Application of Multiple Iso-Surface Rendering to Improvement of Perceived Depth in Transparent Stereoscopic Visualization

Daimon Aoi¹,*, Kyoko Hasegawa², Liang Li², Yuichi Sakano³,⁴, Satoshi Tanaka²

¹Graduate School of Information Science and Engineering, Ritsumeikan University, 1-1-1 Noji-higashi, Kusatsu, Shiga, Japan
²College of Information Science and Engineering, Ritsumeikan University, 1-1-1 Noji-higashi, Kusatsu, Shiga, Japan
³Center for Information and Neural Networks (CiNet), National Institute of Information and Communications Technology, and Osaka University, 1-4 Yamadaoka, Suita, Osaka, Japan
⁴Graduate School of Frontier Biosciences, Osaka University, 1-4 Yamadaoka, Suita, Osaka, Japan

*is0291fe@ed.ritsumei.ac.jp

Abstract. Three-dimensional data visualization employing the CT and MRI techniques is widely used to understand the complex internal structure of the human body. However, the position and depth information often become unclear when three-dimensional data are rendered transparently. In this study, we aimed to improve the accuracy of the perceived 3D structure by introducing multiple iso-surfaces as a visual guide. For the purpose, we conducted psychophysical experiments. The experimental results suggest that multiple iso-surfaces improve the accuracy of the perceived depth. It was also found that the accuracy of perceived depth changes with the distance between the iso-surfaces.

Keywords: Transparent stereoscopic visualization, Multiple iso-surfaces, Depth perception, Medical volumetric data, Visual guide

1. Introduction

Analysis of three-dimensional data is performed in the many fields of science and medicine. Visualization is one such analytical method. It is possible to obtain scanning images of the body by imaging using the computed tomography (CT) and magnetic resonance imaging (MRI) techniques. The ray casting method, the marching cube method, cross-section visualization, and other methods are used to visualize these data. The human body is quite...
complicated because it contains objects with irregular shapes such as bones, blood vessels, and organs. Furthermore, for visualization of lesions inside the body, the body must be transparent. Diagnosis and informed consent are the typical purposes of the visualization of three-dimensional medical data. Therefore, these visualization images are not only viewed by doctors. Thus, it is necessary to create accessible visualizations for patients who do not have medical knowledge. However, previous studies [1, 2] have shown that correct perception of position and depth is challenging.

This complexity makes the created images less comprehensible. In our recent papers [1, 2], we have reported that transparent stereoscopic visualization is effective in reducing the complexity of visualized images. However, we have also found that we cannot always perceive the depth of each object correctly in the transparent stereoscopic visualization. This paper aims to solve this problem.

It is well-known that depth perception is produced via many types of depth cues. For instance, binocular disparity, which is the differences in the retinal images of the two eyes, and motion parallax that causes temporal changes of the retinal images due to motion of the observer are the well-known cues for depth [3]. Relative sizes in the retinal images [4] and occlusion [3] also provide depth information.

In this paper, we focused on providing an artificial hint to improve the accuracy of perceived depth in the iso-surface visualization of human volume data. In addition, there are many existing studies on the depth in volume rendering [5, 6, 7, 8, 9, 10]. The new contribution of this research is to improve the depth perception that occurs when volume rendering is combined with stereoscopic visualization. Specifically, it is a novel idea of overlapping an additional iso-surface as a visual guide, which improves the depth perception. The hint we propose is to place “an additional iso-surface” near the target iso-surface to be analyzed. In other words, we overlap an iso-surface with a slightly different iso-value with the target iso-surface. This means that we use the technique called “the multiple iso-surface” for volume-data visualization. Mutual occlusion between the target and the additional iso-surfaces becomes the hint to improve the depth perception. In our implementation, the multiple iso-surfaces are visualized by using stochastic point-based rendering (SPBR) [11, 12] which is a point-based transparent rendering. We convert the surfaces to point sets according to the procedure reported in reference [13] and apply SPBR to the generated data.

2. Visualization of multiple transparent iso-surfaces

Iso-surface visualization, which enables comprehensible viewing of the focused iso-levels of volume data regions, is a commonly-used volume rendering method. An iso-surfaces is often defined as a polygon mesh created by the marching-cubes method. However, in this study, we rather use the implicit surface, which is extracted from the smooth scalar field obtained by the Spline interpolation of the given volume data. The implicit-surface expression is precise and smooth compared with the polygon mesh created by the marching-cubes method. Therefore, we can avoid unwanted rendering artifacts, such as the effects of polygon edges. In this sense, the implicit-surface expression should be suitable for improving our perceptual depth recognition. We generate dense and uniform sampling points on the
smooth iso-surfaces using the stochastic sampling method (SSM) [14, 15, 16]. Then, we
transparently visualize the point-based iso-surfaces based on the stochastic point-based
rendering (SPBR) [12, 13].

2.1. Creation of point-based iso-surfaces using SSM
Let us consider twice-differentiable scalar field \( F(q) \) with \( q = (q_1, q_2, q_3) \) the 3D position
vector. SSM is the method that creates dense and uniform sampling points on an implicit
surface,

\[
F(q) = 0.
\]  

(1)

To sample the implicit surface based on a properly defined stochastic process, we introduce
a fictitious Brownian particle whose position vector is \( q \). We replace \( q \) with a function of
a fictitious time variable \( t \), i.e., with \( q(t) \). Then, we define the particle’s time development
based on the stochastic differential equation, whose solutions are confined to the implicit
surface defined by Eq. (1) [17, 18]. Correspondingly, the particle becomes a stochastic
particle that performs Brownian motion confined to the implicit surface. The stochastic
differential equation has the following form:

\[
dq_i(t) = dq_i^{(T)}(t) + dq_i^{(S)}(t),
\]

(2)

where the two terms on the right-hand side are defined as follows:

\[
dq_i^{(T)} = \sum_{j=1}^{d} P_{ij} dw_j,
\]

(3)

\[
dq_i^{(S)} = -\frac{\alpha}{|\nabla F|^2} \left( \frac{\partial F}{\partial q_i} \right) \text{Tr}[(\partial^2 F) \cdot P] dt.
\]

(4)

In Eq. (3), \( dw_j \) is a component of the Gaussian white noise vector satisfying the following
statistical property: \( \langle dw_j \rangle = 0, \langle dw_j dw_j \rangle = 2\delta_{jj} \). The bracket \( \langle \cdot \rangle = 0 \) means an ensemble
average. In Eqs. (3) and (4), \( P \) is the projection matrix whose components are defined by
\( \delta_{ij} - (\nabla F)_j (\nabla F)_j / |\nabla F|^2 \). By solving the above stochastic differential equation numerically,
we can generate dense and uniformly-distributed points on implicit surface (1).

How to apply SSM to an iso-surface of volume data is straightforward. All we have to
do is to define the scalar field \( F(q) \) as

\[
F(q) = S(q) - C,
\]

(5)

if we hope to generate sampling points on iso-surface \( S(q) = C \). Here, \( S(q) \) is a smooth
and continuous scalar field defined by applying the Spline interpolation to voxel data of
the target volume, and \( C \) is a user-defined iso-value. By solving the stochastic differential
equation (2) numerically for \( F(q) \) of Eq. (5), we can generate high-quality sampling points
that are dense and uniform enough for precise point-based surface rendering.

For point-based visualization of multiple iso-surfaces, we repeat the sampling for differ-
et values of \( C \). We can then obtain an entire point set that defines all the iso-surfaces by
merging all the obtained point datasets.
2.2. Stochastic point-based rendering

Stochastic point-based rendering (SPBR) [11, 12, 13] is the high-quality transparent visualization method applicable to point-based surface data. The method is free from the rendering artifacts that originate from the ambiguity of the depth-sorted orders of rendering primitives. The method realizes the correct depth feel in the transparent visualization with interactive rendering speeds.

The procedure of SPBR is as follows:

**Step 1:** Point generation
Prepare uniformly distributed sampling points on the target surface. In our study, the execution of SSM for the iso-surfaces becomes this step.

**Step 2:** Division of the point dataset into multiple point ensembles
The point dataset prepared in Step 1 is randomly divided into multiple point ensembles. We call the number of point ensembles “repeat level” that is denoted as \( L_R \) below.

**Step 3:** Point projection per point ensemble
For each point ensemble, project its constituent 3D points to the image plane independently. As a result, \( L_R \) intermediate images are created. In the projection process, we incorporate the point occlusion effect per pixel.

**Step 4:** Averaging the intermediate images
Create the final transparent image by averaging brightness values per pixel for the \( L_R \) intermediate images created in Step 3. The repeat level \( L_R \) controls the statistical accuracy and works as an image-quality parameter for this final image.

In the above-mentioned transparent visualization using SPBR, surface opacity is flexibly controllable by tuning point density. Under the assumption that the points distribute on the surface uniformly, opacity \( \alpha \) obeys the following formula:

\[
\alpha = 1 - \left( 1 - \frac{s_A}{s_p} \right)^{\frac{L_R}{n}} ,
\]  

where \( n \) is the number of points within an arbitrarily selected local surface portion, \( s_A \) is the surface portion area, \( s_p \) is the area size whose image becomes just one pixel, and \( L_R \) is the repeat level defined above.

SPBR realizes transparent visualization with correct depth feel [19]. However, we have recently proved that it is not true for transparent stereoscopic visualization [1, 2].

3. Visual Assistance Based on Multiple Iso-Surfaces (Proposed Method)

Based on the idea to add an iso-surface to improve the depth perception, the procedure of the proposed method is formulated as follows:
1. Determine the iso-value $C_0$ of the target iso-surface to be observed.

2. Determine an additional iso-value $C_1$ that is slightly different from $C_0$ such that the additional iso-surface with iso-value $C_1$ is placed near and inside the target iso-surface.

3. Execute the transparent stereoscopic visualization of the target iso-surface together with the additional iso-surface.

The additional iso-surface has a shape similar to the target iso-surface, and is placed near and inside the target iso-surface. We place an additional inner iso-surface, because this obtains a better observation of the target iso-surface than that obtained by adding an outer iso-surface. We note that the inner surface also creates occlusion because we observe both the target and additional iso-surfaces in transparent visualization. In this visualization of the multiple (dual) iso-surfaces, we can also use two rendering effects to improve the depth perception. The first effect is “luminance contrast”, and the second effect is “luminance gradient”. We investigate the two effects in our experiments as described below.

Let us explain the two effects mentioned above. The “luminance contrast” is related to the selection of the background color in the visualization. It is known that the perceived depth order depends on the luminance contrast between the visualized objects and the background [20, 21, 22, 23, 24]. An observer tends to perceive an object with higher contrast against the background as being closer. This perceptual effect of luminance contrast corresponds to that of aerial perspective [22]. The “luminance gradient” is a shading effect inherent to SPBR [15, 25]. SPBR controls surface opacity through point density. If a surface portion is inclined from the viewing direction, its apparent area for the observer decreases compared with the perpendicular viewing. Assuming that points that are the rendering primitives of SPBR are distributed uniformly on the visualized surface, the inclined portion of the iso-surface becomes opaquer than the other portions. This increasing opacity acts as a shading effect and a perception hint.

4. Experiments

4.1. Experimental conditions

To present stimulus images, we used a 42-inch autostereoscopic display utilizing a parallax barrier (TRIDELITY Display Solutions LLC, New Jersey, United States). This 3D display presented five views that provided binocular disparity and motion parallax so that the observers could perceive the presented images in 3D without glasses [26, 27, 28, 29, 30, 31]. The image resolution for each view was $1920 \times 1080$. The viewing distance for the best 3D image quality of the display was 350 cm. In the experiment, the subjects viewed the display at this distance.

In the experiments, the subjects observed the images binocularly or monocularly. In the monocular conditions, the nondominant eye was occluded by an opaque eye patch so that no binocular disparity was provided. While observing the images, the subjects fixed their heads or moved their heads laterally. In the no head-motion condition, the subjects placed their chins on a chin rest so that no motion parallax was provided.
Eighteen volunteers in their 20s participated in the experiments. They wore their own glasses or contact lenses if needed. All of the volunteers had normal or corrected-to-normal visual acuity and normal stereo vision [32]. Prior to the experiments, we confirmed that all of the subjects could see the 3D image with the motion parallax only by using the autostereoscopic 3D display. The stimulus images were presented in random order for each subject.

4.2. Experiment using cuboid images

The test stimulus was a cuboid of the surface data. The frontal surface was a square of 100 mm × 100 mm, and the depth was 100 mm (i.e., a cube), 150 mm, or 200 mm. (see Fig. 1)

![Figure 1: Stimuli used in the experiment.](image)

In some conditions, a smaller cuboid of surface data was also presented inside the cuboidal test surface to improve the accuracy of the perceived depth of the test surface. The length of each side of the inner surface was half or 3/4 of the side of the outer test surface. The opacity (α) of the test surface was 0.2 while that of the inner surface was 0.1 (brighter; Fig. 2a, Fig. 3a) or 0.3 (darker; Fig. 2b, Fig. 3b). Therefore, four cases of the inner surface conditions were examined in addition to the case of the data without the inner surface. A total of 60 experimental cases (three magnitudes of depth of the test surface, five conditions of the inner surface, with and without binocular disparity, and with and without motion parallax) were examined.

The subjects were asked to report the depth magnitude of the outer test surface by giving a number based on the assumption that the length of one side of the front square of the test surface was equal to one. The correct answer was 1, 1.5, or 2. The trial order of all 60 cases was randomized for each subject.

Figure 4 shows the experimental results under different conditions. As observed from Fig. 4, in the absence of an inner surface, the depth magnitude of the test surface was underestimated by approximately 20-65% in all of the tests conditions. This result is consistent with the results obtained in previous studies [1, 2]. However, this depth underestimation was alleviated by introducing binocular disparity and motion parallax. This result suggests that binocular disparity and motion parallax provided by an autostereoscopic display are effective for improving the accuracy of the perceived depth of a transparently visualized object.
When neither binocular disparity nor motion parallax were provided, the inner surface alleviated the depth underestimation of the test surface irrespective of the simulated depth or the opacity of the inner surface. This alleviation of depth underestimation may be due to the visual contrast effect in terms of the 3D size [33, 34, 35, 36, 37, 38]. That is the test surface may have been perceived to be larger due to the presence of the smaller inner surface.

When the inner surface was half the size of the outer surface, the depth underestimation was alleviated irrespective of the existence of binocular disparity or motion parallax. On the other hand, when the inner surface was 3/4 of the size of the outer surface, the alleviation effect was not observed consistently. This difference in the alleviation effect between the different sizes of the inner surface can be attributed at least in part to the fact that while the half-sized inner surface did not overlap with the test surface in any view, the 3/4-sized inner surface did so in some views (Fig. 5). Such overlap may have precluded the visual system from detecting binocular disparity and motion parallax of the overlapped part in the views; that is, the vertical back edge of the test surface and the vertical front edge of the inner surface.
Figure 4: Results of the cuboid experiment. The error bars indicate the standard error of the mean (SEM).

Figure 5: Enlarged view of the upper portion of Fig. 3(b).
4.3. Experiments using medical images

The medical data used in this experiment were three-dimensional volume data generated from CT images. The value represented by the volume data was the density value (hereafter called the “iso-value”). We prepared four kinds of medical surface data with the iso-values of 78.90, 119.75, 201.44, and 242.49 as the iso-surfaces. We express an iso-value as \( C_0 \), \( C_1 \) and the opacity as \( \alpha \). The outer iso-value of all the stimulus images was \( C_0 = 78.90 \) (Fig. 6a). The inner iso-surface was \( C_1 = 119.75, 201.44 \) (Fig. 6b), and 242.49. The stimulus image was composed of a single (test) iso-surface or of multiple (both test and inner) iso-surfaces. In the case of multiple iso-surfaces, there were three inner iso-surface conditions \( C_1 = 119.75, 201.44, \) and 242.49) and two opacity conditions \( \alpha = 0.03 \) and 0.09). The opacity of the test surface was fixed at 0.06.

Figures 7 and 8 show the cases where the inner iso-surface was lighter and darker, respectively. These images were presented with or without binocular disparity and/or motion parallax.

The subjects were asked to report the distance in the depth direction from the frontal cross-section of the spine (the lower cylinder) to a point on the outer edge of the heart (the orange dot in Fig. 9) by giving a number based on the assumption that the radius of the red circle (the red circle in Fig. 9) was one. The correct answer was 2.45. All of the 28 stimulus images were presented in random order for each subject.

![Figure 6: The outer test iso-surface (a) and the inner iso-surface (b).](image_url)
Figure 7: Multiple iso-surfaces of the outer test iso-surface (Fig. 6a) and the inner iso-surface (Fig. 6b).

Figure 8: Multiple iso-surfaces with the higher opacity of the inner surface (0.09).

Figure 9: Image stimuli used in the experiment. The orange dot and the red circle were presented only on the questionnaire paper in the experiment.

As in the experiment using cuboid images, the depth magnitude of the test surface was underestimated in the absence of the inner surface (Fig. 10). This depth underestimation was slightly alleviated by providing motion parallax. The depth underestimation of the test surface was alleviated by introducing an inner surface. This alleviation was clearer when binocular disparity was provided. On the other hand, the effects of the iso-value and opacity were not clearly observed.
4.4. Comparison of the results of the two experiments

Most importantly, in both experiments the depth of the test surface was underestimated, yet this depth underestimation was alleviated by the introduction of either an inner surface or a motion parallax.

On the other hand, in the experiment using medical data, the alleviation of the depth underestimation appeared to be somewhat weaker than that in the cuboid experiment, including in the condition under which no binocular disparity was provided. Since there were many differences in the images presented in the two experiments, we cannot determine what caused the differences in the results of the two experiments. Nevertheless, there are at least two possible reasons for these differences. First, the medical inner surface was not a similar figure to the test surface (Fig. 11). The similarity may have enhanced the alleviation of the depth underestimation in the cuboid experiment. Second, in the experiment using the medical data, the inner surface may have been too close to the test surface, as in the 3/4-sized...
inner surface used in the cuboid experiment. It is still necessary to elucidate the origin of
the differences between the results of the two experiments.

Figure 11: Enlarged view of the upper left portion of Fig. 8.

5. Conclusion and discussion

In medical visualization, transparent visualization is essential to observe inside a human
body. However, in our previous study [2], we found that the depth of a transparently-
visualized surface tends to be perceptually underestimated. This phenomenon occurs for
substantially high transparency. In this paper, we have shown that such perceptual-depth
underestimation is alleviated by the artificially added assisting inner surface. Based on the
experiments, we have proved that the proposed method does work for improving depth per-
ception.

Although we have defined the assisting inner surface as the implicit surface, we can
also define the surface with another method. For example, we can use the marching cubes
method or the peak-finding approaches of the volume rendering. It should also be mentioned
here that the assisted target (the object to be investigated) can be either the surface or the
volume. In our future study, we will apply our method to improve the depth perception of
the direct volume rendering.

The proposed method can indeed improve depth perception. However, the improved
depth is still lower than the true value, which means we should further improve the method.
There are several possibilities for improvement. First, we should find an optimized distance
between the target surface and the assisting inner surface. We have demonstrated that the in-
ner assisting surface works more effectively when it does not overlap with the target surface
in the rendered image. This result also suggests we should optimize the distance. Second,
we can use the proposed method in combination with other visual guides. For example,
we can highlight high-curvature regions of the inner assisting surface to improve its stereo-
scopic effect [15]. It should also be noted that implicit surface expression is convenient for
calculating the surface curvatures. In the above-mentioned future work, we will also con-
duct experiments for subjects with more varieties of ages and genders, which should refine
the method up to the practical level.

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