Mesh-Driven Vector Field Clustering and Visualization: An Image-Based Approach

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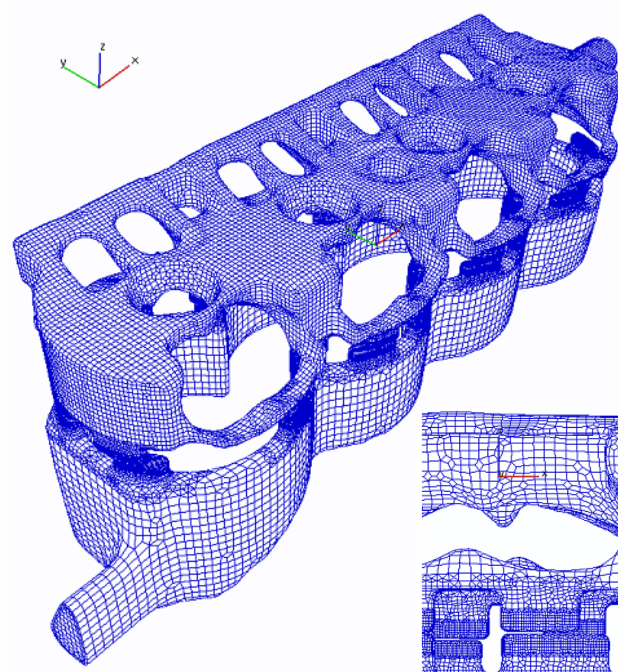
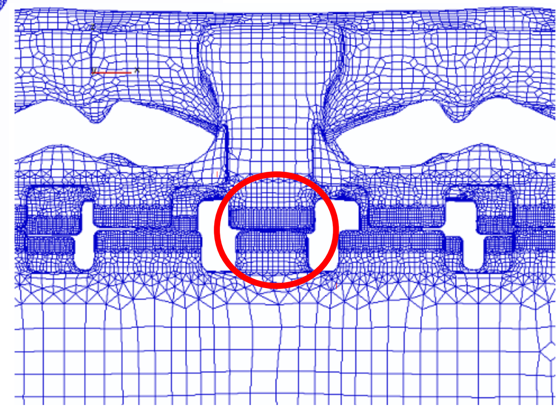
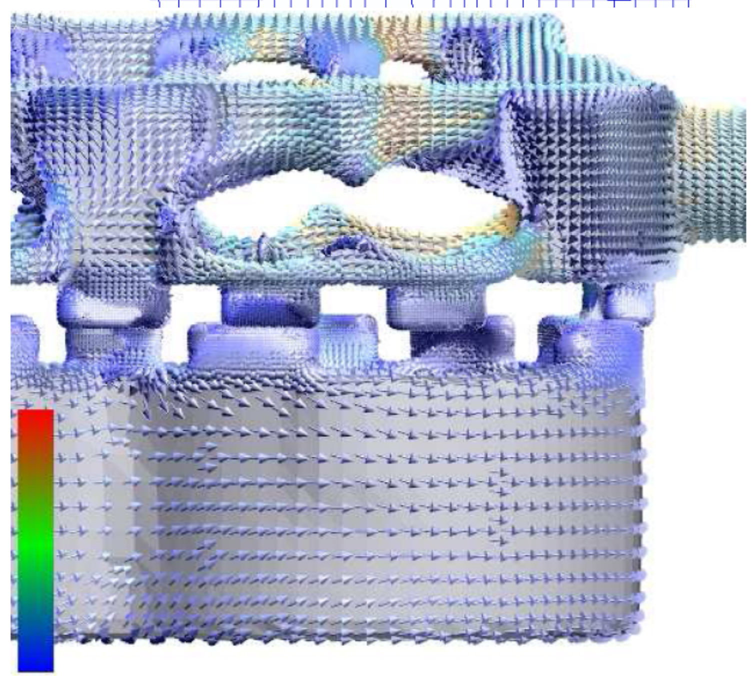
Introduction and Motivation

- CFD simulations result in large, complex, multi-field data sets.
- +Unstructured, adaptive resolution meshes pose challenges for visualization
- Vector field clustering can provide details in selective areas of the domain that correspond to interesting areas
- High resolution mesh regions are associated with important areas of the domain
- 50% of CFD process is spent on mesh generation [5]



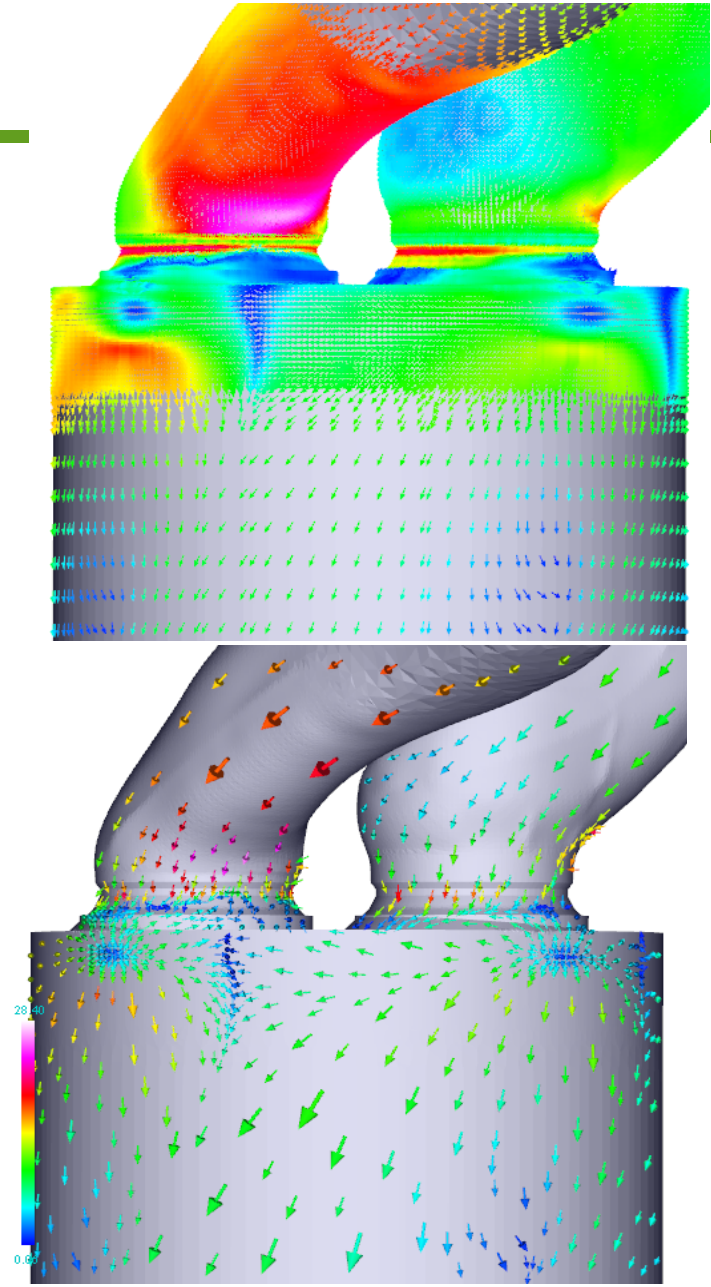




Contributions

Main Contributions of this paper are:

- Novel, general, automatic, vector field clustering algorithm that incorporates properties of mesh and flow field
- Visual emphasis is placed on more important regions of the domain
- Large, adaptive resolution meshes are handled efficiently: no processing time is spent on occluded portions of the geometry
- We introduce some novel glyph-based visualizations with use-controlled algorithm and visualization parameters



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Related Work

- Xu and Wunsch II [1] present comprehensive clustering survey rooted in statistics
- Group 1: Hierarchical algorithms, e.g., Telea and Van Wijk [6], Heckel [7], etc
- Group 2: Partition-based algorithms: e.g., Du and Wang [16]
- Previous work generally addresses structure grids (many more references in paper)
- We target unstructured, adaptive resolution meshes and take underlying properties of mesh into account.

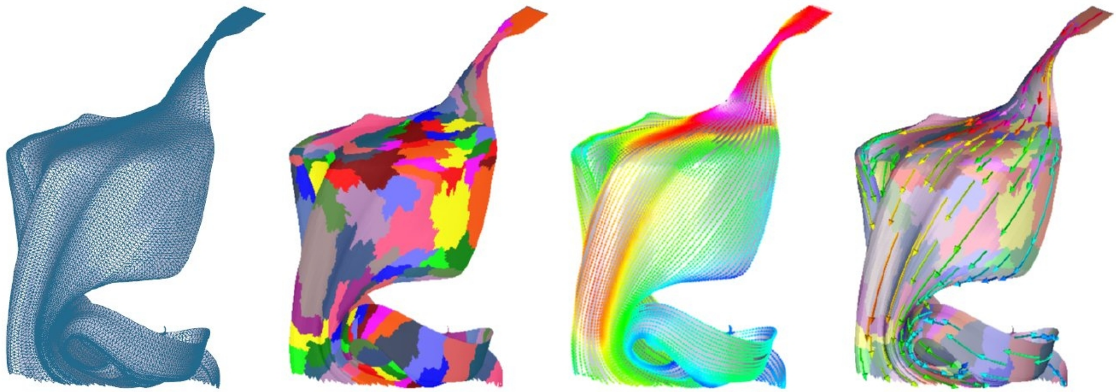

Fig. 1. The visualization of flow at the stream surface of a gas engine simulation [2], [3]. (left) The stream surface mesh is composed of unstructured, adaptive-resolution polygons. For stream surface generation, we use the algorithm of Garth et al. [4] which handles unstructured, adaptive resolution meshes. (middle-left) Clusters rendered with by $\varepsilon = 15\%$. The comparison of glyph-based hedgehog visualization (middle-right) and cluster-based streamlet visualization with semi-transparent clusters (right). Here we can visualize vector field clusters on stream surfaces for the first time. The color of glyphs (middle-right) and streamlets (right) is mapped to velocity magnitude.

Method Overview

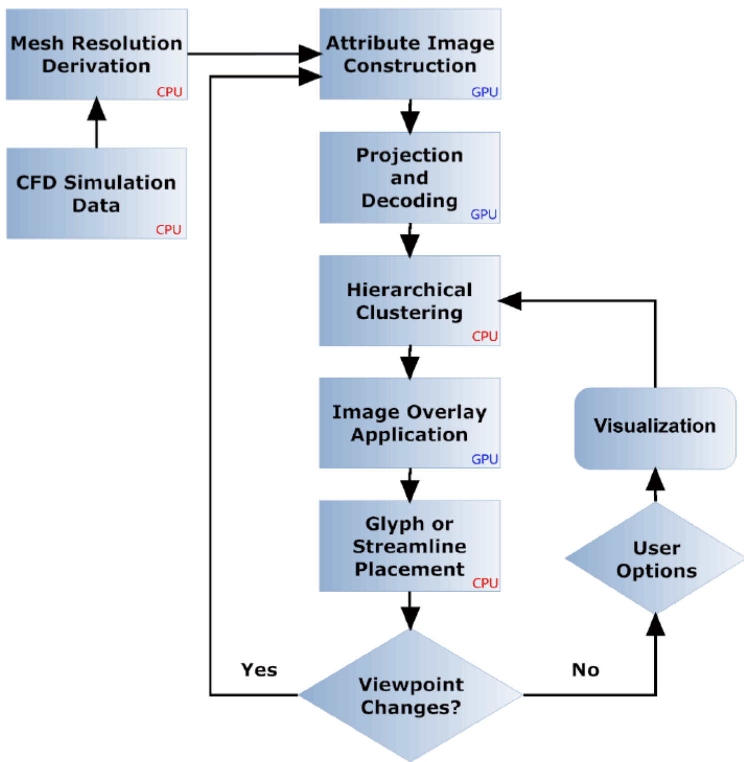

Fig. 3. An overview chart of our mesh-driven vector field clustering algorithm for surfaces.

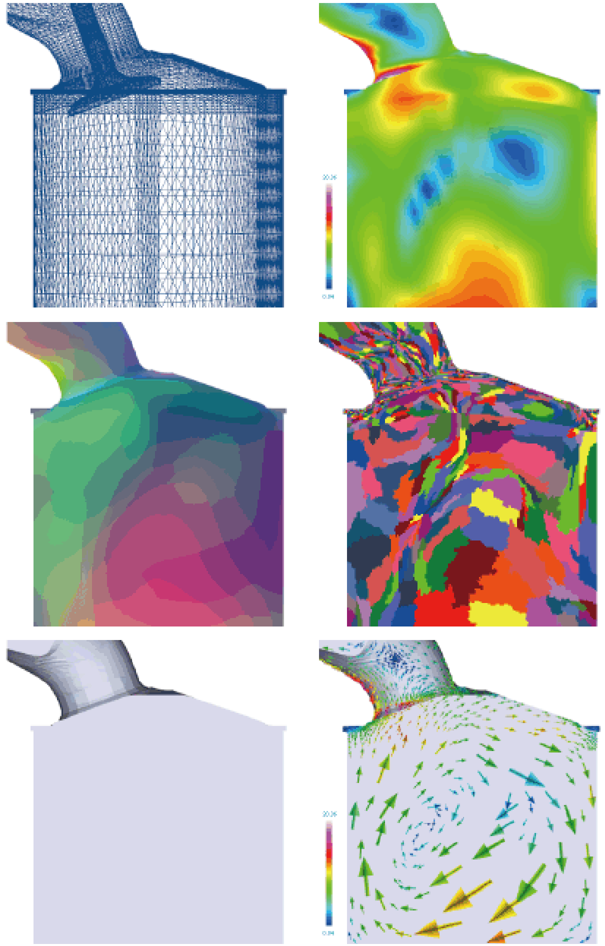

Fig. 4. Here are 5 constituent images, plus a 6th final image, used for the visualization of surface flow on a gas engine: (top, left) the initial adaptive resolution mesh, (top, right) a velocity magnitude color mapped image, (middle,left) the attribute image corresponding to the vector field and underlying mesh resolution, (middle, right) a color mapped image which shows the different resulting clusters, (bottom, left) an image overlay, (bottom, right) the final visualization using glyphs, and the image overlay. Color is mapped to velocity magnitude. The tumble motion depicted in the lower-right image is consistent with previous visualization of the same data [3].

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Mesh Resolution Derivation

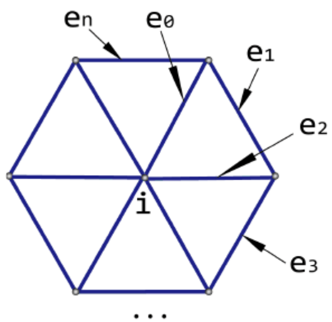

Fig. 5. A composition of 6 triangles which share a common vertex *i* represents a 1-Ring neighborhood of the underlying mesh from which a local resolution measure is derived.

$$\bar{e}_{avg} = \frac{1}{n+1}\sum_{i=0}^{i=n} e_i$$

- Mesh resolution is defined as: $m = 1 / e_{avg}$
- Other metrics are possible such as area based or computing the density of vertices

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Attribute Image Construction

Vector field + derived mesh resolution field is projected to image space via frame buffer.

- Hidden or occluded regions of the geometry are culled
- The computational space is transformed: unstructured → uniform
- Interpolation is performed by hardware
- Object space complexity is reduced to image space

The formula to encode the components is:

$$\mathbf{C}_i = \frac{\mathbf{v}_i - min(\mathbf{v}_i)}{max(\mathbf{v}_i) - min(\mathbf{v}_i)} \quad where\ \mathbf{C}_i = (C_R, C_G, C_B) \tag{2}$$

The formula for encoding the object-space mesh resolution is:

$$m_i = \frac{e_{min} \cdot (e_{max} - \overline{e}_{avg}(i))}{\overline{e}_{avg}(i) \cdot (e_{max} - e_{min})} \tag{3}$$

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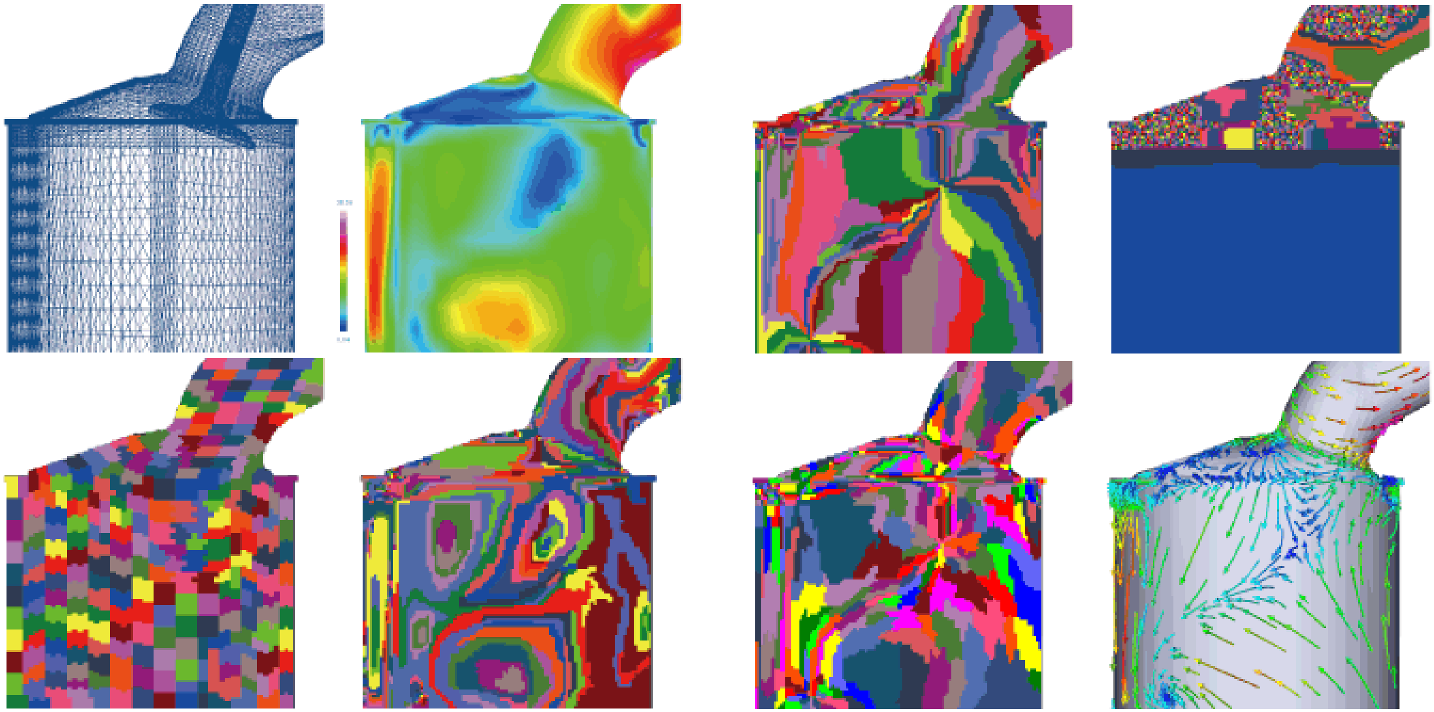
Hierarchical Clustering: A Mesh Driven Error Metric



$$\boldsymbol{\varepsilon}(\psi) = c_d \cdot \frac{d}{d_{max}} + c_{\overline{\mathbf{v}}} \cdot \frac{\overline{\mathbf{v}}}{\mathbf{v}_{max}} + c_\alpha \cdot \frac{\alpha}{\alpha_{max}} + c_m \cdot \frac{m}{m_{max}} \qquad (6)$$

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Hierarchical Clustering: Generating the Cluster Hierarchy

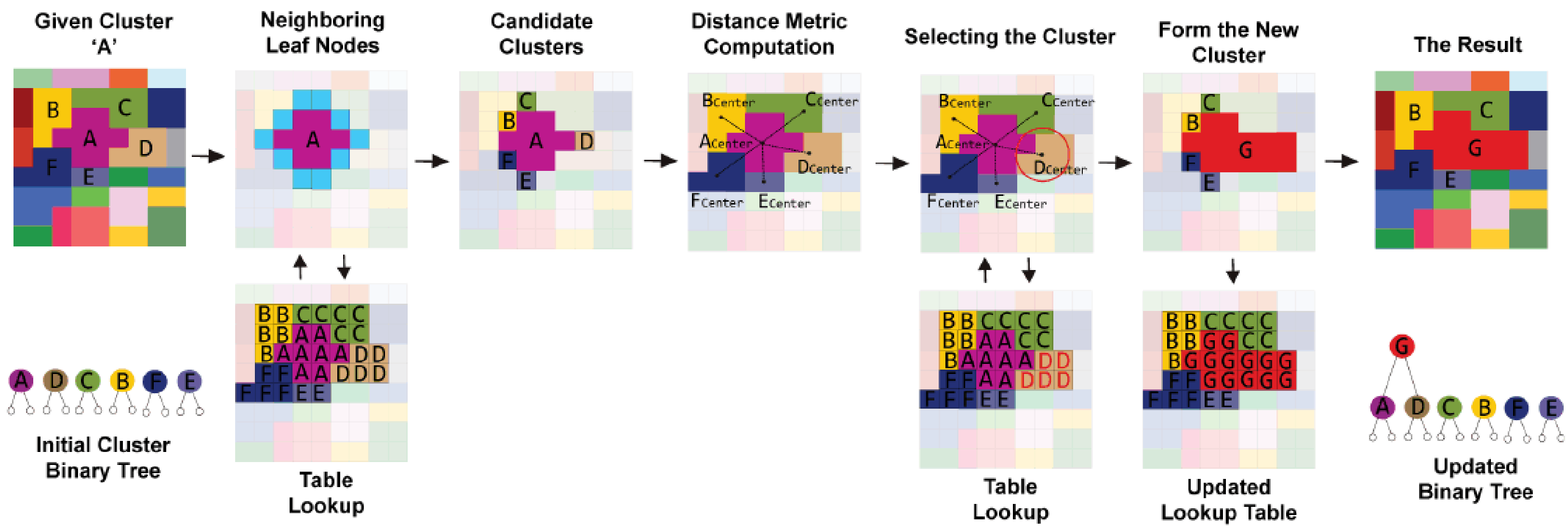

Fig. 7. An example illustrates the clustering method. It starts with a given cluster, *A*, and a cluster list $L(\psi)$ which stores the initial leaf clusters for the hierarchical clustering process. After the search process is finished, a new cluster, cluster *G*, is formed from two child clusters, *A* and *D*, which have the shortest distance $\boldsymbol{\varepsilon}(\psi_A - \psi_N)$. *G* is added to the back of $L(\psi)$. The corresponding binary tree is updated to store the new parent cluster and its children.

$$\boldsymbol{\varepsilon}(\psi) = c_d \cdot \frac{d}{d_{max}} + c_{\overline{\mathbf{v}}} \cdot \frac{\overline{\mathbf{v}}}{\mathbf{v}_{max}} + c_\alpha \cdot \frac{\alpha}{\alpha_{max}} + c_m \cdot \frac{m}{m_{max}} \qquad (6)$$

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Hierarchical Clustering: Edge Detection, Image Overlay, Generalizing

- Edge detection, based on discontinuities in depth map, are used to prevent artificial clusters from forming.
- An image overlay is used to incorporate shading into the scene
- The algorithm is generalizable

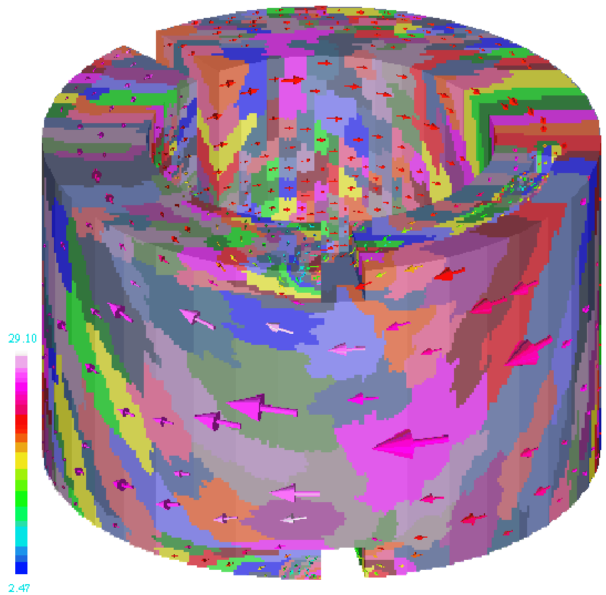

Fig. 8. The result of the clustering driven by an error measure ($\boldsymbol{\varepsilon} = 12\%$) which uses the depth as a distance measure constituent. Notice how the overall density is much higher towards the rear.

Visualization with Glyphs

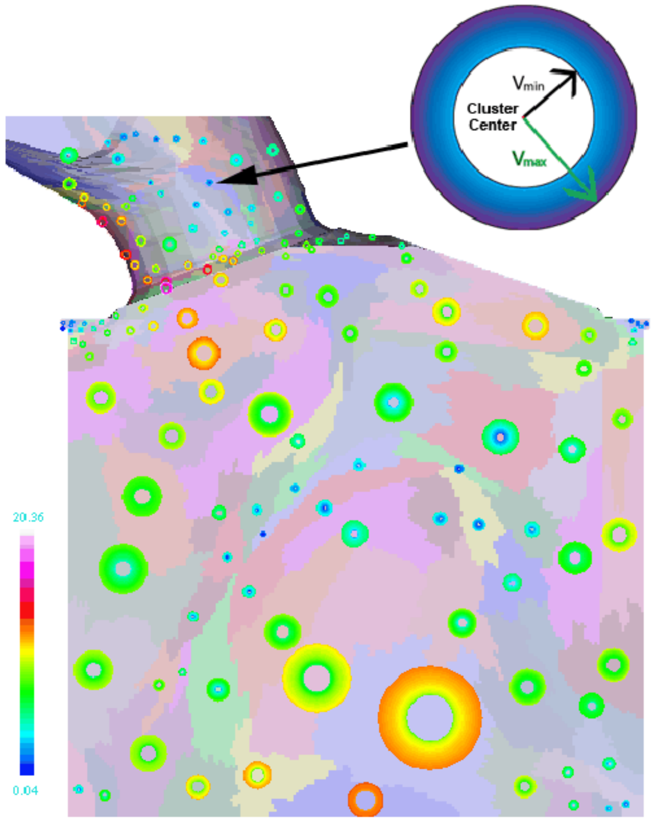

Fig. 9. |**v**|-range glyphs: (Top) a close-up look at a |**v**|-range glyph whose inner radius represents the minimum velocity magnitude while outer is mapped to the maximum. (Bottom) the result image with |**v**|-range glyphs applied to depict the variation in magnitude within each cluster .The result of the clustering driven by an error measure ($\boldsymbol{\varepsilon} = 15\%$). Glyph color is mapped to velocity magnitude.

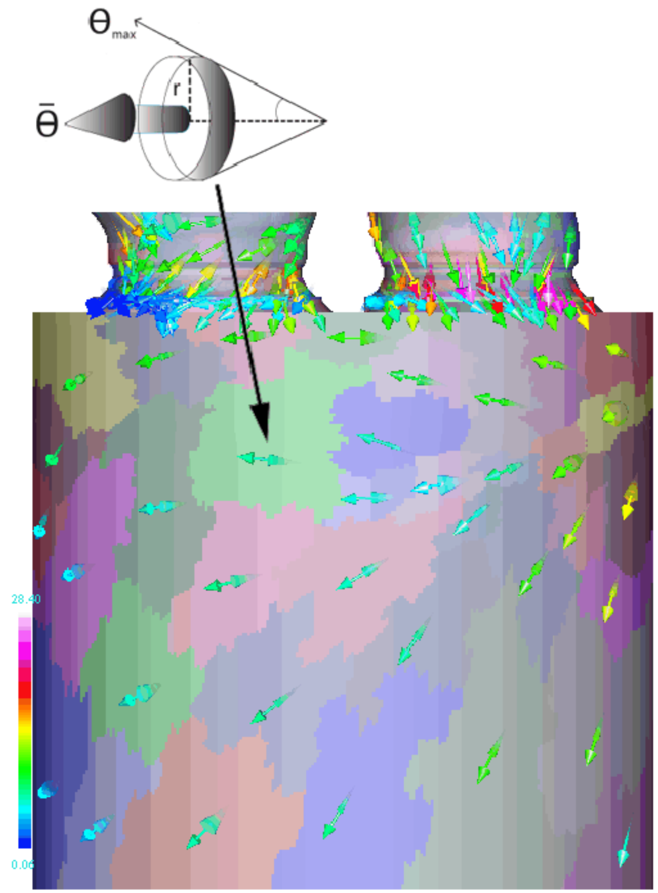

Fig. 10. (Top) the θ-range glyph whose radius represents the maximum range of vector field direction is illustrated. The result image with θ-range glyphs is shown in (Bottom). The result of the clustering is driven by an error measure ($\boldsymbol{\varepsilon} = 18\%$). Glyph color is mapped to the velocity magnitude.

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Results and Performance

(video)

Data Set	Total number of clusters			
	131071	32767	8191	2047
Ring (10k)	10.07s	1.06s	0.085s	10.17ms
Combustion Chamber (79k)	10.06s	1.07s	0.087s	10.06ms
Intake Port (221k)	10.13s	1.07s	0.088s	10.65ms
Cooling Jacket (228k)	10.20s	1.09s	0.09s	10.96ms

TABLE 1

Cluster hierarchy generation timing figures for total cluster quantities. An image resolution of 512^2 is used with about 75% image space area covered. The total numbers of clusters include the leaf and parent node clusters.

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Conclusions and Domain Expert Feedback

- We worked closely with CFD expert, Dr Nick Croft of Swansea University for ~1 year while developing our algorithm and glyph-based visualizations. He provided the Domain Expert Feedback section.
- He agrees with our observation that high-resolution mesh regions are associated with importance.
- Glyph-based visualization of vector fields is common and desirable for intuitiveness and simplicity
- Traditionally, in commercial packages, effective glyph-based visualizations are virtually impossible to generate due to overlapping glyphs and vector magnitudes of largely varying scale.
- The glyph-placement strategy based on clustering is very effective for alleviating this problem and generating insightful visualizations
- The novel glyphs are very helpful in conveying the information about clusters including the range of values found in a given cluster

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Acknowledgements

- Thank you for your attention!
- Any Questions?

Thanks to funding from EPSRC EP/F002335/1 and RIVIC (rivic.org):

Any Loss of Accuracy Due to Projection to Image Space?

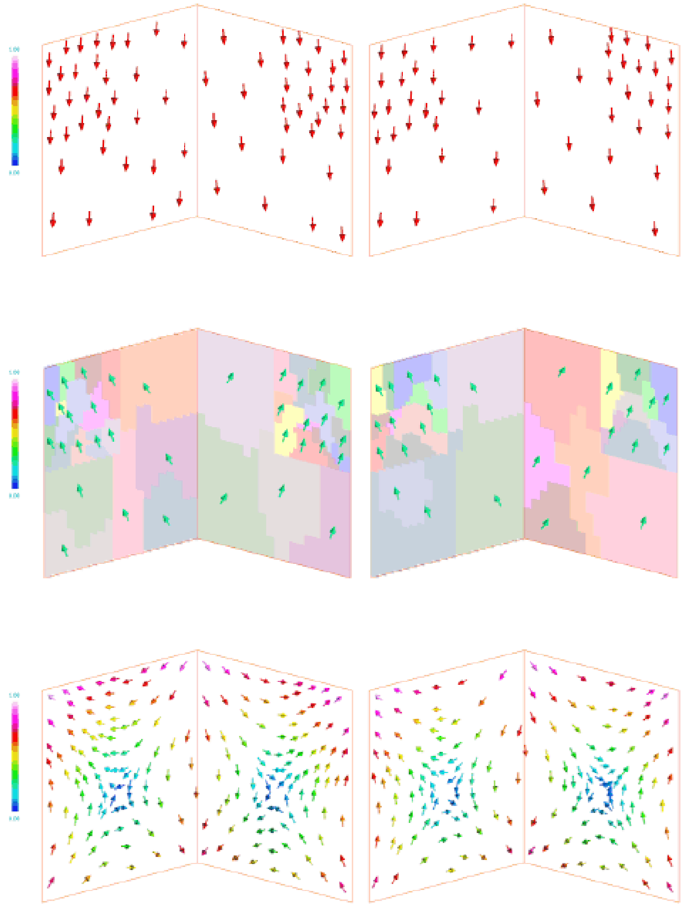
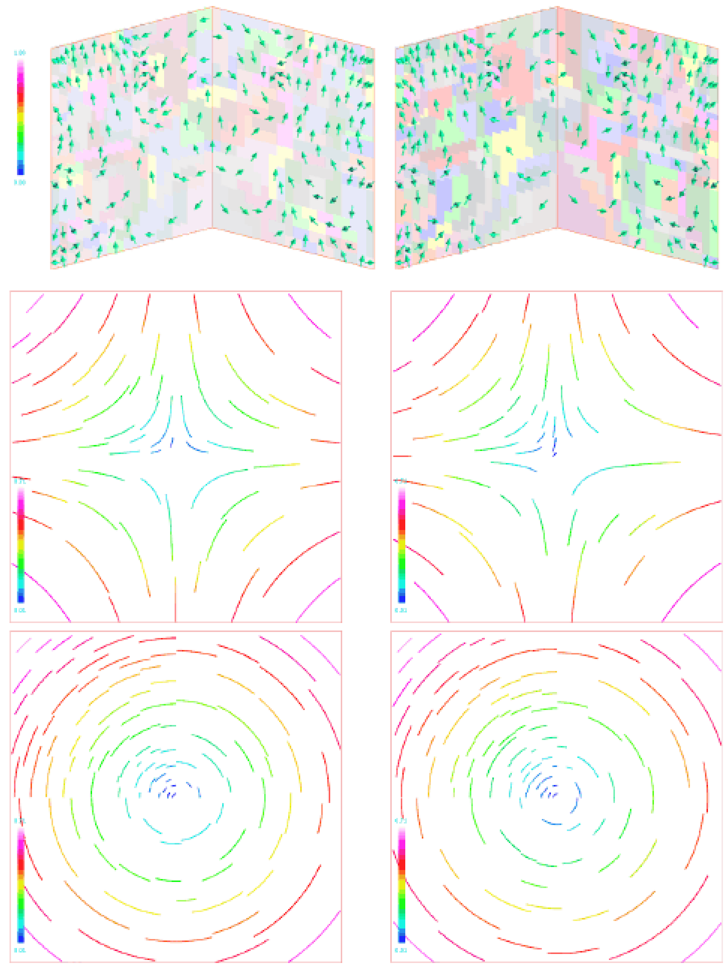


Fig. 17. The visualization of image vs. object based clustering from synthetic flow data sets. (left) Images shows the clusters generated using a full-precision, object-based clustering algorithm. (right) The results from our novel, image-based clustering algorithm. Planes are at right angles to one another.

- Excellent Question!



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