IN PARTNERSHIP WITH:
CNRS

Institut d'Optique Graduate School

Université de Bordeaux

Activity Report 2017

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
Bordeaux - Sud-Ouest

THEME
Interaction and visualization

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Project-Team MANAO

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

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A5.3.5. - Computational photography
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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 [58], [36] 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 [68] and Light-Field rendering [34]). 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 [66], [69], 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 [89] 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 [50]

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 [79], stereo displays or new display technologies [54], and physical fabrication [25], [42], [50]) the frontiers between real and virtual worlds are vanishing [38]. 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

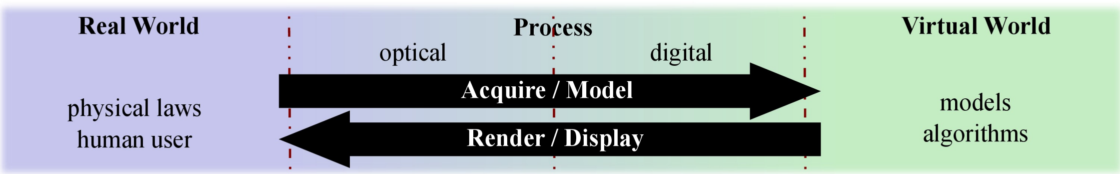


Figure 2. Interactions/Transfers between real and virtual worlds. One of our goal is to combine optical instruments with processes from computer science in order to blend the two worlds.

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 [31] or geometric properties [95], as mastered by professional photographers;
- The modification of material characteristics or lighting conditions [96] to better understand shape features, for instance to decipher archaeological artifacts;
- The large influence of shape on the captured variation of shading [77] and thus on the perception of material properties [92].

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) [41] 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 [65]. 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 [30], [38] and computational photography [78].
- **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 [89]. 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

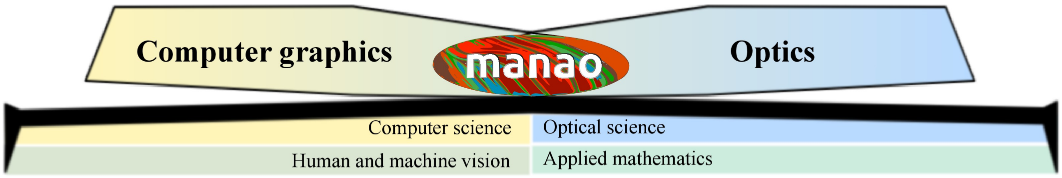


Figure 3. Related scientific domains of the MANAO project.

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 [43] 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 [55], [56] and display [54] 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 [45] or differential analysis [77], linear and non-linear approximation techniques, stochastic and deterministic integrations, and linear algebra. We not only rely on classical tools, but also investigate and adapt recent techniques (e.g., improvements in approximation techniques), focusing on their ability to run on modern hardware: the development of our own tools (such as Eigen) is essential to control their performances and their abilities to be integrated into real-time solutions or into new instruments.

3.2. Research axes

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

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

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

Axes 3 and 4 focus on two aspects of computer graphics: rendering, visualization and illustration in Axis 3, and editing and modeling (content creation) in Axis 4. In these two axes, the final observers are mainly human users, either generic users or expert ones (e.g., archaeologist [81], computer graphics artists).

3.3. Axis 1: Analysis and Simulation

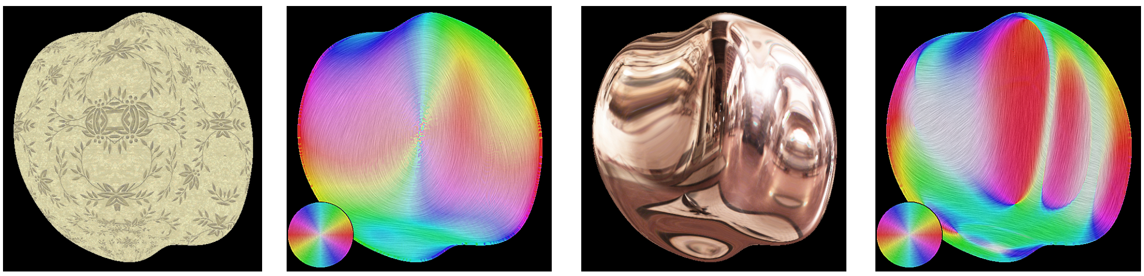
Challenge: Definition and understanding of phenomena resulting from interactions between light, shape, and matter as seen from an observer point of view.

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 [51] in order to develop tailored strategies [93]. For instance, starting from simple direct lighting, more complex phenomena have been progressively introduced: first diffuse indirect illumination [49], [85], then more generic inter-reflections [58], [43] and volumetric scattering [82], [40]. 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 [39]. 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 [84] but are difficult to extend to non-piecewise-constant data [87]. More recently, researches prefer the use of Spherical Radial Basis Functions [90] or Spherical Harmonics [76]. For more complex data, such as reflective properties (e.g., BRDF [70], [59] - 4D), ray-space (e.g., Light-Field [67] - 4D), spatially varying reflective properties (6D - [80]), new models, and representations are still investigated such as rational functions [73] or dedicated models [28] and parameterizations [83], [88]. 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 [73].



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

Figure 4. First-oder analysis [94] 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 [77] and frequency analysis [45]). 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 [46] 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.

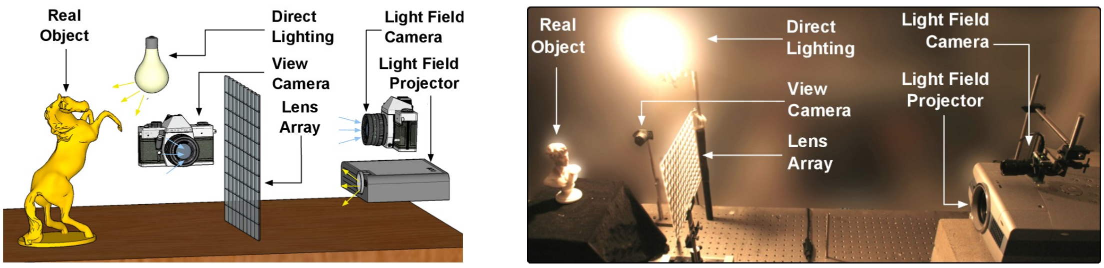


Figure 5. Light-Field transfer: global illumination between real and synthetic objects [38]

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 [67], [54]. We consider projecting systems and surfaces [35], for personal use, virtual reality and augmented reality [30]. 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 [48], [47]. These resulting systems have to acquire the different phenomena described in Axis 1 and to display them, in an efficient manner [52], [29], [53], [56]. 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 [57].

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 [56], [75]). Similarly, increasing the number of viewpoints is a way toward the creation of full 3D displays [67]. 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., [74], [99]).

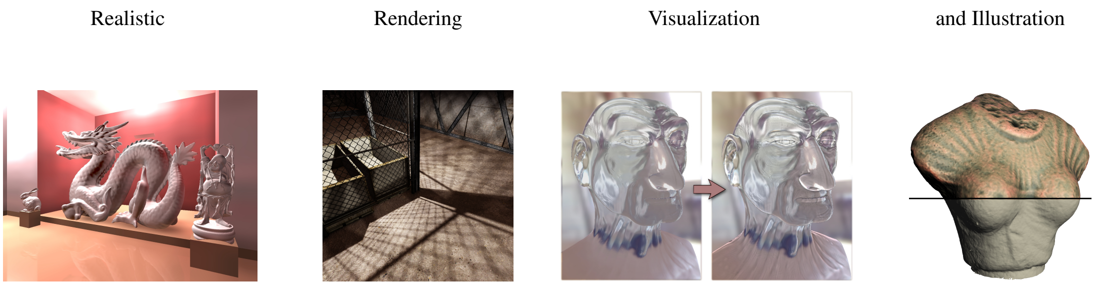
We prefer to achieve this goal by avoiding as much as possible the classical approach where acquisition is followed by a fitting step: this requires in general a large amount of measurements and the fitting itself may consume consequently too much memory and preprocessing time. By **preventing unnecessary 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. [38]. 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 [64] are one of the key technologies to develop such acquisition (e.g., Light-Field camera [1] [57] and acquisition of light-sources [48]), projection systems (e.g., auto-stereoscopic displays). Such an approach is versatile and may be applied to improve classical optical instruments [62]. More generally, by designing unified optical and digital systems [71], 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 [73]. Second, we have to integrate signals from multiple sensors (such as GPS, accelerometer, ...) to prevent some computation (e.g., [65]). Finally, the experience of the group in surface modeling help the design of optical surfaces [60] 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 [72] (b) Shadows [100] (c) Shape enhancement [96] (d) Shape depiction [27]

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

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

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

In the context of scientific illustration and visualization, we are primarily interested in tools to convey shape or material characteristics of objects in animated 3D scenes. **Expressive rendering** techniques (see Figure 6c,d) provide means for users to depict such features with their own style. To introduce our approach, we detail it from a shape-depiction point of view, domain where we have acquired a recognized expertise. Prior work in this area mostly focused on stylization primitives to achieve line-based rendering [97], [61] or stylized shading [33], [96] 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 [26] 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 [98], motion blur [45], depth of field [86], 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 [63], [44]. 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 [37]. Independent image processing for each viewpoint may disturb the feeling of depth by introducing inconsistent information in each images. Finally, more dedicated displays [54] 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.

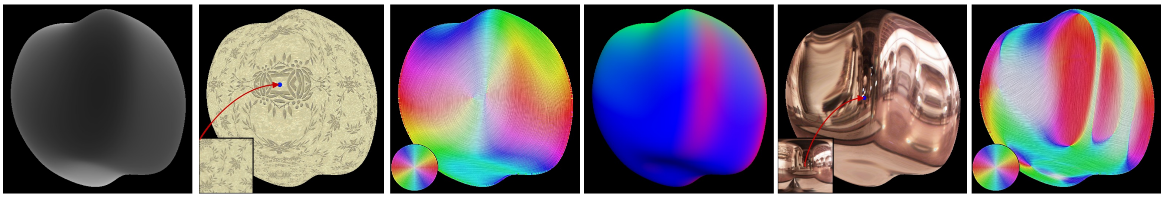
During the last decade, the domain of computer graphics has exhibited tremendous improvements in image quality, both for 2D applications and 3D engines. This is mainly due to the availability of an ever increasing amount of shape details, and sophisticated appearance effects including complex lighting 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] [32]. 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., [91]): 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 [91]), and replicate it to novel illumination environments and 3D models. For this purpose, we will rely on the decompositions and tools issued from Axis 1.

4. Application Domains

4.1. Physical Systems



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

Figure 7. Based on our analysis [94] (Axis 1), we have designed a system that mimics texture (left) and shading (right) effects using image processing alone. It takes depth (a) and normal (d) images as input, and uses them to deform images (b-e) in ways that closely approximate surface flows (c-f). It provides a convincing, yet artistically controllable illusion of 3D shape conveyed through texture or shading cues.

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

4.2. Interactive Visualization and Modeling

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

5. Highlights of the Year

5.1. Highlights of the Year

We are regularly publishing our work at the prestigious conference Siggraph. This year was particularly successful with three plain papers [11], [12], [14].

6. New Software and Platforms

6.1. Eigen

KEYWORD: Linear algebra

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

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

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

6.2. Elasticity Skinning

KEYWORD: 3D animation

FUNCTIONAL 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: Brian Wyvill, Damien Rohmer, Florian Canezin, Gaël Guennebaud, Loïc Barthe, Marie-Paule Cani, Mathias Paulin, Olivier Gourmel and Rodolphe Vaillant
- 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

7. New Results

7.1. Analysis and Simulation

7.1.1. A Two-Scale Microfacet Reflectance Model Combining Reflection and Diffraction , ,

Adequate reflectance models are essential for the production of photorealistic images. Microfacet reflectance models predict the appearance of a material at the macroscopic level based on microscopic surface details. They provide a good match with measured reflectance in some cases, but not always. This discrepancy between the behavior predicted by microfacet models and the observed behavior has puzzled researchers for a long time. In these papers [14], [24], [19], we show that diffraction effects in the micro-geometry provide a plausible explanation. We describe a two-scale reflectance model (cf. Figure 8), separating between geometry details much larger than wavelength and those of size comparable to wavelength. The former model results in the standard Cook-Torrance model. The latter model is responsible for diffraction effects. Diffraction effects at the smaller scale are convolved by the micro-geometry normal distribution. The resulting two-scale model provides a very good approximation to measured reflectances.

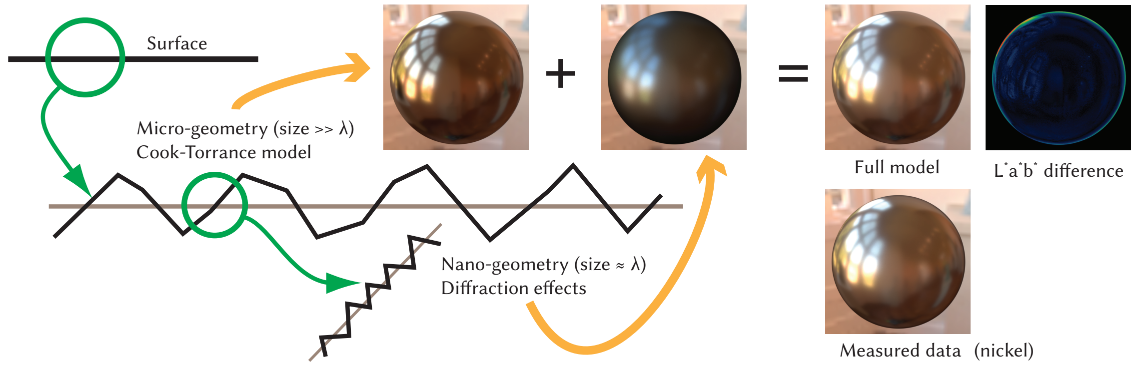


Figure 8. Material reflectance properties are caused by small variations in surface geometry. We separate these surface variations into micro-geometry, of size larger than the wavelength of visible light, and nano-geometry, of size comparable to the wavelength. The latter produces diffraction effects, with wavelength-dependent effects. The former corresponds to the classical Cook-Torrance lobe. We explain how these two levels interact and show that combined together, they reproduce measured materials faithfully, including subtle color shifts.

7.1.2. A Practical Extension to Microfacet Theory for the Modeling of Varying Iridescence

Thin film iridescence permits to reproduce the appearance of leather. However, this theory requires spectral rendering engines (such as Maxwell Render) to correctly integrate the change of appearance with respect to viewpoint (known as goniochromatism). This is due to aliasing in the spectral domain as real-time renderers only work with three components (RGB) for the entire range of visible light. In this work [11], we show how to anti-alias a thin-film model, how to incorporate it in microfacet theory, and how to integrate it in a real-time rendering engine. This widens the range of reproducible appearances with microfacet models (cf. Figure 9).

7.2. From Acquisition to Display

7.2.1. Diffraction effects detection for HDR image-based measurements ,

Modern imaging techniques have proved to be very efficient to recover a scene with high dynamic range (HDR) values. However, this high dynamic range can introduce star-burst patterns around highlights arising from the diffraction of the camera aperture. The spatial extent of this effect can be very wide and alters pixels values, which, in a measurement context, are not reliable anymore. To address this problem, we introduce [21], [15] a novel algorithm that, utilizing a closed-form PSF, predicts where the diffraction will affect the pixels of an HDR image, making it possible to discard them from the measurement. Our approach gives better results (cf. Figure 10) than common deconvolution techniques and the uncertainty values (convolution kernel and noise) of the algorithm output are recovered.

7.2.2. A low-cost multitouch spherical display: hardware and software design ,

Spherical mulitouch displays offer exciting possibilities but are still costly. In this work [17], we first describe hardware and software considerations to build a more affordable one, with off-the-shelf optical components and 3D printed elements. We exploit the technology of laser-beam steering projectors and use optical tracking for multitouch. Besides, although spherical displays become more and more pervasive, the design of interactive content for these displays still remains difficult as it requires most developers to get familiar with specific tools for managing the output and input. We thus present [18] a framework for developing applications for multitouch spherical displays that makes it possible to create interactive content by programming standard GUI applications, as for example interactive web pages. The principal idea is to adapt the window output

Figure 9. Material appearance such as that of leather is usually reproduced with microfacet models in computer graphics. A more realistic result is achieved by adding a thin-film coating that produces iridescent colors. We replace the classic Fresnel reflectance term with a new Airy reflectance term that accounts for iridescence due to thin-film interference. Our main contribution consists in an analytical integration of the high-frequency spectral oscillations exhibited by Airy reflectance, which is essential for practical rendering in RGB. When the scene is rotated, goniochromatic effects such as subtle purple colors may be observed at grazing angles.

and interaction input of classical GUIs outside the application. To this end, our framework consists of two standalone applications where the first one captures the window output and changes the projection via GPU shaders, and the second one adapts the input with a Node.js server and sends interaction and mouse events. In this way, the same application runs on a standard desktop, and on the spherical display. Advantages of our approach include fast prototyping, and the fact that masses of developers can create applications for spherical displays just as if it were, for example, classical web applications. We believe that our framework will contribute to making spherical displays even more pervasive in the future.

7.3. Rendering, Visualization and Illustration

7.3.1. Example-Based Expressive Animation of 2D Rigid Bodies

We have presented [12] a novel approach to facilitate the creation of stylized 2D rigid body animations. Our approach can handle multiple rigid objects following complex physically-simulated trajectories with collisions, while retaining a unique artistic style directly specified by the user. Starting with an existing target animation (e.g., produced by a physical simulation engine) an artist interactively draws over a sparse set of frames, and the desired appearance and motion stylization is automatically propagated to the rest of the sequence (fig. 11). The stylization process may also be performed in an off-line batch process from a small set of drawn sequences. To achieve these goals, we combine parametric deformation synthesis that generalizes and reuses hand-drawn exemplars, with non-parametric techniques that enhance the hand-drawn appearance of the synthesized sequence. We demonstrate the potential of our method on various complex rigid body animations which are created with an expressive hand-drawn look using notably less manual interventions as compared to traditional techniques.

7.3.2. Edge- and Substrate-based Effects for Watercolor Stylization ,

We investigated [20] characteristic edge-and substrate-based effects for watercolor stylization. These two fundamental elements of painted art play a significant role in traditional watercolors and highly influence the pigment's behavior and application. Yet a detailed consideration of these specific elements for the stylization of

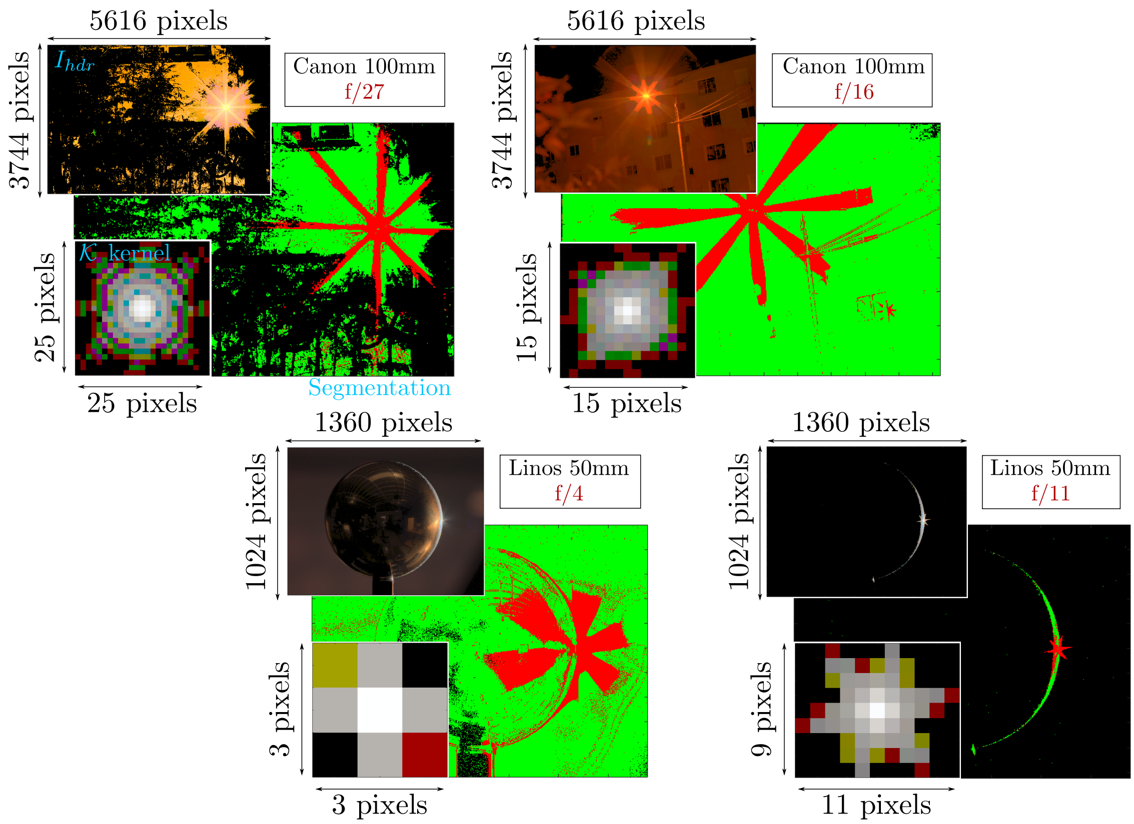


Figure 10. Results of the algorithm applied on real HDR images for various camera configurations, with input parameters $D_b = 10$ and $\rho = 5\%$. The wavelengths used for each color channel are $[\lambda_R, \lambda_G, \lambda_B] = [600nm, 540nm, 470nm]$. The segmentation images show the discarded pixels (red), the valid pixels (green), and the under-exposed ones (black). If the HDR images exhibits obvious star shaped patterns, the algorithm detects it, and they are finally removed. Such result is qualitative in nature, because there is no reference HDR image without diffraction. False predictions are present in the first two cases (l), where the diffraction prediction seems rotated from the real one. This problem emerges from the misfit of the lens diaphragm, as discussed in subsection 7.7.1.

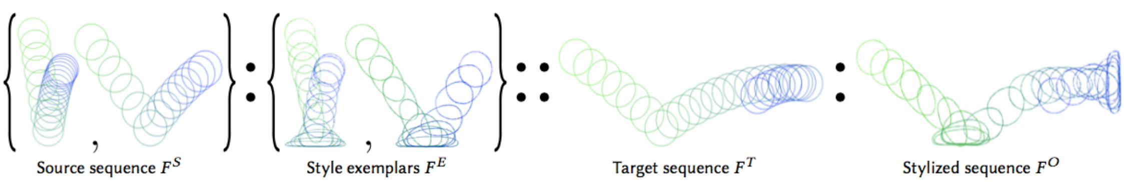


Figure 11. Given a set of frames F^S coming from reference 2D rigid body source animations, corresponding hand-animated exemplars ^{E}, and a new target animation F^T, the synthesis algorithm relates physical parameters in F^S and F^T to produce the output stylized sequence F^O that resembles F^E.

Figure 12. Our methods allow new and improved edge- and substrate-based effects for watercolor stylization: edge darkening (red), gaps (blue), overlaps (green) and dry-brush (yellow). Still Life, model by Dylan Sisson ©Pixar Animation Studios.

3D scenes has not been attempted before. Through this investigation, we contributed to the field by presenting ways to emulate two novel effects: dry-brush and gaps & overlaps. By doing so, we also found ways to improve upon well-studied watercolor effects such as edge-darkening and substrate granulation. Finally, we integrated controllable external lighting influences over the watercolorized result, together with other previously researched watercolor effects. These effects are combined through a direct stylization pipeline [22] to produce sophisticated watercolor imagery (fig. 12), which retains spatial coherence in object-space and is locally controllable in real-time.

7.3.3. Specular Motion and 3D Shape Estimation

Dynamic visual information facilitates three-dimensional shape recognition. It is still unclear, however, whether the motion information generated by moving specularities across a surface is congruent to that available from optic flow produced by a matte-textured shape. Whereas the latter is directly linked to the first-order properties of the shape and its motion relative to the observer, the specular flow, the image flow generated by a specular object, is less sensitive to the object's motion and is tightly related to second-order properties of the shape. We therefore hypothesize [13] that the perceived bumpiness (a perceptual attribute related to curvature magnitude) is more stable to changes in the type of motion in specular objects compared with their matte-textured counterparts. Results from two two-interval forced-choice experiments in which observers judged the perceived bumpiness of perturbed spherelike objects support this idea and provide an additional layer of evidence for the capacity of the visual system to exploit image information for shape inference.

7.3.4. The Perception of Hazy Gloss

Most previous work on gloss perception has examined the strength and sharpness of specular reflections in simple bidirectional reflectance distribution functions (BRDFs) having a single specular component. However, BRDFs can be substantially more complex and it is interesting to ask how many additional perceptual dimensions there could be in the visual representation of surface reflectance qualities. To address this, we tested [16] materials with two specular components that elicit an impression of hazy gloss. Stimuli were renderings of irregularly shaped objects under environment illumination, with either a single specular BRDF component, or two such components, with the same total specular reflectance but different sharpness parameters, yielding both sharp and blurry highlights simultaneously. Differently shaped objects were presented side by side in matching, discrimination, and rating tasks. Our results show that observers mainly attend to the sharpest reflections in matching tasks, but they can indeed discriminate between single-component and two-component specular materials in discrimination and rating tasks. The results reveal an additional perceptual dimension of gloss—beyond strength and sharpness—akin to "haze gloss". However, neither the physical measurements of Hunter and Harold nor the kurtosis of the specular term predict perception in our tasks. We suggest the visual system may use a decomposition of specular reflections in the perception of hazy gloss, and we compare two possible candidates: a physical representation made of two gloss components, and an alternative representation made of a central gloss component and a surrounding halo component.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. CIFRE PhD contract with Technicolor (2014-2018)

Participants: A. Dufay, X. Granier & R. Pacanowski
For this project, we aim at providing interactive previsualization of complex lighting with a smooth transition to the final solution.

8.1.2. CIFRE PhD contract with Thermo Fisher Scientific (2014-2018)

Participants: D. Murray & X. Granier
For this project, we aim at providing expressive rendering techniques for volumes.

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

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

9. Partnerships and Cooperations

9.1. 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" VIDA (2017-2021)

LP2N-CNRS-IOGS Inria
Leader R. Pacanowski (LP2N-CNRS-IOGS)
Participant P. Barla (Inria)

9.2.1.2. Context.

Since the beginning of the industrial era, prototyping has been an important stage for manufacturers as a preliminary step before mass production. With the rise of Computer Science and the recent advances of intensive computation, the industry is progressively shifting from a tangible prototype to a fully numerical and virtual prototype with the goal of reducing costs during the R&D phase. During the past few years, the emergence of 3D printers has enabled virtual prototyping methods to take into account, at an early stage, some degree of fabricability, especially regarding the shape of the manufactured object. Beyond the shape of an object, predicting the final appearance of a virtual prototype remains a challenge of high potential for many domains (e.g., furniture, textile, architecture). The challenge is mainly due to the fact that the final appearance of an object is dependent on its shape, the material(s) applied on it as well as the viewing and lighting conditions. As shown in Figure 13, solving the inverse problem that goes from Pictorial Design [A] to the Operational Design [D], where a specialist controls the fabrication process, is very hard and ill-posed.

9.2.1.3. Scientific Objectives.

The VIDA project aims at removing the several scientific locks by establishing a framework for direct and inverse design of material appearance for objects of complex shape. Since the manufacturing processes are always changing and evolving, our goal is to establish a framework that is not tied to a fabrication stage. To provide a rich variety of possible appearances, we will target multi-layered materials. We will ensure that every step of our framework is **validated** by either predictive simulation and/or measurements of the appearance. To illustrate the fabricability of our results, material samples as well as object samples will be fabricated locally or out-sourced to *Ecole des Mines de Saint-Etienne* (http://www.mines-stetienne.fr/en/EMSE) or http://www.saint-gobain-recherche.frSaint-Gobain Recherche and their appearance will also be validated with specific devices developed at the *https://www.institutoptique.fr/enInstitut d'Optique*-http://www.lp2n.frLP2N.

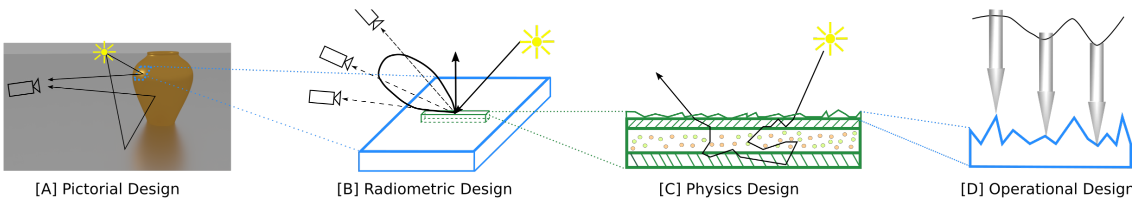


Figure 13. The different scales involved in the design of object appearance. [A] Pictorial scale: the object is seen as a whole. [B] Radiometric scale: represents the behaviour of a material when light interacts with it. [C] Microscopic scale: the material is described by physical parameters (e.g., index of refraction, absorption coefficient). [D] Operational scale: the parameters control the machine-dependent fabrication process.

9.2.1.4. "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.

9.2.1.5. ISAR (2014-2018)

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.

9.2.1.6. 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.

9.2.1.7. FOLD-Dyn (2017-2021)

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. International Research Visitors

9.3.1. Visits of International Scientists

Invited professor: Pierre Poulin, professor at Université de Montréal, Visiting scholar program of IdEx Bordeaux

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Chair of Conference Program Committees

Eurographics 2017 Posters chair

10.1.1.2. Member of the Conference Program Committees

Expressive 2017 (NPAR-SBIM-CAe), Eurographics 2017 and 2018, Eurographics Symposium on Rendering 2017 (EGSR), Eurographics Workshop on Graphics and Cultural Heritage 2017 (GCH), Symposium on Geometry Processing 2017 (SGP), Geometric Modeling and Processing 2017 (GMP), SIBGRAPI 2017, Web3D 2017

10.1.1.3. Reviewer

ACM Siggraph 2017, ACM Siggraph Asia 2017, Eurographics 2017, Graphics Interface 2017, Computer Graphics International 2017, CHI 2018, Vision meets Graphics 2017

10.1.2. Journal

10.1.2.1. Reviewer - Reviewing Activities

ACM Transactions on Graphics (TOG), IEEE Transactions on Visualization and Computer Graphics (TVCG), Computer Graphics Forum (CGF), Journal of Vision (JoV), i-Perception, Computers & Graphics

10.1.3. Scientific Expertise

Horizon 2020 Program

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 & Antoine Lucat, 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 : Gaël Guennebaud, Thibaud Lambert, Parallel Programming, 19 HETD, M1, 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, 3D Worlds, 60 HETD, M1, Univ. Bdx and IOGS, France.

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

Master : Patrick Reuter, Graphical user interfaces and Spatial augmented reality seminars, M2, ESTIA, France.

Master : Pierre Bénard, Image Synthesis and 3D modeling, 20 HETD, M2, ENSEIRB, France.

Licence : Patrick Reuter, Digital Imaging, 30 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

HdR : Pascal Barla, Toward a Perceptually-relevant Theory of Appearance, Inria & Univ. Bordeaux, 9 October 2017

PhD : Arthur Dufay, Adaptive high-quality of virtual environments with complex photometry, Technicolor & Univ. Bordeaux, 10 October 2017, J.-E. Marvie R. Pacanowski & X. Granier

PhD : Thibaud Lambert, Real-time rendering of highly detailed 3D models, Inria & Univ. Bordeaux, 18 December 2017, G. Guennebaud & P. Bénard

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

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

PhD in progress : David Murray, Expressive Rendering of Volumetric Data, Thermo Fisher Scientific & Univ. Bordeaux, J. Baril & X. Granier

PhD in progress : Thomas Crespel, Autostereoscopic 3D display, Inria & Univ. Bordeaux, P. Reuter & X. Granier

PhD in progress : Charlotte Herzog, 3 dimensions X-rays imaging for medical applications, Imaging Optics, IOGS & Univ. Bordeaux, X. Granier

PhD in progress : Camille Brunel, Real-Time Animation and Deformation of 3D Characters, Inria & Univ. Bordeaux, P. Barla, G. Guennebaud & P. Bénard

10.3. Popularization

We took part in "FACTS", the art and science festival of Université de Bordeaux, and more precisely in the exhibition "Open Lab", which took place from November 14 to 21 at Espace 29. In collaboration with the artist Maud Mulliez, we presented our ongoing work, "L'empreinte du Geste", which aims at analyzing the connection between the gesture of the artist and the mark that the brush or pen produces on the final art piece. An installation combining videos and projection was allowing the audiance to discover our preliminary results.

Pierre Bénard gave a talk titled *L'art et la science des films d'animation 3D* during the internal Inria BSO seminar "Unithé ou café" in January 2017 (45 minutes + questions) and in front of secondary students (120 split into 5 groups) during "la Fête de la Science" (30 minutes) in September 2017. This talk presents the main steps and ingredients required to create a 3D animated film (3D modeling, animation, lighting, rendering) and, for each of them, it shows the subtle but indispensable mix of physical and mathematical models, computer algorithms and artistic talent that it implies. It also highlights how the work of manao contributes to this field.

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