A. Executive Summary

Computational power has increased dramatically over the past decade and has allowed computational fluid dynamics (CFD) researchers to more accurately simulate many types of flow with more detailed computational meshes. However, this new power has also yielded terabytes of data, and CFD researchers now face a very difficult task in trying to find, extract, and analyze important flow features (e.g., time varying vortices, shock waves) buried within these monstrous datasets. Unlike the explosive growth in computational power, visualization tools for these very large datasets have experienced a more modest evolution, and are not yet sufficiently developed to significantly aid the feature detection, extraction, and analysis process. Most visualization tools require the user to work at a very cumbersome, low level with the data. Users are required to dice their datasets into appropriate data parameter ranges to search for the features of interest, since detailed visualization of such large datasets is impractical.

Improved visualization tools for CFD researchers could have a drastic impact on the design and safety of aircraft, ships, submarines, spacecraft, and automobiles. For instance, the Simulation and Design Center (SimCenter) at Mississippi State University has recently computed an unsteady simulation to the problem of icing and wind gusts on an Osprey-like aircraft. When the simulation was complete, it was found that this aircraft had a potentially serious tail-buffeting problem that could cause the craft to become unstable during some maneuvers. Given the fact that two Ospreys have recently crashed, killing all passengers on board, the use of more accurate, streamlined visualization tools in the design process could have had a major impact on averting these tragedies.

CFD researchers desperately need new techniques that simplify and automate the iterative search and extraction process of finding the appropriate portion of their dataset. This community needs a new system that will allow the user to articulate appropriate types of features of interest, provide a compact representation of those features that preserves their intrinsic qualities, and then allow the user to effectively and interactively visualize the feature information on a desktop computer. Such a system would also have to overcome the additional challenges of loading a sufficient portion of the data set into the available memory of a modest desktop machine, transferring these datasets over a network connection between the archive and local machine, mapping the entire data set to a visual representation in a reasonable amount of time, and rendering the results at interactive rates.

We will solve these CFD visualization problems by developing techniques for creating a procedural abstraction for a very large dataset, developing effective and efficient methods for mapping from the procedural to visual representation, and applying these techniques to the problem of visualizing large CFD simulations. Our new methods will provide interactive visualization of very large datasets on a desktop computer, and will scale gracefully across a range of compute power and bandwidth situations. Our major research objectives are to:

1. Detect important features (e.g. shocks) in complex, highly-detailed flows using topological operators based on critical points and separatrix curves and surfaces.
2. Characterize the immense amount of data relative to these features using a procedural representation consisting of implicit models based on radial basis functions and free-form deformations based on subdivision solids.
3. Adapt the procedural representation to the appropriate level of detail using multi-resolution techniques based on multigrid methods.
4. Encapsulate domain specific knowledge as metadata to explore these extremely large datasets both at the feature level and, more importantly, at the higher level of relationships among features (e.g., tip vortices).
5. Visualize the data directly from the procedural representation, using and extending numerous existing CFD visualization techniques (e.g. cutting planes, isosurfacing, volume splatting, direct volume rendering, particle clouds, streams, rakes, line-integral convolution and glyphs).
6. Verify the accuracy of the procedural representation with careful tracking of approximation error throughout the entire process, including scanning, modeling, reconstruction and visualization.
7. Apply these techniques to the large-scale computational flow simulation problems currently studied at Stanford and at the SimCenter at the NSF Engineering Research Center at Mississippi State University.

The resulting system will allow CFD researchers to work more effectively by interactively exploring their data to pinpoint the features of interest. They can then adaptively refine their solution grids within those areas, and iteratively compute solutions on these adapted grids to improve their simulations and solve the underlying flow problem more quickly. Moreover, the results of this project will provide solutions not only for CFD researchers, but also for a wide variety of visualization challenges and applications. Our main goal is to develop techniques that allow visualization exploration, feature detection, extraction, and analysis at a higher, more effective level through the use of procedural data abstraction and representation.