Ray Tracing Non-Linear Spacewarps

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Abstract

Our work deals with visualizing scenes in the warped space (or global deformations of the scenes) based on the ray tracing method. Rather than deforming objects in the scene directly, the inverse spacewarp is applied to the sight rays transforming them into curves. Rendering with the curved rays evokes then illusion of the warped space. Proposed method keeps all qualities of ray tracing as the most popular method for photorealistic rendering and presents an unified solution for deformation of solids in either surface, analytic and volume representations. Algorithms for tracing the curved rays are investigated and illustrated in an experimental implementation.

Keywords: spacewarp, deformation, visualization, ray tracing, curved ray

1 Introduction

One of the popular and very powerful effects on images is the *image warping*, residing in an intentional deformation of the image by a non-linear transformation. An idea arises – what about doing something alike in three dimensions, let's call it *space warping*. A question, how a particular scene looks like in a deformed space, different from the common Euclidean one. A possibility to define one's own shape of the space in a virtual world. One example of a spacewarp in the real world is the space in a strong gravitational field, e.g. around the black holes in the universe.

The spacewarp can be considered as a kind of global deformation of the scene. There are some standard deformations established in the field of computer modeling (e.g. tapper, twist, bend or free-form deformation), applied easily to objects in polygonal representation (triangular mesh). Our vision is visualizing an (almost) arbitary deformation of the space applied to an arbitrarily represented scene, or even a scene with individual objects in various representations (e.g. analytic, implicit, volume). The key idea is the incorporating the space warping feature into the renderer. Thus there are two separate inputs to the renderer – the scene itself and a space deformation. Choosing ray tracing as the rendering method, besides all its valued qualities, gives rise to an elegant way how to visualize the deformed scene – using curved rays, instead of the straight ones, and keeping the scene intact. This unconventional idea with a couple of benefits appeared also in a few works in the past, see the References section.

2 Mathematical Model

We define the *spacewarp* (or *deformation of the space*) in accordance with one's intuitive expectations as a bijective and continuous mapping $\mathbf{w} : \mathbb{R}^3 \to \mathbb{R}^3$. So the spacewarp maps each point $\mathbf{p}$ of the space to an another point $\mathbf{w}(\mathbf{p})$. Bijectivity of $\mathbf{w}$ guarantees the inverse function existence and the continuity requirement is for reasonable spacewarp and makes its ray tracing feasible.

Applying the spacewarp $\mathbf{w}$ to all points forming a solid, we obtain the solid in the warped space, different in shape but with the same topological qualities (guaranteed by continuity of $\mathbf{w}$). We talk about 'warped space' since the coordinates have different meaning here, determining the point $\mathbf{w}(\mathbf{p})$ instead of $\mathbf{p}$. We consider the non-linear spacewarps primarily, though more difficult to evaluate, producing much more interesting results.

Example of a simple spacewarp is the parabolic spacewarp given by

$$\mathbf{w}(x, y, z) = (x, y + \frac{1}{2}x^2, z).$$

It is illustrated in Figure 1 with a sample solid.

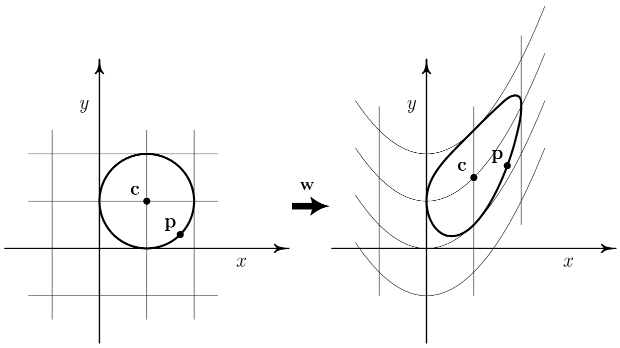

Figure 1. The parabolic spacewarp.

In order to visualize the deformed solid by ray tracing, we need to compute the intersection of a ray and a warped

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solid. It is most simple to derive it from the implicit form of the solid – let it be $F(\mathbf{p}) = 0$. Implicit form of the warped solid is then $F(\mathbf{w}^{-1}(\mathbf{p})) = 0$ and the intersection with the ray $\mathbf{r}(t)$ is such a point of the ray satisfying the implicit equation of the warped solid, thus

$$F(\mathbf{w}^{-1}(\mathbf{r}(t))) = 0.$$

The above equation was derived as a substitution of the ray points $\mathbf{r}(t)$ into the implicit equation of the warped solid $F(\mathbf{w}^{-1}(\mathbf{p})) = 0$. That equation can be, however, interpreted in a different way – as a substitution of points $\mathbf{w}^{-1}(\mathbf{r}(t))$, which are points of the inverse warped curved ray, into the implicit equation of the original solid $F(\mathbf{p}) = 0$.

We have proved now the fact, that intersection of the ray and a warped solid is the same as intersection of the inverse warped, curved ray and the original solid (the same result can be derived from the parametric form of the solid, see [5]). Expanding the idea results in the following method for rendering a scene in teh warped space. The whole scene remains as it is, unmodified and all rays become the curves made as inverse image of the straight rays under the spacewarp. Note that not only the rays have to be inverse warped, but all rendering agents as well, it means the viewpoint and projection plane, since they determine generated rays. See Figure 2 for a visual image of the situation. Using this principle it's evident that the scene "suspect" nothing about any warping, absolutely no coordinates, vertices or representations of the solids change, it is just rendered by an unusual method with curved rays instead of straight. That's one of the reasons why we say "spacewarp" and not a "global deformation of the scene".

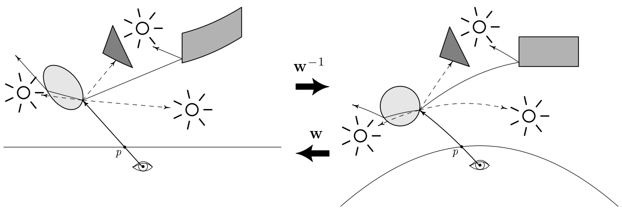

Figure 2. Ray tracing a scene in the warped space. Duality of tracing straight rays in deformed scene and tracing curved rays in unchanged scene.

3 Tracing the Curved Rays

Unlike the beautiful mathematical theory in previous section the intersection calculations are based on approximation methods and numerical math as the price of freedom for the spacewarp mapping. For thorough treatment of the curved ray tracing and some related issues we refer to the full thesis [5], here we briefly mention some key issues.

One fundamental problem is the inverse spacewarp $\mathbf{w}^{-1}$ calculation. If the designer supplies together with the spacewarp also a procedure for the inverse mapping (and it was the case for the most of the used spacewarps, e.g. the parabolic one), it is the simplest way and fastest in the rendering stage. Otherwise our general iterative algorithm approximating the value of the inverse mapping is employed, which is, however, incomparably slower and due to its heuristic nature, not always reliable.

As the most feasible method for tracing the curved ray was concluded the approximation by short line segments, allowing to use all existing procedures for ray-object intersection. Sampling of the ray can be uniform with a constant step or a more efficient one, adaptive sampling – ray curvature based or with sampling step dependent on the distance of the nearest object.

4 Implementation

To verify the correctness and feasibility of our approach an experimental implementation was developed, based on the popular free POV-Ray ray tracer. There are some predefined spacewarps or an arbitrary new one can be plugged in as a dynamic linked module (DLL on MS Windows). A scene for POV-Ray is given in a text file describing the scene composition from primitives, their attributes and modifiers, written in POV-Ray Scene Description Language. That language was extended by new commands specifying the spacewarp applied to the scene and its parameters (e.g. strength, etc.).

5 Conclusion & Results

We have proposed an unconventional approach for rendering warps of the space by ray tracing with curved rays. We have showed the duality of intersections in warped and common Euclidean space and outlined the tracing curved rays solutions. Feasibily of the approach is demonstrated by an experimental implementation.

The main advantage of our approach is universality – perhaps all representations can be handled by ray tracing and hence deformed by our method. Moreover only the visible part of the scene is actually deformed. On the other hand, a drawback of our approach is in computational time. But although severalfold slower than ray tracing the original undeformed scene, the rendering times are still reasonable. A weak point of our implementation is the general inversion heuristic, in spite of its reliablity about 99%, there are still visible artifacts degrading the image quality.

Our work is also one of early experiments with "rendertime modeling" or an "active renderer" concept, characteristic by tighter cooperation of the renderer and the scene, which may arise in the next years. It can be especially suitable for rendering natural phenomena or scenes extremely complex when modeled by present-day approach.

The full text of the thesis can be downloaded from http://www.geocities.com/jaroslav_semancik/projekty#diplom.

Finally a few images of our implementation follows, more images can be found on the webpage mentioned above.

References

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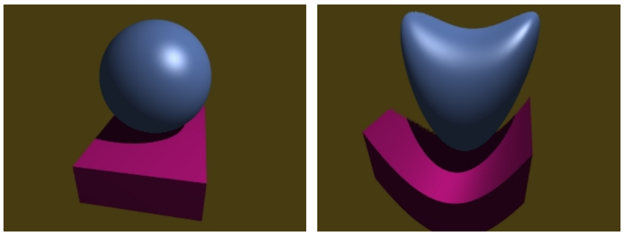

Figure 3. A simple scene in a parabolic spacewarp.

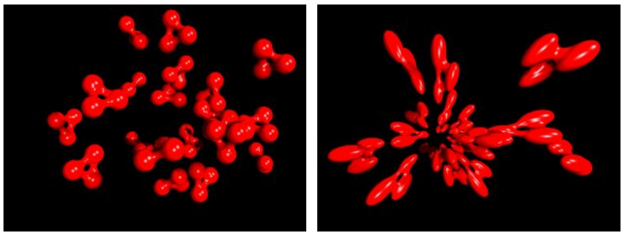

Figure 4. A cluster of blobs in a black hole spacewarp.

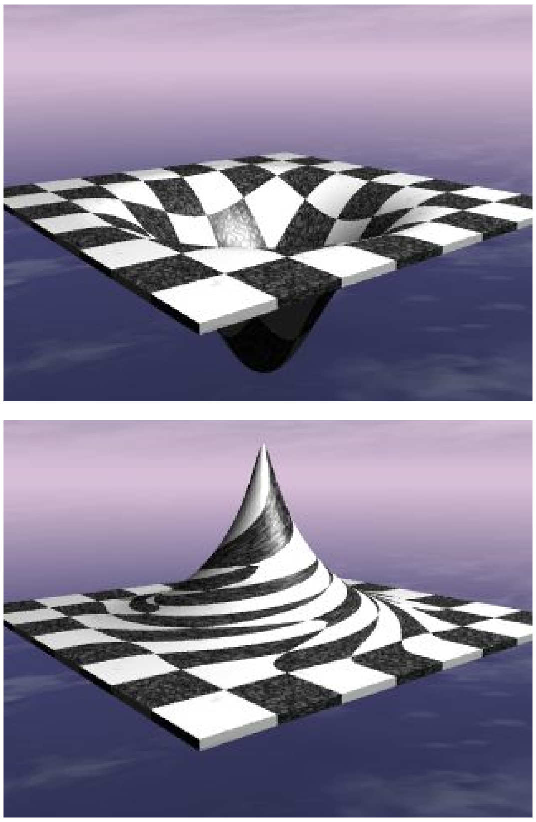

Figure 5. Variations of a whirl spacewarp on a chessboard.

Figure 6. Example of a complex scene in a whirl spacewarp.