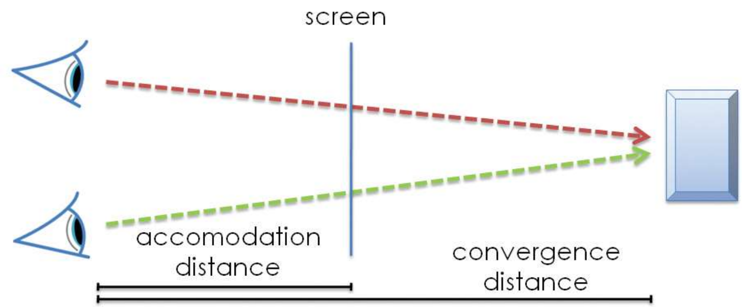


Figure 18.3: Accommodation distance is not equal to convergence distance in a S3D projection on a 2D screen, causing contradicting visual cues.

At the core, using a 2D display at a fixed distance to the viewer cannot produce a natural impression, but is instead an illusion for the human visual system that produces inconsistencies which need to be concealed, if the viewer is not to be overstressed. In particular, the accommodation (focal sharpness) distance is not equal to the convergence distance (Figure 18.3, "convergence-accomodation conflict").

Since the HVS will only tolerate a limited amount of inconsistency between cues, this limits the usable depth around the screen plane. First, the eyes' focus must always be on the screen in order to see sharp images. Now if a viewer converges on an object too far away from the screen, and the maximum sharpness is still on the screen plane, the monocular focus cue and the binocular convergence cue are inconsistent. The brain has to constantly fight against the contradicting input and may get stressed over time.

Content producers therefore carefully plan the use of the z-space, called "stereo budget" (or "depth budget"). Keeping the main action close to the screen at most times ensures the least stressful viewing experience for the audience. This can be characterized as a S3D comfort zone (Figure 18.4). Viewers will receive minimal stress within the green zone, and increasingly toward the red zone. In this manner, creatives today pay a lot of attention to the mindful and expressive depth design of each scene shot.

Additionally, the temporal aspects of depth must be considered. Scene transitions should limit aggressive jumps in depth between salient objects, as the forceful quick realignment of the eyes can be stressful. On the other hand, gentle guidance can stretch the comfort zone, as done, e.g., in a scene of the movie "Hugo"[3] where the main character slowly runs out of the screen while narrative climax, music, and depth-of-field encourage viewers

[3]Hugo movie – http://www.imdb.com/title/tt0970179/

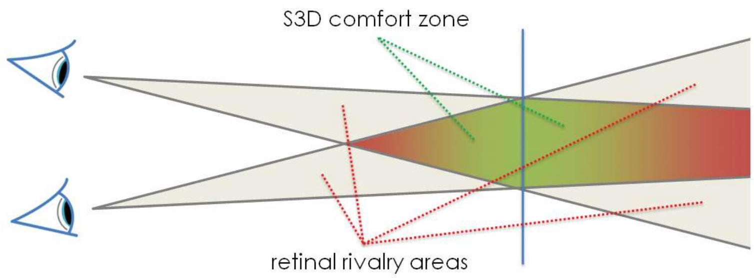


Figure 18.4: Viewer comfort is maximized by staying within the S3D comfort zone.

to fix all attention on the character. This leads to a final depth position that would be considered painful to the eyes when trying to converge on it without any setup.

Cuts should also be not too frequent because adjusting to a new scene requires more time when processing binocular cues [Berends and Erkelens 01]. Therefore, 3D movies typically feature more sweeping shots, contain fewer cuts in action scenes, and keep the depth at the same level during transitions. Applying this style is challenging for trailers, which typically have to include a multitude of cuts. Another factor is the adversarial situation of motion blur in the context of S3D, since depth is perceived more precisely at sharp object boundaries which are absent in the presence of motion blur, encouraging creatives to either increase frame rate or choose a different shooting angle or distance.

Finally, an entire class of post-production issues comes up with stereoscopic footage. The images must be aligned such that vertical disparity is eliminated, since natural scenes never produce it and it is thus perceived as stressful. Even slight inter-camera rotation or lens distortion can introduce this negative effect. Minor differences between camera sensors and lenses remain even after white balancing (more so if a mirror rig is used), and must be fixed via color grading.

18.5 3D Video Representation

Like all media, S3D defines a pipeline ranging from capture to display. When compared to standard 2D video, the additional data implies that 3D is more complex and thus bandwidth-demanding through all stages of processing (Figure 18.1). Even in the simplest case, an additional frame for the second eye has to be produced, transmitted, and displayed. While binocular S3D is currently the only commercial manifestation, other variants appear

Table 18.2: 3D scene representations can be classified as image-, depth-, or geometry-based.

Image-based	Depth-based	Model-based
Lightfield	S3D one + depth	Video textures
Lumigraph	Oriented billboards	3D mesh models
S3D two-frames	Layered depth videos	

either as part of post-production or as prototypes. The variant closest to binocular S3D uses one image plus depth map and renders the scene at the user's display. This confers a fine-tuning advantage to an individual viewer, e.g., interocular baseline adjustment or depth range remapping. Also, this representation is more compressible, an important property when streaming. On the other hand, computational cost for the display system increases, and the required inpainting at object borders and less-than-perfect depth maps may produce errors that the producers cannot remove in advance.

Taking a broader view, many other 3D representations exist which can be classified as a continuum between the two bounds of image-based vs. model-based forms (Table 18.2 and Figure 17.1).

One end consists of purely image-based approaches like dynamic light fields [Levoy and Hanrahan 96, Buehler et al. 01] or multi-view video, which do not use geometry at all and typically require many cameras for dynamic scenes. The other end is represented by approaches that use the full 3D information of a scene, e.g., by reconstructing 3D models from multi-view footage or by creating them manually by modeling and animation. In between are representations that borrow from both sides. Classical two-view S3D is sparsely image-based and borders on depth-based systems, with one-view plus depth[4] on the other side of that border [Fehn 03]. Layered depth videos are still fronto-parallel [Zitnick et al. 04], while oriented billboards [Kilner et al. 06] can already be seen as very coarse 3D video textures [Schödl et al. 00].

Different 3D representations imply different advantages and disadvantages to content producers, as shown in Table 18.3. Once chosen, the type of data is decisive for the design of the entire processing pipeline: It constrains acquisition systems and post-production algorithms, and determines rendering algorithms and view synthesis range.

As a general guideline, reconstruction costs (both computational and in terms of manual post-production refinement) are lowest for image-based systems and highest for model-based ones; conversely, the data storage and transmission demands are highest for images and lowest for models.

[4]known as depth image based rendering (DIBR)

Table 18.3: Different 3D representations imply different reconstruction efforts and amounts of data.

	Image-based	Depth-based	Model-based
Capture	Many cameras Dense sampling	Few cameras	No cameras for manual modeling or many cameras for reconstruction
Reconstruction	No effort	Depth estimation error-prone	Manual modeling labor-intensive Full 3D reconstruction error-prone, high effort for perfect results
Model insertion	Difficult	Simple if depth estimate accurate	Trivial
Coding	High bitrate, depends on number of views	Medium bitrate	Comparably low bitrate, very efficient compression possible
Rendering	Light field rendering or view interpolation, closest to footage	Depth-supported view interpolation, typically close to footage	Classical computer graphics, close to footage when rendering with high resources
Field of view	Narrow, view interpolation only	Narrow, limited extrapolation possible	Full freedom of viewing angle

Content producers must consider both filming and post-production effort, and it seems that two-view S3D movies are currently the most cost-efficient.

18.6 S3D Video Production from Real-World Data

In the 1950s, still in the analog film world, high-quality S3D production was arduous. Analog film from two cameras with limited synchronization caused errors through lens and sensor abberations; analog frames could only barely be color-calibrated by chemical means; and inserting models in post-production was only possible with physical layering, making the inclusion of temporally coherent 3D models very demanding.

Today, stereoscopic capture still suffers from lens/sensor abberations, caused, e.g., by the beam-splitting mirror in two-camera stereo rigs; lens distortion, sensor miscalibration, and inter-camera positioning errors are still present, though to a lesser degree. However, correcting these errors is much easier with digital footage. Typically in the first phase of post-production, artists remove errors with the help of commercial tools, including lens undistortion, color balancing, and vertical disparity removal, before performing depth estimation wherever needed. Because an estimated depth map is often not perfect, manual corrections are necessary and usually represent considerable effort. Alternatively, in 2D-to-3D conversion cases, a depth map may be produced manually from rotoscoping and depth map painting, possibly aided by semi-automatic approaches [Wang et al. 11c].

Depth itself is a dimension that can be edited to enhance the viewing experience as well as the narrative. Artists can use a stereoscopic analyzer like the one contained within TheFoundry Ocula[5] to visualize the depth distribution over a captured shot, and provide corrections if depth parameters get out of the S3D comfort zone (Figure 18.4); in cases where too much disparity would induce viewer discomfort, the cameras can be moved closer through disparity scaling. Capture-time stereoscopic analyzers for use with cameras also exist [Zilly et al. 10].

Another basic correction known as shift convergence adjusts the screen plane, initially determined by inter-camera positioning and their convergence. In post-production, the scene can be shifted forward or backward relative to the screen by shifting the left and right images toward or away from each other [Stelmach et al. 03]. However at the border of the images this leads to disocclusions, which can be circumvented by using bigger sensors capturing more pixels than actually needed on screen, or by cropping or inpainting.

Non-linear depth remapping is another tool-supported technique used to enhance storytelling [Lang et al. 10], e.g., for deep landscapes or to express the relative importance of actors, objects, and motions. For example, in one scene of the movie "Gravity",[6] the main character reaches out of the screen for a crucial handbook which is just floating away. Her arm has been depth-remapped to more than twice the length it could plausibly have, in order to emphasize the criticality of the moment.

A typical production can also feature the insertion of 3D models, be it actors, objects, or environmental effects like fog or fire. The amount

[5]TheFoundry Ocula – http://www.thefoundry.co.uk/products/ocula/
[6]Gravity movie – http://www.imdb.com/title/tt1454468/

of computer-generated graphics with respect to real-world footage is very flexible: Typical cases involve green-screen filmed actors being combined with completely modeled surroundings and effects, or real-world footage being enhanced by virtual objects.

All these depth-based frame editing steps have in common that the depth maps must be of high quality, otherwise depth abberations, damaged textures, and object boundaries must be repaired frame-by-frame in image space in another post-processing step. A typical approach is to fix depth map errors by manual depth map painting, where segmentation from rotoscoping can be re-used as well. This production step is labor-intensive and can generate substantial costs.

Alternatively, the depth can also be estimated and corrected interactively [Ruhl et al. 13], as described in the following. In this approach, initial depth estimation is based on fast cost volume filtering [Rhemann et al. 11], a real-time capable method to estimate depth from a stereo image pair. Given left and right views $I_l(\mathbf{x})$ and $I_r(\mathbf{x})$ with pixel coordinates $\mathbf{x} = (x, y) \in \Omega$ and RGB color values in the range $[0, 1]$, the method aims to attain for each $\mathbf{x}$ an optimal depth $Z_l(\mathbf{x}) \in [d_{\min}, d_{\max}]$, discretized to labels $d \in D = \{d_{\min}, .., d_{\max}\}$ from a set D of depth values.

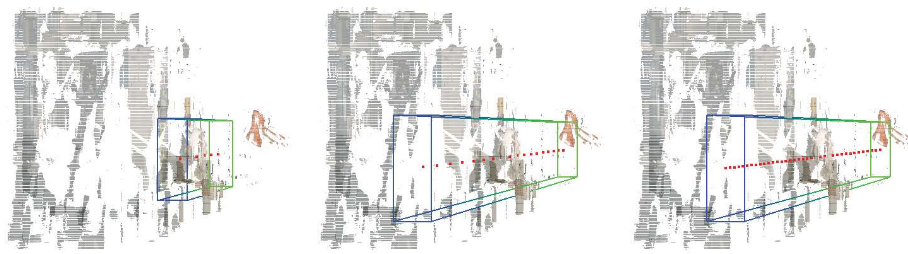
Toward this purpose, a 3-dimensional cost volume $C_l(\mathbf{x}, d)$ for one (e.g., the left) view I_l is constructed. The first two dimensions of C_l are the image size, and the third dimension constitutes the number of depth labels. Each entry within the cost volume is initially a truncated sum of absolute differences (SAD) between the views, using a projection $\pi(\mathbf{x}, d)$ from left to right view based on epipolar geometry from standard calibration [Snavely et al. 06] instead of using disparity.

$$\begin{aligned} C_l(\mathbf{x}, d) = \quad & (1-\alpha)\cdot \quad \min(\tau_1, ||I_l(\mathbf{x})) - I_r(\pi(\mathbf{x}, d))||) \\ + \quad & \alpha\cdot \quad \min(\tau_2, \|\nabla I_l(\mathbf{x})) - \nabla I_r(\pi(\mathbf{x}, d))\|) \end{aligned} \tag{18.1}$$

A value of $\alpha = 0.11$ is used to favor the color term over the gradient term and $\tau_1 = 0.03$ and $\tau_2 = 0.008$ to favor only very exact matches. With the data term set, the next step is to perform a weighted filtering on C_l to arrive at a smoothed cost volume C_l':

$$C_l'(\mathbf{x}, d) = \sum_{\mathbf{x}' \in N_r(\mathbf{x})} W_{\mathbf{x},\mathbf{x}'}(I_l(\mathbf{x}')) \cdot C_l(\mathbf{x}', d) \tag{18.2}$$

The filter weights $W_{\mathbf{x},\mathbf{x}'}$ depend on the guidance image I_l [He et al. 10] similar in spirit to the anisotropic smoothness found in many variational approaches, and are computed on pairs of pixels $(\mathbf{x}, \mathbf{x}')$ in a neighborhood N_r within a filter radius r. Cost filtering is performed on each depth layer, but not between depth layers since there is no guide in the depth direction available.



(a) (b) (c)

Figure 18.5: Cost block within the initial cost volume, visualized as green-blue bounding box; z-layers are shown as red dots in the center. (a) Cost block with a default size in z-direction; (b) the user has increased the z-extent of the cost block; (c) the user has increased the number of z-labels within the cost block.

Runtime is independent of filter radius r (9–24 are sensible radii, depending on image size) when using weighted box filters based on summed area tables, instead of evaluating the weights naively. The OpenCL implementation of [Ruhl et al. 13] uses a tile-based sliding-window variant which works in $O(n)$ on the GPU [Hosni et al. 11a]. Finally, the depth map Z_l is chosen by seeking the depth label with minimal cost per pixel:

$$Z_l(\mathbf{x}) = \arg\min_d C'_l(\mathbf{x}, d) \tag{18.3}$$

Since the results of any stereo algorithm are not perfect, errors cannot be avoided completely particularly on challenging natural scenes which tend to produce artifacts, among them:

Occluded regions. Objects that are occluded differently in the two views can lose significant overlap, preventing unambiguous matching. In a typical stereo configuration, this happens prominently for any object's left and right edges, which are each only visible in one camera. The closer the object is to the camera, the more pronounced the effect becomes. Automated algorithms cannot avoid this error since the information is simply not available; symmetric estimation is at least able to identify occluded regions, but inpainting is still largely heuristic. A human user, on the other hand, is able to provide plausible depth information for those non-visible parts by intuition about the object's shape.

Ill-textured regions. The majority of stereo algorithms for natural scenes (as opposed to controlled lab settings) rely on the color constancy assumption, which may be violated by lighting or camera sensor differences, noise, specular reflectance, translucent objects, caustics, etc. This impedes the matching of objects between both views. Largely uniform or repeating regions in conjunction with different occlusion boundaries in the two views (e.g., columned halls, gratings) are also not solvable with the available information. Again, a human user can assess which objects belong together, and thus distinguish between true and false matches.

The question now is how to integrate human scene understanding in a way that minimizes interaction times. Currently, the most common way is to use image editing tools to select a region via rotoscoping or segmentation, and then use stamp, cloning, and other tools to assign better depth labels.[7] The approach by [Ruhl et al. 13] also starts with a segmentation/mask in 2D image space, but instead of cloning without validation of the resulting depth, a possible range in z-direction is assigned, forming a 3-dimensional "cost block" $K_l \subseteq C_l$ (Figure 18.5). In the first two dimensions, the cost block is a bounding box around the masked or selected pixels and restricts $\mathbf{x}$ to come from $\Omega' \subseteq \Omega$. In the third dimension, the cost block is centered around the median depth of the selection $med(Z_l(\mathbf{x}'))$ with $\mathbf{x}' \in \Omega'$ to expunge outliers (other strategies are also possible) and has some extent that restricts d to come from $D' \subseteq D$. The initial extent in z-direction can either be a fixed parameter or some percentile of $Z_l(\mathbf{x}')$.

In a 3D view of the scene (Figure 18.5), both the current depth estimate and the cost block K_l are visualized. An artist can now shift the cost block along the z-axis until the estimation "snaps" the depth to the most plausible position. With each editing step, $Z_l(\mathbf{x}')$ is locally re-evaluated for all pixels in the mask, providing visual feedback in real-time. The z-extent of the cost block can be widened if objects in the selected area do not fit into it, or narrowed to eliminate superfluous estimates. As a third option, the depth label subset D' can be subdivided to include more depth labels, even to the point where $|D'| > |D|$. This increases the accuracy of z-values but takes longer to compute when the cost block is large.

Using cost blocks does not solve the problem of ill-defined regions in a mathematical sense. Instead, it merely reduces the effect of incorrect cost computation: In a narrowed set of labels d', the cost block $K_l(\mathbf{x}', d')$ merely evaluates to a more plausible depth $Z_l(\mathbf{x}')$, since a search window $I_l(\mathbf{x}')$ has a much lower probability of being matched to a randomly low-cost window $I_r(\pi(\mathbf{x}', d'))$. In the worst case when no support information can be found within filter radius r, the final depth Z_l will be essentially random, but still within the bounds of D'. If implausible, an artist can still narrow down the z-extent of K_l to a thin slice.

In essence, the user interaction cuts away large superfluous blocks from the cost volume, rather than refining the stereo matching itself. Due to

[7] http://www.fxguide.com/featured/art-of-stereo-conversion-2d-to-3d-2012/

Table 18.4: S3D coding standards will facilitate wider adoption of S3D content.

Format/Standard	Properties
Frame compatible coding	Works on existing 2D infrastructure 50% loss of resolution Not a standard
Blu-Ray 3D	Stereo high MVC profile Uses both temporal/inter-view redundancy Backwards compatible to H.264/AVC Standard since 2009
HEVC	Uses both temporal/inter-view redundancy Successor to H.264/MPEG-4 AVC Upcoming standard

the snapping behavior, artists can save considerable effort during depth map correction, and still switch back to depth map painting in case of any remaining failure cases. In the end, a high-quality depth map is available for all further stages of the S3D production and presentation pipeline.

18.7 S3D Delivery

For any type of data delivery, efficient coding and transmission is crucial, most noticeably when streaming individually (and less so when pre-loaded as in a movie theater setting). In order to achieve wide adoption, coding standards are necessary for S3D [Smolic et al. 09], complementing standards such as MPEG or VCEG (H.26x) for 2D movies. A number of coding format standards already exist for some of the 3D representations introduced in Section 18.5, where "representation" determines the format of the data and "coding" refers to the efficient compression of this data. Table 18.4 outlines a selection of current and future formats and standards.

One of the simplest coding formats regarding S3D is frame-compatible coding, whose principle is to embed a S3D stream side-by-side into a 2D stream [Vetro et al. 11]. As input, it takes a two-view stereo video and downsamples each frame by half (either vertically or horizontally). It then combines them back into a single-stream video of the same size as a single-view one, which can then be transmitted and decoded on existing broadcast infrastructure. Because of its simplicity, this approach was used in the first S3D broadcast channels, since only high-level syntax at the receiver is needed to separate the two streams and upsample them again for rendering. However, the loss in resolution is as noticeable as in interleaved 2D video, and is being considered as one of the reasons for the limited success of S3D on home television so far. TV production cost is another factor.

More recent S3D or multi-view video (MVV) approaches encode the full pixel resolution, and exploit spatial (inter-view) as well as temporal (inter-frame) redundancy for efficient compression. Classic 2D video coding makes use of temporal redundancies, i.e., not all pixels will change in neighboring frames, and many movements are regular and can thus be predicted for some number of frames. In S3D video, subsequent frames are not only related temporally but also spatially: Barring occlusion and reflectance effects, objects at the screen plane (same depth) show the same appearance, and objects in front or behind are horizontally shifted [Vetro et al. 11].

Where 2D video uses motion estimation and compensation, S3D allows for additional inter-view disparity estimation and compensation, as e.g., proposed for the 3D-Blu-Ray specification, where the second view typically adds 25-50% bitrate to the first one. Another example is the upcoming HEVC standard, which also features temporal/inter-view prediction [Müller et al. 13].

18.8 Summary

S3D video has come a long way, with a mature production/presentation pipeline and commercially successful products available today. A professional S3D movie ameliorates any adverse side-effects on the human visual system to induce a pleasent viewing experience. While an entire continuum of 3D scene representations exists, efficient hardware, tools, and processes from capture to encoding are most prevalent for two-view S3D videos enhanced by manual modeling. Other approaches are more experimental and do not have cost-effective target hardware at the current time, but are sometimes used for special effects. The perfect theoretical S3D experience featuring full view and focus flexibility is yet to be achieved.

19
Visual Quality Assessment

Holly Rushmeier

19.1 Introduction

The ultimate success of real-world visual computing applications depends on how it is perceived by its users. Integrating an understanding of visual perception into modeling systems and evaluating visual quality of rendered output have always been an essential part of computer graphics research. An example of this from the 1970s is Phong's seminal presentation of a then new reflectance model that used observation of real object highlights as motivation, and a real photograph of a sphere as validation [Phong 75]. Systematic user studies to evaluate and refine methods began to appear in the 1980s, such as Atherton and Caporeal's study of the discretization and shading of curved surfaces [Atherton and Caporael 85].

Visual quality assessment methods build on models from the extensive literature on human visual perception that have been published over more than a century. Perceptual experiments that addressed engineering applications involving human–computer interaction have resulted in useful compendiums of individual models that computer graphics researchers and practitioners can draw on [Boff et al. 88]. For many applications, however, existing human visual models are not yet adequate to address the perceptual questions of computer graphics. There is still a need in many cases to run human subject experiments [Ferwerda 08].

Methods and techniques from the study of human vision are applied both to the development of individual components of visual computing and the development of full systems. Visual assessment determines the accuracy that is needed for geometric reconstruction (Chapter 10) and motion reconstruction (Chapter 11). Visual measures are needed to determine the accuracy of illumination simulations that are used to render the reconstructed geometry and motion (Chapter 6). Alternative assessment techniques are needed for image-based rendering systems (Chapter 17). Image-based rendering systems use natural images to leverage nature's solution to part of the modeling and simulation of a new scene, but may introduce artifacts in the warping and re-sampling processes required to generate new images.

Visual quality assessment for real-world visual computing is problematic because artifacts can arise as the result of individual choices in building a system. To tackle these complex system challenges, traditional models and experiments are gradually being replaced by new tools, new concepts of what aspect of perception is to be measured, the use of crowd sourcing, and the use of new instrumentation.

In this chapter resources are given for perceptual modeling and experimentation that computer graphics researchers can draw on. Examples are given of how visual quality assessment techniques have been applied in illumination simulation, geometric modeling, motion simulation and image-based rendering. Finally, innovative approaches developed in computer graphics for quality assessment are discussed.

19.2 Models from Human Perception

The existing literature in human visual perception is used in two ways in computer graphics. First, computational models of individual aspects of perception are adapted from the biological vision literature to inform algorithms. Second, experimental techniques for studying perception in human subjects are applied to problems that uniquely arise in computer graphics. Human subject experiments are used both to explore new aspects of perception for which models are needed in graphics systems, and to evaluate final rendered results from complex systems.

Computational models used in the design of graphics systems have been drawn from basic models of human vision that were originally developed for printing, photography, and television. Most prominently, graphics has used models of color perception. Radiometry and color have already been discussed in the context of camera systems in Chapter 1. Real-world systems scatter light at wavelengths in the visible spectrum of electromagnetic radiation that ranges from 400 nm to 700 nm. The accuracy needed in spectral values is dictated by human perception of color. Human sensitivity to spectral variation is limited by the response of the eye's cones (at normal daylight conditions) and rods (under low light conditions). Formulae for the conversion of spectral distributions to standard color spaces was developed by researchers in the color and illumination fields in the early twentieth century. Different spectra but with the same coordinates in a standard space (such as the CIE XYZ space) appear identical to humans. In addition to this fundamental insight, there are numerous other models of color appearance that have been and could further be exploited such as color constancy and the change in hue with luminance. Fairchild describes these various effects as well as comprehensive models to characterize color appearance [Fairchild 13].

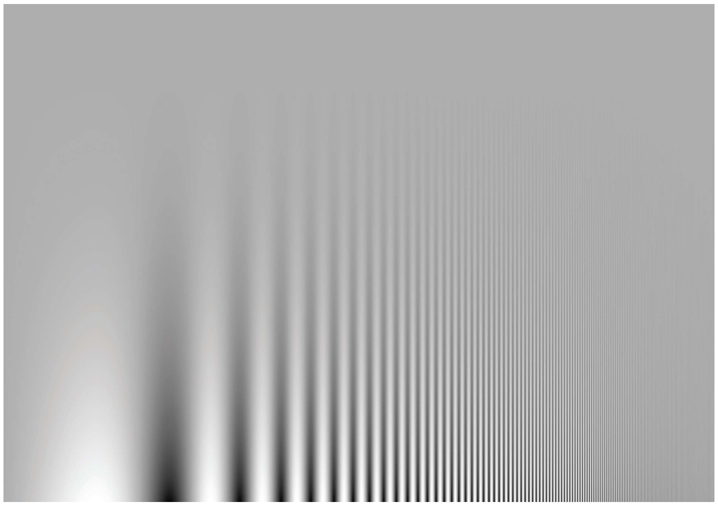


Figure 19.1: The contrast sensitivity function for human vision is illustrated by a spatial variation in intensity, with spatial frequency increasing on the horizontal axis, and contrast decreasing on the vertical axis. The illustration demonstrates that the visibility of a spatial variation is reduced at both very low and very high spatial frequencies.

In addition to color, another fundamental model that applies across many applications is the human contrast sensitivity function (CSF), illustrated in Figure 19.1. Essentially, human sensitivity to contrast is a function of the spatial frequency of the variation, with sensitivity peaking at about 5 cycles per visual degree. This set a lower limit graphics as to how spatially accurate renderings have to be. It is also important for understanding how artifacts that are invisible at one viewing distance become visible at another. For example, for a synthetic texture low spatial variations in intensity are not visible when an image is viewed closeup, but become distracting regular patterns when the image is viewed from a distance where the spatial variations increase in frequency per visual degree. Related to the CSF is the spatial masking effect. The presence of a pattern at a particular spatial frequency can mask other patterns at the same frequency. This is used in various ways to hide artifacts that could be computationally expensive to avoid [Ferwerda et al. 97].

The assessment of overall quality is a long-standing issue in photography and video, and numerous metrics have been developed over the years in the optics, photography, and video communities that combine basic perceptual models. A particularly influential metric in the computer graphics community has been daly's visible difference predictor [Daly 93]. Daly's model combines models of human sensitivity to luminance, contrast sensitivity, and masking to predict the perceivable differences in two images. This model has been used to drive iterative rendering methods [Myszkowski 98] and has served as a model for constructing image-level metrics from low-level vision models.

19.3 Experimental Techniques from Human Perception

Well-established techniques have been developed for running experiments to draw valid conclusions with respect to individual human perception phenomena. An overview of experimental methods and analysis for computer graphics have been summarized by Ferwerda [Ferwerda 08]. Different techniques are needed depending on whether threshold (just noticeable effects) or super-threshold (scaling effects) problems are being studied.

The fundamental techniques still in use today were developed in the nineteenth century. Gustav Fechner (1801–1887) described three ways to approach threshold effects. One, the method of adjustment, asks users to adjust a test display until it matches a standard. A second, the method of limits, displays pairs—a standard and a test. The test display is adjusted to approach the standard, and the user's comparison of the two, in the form of "is the test more or lest *foo* than the standard" (where *foo* is the effect being tested) is recorded. In the third, the method of constant stimuli, random test displays are shown along with the standard and the user's responses are recorded. Each approach has its inherent limitations and requires some different analysis. Super-threshold (scaling) effects can also be measured by various techniques including indirect rating, pair comparison, ranking and category scaling, as well as direct scaling. These methods range from asking directly for a rating of an impression (on, say, a scale of 0 to 100), to making multiple pairwise comparisons and using Louis Thurstone's (1887–1955) "law of comparative judgment" to derive a scale.

In general, before setting up a study, an investigator should either consult an experimental psychologist, or should carefully read the descriptions of many previous studies. The *ACM Transactions on Applied Perception* is an excellent source for descriptions of previous work, since it is particularly oriented to obtaining results that can be applied to computing. An investigator needs to pay attention to the controlled conditions and materials used, conducting the experiment with a protocol and ordering that prevents bias, and appropriate statistical analysis of the results. Controlled conditions require that calibrated display equipment is used. The experimental protocol typically includes randomized ordering of tests for the various subjects to avoid bias.

In the area of statistical analysis of human subject studies, a frequently misunderstood point is the number of subjects required by a study. As a rule of thumb, the study of very low-level effects, such as contrast perception for a sinosoidal display, require a small number of subjects. Higher level effects, such as color preferences, require larger numbers of subjects. The rationale for these numbers is that significant low-level effects are the same across the human population, and if they are found consistently for a small number of observers, they can be expected to be found for the general population. For higher level effects there is no magic number that is "enough" or typical. The adequacy of the number of subjects is indicated by the statistical significance computed for the results.

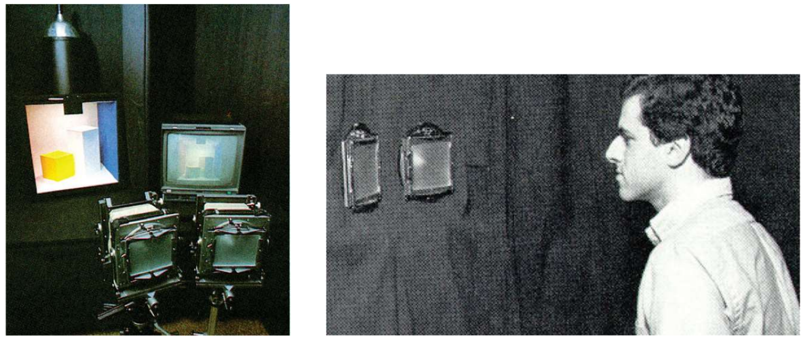
There is synergy between computer graphics and research in human perception. Computer graphics has made possible controlled conditions for investigating various types of perceptual phenomena. One result of this synergy is that a computational tool box has been developed for psychophysical experiments [Brainard 97]. This MATLAB toolbox[1] and lower level code is a long-term stable resource that offers many practical features for the mechanics of setting up an experiment.

Even simple experiments that ask observers to look at pictures and hit a button to respond are human subject experiments. Different procedures for being permitted to do such experiments apply in different countries. In the United States, it is typical that an experimental protocol that documents the measures to ensure subjects' safety and privacy must be submitted to an institutional review board (IRB) before the experiment can be conducted.

19.4 Evaluation in Lighting and Material Modeling

Perceptual methods have been used to extensively evaluate the accuracy of global illumination techniques. An early example is the Cornell box experiment conducted to evaluate radiosity solutions and color calculations [Meyer et al. 86]. The set up for this experiment is shown in Figure 19.2. Rather than establishing a scale or threshold, this work was concerned with whether an observer could reliably discern a simulation from a natural image of a simple scene. The experimental design was the classic "two alternative forced choice." Presented with two images, the observer was forced to make a selection of which was the simulated image. Obvious cues were eliminated by having the observer view both the 3D scene and the image on a display through view cameras. Observers choosing the simulation over the original approximately fifty percent of the time, the same as guessing, indicated the success of the simulation.

[1] ttp://psyctoolbox.org/



(a) (b)

Figure 19.2: The Cornell box experiment was conducted to evaluate global illumination solution techniques. In (a) a real scene and its visual simulation are shown. Human subjects saw the real and simulated scenes through view cameras, as shown in (b). The use of the view cameras made it possible to obscure the obvious cues that indicated which was the real scene. Images from [Meyer et al. 86].

A more extensive dataset for evaluation was provided by Myszkowski et al. in "the Atrium study" [Drago and Myszkowski 01]. Both the Cornell box and Atrium used side-by-side comparisons and were focused on evaluating the ability of particular global illumination techniques in reproducing a natural image. An alternative approach is task-oriented evaluation of real and synthetic scenes introduced by McNamara et al. [McNamara et al. 00]. In a task-oriented evaluation, a user is asked to do the same task in physical and simulated environments. The goal is to find whether the user makes the same choices, whether correct or incorrect, in both the physical and simulated environments.

Local illumination models describe how individual materials scatter light. Perceptual studies to inform local models include a perceptual space for gloss [Pellacini et al. 00] and more recent studies of perceptual material evaluation [Fleming 14]. Pellacini et al. were able to establish a low dimensional gloss space by means of a scaling experiment where observers used sliders to indicate the magnitude of gloss difference between two renderings of a sphere on a checkerboard [Pellacini et al. 00]. Defining and parameterizing a perceptual space for more general scattering properties has proved more difficult because of the high dimensionality of the space and the infeasibility of asking observers to do the required very high number of comparisons. Furthermore, Fleming's more recent work suggests that humans don't recognize materials by estimating the parameters of scattering models. He suggests that human perception works with "statistical

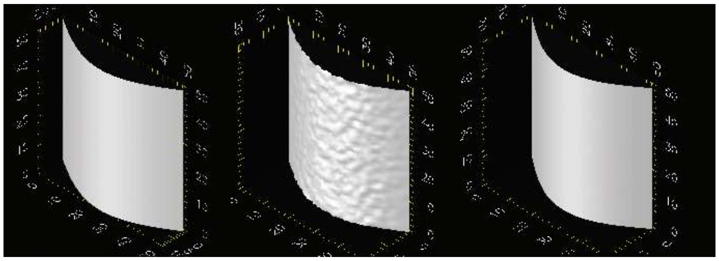


Figure 19.3: Positional accuracy in geometry is not necessarily equivalent to visual accuracy. On the left is a reference surface. The center surface is a vertex-by-vertex more accurate approximation of the reference surface than the surface on the right. However, the distribution of positional errors on the center surface introduce objectionable visual artifacts that are not visible on the right.

appearance models." Understanding what image appearance features are important in judging different classes of materials, and relating modeling parameters to the formation of these features will require much more experimental investigation.

Even if narrowing from the general problem of material appearance to the specific instance of rendering faces, there is still much more experimental work to be done. Fan et al. asked observers to classify each face in a collection of natural and computer generated images whether they were photographs of actual people, or simulations [Fan et al. 12]. In analyzing the results, Fan et al. found variability in the influence of fundamental rendering components such as color, small-scale geometric detail, and gloss. The study demonstrates that there are subtle interacting effects in modeling reflectance, geometry, and illumination that affect the perception of faces that are not yet well understood.

19.5 Geometric Modeling

Following Atherton and Caporeal's model study of geometric representation [Atherton and Caporael 85], studies have been performed to understand the requirements for modeling shape for realistic rendering. As shown in Figure 19.3, higher local positional accuracy doesn't necessarily produce visually more desirable results. Representations that introduce or remove salient, i.e., attention drawing, features are both objectionable.

Real-time rendering typically uses triangle meshes because of their compatibility with the hardware rendering pipeline. The 1990s and early 2000s saw a large volume of work on different techniques for mesh simplification to increase rendering efficiency, and this motivated the need for measuring mesh quality. Innovative work by Watson et al. used "naming time" to study simplification methods [Watson et al. 00]. Instead of comparing side-by-side renderings, model quality was judged by how long it took observers to name the object being represented. "Naming time" is a useful measure in that it does not require the user to compare directly to some "ideal" rendering of a model. In another alternative to side-by-side comparisons, Howlett et al. used gaze tracking to understand the saliency of mesh features, and the effect of simplification of more salient features [Howlett et al. 05]. Subsequently Kim et al. used eye tracking to evaluate various computational models of mesh salience [Kim et al. 10].

Finally, material properties and lighting both affect shape perception [Ferwerda et al. 04], meaning that errors in materials and geometric representations are related.

19.6 Motion

Perception has been used to understand acceptable limits in motion simulation and its presentation. It is well known that humans are sensitive to motion, and that simple animations showing bright dots moving can convey ideas such as a human walking [Hodgins et al. 98]. Since fully realized animation is expensive to compute, previewing a motion sequence in simplified form is desirable. However, in an early paper on human animation and perception Hodgins et al. presented human subject experiments that showed that people are able to detect more subtle variations in motion with full polygonal models [Hodgins et al. 98]. Doing side-by-side comparisons is even more difficult for animations than for static images. Experiments need to be designed so that they don't require too many judgments at a time and don't require judgments that are difficult for the experimenter to convey. In Hodgins et al.'s work the observers were asked to compare the motions of figures rendered with the same geometric models and to assess when they were able to detect subtle differences in motion. In later work in the same area, Hodgins, working with colleagues in neuroscience, found that there is a relationship between the perceived realism or naturalness of character motion and a character's anthropomorphism [Chaminade et al. 07].

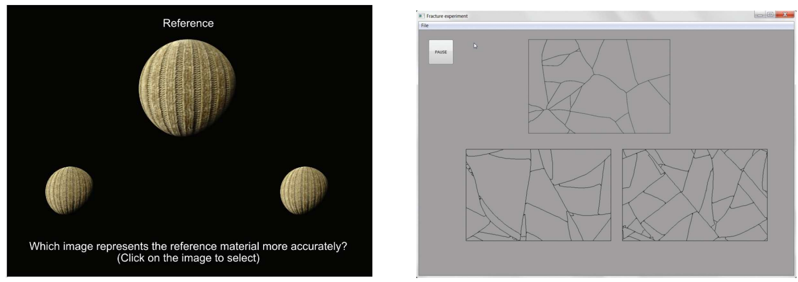
The perception of individual character motion is different from the perception of motion in crowds. From practical industrial experience, realistic large crowd animation does not require every character to be distinct. Instancing is a heavily used technique to reduce computational expense. McDonnell et al. studied the visibility of instanced characters, or clones, in a crowd [McDonnell et al. 08]. The technique used was to present observers with sets of characters that were either appearance clones (i.e., same shape and clothing) or motion clones (walking with the same gait). The time for observers to spot the clones was recorded. It was found that motion clones were much harder to detect than appearance clones.

While humans are very sensitive to nuances in human and character motion, they can also detect errors in the physical motion of inanimate objects. O'Sullivan and Dingliana studied human sensitivity to the accuracy of collisions of simple objects [O'Sullivan and Dingliana 01]. In this work, observers were asked to make judgments about collisions between spheres. For example, they were shown collisions where varying gaps were left between the spheres rather than showing the spheres actually touching during the collisions. The observers were asked whether the spheres had touched during the collision. The result that the observers reported the spheres touching in cases where there was actually a gap suggested a level of detail algorithm for detecting collisions that allowed for error that would not be detected visually [O'Sullivan and Dingliana 01].

19.7 Image-Based Systems

Image-based systems rely on natural images for many component elements to be correct (Chapter 17). However, the source input images frequently need to be warped and resampled to generate new images. Techniques are needed to see if the operations on the images introduce visual artifacts.

An example of the evaluation of an image-based rendering system is the study by Vangorp et al. of perspective distortions in a virtual tour along city streets [Vangorp et al. 13]. The study outlined a model for how virtual tours are created. Multiple images of building facades are captured as a vehicle moves down a street. The images form a panorama which is then displayed for arbitrary views along the route by projecting the images onto planar proxies for each of the buildings. The problem is that if images aren't captured closely enough, the projected images will look obviously incorrect, with corners of buildings that should have faces meeting at 90 degrees making the distortions most obvious. The experimental procedure used had observers indicate their estimate of the angle of corners presented to them by adjusting the relative orientations of two boards on a hinge, rather than asking the observers to give a number. This allowed the observers to report their judgments more directly. The result of the study was a recommendation for how closely images needed to be captured given a particular depth variation for buildings along the street.



(a) (b)

Figure 19.4: Examples of tests for visual equivalence. In (a) filtering techniques for bidirectional textures are tested for the visual equivalence of filtered and downsized images of an object covered by a complex material (image from [Jarabo et al. 14]). In (b) the visual equivalence of crack patterns are tested relative to a reference standard (image from [Glondu et al. 12]).

19.8 Beyond Classic Models and Experimental Techniques

Approaches for modeling and evaluation have in many ways moved past traditional perceptual models and psychophysical experiments. New ideas for visual assessment that have emerged in computer graphics include no-reference metrics, visual equivalence, crowd sourcing, and novel measurement techniques.

In general, the ideal image or animation is not available or is too expensive to compute. An assessment method that doesn't rely on a comparison is desirable. The idea of "no reference" metrics addresses this issue. For assessing the quality of a rendering given reliable geometric, material, and motion representations, a no-reference metric was developed by Herzog et al. [Herzog et al. 12]. The metric is built using machine learning on a database of good and bad renderings. The quality of the rendering is learned as a function of the data that a rendering algorithm has easily available—depth information and diffuse textures.

Taking the full problem of determining the quality of input representation and accuracy needed of the rendering technique, an important issue is that accuracy does not mean pixel-by-pixel equivalence to the "perfect image." It is a rare, and perhaps never occurring case, that images are needed that are pixel-perfect. Instead, what is needed is a picture that represents the same thing, made of the same stuff, in the same environment. Ramanarayanan referred to this type of similarity as "visual equivalence" [Ramanarayanan et al. 07]. For example, from work by Jarabo et al. [Jarabo et al. 14], an object covered by material rendered at two different spatial scales is shown in Figure 19.4(a). The method for filtering the material texture is being tested. It is not expected that the images are pixel-identical because they are at different scales. It is necessary, however, that a successful filtering technique produces an image that appears to be the same object made of the same material—that is, that they are visually equivalent. Another example, from Glondu et al. is shown in Figure 19.4(b) [Glondu et al. 12]. In this example, it is desired to create a material that has been cracked the same as an exemplar. An experiment was conducted to ask observers whether the cracks on the left or right looked like they were from the same process on the same material—that is, whether they were visually equivalent. In this second case, statistics were obtained to characterize when patterns were visually equivalent, and this was used to drive a simulation to create virtual materials that appeared to be equivalent to an example from a natural photograph.

A "weak link" in most perceptual experiments is that observers have to give an active response—verbalizing a response or hitting a button. Recent work has exploited alternative, passive techniques for measuring response. Lindeman et al. used electroencephalograph (EEG) [Lindemann et al. 11] to measure an observer's response to artifacts in image-based rendering. Advances in hardware that have made EEG economically accessible, and in signal processing techniques to deal with the noise in the EEG signal have made this a viable technique. Mustafa et al. demonstrated that certain types of video artifacts can produce consistent EEG responses [Mustafa et al. 12].

Another problematic issue in conducting experiments is recruiting an adequate number of diverse observers. For some cases crowd sourcing is a viable approach [Heer and Bostock 10]. Heer and Bostock found that for some basic perceptual experiments crowd sourcing produced the same results as controlled experiments. They hypothesized that the larger number of subjects that are possible in a crowd-sourced experiment offsets the lack of control in experimental conditions. In a sense, with a large group the diverse conditions are "averaged out" by the large number.

19.9 Summary

There is a long history of using perceptual insights and human subject experiments to create realistic images and evaluate them. Past work has built a lot on performing experiments in laboratory-controlled conditions, with an emphasis on traditional approaches such as two-alternatives-forced-choice. Recent work has moved beyond this to systems that predict perceptual impact by validated metrics that encompass a wide range of effects, the use of crowd sourcing, and by using systems to gather user responses that do not require active, conscious, user input. The problem, though, of producing and assessing realistic imagery remains challenging because of the non-linear, convoluted interaction of many perceptual effects simultaneously.

Part V

Applications

20
Facial Capture and Animation in Visual Effects

Darren Cosker, Peter Eisert, and Volker Helzle

20.1 Introduction

In recent years, there has been increasing interest in facial animation research from both academia and the entertainment industry. Visual effects and video game companies both want to deliver new audience experiences—whether that is a hyper-realistic human character [Duncan 09] or a fantasy creature driven by a human performer [Duncan 10]. Having more efficient ways of delivering high-quality animation, as well as increasing the visual realism of performances, has motivated a surge of innovative academic and industrial developments.

Central to many of these developments are key technical advances in computer vision and graphics. Of particular note are advances in multi-view stereo reconstruction, facial tracking and motion capture, dense non-rigid registration of meshes, measurement of skin rendering attributes (e.g., BRDFs for skin and skin subsurface scattering models), and sensing technology.

This chapter builds on concepts already described earlier in this book—such as 3D capture, rigging, and non-rigid registration—and takes a more practical look at how they might typically be applied in visual effects. First, methods and applications for facial static capture and rendering are considered, before dynamic capture is addressed. Finally, a case study is examined called *The Gathering* involving the creation of an animated face from animation to final composite.

20.2 Static Facial Realism and Capture

In today's world, static facial realism has reached a level where humans cannot distinguish 3D facial models from real photographs anymore.

Technology such as the Light-Stage [Ma et al. 07] allow the capture of highly detailed facial surface information. Coupled with sub-surface reflectance data [Donner et al. 08] facial models now display photo-realistic likenesses to real faces. Such technology is now widely used in modern motion pictures, e.g., *Spider Man 2* [Fordham 04] being one recent high-profile use of the Light-Stage. In these circumstances, the high-detail static scans are composited onto either a stunt-actor's body, or a digital double. This is where the actor is to be placed in situations that may not be practical or safe (such as explosions). However, it is still the case that the actor's expression is typically static in these situations, and close examination of such shots reveal a dead-like facial quality. An early high-profile example of facial replacement was in the *Matrix* sequels [Borshukov et al. 05], where passive facial scanning was used to obtain 3D faces with high detail facial texture. An important aspect of the use of facial scans for movies and video games is that faces must be renderable in a wide range of environments so that the face can be convincingly composited into the overall scene. Therefore, the UV map (texture data) is typically diffuse albedo. Skin detail is enhanced through high-resolution normal maps [Ma et al. 07] or geometry [Beeler et al. 10], and rendering is enhanced through sophisticated BRDFs/BSSRDFs modeling material properties [Donner and Jensen 06, Jensen et al. 01]. Acquisition of such reflection properties has advanced widely over recent years, resulting in highly detailed rendering [Donner et al. 08].

An important aspect to the realism of synthetic humans is the realistic rendering of hair, which has made significant progress in the last years. Single hair fibers have been modeled [Marschner et al. 03] as semi-transparent elliptical cylinders. By defining surface reflection as well as scattering inside the hair, the complex lighting characteristics of real hair with its view dependency, highlights, and color changes can be accurately reproduced with moderate rendering complexity [Ren et al. 10]. The possibilities to model several fibers up to a complete hairstyle range from NURBS surfaces via thin shell volumes to strain-based modeling by parameterized clusters, fluid flow, or vector and motion fields [Ward et al. 07]. In order to simulate the complex lighting interaction between strands of hair, Lokovich et al. [Lokovic and Veach 00] propose a deep shadow map which relates visibility to depth for each pixel, yielding realistic but computationally expensive self-shadowing. Approximation algorithms for making the simulation of multiple scattering among hair fibers tractable have been proposed using methods like photon mapping [Moon and Marschner 06b] or spherical harmonics [Moon and Marschner 06a].

Whereas laser scanning technology was initially the most accurate way to derive static facial detail, passive scanning technology using consumer hardware is now popular [Beeler et al. 10, Blumenthal-Barby and Eisert 14]. Multiple consumer-level SLR cameras are used to acquire high-detail images which provide strong features for stereo matching algorithms (Chapter 8), and can result in captures with skin pore (mesoscopic-level) facial details [Beeler et al. 10]. One aspect to consider when using such data is practicality, as the meshes can contain millions of vertices. This is a different approach to those methods currently considered in, for example, movies where low polygonal meshes are used along with high-detail normal maps to display facial meso-structure. There is therefore still a great deal of work to be done on using such technology practically for video games and modern VFX.

Many state-of-the-art stereo and multi-view approaches are local in the sense that they reconstruct the 3D location, and sometimes orientation, of isolated image patches [Furukawa and Ponce 10]. While this strategy is beneficial for parallelization, it requires a post-processing stage to generate a mesh. The reconstruction yields a point cloud with outliers which has to be filtered and meshed with appropriate algorithms (Chapter 10), such as Poisson meshing [Kazhdan et al. 06]. Smoothness priors are often only considered at the meshing stage. Local reconstruction is difficult to combine with efficient interactive tools. As each patch is unaware of its neighbors, the correction of a single mismatched patch by the user will not affect its neighbors, although they are likely to be erroneous as well. Therefore, [Blumenthal-Barby and Eisert 14] follow a similar approach as [Beeler et al. 10] but uses mesh-based deformable image alignment for the reconstruction of high-detail face geometry (including hair) from two or more SLR cameras (Figure 20.1). Instead of iteratively matching small image patches along the epipolar line, an entire view is warped to target views in an uncalibrated framework incorporating a mesh-based deformation model. The additional connectivity information enables the incorporation of surface-dependent smoothness priors and optional user guidance for robust and interactive geometry estimation [Schneider and Eisert 12].

Figure 20.1: Static reconstruction of the head including hair from two images [Blumenthal-Barby and Eisert 14].

Most digital face replacement in movies involves static face replacement, with the actor having little or no movement in facial expression. Although this might be satisfactory for a few frames, as soon as the face moves, or the shot continues for more than a few seconds, this illusion becomes hard to maintain. In the next section, the movement of faces is considered, especially with respect to maintaining an illusion of realism.

20.3 Dynamic Facial Capture and Animation

The holy grail of facial animation research is the portrayal of characters indistinguishable from real humans. This is extremely difficult since humans are experts in detecting the slightest flaws in faces. Even minor defects can break the illusion of realism. In the previous section, static faces are considered where realism has reached a point where it is impossible to distinguish computer graphics from real photographs. However, in order to display a synthetic human that is truly life-like, the movement of the face remains a major challenge.

Arguably, it is easier to convey dynamic realism in the play-back of actual recorded performances than to author a new animation. In order to highlight this, the acquisition of dynamic 3D facial sequences (termed here as 4D for brevity) is first considered.

There are now many commercial companies that market 4D facial capture systems, i.e., those that can obtain 3D mesh data at video recording rate (e.g., Dimensional Imaging,[1] 3DMD[2]). However, the focus here is primarily on academic research in this area. One of the first compelling uses of dynamic facial capture in movies was in the *Matrix* sequels [Borshukov et al. 05]. A passive stereo capture system was constructed where 3D mesh data can be acquired from a face at video rate along with high-resolution texture. The recorded sequences were then composited onto the actors in key action sequences. An extension of this system called *Universal Capture* was later used in several Electronic Arts (EA) promotions and video games (e.g., Tiger Woods Golf [Borshukov et al. 03]). Here, the system was made more robust by adding markers to the actor's face. This could be used to stabilize and track a canonical mesh (i.e., mesh with a known topology) through the captured sequence. Bickel et al. adopt a similar approach with the addition of extra facial paint to appropriately capture wrinkles on the face [Bickel et al. 07].

The use of markers has overcome previous issues related to tracking a face mesh using optical flow. Such methods are notorious to drift, caused

[1] http://www.di3d.com
[2] http://www.3dmd.com

primarily by fast facial changes, for example during speech. Early approaches to avoid the drift in markerless tracking over longer sequences are the incorporation of additional constraints from the silhouette [DeCarlo and Metaxas 00] or the use of an analysis-by-synthesis estimation as in [Eisert 03]. Both methods ensure that estimates are referred to a global reference and avoid error accumulation over time. This approach is also followed by Bradley et al., who propose a multi-view stereo capture system comprising 14 HD cameras mosaiced together [Bradley et al. 10]. This results in a highly detailed set of images upon which to apply optical flow for mesh tracking. Referencing the initial frames of the sequence results in improved mesh stabilization over time. Expanding further on this work, Beeler et al. introduced the concept of anchor frames for stabilizing 4D passive facial capture [Beeler et al. 11]. In this work, neutral frames in the sequences are searched for and then used to essentially reinitialize mesh tracking where possible. This also has the added benefit of offering robustness to certain facial self-occlusions (e.g., as caused by the lips). Although having a lower geometric resolution than previous, passive static capture work [Beeler et al. 10]—which includes approximated skin pore geometry—the extension to 4D including the impressive temporal mesh coherence is a high current benchmark in contemporary facial capture research and development.

One highly successful recent demonstration of the use of 4D capture in industry is from the video game LA Noire.[3] Hundreds of hours of actor footage were recorded in a controlled lighting environment. Key 3D character scenes were then composited with the volumetric facial performances resulting in highly detailed and realistic results. Another high profile use of 3D technology for industrial use was by Alexander et al. [Alexander et al. 10]. The Digital Emily Project was a collaboration between Imagemetrics and USC using Light-Stage technology to capture high detail normal map and surface reflectance properties from an actor's face [Hawkins et al. 07]. A facial blendshape rig was constructed from captured 3D data and then matched to the performance of the actor using proprietary Imagemetrics markerless facial capture technology. Blendshapes are facial poses of different expressions—from stereotypical (happy, sad) to extremely subtle (narrow eyes). The term *rig* is used to describe the complete facial model with all its control parameters. The degrees of freedom of the facial rig are a function of the number and complexity of the blendshapes, and new facial poses are created by combining blendshapes with different weights (Chapter 13). More recently, the Digital Ira Project [von der Pahlen et al. 14] demonstrated how high levels of static and dynamic realism could be animated and rendered in real-time. Thirty high-resolution facial scans were

[3]http://www.rockstargames.com/lanoire

captured using the new Light-Stage X system [Ghosh et al. 11], providing data for a facial rig. Video performance was then captured of an actor and used to animate the facial performance, combined with sophisticated real-time rendering of multiple effects [Jimenez et al. 12].

While the LA Noire production is a high-profile use of 4D capture, it is essentially playback of the recorded data. On the other hand, the Digital Emily and Ira projects demonstrate a degree of performance-driven animation, or retargeting. This type of animation is highly popular in academia and industry, where a performer animates a *puppet* via motion capture or speech (audio only or phonemes). In the case of the both the Digital Emily and Ira projects, the rigs are tracked and animated directly from the actor reference video footage. However, in other cases it is often necessary to retarget between two different rigs one created as a likeness to the actor's face (which is tracked to the input performance) and a second (often a creature or non-human character) animated from output controls of the first rig. In such cases, a rule-based or example-based mapping must be learned between the two rigs. This is a current active area of academic and industry research [Bhat et al. 13]. While it is not the intention of this chapter to give a detailed review of retargeting methods, the excellent course material in [Havaldar et al. 06] encompasses many of the ideas in this area still used today. The aim here is rather to make the distinction between direct playback of captured volumetric animation and the creation of realistic character animation given some reference (e.g., actor performance). However, one important point to make is that even given the best tracking or analysis of a human performer, *automatic* animation of a rig to a level satisfactory for visual effects is still an open problem. Typically, after automatically animating a face in this way, an artist is still required to spend considerable time matching and adding secondary rig movements to the reference performance. In video games, this process can be a hindrance—where hundreds of hours of generated performance may be required for delivery under a short time constraint. In this scenario, a lower level of quality than VFX may therefore be acceptable, as generating VFX quality for current video game productions would add an unrealistic burden on third-party facial animation production or in-house game studios.

The movie *The Curious Case of Benjamin Button* [Duncan 09] contains another successful example of human realistic performance-driven animation and retargeting. MOVA[4] performance capture technology was used to collect 3D scans of Brad Pitt's face and used for blendshape rig construction. Animation was then carried out with the aid of markerless performance mapping from reference footage of the actor. The movie *Avatar* [Duncan 10] also pushed forward the technology of facial

[4]http://www.mova.com

performance capture and retargeting. Although the characters were not human, the movie demonstrated that modern techniques involving motion capture and artistic input could be used for producing large volumes of high-quality performances. The production involved the use of head-mounted cameras, targeted at the actor's face for recording the movements of painted markers. These movements were transferred into a combination of blendshapes per-frame, and the resulting animation used to *block out* an initial animation as a first pass for artists—who later edited and enhanced the performance with the aid of additional video reference (akin to the method previously described earlier in this chapter).

While marker-based motion capture techniques are widely popular e.g., using commercial optical capture systems or painted markers (e.g., Vicon's CARA system[5]), markerless methods provide the potential to capture areas of the face where marker placement is too obtrusive. In addition, it raises the possibility of obtaining a dense capture field for the face, for example based on skin pores. Where the facial rig is based on blendshapes [Havaldar et al. 06], the aim is to optimize a set of weights that approximate the positions of the markers. In marker-less systems, such markers might be located using image-based deformable tracking techniques such as active appearance models [Cootes et al. 98]. Another alternative is to fit the blendshapes to 4D surface data [Weise et al. 09, Valgaerts et al. 12]. This latter method has also been shown to work with consumer 2.5D capture devices such as the Kinect [Weise et al. 11]. However, whether this technology alone can provide the fidelity required for VFX to move beyond optical or marker-based methods remains unclear. It may therefore be sensible in the future to consider a combined approach: markers, high quality RGB, and depth sensors.

In the examples so far, facial dynamics have been captured and replayed, often with considerable artistic manual intervention [Alexander et al. 10]. However, the concept of using such data to author entirely novel performances without reference footage remains a difficult challenge. The success of such methods still largely depends on artistic talent. Advances in interactive facial models, and new methods to create efficient rigs, are promising avenues for improvement. In the last part of this section, some recent advances in blendshape rig construction are briefly considered that could help animators use performance capture data more efficiently and provide better artist tools.

One challenge is how to create effective blendshapes. A standard approach in modern VFX is based on action units (AUs) from the facial action coding system (FACS) [Ekman and Friesen 78], e.g., in *Monsters House* [Havaldar et al. 06] and *Watchmen* [Fordham 09]. Having a FACS

[5]http://www.vicon.com/System/Cara

basis can potentially provide a mapping between different facial rigs. This can be especially useful if one blendshape model is based on actor facial scans and fitted to an actor, and then the weights are transferred onto a puppet model, perhaps of a creature. More recently, Li et al. considered creating blendshape rigs given only a few example expressions and a generic blendshape rig with a wider number of expressions [Li et al. 10]. Such systems can potentially reduce artist time when manually sculpting blendshapes for rigs, and also for reusing existing blendshape models when new rig creating is required. Facial rigs in movies can potentially become very large, with hundreds of blendshapes for *hero rigs*, i.e., rigs required to deliver close-up expressive performances [Fordham 03]. Any technique for increasing efficiency is therefore of high value to industry.

Facial animation bases, or blendshape bases, are also not restricted to artistically sculpted facial expressions or captured 3D scans. Principal component analysis (PCA) also offers a basis for animating faces. However, although this basis is orthogonal—meaning that each expression has a unique solution with respect to the basis—these are often not intuitive enough for artistic animation. In order to address this, Tena et al. [Tena et al. 11] recently proposed a region-based PCA modeling approach that allows more intuitive direct manipulation of local facial regions. Their method also highlights how solving for expression weights locally can provide better approximation of motion capture data. Ultimately however, what an artist will desire of the facial model is a set of controls that are both intuitive and also orthogonal such that altering one expression does not interfere too much with others. To counter this, blendshape rigs become highly complex, with additional shapes (corrective blend shapes) included to counter interference cases. In an ideal world such correctives would not be necessary given the extra work burden they impose, and future work is still required to address this core problem.

Given the discussion of static and dynamic facial capture, the next section considers a case study where facial models based on the likeness of real people were animated and composited onto real footage. This builds on many of the ideas expressed previously in this chapter, and also highlights many of the practical and real-world constraints such a project imposes on animators and technical directors.

20.4 Case Study: The Gathering

The Gathering is a final year short film of Filmakademie Baden-Wuerttemberg.[6] The protagonists in this short film were created digitally

[6]http://www.svendreesbach.com/the-gathering/

based on photo references. The process relied completely on artistic skills since no real reference for 3D scanning or reflectance measurement could be employed. The budget and time constraints of the project demanded to create all assets digitally.

Once the digital models were completed, their facial animation rigs were created by applying the *Adaptable Setup for Performance Driven Facial Animation*[7] [Helzle et al. 04]. This extension for Autodesk Maya[8] enables a rigging artist to apply a generalized library of muscle group movements conforming to the FACS [Ekman and Friesen 78] system to any humanoid geometry. The deformations are driven by a dense data model which includes the non-linear characteristic of facial actions. Compared to static modeling and interpolation of blendshapes, this approach allows for fast and flexible control over the individual facial deformations. The toolset allows complete control in how this data is applied and adjusts to the physiognomies of the geometry. The rigging artist has to manually apply facial landmarks that drive the deformation. The approach has its limitations mainly with respect to the amount and influence of the 69 deformation objects. One way to overcome this limitation was with the use of a limited number of corrective blendshapes, i.e., new blendshapes that trigger other key blendshape combinations to alleviate unwanted or unnatural movements.

Custom extensions to the toolset allow controlling the stickiness of the lips as they part when speaking. This effect is due to moisture on the lips, causing them to open from the inside to the outside as the lips part. Furthermore, the effect of the eyes bulging the upper or lower lids as the gaze changes was realized using a complex constellation of additional deformation rig objects. A fast animation rig allowed quick iterations when animating the sequences and kept the animation artists motivated. All facial animation was realized by rotoscoping the movements recorded from the real actors on set. The head movement could be extracted by rigid body tracking of the markers applied to the actors' heads as shown in the top left of Figure 20.2.

The animated models were rendered using Newteks Lightwave 3D[9] software package. The top right of Figure 20.2 shows the raw rendering which included additional information like motion vectors, reflection and diffuse values embedded inside Open-EXR files, which were provided for compositing. The final compositing was accomplished in The Foundry's Nuke[10] software, integrating the CGI elements into the plates (lower left of Figure 20.2)

[7] http://fat.research.animationsinstitut.de
[8] http://www.autodesk.com/maya
[9] http://www.lightwave3d.com/
[10] http://www.thefoundry.co.uk/nuke/

Figure 20.2: The Gathering: Case study on facial animation. ©Filmakademie Baden-Wuerttemberg, The Gathering, 2011.

before final coloring and additional effects like cigarette smoke were added (lower right of Figure 20.2).

The Gathering shows that it is possible to create convincing digital faces by relying mostly on artistic skills and powerful tools for facial animation. However, it also highlights that the complexities of creating a face and its movements digitally demand a wide set of skills.

20.5 Summary

Capturing real faces with modern technologies like Light-Stage provides 3D face models with high geometric detail and sophisticated material properties that enable face synthesis that is almost indistinguishable from a real picture. While static face models can be used for replacing an actor's face for a few frames, often dynamic face capturing is also desired, which is still a challenging task due to the sensitivity of a human observer for subtle inconsistencies in facial motion. Facial dynamics are usually modeled by a blendshape rig, either from scans, multiview images, or manual work of an artist, while animation data is often derived from marker-based or, more recently, markerless motion capture systems. As shown in the presented case study, convincing digital faces can be animated with such techniques. However, creating realistic facial animations and models still requires significant manual work by artists, leaving room for novel algorithms and toolsets to simplify and automate the process. In terms of research challenges, there is still a large scope for further work in this area. Creating rigs is a time-consuming process, and methods to automate this at production quality are highly desirable. Another core area for future work is in the retargeting of actor faces to new creatures. One challenge in achieving this aim, however, lies perhaps in the contrast between the academic and industrial worlds: academia often has the time to focus on algorithms that could solve this problem while lacking the complex rigs required to test their ideas. Conversely, industry has the expertise to produce such rigs but given practical movie constraints often does not have the time to focus on the algorithms. It is therefore unsurprising that the best advances in this area have been from academic and industrial collaboration.

21
Television and Live Broadcasting

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21.1 Introduction

A popular current use of visual computing in live television broadcasting is in the production of graphics and effects for sports analysis. Applications can help the broadcaster illustrate, analyze, and explain sporting events by the generation of images and graphics that can be incorporated in the broadcast, providing visual support to the commentators and pundits. While currently limited to sport, in the future these techniques might spread to other areas of TV broadcasting, to other genres and for use in other aspects of production. Some broadcasters are already experimenting with free-viewpoint, panoramic, and omni-directional video to see how these technologies might change the traditional methods of live TV production.

This chapter looks at some of the challenges involved in developing visual computing tools for use in television coverage and at the techniques that some example systems have developed to tackle them.

21.2 Sports Graphics

Sports directors often refer to "telling a story" to the viewer and are keen to use the best tools available to bring out the key points in a clear, visually interesting, and succinct way. Graphics are a key tool for the TV program maker to help explain sporting events to viewers. The earliest systems, known as telestrators, allowed the pundit or "color commentator" to draw on top of a still image to illustrate some aspect of their analysis. More modern and advanced systems make use of image- or sensor-based systems to extract information about the scene and generate more detailed analysis or visually impressive graphics.

Examples of current state-of-the art graphical analysis systems which involve aspects of visual computing include tools for drawing offside lines and other contextual information into a soccer pitch for tracking the movement of balls in 3D. Other tools provide new views on the action, such as zooming into the image to provide a close-up or overlaying multiple races or heats (such as in downhill skiing) on top of one another so direct comparisons can be made between them. Virtual views of the action can be generated either to provide a new angle on the action that the broadcast camera didn't offer, or to provide a smooth way of transitioning between two different cameras without jumping from one to the other.

These graphics technologies have become so important and integral to their respective sports that some are now used as aids for the judges or referees. For example, the positional information generated for the America's Cup yacht race graphics is used by the event's umpires, and in soccer the Hawk-Eye system[1] is used by the English Premier League for deciding when a ball has crossed the goal line.

21.3 Challenges for Visual Computing in Sports Broadcasting

In some ways visual computing techniques are ideal for use in sports coverage. It is very hard to add extra physical equipment such as sensors into the sporting areas themselves. They might get in the way of the sport being played or affect the performances of the players and athletes. Instead, unobtrusive cameras can be placed around the area of action. Very often the cameras already in place for the television broadcast can be used.

However, there are many significant challenges to the use of visual computing in TV sports coverage that are not found in the laboratory. The environment is out of the control of the system designers; the rules and practices of the sports, such as the type and color of the clothes of the participants, and the size, shape, and fabric of the arenas are normally long established and not necessarily conducive to easy scene analysis. The event can take place over a large area and the locations of the action cannot always be easily predicted. The participants may wear baggy clothing or all wear the same clothing and will often occlude one another. Most sports are played outdoors without controlled lighting or weather conditions and as a result the appearance can change dramatically. Some sporting bodies may be prepared to make changes to their sport if it can be justified by improved television coverage. Perhaps most famously, the fluorescent yellow of tennis balls was chosen to ensure greater visibility on color television.

[1] http://www.hawkeyeinnovations.co.uk/

Sporting events can also be chaotic, with hundreds of people around performing their individual roles. The environment is dynamic, so while a piece of the arena might form a useful calibration point in the morning, it may no longer be there in the afternoon. Similarly, furniture or advertising hoardings may be moved around as the event progresses. Athletics stadiums, for example, will construct or dismantle equipment based on whatever event is happening at that time. This even includes seemingly fixed objects such as the distance markers on the javelin field which consist of pinned down white tape that will disappear when the discus starts from the other end of the field. Some events such as the long jump can even change location when the direction of wind changes.

Broadcasting has historically used interlaced cameras where a series of pairs of fields captured at different times make up each frame. One field contains all the odd lines in the image, the other contains all the even lines. This effectively doubles the temporal resolution of the video, but each field only has half the vertical resolution of the full frame. Combining the two fields into one frame can introduce artifacts because of the time difference between them. The use of interlace is declining but this is still how pictures are transmitted to the home, and if a video feed is made available from a TV camera or recording then it will generally be interlaced. As a result any analysis or graphics systems have to be able to cope with interlace fields rather than the progressive frames as might be expected in the lab.

The use of zoom lenses on broadcast cameras inevitably makes intrinsic calibration more difficult. Lens distortion, image center point, and chromatic aberration can all vary as a function of both zoom and focus settings, and in the absence of data from lens sensors it can be difficult to accurately determine their values. Coverage of sports events also involves a large range of zooms. It is not unusual for a camera covering athletics, for example, to move from a field of 3 or 4 degrees to 45 degrees in a single sequence.

Broadcast cameras have a control known as aperture correction or sometimes "detail," The aperture correction is used to "sharpen" an image and is one element that distinguishes the "TV-look" from "film-look." Effectively, the correction emphasizes high-frequency image components and is therefore a high-boost filter. A high level of aperture correction causes a significant color shift to pixels close to luminance edges. This can affect an area of about 2-3 pixels around contour edges and leads to incorrect segmentation results using color-based segmentation methods. The segmentation can be improved by compensating for the effects of the aperture correction [Grau and Easterbrook 08].

Camera calibration is difficult in uncontrolled scenes which typically have few features with accurately known 3D positions. Although lines on sports pitches are notionally in well-defined positions, pitches are rarely flat (being deliberately domed to improve drainage) and lines are often not painted in exactly the right positions. Techniques such as 3D laser scanning sometimes need to be used to build an accurate model of the environment which can then be used for camera calibration. When calibrating sparsely spaced cameras with a wide baseline, features in the scene can change their appearance significantly between camera viewpoints, making reliable feature matching between cameras difficult. Cameras can often get moved accidentally so calibration may need to be repeated.

Sports broadcasting has its own methods and workflows, into which any graphics system must try and fit. Live sport in particular requires real-time or very fast turnaround results, and the conventions of the coverage may limit the camera choices available. The system also has to be robust enough that the sports director can be confident that it won't break when potentially millions of people are watching.

Unless extra cameras can be installed at a venue, the event will only be available as a video feed from the main broadcast cameras. This means that the operators of any analysis or graphics system will have little or no control over the camera positions and movements. Communication to and from the camera will normally have to pass through the broadcaster's lines of communication with requests for camera movements being passed to the director and then to the camera operator. Camera operators will often cover more than just the game and may start recording the crowd or other interesting events that have no direct relevance to the sport.

A successful system should also offer good value-for-money to the broadcaster compared to other ways of enhancing sports coverage. Sports producers have many ways to improve their coverage and to add significant value. For example, they can add extra cameras around the ground—including special cameras such as infrared heat cameras for cricket analysis, flying cameras suspended from wires attached to the stands, or some of the cameras discussed in Section 21.7 and Chapter 3—microphones on the umpires to hear their decisions and orders or even, and technically rather less interesting, they can just hire a new pundit to provide the analysis.

21.4 Foreground Segmentation

For many visual computing systems it is important to get a high-quality segmentation of the participants from their environment.[2] For example graphics may want to be drawn on the pitch or arena such that they appear

[2]Segmentation is histrionically called keying in the broadcast industry and matting in the movie industry.

to be under the players. If the background is of a reasonably uniform color then some relatively simple image processing can be used. For example, with soccer the players are normally stood on green grass so a color-based segmentation algorithm (known as a chroma-keyer) can be employed such that graphics only appear in regions that are suitably grass-colored. The result is that nothing is drawn on the players themselves but may be drawn on either side of them, giving the impression the graphics are behind him or her.

The color of grass on pitches can vary significantly. This is due to uneven illumination and anisotropic effects in the grass caused by the process of lawn-mowing in alternating directions. After periods of bad weather or late in the season patches of mud can appear to further discolor the pitch. In some applications the fact that the chroma-keyer will not generate a key for discolored areas can actually be an advantage as this adds to the realism that the graphics are painted on the grass, as long as such areas are not large. However, these challenges for the chroma-keyer can give a segmentation that is too noisy to produce the high-quality key needed for applications that require scene reconstruction such as free viewpoint video. Difference keying can produce better results and is also able to segment pitch lines, logos, and other markings of the background. The background model or "background plate" can be created by either taking a picture of the scene without any foreground objects or, if this is not possible, the background plate can be generated by applying a temporal median filter over a sequence to remove moving foreground objects.

For some applications, such as those that draw graphics onto live video, the keying and graphics rendering processes most be performed in real-time.

21.5 Camera Calibration for Sports Events

Early telestrator systems allowed 2D annotations to be drawn on top of a video still. However, if the camera's position, pan, tilt, and zoom are known (together with off-line lens calibration to relate zoom ring position to focal length) then graphics can be overlaid on the image such that they appear in the same orientation as the scene. This is known as registration (Chapter 7). For example, off-side lines can be drawn on the pitch such that they appear to be painted on the soccer field. This camera calibration, combined with knowledge of the geometry of the scene allow measurements such as distance to be taken and displayed. Figures 21.1 and 21.2 illustrates this. American football down lines, for example, must be placed at specific distances along the pitch. Often, some assumptions will be made about the scene to help translate 2D knowledge into 3D. For example, when finding the position of a soccer player it is assumed that he is stood on the

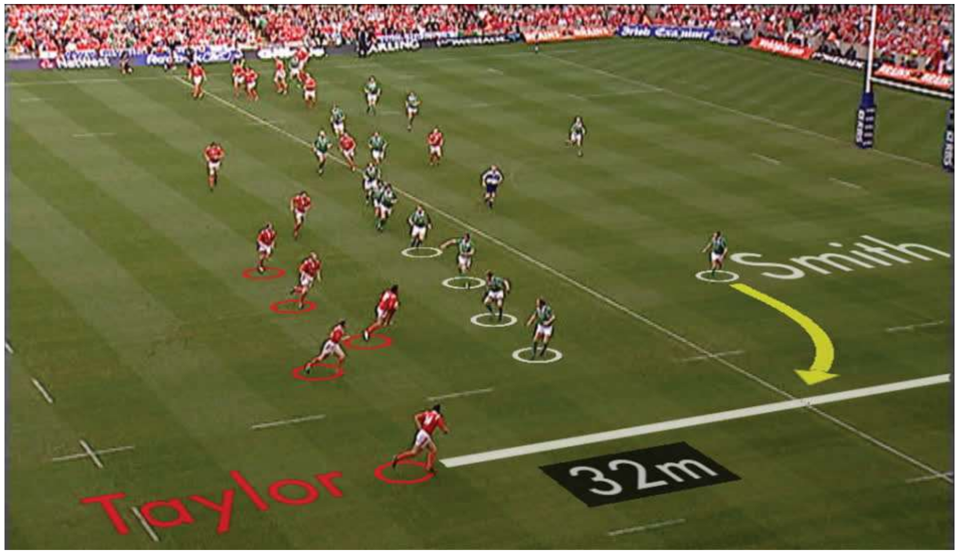

Figure 21.1: Player positions and movements along with distance measurements are added to the scene as if drawn on the pitch.

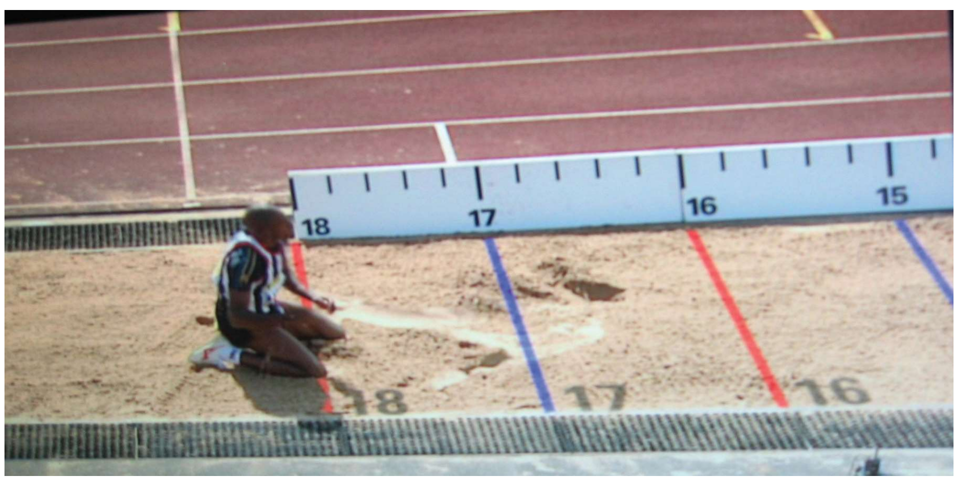

Figure 21.2: Graphics added to the triple jump to aid viewers in judging the distance of a jump. The graphics are drawn on screen as the camera follows the athlete into the pit.

ground so his height off the ground plane will be zero. As a result the other two dimensions can be calculated using the player's 2D position in the image. Multiple calibrated cameras allow for more sophisticated 3D effects, discussed in Section 21.6.

21.5.1 Image-Based Calibration and Moving Cameras

Calibration is most easily obtained from a static camera of known position and orientation. However, it is often desirable to be able to move the camera. Indeed if a broadcast camera is being used it will be moving. As the camera moves, many modern graphics systems such as Piero[3] retain the position of the drawn graphics relative to the real world. This has the effect of making them look even more like they are part of the scene. This is sometimes referred to as tied-to-pitch graphics. Such systems can be applied to many sports, not just those with soccer style pitches, including swimming, running events, and long jump, adding lines to indicate world records or qualifying distances. They can also be used to add logos or sponsorship to the scene either on the pitch or court or to the side as virtual billboards.

To produce this effect the movement of the camera must be tracked so that the calibration information about camera pose can be updated. This was originally achieved using a mechanical sensor on the camera and mount which measured the changing pan, tilt, and zoom. However, there are now several systems, including Piero, that are entirely image-based. This has the benefit that the same system can be used on multiple camera feeds without the need for expensive equipment on each camera or the need to be located near the camera itself. Indeed, such image-based systems can work just as well on recorded material without the need to work live.

21.5.2 Line-Based Tracking

One method of tracking camera pose is to use the lines on the pitch. Sports such as rugby, soccer, and tennis have regular pitch markings with known (or easily measurable) geometry which can be used to calculate the camera's position and pan, tilt, and zoom. The lines on the pitch are in known positions in the real world. If corresponding lines are visible in the camera view the correspondence can be used to compute camera pose. Typically, calibration charts are used (Section 1.6). In the case of sports analysis, however, the use of lines is more practical. With sports coverage it is generally not practical to get access to the camera or to be able to place objects into its view. Instead it is more reliable to use what is known to be visible to the camera in the scene. This has the added benefit that calibration can be performed after the fact from recordings, even if there had been no intention to use the video at the time of filming. A minimum of four lines (which cannot all be parallel) must be visible to solve for the unknowns and fully compute the camera position and pose, fewer are needed if the pose is known. One implementation of this approach is described in [Thomas 07] and forms the basis of the pitch line tracking features within the Piero and

[3]http://www.redbeemedia.com/piero/piero

tOG-Sports[4] graphics systems. The tracking process is split into stages. First, the position of the camera is estimated, then the tracker is started with a view of the pitch from which it must calculate an initial pose. From then on the tracker runs from frame to frame at full video rate.

Most cameras covering events such as soccer generally remain in fixed positions during a match. Indeed, the positions can remain almost unchanged between different matches at the same ground, as the camera mounting points are often rigidly fixed to the stadium structure. It therefore makes sense to use this prior knowledge to compute an accurate camera position which is then used as a constraint during the subsequent tracking process.

Estimating the position of a camera from a set of features in a single image can be a poorly-constrained problem, particularly if focal length also needs to be estimated. Changes to the focal length have a very similar effect on the image to moving the camera along the direction of view. To improve accuracy, multiple images can be used to solve for a common camera position value. The pose for all images is computed simultaneously, and the position is constrained to a common value for all the images. The images should cover a wide range of different pan angles (e.g., in soccer it should cover both goal areas) so that each image's line of position/focal length uncertainty lies in a different direction. In this way the differing views provide complementary information about the pose and solving for all of them together allows for a significant reduction in the ambiguity.

This process can be repeated using images from all the cameras feeds onto which the production team want to add virtual graphics. For soccer, this is likely to include the camera on the center line, the cameras in line with the two 18 yard lines, and possibly the cameras behind the goals. The computed camera positions are then stored for future use.

The frame-to-frame tracking process uses the pose estimate from the previous image and searches a window of the image centered on each predicted line position for points likely to correspond to pitch lines. A straight line is fitted through each set of points, and an iterative minimization process is used to find the values of pan, tilt, and focal length that minimize the distance in the image between the ends of each observed line and the corresponding line in the model when projected into the camera image. The observed and projected lines are highlighted in Figure 21.3. In such a way the lines can be tracked from frame to frame in an efficient and robust manner.

The operators of the graphics software need to be able to start working on generating their analysis clips very quickly after a suitable incident has occurred. For example, if a goal is scored just before half time in a

[4]http://rtsw.co.uk/products/tog-sports/tog-sports-lite/

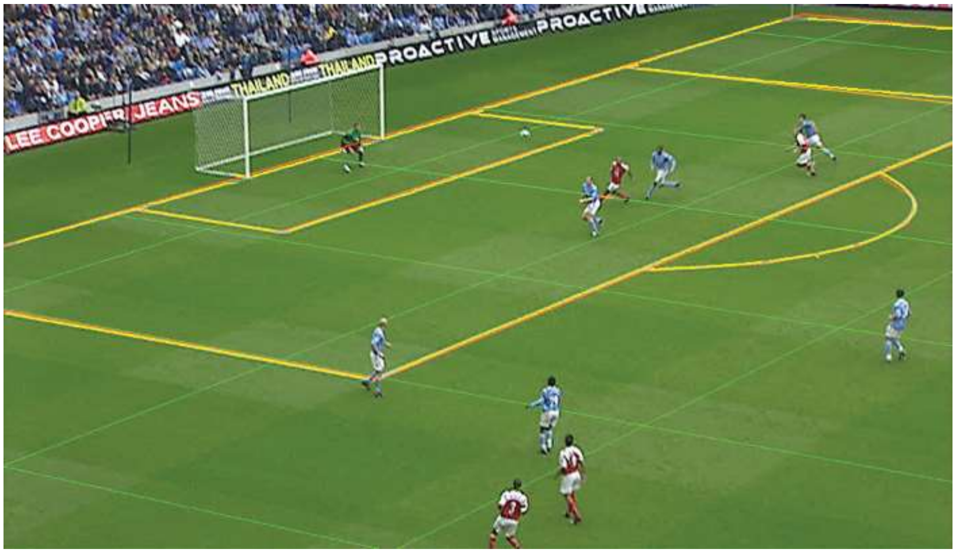

Figure 21.3: The pitch model is projected onto the scene highlighting the lines being tracked. The red lines represent the projected model while the yellow lines are the lines found in the image.

soccer match then a clip to aid analysis and discussion of the goal might be required within around 5 minutes. As such they cannot spend time calibrating the camera with image correspondences every time they want to make a clip. Similarly, if the system is tracking on live footage it needs to get the correct pose very quickly once it starts to receive the video—calibration would again take too long. The system must be able to initialize to a suitable camera pose as quickly as possible when presented with a new scene. Various methods can be used, including classifier based systems that recognize the scene [Dawes et al. 09] or by matching features using the descriptors described in Section 7.2. A very reliable method is to use the camera position saved earlier in the process and then perform an exhaustive search of all possible pan, tilt, and zoom values to find the one that best matches the lines visible in the scene. This, however, would be very slow so the process is sped up by performing the search in Hough space after first generating a Hough image based on lines in the video image [Thomas 07].

21.5.3 Feature-Based Tracking

For sports such as athletics, the camera image will generally show limited numbers of well-defined lines, and those that are visible may be insufficient to allow the camera pose to be computed. For example, lines on a running track are generally all parallel and thus give no indication of the current distance along the track, making pose computation impossible from the lines alone. For events such as long jump, the main area of interest (the sand pit) has no lines in it at all, (see Figure 21.2). Thus for these kinds of events to accurately estimate the camera pose for the insertion of virtual graphics an alternative approach is needed.

One approach is to view the problem as a specific example of SLAM (simultaneous location and mapping [Smith and Cheeseman 86]), in which the pose of the camera and the 3D location of tracked image features are estimated as the camera moves. The system is given an initial pose for the camera and then uses image features to track the pose from frame-to-frame (Chapter 7). There are some special considerations to take into account in the context of sports coverage. Specifically, significant changes in camera focal length can occur. But at the same time, camera position is constrained since it is generally mounted on a fixed point. This is in contrast to most implementations of SLAM which assume a fixed focal length camera but allow full camera movement. A significant degree of motion blur can occur as motion speeds of 40-50 pixels per frame are not uncommon when covering sports events with tightly-zoomed-in cameras. The approach described in [Dawes et al. 09] is designed to meet these requirements. It uses a combination of fixed reference features to prevent long-term drift (whose image texture is always that taken from the first frame in which the feature was seen), and temporary features to allow non-static scene elements (such as faces in the crowd) to play a useful part in the tracking process. The image features are assigned an arbitrary depth, as their depth cannot be determined from a fixed viewpoint. Although it would be possible to treat the whole image as a single texture and determine a homography that maps it to a stored panoramic reference image (since the fixed position of the camera makes the 3D nature of the scene irrelevant), the presence of a large number of moving features (the athletes) makes it advantageous to consider the image as a set of separate features so that outlying features caused by athlete movement can be discarded using a technique such as RANSAC (Section 7.2).

21.6 3D Analysis

As described, the combination of foreground object segmentation and camera calibration can allow the approximate 3D positions of objects to be inferred. This simple approach can also be used to create a crude 3D model of the scene. To place the segmented players into a 3D model of a stadium they can be rendered on flat planes, sometimes know as billboards (Section 17.3), at the estimated locations (Figure 21.4). This allows the generation of virtual views of the game from locations other than those at which real

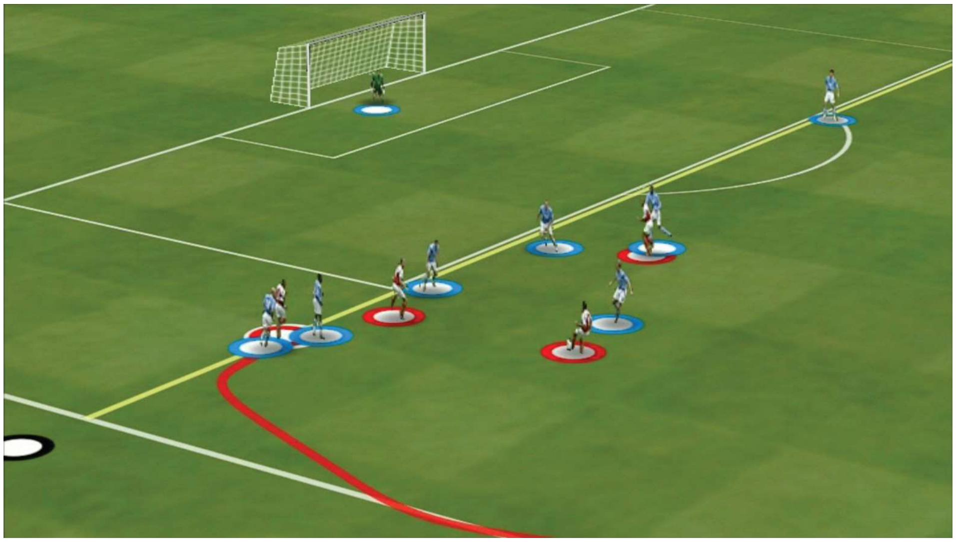

Figure 21.4: Player billboards are placed into a 3D model of the stadium.

cameras are placed. If this process has been conducted on two different cameras, a sequence can be rendered where the virtual camera moves from one real camera to the next. The two sets of flat player textures are blended into one another as the camera transitions. Systems such as Viz Libero[5] make use of this effect.

The simple player-modeling approach works well in many situations, but the use of a single camera for creating the models restricts the range of virtual camera movement. The planar nature of the players becomes apparent when the viewing direction changes by more than about 15 degrees from that of the original camera. One solution is to use pre-generated 3D player models, manually selected and positioned to match the view from the camera, as is the case with the Piero "3D Players" feature.[6] It can take a skilled operator several minutes to model such a scene, which is acceptable for a post-match analysis program, but too slow for use in an instant replay. The player models also lack realism. Some tweaking can be made to the flat textures to give them 3D character, such as altering the orientation of some part of the texture, particularly the limbs. However, this has only a limited effect. Very often the transition between two camera views, as described above, will be performed quickly to ensure that any oddities in the flat player models aren't too apparent [Kilner et al. 09] (Chapter 11).

[5]http://www.vizrt.com/products/viz_libero/

[6]http://www.redbeemedia.com/piero/solutions/3d-players

A multi-camera modeling approach provides an alternative. As described in Chapters 2, 12, and 17, multiple cameras arranged around the scene can be used to generate a 3D model. This process can be conducted over a video sequence to add a temporal element to the scene representation. The camera can then be entirely virtual and view the model of the scene from any point. This free viewpoint video enables sport presenters to explore interesting incidents by moving to new viewpoints, like a virtual flight down to pitch level or overhead [Hilton et al. 10, Goorts et al. 13]. This is a powerful tool to visualize spatial relationships between players and their tactics. It also allows for the transition between real cameras without the need to move to an entirely virtual world or try and work round the flat texture problems previously described. However, the few broadcast cameras used might see too little detail of the action or from angles too different to provide the basis for good 3D shape reconstruction. Extra specialist-cameras may be needed in the stadium which adds to the cost and logistical difficulty. Even with multiple cameras, the size of a typical soccer field and the distance of the stadium from the pitch mean that the image quality is not ideal and any small calibration inaccuracies can have a large effect. This can lead to low resolution models.

The regular problem of occlusion becomes more acute while covering team sports where players can easily block a camera's view of other players. The players can also contort themselves into shapes and interact with one another in ways that makes their 3D reconstruction particularly difficult. The crowd watching the games from the stands can also make segmentation particularly difficult from certain views. As a dynamic multi-colored texture they can sometimes prove indistinguishable from the players and ball.

The freeD system, developed by Replay Technologies,[7] avoids some of these issues by concentrating on small areas of known action, such as a piece of gymnastic equipment, the tee off in golf, or the plate in baseball. For recording a baseball sequence around 12 HD cameras were placed around the ground focused and framed on the batter.

Visual effects such as free viewpoint video face the problem of turnaround time. To generate a good quality free viewpoint video may currently take several minutes. However, live sports coverage would ideally like such effects to be available for immediate replay. Even in the case of highlights programming, when there is more time to create sequences, the time a sequence takes to render becomes an issue. Unless the effect is particularly spectacular and insightful, a TV production would rather generate several less complicated sequences than spend that time creating a single complicated one. As processing power improves and better cameras come

[7] http://replay-technologies.com/

onto the market, such effects can be generated far more quickly. The freeD system claims to be able to render out sequences in around 30 seconds.

Free viewpoint video also opens up new possibilities for how viewers would interact with sports coverage. An event could be delivered to the viewer over the web as a free viewpoint video allowing them to view the action from whatever viewpoint they choose [Budd et al. 12].

Hawk-Eye was one of the first commercially available visual computing systems used in sports coverage. Developed for tracking balls in 3D using a multi-camera system, it was first commercially applied in the tracking of cricket balls to aid the analysis featured in TV coverage of international cricket. Since then it has been applied to tennis and, more recently, soccer, among others. The system is deployed with a number of dedicated high-frame-rate, synchronized cameras arranged around and framed on the area of interest, such as the tennis court, goal mouth, cricket wicket, etc. There is normally space around the court or pitch (often on the roofs of the stands) to install the cameras. As static cameras they are easier to calibrate, and because they are not used to generate broadcast footage short shutter times and higher frame rates can be used to create the optimal pictures for processing. The problems of interlaced video can be entirely avoided by using progressive scan. There is a lot of prior knowledge about each sport that the system can use, including the size and appearance of the ball, its motion (once it is hit, its motion can be predicted using the laws of physics), and the area over which it needs to be tracked. The system first identifies possible balls in each camera image by looking for elliptical regions in the expected size range. Candidates for balls are linked with tracks across multiple frames, and plausible tracks are then matched between multiple cameras to generate a trajectory in 3D. This records the path and position of the ball during play and can even be used to predict the likely movement of the ball had it not struck another object or has spin applied. Other multi-camera analysis systems for balls in sporting events include QuesTec's Umpire Information System[8] for baseball and the similar Zone Evaluation System.

21.7 Virtual Broadcast Cameras and Second Screen

Panoramic, omni-directional, and free viewpoint video promise to change the way events are being captured for broadcasting. The common work flow today is to have one camera operator per broadcast camera. The main duty of this operator is to make sure that an event is captured with appropriate framing from the vantage point of the camera position. In high-end live

[8] http://www.questec.com/q2001/prod_uis.htm

productions, the exposure and color settings of the cameras are controlled by shading operators in the outside broadcast van, so a camera operator really can solely focus on framing. This takes particular skills of attention and context awareness in order to predict to a certain extent what is about to happen and how to perform the actual framing.

Different cameras provide raw footage from different vantage points. In soccer, for instance, the camera positions are standardized by FIFA, and assigned numbers so that everyone can refer to a camera position in a non-ambiguous way. But also different types of events are usually captured from established sets of camera positions. Major rock concerts, for instance, are captured by a camera on either side of the stage, a camera middle front stage (shooting in "frogs" perspective), a camera (often on a crane) from within the audience, and sometimes more cameras from back-stage corners.

The raw footage from each of these camera vantage points is presented to a director on an array of video monitors in the outside broadcast van. The director makes live decisions on what stream on the mosaic is dispatched for live broadcasting.

In offline broadcasting, one or more camera operators autonomously choose vantage points, frame an event and control exposure themselves, with the same goal of producing the best possible source footage that can be combined later into the final program. The process of putting together a program after filming has finished is known as post-production. During the editing stage of post-production, footage may be cropped slightly in order to correct framing.

This current work flow is dictated by the fact that camera pixels are expensive, and used to be very expensive. However, pixels are getting cheaper nowadays. As a consequence, it becomes feasible to capture events with a high-resolution camera, at a wide shooting angle, so that framing can be performed by an operator in an outside broadcast van, or in post-production for off-line productions. During the 2014 Super Bowl, for instance, 4K broadcast cameras were used in this way to generate full HD footage. The advent of 8K cameras promises a fourfold zooming capability without loss of quality, offering considerable freedom in reframing events. This comes at its highest benefit in the context of replays, in order to "tell the story" of what has happened at an event, shortly after a particular incident. Post-factum framing no longer requires the prediction skills of a good camera operator today.

Such "panoramic" virtual camera technology is already feasible today at a commercial level by stitching together images of closely spaced, full-HD, cameras. In the context of pitch sports, the stitching can be performed to sub-pixel accuracy today with relatively simple algorithms since the scene being captured is at a large distance compared to the inter-camera spacing

Figure 21.5: 16-times full-HD panoramic camera system for sports broadcasting (left), camera installed in American football stadium (middle), operator reframing footage while programming an instant replay using a joystick controller (right).

Figure 21.6: Omni-directional video capture for broadcast TV (left), director controlling framing and lens effects using a joystick controller in a montage booth (middle), resulting video clip frame with stereographic "virtual lens" (right).

(tens of meters versus centimeters), and depth variations are relatively small (Chapter 3).

Another application scenario of omni-directional cameras is to facilitate video capture on location. A compact omni-directional camera is installed on site and captures whatever happened around the location where it was set up. Actual framing of events takes place in post-production, in a montage or edit booth, at the broadcaster's facility. Creative decisions concerning the field of view or lens effects in order to frame an event are no longer taken in a predictive manner by a camera operator on location, but based on posterior knowledge of what has happened. This work flow may eventually reduce costs, while allowing additional creative freedom. The work flow was tested, among others, in the context of a popular prime time program in "1000 zonnen" by Belgian national broadcaster VRT, with two 1- to 4-minute items produced this way weekly over a period of three months.

In addition to allowing cost reduction and additional creative freedom, panoramic and omni-directional video capture techniques can also be used to provide content for second screen applications that complement a traditional broadcast watched on the main television. A second screen is a viewer's personal device such as a mobile phone or tablet which they may use while watching a program on the shared primary television. A second screen spectator can follow the same event as shown on the primary TV screen but the way the event is shown could be fundamentally different. On the primary screen, a director's cut may be shown, while on the secondary screen, a spectator can be allowed the freedom to "look around" at the event him/herself. Experience from actually bringing this into practice in the context of a popular Belgian talk show, and for sports coverage, showed that the primary screen is by far the best way to show details (close-ups) and steer the spectators' attention (as it always and exclusively is on primary screen), while the surround video content on the second screen helps to convey the ambiance of an event location better than by any other means. In the context of talk shows or political discussions, usually just the person speaking is shown on TV, while surround video on a second screen allows viewers to observe the body language of the others, which may be very informative on occasions.

21.8 Summary

Visual computing systems face various challenges if used in live television broadcasting and in sports coverage. Some systems are already in use, and the approaches they take to tackle the challenges are encouraging. In the next few years, as technology improves there is the potential for visual computing to play an increasingly important role in TV broadcasting. Free viewpoint video systems and wide angle cameras may change how television is produced and even create new ways for the viewer to consume and interact with TV productions.

22
Web-Based Delivery of 3D Mesh Data

Max Limper, Johannes Behr, and Dieter W. Fellner

22.1 Introduction

Visual computing applications are often dealing with 3D mesh data, in order to represent objects that have been captured within the real world. Such data can stem from various 3D scanning methods, which usually output point clouds and then apply some mesh generation method, for example by using the marching cubes algorithm, Delaunay meshing, or the *3D Snakes* method (Chapters 9 and 10). Depending on the size of the data, as well as on the target application, the meshed result might then be processed further, for example through simplification or remeshing methods, before a final, meshed 3D model is ready for presentation.

A trend that can be observed over the last few years is that there is, on the one hand, a growing number of devices with powerful graphics hardware, and on the other hand almost no device any more that is not potentially connected to the Internet, or to a local intranet. As a natural consequence, 3D Web technology serves more and more as a powerful integration platform for visual computing applications: Suddenly, with low-level graphics APIs like WebGL, it has become possible to deliver 3D mesh data to a wide variety of devices, ranging from desktop PCs to smart phones, in a consistent, platform-independent way. Figure 22.1 shows a conceptual overview of this situation.

22.2 3D Meshes vs. Image-Based Representations

There are several possible ways for visually presenting captured real-world scenes or objects to a user. In general, when considering the data transmission format, a distinction can be made according to two basic categories. On the one hand, 3D data may be stored for presentation as polygonal

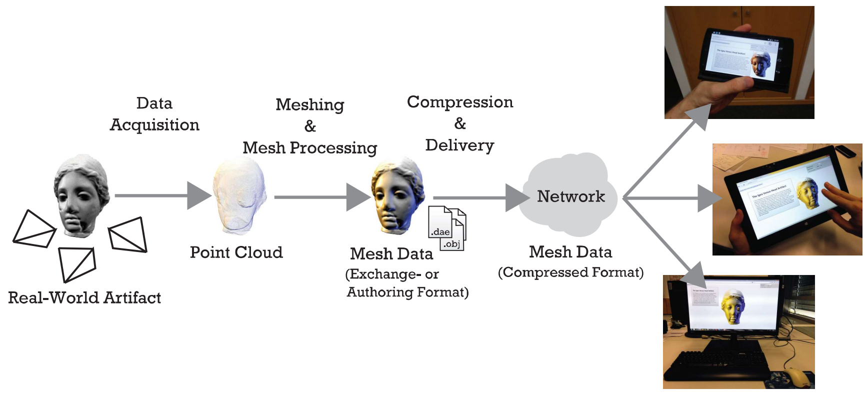

Figure 22.1: Pipeline for a typical visual computing application from the field of cultural heritage. Data is acquired through a 3D scanning method and then meshed. The meshed data may be further processed by simplification algorithms, for instance. It is then compressed for delivery over a network, transmitted, and finally presented on a client device.

mesh. In the most simple case, this mesh is simply a list of triangles, which represent the surface of an object. Appearance details (such as surface normals, displacement or colors) are usually represented at the vertex level, or in the form of texture images. The client application then generates images on-the-fly, using common 3D rendering techniques, as they are also used in computer games, for example. Within this section, such representations are referred to as *mesh-based representations*.

On the other hand, captured data may be directly represented via images. Instead of generating perspective views, along with matching lighting and appearance information, on the client side, all the client has to do is to display the correct image, or to interpolate between a set of given images. Methods that use such representations are usually referred to as image-based rendering (IBR) or video-based rendering (VBR). It is worth noting that there are also other ways of storing captured 3D data for presentation, such as point clouds or depth maps—an overview can be found in Chapter 17. In Figure 17.1, mesh-based 3D representations can be found at the very right edge. Both of the mentioned basic approaches for representing captured data for remote presentation, mesh-based representations as well as IBR/VBR solutions, have specific advantages and disadvantages.

Advantages of IBR and VBR methods. Rendering mesh-based representations in an efficient way requires full access to a dedicated 3D graphics API and hardware. In contrast, VBR or IBR solutions potentially have lower device requirements, and therefore might be a better fit for a maximum portability. If critical data (for instance, protected CAD product data) should be displayed over an unsecure network, security restrictions may also prohibit a delivery of mesh-based representations. With IBR or VBR solutions, deriving such critical data from the displayed images is a much harder (and error-prone) task, therefore these methods might be preferred in such cases. Another great advantage of VBR and IBR solutions is that they are basically independent from the complexity of the model and its appearance properties. Extremely high polygon counts, or the request for a very detailed view of complex material or illumination properties, might therefore also prohibit the use of mesh data, and lead to IBR or VBR solutions instead.

Advantages of mesh-based representations. Depending on the application, the user might not be satisfied with viewing a non-interactive scene, as is usually the case with IBR and VBR solutions. If the user wants, for example, to be able to change object materials, or to move objects or light sources around, IBR or VBR solutions cannot provide this degree of interactivity (Figure 22.4). In such cases, the necessary visual information has to be dynamically generated on the client side, using common 3D graphics techniques and mesh-based representations. If network bandwidth is a critical factor, using mesh-based 3D representations is also the method of choice, especially compared to approaches like light fields, which require the storage of huge amounts of data. As already noted in Chapter 17, this is due to the fact that an optimized, meshed 3D model of a scene, along with a texture atlas, makes very compact scene representations possible. One possible solution to achieve maximum quality along with a maximum degree of interactivity, on almost any client device, is the use of a dedicated server for remote rendering. However, the big disadvantage of this image- or video-based approach is its bad scalability: As soon as multiple clients connect, a dedicated rendering server or process must be maintained for each of them, which is not possible for many kinds of public, large-scale Web applications (such as online shops or exhibitions). Another problem in this context is the need for a connection with minimum latency, in order to be able to provide fluent user interaction. Therefore, mesh-based representations are usually preferred for interactive small and medium-size scenes, which should be accessable for a large number of clients.

Considering the specific advantages and disadvantages of IBR/IBR solutions and mesh-based representations, it strongly depends on the context of the application which representation is best-suited. Using service-oriented architectures (SOA) and RESTful APIs allows to deliver 3D assets along with context-specific application templates, as it is done by Instant3DHub [Jung et al. 12] or XML3DRepo [Doboš et al. 13], for example.

Client devices can then, for instance, automatically receive a specific representation, matching their CPU or GPU capabilities, the available bandwidth, and security-related contraints. This way, the decision between using IBR / VBR methods or using mesh-based representations can even be dynamically performed per client. A server might, for example, decide to share only images instead of real 3D information across unsecure networks, in order to prevent theft of proprietary 3D construction data. Providing an image stream for an interactive 3D experience, on the other hand, is only possible with server-side rendering, which requires a powerful server architecture to scale well, even for a small number of clients. Therefore, the approach of statically providing compact, mesh-based representations is usually the preferred way to deliver 3D assets on the Web, and already applied for a wide variety of use cases.

22.3 Application Scenarios

The field of application for high-performance 3D Web technology is growing every day, including many interesting scenarios from the field of real-world visual computing. One obvious use is the online presentation of scanned products for marketing purposes.

Another use case, which might be not that obvious, is shown in Figure 22.2(right). Here, research data from the CAESAR anthrophometric database has been made accessible as part of an interactive 3D Web application. Such fast, portable, and convenient access to the 3D mesh data allows quick looks on specific poses, without needing to explicitly download the corresponding files and then open them in a specialized viewing application.

One increasingly important class of real-world visual computing applications, using 3D Web technology, can be found in the domain of cultural heritage. Artifacts from this domain are mainly preserved in large archives, mostly belonging to museums all over the world. Usually, such archives contain too many artifacts to fit into a single exhibition, and they are often managed in traditional, paper-based archive infrastructures. The current shift toward digitized archive data also includes the storage and distribution of 3D scans for each artifact (Figure 22.1). This enables people around the world to remotely inspect collections in distant archives via the internet—in an ideal case, such inspection scenarios can be performed using regular Web browsers. An example from a recently initiated Web portal [Martínez et al. 14], using the open-source X3DOM framework for visualization, is depicted in Figure 22.2(left).

As a typical real-world visual computing application from this domain, Schwartz et al. have presented both, a capturing setup as well as a WebGL-

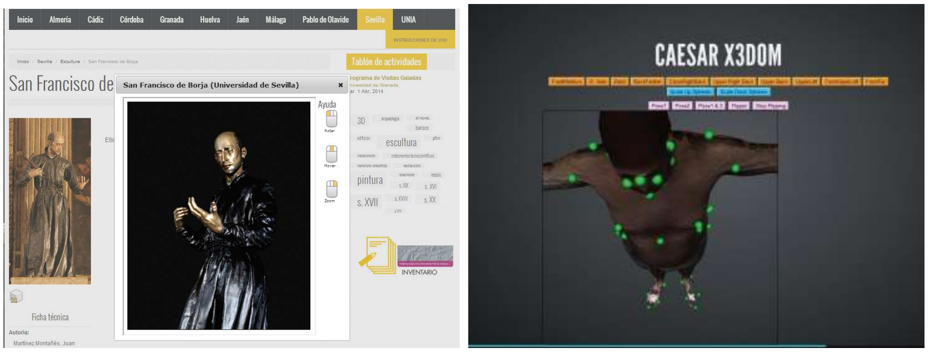

Figure 22.2: 3D Web technology, used for real-world visual computing applications. Left: A scanned cultural heritage object, which is part of an online exhibition. Right: Online inspection of the CAESAR antrophometric database.

based streaming framework, for acquisition and presentation of cultural heritage artifacts. Figure 22.3 gives an impression of their DOME II capturing setup, as well as of the 3D Web application that is used to present the results [Schwartz et al. 13, Schwartz et al. 11a]. Captured reflectance information is represented via bidirectional texture functions (BTF), which are approximated by texture images and progressively transmitted for presentation (Section 22.4). The user is able to interactively modify the lighting conditions inside the viewing application, which allows for a detailed inspection of not only geometry, but also material properties.

In a similar fashion, but using a less sophisticated material representation, the *Radiance Scaling* method enables the user to inspect surface details on an arbitrary 3D mesh [Vergne et al. 10] (Figure 22.4). During

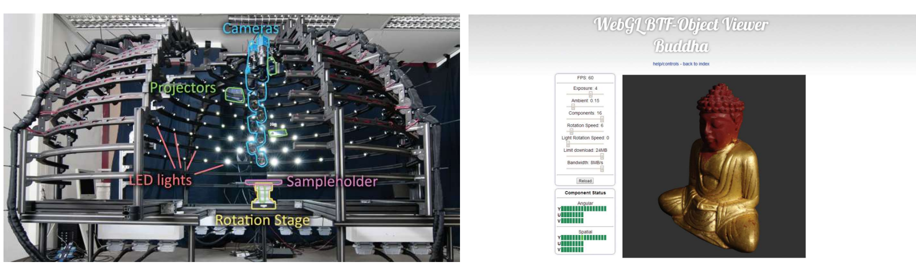

Figure 22.3: First and last stages of a pipeline for online presentation of cultural heritage, as presented by Schwartz et al.: DOME II setup for data acquisition (left), and Web-based BTF streaming and rendering framework (right).

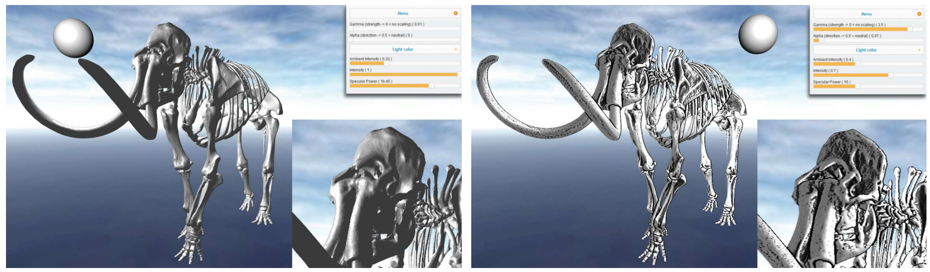

Figure 22.4: WebGL-based viewer, showing a wooly mammoth model that has been digitized and kindly provided by the Smithsonian Institution (see http://3d.si.edu/). The sphere acts as a handle for manipulating the position of the light source. Lighting parameters can be interactively modified to inspect different parts of the model, or to reveal surface details.

the shading stage of the rendering process, surface concavities and convexities are enhanced, depending on some parameters that can be interactively modified by the user. This technique only requires surface normals, and can therefore be used with any capturing setup, even if it only acquires geometry data.

22.4 Compression and Transmission

As soon as the acquired geometry has been reconstructed in the form of a polygonal mesh, additional mesh simplification or resampling steps might take place (Section 10.8). At this stage, mesh data is represented in the form of a topological and geometrical description, which can, for instance, be simply a text-based description in the form of a *Wavefront OBJ* (.obj) or *COLLADA* (.dae) file (Figure 22.1). This representation of the 3D mesh data (potentially enriched by texture data in the form of images) is then transferred to the Web-based delivery pipeline (Figure 22.1). To achieve a convenient user experience, it becomes necessary to apply compression and progressive transmission methods when delivering the data over a network. The conversion from the input format (e.g., from an .obj or .wrl file) to a compressed transmission format is either performed once (for static data) or as soon as needed (for dynamically changing data). The latter approach is, for example, taken by the transcoder component of the Instant3DHub architecture, as proposed by Jung et al. [Jung et al. 12]: As soon as a client requests a page that shows a specific mesh, the server decides whether the current compressed version of the requested mesh inside the server cache is up-to-date. If this is not the case, the outdated version inside the cache is directly replaced by compressing the input file again. Within this step, additional adaption to other parameters like network bandwidth, security constraints, or client device can also take place. A server could, for example, perform additional simplification steps to store representations at different level-of-detail (LOD) inside its cache. Depending on the client device that posts a request, the server might then pick a matching LOD for delivery.

Compressing Mesh Data

A crucial aspect of mobile and Web-based real-world visual computing applications dealing with 3D mesh data is efficient data compression and transmission. In contrast to common desktop 3D applications, the typical user scenario is radically different: users will browse to a specific URL where a 3D showcase should be available, or click a thumbnail in an online catalogue. As soon as the 3D Web application starts to load, users will typically expect *instant* results, as they are used to from other Web pages. This does not necessarily mean that everything should be directly loaded, but that a progressive refinement of the whole page must instantaneously take place.

Regarding compression methods, this means that a very important trade-off has to be made: On one hand, a good compression method could be necessary to deliver the mesh data in acceptable time over the network. On the other hand, a fast decompression is also crucial, since a complex decompression step could take more time than directly sending the uncompressed data would do [Hoppe 98, Pajarola and Rossignac 00, Limper et al. 13b]. This aspect becomes even more crucial for specific application setups, like mobile client devices (with less CPU or GPU power for decoding) in a fast company intranet (using a high bandwidth).

Therefore, only methods that allow a quick and straightforward decompression can be considered as candidate technology for Web-based and mobile 3D graphics applications. For an exhaustive overview over the wide field of research related to mesh compression in general, the survey of Peng et al. might serve as a good starting point [Peng et al. 05].

Lossy compression. The simplest method used to reduce the size of a mesh, and at the same time the most important one, is the use of quantized data. For the most popular quantization in Cartesian space, the idea is fairly simple: if the 3D mesh can be described with its vertex positions lying on a regular grid, without a visible loss of precision, then floating-point coordinates can be safely replaced by integer coordinates. The decoder will compute the original vertex positions from the normalized and quantized representation, using the original size of the mesh's bounding box that has been provided along with the data. Decoding can be performed in parallel on the GPU, inside a vertex shader. This approach has several advantages.

First, it leads to a significant reduction of memory that is needed to store the vertex buffers. Second, and even more important in a browser context, the time spent for CPU-based decoding steps becomes effectively zero, since clients simply need to pass the downloaded data chunks to the GPU, where the decoding is performed during rendering.

It strongly depends on the resolution of the model how many bits of precision are sufficient; typical values vary between 8 and 14 bits per vertex position component [Pajarola and Rossignac 00, Peng et al. 05, Lee et al. 10a].

A simple yet efficient approach to reduce the size of the compressed mesh is the subdivision into several sub-meshes. Such sub-meshes can be obtained from the original mesh with several partitioning methods, and the subdivision does not necessarily relate to manifold surface patches. A simple method is to use a kD-Tree to partition the mesh into regions that contain an approximately equal number of triangles. Another method for subdividing a mesh into multiple sub-meshes is to use a cache-optimization strategy to re-arrange the vertex data, and then cutting slices out of the resulting lists [Chun 12]. A third possibility is to use a hierarchical face clustering approach, where a cost function can be used to produce compact bounding boxes [Lee et al. 10a].

The use of several locally bounded, compact sub-meshes enables the encoder to achieve a very compact representation, since a lower quantization precision can be used to encode the vertex data within each sub-mesh, without having to sacrifice the overall quality of the full mesh after compression (the overhead of additional bounding box data is usually of neglectable size). However, subdividing a surface potentially introduces another problem, which occurs in the form of visible seams between the sub-meshes. To solve this problem, quantization is performed with respect to a common bounding box size, which is, for each spatial dimension, equal to the largest bounding box available among all sub-meshes [Sander and Mitchell 05, Lee et al. 10a].

Besides the vertex positions, other vertex attributes can also be stored in a quantized form for compression purposes. For RGBA colors, it is very common to use an 8 bit range per channel anyway. To store vertex normals in a quantized form, several approaches exist. Jung et al. use spherical coordinates (employing two angles on the sphere instead of 3D Cartesian coordinates) to store normal data for compact transmission, enabling decompression during rendering [Jung et al. 13]. Meyer et al. have provided a study on floating-point normal vectors and several quantized normal vector parameterizations, showing that an octahedron parameterization gives the best results, compared to 3D Cartesian or spherical parameterizations [Meyer et al. 10]. No matter which particular normal storage format is finally picked, it is always the main aim of an interactive 3D Web or mobile application to perform decompression on-the-fly during rendering (usually inside the vertex shader) in order to avoid slow CPU-based decoding.

Aiming at a browser-based inspection of human anatomy, Google conducted experiments that resulted in *WebGL-Loader*, a minimalistic library for compact 3D mesh transmission [Chun 12]. The most interesting aspect of this method is that the UTF-8 file format is a good alternative to binary formats, because it can be parsed very quickly within the browser, while also providing a simple variable-length encoding. The algorithm achieves a comparatively good compression and, combined with the native GZIP implementation of the browser, realizes fast decompression.

It is worth noting that limiting data precision to the minimum amount which is necessary does not only help to reduce transmission time. It has also been shown that it can improve geometric calculations and lighting computations, in terms of execution speed and energy consumption [Hao and Varshney 01, Pool et al. 11]. This aspect becomes especially important in the context of mobile graphics.

Loss-free compression. Besides lossy compression methods, there is a variety of loss-free compression algorithms that potentially fit well with a Web or mobile environment.

A very quick and efficient method is delta-coding and additional entropy-coding, like provided by GZIP compression [Chun 12]. Considering Web-based transmission, GZIP compression is available as a standard encoding method in HTTP, therefore applications can rely on fast, built-in browser implementations.

The open compressed triangle mesh (OpenCTM) format,[1] intended for fast exchange of compressed mesh data, uses LZMA compression, which is potentially superior to GZIP when applied to 3D binary mesh data. However, since there is no Web browser that supports LZMA natively, Web applications have to provide their own LZMA decompression implementation. This in turn might lead to the overall loading time (consisting of download time plus decode time) becoming much longer than for methods that rely on less sophisticated compression algorithms, but provide a faster decoding [Limper et al. 13b].

The Khronos group has recently considered several compression methods as candidate technology for the GL transmission format *glTF*. Among those, an important candidate technology to be included into the glTF specification is the TFAN approach, which has also been considered for ISO standardization within the MPEG-4 standard [Mamou et al. 09]. The idea is to provide good compression rates, support for all kinds of meshes (including non-manifold geometry), along with a low-complexity, fast

[1] http://openctm.sourceforge.net/

decoding method. The encoding algorithm first constructs a set of triangle fans from the input mesh data. The most frequently appearing triangle fan configurations are then used to efficiently encode the mesh connectivity, along with an arithmetic coder [Moffat et al. 95].

Progressive Mesh Data Compression

Since common Web applications demand an instantaneous user experience, the question arises how 3D mesh content can be progressively retrieved. In the ideal case, a compressed representation can be quickly delivered over the network, and at the same time be progressively decompressed without much overhead inside the client application.

A trivial yet efficient method to transmit a mesh in several stages is also provided with mesh partitioning approaches (Section 22.4). However, the term *progressive* is usually used for methods that progressively transmit the data of the full mesh. First approaches were made in this direction in the late 1990s, a long time before Web and mobile graphics APIs and the modern graphics pipeline were available. The pioneering work of Hoppe encodes mesh data in a compact and progressive structure, based on sequential edge collapse and vertex split operators [Hoppe 96]. Mesh data is initially provided in the form of a simplified, coarse mesh, which can be obtained using error-controlled edge collapse operations [Garland and Heckbert 97]. The original high-resolution mesh is then iteratively reconstructed by splitting vertices, which are read from the incoming stream of mesh data. In a later publication, Hoppe provided a short study on when additional compression of vertex data is worth the effort, depending on the decoding speed and bandwidth available [Hoppe 98]. In a similar manner, Pajarola and Rossignac stated that an efficient progressive mesh compression method has to balance between three contradictory constraints [Pajarola and Rossignac 00]. First, it needs to provide fine-grained progressive refinements. Second, high compression ratios should be achieved. Finally, the third important goal is fast decompression.

In the Web and mobile context, fast decompression has a very high priority. But even on desktop machines, sophisticated progressive mesh compression algorithms do not always pay off in terms of decode time compared to download time. Therefore, game developers have tried to port parts of Hoppe's method to the GPU [Svarovsky 99]. The focus of latter work is primarily shifted toward the optimization of rate-distortion performance [Peng et al. 05], which, however, mostly completely ignores the aspect of decode time. Lavoué et al. recently presented a modified progressive mesh compression algorithm which works relatively well on the Web [Lavoué et al. 13] (Figure 22.5). However, it is unable to deal with non-manifold geometry, and decoding steps still have to be performed on

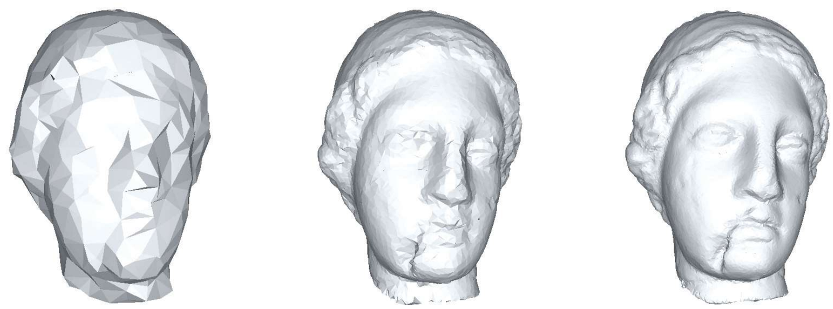

Figure 22.5: Progressive loading, using a progressive mesh. The method produces very good approximations during refinement, while maintainig a good compression rate. On the downside, it is unable to deal with non-manifold geometry, and thereby introduces additional pre-processing steps, and decode time might also become a critical factor.

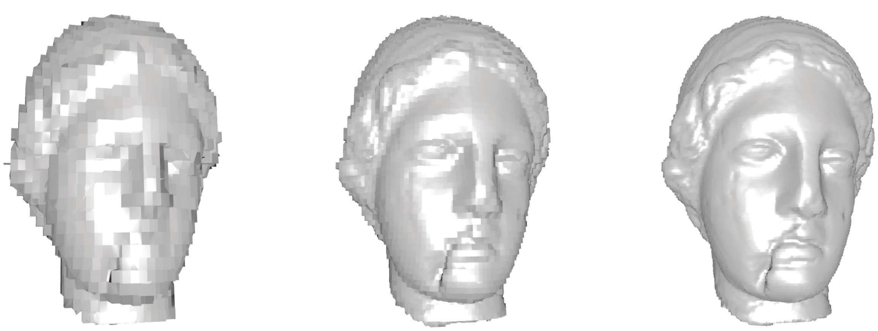

Figure 22.6: Progressive loading, using the POP buffer method. The idea is comparable to progressive PNG images, but transferred to 3D mesh data. It provides fast decoding without any CPU-based steps and is able to handle arbitrary triangle soups, but sacrifices compression performance and quality of the intermediate representations.

the CPU. An alternative, which has been specifically designed for the Web and mobile environment are POP Buffers resembling progressively loaded PNG images [Limper et al. 13a] (Figure 22.6). The idea of the algorithm is very straightforward: Since aggressive quantization of the geometry (for instance, with 5 or 6 bits) results in many triangles being collapsed to a line or even to a single point, it is possible to progressively sort out those triangles when using a coarser quantization resolution. The triangles can then be grouped according to the precision level where they first appear,

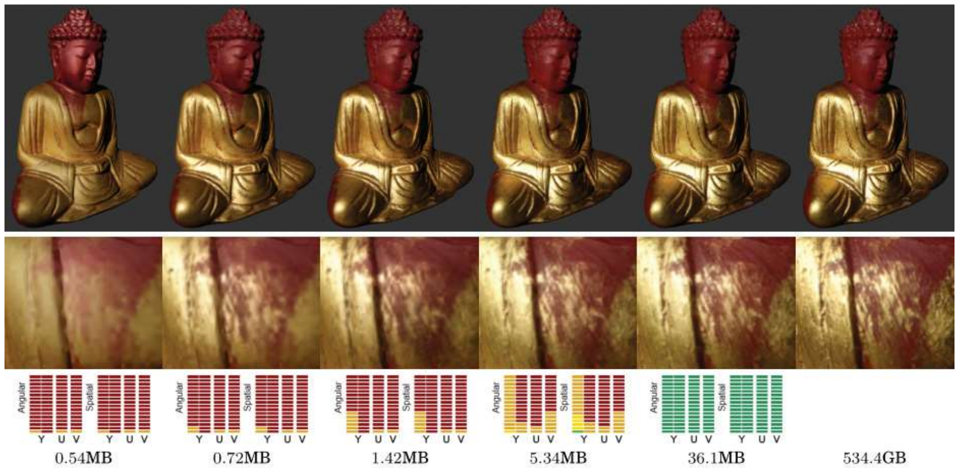

Figure 22.7: Web-based BTF streaming. The BTF data, which is used to shade the textured surface of a 3D mesh, is progressively transmitted as a compressed, decorrelated matrix factorization, with additional wavelet compression for the corresponding images.

which enables the creation of a nested, progressive structure. The method is able to handle arbitrary meshes, and it does not involve any CPU-based decoding steps. However, the quality of intermediate representations is not as good as for other progressive compression methods.

Schwartz et al. have presented a framework for progressively streaming bidirectional texture functions (BTFs), representing the appearance data of digitized artifacts [Schwartz et al. 11a]. The BTF data, which has been acquired from their DOME II capturing setup (Figure 22.3) is compressed using the decorrelated full matrix factorization (DFMF), as proposed by Müller [Müller 09]. Like other compression methods that are used in the Web and mobile context, this method provides a balanced trade-off between compression performance and decode time, and allows for real-time rendering on the client's GPU. The BTF is represented as a product of two functions, one depending on view- and light direction (angular function), and one depending on the spatial position of the sample (spatial function). By performing a singular value decomposition and streaming the resulting components of both functions, this information can be progressively transmitted to the client application, which produces high-quality results after just a few seconds (Figure 22.7). The corresponding images, which are used to store the component data, are compressed for faster transmission, using a wavelet compressor.

22.5 Summary

Remote presentation of real-world data, obtained through different scanning methods, has already become a common use case within many fields of application. Cultural heritage is only one example where the full potential of a visual computing pipeline has not been completely explored yet.

With the current technology trends, like cloud-based applications, the *Industry 4.0* initiative, and the Internet of things, there are also high chances that lightweight, mobile and Web-based 3D graphics applications will continue to gain further importance. Especially, the confluence of mobile vision and mobile graphics, performed on a single, Web-capable device—namely, the smart phone—bears high potential for many new, innovative, real-world visual computing applications. One important field of research in this context remains the search for a commonly accepted standard format for compression and progressive transmission of 3D mesh data.

23
Virtual Production

Volker Helzle, Oliver Grau, and Thomas Knop

23.1 Introduction

The concept of producing digital media content with software operated on affordable workstations has been established during the last two decades. It was mainly influenced by the gain of processing power and is applied in disciplines like visual effects (VFX), 3D character animation, visualization, simulation, or videos games, to name a few. The majority of work, however, is carried out in an offline process which separates the artist from other members of the creative team.

The concept of virtual production foresees to combine key aspects of media production in a real-time, or close to real-time, environment where creative decisions can be taken in direct consultation with other members of the team. Virtual production utilizes existing technology and concepts already established in television (chroma-keying, camera tracking, virtual studio), industrial visualization and design processes (virtual reality and augmented reality) or progress in capturing human motion, for example, in medical or sport applications.

The contemporary situation provides a unique opportunity to cause a major shift in how media is being produced based on the multitude of existing and upcoming hard- and software technologies. Those allow onset content interaction, visualization, and modification, with intuitive methods of controlling creative parameters. This can be achieved by combining modules like accelerated software algorithms for image synthesis, performance capture, sophisticated tracking of cameras and input devices, gesture recognition, virtual and augmented reality display devices, and capturing of additional information such as depth, geometry, or omni-directional video. In this chapter, different aspects of virtual production beginning with the already established virtual studio in television will be looked at. For instance, set extensions and filming on virtual locations offers a unique opportunity compared to the complexities involved in shooting at real locations. Finally, a case study production in which game engine technology and a motion capture system were used for pre-visualization and final render of an advertisement spot will be discussed.

23.2 Virtual Studios

Virtual studio systems were pioneered in broadcast in the 1990s. They were designed to be used in real-time in live broadcast productions. Early systems were using 2D digital video effects hardware systems (DVEs) combined with available studio chroma-keying equipment and mechanical camera sensors to capture pan, tilt, and zoom variations. With the advent of graphic hardware, like the Silicon Graphics Reality Engine™in the mid 1990s, it was possible to render 3D graphics in real-time at video frame rates. An early virtual studio system was developed in the EU-project Mona Lisa [Blonde et al. 96] and led to one of the first commercially available virtual studio system on the market.[1]

A specific problem of virtual studio systems is the tracking of camera movements. Mechanical sensors are only capable of capturing the movement of a TV camera on a pedestal, as pan and tilt[2] and in addition the zoom and focus settings of the camera lens. Early solutions to capture the 3D camera movement (6 DOF pose) were already based on visual tracking of special markers. Examples of this technology are the ORAD pattern-based system or the Vinten-Radamec Free-D system, developed by BBC [Thomas et al. 97]. Recent progress in computer vision in combination with inertial and gyro-sensors led to the development of real-time capable 6 DOF camera tracking without the requirement of special markers in the studio. Moreover, these systems work even outside a studio and are based on natural image features [Chandaria et al. 07] and are now available as commercial products, e.g., from Ncam[3] or SolidTrack.[4]

The take-up of virtual studio systems was initially slow. The hope that virtual techniques would save cost in set design was contrary to very expensive equipment and additional complexity in the preparation and production. With significantly reduced hardware cost virtual studio techniques are today used in many TV productions, in particular in news and factual shows.

Since the techniques developed for virtual studios are real-time capable by design, they were also used in early virtual production approaches in movies. In particular, virtual production systems were used in on-set pre-visualization in a number of movie productions involving real actors

[1] The ELSET™system developed by VAP.

[2] There is usually no roll on a studio camera pedestal.

[3] http://www.ncam-tech.com/

[4] http://www.solid-track.com/

interacting with otherwise invisible virtual actors by giving a real-time preview of the final composited scene [Rosenthal et al. 01]. The ORIGAMI project developed an actor-feedback system using view-dependent projection [Grau et al. 04]. Projector-based feedback was used in TV productions, like the BBC "BAMZOOKi" program for children. Many recent virtual production implementations make use of advances in display technology and are using bright projectors and displays directly in the studio to insert graphical or video content without the need for chroma-keying. This avoids problems of chroma-keying, like color back-spill on presenters and actors and also makes it easier for the presenters on set as they have visual feedback of the inserted content.

Further evolution of virtual studio techniques happened to some extent in techniques developed for use outside the studio space, in particular for sports visualization (Chapter 21).

23.3 Virtual Production for Cinema and TV

Virtual production employs a number of tools throughout the whole pipeline to make a movie or even smaller productions like commercials and drama series. These tools include software and hardware to create virtual assets[5] and/or capture reality with 3D scanning technology. Further, it includes software tools to manage the workflow and to visualize the virtual and virtualized components throughout the production process [Grau 05]. The workflow in movie and (high-end) TV production is divided into phases: The preparation and planning phase is based on the story board and script and implements or acquires all assets (virtual and real). In the on-set phase real assets and actors are captured (filmed) and in the post-production phase final quality renderings are produced and combined with the real camera footage in a process called compositing. The post-production phase is a very expensive step; in some cinema productions the combined cost for visual effects and post-production match the other production cost. It involves highly specialized and skilled jobs, like modeling, animation, virtual lighting, compositing, color grading, and linear editing of the final video/movie. Because of significantly lower budgets in TV, post-production is kept to a minimum and still the tendency in TV is to produce "in real-time."

It became more and more essential to the production team members to experience the sometimes fully or partially virtual scenes and assets. This has led to a drastic change in making moving pictures and resulted in

[5] In media production all items that are created in a creative process, including images, text, 3D content, and video clips are called assets.

higher efficiency, higher quality, and greater variety. It also challenges each team member to adapt to new technologies and methods such as set extensions, character animation, environmental controls, and pre-visualization [Nitsche 08].[6] Cinematography increasingly makes use of virtual data: Its elements and assets are created in the virtual realm all the way from the very first script until the very last frame on the screen.

Currently, there are barely any available systems to connect the different stages of a virtual production, and if so, they are proprietary and not accessible to other companies and parties. The vast variety in technical development (new cameras, new codecs, programming languages, interfaces, sensors, data transfers, etc.) renders the integration of different systems a very complicated task. The different approaches in producing moving pictures challenge at the same time vendors of technology to adapt their products for these needs, and demand from users new and more knowledge.

Using virtual production provides a direct and interactive visual feedback for everyone on the set, making decisions easier and more reliable. For instance, seeing the actual surrounding gives the director the chance to adjust camera framing and moves while shooting. Further, it gives actors visual feedback of virtual objects. Although actors are trained to perform without visual reference, it is hard to impossible to achieve a natural appearing interaction between real and virtual actors without on-set visualization, leading, e.g., to not matching eye-lines.

Besides these creative benefits, virtual production makes the film crew more independent of physical facts. For example, it is not necessary to wait until the right lighting situation outdoors arises, leaving the crew only a small time slot to shoot. The background as well as the fine-tuning of the lighting can be done later in a post-production step. This gives the film team much more time to retry a specific shot or to adjust it if needed. Furthermore, weather conditions or spatial limitations are almost no issue. It might be very costly to block a whole street or bring the whole team to the desired location in the Arctic. Using virtual production, the location in question can be filmed separately or created by artist on the PC, while the shooting of the scene takes place in the backyard or a film studio.

Apart from the direct interaction on set and the independence from time and space, virtual production can be used to decrease the time and cost that is needed for post-production. The actual amount of time that can be saved depends on the type and complexity of a specific production. It is possible to record the virtual background as well as the real foreground and compose both in real-time. This recorded material can be handed to the final cut, without being touched by any post-production. With TV and

[6] Also called previz.

movie productions getting visually more and more complex, this is rather an exception today.

Still, virtual production makes the post-production process easier in many ways. Recording a composed version of the shot beside the foreground gives the video editor, directors, producers, and 2D artists a solid and reliable impression of what the actual scene should look like. Using this reference can decrease the time that would be needed for an iterative process between director and artist until all scene elements are in their proper places. Misunderstandings are less likely to happen as the reference shot visually explains the scene.

Virtual production is a tool for the interaction between everyone involved in the production process. It is ideally designed for all different departments necessary to produce a film, TV show, commercial, live show, etc., and to connect those departments in an early stage and all through the whole process until the finished product.

Virtual production enables a very close relationship between clients and service providers, with the aim of ensuring that any questions and issues can be dealt with at a very early stage of production. The exchange of the (virtual) production data enables an efficient workflow between the departments. This can only be achieved with software and hardware systems that allow the exchange between the components involved in the production. Tasks can be split up after the idea or vision has been discussed and it is possible to imagine the result with the aid of pre-visualization.

Set Extensions and Virtual Backdrops in Commercials and Film

Filming at virtual locations can dramatically reduce costs compared to shooting on a real location. Critical production scenarios which allow filming only at short frames, like dawn or dusk, can be used continuously for an arbitrary duration in a virtual environment. Logistics of blocking streets for a production involving a dialogue in a driving car are no longer required if the scene can be convincingly produced in a virtual production scenario.

Moreover, this technique also allows situating film sets in locations that are inaccessible, or completely based on fictitious content. This applies for studio productions as well as for productions at outside locations where the real foreground is merged with virtual environment at medium to far distance. An example is shown in Figure 23.1 showcasing the real location which was shot at a former airfield in East Germany. The lower image displays the final scenery in which the location was extended to be situated in Guantanamo, Cuba.

For extending the scenery, digital assets and matte painting were created and combined with the filmed material. To fit the virtual elements into the filmed scene, it was necessary to match the set, the camera, and the

Figure 23.1: Set extension before and after. ©Filmakademie Baden-Wuerttemberg, 5 Jahre Leben, 2013.

lighting conditions. Additionally, the virtual camera needed to be as close as possible to the real one, including movement, lens effects, color, and even imperfections and artifacts caused by the real camera. The first step was to perform an exact match move to get information about the camera's movement and the lens geometry. Lighting and the surface definition were typically realized during, or directly after, the 3D asset creation process using digital content creation applications like Autodesk Maya or Maxon Cinema 3D. All 2D extensions, matte paintings, and cardboard styled assets were painted in tools like Adobe Photoshop or similar. These elements could also be animated or mixed with filmed footage. In the final step the generated assets were combined, visually matched and color grated in a compositing tool like the Foundry's Nuke or Adobe After Effects. For the given example the effective working time was about 20 man-days: 12 for the asset generation, 5 for the match move, 3 days compositing, and 1 day for revision requests.

A complete technical solution that enables virtual set production scenarios with realistic backdrops has been developed by Stargate Studios.[7] To meet the growing demand for low-cost alternatives to location shooting, Stargate Studios has developed the "next generation" stock footage library which specializes in virtual environments and customizable stock "locations." Branded by Stargate Studios in 2002 as the VIRTUAL BACKLOT (VB), the VB Library allows actors to literally walk into pre-shot footage—as if they were actually on location—without ever having to leave town.

The Virtual Backlot uses various techniques and methods to provide a range of options for creative production staff. The major components on producing in studio or outdoors are 3D rendering, camera tracking, and color keying (green and blue screen), all in real-time. Essential to the whole workflow is pre-production where, for example, the locations defined in the script are pre-recorded only with a small VFX team, instead of moving the whole production crew of up to 100 people to a designated destination. The recordings are called plates or background plates because they are used to replace the green screen.

Already a proven success in broadcast television, the VB "immersive environments" Library is beyond anything available in today's stock footage market. The environments vary from panoramic photographed and video sequences up to full 3D sceneries. Hundreds of hours of immersive footage have been acquired from multiple locations and successfully used by more than 165 feature, television, and commercial productions like the PanAm Demo[8] shown in Figure 23.2. As in 2014, 12 major television series are using VB on a regular basis. The cost model is so compelling that television networks are actually adopting creative content to match what is available in the VB library.

The most challenging and therefore also expensive piece of technology is the real-time component because its development is both time- and knowledge-consuming, and the market is still small. To register the movements of a film camera in real-time, only a few different technologies are available that allow the use in- and outdoors and are simple enough to be set up in as short as 1-3 hours on a stage or outdoors.

One of the most recent systems used in VB is the Lightcraft Previzion[9] system using Intersense technology. Here fiducial markers with circular barcodes are recorded by a small camera. The signal is processed in real-time to identify where each of the up to 300 circular barcodes is placed on the set and allow the real-time 3D render engine to define the current position and render a matching video stream according to the practical camera signal with only a short delay of 7 frames (@25 fps in 1920x1080).

[7] http://www.stargatestudios.net/
[8] http://vimeo.com/25483317
[9] http://www.lightcrafttech.com

Figure 23.2: PanAm Demo using Stargate VB, top to bottom: camera green screen material, on set previz (pre-composite), final composite after post-production. ©Stargate Studios.

A weaknesses of the Intersense tracking system is that its tracking camera has only a preset resolution, operational frame rate and light sensitivity. This means the fiducial markers have to be lit properly, have to be 100% fix (no movement is allowed). In some cases the limitation of only 300 fiducials allows for only a limited space to be tracked. The mounting of both fiducials and the Intersense camera on the production camera can be complicated.

Another extra procedure added to the production is the requirement to calibrate the lenses of the production camera before green screen shooting. This requires extra effort, and in the case of the Intersense system, a complex rig using pattern recognition on a large board of roughly the size of a mid-size desktop. To measure a prime lens (for example 35 mm Ultra Prime) takes from 30 to 60 minutes. To measure a zoom lens takes about 6-7 hours per lens. It is common to use, on average, film shooting 10 to 20 different lenses. Every single individual lens has to be calibrated because none is alike.

23.4 Real-Time Rendering with Game Engines

Game engines include reliable tools for real-time visualization addressing some of the needs of virtual production scenarios [Nitsche 08]. One solution currently in development is the Cinebox™system from the game developer studio Crytek™. The Cinebox™system is based on the Cryengine™[10] and provides extended functionality to meet filmmaking requirements. The software was used in the 3-minute branded-entertainment virtual production graduation short-film Dark Matter[11] [Y. Sahin and Backhaus 14].

The Dark Matter production combined digital video footage in 3k (ARRIRAW 16:9, 2880 x 1620 pixels) with real-time renderings from the game engine for live, on-set visualization, and the final render for the post-production. The game engine was the main and only tool for lighting and rendering of the short film. The workflow allowed having an editor on-set working with the produced media and preparing new versions of the short-film by the end of each production day, which could then be reviewed by the entire team.

One challenging issue in the workflow was to synchronize the game engine output, the live camera imagery, and the motion-capture data in a frame accurate way. This was accomplished by manually delaying the data streams using a custom software solution. Nevertheless, the game engine signal was not delivered at a fixed delay, which in minor cases resulted in asynchronous image output. A possible solution for this problem would be the integration of the live camera image directly in the game engine, thus reducing the complexity of syncing two sources to just one. Another aspect was camera tracking accuracy. Given that the motion capture systems precision was in the sub-millimeter range, the position definition of the real

[10] http://www.crytek.com/cryengine
[11] http://youtu.be/XlDL8hHVdDw

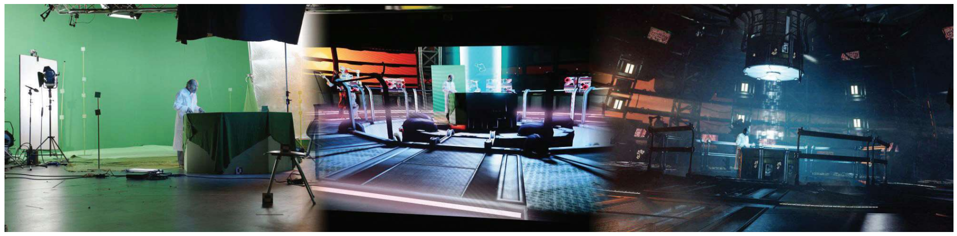

Figure 23.3: The Dark Matter production combined real camera footage with computer-generated imagery from game engine to provide interactive high-quality previsualization directly on a film set. ©Filmakademie Baden-Wuerttemberg, Dark Matter, 2014.

cameras film-back and the lenses nodal point was not sufficient. This led to a mismatching overlay of the real-footage and the CG elements. In post-production, the accuracy was still sufficient for most of the takes, and only 4 of the total of 33 sequences involving dynamic camera movement needed additional match move handling.

The alignment of the virtual with the real scene elements turned out to be another important issue. Lens and camera parameters were encoded as metadata [ALE 14] located in non-picture regions of the individual image frames, known as vertical ancillary data (VANC), to match the virtual lenses with the real ones. Real-time, high-quality chroma-keying and extraction of the actors, and practical assets have been other major obstacles to overcome in rendering the final images directly on set. In traditional VFX productions this is established as a classical post-production process, whereas in this production a dedicated hardware chroma-keying device was used that combined the game engine output with the keyed camera signal.

The Dark Matter short-film showcased an exemplary production pipeline for generating interactive, high-quality previsualization directly on the film set. Lighting parameters of the real set could be adjusted in the virtual scenery on the fly. The director of photography was able to preview the composed video signal directly in the camera. The visual consistency between on-set and final image was extremely close due to the continuous use of the same game engine technology throughout the entire production process. Exchanging and integrating assets in the post process was also possible in real-time. This resulted in a much more efficient post-production phase requiring only half of the time compared to a traditional workflow. Figure 23.3 shows the live camera, the real-time output of the game engine combined with the camera feed, and the final image.

23.5 Summary

Virtual production processes promise a new, more collaborative and interactive form of filmmaking. Advances in visual computing, in particular in sensing real-world parameters of cameras, assets and actors on one hand and progress in rendering and visualization on the other side show currently a major impact on the production process. With more visual computing tools to come it is expected that the process will be using more and more virtual techniques.

The state-of-the-art today is in most cases a rather complex custom development of all required technological aspects. Further development toward open standards will help to overcome some of these obstacles and allow for a more seamless exchange of data between individual hard- and software solutions. There are only a few turn-key solutions which can be picked up effortlessly. Game engines provide flexible, real-time tools, and their rendering quality and capabilities are constantly improving. Many film productions, however, demand physically correct image synthesis which in most cases relies on ray tracing. The future will show if these two can be combined in a meaningful way to support virtual production processes.

Preparing for virtual productions will also require a lot of rethinking of how assets and creative decisions will be made. The new creative freedom to make visual decisions directly on-set might also mix up established production pipelines (where most decisions are taken in post-production). Virtual production tools are also highly capable of democratizing the filmmaking process to individuals, independent filmmakers, tight budget, and academic productions.

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