IN PARTNERSHIP WITH:
CNRS

Institut d’Optique Graduate School

Université de Bordeaux

Activity Report 2016

Project-Team MANAO

Melting the frontiers between Light, Shape and Matter

IN COLLABORATION WITH: Laboratoire Bordelais de Recherche en Informatique (LaBRI), Laboratoire Photonique, Numérique et Nanosciences (LP2N)

RESEARCH CENTER
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THEME
Interaction and visualization

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Other Research Topics and Application Domains:

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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 [62], [39] 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 [75] and Light-Field rendering [37]). 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 [72], [76], 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 [97] 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
[54]

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 [87], stereo displays or new display technologies [58], and physical fabrication [28], [45], [54]) the frontiers between real and virtual worlds are vanishing [41]. 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

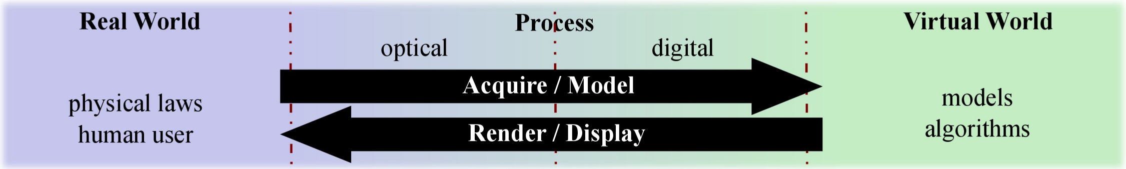

Figure 2. Interactions/Transfers between real and virtual worlds. One of our goal is to combine optical instruments with processes from computer science in order to blend the two worlds.

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 [34] or geometric properties [103], as mastered by professional photographers;
- The modification of material characteristics or lighting conditions [104] to better understand shape features, for instance to decipher archaeological artifacts;
- The large influence of shape on the captured variation of shading [85] and thus on the perception of material properties [100].

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) [44] 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 [71]. 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 [33], [41] and computational photography [86].
- **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 [97]. 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

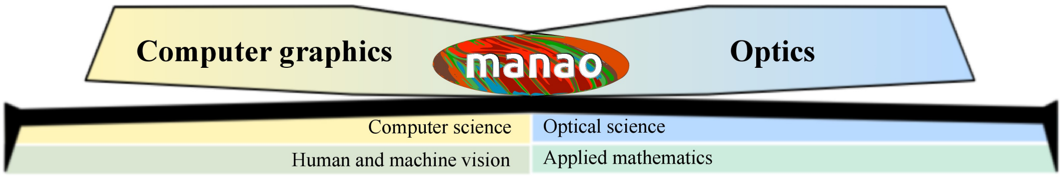

Figure 3. Related scientific domains of the MANAO project.

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 [46] 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 [59], [60] and display [58] 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 [48] or differential analysis [85], 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, see Section 6.3) 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 [89], 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 [55] in order to develop tailored strategies [101]. For instance, starting from simple direct lighting, more complex phenomena have been progressively introduced: first diffuse indirect illumination [53], [93], then more generic inter-reflections [62], [46] and volumetric scattering [90], [43]. 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 [42]. 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 [92] but are difficult to extend to non-piecewise-constant data [95]. More recently, researches prefer the use of Spherical Radial Basis Functions [98] or Spherical Harmonics [84]. For more complex data, such as reflective properties (e.g., BRDF [77], [63] - 4D), ray-space (e.g., Light-Field [73] - 4D), spatially varying reflective properties (6D - [88]), new models, and representations are still investigated such as rational functions [80] or dedicated models [31] and parameterizations [91], [96]. 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 [80].

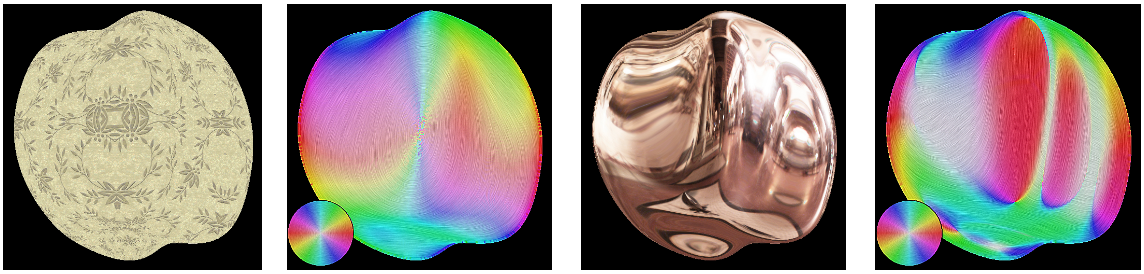
Texuring 1$^{\text{st}}$ order gradient field Environment reflection 2$^{\text{st}}$ order gradient field

Figure 4. First-oder analysis [102] 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 [85] and frequency analysis [48]). 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 [49] 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.

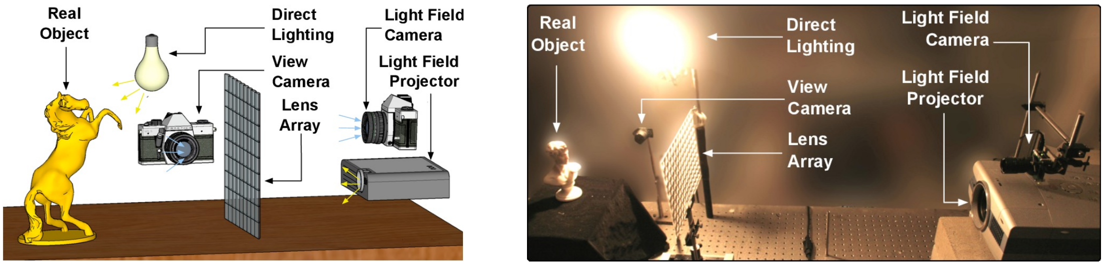

Figure 5. Light-Field transfer: global illumination between real and synthetic objects [41]

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 [73], [58]. We consider projecting systems and surfaces [38], for personal use, virtual reality and augmented reality [33]. 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 [52], [51]. These resulting systems have to acquire the different phenomena described in Axis 1 and to display them, in an efficient manner [56], [32], [57], [60]. 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 [61].

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 [60], [82]). Similarly, increasing the number of viewpoints is a way toward the creation of full 3D displays [73]. 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., [81], [107]).

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. [41]. 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 [70] are one of the key technologies to develop such acquisition (e.g., Light-Field camera[1] [61] and acquisition of light-sources [52]), projection systems (e.g., auto-stereoscopic displays). Such an approach is versatile and may be applied to improve classical optical instruments [68]. More generally, by designing unified optical and digital systems [78], 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 [80]. Second, we have to integrate signals from multiple sensors (such as GPS, accelerometer, ...) to prevent some computation (e.g., [71]). Finally, the experience of the group in surface modeling help the design of optical surfaces [64] 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 [79] (b) Shadows [108] (c) Shape enhancement [104] (d) Shape depiction [30]

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

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

essential information in the most pertinent way. Here, the word *pertinent* can take various forms depending on the application.

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 [105], [67] or stylized shading [36], [104] 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 [29] 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 [106], motion blur [48], depth of field [94], 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 [69], [47]. 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 [40]. Independent image processing for each viewpoint may disturb the feeling of depth by introducing inconsistent information in each images. Finally, more dedicated displays [58] 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 [4] [35]. 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., [99]): 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 [99]), 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.

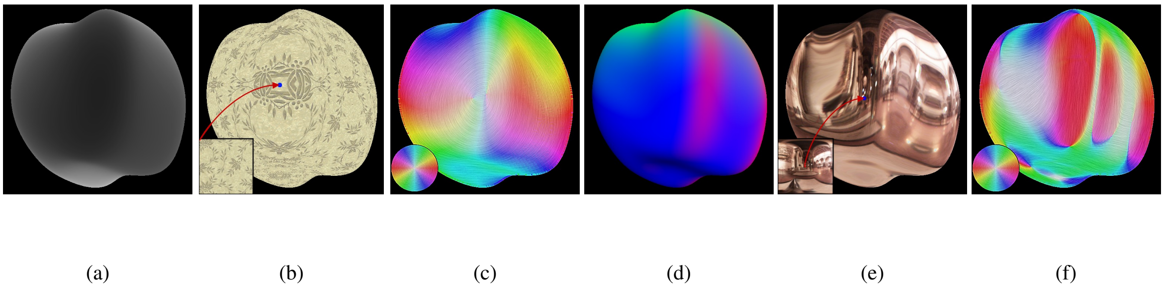

Figure 7. Based on our analysis [102] (Axis 1), we have designed a system that mimics texture (left) and shading (right) effects using image processing alone. It takes depth (a) and normal (d) images as input, and uses them to deform images (b-e) in ways that closely approximate surface flows (c-f). It provides a convincing, yet artistically controllable illusion of 3D shape conveyed through texture or shading cues.

4. Application Domains

4.1. Physical Systems

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

In term of publication, we are regulary publishing our work at the prestigious conference SIGGRAPH. This year was particularly successfull with two plain papers [17], [16] and one talk [19]. But this year more especially, an image from our work [16] were selected as the front cover of the corresponding special issue of ACM Transactions on Graphics.

Another great success is the creation, leaded by members of the LP2N, of a first workshop on nano-appearance. The goal of this workshop was to bring together people from the industry and the academia, and from domains that seem very different considering the scale they are interested in but close by the object of their studies: the appearance of materials. A rare initiative, this workshop took place during two days in November 2016.

6. New Software and Platforms

6.1. ALTA Lib

The ALTA Library
KEYWORDS: Statistic analysis - Fitting - Measures
FUNCTIONAL DESCRIPTION

ALTA is a multi-platform software library to analyze, fit and understand BRDFs. It provides a set of command line software to fit measured data to analytical forms, tools to understand models and data.

- Participants: Laurent Belcour, Romain Pacanowski, Xavier Granier and Pascal Barla
- Partner: LP2N (CNRS - UMR 5298)
- Contact: Romain Pacanowski
- URL: http://alta.gforge.inria.fr/

6.2. Elasticity Skinning

SCIENTIFIC DESCRIPTION

Geometric skinning techniques are very popular in the industry for their high performances, but fail to mimic realistic deformations. With elastic implicit skinning the skin stretches automatically (without skinning weights) and the vertices distribution is more pleasing. Our approach is more robust, for instance the angle's range of joints is larger than implicit skinning.
This software has been ported as a plugin for the Modo software (The Foundry) in collaboration with *Toulouse Tech Transfer*. This plugin has been bought by The Foundry, which maintains and sells it.

- Participants: Rodolphe Vaillant, Loïc Barthe, Florian Canezin, Gaël Guennebaud, Marie-Paule Cani, Damien Rohmer, Brian Wyvill, Olivier Gourmel and Mathias Paulin
- Partners: Université de Bordeaux - CNRS - INP Bordeaux - Université de Toulouse - Institut Polytechnique de Grenoble - Ecole Supérieure de Chimie Physique Electronique de Lyon
- Contact: Gaël Guennebaud
- URL: http://rodolphe-vaillant.fr/?e=59

6.3. Eigen

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, AVX, FMA, AVX512, AltiVec, VSX 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.

In 2016, we released three revisions of the 3.2 branch, as well as the new 3.3 version that leverages numerous major novel features and improvements. Those include, a novel evaluation mechanism of expressions, support for AVX, FMA, AVX512, VSX and ZVector vector instructions, unaligned vectorization, nvcc/CUDA, more OpenMP parallelism, a fast divide and conquer SVD algorithm, a CompleteOrthogonalDecomposition class for fast minimal norm solving, a LS-CG solver, a fast reciprocal condition number estimators in LU and Cholesky factorizations, LU::transpose()/adjoint() API, support for inplace decompositions, support for matrix-free iterative solvers, new array functions, support for any BLAS/LAPACK libraries as backend, improved support for mixing scalar types, eigenvectors in GeneralizedEigenSolver, a complete rewrite of LinSpaced, a non officially supported but massively used Tensor module with CUDA and OpenCL support, and more.

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

6.4. HDRSee

KEYWORDS: OpenGL-GLSL HDR/LDR Viewer FUNCTIONAL DESCRIPTION HDRSee is a OpenGL/GLSL software that displays High Dynamic Range (HDR) and Low Dynamic Range (LDR) images. It is based on several libraries (e.g., glut, see below for full dependencies). To display HDR images, HDRSee implements a few tone-mapping operators. Moreover, it is designed with a plugin mechanism that let developers add, as easily as possible, their own tone-mapping operator. All tone-mapping operations are done using Graphics Hardware through pixel shader operations. The GUI currently used is nvWidgets.

- Participants: Romain Pacanowski, Xavier Granier.
- Partner: LP2N (CNRS - UMR 5298)
- Contact: Romain Pacanowski
- URL: http://mhdrviewer.gforge.inria.fr/

6.5. Patate Lib

KEYWORDS: Expressive rendering - Multi-scale analysis - Material appearance - Vector graphics - 2D animation

FUNCTIONAL DESCRIPTION

Patate is a header only C++/CUDA library for graphics applications. It provides a collection of Computer Graphics techniques that incorporate the latest innovations from Inria research teams working in the field. It strives for efficiency and ease-of-use by focusing on low-level core operators and key algorithms, organized in modules, each tackling a specific set of issues. The central goal of the library is to drastically reduce the time and efforts required to turn a research paper into a ready-to-use solution, for both commercial and academic purposes.

The library is still in its infancy and we are actively working on it to include the latest of our published research techniques. Modules will be dealing with graphics domains as varied as multi-scale analysis, material appearance, vector graphics, expressive rendering and 2D animation.

- Participants: Gaël Guennebaud, Pascal Barla, Simon Boyé, Gautier Ciaudo and Nicolas Mellado
- Contact: Gaël Guennebaud
- URL: http://patate.gforge.inria.fr/html/

7. New Results

7.1. Analysis and Simulation

7.1.1. Principles of Light Field Imaging

Light field imaging offers powerful new capabilities through sophisticated digital processing techniques that are tightly merged with unconventional optical designs. This combination of imaging technology and computation necessitates a fundamentally different view of the optical properties of imaging systems and poses new challenges for the traditional signal and image processing domains. We aimed to provide a comprehensive review [14] of the considerations involved and the difficulties encountered in working with light field data during 25 years of research.

7.1.2. Physically-Based Reflectance Model Combining Reflection and Diffraction

Reflectance properties express how objects in a virtual scene interact with light; they control the appearance of the object: whether it looks shiny or not, whether it has a metallic or plastic appearance. Having a good reflectance model is essential for the production of photo-realistic pictures. Measured reflectance functions provide high realism at the expense of memory cost. Parametric models are compact, but finding the right parameters to approximate measured reflectance can be difficult. Most parametric models use a model of the surface micro-geometry to predict the reflectance at the macroscopic level. We have shown [26] that this micro-geometry causes two different physical phenomena: reflection and diffraction. Their relative importance is connected to the surface roughness. Taking both phenomena into account, we develop a new reflectance model that is compact, based on physical properties and provides a good approximation of measured reflectance.

7.1.3. Multi-Scale and Structured SV-BRDF Model for Scratched Materials

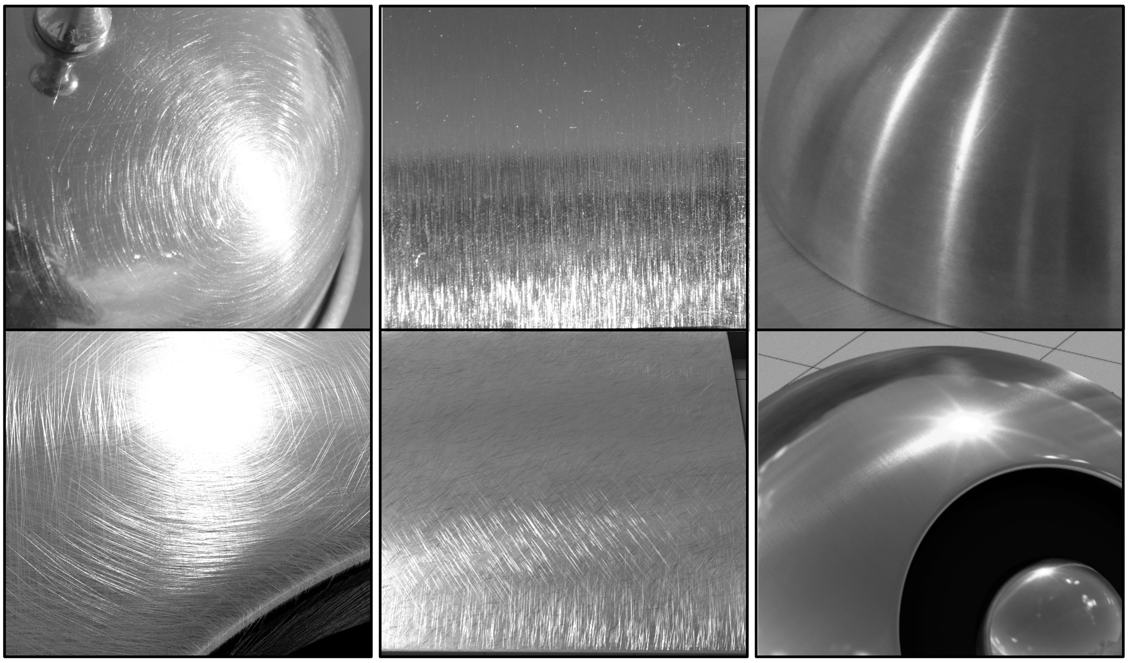

Figure 8. Our scratch BRDF (top) can reproduce several effects similar to real photographs (bottom).

We developed a Spatially-Varying BRDF model tailored to the multi-scale rendering of scratched materials such as metals, plastics or finished woods. Our approach takes advantage of the regular structure of scratch distributions to achieve high performance without compromising visual quality (fig. 8). The BRDF for a single scratch is simulated using an optimized 2D ray-tracer and compactly stored in a three-component 2D texture. In contrast to existing models, our approach takes into account all inter-reflections inside a scratch, including Fresnel effects. At render time, the SV-BRDF for the scratch distribution under a pixel or ray footprint is obtained by linear combination of individual scratch BRDFs. Our model can be evaluated using both importance and light sampling, in direct and global illumination settings. Our approach provides users with controls over the profile, micro-BRDF, density and orientation of scratches. All these material properties are updated at interactive rates. This work has been published at ACM Siggraph 2016 [16] and one our result has been selected as the cover of the ACM Siggraph 2016 proceedings. It is part of the PhD Thesis "Control of anisotropic materials appearance" [11] defended this year.

7.1.4. Cues for Perception of Appearance

Thanks for the FP7 ITN PRISM, we have participated to several user studies to understand the perception of an object appearance. First, for fluids and other deformable materials, we find [25] that observers show a high degree of constancy in matching the viscosity across the different variations. However, volume differences between test and match stimulus, especially with static stimuli, caused large effects of over- and underestimation of viscosity. We also find that a number of cues related to curvatures, periodic movements of the liquids, and the way they spread out predict aspects of the observer’s performance, but that humans achieve better constancy than the cues predict.

We have also investigated gloss haze [22]. The results reveals that haziness is a distinct visual dimension orthogonal to the commonly studied glossiness and blurriness. Coatedness appears to be nearly synonymous with haziness, as this is one of the main physical causes of haze in real world materials. Polish seems to be a combination of glossiness and haziness, as materials go from dull to hazy to highly glossy during the physical polishing process. The inferred tactile quality of friction is apparently uncorrelated with haziness. Our results demonstrate that haze is indeed a distinct perceptual dimension of gloss, which is systematically related to the kurtosis of the specular lobe.

7.2. From Acquisition to Display

7.2.1. Spatial Augmented Reality

Spatial augmented reality allows to improve or modify the perception of the reality with virtual information displayed directly in the real world, using video-projection. Many fields such as tourism, entertainment, education, medicine, industry or cultural heritage may benefit from it. Recent computer science techniques allow to measure, analyse and visualise the geometry of the surface of real objects, as for instance archeological artefacts. We have proposed a SAR interaction and visualisation technique (part of the PhD thesis "Interaction techniques, personalized experience and surface reconstruction for spatial augmented reality" [12] defended this year) that combines the advantages of the study of both real and 3D archeological artefacts. Thus, we superimpose on the object an expressive rendering based on curvatures with SAR, allowing for example to show details of engravings. Next, we simulate the use of a flashlight with the help of a 6-degree-of-freedom controller. The user can then specify the area on the object to be augmented and adjust the various necessary parameters of the expressive rendering. One of the main caracteristics of SAR is to enable multiple users to simultaneously participate to the same experience. However, depending on the target application, this can be seen as a drawback.

We have also proposed a new display device [27] that allows to create experiences in SAR that are both multiuser and personalised by taking into account the user point of view. In order to do so, the projection display, set in front of the object to augment, is made from a material that is both retro-reflective and semi-transparent. We suggest two different uses of this new device, as well as two scenarios of application.

7.2.2. Isotropic BRDF Measurements

Image-based BRDF measurements on spherical material samples present a great opportunity to shorten significantly the acquisition time with respect to more traditional, non-multiplexed measurement methods for isotropic BRDFs. However, it has never been analyzed deeply, what measurement accuracy can be achieved in such a setup; what are the main contributing uncertainty factors and how do they relate to calibration procedures. We have developed [20] a new set of isotropic BRDF measurements with their radiometric and geometric uncertainties acquired within such an imaging setup. We have analyzed the most prominent optical phenomena that affect measurement accuracy and pave the way for more thorough uncertainty analysis in forthcoming image-based BRDF measurements. Our newly acquired data with their quantified uncertainties will be helpful for comparing the quality and accuracy of the different experimental setups and for designing other such image-based BRDF measurement devices.

7.3. Rendering, Visualization and Illustration

7.3.1. Cache-friendly Sampling

Monte-Carlo integration techniques for global illumination are popular on GPUs thanks to their massive parallel architecture, but efficient implementation remains challenging. The use of randomly de-correlated low-discrepancy sequences in the path-tracing algorithm allows faster visual convergence. However, the parallel tracing of incoherent rays often results in poor memory cache utilization, reducing the ray bandwidth efficiency. Interleaved sampling [65] partially solves this problem, by using a small set of distributions split in coherent ray-tracing passes, but the solution is prone to structured noise. On the other hand, ray-reordering methods [83] group stochastic rays into coherent ray packets but their implementation add an additional sorting cost on the GPU [74], [50]. We have introduced [19] a micro-jittering technique for faster multi-dimensional Monte-Carlo integration in ray-based rendering engines. Our method, improves ray coherency between GPU threads using a slightly altered low-discrepancy sequence rather than using ray-reordering methods. Compatible with any low-discrepancy sequence and independent of the importance sampling strategy, our method achieves comparable visual quality with classic de-correlation methods, like Cranley-Patterson rotation [66], while reducing rendering times in all scenarios.

7.3.2. Multi-Resolution Meshes for Feature-Aware Hardware Tessellation

Hardware tessellation is de facto the preferred mechanism to adaptively control mesh resolution with maximal performances. However, owing to its fixed and uniform pattern, leveraging tessellation for feature-aware LOD rendering remains a challenging problem. In [15], we relax this fundamental constraint by introducing a new spatial and temporal blending mechanism of tessellation levels, which is built on top of a novel hierarchical representation of multi-resolution meshes. This mechanism allows to finely control topological changes so that vertices can be removed or added at the most appropriate location to preserve geometric features in a continuous and artifact-free manner (cf. Figure 9). We then show how to extend edge-collapse based decimation methods to build feature-aware multi-resolution meshes that match the tessellation patterns. Our approach is fully compatible with current hardware tessellators and only adds a small overhead on memory consumption and tessellation cost. This work as been published at Eurographics 2016 [15].

7.3.3. Shape Depiction for Transparent Objects

Shading techniques are useful to deliver a better understanding of object shapes. When transparent objects are involved, depicting the shape characteristics of each surface is even more relevant. We have developed [21] a method for rendering transparent scenes or objects using classical tools for shape depiction in real time. Our method provides an efficient way to compute screen space curvature on transparent objects by using a novel screen space representation of a scene derived from Order Independent Transparency techniques. Moreover, we propose a customizable stylization that modulates the transparency per fragment, according to its curvature and its depth, which can be adapted for various kinds of applications.

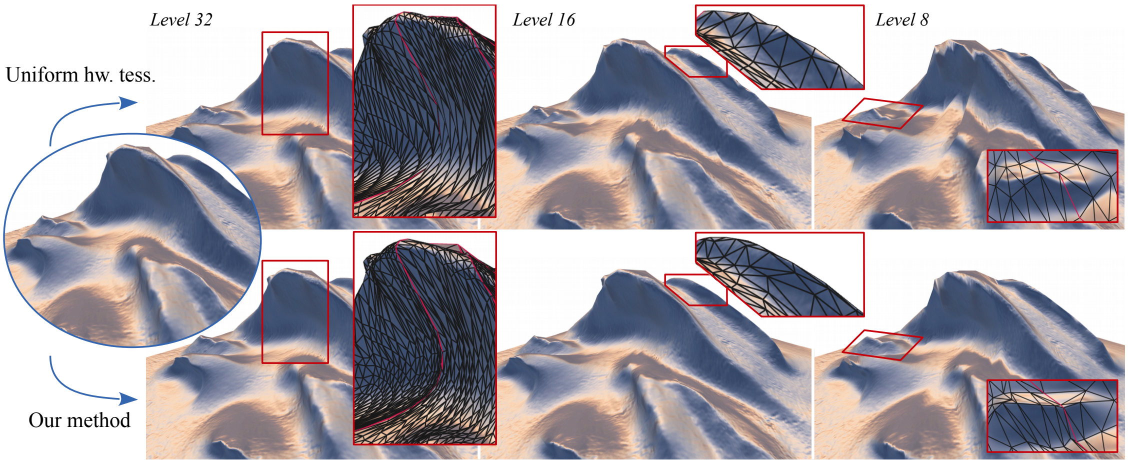

Figure 9. Uniform hardware tessellation ***(top)*** *fails at representing accurately sharp features and areas of high curvature, such as the top and deep part of the drifts, which produces tessellation artifacts. Our method* ***(bottom)*** *better preserves those regions by adapting the triangle size and aligning their edges with those features.*

7.4. Editing and Modeling

7.4.1. Flow-guided Warping for Image-based Shape Manipulation

Manipulating object shape in images usually require a-priori on their 3D geometry, and either user interactions or huge databases of 3D objects. In collaboration with the Maverick team (Inria Rhone Alpes), we have developped a method that manipulates perceived object shape from a single input color image without the need of addional 3D information, user input or 3D data. The key idea is to give the illusion of shape sharpening or rounding by exaggerating orientation patterns in the image that are strongly correlated to surface curvature (fig. 10). We build on a growing literature in both human and computer vision showing the importance of orientation patterns in the communication of shape, which we complement with mathematical relationships and a statistical image analysis revealing that structure tensors are indeed strongly correlated to surface shape features. We then rely on these correlations to introduce a flow-guided image warping algorithm, which in effect exaggerates orientation patterns involved in shape perception. We evaluate our technique by 1) comparing it to ground truth shape deformations, and 2) performing two perceptual experiments to assess its effects. Our algorithm produces convincing shape manipulation results on synthetic images and photographs, for various materials and lighting environments. This work has been published at ACM Siggraph 2016 [17].

7.4.2. Local Shape Editing at the Compositing Stage

Modern compositing software permit to linearly recombine different 3D rendered outputs (e.g., diffuse and reflection shading) in post-process, providing for simple but interactive appearance manipulations. Renderers also routinely provide auxiliary buffers (e.g., normals, positions) that may be used to add local light sources or depth-of-field effects at the compositing stage. These methods are attractive both in product design and movie production, as they allow designers and technical directors to test different ideas without having to re-render an entire 3D scene. In this work, we extended this approach to the editing of local shape: users modify the rendered normal buffer, and our system automatically modifies diffuse and reflection buffers to provide a plausible result. Our method is based on the reconstruction of a pair of diffuse and reflection prefiltered environment maps for each distinct object/material appearing in the image. We seamlessly combine the reconstructed buffers in a recompositing pipeline that works in real-time on the GPU using arbitrarily modified normals. This work as been published at the Eurographics Symposium on Rendering [24].

(a) Input image - ©Expertissim (b) Shape sharpening (c) Shape rounding

Figure 10. Our warping technique takes as input (a) a single image (Jules Bennes, after Barye: "walking lion") and modifies its perceived surface shape, either making it sharper in (b) or rounder in (c).

7.4.3. Topology-Aware Neighborhoods for Point-Based Simulation and Reconstruction

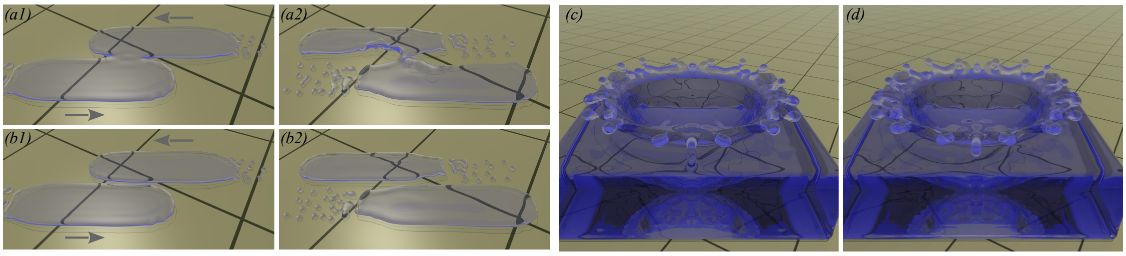

Figure 11. Two SPH fluid simulations using a standard Euclidean particle neighborhood (a,c), and our new topological neighborhood (b,d). On the left, two fluid components are crossing while moving in opposite directions. Our new neighborhood performs accurate merging computations and avoids both unwanted fusion in the reconstruction and incorrect fluid interaction in the simulation. On the right, our accurate neighborhoods lead to different shape of the splash, and enable the reconstruction of the fluid with an adequate topology while avoiding bulging at distance.

Particle based simulations are widely used in computer graphics. In this field, several recent results have improved the simulation itself or improved the tension of the final fluid surface. In current particle based implementations, the particle neighborhood is computed by considering the Euclidean distance between fluid particles only. Thus particles from different fluid components interact, which generates both local incorrect behavior in the simulation and blending artifacts in the reconstructed fluid surface. In collaboration with IRIT, we developed a better neighborhood computation for both the physical simulation and surface reconstruction steps (fig. 11). Our approach tracks and stores the local fluid topology around each particle using a graph structure. In this graph, only particles within the same local fluid component are neighbors and other disconnected fluid particles are inserted only if they come into contact. The graph connectivity also takes into account the asymmetric behavior of particles when they merge and split, and the fluid surface is reconstructed accordingly, thus avoiding their blending at distance before a merge. In the simulation, this neighborhood information is exploited for better controlling the fluid density and the force interactions at the vicinity of its boundaries. For instance, it prevents the introduction of collision events when two distinct fluid components are crossing without contact, and it avoids fluid interactions through thin waterproof walls. This leads to an overall more consistent fluid simulation and reconstruction. This work as been published at the Eurographics/ ACM SIGGRAPH Symposium on Computer Animation [18].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- CIFRE PhD contract with Technicolor (2014-2018)
  Participants: A. Dufay, X. Granier, and R. Pacanowski
  For this project, we aim at providing interactive previsualization of complex lighting with a smooth transition to the final solution.
- CIFRE PhD contract with FEI (2014-2018)
  Participants: D. Murray, and X. Granier
  For this project, we aim at providing expressive rendering techniques for volumes.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Carer xD: "Caractérisation et restitution du réel xD"

Currently, the characterization and display of the real world are limited to techniques focusing on a subset of the necessary physical phenomena. A lot of work has been done to acquire geometric properties. However, the acquisition of a geometry on an object with complex reflection property or dynamic behavior is still a challenge. Similarly, the characterization of a material is limited to a uniform object for complex material or a diffuse material when one is interested in its spatial variations.

To reach full interaction between real and virtual worlds (augmented reality, mixed reality), it is necessary to acquire the real world in all its aspects (spatial, spectral, temporal) and to return it as in all these dimensions. To achieve this goal, a number of theoretical and practical tools will be developed around the development of mixed reality solutions and the development of some theoretical framework that supports the entire project.

9.2. National Initiatives

9.2.1. ANR

9.2.1.1. “Young Researcher” RichShape (2014-2018)

MANAO
Leader G. Guennebaud
This project aims at the development of novel representations for the efficient rendering and manipulation of highly detailed shapes in a multi-resolution context.

9.2.1.2. ALTA (2011-2016)

MAVERICK, REVES
Leader N. Holzschuch (MAVERICK)
The project ALTA aims at analyzing the light transport equations and at using the resulting representations and algorithms for more efficient computation. We target lighting simulations, either off-line, high-quality simulations or interactive simulations.

9.2.1.3. ISAR (2014-2017)

POTIOC, MANAO, LIG-CNRS-UJF, Diotasoft
Leader M. Hachet (POTIOC)
The ISAR project focuses on the design, implementation and evaluation of new interaction paradigms for spatial augmented reality, and to systematically explore the design space.

9.2.1.4. MATERIALS (2015-2019)

MAVERICK, LP2N-CNRS (MANAO), Musée d'Ethnographie de Bordeaux, OCÉ-Print
Leader N. Holzschuch (MAVERICK)
Local Leader R. Pacanowski (LP2N-CNRS)
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.

9.2.1.5. FOLD-Dyn (2016-2020)

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

9.2.2. Competitivity Clusters

9.2.2.1. LabEx CPU

IMB (UPR 5251), LABRI (UMR 5800), Inria (CENTRE BORDEAUX SUD-OUEST), I2M (NEW UMR FROM 2011), IMS (UMR 5218), CEA/DAM
Some members of *MANAO* participate in the local initiative CPU. As it includes many thematics, from fluid mechanics computation to structure safety but also management of timetable, safety of networks and protocols, management of energy consumption, etc., numerical technology can impact a whole industrial sector. In order to address problems in the domain of certification or qualification, we want to develop numerical sciences at such a level that it can be used as a certification tool.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. PRISM

Title: Perceptual Representation of Illumination, Shape and Material

Programm: FP7

Duration: January 2013 - December 2016

Coordinator: JUSTUS-LIEBIG-UNIVERSITAET GIESSEN

Partners:

- Justus-Liebig-Universitaet Giessen (Germany)
- Katholieke Universiteit Leuven (Belgium)
- Next Limit Sl (Spain)
- Technische Universiteit Delft (Netherlands)
- the Chancellor, Masters and Scholars of The University of Cambridge (United Kingdom)
- Bilkent Üniversitesi (Turkey)
- Universite Paris Descartes (France)
- The University of Birmingham (United Kingdom)

Local Leader: Pascal Barla

Visual perception provides us with a richly detailed representation of the surrounding world, enabling us to make subtle judgements of 1) 3D shape, 2) the material properties of objects, and 3) the flow of illumination within a scene. Together, these three factors determine the intensity of a surface in the image. Estimating scene properties is crucial for guiding action and making decisions like whether food is edible. Visual 'look and feel' also plays a key role in industrial design, computer graphics and other industries. Despite this, little is known about how we visually estimate the physical properties of objects and illumination. Previous research has mainly focussed on one or two of the three causal factors independently, and from the viewpoint of a specific discipline. By contrast, in PRISM we take an integrative approach, to understand how the brain creates a richly detailed representation of the world by looking at how all three factors interact simultaneously. PRISM is radically interdisciplinary, uniting experts from psychology, neuroscience, computer science and physics to understand both the analysis and synthesis of shape, shading and materials. PRISM is intersectoral by uniting researchers from seven leading Universities and two industrial partners, enabling impact in basic research, technology and the creative industries. Through research projects, cross-discipline visits, and structured Course Modules delivered through local and network-wide training events, we will endow PRISM fellows with an unusually broad overview and the cross-sector skills they need to become future leaders in European research and development. Thus, by delivering early-career training embedded in a cutting-edge research programme, we aim to 1) springboard the next generation of interdisciplinary researchers on perceptual representations of 3D scenes and 2) cement long-term collaborations between sectors to enhance European perception research and its applications.

9.4. International Initiatives

9.4.1. International Partners

9.4.1.1. Rainbow Particle Imaging Velocimetry

Partner : KAUST - King Abdullah University of Science & Technology

We propose a new approach for snapshot imaging of time-resolved, non-stationary 3D fluid flows, which we term Rainbow Particle Imaging Velocimetry (RainbowPIV). Using only a single camera, RainbowPIV will be able to track a dense set of particles advected in the flow. This is achieved by illuminating the flow volume with a stack of monochromatic light planes at different wavelengths (a "rainbow"). Particles are tracked in 3D by both following their 2D spatial position and their change in color, depending on which light plane they traverse.

RainbowPIV will provide dense measurements of 3D velocity vectors, thus obtaining a dense 3D representation of a 3D velocity field. This will allow us to accurately image and understand many new types of flow, including turbulent flows within complex 3D geometries and particle trajectories, with limited optical access. After the initial exploration stage covered in this proposal, RainbowPIV could find many applications in science and engineering, for example to help understand combustion processes or flow through catalytic converters, between turbine blades, and inside inlet manifolds.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

Expressive 2016 (NPAR-SBIM-CAe), Workshop on NanoAppearance

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

ACM Siggraph 2016, ACM Siggraph Asia 2016, Symposium on Geometry Processing (SGP) 2016, Geometric Modeling and Processing (GMP) 2016, SIBGRAPI (Conference on Graphics, Patterns and Images) 2016

10.1.2.2. Reviewer

Eurographics 2016, Pacific Graphics 2016, High Performance Graphics 2016

10.1.3. Journal

10.1.3.1. Reviewer - Reviewing Activities

ACM Transactions on Graphics (TOG), IEEE Transactions on Visualization and Computer Graphics (TVCG), Computer Graphics Forum (CGF),

10.1.4. Invited Talks

> Implicit Skinning : une méthode d'animation de personnages interactive avec contacts et étirements de la peau. Rencontres Animation Développement Innovation (RADI).

10.1.5. Research Administration

Inria Evaluation Committee

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

The members of our team are involved in teaching computer science at University of Bordeaux, ENSEIRB Engineering School, 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, Romain Pacanowski, Advanced Image Synthesis, 60 HETD, M2, Univ. Bdx, France.

Master : Gaël Guennebaud, Numerical Techniques, 45 HETD, M1, IOGS, France

Master : Xavier Granier, Image Synthesis, 14 HETD, M2, IOGS, France

Master : Gaël Guennebaud, Geometric Modeling, 22 HETD, M2, IOGS, France

Master : Romain Pacanowski, Thibaud Lambert, Antoine Lucat & Brett Ridel, Algorithmic and Object Programming, 60 HETD, M1, IOGS, France

Master : Xavier Granier, Romain Pacanowski, Colorimetry and Appearance Modeling, 20 HETD, M1, IOGS, France.

Master : Gaël Guennebaud and Pierre Bénard, High-performance 3D Graphics, 60 HETD, M1, Univ. Bdx and IOGS, France.

Master : Pierre Bénard, Virtual Reality, 24 HETD, M2, Univ. Bdx, France.

Master : Ivo Ihrke, Advanced Display Technology, 12 HETD, M1, IOGS, France

Master : Pierre Bénard, Image Synthesis and 3D modeling, 60 HETD, M2, ENSEIRB, France

Licence : Patrick Reuter, Digital Imaging, 36 HETD, L3, Univ. Bdx, France.

Some members are also in charge of some fields of study:

Master : Xavier Granier, M2, IOGS (Bordeaux), France.

License : Patrick Reuter, Science and Modeling, L2, Univ. Bdx, France.

10.2.2. Supervision

PhD : Boris Raymond, Rendering and manipulation of anisotropic materials, Univ. Bordeaux, P. Barla & G. Guennebaud & X. Granier

PhD : John Restrepo, Plenoptic Imaging and Computational Image Quality Metrics, Inria & Univ. Bordeaux, I. Ihrke

PhD : Brett Ridel, Interactive spatial augmented reality, Inria & Univ. Bordeaux, P. Reuter & X. Granier

PhD : Carlos Zubiaga Pena, Image-space editing of appearance, Inria & Univ. Bordeaux, P. Barla & X. Granier

PhD : Florian Canezin, Implicit Modeling, Univ. Toulouse III, G. Guennebaud & Loïc Barthe

PhD : Arthur Dufay, Adaptive high-quality of virtual environments with complex photometry, Technicolor & Univ. Bordeaux, J.-E. Marvie R. Pacanowski & X. Granier

PhD : Thibaud Lambert, Real-time rendering of highly detailed 3D models, Inria & Univ. Bordeaux, G. Guennebaud & P. Bénard

PhD : Loïs Mignard-Debize, Plenoptic function and its application to spatial augmented reality, Inria & Univ. Bordeaux, P. Reuter & I. Ihrke

PhD : Antoine Lucat, Appearance Acquisition and Rendering, IOGS & Univ. Bordeaux, R. Pacanowski & X. Granier

PhD : David Murray, Expressive Rendering of Volumetric Data, FEI & Univ. Bordeaux, J. Baril & X. Granier

11. Bibliography

Major publications by the team in recent years

[1] L. Belcour, R. Pacanowski, M. Delahaie, A. Laville-Geay, L. Eupherte. *BRDF Measurements and Analysis of Retroreflective Materials*, in "Journal of the Optical Society of America", December 2014, vol. 31, n^{o} 12, pp. 2561–2572, https://hal.inria.fr/hal-01083366

[2] M. Berger, A. Tagliasacchi, L. Seversky, P. Alliez, G. Guennebaud, J. Levine, A. Sharf, C. Silva. *A Survey of Surface Reconstruction from Point Clouds*, in "Computer Graphics Forum", 2016, 27 p. [*DOI :* 10.1111/cgf.12802], https://hal.inria.fr/hal-01348404

[3] P. Bénard, A. Hertzmann, M. Kass. *Computing Smooth Surface Contours with Accurate Topology*, in "ACM Transactions on Graphics", 2014, http://hal.inria.fr/hal-00924273

[4] J. Chen, G. Guennebaud, P. Barla, X. Granier. *Non-oriented MLS Gradient Fields*, in "Computer Graphics Forum", December 2013, http://hal.inria.fr/hal-00857265

[5] I. Ihrke, J. Restrepo, L. Mignard-Debise. *Principles of Light Field Imaging: Briefly revisiting 25 years of research*, in "IEEE Signal Processing Magazine", September 2016, vol. 33, n^{o} 5, pp. 59-69 [*DOI :* 10.1109/MSP.2016.2582220], https://hal.inria.fr/hal-01377379

[6] H. Lu, R. Pacanowski, X. Granier. *Position-Dependent Importance Sampling of Light Field Luminaires*, in "IEEE Transactions on Visualization and Computer Graphics", 2015, vol. 21, n^{o} 2, pp. 241 - 251 [*DOI :* 10.1109/TVCG.2014.2359466], https://hal.inria.fr/hal-01103782

[7] A. Manakov, J. Restrepo, O. Klehm, R. Hegedüs, E. Eisemann, H.-P. Seidel, I. Ihrke. *A Reconfigurable Camera Add-On for High Dynamic Range, Multispectral, Polarization, and Light-Field Imaging*, in "ACM Transactions on Graphics", July 2013, vol. 32, n^{o} 4 [*DOI :* 10.1145/2461912.2461937], http://hal.inria.fr/hal-00835898

[8] B. Raymond, G. Guennebaud, P. Barla. *Multi-Scale Rendering of Scratched Materials using a Structured SV-BRDF Model*, in "ACM Transactions on Graphics", July 2016 [*DOI :* 10.1145/2897824.2925945], https://hal.inria.fr/hal-01321289

[9] J. Restrepo, P. J. Stoerck, I. Ihrke. *Ray and Wave Aberrations Revisited: A Huygens-Like Construction Yields Exact Relations*, in "Journal of the Optical Society of America", November 2015, https://hal.inria.fr/hal-01240231

[10] B. Ridel, P. Reuter, J. Laviole, N. Mellado, N. Couture, X. Granier. *The Revealing Flashlight: Interactive spatial augmented reality for detail exploration of cultural heritage artifacts*, in "Journal on Computing and Cultural Heritage", May 2014, vol. 7, n^{o} 2, pp. 1–18 [*DOI :* 10.1145/2611376], https://hal.inria.fr/hal-00986905

Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] B. RAYMOND. *Control of anisotropic materials appearance*, Université de Bordeaux, September 2016, https://tel.archives-ouvertes.fr/tel-01387867

[12] B. RIDEL. *Interaction techniques, personalized experience and surface reconstruction for spatial augmented reality.*, Université de bordeaux, October 2016, https://hal.inria.fr/tel-01414792

Articles in International Peer-Reviewed Journals

[13] M. BERGER, A. TAGLIASACCHI, L. SEVERSKY, P. ALLIEZ, G. GUENNEBAUD, J. LEVINE, A. SHARF, C. SILVA. *A Survey of Surface Reconstruction from Point Clouds*, in "Computer Graphics Forum", 2016, 27 p. [*DOI :* 10.1111/CGF.12802], https://hal.inria.fr/hal-01348404

[14] I. IHRKE, J. RESTREPO, L. MIGNARD-DEBISE. *Principles of Light Field Imaging: Briefly revisiting 25 years of research*, in "IEEE Signal Processing Magazine", September 2016, vol. 33, n^{o} 5, pp. 59-69 [*DOI :* 10.1109/MSP.2016.2582220], https://hal.inria.fr/hal-01377379

[15] T. LAMBERT, P. BÉNARD, G. GUENNEBAUD. *Multi-Resolution Meshes for Feature-Aware Hardware Tessellation*, in "Computer Graphics Forum", 2016, https://hal.inria.fr/hal-01266179

[16] B. RAYMOND, G. GUENNEBAUD, P. BARLA. *Multi-Scale Rendering of Scratched Materials using a Structured SV-BRDF Model*, in "ACM Transactions on Graphics", July 2016 [*DOI :* 10.1145/2897824.2925945], https://hal.inria.fr/hal-01321289

[17] R. VERGNE, P. BARLA, G.-P. BONNEAU, R. FLEMING. *Flow-Guided Warping for Image-Based Shape Manipulation*, in "ACM Transactions on Graphics (TOG)", July 2016 [*DOI :* 10.1145/2897824.2925937], https://hal.inria.fr/hal-01307571

International Conferences with Proceedings

[18] F. CANEZIN, G. GUENNEBAUD, L. BARTHE. *Topology-Aware Neighborhoods for Point-Based Simulation and Reconstruction*, in "Eurographics/ ACM SIGGRAPH Symposium on Computer Animation", Zurich, France, Symposium on Computer Animation, July 2016, https://hal.inria.fr/hal-01338636

Conferences without Proceedings

[19] A. DUFAY, P. LECOCQ, R. PACANOWSKI, J.-E. MARVIE, X. GRANIER. *Cache-friendly micro-jittered sampling*, in "SIGGRAPH 2016", Anaheim, United States, July 2016 [*DOI :* 10.1145/2897839.2927392], https://hal.inria.fr/hal-01325702

[20] R. HEGEDUS, A. LUCAT, J. REDON, R. PACANOWSKI. *Isotropic BRDF Measurements with Quantified Uncertainties*, in "EUROGRAPHICS WORKSHOP ON MATERIAL APPEARANCE MODELING", Dublin, Ireland, June 2016, https://hal.inria.fr/hal-01342568

[21] D. MURRAY, J. BARIL, X. GRANIER. *Shape Depiction for Transparent Objects with Bucketed k-Buffer*, in "EuroGraphics Symposium on Rendering", Dublin, Ireland, June 2016, https://hal.inria.fr/hal-01338535

[22] P. VANGORP, P. BARLA, C. J. ZUBIAGA PEÑA, R. FLEMING. *Specular kurtosis and the perception of hazy gloss*, in "Vision Science Society", St Petersburg, United States, May 2016, https://hal.inria.fr/hal-01323163

[23] K. VYNCK, R. PACANOWSKI, P. BARLA, X. GRANIER, P. LALANNE. *Modélisation de l'apparence de nanostructures plasmoniques complexes*, in "Workshop "Propriétés optiques de nanostructures et apparence"", Talence, France, November 2016, https://hal.archives-ouvertes.fr/hal-01403346

[24] C. J. ZUBIAGA, G. GUENNEBAUD, R. VERGNE, P. BARLA. *Local Shape Editing at the Compositing Stage*, in "EGSR", Dublin, Ireland, June 2016, https://hal.inria.fr/hal-01338414

[25] J. J. VAN ASSEN, P. BARLA, R. FLEMING. *Cues Underlying Liquid Constancy*, in "Vision Science Society", St Petersburg, United States, May 2016, https://hal.inria.fr/hal-01323169

Research Reports

[26] N. HOLZSCHUCH, R. PACANOWSKI. *A Physically-Based Reflectance Model Combining Reflection and Diffraction*, Inria, October 2016, n^o RR-8964, https://hal.inria.fr/hal-01386157

Other Publications

[27] B. RIDEL, L. MIGNARD-DEBISE, X. GRANIER, P. REUTER. *EgoSAR: Towards a personalized spatial augmented reality experience in multi-user environments*, September 2016, 15th IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Poster, https://hal.inria.fr/hal-01359250

References in notes

[28] M. ALEXA, W. MATUSIK. *Reliefs as images*, in "ACM Trans. Graph.", 2010, vol. 29, n^o 4, http://doi.acm.org/10.1145/1778765.1778797

[29] L. AMMANN, P. BARLA, X. GRANIER, G. GUENNEBAUD, P. REUTER. *Surface Relief Analysis for Illustrative Shading*, in "Computer Graphics Forum", June 2012, vol. 31, n^o 4, pp. 1481-1490 [*DOI :* 10.1111/J.1467-8659.2012.03144.X], http://hal.inria.fr/hal-00709492

[30] L. AMMANN, P. BARLA, X. GRANIER, G. GUENNEBAUD, P. REUTER. *Surface Relief Analysis for Illustrative Shading*, in "Comput. Graph. Forum", 2012, vol. 31, n^o 4, http://hal.inria.fr/hal-00709492

[31] M. ASHIKHMIN, S. PREMOZE. *Distribution-based BRDFs*, Univ. of Utah, 2007, n^o unpublished

[32] B. ATCHESON, I. IHRKE, W. HEIDRICH, A. TEVS, D. BRADLEY, M. MAGNOR, H.-P. SEIDEL. *Time-resolved 3D Capture of Non-stationary Gas Flows*, in "ACM Trans. Graph.", 2008, vol. 27, n^o 5

[33] O. BIMBER, R. RASKAR. *Spatial Augmented Reality: Merging Real and Virtual Worlds*, A K Peters/CRC Press, 2005

[34] A. BOUSSEAU, E. CHAPOULIE, R. RAMAMOORTHI, M. AGRAWALA. *Optimizing Environment Maps for Material Depiction*, in "Comput. Graph. Forum (Proceedings of the Eurographics Symposium on Rendering)", 2011, vol. 30, n^o 4, http://www-sop.inria.fr/reves/Basilic/2011/BCRA11

[35] S. BOYÉ, G. GUENNEBAUD, C. SCHLICK. *Least Squares Subdivision Surfaces*, in "Comput. Graph. Forum", 2010, vol. 29, n^o 7, pp. 2021-2028, http://hal.inria.fr/inria-00524555/en

[36] S. BRUCKNER, M. E. GRÖLLER. *Style Transfer Functions for Illustrative Volume Rendering*, in "Comput. Graph. Forum", 2007, vol. 26, n^{o} 3, pp. 715-724, http://www.cg.tuwien.ac.at/research/publications/2007/bruckner-2007-STF/

[37] C. BUEHLER, M. BOSSE, L. MCMILLAN, S. GORTLER, M. COHEN. *Unstructured lumigraph rendering*, in "Proc. ACM SIGGRAPH", 2001, pp. 425-432, http://doi.acm.org/10.1145/383259.383309

[38] O. CAKMAKCI, S. VO, K. P. THOMPSON, J. P. ROLLAND. *Application of radial basis functions to shape description in a dual-element off-axis eyewear display: Field-of-view limit*, in "J. Society for Information Display", 2008, vol. 16, n^{o} 11, pp. 1089-1098 [*DOI :* 10.1889/JSID16.11.1089]

[39] E. CEREZO, F. PEREZ-CAZORLA, X. PUEYO, F. SERON, F. X. SILLION. *A Survey on Participating Media Rendering Techniques*, in "The Visual Computer", 2005, http://hal.inria.fr/inria-00510151

[40] J. CHEN, X. GRANIER, N. LIN, Q. PENG. *On-Line Visualization of Underground Structures using Context Features*, in "Symposium on Virtual Reality Software and Technology (VRST)", ACM, 2010, pp. 167-170 [*DOI :* 10.1145/1889863.1889898], http://hal.inria.fr/inria-00524818/en

[41] O. COSSAIRT, S. NAYAR, R. RAMAMOORTHI. *Light field transfer: global illumination between real and synthetic objects*, in "ACM Trans. Graph.", 2008, vol. 27, n^{o} 3, http://doi.acm.org/10.1145/1360612.1360656

[42] F. CUNY, L. ALONSO, N. HOLZSCHUCH. *A novel approach makes higher order wavelets really efficient for radiosity*, in "Comput. Graph. Forum", 2000, vol. 19, n^{o} 3, pp. 99-108

[43] E. D'EON, G. IRVING. *A quantized-diffusion model for rendering translucent materials*, in "ACM Trans. Graph.", 2011, vol. 30, n^{o} 4, http://doi.acm.org/10.1145/2010324.1964951

[44] K. J. DANA, B. VAN GINNEKEN, S. NAYAR, J. J. KOENDERINK. *Reflectance and texture of real-world surfaces*, in "IEEE Conference on Computer Vision and Pattern Recognition (ICCV)", 1997, pp. 151-157

[45] Y. DONG, J. WANG, F. PELLACINI, X. TONG, B. GUO. *Fabricating spatially-varying subsurface scattering*, in "ACM Trans. Graph.", 2010, vol. 29, n^{o} 4, http://doi.acm.org/10.1145/1778765.1778799

[46] P. DUTRÉ, K. BALA, P. BEKAERT. *Advanced Global Illumination*, A.K. Peters, 2006

[47] K. EGAN, F. HECHT, F. DURAND, R. RAMAMOORTHI. *Frequency analysis and sheared filtering for shadow light fields of complex occluders*, in "ACM Trans. Graph.", 2011, vol. 30, http://doi.acm.org/10.1145/1944846.1944849

[48] K. EGAN, Y.-T. TSENG, N. HOLZSCHUCH, F. DURAND, R. RAMAMOORTHI. *Frequency Analysis and Sheared Reconstruction for Rendering Motion Blur*, in "ACM Trans. Graph.", 2009, vol. 28, n^{o} 3 [*DOI :* 10.1145/1531326.1531399], http://hal.inria.fr/inria-00388461/en

[49] R. FLEMING, A. TORRALBA, E. H. ADELSON. *Specular reflections and the perception of shape*, in "J. Vis.", 2004, vol. 4, n^{o} 9, pp. 798-820, http://journalofvision.org/4/9/10/

[50] K. GARANZHA, C. LOOP. *Fast Ray Sorting and Breadth-First Packet Traversal for GPU Ray Tracing*, in "Computer Graphics Forum", Wiley Online Library, 2010, vol. 29, n^{o} 2, pp. 289–298

[51] A. Ghosh, S. Achutha, W. Heidrich, M. O'Toole. *BRDF Acquisition with Basis Illumination*, in "IEEE International Conference on Computer Vision (ICCV)", 2007, pp. 1-8

[52] M. Goesele, X. Granier, W. Heidrich, H.-P. Seidel. *Accurate Light Source Acquisition and Rendering*, in "ACM Trans. Graph.", 2003, vol. 22, n^{o} 3, pp. 621-630 [*DOI :* 10.1145/882262.882316], http://hal.inria.fr/hal-00308294

[53] C. M. Goral, K. E. Torrance, D. P. Greenberg, B. Battaile. *Modeling the interaction of light between diffuse surfaces*, in "Proc. ACM SIGGRAPH", 1984, pp. 213-222

[54] M. Hasan, M. Fuchs, W. Matusik, H. Pfister, S. Rusinkiewicz. *Physical reproduction of materials with specified subsurface scattering*, in "ACM Trans. Graph.", 2010, vol. 29, n^{o} 4, http://doi.acm.org/10.1145/1778765.1778798

[55] P. S. Heckbert. *Simulating Global Illumination Using Adaptative Meshing*, University of California, 1991

[56] M. B. Hullin, M. Fuchs, I. Ihrke, H.-P. Seidel, H. P. A. Lensch. *Fluorescent immersion range scanning*, in "ACM Trans. Graph.", 2008, vol. 27, n^{o} 3, http://doi.acm.org/10.1145/1360612.1360686

[57] M. B. Hullin, J. Hanika, B. Ajdin, H.-P. Seidel, J. Kautz, H. P. A. Lensch. *Acquisition and analysis of bispectral bidirectional reflectance and reradiation distribution functions*, in "ACM Trans. Graph.", 2010, vol. 29, http://doi.acm.org/10.1145/1778765.1778834

[58] M. B. Hullin, H. P. A. Lensch, R. Raskar, H.-P. Seidel, I. Ihrke. *Dynamic Display of BRDFs*, in "Comput. Graph. Forum", 2011, vol. 30, n^{o} 2, pp. 475–483, http://dx.doi.org/10.1111/j.1467-8659.2011.01891.x

[59] I. Ihrke, K. N. Kutulakos, H. P. A. Lensch, M. Magnor, W. Heidrich. *Transparent and Specular Object Reconstruction*, in "Comput. Graph. Forum", 2010, vol. 29, n^{o} 8, pp. 2400-2426

[60] I. Ihrke, I. Reshetouski, A. Manakov, A. Tevs, M. Wand, H.-P. Seidel. *A Kaleidoscopic Approach to Surround Geometry and Reflectance Acquisition*, in "IEEE Conf. Computer Vision and Pattern Recognition Workshops (CVPRW)", IEEE Computer Society, 2012, pp. 29-36

[61] I. Ihrke, G. Wetzstein, W. Heidrich. *A theory of plenoptic multiplexing*, in "IEEE Conf. Computer Vision and Pattern Recognition (CVPR)", IEEE Computer Society, 2010, pp. 483-490, oral

[62] J. T. Kajiya. *The rendering equation*, in "Proc. ACM SIGGRAPH", 1986, pp. 143-150, http://doi.acm.org/10.1145/15922.15902

[63] J. Kautz, P.-P. Sloan, J. Snyder. *Fast, arbitrary BRDF shading for low-frequency lighting using spherical harmonics*, in "Proc. Eurographics workshop on Rendering (EGWR)", 2002, pp. 291-296

[64] I. Kaya, K. P. Thompson, J. P. Rolland. *Edge clustered fitting grids for ϕ-polynomial characterization of freeform optical surfaces*, in "Opt. Express", 2011, vol. 19, n^{o} 27, pp. 26962-26974 [*DOI :* 10.1364/OE.19.026962], http://www.opticsexpress.org/abstract.cfm?URI=oe-19-27-26962

[65] A. KELLER, E. KELLER, W. HEIDRICH. *Interleaved Sampling*, in "Rendering Techniques 2001 (Proc. 12th Eurographics Workshop on Rendering)", Springer, 2001, pp. 269–276

[66] T. KOLLIG, A. KELLER. *Efficient multidimensional sampling*, in "Computer Graphics Forum", Wiley Online Library, 2002, vol. 21, n^O 3, pp. 557–563

[67] M. KOLOMENKIN, I. SHIMSHONI, A. TAL. *Demarcating curves for shape illustration*, in "ACM Trans. Graph. (SIGGRAPH Asia)", 2008, vol. 27, http://doi.acm.org/10.1145/1409060.1409110

[68] M. LEVOY, Z. ZHANG, I. MCDOWALL. *Recording and controlling the 4D light field in a microscope using microlens arrays*, in "J. Microscopy", 2009, vol. 235, n^O 2, pp. 144-162, http://dx.doi.org/10.1111/j.1365-2818.2009.03195.x

[69] S. LI, G. GUENNEBAUD, B. YANG, J. FENG. *Predicted Virtual Soft Shadow Maps with High Quality Filtering*, in "Comput. Graph. Forum", 2011, vol. 30, n^O 2, pp. 493-502, http://hal.inria.fr/inria-00566223/en

[70] C.-K. LIANG, T.-H. LIN, B.-Y. WONG, C. LIU, H. H. CHEN. *Programmable aperture photography: multiplexed light field acquisition*, in "ACM Trans. Graph.", 2008, vol. 27, n^O 3, http://doi.acm.org/10.1145/1360612.1360654

[71] Y. LIU, X. GRANIER. *Online Tracking of Outdoor Lighting Variations for Augmented Reality with Moving Cameras*, in "IEEE Transactions on Visualization and Computer Graphics", March 2012, vol. 18, n^O 4, pp. 573-580 [*DOI :* 10.1109/TVCG.2012.53], http://hal.inria.fr/hal-00664943

[72] W. MATUSIK, H. PFISTER, M. BRAND, L. MCMILLAN. *A data-driven reflectance model*, in "ACM Trans. Graph.", 2003, vol. 22, n^O 3, pp. 759-769, http://doi.acm.org/10.1145/882262.882343

[73] W. MATUSIK, H. PFISTER. *3D TV: a scalable system for real-time acquisition, transmission, and autostereoscopic display of dynamic scenes*, in "ACM Trans. Graph.", 2004, vol. 23, n^O 3, pp. 814-824, http://doi.acm.org/10.1145/1015706.1015805

[74] B. MOON, Y. BYUN, T.-J. KIM, P. CLAUDIO, H.-S. KIM, Y.-J. BAN, S. W. NAM, S.-E. YOON. *Cache-oblivious Ray Reordering*, in "ACM Trans. Graph.", July 2010, vol. 29, n^O 3, pp. 28:1–28:10, http://doi.acm.org/10.1145/1805964.1805972

[75] G. MÜLLER, J. MESETH, M. SATTLER, R. SARLETTE, R. KLEIN. *Acquisition, Synthesis and Rendering of Bidirectional Texture Functions*, in "Eurographics 2004, State of the Art Reports", 2004, pp. 69-94

[76] A. NGAN, F. DURAND, W. MATUSIK. *Experimental Analysis of BRDF Models*, in "Proc. Eurographics Symposium on Rendering (EGSR)", 2005, pp. 117-226

[77] F. E. NICODEMUS, J. C. RICHMOND, J. J. HSIA, I. W. GINSBERG, T. LIMPERIS. *Geometrical Considerations and Nomenclature for Reflectance*, National Bureau of Standards, 1977

[78] M. O'TOOLE, K. N. KUTULAKOS. *Optical computing for fast light transport analysis*, in "ACM Trans. Graph.", 2010, vol. 29, n^O 6

[79] R. PACANOWSKI, X. GRANIER, C. SCHLICK, P. POULIN. *Volumetric Vector-based Representation for Indirect Illumination Caching*, in "J. Computer Science and Technology (JCST)", 2010, vol. 25, n^{o} 5, pp. 925-932 [*DOI :* 10.1007/s11390-010-1073-8], http://hal.inria.fr/inria-00505132/en

[80] R. PACANOWSKI, O. SALAZAR-CELIS, C. SCHLICK, X. GRANIER, P. POULIN, A. CUYT. *Rational BRDF*, in "IEEE Transactions on Visualization and Computer Graphics", February 2012, vol. 18, n^{o} 11, pp. 1824-1835 [*DOI :* 10.1109/TVCG.2012.73], http://hal.inria.fr/hal-00678885

[81] P. PEERS, D. MAHAJAN, B. LAMOND, A. GHOSH, W. MATUSIK, R. RAMAMOORTHI, P. DEBEVEC. *Compressive light transport sensing*, in "ACM Trans. Graph.", 2009, vol. 28, n^{o} 1

[82] B. PETIT, J.-D. LESAGE, C. MENIER, J. ALLARD, J.-S. FRANCO, B. RAFFIN, E. BOYER, F. FAURE. *Multicamera Real-Time 3D Modeling for Telepresence and Remote Collaboration*, in "Int. J. digital multimedia broadcasting", 2010, vol. 2010, Article ID 247108, 12 pages [*DOI :* 10.1155/2010/247108], http://hal.inria.fr/inria-00436467

[83] M. PHARR, C. KOLB, R. GERSHBEIN, P. HANRAHAN. *Rendering Complex Scenes with Memory-coherent Ray Tracing*, in "Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques", New York, NY, USA, SIGGRAPH '97, ACM Press/Addison-Wesley Publishing Co., 1997, pp. 101–108, http://dx.doi.org/10.1145/258734.258791

[84] R. RAMAMOORTHI, P. HANRAHAN. *On the relationship between radiance and irradiance: determining the illumination from images of a convex Lambertian object*, in "J. Opt. Soc. Am. A", 2001, vol. 18, n^{o} 10, pp. 2448-2459

[85] R. RAMAMOORTHI, D. MAHAJAN, P. BELHUMEUR. *A first-order analysis of lighting, shading, and shadows*, in "ACM Trans. Graph.", 2007, vol. 26, n^{o} 1, http://doi.acm.org/10.1145/1189762.1189764

[86] R. RASKAR, J. TUMBLIN. *Computational Photography: Mastering New Techniques for Lenses, Lighting, and Sensors*, A K Peters/CRC Press, 2012

[87] E. REINHARD, W. HEIDRICH, P. DEBEVEC, S. PATTANAIK, G. WARD, K. MYSZKOWSKI. *High Dynamic Range Imaging: Acquisition, Display and Image-Based Lighting*, Morgan Kaufmann Publishers, 2010, 2nd edition

[88] P. REN, J. WANG, J. SNYDER, X. TONG, B. GUO. *Pocket reflectometry*, in "ACM Trans. Graph.", 2011, vol. 30, n^{o} 4

[89] P. REUTER, G. RIVIERE, N. COUTURE, S. MAHUT, L. ESPINASSE. *ArcheoTUI-Driving virtual reassemblies with tangible 3D interaction*, in "J. Computing and Cultural Heritage", 2010, vol. 3, n^{o} 2, pp. 1-13 [*DOI :* 10.1145/1841317.1841319], http://hal.inria.fr/hal-00523688/en

[90] H. E. RUSHMEIER, K. E. TORRANCE. *The zonal method for calculating light intensities in the presence of a participating medium*, in "ACM SIGGRAPH Comput. Graph.", 1987, vol. 21, n^{o} 4, pp. 293-302, http://doi.acm.org/10.1145/37402.37436

[91] S. RUSINKIEWICZ. *A New Change of Variables for Efficient BRDF Representation*, in "Proc. EGWR '98", 1998, pp. 11-22

[92] P. Schröder, W. Sweldens. *Spherical wavelets: efficiently representing functions on the sphere*, in "Proc. ACM SIGGRAPH", annual conference on Computer graphics and interactive techniques, 1995, pp. 161-172, http://doi.acm.org/10.1145/218380.218439

[93] F. X. Sillion, C. Puech. *Radiosity and Global Illumination*, Morgan Kaufmann Publishers, 1994

[94] C. Soler, K. Subr, F. Durand, N. Holzschuch, F. X. Sillion. *Fourier Depth of Field*, in "ACM Transactions on Graphics", 2009, vol. 28, n^{o} 2 [*DOI :* 10.1145/1516522.1516529], http://hal.inria.fr/inria-00345902

[95] M. Stamminger, A. Scheel, X. Granier, F. Perez-Cazorla, G. Drettakis, F. X. Sillion. *Efficient Glossy Global Illumination with Interactive Viewing*, in "Computer Graphics Forum", 2000, vol. 19, n^{o} 1, pp. 13-25

[96] M. Stark, J. Arvo, B. Smits. *Barycentric Parameterizations for Isotropic BRDFs*, in "IEEE Trans. Vis. and Comp. Graph.", 2005, vol. 11, n^{o} 2, pp. 126-138, http://dx.doi.org/10.1109/TVCG.2005.26

[97] W. Thompson, R. Fleming, S. Creem-Regehr, J. K. Stefanucci. *Visual Perception from a Computer Graphics Perspective*, A K Peters/CRC Press, 2011

[98] Y.-T. Tsai, Z.-C. Shih. *All-Frequency Precomputed Radiance Transfer Using Spherical Radial Basis Functions and Clustered Tensor Approximation*, in "ACM Trans. Graph.", 2006, vol. 25, n^{o} 3, pp. 967-976

[99] D. Vanderhaeghe, R. Vergne, P. Barla, W. Baxter. *Dynamic Stylized Shading Primitives*, in "Proc. Int. Symposium on Non-Photorealistic Animation and Rendering (NPAR)", ACM, 2011, pp. 99-104, http://hal.inria.fr/hal-00617157/en

[100] P. Vangorp, J. Laurijssen, P. Dutré. *The influence of shape on the perception of material reflectance*, in "ACM Trans. Graph.", 2007, vol. 26, n^{o} 3, http://doi.acm.org/10.1145/1276377.1276473

[101] E. Veach, L. J. Guibas. *Metropolis light transport*, in "Proc. SIGGRAPH '97", annual conference on Computer graphics and interactive techniques, ACM/Addison-Wesley Publishing Co., 1997, pp. 65-76, http://doi.acm.org/10.1145/258734.258775

[102] R. Vergne, P. Barla, R. Fleming, X. Granier. *Surface Flows for Image-based Shading Design*, in "ACM Transactions on Graphics", August 2012, vol. 31, n^{o} 3 [*DOI :* 10.1145/2185520.2185590], http://hal.inria.fr/hal-00702280

[103] R. Vergne, R. Pacanowski, P. Barla, X. Granier, C. Schlick. *Light warping for enhanced surface depiction*, in "ACM Trans. Graph.", 2009, vol. 28, n^{o} 3, 25:1 p. , front cover, http://doi.acm.org/10.1145/1531326.1531331

[104] R. Vergne, R. Pacanowski, P. Barla, X. Granier, C. Schlick. *Improving Shape Depiction under Arbitrary Rendering*, in "IEEE Trans. Visualization and Computer Graphics", 2011, vol. 17, n^{o} 8, pp. 1071-1081 [*DOI :* 10.1109/TVCG.2010.252], http://hal.inria.fr/inria-00585144/en

[105] R. VERGNE, D. VANDERHAEGHE, J. CHEN, P. BARLA, X. GRANIER, C. SCHLICK. *Implicit Brushes for Stylized Line-based Rendering*, in "Comput. Graph. Forum", 2011, vol. 30, n$^{\mathrm{o}}$ 2, pp. 513-522, 3$^{\mathrm{rd}}$ best paper award [*DOI :* 10.1111/J.1467-8659.2011.01892.X], http://hal.inria.fr/inria-00569958/en

[106] F. VINCENT, L. BARTHE, G. GUENNEBAUD, M. PAULIN. *Soft Textured Shadow Volume*, in "Comput. Graph. Forum", 2009, vol. 28, n$^{\mathrm{o}}$ 4, pp. 1111-1120, http://hal.inria.fr/inria-00390534/en

[107] J. WANG, Y. DONG, X. TONG, Z. LIN, B. GUO. *Kernel Nyström method for light transport*, in "ACM Trans. Graph.", 2009, vol. 28, n$^{\mathrm{o}}$ 3

[108] B. YANG, J. FENG, G. GUENNEBAUD, X. LIU. *Packet-based Hierarchical Soft Shadow Mapping*, in "Comput. Graph. Forum", 2009, vol. 28, n$^{\mathrm{o}}$ 4, pp. 1121-1130, http://hal.inria.fr/inria-00390541/en