Perception-Aware Uncertainty Glyphs in the 3D Vector Fields

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Abstract

We often cannot avoid value uncertainties when curating raw data to obtain a final visualization image. Although numerous studies maintain the importance of uncertainty visualization, there lack a standard means of depicting the information, especially in 3D flow visualization tasks. We introduce a novel glyph design referred to as the disk-tailed arrow which shows the trends and uncertainties in 3D vector fields concisely. The proposed design includes a glyph shape and modeling strategies which map statistical information to visual cues. Our scheme is devised so that the user can perceive 3D uncertainty information effectively. We also present a case study of the application of the proposed glyph to an actual flow dataset as an assessment.

CCS Concepts

•***Human-centered computing*** → ***Scientific visualization;***

1. Introduction

In 3D flow visualization, the vector glyph is one of the widely used methods to depict local vector field directly. If we place too many glyphs in the vector fields using this method, however, severe visual clutter can arise. Thus, one may resample and interpolate the vector fields to reduce the number of glyphs so as to prevent visual clutter and show the essential features of the data. When transforming raw data into a reduced form, the uncertainty in the values increases [PWL97]. Many visualization methods for vector fields, however, ignore the uncertainty and seldom depict it. They may calculate a mean vector of the given region and show it as a representative vector while ignoring its dispersion. Because uncertainty typically determines the confidence or error level of raw data, disregarding it can lead to misrepresentations and incorrect conclusions [PWL97] [PKRJ10].

Humans have a weaker perception of the length and angle in 3D space than in 2D [War08] [Mun14] because spatial perception towards the depth shows poorer accuracy than in other directions. Many previous glyph designs, however, naively map vector attributes into a 3D glyph shape such as a standard arrow or cone without considering asymmetric perception in the 3D space. Although many glyph designs fail to show 3D vector attributes perceptibly, few visualization studies have considered human factors such as visual perception [TM04]. In this paper, we present a novel visualization method on the uncertainty of 3D vector fields. The contributions of this paper are as follows:

- A novel 3D vector glyph design which gives strong 3D orientation cues and rich visual hints to show trends and uncertainties perceivably
- An effective modeling strategy to map the trends and uncertainties of vectors into the proposed glyph design

2. Related Works

2.1. Uncertainty Visualization

Many methods have been proposed to visualize uncertainties. For vector field data, presented in the past two decades, traditional statistical method such as the mean and variance have been applied to compute uncertainties. With regard to visualization, Wittenbrink et al. [WPL96] proposed a vector glyph design to show the uncertainties of vector fields. Moreover, they presented both quantitative and qualitative methods to evaluate their works in comparison with traditional techniques. Peng et al. [PGL*12] showed trends and uncertainties of vector fields on the 3D surfaces. They presented $|v|$-range glyphs and θ-range glyphs to depict the variance in the magnitude and direction of a vector field. Tong et al. [TZJ*16] proposed the crystal glyph method, which shows the distribution of vector directions in 3D space. A few studies which extracted the uncertainties in ensemble vector fields have been published as well. Potter et al. [PWB*09] presented a visualization method that shows the mean and standard deviation of ensemble members via color encoding and with contour lines to depict high (or low) uncertainty areas throughout the data. Jarema et al. [JDKW15] proposed a method which can be used to draw the distribution of vector directions in ensemble vector fields using a Gaussian mixture model. They also presented a glyph design for uncertainty visualization, especially for 2D vector fields. Mirzargar et al. [MWK14] suggested visualization method named the curve boxplot which shows a statistical summary of particle trajectories adopting a traditional boxplot scheme. The technique can depict various statis-

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Figure 1: *Slant orientations of the proposed glyph design. One may be able to perceive the change in the rotation using two visual cues: the shape of the arrow tip and the aspect ratio of the base disk.*

tical information such as mean, median, and outliers. Ferstl et al. [FKRW16] proposed a method which determines the uncertainty of flow streams in 3D ensemble vector fields. Their technique produces several clusters of pathlines and computes a Gaussian distribution model to generate a median pathline and confidence lobe for all pathlines. Schultz et al. [SSSSW13] suggested the HiFiVE glyph to present the uncertainties of the fiber direction with regard to the diffusion MRI datasets.

2.2. Visual Perception in the 3D Space

A few studies of human visual perception of 3D rotations have also been proposed. 3D rotation can be divided by slant and tilt [NTN*06]. Tilt refers to a rotation angle around the line of sight, while slant is the angle between the object axis and the line of sight [OD02]. Multiple studies have shown that tilt perception is much better than slant. Willats [Wil92] argued that the slant perception resolution is around 1 to 10 degrees, whereas the tilt resolution ranges from 0.1 to 1 degrees. Oomes et al. [OD02] also showed similar results. They studied the 3D orientation perception of stick and slab objects and found that the stick type is more perceptible than the slab type at both slant and tilt orientations.

3. Uncertainty Glyphs

We propose a novel glyph design for 3D vector uncertainties in this section. Vector fields with uncertainties can be described by pairs of a representative vector and the associated dispersion [WPL96]. The representative vector shows the trend of the data and dispersion presents the uncertainty.

3.1. Glyph Design

Human tend to map vector attributes onto the following visual channels.

- direction : angle
- magnitude : length (1D), area (2D), volume (3D)

Different visual channels can be adopted for magnitude, while only one channel - angle - is used for direction. This type of visual mapping is easily interpretable for humans without train because it is natural. However, it is not easily perceptible in the 3D space due to the poor depth perception of humans. We propose a novel glyph design referred to as the disk-tailed arrow, which is an arrow with a disk tail, as shown in Figure 1 and Figure 2. The proposed design is inspired by the "gauge figure", which is used in various papers to depict the orientation of a plane and the normal vector [KDK92] [NTN*06] [NTM11]. A human can efficiently perceive the orientation of the proposed glyph because the arrow and disk in the design are orthogonal to each other. In general, the orientations of stick objects such as arrows are difficult to perceive when the long axis of the object is parallel to the line of sight, while slab objects such as a disk are difficult to notice when the normal vector of the slab is perpendicular to the viewing direction [OD02]. Because stick and slab objects are orthogonally assembled in the proposed glyph design, there is mutual compensation. When the arrow is located towards the viewing position, the base disk reinforces the orientation cue, and vice versa. The change of the aspect ratio of the attached disk in the projected image space provides the orientation stimuli such that humans can adequately perceive the representative direction of the vector fields.

3.2. Uncertainty Mappings

There are four different vector attributes used to represent uncertain vector fields as a single glyph.

- Representative magnitude
- Representative direction
- Dispersion of magnitude
- Dispersion of direction

Ordinary vector data consist of two attributes - magnitude and direction. However, uncertainty adds dispersion, which is difficult to depict using traditional glyph designs such as an arrow, a cone, or an ellipsoid. The proposed design provides five different visual cues: the length and orientation of the arrow, the length of the arrow tip, the size and orientation of the disk. Despite the shape provides more cues, such as a radius of the arrow tip and aspect ratio of the disk, most of them are not suitable for information mapping because some are too small for the difference to be noticed, or they mutually interfere with other cues, i.e., the volume and length, the aspect ratio of the base disk and its orientation. Moreover, following the design guideline for glyphs [BKC*13], we discard the option to vary the aspect ratio of the disk which create asymmetric shapes. Among the five visual cues, the length and orientation of the disk-tailed arrow are assigned to two representative attributes, as shown in Figure 2. Because this involves intuitive mapping, people can interpret it easily without training. We mapped dispersions into the remaining cues, i.e., the arrow tip and the base disk. The dispersion of the magnitude is mapped into the length of the arrow tip, and that of the direction is assigned to the size of the base disk. Figure 2 shows the proposed attribute mappings to the visual cues in the disk-tailed arrow glyph. A cone, which widely used for glyph visualization, provides only three exclusive visual cues: the height and orientation of the central axis and the size of the base. Concerning perception, a triangle-shaped projected image into a 2D space may cause a misreading of the direction of the vector. Moreover, because a cone occupies more pixels than the proposed glyph in the final image, it is more likely to produce heavy clutter, as shown in Figure 3. Significantly larger portions of the cutting slice under the cone are hidden compared to that of the disk-tailed arrow in these figures.

4. Modeling Strategy

4.1. Statistical Modeling

In this section, we present a modeling strategy for the representative and dispersion attributes using statistics. First, we adopt the mean magnitude and direction for the representative attributes. Statistically, the mean is one of the most frequently used central values. For the dispersion, we adopted the variance and two absolute deviations, in this case the average absolute deviation (AAD) and the median absolute deviation (MAD). The AAD is the mean of the absolute deviations between the mean and individual raw values, while the MAD is the median of the absolute deviations. The two absolute deviations are defined as follows:

$$AAD = \frac{\sum_{i=1}^{N} |\mu - x_i|}{N}$$
$$MAD = m(|\mu - x_i|)$$

where $x \in X$, that is, a set of x; μ is the mean of X; $m(X)$ is the median of X; and $|A-B|$ is the deviation of two vectors A and B.

To address the deviation of two different vectors, we define an angle deviation $|A-B|$ as the angle included in the two vectors A and B.

4.2. Visual Mapping

In the magnitude case, representative values are visually mapped to the total length of the arrow, while dispersions are assigned to the length of the arrow tip. Because they can be drawn in the same space on an identical scale, we can interpret them naturally. Variance, on the other hand, can also be applied to the length of the arrow tip, but this may produce misleading information because it has a different scale with the mean drawn as an arrow.

When the dispersion is higher than the representative value, the arrow tip should be longer than the arrow itself. In such a case, the arrow tip may elongate the length of the arrow and hide other components in the proposed glyph, such as the shaft and base disk. Because this can cause misinterpretations, we ensure that the length of the arrow tip cannot exceed that of the arrow itself.

5. Case Study

We apply the proposed design to the Hurricane Isabel dataset to compare the visual encodings of the dispersion variables. We divide the data, which has a resolution of 512 × 512 × 100, into 256 small bricks with a resolution of 32 × 32 × 100 to resample the data and create uncertainty glyphs representing a brick. Each glyph is colored by a magnitude dispersion to emphasize it because it is less perceptible than the direction dispersion. This occurs due to the visual cue of the magnitude dispersion - the arrow tip - which is less perceivable than that of the direction dispersion.

Figure 4 shows a comparison of different dispersion encodings, in this case the AAD, MAD and variance. Each figure is originally

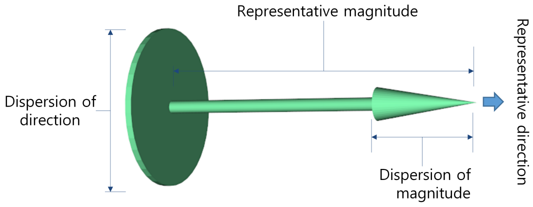
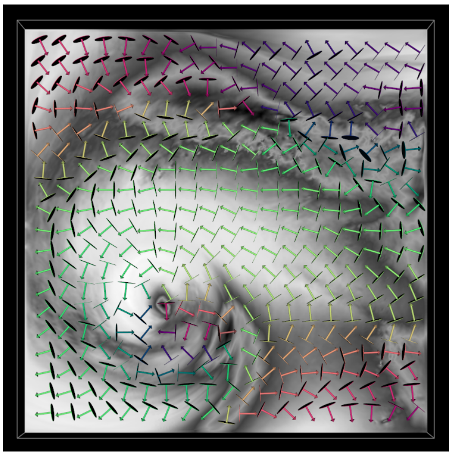
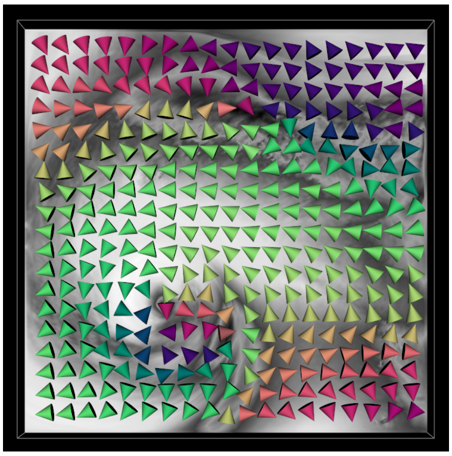


Figure 2: *Disk-tailed arrow glyph*



(a) Disk-tailed Arrow



(b) Cone

Figure 3: *Comparison of the disk-tailed arrow and cone glyph*

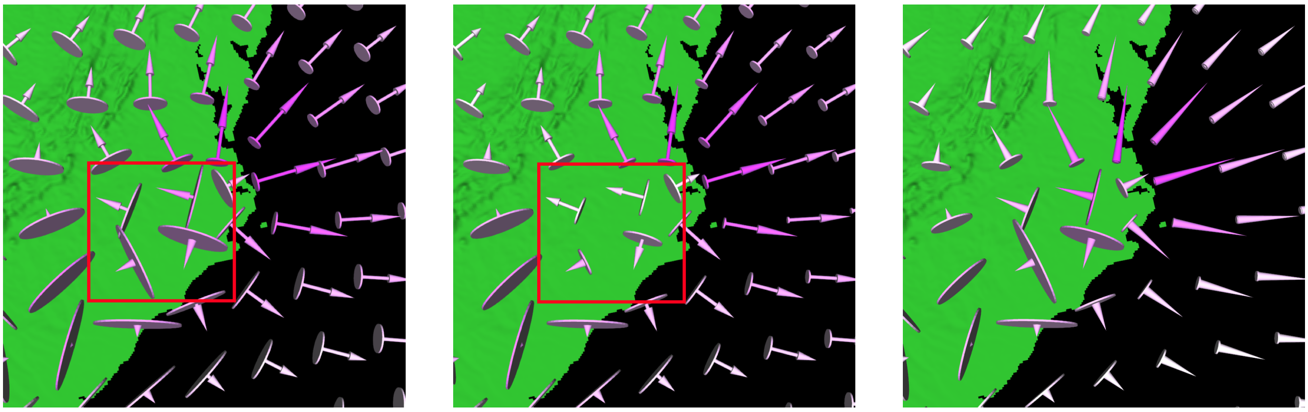

(a) AAD (b) MAD (c) Variance

Figure 4: *Comparisons of different dispersion encodings on the disk-tailed arrow in the Isabel dataset*

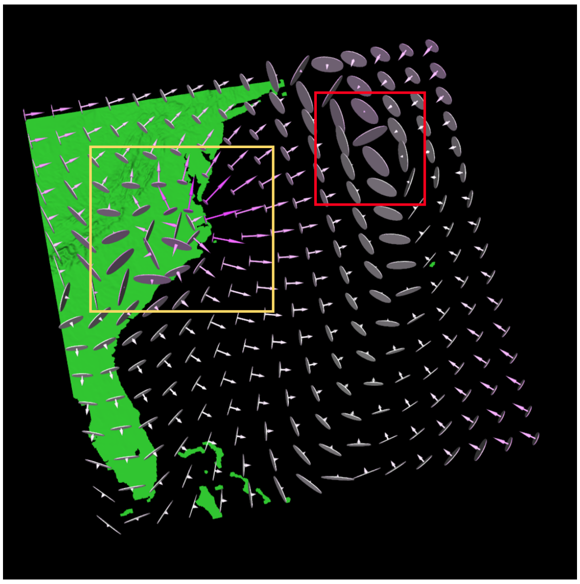


Figure 5: *Overall look of uncertainty glyphs in the Hurricane Isabel data*

generated in the form of Figure 5 and located inside of the yellow box. We magnified them to show the differences more clearly. For the magnitude dispersion, we noted that the variance creates a larger arrow tip than the other cases across all vector fields. This occurs due to the scale difference between the variance and the other cases. The variance changes more dynamically than the absolute deviations in terms of the direction dispersion. A square scale of the variance creates much larger visual cues for a higher dispersion area and smaller ones for a lower area. AAD and MAD produce similar results, although MAD tends to show much smaller direction dispersions than AAD. We also note that the base disks in (b) are smaller than those in (a), as shown in the red boxes in Figure 4. We believe that this is due to the significant number of outliers in that region. MAD reveals the central tendency of the main distribution excluding outliers, while AAD shows the overall tendency with outliers.

Figure 5 shows the overall appearance of the visualization results. There are high direction dispersions in the red box, which indicate the uncertainty of the direction is relatively significant. On the other hand, there are high magnitude trends and uncertainties with low directional uncertainties around the right side of the yellow box. In this case study, we can effectively extract interesting regions with high levels of uncertainty. We also detect areas with considerable outliers where may contain separate trends by comparing two different absolute deviations. Those regions must be divided into finer regions and additionally investigated recursively.

6. Conclusions and Future Works

We have presented an effectively perceivable design for an uncertainty glyph in 3D vector fields in this paper. The proposed glyph is designed to depict major trends and uncertainties perceivably. To accomplish this goal, we introduce a disk-tailed arrow, which gives not only rich 3D orientation cues but also a sufficient number of visual hints to show the important vector attributes all at once. Furthermore, we performed a case study using Hurricane Isabel data and presented comparisons of three different dispersion encoding schemes. The proposed glyph design needs some improvement. In the next phase of this research, we plan to enhance the glyph to present outliers and dispersions in every direction, which may yield volumetric representations. We are currently developing a design for quantitative evaluations of the proposed glyph using additional flow datasets. Moreover, we will investigate our method further by applying it to vector field ensembles as well.

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