Additional Information on Relativistic Visualization

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Additional Information on the Web

A web site with additional information and resources for this course can be accessed on `http://wwwvis.informatik.uni-stuttgart.de/relativity`.

Literature on Relativistic Visualization

Einstein's original work on the theory of special relativity was published in 1905 [9]. Its title "Zur Elektrodynamik bewegter Körper" ("On the electrodynamics of moving bodies") shows that the focus is on the connection between the description of electromagnetic phenomena (based on Maxwell's equations) and the kinematics of moving objects. Miller's book [22] contains a translation of Einstein's paper into English, along with more background information and historic remarks.

There exist numerous textbooks on special relativity, see, e.g., Møller [24] or Rindler [31]. The books by Misner et al. [23], Weinberg [36], d'Inverno [8], and Wald [35] primarily focus on general relativity, but contain some information on special relativity as well.

Remarkably, the issue of visual appearance and perception in special relativity was ignored for a long time, and consequently numerous misleading statements and interpretations persisted. Apart from a previously disregarded article by Lampa [21] in 1924 on the invisibility of the Lorentz contraction, it was only in 1959 that the first coherent solutions to this problem were described by Penrose [29] and Terrell [34]. (Reference [29] is included in the course notes, pages E-1–E-3; reference [34] is included on pages F-1–F-5). Later, more detailed descriptions of the geometrical appearance of fast moving objects were given by Weisskopf [44], Boas [4], Scott and Viner [33], and Scott and van Driel [32].

The first published work of which we are aware that used advanced graphics techniques to produce shaded images of fast-moving objects was that of Hsiung and Dunn [14] and Hsiung and Thibadeau [15]. (Reference [15] is included in the course notes, pages G-1–G-8.) They proposed an extension of normal three-dimensional ray tracing for image shading of fast moving objects. This technique accounts for relativistic effects on the apparent geometry as seen by the observer. Hsiung et al. [17] investigated relativistic ray tracing in more detail and included the visualization of the Doppler effect. Exploiting relativistic ray tracing, Hsiung et al. [16] used the viewer-dependent variation of the observed color of objects in the scene for the visualization of relativistic time dilation.

Real-time visualization of relativistic effects exploiting the *time-buffer* method was introduced by Hsiung et al. [18]. (Reference [18] is included in the course notes, pages H-1–H-7). The time-buffer technique resembles and can be mapped onto the normal z-buffer. It allows for relativistic polygon rendering using a scan-line technique suitable for real-time applications, and makes use of contemporary computer graphics hardware to achieve interactive frame rates. Gekelman et al. [12], Chang et al.[6], and Betts [3] study the polygon rendering approach in more detail and present comprehensive treatments.

Weiskopf et al. [42, 43] investigated special relativistic effects on illumination in detail, considering both the Doppler and the searchlight effects. (Reference [42] is included in the course notes, pages I-1–I-15). They showed how ray tracing and polygon rendering can be adapted to correctly incorporate relativistic illumination effects. Weiskopf et al. [42] contains a new derivation of the transformation of radiance and irradiance, giving the complete mathematical basis for simulating the searchlight effect.

Texture-based special relativistic rendering was proposed by Weiskopf [37] in order to exploit modern graphics hardware—especially, texturing and pixel fragment operations—for the real-time visualization of relativistic effects on geometry and illumination. Image-based special relativistic rendering was introduced by Weiskopf et al. [41], allowing for the production of photo-realistic images and movies without the need for laborious three-dimensional geometric modeling. (Reference [41] is included in the course notes, pages J-1–J-9).

Another issue in special relativistic visualization is user interaction and navigation. Usually, a user navigates through a virtual world by moving a virtual camera. The velocity or direction of motion of the camera is changed by acceleration. Therefore, acceleration is a prerequisite for an interactive virtual environment for special relativity. It is important to point out that special relativity is perfectly capable of describing the accelerated motion of object, as long as gravitation can be neglected. (Gravitation is described by general relativity.) Rau et al. [30] described how acceleration can be incorporated into special relativistic visualization and presented a simple relativistic flight simulator. Weiskopf [38] extends relativistic interaction techniques to support an immersive virtual environment for special relativity.

A comprehensive introduction to the theory of general relativity can be found, e.g., in the textbooks by Misner et al. [23], Weinberg [36], d'Inverno [8], or Wald [35].

The following articles are concerned with the appearance of objects under the influence of gravitational light deflection. Typically, well-known metrics with closed-form solutions are investigated. The most prominent example is the so-called Schwarzschild solution for a spherically symmetric, static distribution of matter. Nollert et al. [28], Ertl et al. [10], and Nemiroff [25], for example, investigated the appearance of a neutron star or the flight to a black hole. Nollert et al. [27] and Kraus [20] described general relativistic ray tracing in more detail. Gröller[13] gave a generic approach to non-linear ray tracing as a visualization technique. Bryson[5] presented a virtual environment for the visualization of geodesics in general relativity, where examples of the Schwarzschild and Kerr solutions are shown. (The Kerr solution describes the spacetime of a rotating black hole.) Weiskopf [39] showed how general relativistic ray tracing can be used as a visualization tool in gravitational research. (Reference [39] is included in the course notes, pages K-1–K-5).

Some specific examples for general relativistic objects and their corresponding curved spacetimes used in this course are the rigidly rotating disk of dust and the warp metric. Neugebauer and Meinel [26] and Ansorg [2] presented background information on the physics of the rigidly rotating disk of dust. The warp metric was proposed by Alcubierre [1] in 1994; Clark et al. [7] investigated the view from inside the warp spaceship. Ford and Roman [11] presented a comprehensible discussion of the problems of negative energy, “exotic” matter, and causality, which occur for the metric of the warp drive and traversable wormholes. Kobras et al. [19] proposed a method for imaged-based rendering in a general relativistic setting, presenting the visualization of the warp metric as an example.

A comprehensive presentation of techniques for special and general relativistic visualization can be found in Weiskopf [40].

Acknowledgments: Reprints Included in Course Notes

We would like to thank the authors and publishers who gave us permission to include the reprints of the papers below in the course notes.

- Roger Penrose and Cambridge University Press, Cambridge, U.K. for the permission to reprint the article: R. Penrose, “The apparent shape of a relativistically moving sphere”, Proceedings of the Cambridge Philosophical Society, vol. 55, 1959, pages 137–139.

- James Terrell and The American Physical Society (APS) for the permission to reprint the article: J. Terrell, “Invisibility of the Lorentz contraction”, Physical Review, vol. 116, no. 4, 1959, pages 1041–1045.

- Robert H. Thibadeau and ACM for the permission to reprint the article: P.-K. Hsiung, R. H. Thibadeau, “Spacetime visualization of relativistic effects”, Proceedings of the 1990 ACM Annual Conference on Cooperation, pages 236–243.
- Robert H. Thibadeau and ACM for the permission to reprint the article: P.-K. Hsiung, R. H. Thibadeau, M. Wu, “T-buffer: fast visualization of relativistic effects in spacetime”, Computer Graphics, vol. 24, no. 2, 1990, pages 83–88.
- ACM for the permission to reprint the article: D. Weiskopf, U. Kraus, H. Ruder, “Searchlight and Doppler effects in the visualization of special relativity: a corrected derivation of the transformation of radiance”, ACM Transactions on Graphics, vol. 18, no. 3, 1999, pages 278–292.
- IEEE for the permission to reprint the article: D. Weiskopf, D. Kobras, H. Ruder, “Real-world relativity: image-based special relativistic visualization”, Proceedings of the IEEE Visualization 2000 Conference, pages 303–310.
- IEEE for the permission to reprint the article: D. Weiskopf, “Non-linear ray tracing as a visualization tool for gravitational physics”, Proceedings of the IEEE Visualization 2000 Conference, pages 445–448.

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