IN PARTNERSHIP WITH:
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Université de Bordeaux

Activity Report 2019

Project-Team MANAO

Melting the frontiers between Light, Shape and Matter

IN COLLABORATION WITH: Laboratoire Bordelais de Recherche en Informatique (LaBRI)

RESEARCH CENTER
Bordeaux - Sud-Ouest

THEME
Interaction and visualization

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Creation of the Team: 2012 January 01, updated into Project-Team: 2014 July 01

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2. Overall Objectives

2.1. General Introduction

Computer generated images are ubiquitous in our everyday life. Such images are the result of a process that has seldom changed over the years: the optical phenomena due to the propagation of *light* in a 3D environment are simulated taking into account how light is scattered [51], [28] according to *shape* and *material* characteristics of objects. The **intersection of optics** (for the underlying laws of physics) and **computer science** (for its modeling and computational efficiency aspects) provides a unique opportunity to tighten the links between these domains in order to first improve the image generation process (computer graphics, optics and virtual reality) and next to develop new acquisition and display technologies (optics, mixed reality and machine vision).

Most of the time, light, shape, and matter properties are studied, acquired, and modeled separately, relying on realistic or stylized rendering processes to combine them in order to create final pixel colors. Such modularity, inherited from classical physics, has the practical advantage of permitting to reuse the same models in various contexts. However, independent developments lead to un-optimized pipelines and difficult-to-control solutions since it is often not clear which part of the expected result is caused by which property. Indeed, the most efficient solutions are most often the ones that **blur the frontiers between light, shape, and matter** to lead to specialized and optimized pipelines, as in real-time applications (like Bidirectional Texture Functions [61] and Light-Field rendering [26]). Keeping these three properties separated may lead to other problems. For instance:

- Measured materials are too detailed to be usable in rendering systems and data reduction techniques have to be developed [59], [62], leading to an inefficient transfer between real and digital worlds;

- It is currently extremely challenging (if not impossible) to directly control or manipulate the interactions between light, shape, and matter. Accurate lighting processes may create solutions that do not fulfill users' expectations;
- Artists can spend hours and days in modeling highly complex surfaces whose details will not be visible [82] due to inappropriate use of certain light sources or reflection properties.

Most traditional applications target human observers. Depending on how deep we take into account the specificity of each user, the requirement of representations, and algorithms may differ.

Auto-stereoscopy display ©Nintendo

HDR display ©Dolby Digital

Printing both geometry and material [43]

Figure 1. Examples of new display technologies. Nowadays, they are not limited to a simple array of 2D low-dynamic RGB values.

With the evolution of measurement and display technologies that go beyond conventional images (e.g., as illustrated in Figure 1, High-Dynamic Range Imaging [72], stereo displays or new display technologies [47], and physical fabrication [17], [35], [43]) the frontiers between real and virtual worlds are vanishing [31]. In this context, a sensor combined with computational capabilities may also be considered as another kind of observer. Creating separate models for light, shape, and matter for such an extended range of applications and observers is often inefficient and sometimes provides unexpected results. Pertinent solutions must be able to **take into account properties of the observer** (human or machine) and application goals.

2.2. Methodology

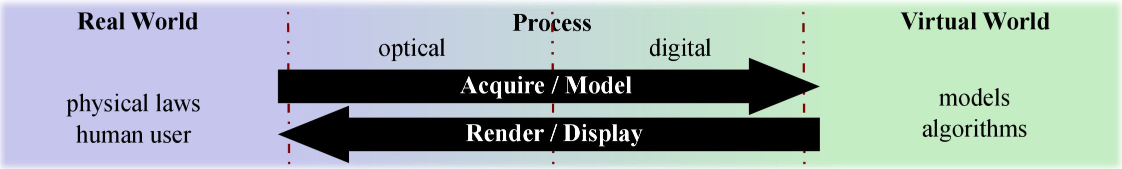


Figure 2. Interactions/Transfers between real and virtual worlds. One of our goal is to combine optical instruments with processes from computer science in order to blend the two worlds.

2.2.1. *Using a global approach*

The main goal of the *MANAO* project is to study phenomena resulting from the interactions between the three components that describe light propagation and scattering in a 3D environment: light, shape, and matter. Improving knowledge about these phenomena facilitates the adaption of the developed digital, numerical, and analytic models to specific contexts. This leads to the development of new analysis tools, new representations, and new instruments for acquisition, visualization, and display.

To reach this goal, we have to first increase our understanding of the different phenomena resulting from the interactions between light, shape, and matter. For this purpose, we consider how they are captured or perceived by the final observer, taking into account the relative influence of each of the three components. Examples include but are not limited to:

- The manipulation of light to reveal reflective [23] or geometric properties [88], as mastered by professional photographers;
- The modification of material characteristics or lighting conditions [89] to better understand shape features, for instance to decipher archaeological artifacts;
- The large influence of shape on the captured variation of shading [70] and thus on the perception of material properties [85].

Based on the acquired knowledge of the influence of each of the components, we aim at developing new models that combine two or three of these components. Examples include the modeling of Bidirectional Texture Functions (BTFs) [34] that encode in a unique representation effects of parallax, multiple light reflections, and also shadows without requiring to store separately the reflective properties and the meso-scale geometric details, or Light-Fields that are used to render 3D scenes by storing only the result of the interactions between light, shape, and matter both in complex real environments and in simulated ones.

One of the strengths of *MANAO* is that we are inter-connecting computer graphics and optics. On one side, the laws of physics are required to create images but may be bent to either increase performance or user's control: this is one of the key advantage of computer graphics approach. It is worth noticing that what is not possible in the real world may be possible in a digital world. However, on the other side, the introduced approximations may help to better comprehend the physical interactions of light, shape, and matter.

2.2.2. Taking observers into account

The *MANAO* project specifically aims at considering information transfer, first from the real world to the virtual world (acquisition and creation), then from computers to observers (visualization and display). For this purpose, we use a larger definition of what an observer is: it may be a human user or a physical sensor equipped with processing capabilities. Sensors and their characteristics must be taken into account in the same way as we take into account the human visual system in computer graphics. Similarly, computational capabilities may be compared to cognitive capabilities of human users. Some characteristics are common to all observers, such as the scale of observed phenomena. Some others are more specifics to a set of observers. For this purpose, we have identified two classes of applications.

- **Physical systems** Provided our partnership that leads to close relationships with optics, one novelty of our approach is to extend the range of possible observers to physical sensors in order to work on domains such as *simulation, mixed reality, and testing*. Capturing, processing, and visualizing complex data is now more and more accessible to everyone, leading to the possible convergence of real and virtual worlds through visual signals. This signal is traditionally captured by cameras. It is now possible to augment them by projecting (e.g., the infrared laser of Microsoft Kinect) and capturing (e.g., GPS localization) other signals that are outside the visible range. These supplemental information replace values traditionally extracted from standard images and thus lower down requirements in computational power [58]. Since the captured images are the result of the interactions between light, shape, and matter, the approaches and the improved knowledge from *MANAO* help in designing interactive acquisition and rendering technologies that are required to merge the real and the virtual world. With the resulting unified systems (optical and digital), transfer of pertinent information is favored and inefficient conversion is likely avoided, leading to new uses in interactive computer graphics applications, like augmented reality [22], [31] and computational photography [71].
- **Interactive visualization** This direction includes domains such as *scientific illustration and visualization, artistic or plausible rendering*. In all these cases, the observer, a human, takes part in the process, justifying once more our focus on real-time methods. When targeting average users, characteristics as well as limitations of the human visual system should be taken into account: in

particular, it is known that some configurations of light, shape, and matter have masking and facilitation effects on visual perception [82]. For specialized applications, the expertise of the final user and the constraints for 3D user interfaces lead to new uses and dedicated solutions for models and algorithms.

3. Research Program

3.1. Related Scientific Domains

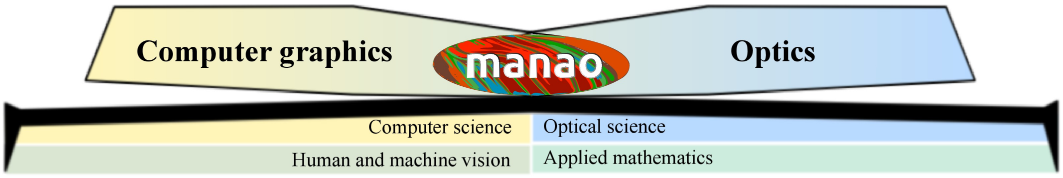


Figure 3. Related scientific domains of the MANAO project.

The *MANAO* project aims at studying, acquiring, modeling, and rendering the interactions between the three components that are light, shape, and matter from the viewpoint of an observer. As detailed more lengthily in the next section, such a work will be done using the following approach: first, we will tend to consider that these three components do not have strict frontiers when considering their impacts on the final observers; then, we will not only work in **computer graphics**, but also at the intersection of computer graphics and **optics**, exploring the mutual benefits that the two domains may provide. It is thus intrinsically a **transdisciplinary** project (as illustrated in Figure 3) and we expect results in both domains.

Thus, the proposed team-project aims at establishing a close collaboration between computer graphics (e.g., 3D modeling, geometry processing, shading techniques, vector graphics, and GPU programming) and optics (e.g., design of optical instruments, and theories of light propagation). The following examples illustrate the strengths of such a partnership. First, in addition to simpler radiative transfer equations [36] commonly used in computer graphics, research in the later will be based on state-of-the-art understanding of light propagation and scattering in real environments. Furthermore, research will rely on appropriate instrumentation expertise for the measurement [48], [49] and display [47] of the different phenomena. Reciprocally, optics researches may benefit from the expertise of computer graphics scientists on efficient processing to investigate interactive simulation, visualization, and design. Furthermore, new systems may be developed by unifying optical and digital processing capabilities. Currently, the scientific background of most of the team members is related to computer graphics and computer vision. A large part of their work have been focused on simulating and analyzing optical phenomena as well as in acquiring and visualizing them. Combined with the close collaboration with the optics laboratory LP2N (http://www.lp2n.fr) and with the students issued from the “Institut d’Optique” (http://www.institutoptique.fr), this background ensures that we can expect the following results from the project: the construction of a common vocabulary for tightening the collaboration between the two scientific domains and creating new research topics. By creating this context, we expect to attract (and even train) more trans-disciplinary researchers.

At the boundaries of the *MANAO* project lie issues in **human and machine vision**. We have to deal with the former whenever a human observer is taken into account. On one side, computational models of human vision are likely to guide the design of our algorithms. On the other side, the study of interactions between light, shape, and matter may shed some light on the understanding of visual perception. The same kind of connections are expected with machine vision. On the one hand, traditional computational methods for acquisition (such as photogrammetry) are going to be part of our toolbox. On the other hand, new display technologies (such as the ones used for augmented reality) are likely to benefit from our integrated approach and systems. In the *MANAO* project we are mostly users of results from human vision. When required, some experimentation might be done in collaboration with experts from this domain, like with the European PRISM project. For machine vision, provided the tight collaboration between optical and digital systems, research will be carried out inside the *MANAO* project.

Analysis and modeling rely on **tools from applied mathematics** such as differential and projective geometry, multi-scale models, frequency analysis [38] or differential analysis [70], linear and non-linear approximation techniques, stochastic and deterministic integrations, and linear algebra. We not only rely on classical tools, but also investigate and adapt recent techniques (e.g., improvements in approximation techniques), focusing on their ability to run on modern hardware: the development of our own tools (such as Eigen) is essential to control their performances and their abilities to be integrated into real-time solutions or into new instruments.

3.2. Research axes

The *MANAO* project is organized around four research axes that cover the large range of expertise of its members and associated members. We briefly introduce these four axes in this section. More details and their inter-influences that are illustrated in the Figure 2 will be given in the following sections.

Axis 1 is the theoretical foundation of the project. Its main goal is to increase the understanding of light, shape, and matter interactions by combining expertise from different domains: optics and human/machine vision for the analysis and computer graphics for the simulation aspect. The goal of our analyses is to identify the different layers/phenomena that compose the observed signal. In a second step, the development of physical simulations and numerical models of these identified phenomena is a way to validate the pertinence of the proposed decompositions.

In Axis 2, the final observers are mainly physical captors. Our goal is thus the development of new acquisition and display technologies that combine optical and digital processes in order to reach fast transfers between real and digital worlds, in order to increase the convergence of these two worlds.

Axes 3 and 4 focus on two aspects of computer graphics: rendering, visualization and illustration in Axis 3, and editing and modeling (content creation) in Axis 4. In these two axes, the final observers are mainly human users, either generic users or expert ones (e.g., archaeologist [74], computer graphics artists).

3.3. Axis 1: Analysis and Simulation

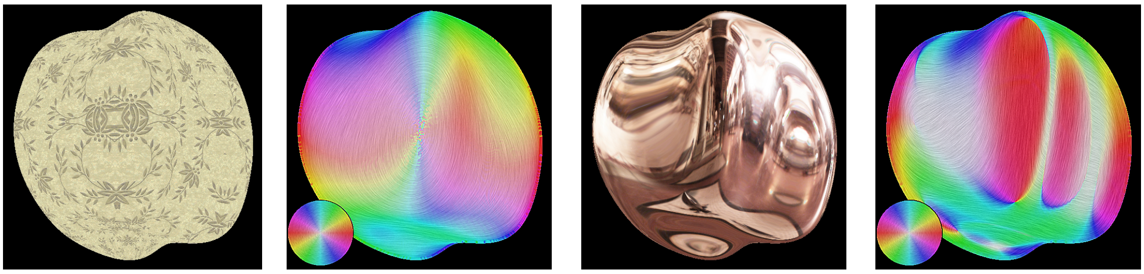
Challenge: Definition and understanding of phenomena resulting from interactions between light, shape, and matter as seen from an observer point of view.

Results: Theoretical tools and numerical models for analyzing and simulating the observed optical phenomena.

To reach the goals of the *MANAO* project, we need to **increase our understanding** of how light, shape, and matter act together in synergy and how the resulting signal is finally observed. For this purpose, we need to identify the different phenomena that may be captured by the targeted observers. This is the main objective of this research axis, and it is achieved by using three approaches: the simulation of interactions between light, shape, and matter, their analysis and the development of new numerical models. This resulting improved knowledge is a foundation for the researches done in the three other axes, and the simulation tools together with the numerical models serve the development of the joint optical/digital systems in Axis 2 and their validation.

One of the main and earliest goals in computer graphics is to faithfully reproduce the real world, focusing mainly on light transport. Compared to researchers in physics, researchers in computer graphics rely on a subset of physical laws (mostly radiative transfer and geometric optics), and their main concern is to efficiently use the limited available computational resources while developing as fast as possible algorithms. For this purpose, a large set of theoretical as well as computational tools has been introduced to take a **maximum benefit of hardware** specificities. These tools are often dedicated to specific phenomena (e.g., direct or indirect lighting, color bleeding, shadows, caustics). An efficiency-driven approach needs such a classification of light paths [44] in order to develop tailored strategies [86]. For instance, starting from simple direct lighting, more complex phenomena have been progressively introduced: first diffuse indirect illumination [42], [78], then more generic inter-reflections [51], [36] and volumetric scattering [75], [33]. Thanks to this search for efficiency and this classification, researchers in computer graphics have developed a now recognized expertise in fast-simulation of light propagation. Based on finite elements (radiosity techniques) or on unbiased Monte Carlo integration schemes (ray-tracing, particle-tracing, ...), the resulting algorithms and their combination are now sufficiently accurate to be used-back in physical simulations. The *MANAO* project will continue the search for **efficient and accurate simulation** techniques, but extending it from computer graphics to optics. Thanks to the close collaboration with scientific researchers from optics, new phenomena beyond radiative transfer and geometric optics will be explored.

Search for algorithmic efficiency and accuracy has to be done in parallel with **numerical models**. The goal of visual fidelity (generalized to accuracy from an observer point of view in the project) combined with the goal of efficiency leads to the development of alternative representations. For instance, common classical finite-element techniques compute only basis coefficients for each discretization element: the required discretization density would be too large and to computationally expensive to obtain detailed spatial variations and thus visual fidelity. Examples includes texture for decorrelating surface details from surface geometry and high-order wavelets for a multi-scale representation of lighting [32]. The numerical complexity explodes when considering directional properties of light transport such as radiance intensity (Watt per square meter and per steradian - $W.m^{-2}.sr^{-1}$), reducing the possibility to simulate or accurately represent some optical phenomena. For instance, Haar wavelets have been extended to the spherical domain [77] but are difficult to extend to non-piecewise-constant data [80]. More recently, researches prefer the use of Spherical Radial Basis Functions [83] or Spherical Harmonics [69]. For more complex data, such as reflective properties (e.g., BRDF [63], [52] - 4D), ray-space (e.g., Light-Field [60] - 4D), spatially varying reflective properties (6D - [73]), new models, and representations are still investigated such as rational functions [66] or dedicated models [20] and parameterizations [76], [81]. For each (newly) defined phenomena, we thus explore the space of possible numerical representations to determine the **most suited one for a given application**, like we have done for BRDF [66].



Texuring 1^{st} order gradient field Environment reflection 2^{st} order gradient field

Figure 4. First-oder analysis [87] have shown that shading variations are caused by depth variations (first-order gradient field) and by normal variations (second-order fields). These fields are visualized using hue and saturation to indicate direction and magnitude of the flow respectively.

Before being able to simulate or to represent the different **observed phenomena**, we need to define and describe them. To understand the difference between an observed phenomenon and the classical light, shape, and matter decomposition, we can take the example of a highlight. Its observed shape (by a human user or a sensor) is the resulting process of the interaction of these three components, and can be simulated this way. However, this does not provide any intuitive understanding of their relative influence on the final shape:

an artist will directly describe the resulting shape, and not each of the three properties. We thus want to decompose the observed signal into models for each scale that can be easily understandable, representable, and manipulable. For this purpose, we will rely on the **analysis** of the resulting interaction of light, shape, and matter as observed by a human or a physical sensor. We first consider this analysis from an **optical point of view**, trying to identify the different phenomena and their scale according to their mathematical properties (e.g., differential [70] and frequency analysis [38]). Such an approach has leaded us to exhibit the influence of surfaces flows (depth and normal gradients) into lighting pattern deformation (see Figure 4). For a **human observer**, this correspond to one recent trend in computer graphics that takes into account the human visual systems [39] both to evaluate the results and to guide the simulations.

3.4. Axis 2: From Acquisition to Display

Challenge: Convergence of optical and digital systems to blend real and virtual worlds.

Results: Instruments to acquire real world, to display virtual world, and to make both of them interact.

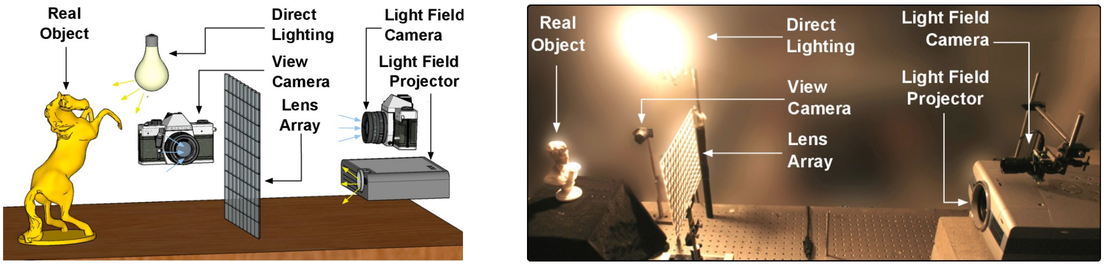


Figure 5. Light-Field transfer: global illumination between real and synthetic objects [31]

In this axis, we investigate *unified acquisition and display systems*, that is systems which combine optical instruments with digital processing. From digital to real, we investigate new display approaches [60], [47]. We consider projecting systems and surfaces [27], for personal use, virtual reality and augmented reality [22]. From the real world to the digital world, we favor direct measurements of parameters for models and representations, using (new) optical systems unless digitization is required [41], [40]. These resulting systems have to acquire the different phenomena described in Axis 1 and to display them, in an efficient manner [45], [21], [46], [49]. By efficient, we mean that we want to shorten the path between the real world and the virtual world by increasing the data bandwidth between the real (analog) and the virtual (digital) worlds, and by reducing the latency for real-time interactions (we have to prevent unnecessary conversions, and to reduce processing time). To reach this goal, the systems have to be designed as a whole, not by a simple concatenation of optical systems and digital processes, nor by considering each component independently [50].

To increase data bandwidth, one solution is to **parallelize more and more the physical systems**. One possible solution is to multiply the number of simultaneous acquisitions (e.g., simultaneous images from multiple viewpoints [49], [68]). Similarly, increasing the number of viewpoints is a way toward the creation of full 3D displays [60]. However, full acquisition or display of 3D real environments theoretically requires a continuous field of viewpoints, leading to huge data size. Despite the current belief that the increase of computational power will fill the missing gap, when it comes to visual or physical realism, if you double the processing power, people may want four times more accuracy, thus increasing data size as well. To reach the best performances, a trade-off has to be found between the amount of data required to represent accurately the reality and the amount of required processing. This trade-off may be achieved using **compressive sensing**. Compressive sensing is a new trend issued from the applied mathematics community that provides tools to accurately reconstruct a signal from a small set of measurements assuming that it is sparse in a transform domain (e.g., [67], [92]).

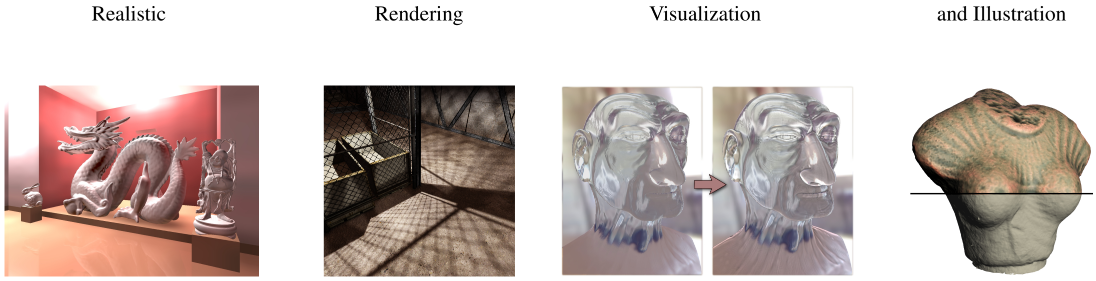
We prefer to achieve this goal by avoiding as much as possible the classical approach where acquisition is followed by a fitting step: this requires in general a large amount of measurements and the fitting itself may consume consequently too much memory and preprocessing time. By **preventing unnecessary conversion** through fitting techniques, such an approach increase the speed and reduce the data transfer for acquisition but also for display. One of the best recent examples is the work of Cossairt et al. [31]. The whole system is designed around a unique representation of the energy-field issued from (or leaving) a 3D object, either virtual or real: the Light-Field. A Light-Field encodes the light emitted in any direction from any position on an object. It is acquired thanks to a lens-array that leads to the capture of, and projection from, multiple simultaneous viewpoints. A unique representation is used for all the steps of this system. Lens-arrays, parallax barriers, and coded-aperture [57] are one of the key technologies to develop such acquisition (e.g., Light-Field camera [1] [50] and acquisition of light-sources [41]), projection systems (e.g., auto-stereoscopic displays). Such an approach is versatile and may be applied to improve classical optical instruments [55]. More generally, by designing unified optical and digital systems [64], it is possible to leverage the requirement of processing power, the memory footprint, and the cost of optical instruments.

Those are only some examples of what we investigate. We also consider the following approaches to develop new unified systems. First, similar to (and based on) the analysis goal of Axis 1, we have to take into account as much as possible the characteristics of the measurement setup. For instance, when fitting cannot be avoided, integrating them may improve both the processing efficiency and accuracy [66]. Second, we have to integrate signals from multiple sensors (such as GPS, accelerometer, ...) to prevent some computation (e.g., [58]). Finally, the experience of the group in surface modeling help the design of optical surfaces [53] for light sources or head-mounted displays.

3.5. Axis 3: Rendering, Visualization and Illustration

Challenge: How to offer the most legible signal to the final observer in real-time?

Results: High-level shading primitives, expressive rendering techniques for object depiction, real-time realistic rendering algorithms



(a) Global illumination [65] (b) Shadows [93] (c) Shape enhancement [89] (d) Shape depiction [19]

Figure 6. In the MANAO project, we are investigating rendering techniques from realistic solutions (e.g., inter-reflections (a) and shadows (b)) to more expressive ones (shape enhancement (c) with realistic style and shape depiction (d) with stylized style) for visualization.

The main goal of this axis is to offer to the final observer, in this case mostly a human user, the most legible signal in real-time. Thanks to the analysis and to the decomposition in different phenomena resulting from interactions between light, shape, and matter (Axis 1), and their perception, we can use them to convey essential information in the most pertinent way. Here, the word *pertinent* can take various forms depending on the application.

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[1] Lytro, http://www.lytro.com/

In the context of scientific illustration and visualization, we are primarily interested in tools to convey shape or material characteristics of objects in animated 3D scenes. **Expressive rendering** techniques (see Figure 6c,d) provide means for users to depict such features with their own style. To introduce our approach, we detail it from a shape-depiction point of view, domain where we have acquired a recognized expertise. Prior work in this area mostly focused on stylization primitives to achieve line-based rendering [90], [54] or stylized shading [25], [89] with various levels of abstraction. A clear representation of important 3D **object features** remains a major challenge for better shape depiction, stylization and abstraction purposes. Most existing representations provide only local properties (e.g., curvature), and thus lack characterization of broader shape features. To overcome this limitation, we are developing higher level descriptions of shape [18] with increased robustness to sparsity, noise, and outliers. This is achieved in close collaboration with Axis 1 by the use of higher-order local fitting methods, multi-scale analysis, and global regularization techniques. In order not to neglect the observer and the material characteristics of the objects, we couple this approach with an analysis of the appearance model. To our knowledge, this is an approach which has not been considered yet. This research direction is at the heart of the *MANAO* project, and has a strong connection with the analysis we plan to conduct in Axis 1. Material characteristics are always considered at the light ray level, but an understanding of **higher-level primitives** (like the shape of highlights and their motion) would help us to produce more legible renderings and permit novel stylizations; for instance, there is no method that is today able to create stylized renderings that follow the motion of highlights or shadows. We also believe such tools also play a fundamental role for geometry processing purposes (such as shape matching, reassembly, simplification), as well as for editing purposes as discussed in Axis 4.

In the context of **real-time photo-realistic rendering** ((see Figure 6a,b), the challenge is to compute the most plausible images with minimal effort. During the last decade, a lot of work has been devoted to design approximate but real-time rendering algorithms of complex lighting phenomena such as soft-shadows [91], motion blur [38], depth of field [79], reflexions, refractions, and inter-reflexions. For most of these effects it becomes harder to discover fundamentally new and faster methods. On the other hand, we believe that significant speedup can still be achieved through more clever use of **massively parallel architectures** of the current and upcoming hardware, and/or through more clever tuning of the current algorithms. In particular, regarding the second aspect, we remark that most of the proposed algorithms depend on several parameters which can be used to **trade the speed over the quality**. Significant speed-up could thus be achieved by identifying effects that would be masked or facilitated and thus devote appropriate computational resources to the rendering [56], [37]. Indeed, the algorithm parameters controlling the quality vs speed are numerous without a direct mapping between their values and their effect. Moreover, their ideal values vary over space and time, and to be effective such an auto-tuning mechanism has to be extremely fast such that its cost is largely compensated by its gain. We believe that our various work on the analysis of the appearance such as in Axis 1 could be beneficial for such purpose too.

Realistic and real-time rendering is closely related to Axis 2: real-time rendering is a requirement to close the loop between real world and digital world. We have to thus develop algorithms and rendering primitives that allow the integration of the acquired data into real-time techniques. We have also to take care of that these real-time techniques have to work with new display systems. For instance, stereo, and more generally multi-view displays are based on the multiplication of simultaneous images. Brute force solutions consist in independent rendering pipeline for each viewpoint. A more energy-efficient solution would take advantages of the computation parts that may be factorized. Another example is the rendering techniques based on image processing, such as our work on augmented reality [29]. Independent image processing for each viewpoint may disturb the feeling of depth by introducing inconsistent information in each images. Finally, more dedicated displays [47] would require new rendering pipelines.

3.6. Axis 4: Editing and Modeling

Challenge: Editing and modeling appearance using drawing- or sculpting-like tools through high level representations.

Results: High-level primitives and hybrid representations for appearance and shape.

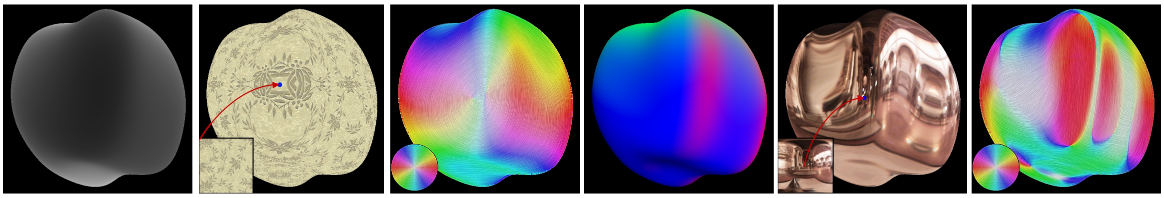
During the last decade, the domain of computer graphics has exhibited tremendous improvements in image quality, both for 2D applications and 3D engines. This is mainly due to the availability of an ever increasing amount of shape details, and sophisticated appearance effects including complex lighting environments. Unfortunately, with such a growth in visual richness, even so-called *vectorial* representations (e.g., subdivision surfaces, Bézier curves, gradient meshes, etc.) become very dense and unmanageable for the end user who has to deal with a huge mass of control points, color labels, and other parameters. This is becoming a major challenge, with a necessity for novel representations. This Axis is thus complementary of Axis 3: the focus is the development of primitives that are easy to use for modeling and editing.

More specifically, we plan to investigate *vectorial representations* that would be amenable to the production of rich shapes with a minimal set of primitives and/or parameters. To this end we plan to build upon our insights on dynamic local reconstruction techniques and implicit surfaces [30] [24]. When working in 3D, an interesting approach to produce detailed shapes is by means of procedural geometry generation. For instance, many natural phenomena like waves or clouds may be modeled using a combination of procedural functions. Turning such functions into triangle meshes (main rendering primitives of GPUs) is a tedious process that appears not to be necessary with an adapted vectorial shape representation where one could directly turn procedural functions into implicit geometric primitives. Since we want to prevent unnecessary conversions in the whole pipeline (here, between modeling and rendering steps), we will also consider *hybrid representations* mixing meshes and implicit representations. Such research has thus to be conducted while considering the associated editing tools as well as performance issues. It is indeed important to keep *real-time performance* (cf. Axis 2) throughout the interaction loop, from user inputs to display, via editing and rendering operations. Finally, it would be interesting to add *semantic information* into 2D or 3D geometric representations. Semantic geometry appears to be particularly useful for many applications such as the design of more efficient manipulation and animation tools, for automatic simplification and abstraction, or even for automatic indexing and searching. This constitutes a complementary but longer term research direction.

In the *MANAO* project, we want to investigate representations beyond the classical light, shape, and matter decomposition. We thus want to directly control the appearance of objects both in 2D and 3D applications (e.g., [84]): this is a core topic of computer graphics. When working with 2D vector graphics, digital artists must carefully set up color gradients and textures: examples range from the creation of 2D logos to the photo-realistic imitation of object materials. Classic vector primitives quickly become impractical for creating illusions of complex materials and illuminations, and as a result an increasing amount of time and skill is required. This is only for still images. For animations, vector graphics are only used to create legible appearances composed of simple lines and color gradients. There is thus a need for more complex primitives that are able to accommodate complex reflection or texture patterns, while keeping the ease of use of vector graphics. For instance, instead of drawing color gradients directly, it is more advantageous to draw flow lines that represent local surface concavities and convexities. Going through such an intermediate structure then allows to deform simple material gradients and textures in a coherent way (see Figure 7), and animate them all at once. The manipulation of 3D object materials also raises important issues. Most existing material models are tailored to faithfully reproduce physical behaviors, not to be *easily controllable* by artists. Therefore artists learn to tweak model parameters to satisfy the needs of a particular shading appearance, which can quickly become cumbersome as the complexity of a 3D scene increases. We believe that an alternative approach is required, whereby material appearance of an object in a typical lighting environment is directly input (e.g., painted or drawn), and adapted to match a plausible material behavior. This way, artists will be able to create their own appearance (e.g., by using our shading primitives [84]), and replicate it to novel illumination environments and 3D models. For this purpose, we will rely on the decompositions and tools issued from Axis 1.

4. Application Domains

4.1. Physical Systems



(a) (b) (c) (d) (e) (f)

Figure 7. Based on our analysis [87] (Axis 1), we have designed a system that mimics texture (left) and shading (right) effects using image processing alone. It takes depth (a) and normal (d) images as input, and uses them to deform images (b-e) in ways that closely approximate surface flows (c-f). It provides a convincing, yet artistically controllable illusion of 3D shape conveyed through texture or shading cues.

Given our close relationships with researchers in optics, one novelty of our approach is to extend the range of possible observers to physical sensors in order to work on domains such as simulation, mixed reality, and testing. Capturing, processing, and visualizing complex data is now more and more accessible to everyone, leading to the possible convergence of real and virtual worlds through visual signals. This signal is traditionally captured by cameras. It is now possible to augment them by projecting (e.g., the infrared laser of Microsoft Kinect) and capturing (e.g., GPS localization) other signals that are outside the visible range. This supplemental information replaces values traditionally extracted from standard images and thus lowers down requirements in computational power. Since the captured images are the result of the interactions between light, shape, and matter, the approaches and the improved knowledge from *MANAO* help in designing interactive acquisition and rendering technologies that are required to merge the real and the virtual worlds. With the resulting unified systems (optical and digital), transfer of pertinent information is favored and inefficient conversion is likely avoided, leading to new uses in interactive computer graphics applications, like **augmented reality**, **displays** and **computational photography**.

4.2. Interactive Visualization and Modeling

This direction includes domains such as **scientific illustration and visualization**, **artistic or plausible rendering**, and **3D modeling**. In all these cases, the observer, a human, takes part in the process, justifying once more our focus on real-time methods. When targeting average users, characteristics as well as limitations of the human visual system should be taken into account: in particular, it is known that some configurations of light, shape, and matter have masking and facilitation effects on visual perception. For specialized applications (such as archeology), the expertise of the final user and the constraints for 3D user interfaces lead to new uses and dedicated solutions for models and algorithms.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Public exhibitions

Textile(s) 3D, exhibition at the Musée Ethnographique de Bordeaux (MEB), until May 29th, 2020: measurement and reproduction of textiles.

The program has targeted the faithful reproduction of the appearance of fragile textiles. To this end, an optical appearance measurement setup has been developped and installed in the basement of the museum. Several textiles have been measured, including ancient asian textiles from the MEB collection; the originals along with their digital reproduction have been shown to the visitors of the museum.

5.1.2. Demonstration

SID Display Week I-Zone, San José Convention Center, May 14-16, 2019: Prototype of an autostereoscopic transparent display

We have showcased a 5-view, full-color, autostereoscopic transparent display prototype that we have developed [8], [13]. Its solution is much like a window that is able to superimpose autostereoscopic 3D data over the real world without the need of any wearables. There are many potential applications in augmented reality and head-up display fields; for example, in automotive, advertisement, and educational areas.

6. New Software and Platforms

6.1. Eigen

KEYWORD: Linear algebra

FUNCTIONAL DESCRIPTION: Eigen is an efficient and versatile C++ mathematical template library for linear algebra and related algorithms. In particular it provides fixed and dynamic size matrices and vectors, matrix decompositions (LU, LLT, LDLT, QR, eigenvalues, etc.), sparse matrices with iterative and direct solvers, some basic geometry features (transformations, quaternions, axis-angles, Euler angles, hyperplanes, lines, etc.), some non-linear solvers, automatic differentiations, etc. Thanks to expression templates, Eigen provides a very powerful and easy to use API. Explicit vectorization is performed for the SSE, AltiVec and ARM NEON instruction sets, with graceful fallback to non-vectorized code. Expression templates allow to perform global expression optimizations, and to remove unnecessary temporary objects.

RELEASE FUNCTIONAL DESCRIPTION: In 2017, we released three revisions of the 3.3 branch with few fixes of compilation and performance regressions, some doxygen documentation improvements, and the addition of transpose, adjoint, conjugate methods to SelfAdjointView to ease writing generic code.

- Participant: Gaël Guennebaud
- Contact: Gaël Guennebaud
- URL: http://eigen.tuxfamily.org/

6.2. Spectral Viewer

KEYWORD: Image

FUNCTIONAL DESCRIPTION: An open-source (spectral) image viewer that supports several images formats: ENVI (spectral), exr, png, jpg.

- Partner: LP2N (CNRS - UMR 5298)
- Contact: Romain Pacanowski
- URL: https://adufay.gitlabpages.inria.fr/SpectralViewer/index.html

6.3. otmap

C++ optimal transport solver on 2D grids

KEYWORDS: Optimal transportation - Eigen - C++ - Image processing - Numerical solver

FUNCTIONAL DESCRIPTION: This is a lightweight implementation of "Instant Transport Maps on 2D Grids".

It currently supports L2-optimal maps from an arbitrary density defined on a uniform 2D grid (aka an image) to a square with uniform density. Inverse maps and maps between pairs of arbitrary images are then recovered through numerical inversion and composition resulting in density preserving but approximately optimal maps.

This code also includes with 3 mini applications:

- otmap: computes the forward and backward maps between one image and a uniform square or between a pair of images. The maps are exported as .off quad meshes. - stippling: adapt a uniformly distributed point cloud to a given image. - barycenters: computes linear (resp. bilinear) approximate Wasserstein barycenters between a pair (resp. four) images.

- Contact: Gaël Guennebaud

7. New Results

7.1. Analysis and Simulation

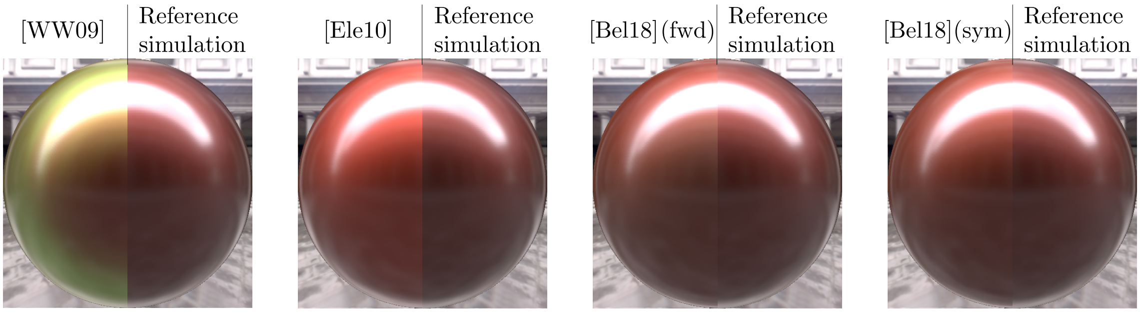


Figure 8. We study how the approximations made by layered material models impact their accuracy, and ultimately material appearance. Here we compare four models side by side with our reference simulation on a frosted metal – one of the 60 material configurations we have considered in our study. This specific choice is particularly problematic for the model of Weidlich and Wilkie [WW09], which creates oddly-colored reflections away from normal incidence. The variant of Elek [Ele10] is devoid of these artefacts, but clearly overestimates the intensity of the metallic base. Belcour's models [Bel18] (forward and symmetric) produce more accurate results, even though the intensity of the metallic base remains slightly higher. They still deviate from the reference simulation, especially at grazing angles as seen for instance at the bottom of the spheres. Our analysis in BRDF (and BTDF) space provides explanations for such departures from the reference.

7.1.1. Numerical Analysis of Layered Materials Models ,

Publications: [12], [14]

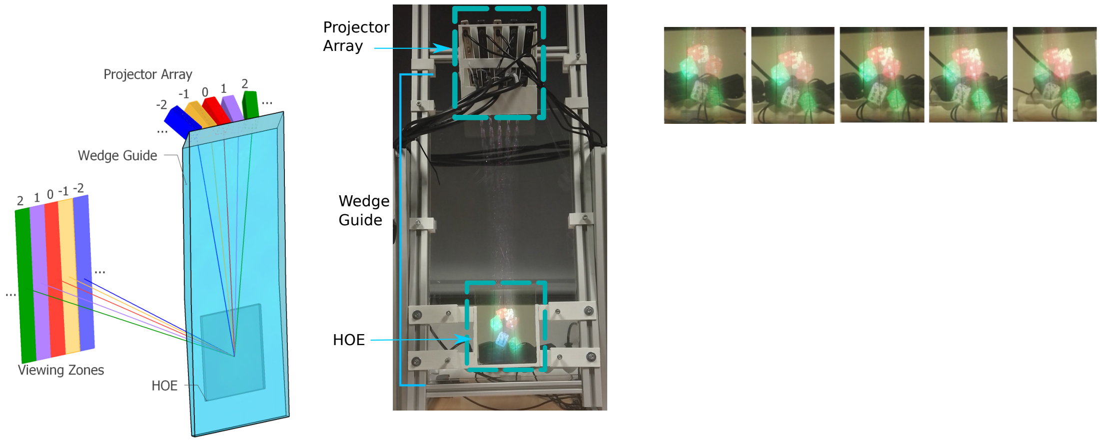
Most real-world materials are composed of multiple layers, whose physical properties impact the appearance of objects. The accurate reproduction of layered material properties is thus an important part of physically-based rendering applications. Since no exact analytical model exists for arbitrary configurations of layer stacks, available models make a number of approximations. In this technical report, we propose to evaluate these approximations with a numerical approach: we simulate BRDFs and BTDFs for layered materials in order to compare existing models against a common reference. More specifically, we consider 60 layered material configurations organized in three categories: plastics, metals and transparent slabs. Our results (see Figure 8) show that: (1) no single model systematically outperforms the others on all categories; and (2) significant discrepancies remain between simulated and modeled materials. We analyse the reasons for these discrepancies and introduce immediate corrections that improve models accuracy with little effort. Finally, we provide a few challenging cases for future layered material models.

7.1.2. A systematic approach to testing and predicting light-material interactions

Publication: [11]

Photographers and lighting designers set up lighting environments that best depict objects and human figures to convey key aspects of the visual appearance of various materials, following rules drawn from experience. Understanding which lighting environment is best adapted to convey which key aspects of materials is an important question in the field of human vision. The endless range of natural materials and lighting environments poses a major problem in this respect. Here we present a systematic approach to make this problem tractable for lighting–material interactions, using optics-based models composed of canonical lighting and material modes. In two psychophysical experiments, different groups of inexperienced observers judged the material qualities of the objects depicted in the stimulus images. In the first experiment, we took photographs of real objects as stimuli under canonical lightings. In a second experiment, we selected three generic natural lighting environments on the basis of their predicted lighting effects and made computer renderings of the objects. The selected natural lighting environments have characteristics similar to the canonical lightings, as computed using a spherical harmonic analysis. Results from the two experiments correlate strongly, showing (a) how canonical material and lighting modes associate with perceived material qualities; and (b) which lighting is best adapted to evoke perceived material qualities, such as softness, smoothness, and glossiness. Our results demonstrate that a system of canonical modes spanning the natural range of lighting and materials provides a good basis to study lighting–material interactions in their full natural ecology.

7.2. From Acquisition to Display



(a) Illustration (b) Photograph (c) 5 views

Figure 9. The autostereoscopic transparent display: light beams from multiple laser beam steering picoprojectors are coupled into a transparent wedge guide, and then the light from each projector is redirected to separate viewing zones using a transparent HOE.

7.2.1. Autostereoscopic transparent display using a wedge light guide and a holographic optical element

Publications: [8], [13]

We designed and developed a novel transparent autostereoscopic display consisting of laser picoprojectors, a wedge light guide, and a custom holographic optical element (HOE). Such a display can superimpose 3D data on the real world without any wearable.

The principle of our display, as depicted in Figure 9, is to couple beams from multiple laser beam steering picoprojectors into a transparent wedge guide and then to redirect each beam to separate viewing zones using a transparent HOE. The HOE is wavelength-multiplexed for full-color efficiency, but only one angular grating is recorded and multiple viewing zones are reconstructed with several projector positions due to the high angular bandwidth. Our current prototype has 5 views but is theoretically able to generate 9 views. The views are located 50cm in front of the display, they are 3cm wide and 10cm high. These values are fixed once the HOE is recorded; they result from our choices and can be changed in the recording step.

This display has great potential for augmented reality applications such as augmented exhibitions in museums or shops, head-up displays for vehicles or aeronautics, and industrial maintenance, among others.

7.2.2. Wedge cameras for minimally invasive archaeology

Publication: [9]

Acquiring images of archaeological artifacts is an essential step for the study and preservation of cultural heritage. In constrained environments, traditional acquisition techniques may fail or be too invasive. We present an optical device including a camera and a wedge waveguide that is optimized for imaging within confined spaces in archeology. The major idea is to redirect light by total internal reflection to circumvent the lack of room, and to compute the final image from the raw data. We tested various applications onsite during an archaeological mission in Medamoud (Egypt). Our device was able to successfully record images of the underground from slim trenches, including underwater trenches, and between rocks composing a wall temple. Experts agreed that the acquired images were good enough to get useful information that cannot be obtained as easily with traditional techniques.

7.2.3. Study of contrast variations with depth in focused plenoptic cameras

Publication: [10]

A focused plenoptic camera has the ability to record and separate spatial and directional information of the incoming light. Combined with the appropriate algorithm, a 3D scene could be reconstructed from a single acquisition, over a depth range called plenoptic depth-of-field. We have studied the contrast variations with depth as a way to assess plenoptic depth-of-field. We take into account the impact of diffraction, defocus, and magnification on the resulting contrast. We measure the contrast directly on both simulated and acquired images. We demonstrate the importance of diffraction and magnification in the final contrast. Contrary to classical optics, the maximum of contrast is not centered around the main object plane, but around a shifted position, with a fast and nonsymmetric decrease of contrast.

7.2.4. Unifying the refocusing algorithms and parameterizations for traditional and focused plenoptic cameras

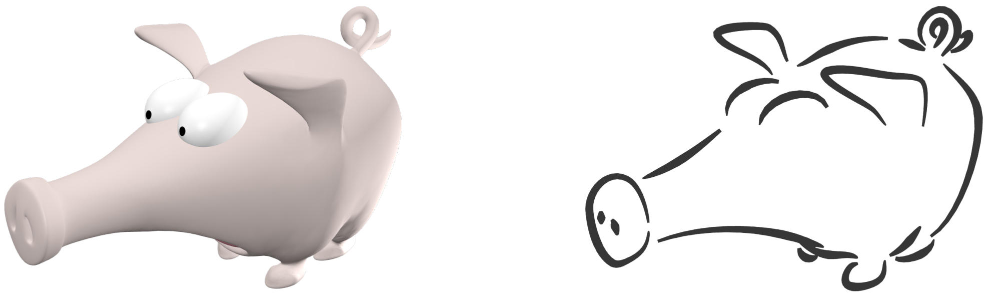
Publication: [16]

We propose a unique parameterization of the light rays in a plenoptic setup, allowing the development of a unique refocusing algorithm valid for any plenoptic configurations, based on this parameterization. With this method we aim at refocusing images at any distances from the camera, without previous discontinuity due to change of optical configuration. We aim to obtain reconstructed images visually similar to the results of the other algorithms, but quantitatively more accurate.

7.3. Rendering, Visualization and Illustration

7.3.1. Line drawings from 3D models: a tutorial

Publication: [7]



(a) 3D object with diffuse shading (b) Stylized curves

Figure 10. The occluding contours of the 3D model “Origins of the Pig” by Keenan Crane, shown in (a) with diffuse shading, are depicted in (b) with calligraphic brush strokes.

This tutorial describes the geometry and algorithms for generating line drawings from 3D models, focusing on occluding contours. The geometry of occluding contours on meshes and on smooth surfaces is described in detail, together with algorithms for extracting contours, computing their visibility, and creating stylized renderings and animations. Exact methods and hardware-accelerated fast methods are both described, and the trade-offs between different methods are discussed. The tutorial brings together and organizes material that, at present, is scattered throughout the literature. It also includes some novel explanations, and implementation tips. A thorough survey of the field of non-photorealistic 3D rendering is also included, covering other kinds of line drawings and artistic shading (Figure 10). In addition, we provide an interactive viewer at https://benardp.github.io/contours_viewer/.

7.4. Editing and Modeling

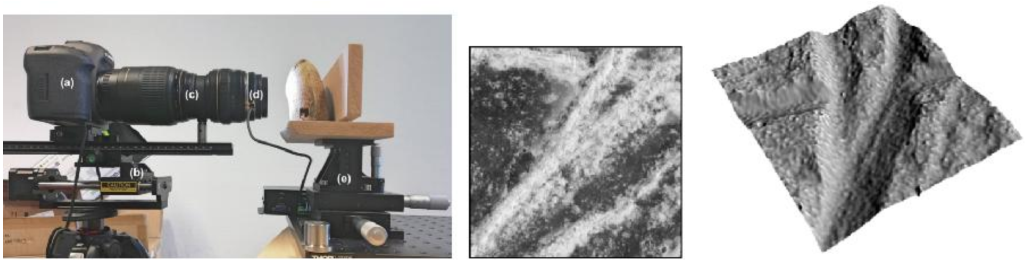


Figure 11. Left: our low-cost depth-from-focus acquisition setup. Right: result of our reconstruction algorithm for the sample shown in the middle image. The width of grooves are about 500 micrometers.

7.4.1. Depth from focus stacks at micrometer scale

In this work we designed a low-cost acquisition setup and a new algorithm for the digitalization of micro reliefs. The setup is based on a common digital camera equipped with a special assembly of different lenses designed to enable a ×2 magnification factor with a very shallow depth of field (fig. 11). A micro-metric motor rail allows us to acquire dense focus stacks with depth information that can be reconstructed through image processing and analysis techniques. To enhance the accuracy of this reconstruction step, we designed novel focus estimators as well as novel focus-point analysis algorithms exploiting novel 3D invariants. Our initial results show that we are able to reconstruct depth maps with sub-step length accuracy.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. CIFRE PhD contract with Imaging Optics (2017-2020)

Participants: C. Herzog & X. Granier
For this project, we aim at developing 3 dimensions X-rays imaging techniques for medical applications.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. "Young Researcher" VIDA (2017-2021)

LP2N-CNRS-IOGS Inria
Leader R. Pacanowski (LP2N-CNRS-IOGS)
Participant P. Barla
This project aims at establishing a framework for direct and inverse design of material appearance for objects of complex shape. Since the manufacturing processes are always evolving, our goal is to establish a framework that is not tied to a fabrication stage.

9.1.1.2. MATERIALS (2015-2019)

MAVERICK, LP2N-CNRS (MANAO), Musée d'Ethnographie de Bordeaux, OCÉ-Print
Leader N. Holzschuch (MAVERICK)
Participant A. Lucat
Museums are operating under conflicting constraints: they have to preserve the artifacts they are storing, while making them available to the public and to researchers. Cultural artifacts are so fragile that simply exposing them to light degrades them. 3D scanning, combined with virtual reality and 3D printing has been used for the preservation and study of sculptures. The approach is limited: it acquires the geometry and the color, but not complex material properties. Current 3D printers are also limited in the range of colors they can reproduce. Our goal in this project is to address the entire chain of material acquisition and restitution. Our idea is to scan complex cultural artifacts, such as silk cloths, capturing all the geometry of their materials at the microscopic level, then reproduce them for study by public and researchers. Reproduction can be either done through 2.5D printing or virtual reality displays.

9.1.1.3. FOLD-Dyn (2017-2021)

IRIT, IMAGINE, MANAO, TeamTo, Mercenaries
Leader L. Barthe (IRIT)
Local Leader G. Guennebaud

The FOLD-Dyn project proposes the study of new theoretical approaches for the effective generation of virtual characters deformations, when they are animated. These deformations are two-folds: character skin deformations (skinning) and garment simulations. We propose to explore the possibilities offered by a novel theoretical way of addressing character deformations: the implicit skinning. This method jointly uses meshes and volumetric scalar functions. By improving the theoretical properties of scalar functions, the study of their joint use with meshes, and the introduction of a new approach and its formalism - called multi-layer 3D scalar functions - we aim at finding effective solutions allowing production studios to easily integrate in their pipeline plausible character deformations together with garment simulations.

9.1.1.4. CaLiTrOp (2017-2021)

IRIT, LIRIS, MANAO, MAVERICK
Leader: M. Paulin (IRIT)
Participant D. Murray
What is the inherent dimensionality, topology and geometry of light-paths space? How can we leverage this information to improve lighting simulation algorithms? These are the questions that this project wants to answer from a comprehensive functional analysis of light transport operators, with respect to the 3D scene's geometry and the reflectance properties of the objects, but also, to link operators with screen-space visual effects, with respect to the resulting picture.

9.2. International Research Visitors

9.2.1. Visits of International Scientists

Masatake Sawayama, Research Scientist, NTT Communication Science Laboratories, Japan (from March 2019 until October 2019)

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Selection

10.1.1.1. Member of the Conference Program Committees

Eurographics Workshop on Graphics and Cultural Heritage (GCH), Eurographics 2019, Eurographics Symposium on Rendering 2019 (EGSR), ACM Siggraph Asia 2019 talks and posters.

10.1.1.2. Reviewer

ACM Siggraph 2019, ACM Siggraph Asia 2019, ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games 2019 (I3D), Eurographics Workshop on Graphics and Cultural Heritage (GCH), Pacific Graphics 2019, SIBGRAPI 2019.

10.1.2. Journal

10.1.2.1. Reviewer - Reviewing Activities

ACM Transactions on Graphics (TOG), Computer Graphics Forum (CGF), Computer and Graphics, ACM Journal on Computing and Cultural Heritage (JOCCH).

10.1.3. Invited Talks

Talk at the DYVITO workshop 2019, in Giessen, Germany.
Talk at the Shitsukan workshop 2019, in Kyoto, Japan.

10.1.4. Leadership within the Scientific Community

One member of the team is member of the Steering Board of the Eurographics Workshop on Graphics and Cultural Heritage.

10.1.5. Scientific Expertise

We review project submissions of the Horizon 2020 - Research and Innovation Action of the European Commission.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

The members of our team are involved in teaching computer science at University of Bordeaux and Institut d'Optique Graduate School (IOGS). General computer science is concerned, as well as the following graphics related topics:

Master : Pierre Bénard, Gaël Guennebaud, Advanced Image Synthesis, 50 HETD, M2, Univ. Bdx, France.
Master : Antoine Lucat, Simulations Radiométriques avancées, 20 HETD, M2, IOGS, France
Master : Gaël Guennebaud, Geometric Modeling, 31 HETD, M2, IOGS, France
Master : Gaël Guennebaud and Pierre Bénard, 3D Worlds, 60 HETD, M1, Univ. Bdx and IOGS, France.
Master : Pierre Bénard, Patrick Reuter, Virtual Reality, 20 HETD, M2, Univ. Bdx, France.
Master : Patrick Reuter, Graphical user interfaces and Spatial augmented reality seminars, M2, ESTIA, France.
Licence : Patrick Reuter, Digital Imaging, 30 HETD, L3, Univ. Bdx, France.

One member is also in charge of a field of study:

Master : Pierre Bénard, M2 "Informatique pour l'Image et le Son", Univ de Bordeaux, France.

Pierre Bénard was also part of the education team of the DIU (Diplôme Inter-Universitaire) titled "Numérique et Sciences Informatiques" which is opened to secondary professors that are teaching Computer Science in high school. The first session took place during the last three weeks of June.

10.2.2. Supervision

PhD: Thomas Crespel, Optical and software tools for the design of a new transparent 3D display, Inria & Univ. Bordeaux, P. Reuter & X. Granier, 9 December 2019
PhD in progress: Antoine Lucat, Appearance Acquisition and Rendering, IOGS & Univ. Bordeaux, R. Pacanowski & X. Granier
PhD in progress: Charlotte Herzog, 3 dimensions X-rays imaging for medical applications, Imaging Optics, IOGS & Univ. Bordeaux, X. Granier
PhD in progress: Camille Brunel, Real-Time Animation and Deformation of 3D Characters, Inria & Univ. Bordeaux, P. Barla, G. Guennebaud & P. Bénard
PhD in progress: Megane Bati, Inverse Design for Complex Material Apperance, IOGS & Univ. Bordeaux, R. Pacanowski & P. Barla
PhD in progress: Charlie Schlick, Augmented reality with transparent multi-view screens, Inria & Univ. Bordeaux, P. Reuter
PhD in progress: Corentin Cou, Characterization of visual appearance for 3D restitution and exploration of monumental heritage, Inria & IOGS & CNRS/INHA, G. Guennebaud, X. Granier, M. Volait, R. Pacanowski.

10.2.3. Juries

PhD (jury member) : Johanna Delanoy, Université Côte d'Azur (June 4th).
PhD (jury member) : Fan Zhang, TU Delft, Netherlands (October 29th).
PhD (reviewer) : Xavier Chermain, Université de Limoges (November 27th).

Pierre Bénard was the president of a jury for the Professional Baccalauréat (June 4th and 9th).

10.3. Popularization

10.3.1. Interventions

- “Textile 3D” exhibition at the MEB (Musée Ethnographique de Bordeaux, from October 1st 2019 to May 29th 2020).
- During the national “Fête de la Science” event at Inria Bordeaux Sud-Ouest, Pierre Bénard gave a 30 minutes talk titled *L'art et la science des films d'animation 3D*, and Camille Brunel presented her background and Phd topic to schoolchildren (October 8th to 10th).
- During the national “Fête de la Science” event at Musée Ethnographique de Bordeaux, Pascal Barla helped organise a workshop for high school students on the topic of the appearance of textiles, in conjunction of the “Textile 3D” exhibition. With Mégane Bati, they have participated during the workshop as scientific animators (October 7th to 8th).
- We organized a Mini-forum 3D to gather Master students together with researches and companies from the Bordeaux area (November 19th).
- Pierre Bénard presented the team research activities to 3rd year Bachelor students from ENS Lyon (December 5th).

11. Bibliography

Major publications by the team in recent years

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[4] T. LAMBERT, P. BÉNARD, G. GUENNEBAUD. *A View-Dependent Metric for Patch-Based LOD Generation & Selection*, in "Proceedings of the ACM on Computer Graphics and Interactive Techniques", May 2018, vol. 1, n^{o} 1 [*DOI :* 10.1145/3203195], https://hal.inria.fr/hal-01779816

[5] G. NADER, G. GUENNEBAUD. *Instant Transport Maps on 2D Grids*, in "ACM Transactions on Graphics", November 2018, vol. 37, n^{o} 6, 13 p. [*DOI :* 10.1145/3272127.3275091], https://hal.inria.fr/hal-01884157

Publications of the year

Doctoral Dissertations and Habilitation Theses

[6] T. CRESPEL. *Optical and software tools for the design of a new transparent 3D display*, Université de Bordeaux, December 2019, https://hal.inria.fr/tel-02453553

Articles in International Peer-Reviewed Journals

[7] P. Bénard, A. Hertzmann. *Line drawings from 3D models: a tutorial*, in "Foundations and Trends in Computer Graphics and Vision", September 2019, vol. 11, n^{o} 1-2, 159 p. , https://arxiv.org/abs/1810.01175 [*DOI :* 10.1561/0600000075], https://hal.inria.fr/hal-02189483

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