial frequencies are really detected here.

This technique has been extended to three-dimensional imaging by a combination with illumination in a broad set of angles [20] [21]. As presented on Figure 22, a laser beam is divided into six beams. Three of them are directed on each side of the specimen where they build a 3D interference pattern by interfering pairwise, which leads to 19 frequency components in Fourier space. The axial resolution is therefore enhanced to nearly the same value of the lateral one (under 100 nm) due to new axial components of the illumination structures and of the detection optical transfer function.

**Figure 21:** Concept of resolution enhancement by structured illumination [82]. (a) If two line patterns are superposed (multiplied), their product will contain moiré larger fringes. (b) The set of low-resolution information that a conventional microscope can detect defines a circular “observable region” of reciprocal space. (c) A sinusoidally striped illumination pattern has only three Fourier components. The possible positions of the two side components are limited by the same circle that defines the observable region (dashed). If the sample is illuminated with such structured light, moiré fringes will appear which represent information that has changed position in reciprocal space. The amounts of that movement correspond to the three Fourier components of the illumination. The observable region will thus contain, in addition to the normal information, moved information that originates in two offset regions (d). From a sequence of such images with different orientation and phase of the pattern, it is possible to recover information from an area twice the size of the normally observable region, corresponding to twice the normal resolution (e).
Figure 22: A schematic drawing of an I$^5$S microscope [21]. The illumination light passes first through a transmission grating, which diffracts it into three beams (green lines), and then through a beam splitter, which splits each beam and directs three beams to each of the two opposing objective lenses. The same beam splitter combines the two beams of emission light (red) from the sample onto the camera. The movable objective lens can be positioned in X, Y, and Z with respect to the stationary objective lens. Mirrors M3 and M4 can be translated together to adjust the path-length difference. The grating is rotated and laterally translated to control the orientation and phase of the illumination pattern.

Summary of microscopic techniques

A wide variety of theoretical concepts can be applied to microscopic 3D acquisition: interferometry, slicing, fringe projection... Among the most well-known and the most efficient are interferometry, which achieves resolution of a fraction of wavelength, and confocal microscopy which leads to very impressive images with fluorescence. Structured illumination microscopy also performs good resolution, but is more difficult to carry out. Most of the microscopic techniques are dedicated to transmissive object and are usually applied to biological or specimen, whereas some of them can be used with reflective objects. Floating lens is not itself a technique but more a setup to carry out 3D acquisitions and wavefront sensing.

Table 7 gathers information about the previously described techniques.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Z Resolution</th>
<th>Scanning speed</th>
<th>Field of view</th>
<th>Surface/volume properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speckle interferometry</td>
<td>~100 nm</td>
<td>No scan</td>
<td>~1 mm$^2$ – 1 cm$^2$</td>
<td>Rough / wavelength</td>
</tr>
<tr>
<td>Optical coherence tomography</td>
<td>~1 μm</td>
<td>Video rate achievable</td>
<td>~1 cm²</td>
<td>Transparent and scattering</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------</td>
<td>-----------------------</td>
<td>--------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Confocal microscopy</td>
<td>~500 nm</td>
<td>200 Hz-200 kHz to scan the points in one image</td>
<td>&lt;1 mm²</td>
<td>Partially transparent</td>
</tr>
<tr>
<td>Floating lens</td>
<td>~1 μm, depending on the lens</td>
<td>~ 0.1 Hz</td>
<td>Depending on the lens</td>
<td>Any kind</td>
</tr>
<tr>
<td>Structured illumination microscopy</td>
<td>~100 nm</td>
<td>No scan Grating displacement</td>
<td>~10-100 μm²</td>
<td>Opaque or partially transparent, scattering</td>
</tr>
</tbody>
</table>

Table 7: Comparison of different microscopic techniques.

b. Digital holographic approaches

This section brings together techniques which are compatible with digital holography, even if they are also used in other contexts. Generally, the main contribution of digital holography is the ability to directly access the phase map.

Digital holographic microscopy with direct optical path length measurement

A digital holographic microscope (DHM) is an interferometric instrument. It measures the same physical parameters than other interferometric techniques such as PSI (phase shifting interferometer) or white light interferometer: the phase of optical wavefront from which a distance measurement is achieved. But, with a slightly off axis configuration of the reference wave, DHM has the unique advantage to measure a two-dimensional map of distance from a single acquisition, in contrary of PSI that needs several images acquisition with different phase shifts, or white light interferometer that need vertical scan. Indeed, instead of alignment of the two beams as in PSI (object O and reference R waves), a small angle \( \theta \) between them is introduced (off-axis geometry) as shown in inset of Figure 23 [22]. The acquired digital hologram consists therefore on a spatial amplitude modulation with successive constructive and destructive interferences. In the frequency domain, the difference between the in-line geometry (PSI) and off-axis geometry (DHM) consists in the position of the frequency orders of the interference. In PSI, because the three orders (zero order: non-diffracted wavefront, and ±1: real and virtual images) are superposed, several acquisitions with different phase shifts are necessary. In contrary, in DHM the off-axis geometry separate spatially the different frequency orders and therefore allows an easy spatial filtering to reconstruct the phase map from a single digital hologram [23]. (This filtering process will be improved in Task 4 2). DHM is therefore a real-time phase imaging technique less sensitive to external vibrations than PSI.
Figure 23: Schematic diagram of DHM. BS: beamsplitter. M: mirrors. C: condenser. MO: microscope objective. RL: lens in the reference arm used to perform a reference wave curvature similar to the object wave curvature.

It is also important to mention that DHM has two different configurations, the reflection one as depicted in Figure 23 that is mostly used for metrology applications (Figure 24) (micro optics, MEMS/ MOEMS,...) in order to measure surface texture, shape, roughness, defects; and a transmission configuration applied to biomedical applications but also for metrology measurement on transparent samples (micro-optics principally).

Figure 24: Up: measurement of movable MEMS (vertical displacement mirror). Down: SiO$_2$ layer thickness measurements on Si wafer.

To evaluate the performance of DHM, it is important to define different parameters in order to be able to compare the value with other techniques. In fact, one can remark that is often very difficult to compare data sheets from different manufactures because the
definition of the specifications are sometimes different. For example, the accuracy is in principle defined by a statistic measurement on a certain number of measurements that can be different for manufacturer to others. Therefore, we will define precisely the function used to evaluate the performance of DHM.

The **lateral resolution** is objective-dependent as in classical optical microscopy and can be down to 300nm with oil immersion objectives (1.4 NA). The field of view is also objective dependent and can be up to 4.4mm. But motorized stages and stitching software could increase the field of view (Task 4.3).

The **vertical accuracy** is defined by measuring the average under all pixels of the temporal phase standard deviation of each pixel by considering $T$ successive measurements:

$$A_{\text{phase}} = \frac{1}{N^2} \sum_{i,j=1}^{N^2} \left( \frac{1}{T} \sum_{t=1}^{T} [\varphi(i,j,t) - \varphi_m(i,j) ]^2 \right)$$

where $\varphi_m(i,j)$ is the mean phase value for the pixel $(i,j)$ and $N^2$ the considered pixels number in the field of view, typically, $N^2 = 650^2$ pixels and $T=30$ successive measurements. The wavelength and the configuration of the DHM allow calculating the accuracy expressed in height (or thickness in transmission) instead of phase. In transmission, the refractive index $n$ of the specimen contributes also. In the specifications, the glass refractive index $n=1.5$ is chosen:

$$A_{\text{height,refl}} = A_{\text{phase}} \frac{\lambda}{4\pi}$$
$$A_{\text{height,trans}} = A_{\text{phase}} \frac{\lambda}{2\pi n}$$

The definition of the **vertical resolution** is certainly the more intuitive specifications for topographic measurement instrument, but it is also the more difficult to evaluate. Indeed, the vertical resolution defines the smallest height that can be resolved by the instrument. But how to measure this resolution when no certified targets allow to measure it? Some manufacturers evaluate the vertical resolution by considering roughness parameters measurement on certified reference mirror (for example typically mirror with flatness $\lambda/50$, $Ra=1.6\AA$). But statistical measurement on the entire field of view is not really adapted to characterize two-dimensional topographic imaging. Therefore, we define the vertical resolution $VR$ as:

$$VR_{\text{phase}} = 2A_{\text{phase}}$$

and as for the accuracy the vertical resolution is converted to height with the relations:

$$VR_{\text{height,refl}} = VR_{\text{phase}} \frac{\lambda}{4\pi}$$

This formulation is justified by Figure 25 that reports the histograms of 900 height measurements on a single pixel. We define the smallest height that can be resolved between two adjacent pixels as two times the standard deviation. For the data sheets, only 30 height measurements are considered.
Figure 25: Histogram of 900 height measurements on a single pixel. The vertical resolution (red line) is evaluated by taking two times the standard deviation (green) of each histogram.

In order to be comparable to other topographic manufacturers, the **repeatability** specification is defined as following:

\[
R_d(\text{phase}) = \sqrt{\frac{1}{N^2} \sum_{i,j=1}^{N^2} \phi^2(i, j, t)}
\]

\[
R_{\text{phase}} = \sqrt{\frac{1}{T} \sum_{t=1}^{T} (R_d(\text{phase}) - R_d(\text{phase}, t))^2}
\]

where is the mean Rq value for T measurement and \( N^2 \) the considered pixels number in the field of view, typically, \( N^2 = 6502 \) pixels and \( T = 30 \) successive measurements. Finally, the repeatability in nanometer for the different configurations is

\[
R_{\text{height,refl}} = P_{\text{phase}} \frac{\lambda}{4\pi}
\]

\[
R_{\text{height,trans}} = R_{\text{phase}} \frac{\lambda}{2\pi n}
\]

The following specifications (Table 8) results were achieved with \( T = 30 \) successive measurement in air for transmission configuration and on a flat mirror (mirror: planarity \( \lambda/50 \) and roughness \( Ra = 1.6\text{Å} \)) for reflection.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Accuracy (n=1.5)</th>
<th>Vertical Resolution</th>
<th>Repeatability</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>0.3nm</td>
<td>0.6nm</td>
<td>0.06nm</td>
<td>Wavelength (682nm)</td>
</tr>
<tr>
<td>Reflection: single wavelength</td>
<td>0.1nm</td>
<td>0.2nm</td>
<td>&lt;0.01 nm</td>
<td>Half wavelength (340nm)</td>
</tr>
</tbody>
</table>

Deliverable 5.1, version 2010.04.12
Table 8: Specifications for transmission and reflection DHM.

<table>
<thead>
<tr>
<th>Reflection dual-wavelength</th>
<th>30nm</th>
<th>60nm</th>
<th>0.25nm</th>
<th>Half synthetic wavelength (10 microns)</th>
</tr>
</thead>
</table>

One can see that there are two different specifications for reflection DHM. Indeed, DHM can perform measurement with a single wavelength but in this case the measurement range is typically half the wavelength when unwrapping procedures are not possible. The use of a second wavelength allows to increase this range up to several microns, but with a loss of resolution [24]. Approaches are investigated in Task 6.7 to integrate different modalities of holography to access the large range achieved in dual-wavelength but by keeping the resolution achieved with single wavelength. Furthermore, the use of two wavelength (Figure 26) can also be used to increase the vertical resolution as shown in Figure 27 [27].

Figure 26: a: dual-wavelength setup (two wavelengths DHM setup). /2: half-plates, M: mirrors, PBS: polarizing beam splitters, BS: non-polarizing beam splitters, DL: delay lines, BE: beam expanders, L: lenses, CL: condenser lens, MO: x3 achromatic microscope objective (0.1 NA), S: specimen, TL: tube lens. Inset: 3D distribution of the incident waves propagation directions upon the CCD plane, \( k_{1r} \) and \( k_{2r} \) are the propagation direction vectors of the reference waves \( R_1 \) for wavelength \( \lambda_1 \) and \( R_2 \) for \( \lambda_2 \).

b: zoom image of a part of the hologram, with the orthogonal fringe spatial frequencies. c: Fourier spectrum of the hologram, where the wavefronts can be individually selected.

Because DHM does not need scan, it depends not on motor calibration and do not suffer from displacement drift or other scanning error. The single parameter that is needed to calibrate the system is the wavelength used. This is an important point for repeatability; DHM is certainly one of the best instruments in term of repeatability. Moreover, it allows a very high acquisition rate, up to 15 frames per second in live mode; and up to 300 frames per second (camera dependent) with post-processing reconstruction. This quality makes DHM an ideal standalone instrument for static and non-static specimen; but it could also serve as a first stage of measurement, for example allowing the precise positioning of a specimen before the measurement with another technique such as an AFM.
To conclude on DHM, one can say that the topographic measurement resolution is equivalent to other optical instruments with several other advantages: high acquisition rate, no scan process, insensitive to external vibrations.

Details on shape measurement and 4D imaging are presented in the attached publications 1 and 2.

**Phase-shifting digital holography**

It has been proposed to make use of the ability of digital holography to focus at any desired plane for 3D images reconstruction, especially using phase-shifting digital holography to ensure an efficient use of the pixel number of the CCD [28]. Phase-shifting holography is usually associated with in-line holography; the issue of superposition of the desired and the conjugate image is overcome by the principle of phase-shifting interferometry: at least three intensity images are recorded out of focus or without imaging optics with a varying phase shift introduced by a mirror mounted on a piezoelectric transducer, as shown on Figure 28.
The phase map is then calculated from a combination of these images and the field amplitude is deduced of an image taken without the reference arm. This complex field is the propagated object field. Fresnel transformation is used to calculate the object field in an arbitrary object plane, which permits to get 3D information.

Figure 28: Arrangement for phase-shifting digital holography [29]. PZT : piezo transducer.

The angular size of the object that can be reconstructed is given by $\alpha = \lambda / p$ where $\lambda$ is the wavelength and $p$ is the pixel size. Then $\alpha$ is a few tens of radians. The resolution cell is related to the number of pixels.

Improvements using a diffraction grating have been proposed in order to record several phase shifts simultaneously and thus perform instantaneous measurements [30].

**Depth-of-field extension using spatial frequencies or edges**

The limited depth-of-field is a main drawback of microscopy that prevents from observing, for example, thick semi-transparent objects with all their features focalized at the same time. Several algorithms have been developed during the past years to fusion images having various planes of focus and thus obtain a completely focalized image.

Nevertheless, in classic microscopy only a limited step that can be imposed on the mechanical system to change the focus plane. Digital holographic microscopy overcomes this disadvantage by permitting an image reconstruction in any plane parallel to the hologram plane. The reconstruction plane can therefore be moved with an arbitrary step. Moreover, digital holography gives access not only to the image intensity but also to the phase carrying information on the variations of refraction index, which may be very useful to observe internal structures into transparent biological objects.

In digital holography, a stack of images, reconstructed at various distances, can easily be obtained from a single experimental hologram acquisition. It avoids any problem of misalignment or object modification from one image to the other, and it is also well suited to depth-of-field extension. In the case described here (work taken from WP6), from a hologram typically recorded in transmission through a microscope objective using a Mach-Zehnder interferometer, we select the virtual image in the Fourier plane and compute a numerical parametric lens in order to correct the tilt aberration, the phase offset and the wavefront curvature [25]. The mean focus distance, roughly corresponding to the centre of the thick specimen, is found visually or using an autofocusing algorithm [26]. A range of distances to be investigated and a longitudinal step are then chosen to generate the stack of images. Two conditions are respected:

- the range of reconstruction distances covers the entire object thickness, thus every part is in focus in at least one image of the stack
• the step is less than the microscope depth-of-field so that the object thickness is over-sampled.

As any reconstruction distance can be computed in digital holography, these conditions can always be fulfilled. An algorithm, like variance or wavelets methods, is chosen to build the entirely focused image using the sharpest edges: each pixel (or subregion) of the composite image is taken in the slice where it is found to be in focus.

Finally, the map composed of slices numbers computed by the focusing algorithm is converted into a distance map calculated from the reconstruction distances of the stack. Then, it is possible to display a 3D view of the object, as shown on Figure 29.

![One image of the stack.](image)

![Result of depth-of-field extension, method 2, N=15.](image)

![3D information, computed from the results of the focusing algorithm.](image)

**Figure 29:** Depth-of-field extension and pseudo 3D reconstruction of microspheres (1 μm) in a gel.

This is a pseudo-3D reconstruction method because features being located one behind the other can never be separated: only the upper one is seen. The other limitations are that some features may be in focus without exhibiting sufficiently sharp edges, and flat parts, even if they have got sharp edges, will never be considered as focused, leading to a random 3D reconstruction of these parts.

**Depth-of-field extension using phase information**

Another method has been proposed by Ferraro et al. for depth-of-field extension, using the 3D information inherent to holography [31]. It can be used in reflection or in transmission with objects exhibiting a homogeneous index of refraction and one flat face. As the previous method, it lies on the creation of a stack of images with varying focus distance, obtained from a digital hologram, in particular in microscopy. Then, to find which parts of the object are in focus at each distance, the unwrapped phase map deduced from the digital holographic reconstruction is used, as it contains information about the topology (provided the refractive index is known in the transmission case). More precisely, the optical path length difference is related to the phase map by the following equation:

$$\text{OPD}(x, y) = \lambda \Delta \varphi(x, y) / 2\pi.$$  

In reflection, for example, the optical path length difference is two times the difference of distance \( \Delta d(x, y) \) between a point of the object and a reference point. Taking into account the objective magnification \( M \), the distance of each point in the image plane is found by the following relation:

$$\Delta d'(x, y) = -M^2 \frac{\Delta \varphi_m(x, y)}{4\pi} \lambda$$

and the total range at which the hologram has to be reconstructed is deduced from the same relation using the maximum phase variation \( \Delta \varphi_m \).
Figure 30 shows the 3D reconstruction of a silicon MEMS cantilever using a reflection setup. The size of the object is 50x100 μm.

This method is interesting when the focused features of the object don't exhibit sharp edges; unlike the previous method (previous section) it provides good results even on plane surfaces. However, in transmission the class of objects that can be reconstructed is very limited.

Figure 30: Numerical reconstruction of the hologram of a cantilever. a: SEM image. b: Hologram. c: Wrapped phase map. d: 3D profile of the cantilever [31].

Filtered backprojection tomography
The technique of tomography using the filtered backprojection algorithm is well-known in the field of X-rays, especially for medical applications. It works under the assumption of straight rays inside the object. In the case of very low variations of the refractive index or in the reflection case, this approach can also be used with optical waves for 3D phase imaging [32]. In this application, the ability of digital holographic microscopy to provide quantitative phase images is an important point.
Figure 31: Reconstruction of an amoeba using filtered backprojection algorithm with phase images obtained in digital holographic microscopy, performed at EPFL. a: image of the amoeba with conventional microscopy. b: sections of the 3D reconstruction of the refractive index.

Experimental results have been obtained with a tek amoeba (*Hyalosphenia papilio*). The rotation is achieved by clamping the observed specimen with a micropipette fixed on a motorized stage, so that it could be rotated within a chamber containing the immersion medium (glycerol, \( n = 1.473 \)). The total angle of rotation is 180° with steps of 1°, the axis being perpendicular to the illumination direction. The sample is illuminated with a laser diode (wavelength: 635 nm), and imaged with a 0.4 NA 20X microscope objective. Figure 31 presents a visualization of the 3D reconstructed amoeba, whose shell is approximately 130 \( \mu \text{m} \) long, 70 \( \mu \text{m} \) wide and 35 \( \mu \text{m} \) deep, where the internal structure can be readily identified. Some internal elements in the amoeba are a few microns in size, showing that the tomographic reconstruction is close to the optical resolution of the setup. The resolution in refractive index is approximately 0.005.

**Optical diffraction tomography**

In many biological objects the assumption of straight rays is not valid and diffraction must be taken into account. The theory of diffraction tomography was described by Wolf [33] but has not been fully experimentally applied in three dimensions until now because of the large amount of computer resources needed. It establishes that when diffraction occurs, the spatial frequencies obtained from one viewing angle are spread on a portion of sphere in the Fourier space. When a large number of measurements is performed by rotating the object or the illumination and acquisition device, the frequency space can be filled in the limit of what is usually called “Ewald’s sphere” and a 3D map of the refractive index can be obtained after 3D inverse Fourier transforming the matrix. As an alternative method, the filtered backpropagation algorithm can be used [34]. In general, reconstructions are achieved under the Born or the Rytov approximation, which both make the assumption of weak refractive index variations. Knowledge of the complex field is required, that is why digital holographic microscopy can be advantageously used for this purpose. The theoretical highest spatial frequency reconstructed is \( \sqrt{2}k \) where \( k \) is the wavenumber, in the case when only the transmitted light is measured.
Figure 32: Bright field images (a-d), and 3D tomogram of HT29 cells reconstructed by the filtered back-projection algorithm (e-h) and diffraction tomography based on the Rytov approximation (i-l). (f) and (j) are slice images corresponding to the objective focus. (e) and (i) are slice images 1.7 μm above the original focus. (g) and (k) are slice images 2.9 μm below the focus. (a-c) are bright field images at the same foci as (e-g). (d), (h) and (l) are zoom-in images of the rectangular boxes in (c), (g) and (k), respectively.

The color bar indicates refractive indices at 633 nm wavelength. Scale bar, 10 μm [35].

Figure 32 presents recent results of optical tomography, where quantitative results from the backpropagation algorithm are compared with those obtained with diffraction tomography [35].

Instead of varying the angle of view, or in complement with it, wavelength diversity can be envisaged. The effect of changing the wavelength is comparable to the one obtained by changing the angle because both lead to a variation of the wave vector $k$. However, in the Fourier space, it corresponds to a change of the sphere’s radius in the reflection case and to a rotation of the sphere in the transmission case. The obtained interference patterns can be analyzed in the Fourier space, using the spectrum of variation of the fringes when the wavelength varies [36]. It can also be used in the direct space by summation of the fields at different wavelengths: the small region of constructive interferences results in a slicing in depth [37].

**Summary of digital holographic techniques**

Digital holography can be used either in reflexion or transmission and permits to calculate optical path lengths from which index or depth variations can be deduced. The two main techniques are off-axis holography and phase-shifting holography. From the collected data, true 3D images can be obtained by post-processing, especially using depth-of-field extension techniques or, in a more physical way, tomographic reconstructions.

As a hologram inherently contains information from the whole path light has followed, digital focusing in various planes is possible and the phase information is preserved. These two characteristics of digital holography make it well suited for 3D reconstructions, especially in the case of microscopic objects for which phase information is really meaningful.
Moreover, holographic acquisition is the ideal technique to be coupled with light modulators to perform 3D holographic reconstructions.

3.1.2. Display techniques

The field of 3D display is taking more and more importance, especially in the general public applications like cinema, television, work of art promotion, etc. But most of the current techniques suffer from many limitations that do not permit them to be used into everyday objects.

a. Non-digital holographic approaches

Our perception of the three dimensional world is due to the fact that our two eyes, located at two different points of our face, receive slightly different images from the same scene. These two images are interpreted by our brain as a single one with depth information. By moving the head, we also get a better 3D visualization of our environment and of our position inside it. Moreover, we have a priory knowledge of usual objects that contributes to give us a precise idea of what we see. The goal of 3D displays is to lead to the same kind of mechanisms for viewers of artificial images. Consequently, most of them rest on sending two different images to the eyes, one to the left eye and another one to the right. This is called stereoscopy.

In the following, we first present the rendering methods, which are widely used to display on 2D screens the 3D information recorded by one of the above techniques. Secondly, we describe stereoscopic methods, which are able to produce a real feeling of three dimensions. We also present some autostereoscopic systems. Finally, the concept of “display” is taken in a wider sense to include the creation of global feeling of immersion in a 3D world, through the presentation of virtual reality techniques.

Rendering

The final stage of creating a 2D image or animation from the acquired measurement points is called rendering. Several different rendering methods have been developed. They range from quick and yet non-realistic wireframe rendering through polygon-based rendering, to more advanced techniques such as: scan-line rendering, ray tracing, or radiosity. Rendering may take from anywhere between seconds and days for a single image. Based on the time it takes for rendering, the methods can be divided into:

- Non real-time (high quality) rendering,
- real-time (lower quality) rendering.

Different methods are better suited for types of rendering. With the development of more efficient CPUs and GPUs the time is constantly decreasing enabling more sophisticated scenes to be renders in real time.

Non-real time rendering is used to obtain higher image quality when having limited processing power. This method is used in animations for non-interactive media, such as movies. Rendering times for individual frames may vary from a few seconds to several days for complex scenes. When multiplying this time by the typical frame rate (24, 25, or 30 frames per second) the time it takes to render an animation takes form anything between from days and months. These methods are employed in digital media and artistic works. The rendering process takes a lot of computing time depending on the complexity of the physical processes being simulated. Computer processing power has increased rapidly over the recent
years, allowing much higher realistic rendering. To shorten the total rendering time render farms are used.

High quality rendering methods include ray tracing and radiosity. These methods simulate naturally-occurring lighting effects such as transparency, reflections or diffusion. This enables particle simulation (rain, smoke, or fire), volumetric sampling (fog, dust and other spatial atmospheric effects), caustics (simulation of light focusing by uneven light-refracting surfaces, such as the light ripples seen on the bottom of a swimming pool), and subsurface scattering (to simulate light reflecting inside the volumes of solid objects such as human skin).

The second method is real-time rendering. The primary goal of this method is to display a fluent animation, not photo-realism. It is used in interactive media, such as games, simulations, presentations, interactive worlds, VRML. It can also be used for the verification of measurement results or for checking of complicated animation before non real time rendering takes place. The rendering result is calculated at rates varying 20 to 120 frames per second and displayed in real time. To achieve this certain simplifications have to be made. The resultant image is not necessarily photo realistic, which may sometimes lead to incorrect results. Various effects (reflection, diffusion, lens flares, depth of field or motion blur) can add realism to a scene, even if they are only applied by the GPU. The rapid increase in computer processing power has allowed a higher degree of realism for real-time rendering.

Using real-time and non real-time rendering methods depends on the complexity of the measured object. Method that produce relatively few measurement points or methods that do not require scanning, but acquire the shape of the entire object in their field of view are suitable for real-time rendering. These include motion capture, structured light, and digital holography. When additional processing or higher rendering quality is necessary non-real time methods are used.

**Stereoscopes**

The first stereoscope was invented in the 19th century to see two drawings as a single 3D picture. Usual stereoscopes include oculars, prisms or mirrors (Figure 33) and are used to see images taken, for example, with special cameras having two objectives. Their aim is to help looking at the two images at the same time, one for each eye. Modern stereoscopes are often designed to observe couples of transparencies. Stereoscopic couples of images can sometimes be viewed in free vision, without any stereoscope, but by some people only.

Head mounted displays (HMD) may be considered as a recent improvement of stereoscopes. Indeed, they consist in two sets of a lens and a small LCD panel, one for each eye, mounted on a device fixed on the head. They naturally have a narrow field of view giving the feeling of tunnel vision, unless additional device is used. This method is well suited for videogames (like 3Dvisor using OLED display).
Anaglyph

Another basic idea to give a feeling of the third dimension is the anaglyph technique, sometimes used in cartoons. The information intended for each eye is differentiated with colours. Observation is achieved using glasses of two colours, typically red for one eye and blue or green for the other. In this technique, colours can not be well rendered on the parts in relief (Figure 34) and the observer experiences tiredness after a long view.

Infitec

This recent method also based on colours overcomes some limitations of anaglyph. The viewer wears glasses equipped with interferential filters working at one wavelength for each RGB channel. The allowed wavelengths are different for each of the two eyes, matching those of the filters placed in front of the two projectors. Thus, each eye receives a different set of wavelengths for RGB. For example, green is made with a filter at 532 nm for the left eye and at 518 nm for the right eye (Figure 35) [39]. With this technology, the glasses are quite expensive and part of the illuminating light is lost.
Polarization

To preserve colours and to get better results than anaglyph, polarized glasses often replace red and blue glasses. Images are again recorded with two cameras. The images are then superimposed on a screen with two different (linear or circular) polarizations, each of them fitting one of the polarizing parts of the glasses. Nevertheless, the observer is not expected to rotate his head in a way that the polarizations between the projected light and his eyewear do not fit any more, especially in the case of linear polarization. This technique, provided by companies like IMAX 3D or REAL D, has been widely used in the 3D cinemas of amusement parks, or in some modern museums. The main drawback is a loss of luminosity due to the polarized filters.

Time-multiplexing

This technique is in competition with time-multiplexed images, mainly spread by the American company Christie. With usual devices, it leads to a reduction of the time resolution by two, which is not an issue with cathodic tube screens. Nevertheless, with the emergence of fast LCD television screens (up to 120 Hz) and large bandwidth cinema projectors images for the left and the right eyes can now follow one another at a comfortable frequency with high definition (up to 1920x1080). The active glasses worn by the observer are liquid crystals shutters which open and block alternately the light coming to each eye at the same frequency. The difficulty is to synchronize each eyewear with the display device, usually with infrared communication. With this technique, no loss of luminosity occurs. A dark interval must be taken into account to avoid colour artefacts and cross-talk between left and right eye images. Some devices include several synchronized sources for a complete immersion of the observers in the 3D image. An advantage is that this method needs a single projector, but with high frequency. Beyond the fields of leisure and culture, manufacturers like Cyviz now turn towards education, research and industry.

For desktop applications, one can find transparent covers (Z-screens) to be put in front of the monitor, which alternate the polarization state of light. The observer then only wears polarized filters glasses. Like other time-multiplexing methods, it suffers from flicker.

Basic considerations on stereoscopic acquisition and display:
To render a correct scale and depth of images seen by the observers, geometrical considerations have to be fulfilled [41]. The key parameters are the interocular distance of the human viewer, the geometry of the viewer with respect to the viewing screen (assuming a single flat display here) and the field of view the viewer sees through the display rectangle. Thus, the ideal acquisition setup includes two cameras separated of 6.5 cm, which is the mean interocular distance for an adult. This distance may be different if the object to be observed has a scale much larger or smaller than usual objects of the human’s world. They must be parallel to each other with colour and brightness matching. For a movie, time and spatial alignments can be made by post-processing. With spatial alignment, the goal is to ensure that only horizontal parallax occurs, with zero parallax in the middle.

Theoretically, there is only one ideal position for the viewer, other positions leading to some distortions: depth stretching or compression, shearing of space... Therefore, some systems include head tracking.

The two streams can be exported separately or joined into a double width or double height stream, depending on the displaying device. Current commercial displays are more than 1 m².

**Autostereoscopy by lenticular lenses**

The generic name of “autostereoscopy” covers the techniques able to give a feeling of 3D without the need for special glasses.

A basic technique designed by “autostereoscopy” is the combination of two very similar images that are rapidly displayed one after the other. The differences between the two images, for example a fix foreground and slightly shifted background, make an impression of relief whereas it is a 2D display. It is often found on the web under the form of animated gif.

A more complex and efficient way to perform autostereoscopy is to interlace vertical frames intended to the left and to the right eyes. The basic method then consists in placing a parallax barrier in front of the screen: this barrier formed with many slits permits each eye to receive the expected frames, provided the viewer’s head stays at a specific location. A better method involves a cover of lenticular lens instead of the barrier (Figure 36) [40]. The effect of the array of lenses is again to make each eye view specific frames. To allow several viewers at the same time, the two series of frames have to be interlaced several times, which means a large increase of the data to be displayed. The German company Newsight GmbH started very recently to sell 3D television sets lying on this principle, from 8.4” to 57”. For each size of screen, a specific viewing distance is specified: 90 cm for the smallest to 4 m for the largest one.

![Figure 36: Principle of lenticular lenses for autostereoscopy.](image-url)
**Auto stereoscopy by integral imaging display**

Integral imaging consists in creating a large amount of micro-images of the same object and placing an array of spherical convex microlenses on them, following the original idea of Gabriel Lippmann in 1903. Unlike the lenticular technique, the aim here is not to interlace the rays sent to the left and the right eye but to produce one micro-image with each lens. What is seen by the observer is the integral of all micro-images, whatever his position inside a certain angle.

The micro-images can be recorded using an array of micro-lenses [42] as shown on Figure 37 or computer-generated. Each micro-image deals with the same object with a slightly different angle of view.

![Figure 37: Optical system to obtain image arrays [42].](image)

Then, the same microlenses array can be used to observe the 3D image, according to the following principle. For one position of the observer, each microlens gives information on one point of the object. The integration of all these points by the eye builds the general image. When the observer moves, each lens images another point of the object, therefore a full impression of 3D is created (Figure 38). Another technique to render the 3D image is, after recording the image on a photographic film, to illuminate the film from behind, which produces again the light paths giving 3D impression. Nowadays, 3D reconstructions are often performed digitally, so that each desired view can be generated and analyzed by a computer [43].

For 3D television purposes, moving scenes can be recorded on a camera on the principle shown on Figure 37 and LCD screens equipped with microlenses arrays or arrays of pinholes have been developed. Usually, a conversion has to be done because the images obtained are pseudostereoscopic, which means that concave parts of the object become convex in the image and vice versa [44]. To solve this problem and avoid interferences between micro-images, gradient-index microlenses have been proposed [45].

![Figure 38: Positions of points to be focused, depending on the position of the observer.](image)
Varifocal mirrors

Varifocal mirrors were invented in 1961 [46] and first used to display a three-dimensional movie in 1968 [47]. A thin Mylar film, which has a mirror-like aluminized surface, is stretched taut over a loudspeaker and driven sinusoidally at about 15 Hz or 30 Hz. Thus, its curvature varies in time. This mirror reflects an image displayed by a CRT screen and varying at the same frequency. The setup is shown on Figure 39. Its permits to display time-multiplexed virtual images seen by the observer as coming from various distances, which gives the impression of three-dimensions because of image persistence on the retina. For example, on Figure 40, the front and back parts of the house were displayed sequentially, leading to the vision of a 3D house.

![Figure 39: Principle of time-multiplexed 3D display using a varifocal mirror.](image)

On the same principle, 3D images can be recorded [48], as shown on Figure 41. Then, they can be displayed with the varifocal system.

Varifocal mirrors are also used in the field of shape measurement and solutions have been found to solve the issue of variation of the magnification with image position [49].

![Figure 40: An image of the first computer-generated movie displayed using a varifocal mirror [47]. The front and back of the house are displayed sequentially, synchronized with the varifocal mirror which causes a variation of the position of the virtual image.](image)
Volumetric 3D display

The most intuitive way to display 3D images seems to be the volumetric display. Several techniques have been invented to perform volumetric display with some kind of fast rotating screen. For example, Blundell et al. have presented a "cathode ray sphere" (Figure 42). Several electron guns are placed outside the display area which contains a phosphor-coated planar screen rotating at 15 Hz, thus sweeping a cylindrical volume. Beams deflection of the electron guns are synchronized with the rotation of the screen to render a 3D image for the observer [50]. Other systems are based on varifocal mirrors. Figure 43 presents a system called "Perspectra Spatial 3D display" that includes a rotating screen and a optical projection device from Texas Instrument using MOEMS micro-arrays for each colour channel. Each micro-display produces a 768x768 image, leading to 100 millions voxels. Applications can be found in the general public but also in medical imaging or molecular synthesis [51].

Figure 41: Principle of 3D image recording using a varifocal mirror [48].

Figure 42: The cathode ray sphere.
The concept of “immaterial screen” has been used to create pseudo 3D display [52]. An immaterial screen is, for example, a thin region of small water droplets in a non-turbulent air flow. The ensemble of water particles serve as a screen where 2D images are displayed. What is very impressive is that observers can cross the “immaterial screen” and the image is immediately reformed behind them. When the projected image is almost black with only some bright objects, the observer sees objects flying in air (Figure 44). By using one beamer on each side of the “screen”, an impression of 3D can be created and the observer can see objects from each side and walk between them, even if it is still essentially a 2D display. For one observer only, a tracking system can be used so that he interacts with the floating image. For a better 3D rendering, stereoscopic systems using eyewears, as those described at the beginning of this section, can be added. Starting from a similar principle, New York University’s Ken Perlin and Jeff Han proposed using dust particles suspended in air to project 3D images [68]. The idea is to scan the dust using an infrared time-of-flight detector to find the locations of the particles and then use a visible light-scanning beam to light up the appropriate particles.

Figure 43: Perspecta Spatial 3D Display, from Actuality Systems. (a) The system generates 10-inch-diameter volume-filling imagery with a full 360-degree field of view. (b) To provide the volumetric imagery, the display projects a series of 198 2D patterns, called slices, onto an optimized diffuser rotating at or above 900 rpm. The display sweeps the entire volume twice for every complete screen revolution, resulting in a visual refresh rate of 30 Hz [51].
Figure 44: FogScreen [52] can create fully opaque (a) or very translucent high-quality images in mid-air (b). It can provide high visual detail.

Some tests have been carried out for 3D volumetric display inside a static volumetric medium, in particular using fluorescence properties of gas [53], crystals or fluorescent metallic particles [54]. Indeed, as visible light can be emitted using two infrared beams of excitation at different wavelengths in the process of fluorescence, a controlled emission of voxels can be achieved. Nevertheless, such displays are often of very limited size and little light is emitted. Some systems use passive scattering: a grid of scatterers is built using, for example, laser-induced damage into a cube of transparent plastic or glass (Figure 45). A high-resolution beamer illuminates each desired point of the cloud of scatterers. The key point is that the cloud is made in a manner that no longitudinal overlapping occurs between the coordinates of the scatterers, so that the beam coming from each pixel of the projector is scattered only one time on its path. It leads to nice visual effects, but with limited choice of the object shape (extruded objects, 2.5D objects...) as shown on Figure 46.

Figure 45: 3D volumetric display using a cube of glass with scatterers produced by laser-induced damage.
The DepthCube, a recent commercial product, is a static volumetric display that uses a stack of 20 scattering LCD sheets that a high-speed digital projector illuminates in sequence [55]. It provides high-quality results but with an expensive device.

**Virtual reality**

After G. Burdea and P. Coiffet, “virtual reality is a high-end user-computer interface that involves realtime simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, and taste” [56]. It includes immersion and interaction for the user, and therefore necessarily involves some method to display the three dimensionality of the world.

The first system, called Sensorama Simulator, was described in a US patent in 1962. It was made of a color 3D stereovision movie with stereo sound, aromas and wind effect due to small fans near the head. The user, placed on a vibrating seat, could experience a motorcycle ride, sensing the wind, the holes in the road and smelling food near shops. Another important step in virtual reality was the invention of head-mounted displays (HMD), which are able to show animated computer-generated scenes displayed by LCD, LCoS or OLEDs (see next section). They are usually stereoscopic to render a 3D feeling.

Some of them use partially reflective mirrors to add a computer-generated object to the directly observed real-world scene. One then talks about augmented reality. Its main stakes are cameras and virtual objects alignment, spatial and temporal coherence, photometric coherence. The concept of augmented reality does exist out of HMD applications, in a wide set of applications in which images are simply watched on a computer screen: furnishing, architecture, industry, heritage, military field, medicine (Figure 47). 3D is then only due to computer rendering. The term “augmented reality” concerns real-time applications in a usually partially or totally known environment. The problematic is indeed different if virtual objects are added a posteriori to make a non-interactive movie.

Figure 46: Example of 3D images obtained with the cube of glass having laser-induced damage scatterers. a : Point of clouds. b : Extruded objects. c : 3D “Pac Man” game in 2.5D (without overlap of Z-coordinates).
Figure 47: Augmented reality on common 2D screens. a. ARIS project (M-O. Berger, Lorraine Laboratory of IT Research and its Applications) for virtually adding furniture from a catalogue in photographs of a customer’s flat before purchase. b. Learning of baby extraction with forceps for midwife students, using interaction with a virtual scene. c. European project ARCHEOGUIDE to see ancient monuments from their ruins. d. Augmented reality on iPhone 3GS using electronic compass: Paris subway information added in a real-world live image.

Some advanced research is carried out on the integration of augmented reality devices into contact lens in order to superimpose texts or pictures to what the eye sees. Several microdevices like an antenna, a LED (Figure 48) or other semi-conductor components have already been separately embedded on contact lenses [57]. One of them including metallic circuits has been worn by a rabbit 20 minutes without adverse effect. Power is provided by RF supply. The aim is to integrate a large amount of LEDs and microlenses, together with power supply, biosensors, etc., so as to display images seen by the user at about one meter in front of him, for example tools for video games, data from the internet or glucose concentration for diabetic people [58].
Figure 48: Optoelectronic devices embedded on contact lenses. a. One lens prototype has several interconnects, single-crystal silicon components, and compound-semiconductor components embedded within. b. Another sample lens contains a radio chip, an antenna, and a red LED.

The medical field is an important domain of applications for 3D interactive devices. Tools are especially developed for aided surgery. In the work of Marti et al., a 3D model of the patient is first build from X-ray or ultrasound scanner and is used to adjust the position of a needle equipped with force-feedback detectors for biopsy [59]. The doctor can modify the needle trajectory at any time. A deformable model has also been developed to take into account patients movements during surgery operation [60].

Virtual reality is now envisaged in a more extensive way in interactive prototyping. It consists in permitting the user to design a prototype on-line, test its behavior in a 3D virtual world and modify it as desired, for example in the case of a production cell [61]. This kind of application has great complexity because it does not deal with pre-defined actions.

One component of virtual reality is the tactile sensation, because it fairly contributes to the immersion in a virtual environment. Ultrasound focusing can be used to give a tactile perception like a droplet falling on the hand [62], as shown on Figure 49. Some recent experiments have been carried out to study how touch perceptions can be induced on some parts of the body by the view of a virtual object. For example, it was shown that if a rubber hand is positioned such that it extends from a person's arm while his actual hand is hidden from view, and both the real hand and the rubber hand are stroked at the same time, he seems to feel the touch in the location where he sees the rubber hand being touched. Some experiments even present disturbed self-location, out-of-body experiments, and show that self is located where a touch is seen [63]. These researches may have strong influence on future 3D interactive devices including touch sensation.
Conclusion on non-digital holographic display approaches

Usually, all methods sending artificially different information to each eye, sometimes with flicker or ghost effects, produce high strain and uncomfortable effects. Moreover, some people (at least 6%) suffer from bad or absence of stereoscopic vision due to squint, to the preponderance of one eye over the other, to a visual deficiency since childhood preventing to develop stereoscopy, etc. Therefore, whereas stereoscopic still show a great success in particular for 3D cinema, studies are carried out on autostereoscopic systems. One of the main fields of application is 3D television, because techniques that need special glasses are not well suited for home devices. Autostereoscopy is an active field of research and some commercial display have recently become available, but allowing the observer to move in front of the screen inside a sufficiently large cone, ensuring a large depth-of-field and comfortable aspect of images, in a large extent, are still uncompletely solved issues. Furthermore, some research teams are working on volumetric displays, either using rotating screens or static scattering or fluorescent media. They usually include tricks to manage a 3D projection. With improvements, these kind of display could have a large public spread in the near future.

Finally, virtual reality is a wide field which deals with 3D representations and interactions with computer-generated scenes. Its increasing role in scientific, industrial and everyday applications is a proof of the great potential for 3D devices ressembling the real world. Indeed, it was shown that a good feeling of immersion can be created even with a small screen, if the user can have various interactions involving several parts of his body [64]. The emerging topic of augmented reality in contact lenses reminds us that interactive technologies are going to be more and more inserted in our everyday life and 3D display is an important part of this.

b. Digital holographic approaches

As this part of the report overlaps deliverable 8.1 written by Bilkent, we refer to this deliverable. Consequently, only a short summary will be given here on holographic displays.

A digital holographic display is basically a device that is able to perform hologram reconstruction. Unlike standard holography on holographic plates or films (Figure 50), the diffracting device is programmable in real-time so that the displayed object can be rotated or
scaled and a holographic movie can be displayed. It consists in a matrix that plays the role of the hologram by modulating the phase of the incident wave, where each pixel can be driven separately. A major issue is to get pixels small enough to reproduce the high spatial frequencies of the hologram interference fringes.

It is noteworthy that some holographic displays are projecting displays, which means that they produce a real image, not a virtual image (in the sense of the geometrical optics), and this image is projected onto a diffuser possibly moved to render the third dimension [65]. Obviously, the interesting ability of holography to reconstruct the whole object wave properties is then partially lost.

![Figure 50: a. Transmission hologram reconstruction from a hologram recorded on a photographic plate. The displayed object exhibits relief and parallax but it is static. b. Standard hologram of the Venus of Milo (Photo Researchers, Inc.).](image)

Hologram reconstruction lies on modulation of a light wave. Spatial light modulators are devices which spatially modulate intensity or phase of the incident light, or both. They can be electrically or optically addressed. The existing technologies for are briefly described in the following. Only the devices exhibiting the ability to modulate both amplitude and phase are efficient for holographic displays.

**Electrically addressed spatial light modulators (EASLM)**

Among electrically addressed SLMs, one can find several technologies:

- Liquid crystals modulators are useful but quite slow and have large pixels. In the transmissive mode, they consist in a liquid crystals panel between two glass sheets driven by thin film transistors. The reflective ones are called Liquid Crystal over Silicon (LCoS); a silicon chip carrying mirrors is placed under the liquid crystal and permits to drive it by switching on/off the mirrors (Figure 51). Larger arrays can be built with this latter technology.
- Deformable mirrors or digital micro-mirror devices (DMD) controlled by electrostatic force (Figure 52) come from nanotechnologies. Each small mirror of the array can be rotated about 10° so that light is sent out of the projection screen, making the corresponding pixel appear dark. To produce greyscale, the mirror is turned on and off at a high frequency. They are expensive and slow but useful for incoherent light. They are widely used in digital light processing projectors.

- Acousto-optic modulators are transparent slabs in which a sinusoidal acoustic wave is propagated from a transducer [66]. The acoustic modulation creates regions of higher and lower refraction indices that behave like a Bragg cell, excepted the frequency of the diffracted orders which is Doppler-shifted and the phase that depends on the phase of the sound wave. Displays based on this kind of device (like the holographic displays “Mark” from MIT [67]) involve a 2D scan of the beam at high frequency to create the image.

- Pixelated crystals switched by array of magnetic coils using magneto-optic effect need high powered drive circuits.

- Multiple quantum well is a non-linear optical effect in very thin layers that leads to very fast modulation but with poor contrast and currently in small arrays. Liquid crystals and deformable mirrors are currently the main technologies used.

![Figure 51: Principle of LCoS (W. Hossack, the University of Edinburgh).](image1)

![Figure 52: Principle of deformable mirrors (W. Hossack, the University of Edinburgh).](image2)
**Optically addressed spatial light modulators (OASLM)**

Optically addressed SLMs basically follow the principle described in Figure 53. "Writing" light intensity, carrying the image, is measured on a detector which converts it into electrical charge that affects the modulator (liquid crystal). "Reading" light is modulated in amplitude or phase. Phase modulation is achieved by change of the refractive index but amplitude modulation can also be performed using polarization.

![Optically addressed SLM](image)

*Figure 53: Principle of optically addressed SLM (W. Hossack, the University of Edinburgh).*

**Summary of holographic techniques**

After the invention of holography in 1960 and the modification made by Leith and Upatnieks in 1962 for off-axis configurations, it became possible to see 3D objects into a photographic plate, including parallax. However, whereas the plate can be exposed two times to get interference fringes from an object in two different states (holographic interferometry), the method does not permit to see moving objects nor to perform measurements. Digital holographic has succeeded in measuring shapes, refractive indices and deformations but displaying real 3D objects became more difficult. Spatial light modulators, provided they have sufficient resolution, power efficiency and speed, are a promising method to perform holographic display with possible interaction of the user to rotate or zoom in the displayed object.

The most currently used SLMs are electronically addressed, and some advances still have to be made to display both amplitude and phase, to permit viewers to lie at any point around the displayed object and to display images of sufficient size.

**3.2. Physical nature of the data**

Two main aspects of digital holography are investigated here concerning the particular interaction between light and matter and its consequences for measurements.

First, theoretical considerations are developed on the nature of the data obtained in digital holography depending on the physical properties of the material under study with respect to optical wavelengths: birefringence, dielectric properties...

Then the added value of digital holography with infrared light, both for microscopy and large scenes, is demonstrated and important industrial applications are highlighted by experimental promising results.
3.2.1. **Nature of the data due to different physical principles in the signal detection (Public)**

The various digital holographic and non-digital holographic 3D image acquisition techniques provide data which are essentially defined by the nature of the light–matter interaction causing the generation of the wavefront for digital holographic methods. For non-digital holographic 3D imaging methods, the generation of the intensity signal describes the light–matter interaction. This understanding will be at the basis of performance and compatibility studies between various 3D imaging methods.

In transmission holography, the interaction with transparent matter is essentially characterized by the refractive index of the object. These dielectric properties of matter modulate the optical pathlength and constitute the basis of the formation of the phase image provided by wavefront reconstruction. In some cases, the anisotropic nature of the material may cause birefringence and a dependence of the reconstructed wavefront on light polarization. The birefringence signal provides invaluable data on the intimate organisation of matter in material science and life sciences.

In reflection holography, the phase signal originates mainly from the topography of the object: the phase signal naturally originate from fluctuations of surface topology. For metallic objects, the phase of light normally reflected by the surface is less affected by the dielectric properties of the material, but these properties may play a predominant role at oblique incidence, and in particular if a plasmon resonance is involved in the physical mechanism of light scattering. The presence of a thin dielectric layer at the surface may also affect the phase signal and may be responsible of unpredictable errors in high precision topology measurements.

Phase signal must be also interpreted in the case of objects with rough surfaces: this roughness causes important phase fluctuations and multiple interferences commonly designated by the term “speckle”. This speckle can be characterized in term of its statistical properties: spectral content, intensities which bring many useful data on surface or volume properties of random media. Shape measurement on rough or light diffusing materials is an important chapter of 3D metrology.

This analysis can be extended to diffusing or randomly organized media, also called “turbid media” like disordered matter and biological media. In this case the scattering mechanisms involved in the genesis of signals and wavefronts can be scrutinized in order to interpret correctly the data delivered in this case by the different 3D imaging techniques.
3.3. Compatibilities and complementarities between techniques (Public)

3.3.1. Compatibilities between data

In this section we compare the performances coming from digital holography and other 3D measurement techniques. As the purpose is to give didactic examples of the non-compatibilities possibly encountered, only the fields of DHM and other microscopic techniques will be considered. Indeed, macroscopic techniques, such as those described in “3.1.1 a: Non-digital holographic approaches”, have very different performances and specifications even if they measure comparable parameters as shape or distance.
a. Same physical parameters

Shape (2.5D)

A direct comparison between 3D data generated by various 3D image acquisition methods needs in principle same or comparable specifications definitions. In order to compare DHM with other microscopic topography measurements techniques, several important specifications as lateral resolution, vertical accuracy, vertical resolution and the repeatability were defined in section “3.1.1 b: Digital holographic approaches” and are given in Table 8 for the two configurations of DHM (reflection and transmission). These values allow a direct comparison of the performance of DHM compared with techniques measuring same microscopic objects with same physical parameters (optical wavefront) and comparable data.

Table 9 shows that optical profiling systems have similar and comparable specifications with DHM. One can notice that for accuracy DHM gives value in nm in contrary of others techniques that use %. The reason is that DHM do not use scanning processes and therefore the accuracy depends only on the wavelength. This is a great advantage of DHM, the accuracy does not depend on the specimen height. Figure 74 illustrates this accuracy by presenting step high measurement on certified steps.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Techniques</th>
<th>Accuracy</th>
<th>Vertical Resolution</th>
<th>Repeatability</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHMR</td>
<td>Digital holography no phase shift</td>
<td>0.1 nm</td>
<td>0.2 nm</td>
<td>&lt;0.01 nm</td>
<td>Half dual-wavelength (10 um)</td>
</tr>
<tr>
<td>Wyko NT9100 Optical Profiling System</td>
<td>PSI</td>
<td>0.80 %</td>
<td>&lt;0.1 nm</td>
<td>0.05 nm</td>
<td>10 mm</td>
</tr>
<tr>
<td>NewViewTM 7300 (Zygo)</td>
<td>VSI</td>
<td>≤ 0.75%</td>
<td>&lt; 0.1 nm</td>
<td>&lt; 0.01 nm</td>
<td>150 μm (Extended scan range to 20 mm)</td>
</tr>
<tr>
<td>Plu4300 Sensofar</td>
<td>PSI, ePSI and VSI</td>
<td>&lt;0.8%</td>
<td>0.1 nm</td>
<td>0.1 nm</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

Table 9: Comparison of specifications.
The main difference between DHM and the other techniques is the measurement range limited to half the wavelength. But this limitation can be partially overcome by using another topographic measurement in order to unwrap the phase ambiguity of the synthetic wavelength, for example by using the vertical scanning implemented in DHMR [84]. This application demonstrates already that DHM and other topographic measurements can be combined to increase the range of measurement by keeping the advantages of DHM. Only the results (Figure 75) is presented here, more details can be found in Ref.[84].

**Volume**

In the previous section, we compared optical profiling methods that measures the specimen shape (2.5D) by using the properties of the phase. Different techniques were
developed to measure 3D microscopic volume. There are tomographic microscopic techniques measuring the 3D distribution of refractive index (tomographic DHM), absorption that are related to phase or amplitude of wave. These approaches are already and always investigated by DHM. The great interest of tomographic measurements is that even the reconstruction processes are most of the time very similar (different orientations of the specimen), the physical parameters could be very different: absorption or refractive index at different wavelengths (x-ray, optical wave, sound...) and give therefore complementary information.

b. Different physical parameters
To achieve volume measurement in reflection, different techniques, such as ellipsometry (polarization) or reflectometry (reflection coefficient), use optical physical parameters that are not completely or not investigated by DHM. Another great difference between DHM and these techniques is the field of view. Indeed, most of thickness layer measurement techniques are limited to single point evaluation. Scanning processes could be implemented, but lateral resolution and time-consuming are without comparison with DHM. Therefore, an investigation of the possibility for DHM to image layer thickness rapidly has to be evaluated. This investigation will take place in task 6.6 and 6.7.

c. Different physical parameters, not comparable data
In some cases, the parameters measured by 3D microscopic techniques are not comparable. For example, surface and volume data or macro and micro measurements do not describe the same physical reality and do not come from comparable measurement techniques. Their performances can not be directly compared and they can usually not be embedded in the same measurement device.

For example, in digital holographic microscopy, a visible wavelength can be used to obtain topological measurement of a MOEMS. As another issue is to perform quality control of devices inside the MOEMS, one can imagine achieving some kind of tomography with DHM at infrared wavelengths for which silicon is transparent. In this way, both the external shape and the internal arrangement of the chip could be obtained. The physical parameters involved in the measurement are quite different: optical path length in reflection in the first case, in transmission in the second case, thus the reasons of phase variations are not the same. Information in these two cases is not of same kind. Nevertheless, it could be gathered to obtain a full 3D description of the object. The main obstacle is the current technology performance. As can be seen from Table 10, none of the commercially available infrared cameras has a sufficient resolution to allow data comparison with measurements in visible light, unless these last measurements are voluntarily degraded in resolution.

d. Discussion on compatibilities
Two different compatibilities have to be discussed. First, there are the compatibilities and complimentary of other topographic techniques with DHM. It has been shown that
topographic measurement with smaller accuracy can be used to increase the range of DHM by keeping the actual accuracy of DHM.

Secondly, the display compatibilities have to be discussed. Basically, the chosen displays have to convert the measured results in 3D by using the same entry data. Therefore, depending of the recording techniques, the results have to be processed to fit the correct entry data. In fact, in the case of SLM display for example, the solution seems to be quite simple, any physical measured parameters has to be translated in phase holograms. If this translation is possible, there is no restriction of compatibilities with displays. For example, by knowing the reconstruction wavelength (wavelength of the beam illuminating the SLM), high can be easily converted in phase data. For parameters that are different than distance or height (refractive index or absorption for example), a linear relation can be constructed to translate measurement parameters to phase and then to be optically reconstructed.

3.3.2. Comparative analysis of 3D imaging and display techniques

a. Presentation of the analysis matrix

A more complete version of the grid below (Figure 76), filled by EPFL, is presented in an annexed document, so that compatibilities and complementarities between imaging and display techniques can be understood.

![Figure 76: General view of the matrix synthesizing all methods of 3D acquisition and display.](image)

From this wide study of complementarities and compatibilities between 3D techniques, some points arise that may be relevant for the future of 3D imaging and display in
commercial applications. In the following, we give the main ideas underlined by the matrix above and further considerations that come with them.

**b. Conclusions on compatibilities and complementarities between techniques**

**Main properties and compatibilities of 3D measurement devices**

The point of complementarities between 3D acquisition techniques is not explicitly underlined in the matrix but can lead to profitable conclusions.

Basically, many of the described techniques are specific to one kind of application due to their inherent properties (range of object size/field of view, object properties with respect to light interaction, etc.). Nevertheless, the wide developments achieved in the automation of detection and measurement techniques lead to the need of combined means. For example, with the progress in robotics and autonomous vehicles, imbedded systems able to perform 3D imaging of large scenes, detection of an object of interest and local analysis of its shape or roughness will become essential. In the biological field, functional imaging sometimes implies several kinds of techniques; however currently available systems are usually based on a single principle. Indeed, it may be convenient to get information on refractive index variations and global shape of a living cell, eventually combined with fluorescence imaging for example. Therefore, one can imagine integrated systems including digital holography collecting light both in reflection and transmission, or combination of speckle interferometry with confocal microscopy, etc. in order to perform full functional imaging.

From an industrial point of view, a large number of applications can take advantage of measuring 3D objects: quality control of mechanical parts, particles monitoring, reverse engineering, art and heritage... Almost all the acquisition techniques can be involved in this wide panel of applications, like time-of-flight measurement, triangulation, speckle interferometry, digital holographic microscopy... The most usual way to display the recorded 3D information for this kind of applications is 3D rendering on conventional 2D displays, because there seems to be no need for real 3D display. However, some fields of application like architecture may benefit from 3D displays, and seeing 3D parts before buying them may be a convincing argument either for a private customer or for an industrial partner.

In the case of scientific applications, the most important applications of 3D acquisition seem to lie in the microscopic domain, especially because of the large recent developments in microelectronics, nano-devices and biology. The problem of resolution is therefore a major stake and a few very specialized techniques are generally dedicated to each application. In this case again, there is no real need for 3D display. The medical field also needs many 3D acquisition techniques at larger scales, in optical domains or (usually) beyond and may benefit from 3D displays. Some scientific applications are strongly concerned with holographic display or with the ability of digital holography to spatially modulate the light. For example, optical tweezers can be built using holography by spatial light modulators, allowing particles control and imaging [85].

**Main properties and stakes of currently available display devices**

Obviously, the ideal 3D display device would be autostereoscopic, it would accept many viewers at the same time and permit as much immersion feeling as possible, eventually including user interaction.

Many 3D displays are currently arriving on the large public market; however none of them answers all these conditions yet. For cinema movies, the usually chosen concept is stereoscopy given by two polarizations or by time-multiplexing (section 3.1.1). Therefore, special glasses are requested, but it seems it does not prevent the success of this concept. A secondary advantage is even found by film companies: multiplex images cannot be recorded.
on usual cameras and shared (pirated) on the web. For familial television, eye wares are not well suited, thus autostereoscopic displays are investigated. Currently available devices use lenticular lenses (section 3.1.1). The number of viewers is very limited and motions of the head disturb the image quality. Furthermore, systems of interaction between users and images from virtual reality are developing, especially in the field of video games but now also in several daily applications. Nevertheless, these interactive tools are seldom mixed with 3D images: the 3D feeling is often due to 3D rendering on a 2D screen or to superposition of a 2D image over real-world images. Holographic displays still suffer from several issues, like the size and brightness of images. This kind of display is still at the beginning of its development.

However, some examples of holographic interactive display can be found, exhibiting limited possibilities. Usually, what is called “interactive holographic display” is a system in which users can rotate and scale the object on a computer, leading to the same visual effect in the 3D electro-optic display, possibly including colors [86]. The image is small and poorly rendered. A more interactive device developed at the MIT in the 1990s included holographic display (using a Bragg cell and a scanned system) and force-feedback stylus [87]. It was designed for virtual craft work, as can be seen from Figure 77: a cylinder was displayed that the user could lathe with the stylus (tracked in 3D), having the feeling of touching the object. The displayed shape was partially updated while machining, and finally the object data was sent to a 3D printer to make a physical copy. The simplifications introduced in the holographic display process imply only horizontal parallax and static display except the very simple (pre-computed) variations introduced by user interaction. Moreover, the device suffers from errors in occlusion effects and time-lag inducing penetration of the stylus into the object.

Thus, at the moment one cannot find any commercial device satisfying the description of the ideal 3D display. The best current solutions seem to be of two kinds. On the one hand, one finds multiplexed movies for which special glasses are needed, because of the good image quality and of the unlimited number of viewers, despite the facts that some people cannot see them correctly. On the other hand, 3D rendering on conventional 2D displays using additional setups to simulate environment immersion are well interpreted by users as

Figure 77: a) General view of the holographic force-feedback device. b) User working on the holographic lathe [87].
actual immersion in a 3D world. Each of them has its own acquisition and processing
technique (stereoscopic, lenticular, processing for 3D rendering from real-world or computer-
generated objects). They are usually not compatible one to another.

Remarks on 3D representation of information

Two-dimensional screens are currently the most usual way to display 3D information,
either in the form of cross-sections or 3D rendering but, depending on the objects
represented, they may not be sufficient. It is known that our brain has particular ways to
interpret 3D shapes when they are only partially visible (Figure 78). For example, we have
the tendency to deduce symmetries and continuity properties to complete the non-visible
parts. Moreover, part of the three-dimensional information is normally inferred from the
parallax due to head motion, and the evaluation of distances, based on angles under which
objects are seen and on the need of eye focusing, is relative (some absolute estimation is
given by a priori knowledge of the object size or other spatial landmarks) [88]. This complex
perception of three dimensions by the brain implies that the way of showing 3D information
needs much care. Therefore, a single view of a complex 3D object is usually not enough to
get a precise idea of its shape and sometimes the user needs to rotate himself the image in
order to understand its shape. It is especially the case for semi-transparent objects having
inner features. Real 3D displays will thus obviously be an important help, provided they are
able to display objects close to their real appearance.

Figure 78: Two bidimensional pictures of a cube exhibiting ambiguities in the 3D perception. A: A 2D or
3D figure can be observed. B: Two positions of the cube are perceptible: view from top or from bottom.

One conclusion that can be drawn from the analysis matrix is the potential compatibility
of virtual reality with many of the 3D acquisition techniques, provided a suited processing is
performed. As shown by perception experiments, the ability to interact with 3D objects gives
the user a much improved feeling of the third dimension. Especially, all scientific and medical
fields would probably take a great advantage of real 3D images with user interaction in order
to improve education, training and scientific popularization. A wide field may thus be open to
making scientific techniques of acquisition, OCT for example, compatible in real-time with the
current 3D displays.

For scientific and industrial purposes, effort probably still have to be made in 3D
rendering in order to display usefully more and more complex 3D data coming from
sophisticated means of acquisition.

Finally, due to the large number of emerging techniques for 3D display, information to
the general public is of great importance. In the context of an increasing interest for 3D
display techniques observed in scientific and technical domains as in the large public
applications, it seems that the word “holography” is a good marketing argument.
Consequently, many autostereoscopic 3D systems and real-time 2D systems (like image
incrustation, lenticular lenses, multi-projectors display, displays using concave mirrors,
intensity projection using fast rotating mirror [89], etc.) are referred to as “holographic”
because they provide some kind of mix between reality and computer-generated or remote images. Nevertheless, none of these techniques is able to render the optical field that would actually reach our eyes if the observed object was real. Some of them provide a kind of 3D rendering, others are only 2D images inserted in the real 3D world. The lack of appropriate terms to classify and designate these techniques for the general public may lead to confusion that can put true digital holography at a disadvantage despite its inherent ability to reconstruct properties of light “as if it was really coming from the object”.
4. Guide to the attached publications (Public)

Publication 1 (this work belongs partially to Real3D)

Measuring Shape and Surfaces down to the Nanometer and Nanosecond scales by Digital Holographic Microscopy
C. Depeursinge, I. Bergoënd, N. Pavillon, J. Kühn, T. Colomb, F. Montfort, E. Cuche, Y. Emery
Fringe'09, ITO, Nürtingen, Germany

Publication 2 (this work belongs partially to Real3D)

4D imaging with nanometer sensitivity with Digital Holographic
C. Depeursinge
OIT'09 Microscopy, Shangai, China

Publication 3 (this is completely Real3D work)

Digital holographic microscopy for micro-systems investigation in near infrared
Yves Delacrétaz, Isabelle Bergoënd and Christian Depeursinge
EOS Topical Meeting on Optical Microsystems conference in Capri

Publication 4 (this is completely Real3D work)

Mid-infrared tunable two-dimensional Talbot array illuminator

Abstract:
We report the realization and characterization of a tunable, two-dimensional Talbot array illuminator for mid-infrared (MIR) wavelengths. A phase array, prepared by depositing tin-doped indium oxide electrodes on a square-lattice-geometry poled LiNbO₃ sample, is
illuminated by a difference-frequency generator emitting at 3μm. Then, combining the
electro-optic with the Talbot effect allows generation of a variety of light patterns under
different values of distance and external electric field. Several potential applications with
great relevance to the MIR spectral region are discussed.

**Publication 5 (this is completely Real3D work)**

*Infrared Digital Holography Using a CO2 laser*

A. Gertrude, M. Locatelli, A. Pelagotti, R. Meucci, M. Paturzo and P. Ferraro

QuS’09-Optical Microsystem, Capri, 27-30 sept. 2009

5. How this work fits into project as a whole (Public)

The work reported in chapters II and IV is a state-of-the-art of current 3D techniques in the
domain of 3D acquisition and display, concerning both scientific and large public fields. It
gives a context for the whole work carried out in this project and defines some promising
ways of development for 3D techniques. Especially, the matrix of analysis (task 5.7) and the
corresponding commentaries given in section 3.3.2 b permits to imagine possible
combinations of techniques in order to answer large demands on the 3D market.
In the domain of multispectral digital holography, the work done is intended to be the major
part of demonstrator 4. New breakthroughs are expected in the domain of silicon devices
quality control and large scenes imaging with thermal cameras. The images acquired in
transmission and reflection in the near and far infrared, with possibly several angles of view,
will be optically displayed using spatial light modulators and visible light. Among the
challenges of this task, common things can be found with demonstrator 3, because both
include the opto-electronic display of transparent objects. Common efforts will be provided
to find suitable solutions for both demonstrators 3 and 4 (EPFL and BILKENT).

6. References (Public)

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7. Attached publications (Public)
Publications related to this deliverable are attached overleaf.