PHOTOGRAMMETRIC AND IMAGE PROCESSING ASPECTS IN QUANTITATIVE FLOW VISUALIZATION

Matthias Machacek and Thomas Rösgen

Institute of Fluid Dynamic ,ETH Zürich, Switzerland

The development of a measurement system to visualize, classify (based on topological features) and quantify complex flows in large-scale wind tunnel experiments is described. A new approach is sought where the topological features of the flow, e.g. stream lines, separation and reattachment regions, stagnation points and vortex lines are extracted directly and preferably visualized in real-time in a virtual wind tunnel environment. The system is based on a stereo arrangement of 2 CCD cameras. A frame rate of 120 f/s allows measurements at high flow velocities. Helium filled soap bubbles are used as tracer particles. The paper focuses on the problem of a fast and accurate reconstruction of path lines in three dimensions (3D). A series of simple algorithmic steps is employed to ensure fast data processing. They include fast image segmentation, a spline approximation of the path lines, a camera model, point correspondence building, the calculation of path line points in 3D and creation of a 3D spline representation, respectively. The path lines, which contain both velocity and topological information, are analyzed to extract the relevant information.

INTRODUCTION

Classical visualization methods (e.g. smoke wire, laser vapor screen, tufts) provide an overview about the flow topology but quantitative data is often not available and much depends on the interpretation by the researcher. The alternative is to take classical qualitative visualization methods and combine them with modern computer vision technology to generate quantitative data. The intuitiveness of the visualization approach in maintained by representing the results in a “virtual wind tunnel” environment with an interactive user interface. The equivalent method on numerical data is given in Bryson and Levit’s study of The virtual wind tunnel[1].

Two different visualization methods are selected for the proposed technique, helium filled soap bubbles and visualization with smoke filaments. In the first case, the images of moving bubbles represent path lines whereas in the second case streak lines are recorded. The spatial processing of the acquired image data is done based on the principles of multiple view geometry theory[2] as applied to the path line model.

EXPERIMENTAL SETUP

The visualizing system consists of the following components. Two progressive-scan interline CCD cameras record images at a frame rate of 120 f/s and with a resolution of 640x480 pixels. Lighting is provided by four halogen spot lamps with a total power of 6000W. The helium filled soap bubbles for seeding are introduced into the test section through a strut mounted nozzle[3]. The bubbles have an approximate diameter of 2 mm. The components are set up in a wind tunnel with a cross section of 2 x 3 m and a wind speed up to 60 m/s.

The Camera Model

The camera model used in the present study was a pinhole model adopted from photogrammetry theory[2]. The model parameters included the focal length f, the principal point (x_0, y_0), the stretching of the x-axis s_x and the skew θ, respectively. In addition, the lens distortion was compensated with two second order polynomials for the radial distortion (k_1, k_2) and for the tangential distortion (p_1, p_2). The camera position and orientation with reference to a global coordinate system is described by the parameters (X_0, Y_0, Z_0) and $(\varphi, \omega, \kappa)$. This represents a camera model with a total of

15 parameters. These parameters are unknown for any given experimental set-up and have to be estimated by a calibration routine[4].
A look-up table is constructed for the mapping from pixel space to normalized image coordinates[2]. This provides a significant speedup for the nonlinear part of the overall coordinate transform and reduces the subsequent processing to linear operations despite the nonlinear formulation.

TWO DIMENSIONAL PATH RECONSTRUCTION

The representation of a path line in the different camera views is needed for a 3D reconstruction. As a first step, the finite thickness bubble tracks have to be reduced to a representative line close to the centerline or to the skeleton of the track. The direct use of a skeleton algorithm proved not be sufficient because of the sensitivity to noise, the slow execution times and the limitations on achievable pixel accuracy. For objects with a relatively small width (a few pixels) a skeleton algorithm can give asymmetric results which poorly approximate the position of the centerline. As an alternative, a third order approximating parametric spline model based on B-splines[5] is used to represent the path lines. Splines have several desirable mathematical properties (e.g. smoothness, differentiability) and they can describe accurately lines with a complex shape.
A crucial aspect in the processing chain is the configuration of the digital cameras which record the bubble images. The bubbles are illuminated with a continuous light source and are recorded with the maximum exposure time (=1/frame rate) by an interline CCD chip with a negligible read out time. This leads to a set of consecutive images in which a moving particle leaves a continuous string of connected path segments, forming a complete path line. Previous attempts[6] have shown that a path line reconstruction based on the analysis of independent path line segments (i.e. independent image frames) can lead to topologically inaccurate solutions. This is due to the difficulty of processing the end points of the segments in a consistent manner when the information of the previous and following segments is not taken into account. Hence in the present approach the high level processing is based on multi-frame path lines as reconstructed from a connected set of path line segments.

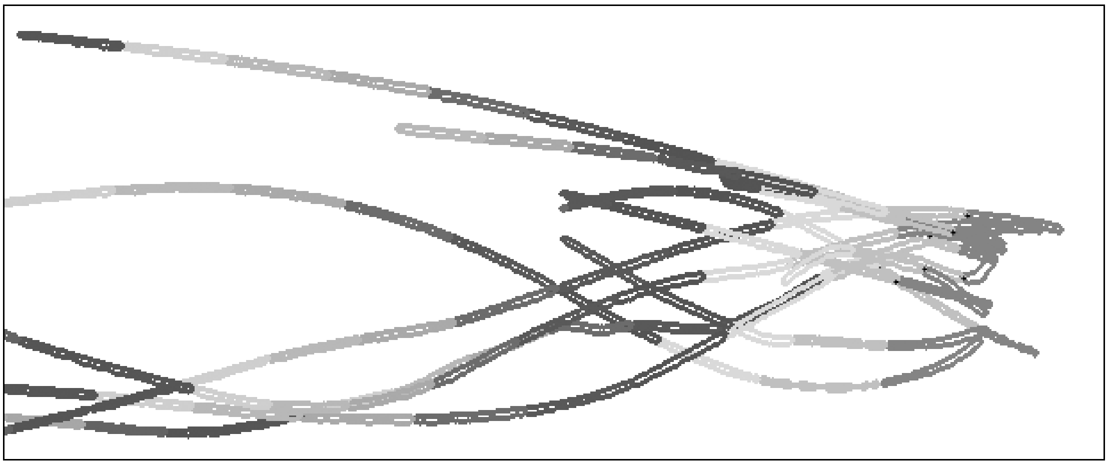

Figure 1. Overlay of 100 processed frames, showing a set of path lines of Helium filled soap bubbles in the flow over a delta wing. The variable shading indicates the individual path line segments.

The initial low level processing is achieved with the following series of steps: background subtraction, binarization with an appropriate thresholding operator and median filtering to reduce the residual noise. The current image is then scanned in the immediate vicinity of the path line segment endpoints detected in the previous frame. In case of a successful match the new segment boundary and its two endpoints are extracted. This procedure is continued until a path line is completed (i.e. the particle left the camera field of view). Thereafter, its representation in spline form can be calculated. For that purpose the pixel coordinates are normalized and the spline representation is initialized with the end points of the path segments. To compensate for possibly inaccurate extracted endpoints an approximating spline rather than an interpolating one is used. A chord length parameterization is chosen, where the parameter is incremented by one at each endpoint. The spline is then improved in an iterative process until a sufficient accurate representation of the centerline line is found.

3D PATH RECONSTRUCTION

For the calculation of the path line coordinates in 3D space corresponding point pairs on corresponding path lines have to be found in both camera views. Corresponding path lines are found by projecting the end points of a path line segment into the second camera image, creating so-called epipolar lines. If the distance between the epipolar line projection and an endpoint is below a critical value, the endpoints and thus the path lines are considered to be corresponding. Since the epipolar condition for two cameras is ambiguous all candidate end points are tested for correspondence until a unique solution is found. Path line points are defined by equidistant spacing on the spline model in the first view. These points are then projected into the second view, again creating a set of epipolar lines. These lines are intersected with the corresponding second image spline approximations to produce corresponding points. All corresponding 2D point pairs are finally used to calculate the coordinate point in the three-dimensional space. The path line is thus reconstructed as a sequence of points. Finally these 3D points are used to rebuild a three-dimensional spline representation of the path line. This spline curve is also based on third order B-splines.

CONCLUSIONS

A method for the accurate and fast calculation of three-dimensional path lines is described, where the measurement data is derived from two independent camera views. It was found that by using approximating splines based on third order B-splines the medial line of a compound, multi-frame path line can be accurately modeled. The use of a non-linear camera model in combination with a look-up table for the normalized pixel coordinates allows the implementation of accurate and fast operations for the photogrammetric reconstruction. The final three-dimensional path lines are also represented with a model based on third order B-splines. These analytical curves provide accurate and continuous representations of the path lines and form a solid base from which topological information on the flow can be extracted. Compared with three-dimensional particle tracking (3D-PTV) the present method does not require elaborate tracking algorithms and provides continuous information on the particle tracks.

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