Realtime 3D sensor based air flow reconstruction

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Abstract

Based on state-of-the art bio-inspired air flow sensors it becomes possible to capture air flow velocity and direction at multiple locations at the same time instance. These sensor values can be used in a simulation environment to visualize and examine the captured air flow pattern. The simulation environment makes interpolations of the flow between the sensors based on the Navier-Stokes equations. These equations can be solved efficiently using a stable approximation technique described by J Stam and making use of the enormous parallel computing power available through the latest graphical processing boards.

Algorithms, Measurement, Performance, Experimentation

Categories and Subject Descriptors (according to ACM CCS): I.5.5 [Computer Graphics]: Pattern recognition—Implementation

1. Introduction

Inspired by the exquisite air flow sensitivity of the hairs found on the rear appendages (cerci) of crickets engineers at TU Twente have build a Micro electromechanical sensor (MEMS) hair array sensor. This sensor consists of an number of closely spaced miniature hairs which are capable of transducing the air flow velocity in a particular (preferred) direction [BJdB*09] (See fig. 1). Based on the readings from a collection of these artificial hairs, all pointing in different preferred directions, a flow reconstruction can be obtained, i.e., a flow vector [VDDMP08]. When multiple flow vectors are captured by these sensors, these sensor values can be fed into an air flow simulator. The Navier Stokes equations are a set of non-linear partial differential equations describing the physical phenomena of flow. Due to the complexity of these equations it is impossible to solve them in general analytically. Therefore these equations are almost always approximated by numerical computations. Typically the simulation time for solving the Navier-Stokes equations is very long, depending on the size of the simulation, the reconstruction accuracy and the complexity of the flow. Different numerical approximations exist, each has its advantages and disadvantages. A relatively recent technique promoted by J. Stam [Sta00] is proven to be inherently stable and to converge to the real Navier Stokes equation. Using this algorithm it is possible to trade processing effort for accuracy with the guarantee that when little time is available, as is the case with real and semi-real time simulations, the approximation can be shown not to diverge. As this algorithm is also capable of making use of the great parallel processing power of modern graphical processing units, the flow approximations will become more accurate for a fixed computation time interval. Based on the combination of this new bio-inspired MEMS sensor and this new numerical method to solve Navier-Stokes equations a flow demonstrator was build to capture and visualise a real air flow in real time.

2. Sensors

The sensor used is a MEMS hair array sensor. Each hair measures the projection of the air flow velocity onto its preferred direction. When the readings from multiple hairs with different directions are combined, the flow vector, assumed to be constant for that set of hairs, at the location of that set of hairs can be approximated, e.g. by a least mean square estimator as derived in [VDDMP09, VDBP11]. Given the multitude of these sensors, multiple air flow velocity vectors can be reconstructed at different locations over the sensor array. These reconstructed air flow velocity vectors can be used as

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boundary values constraining the output of the flow simulator that solves the Navier Stokes equations.

2.1. The Navier Stokes equations

The Navier Stokes equations are set of non-linear partial differential equations which model the physical phenomena of air flow displacement

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \rho\mathbf{g}$$

with ρ representing the density of the fluid, $\mathbf{g} = (g_x, g_y, g_z)$ representing the gravity vector, the pressure is denoted by p, the flow velocity at each point is represented by the vector $\mathbf{v} = (u, v, w)$. They are notoriously difficult to solve. Additional insight in the properties of the solutions of these equations is stated as one of the 7 millennium price problems [Fef06]. Therefore, in practice these equations are approximated numerically. The numerical approximation method described by J.Stam makes use of the Lagrangian approximation. In this approximation, the diffusion and advection term are implemented on the GPU shading engine. In our example, a grid of 200x200x200 voxels was constructed for which refresh rates of 60Hz could be achieved on a AMD ATI Radeon HD5970.

Together with the continuity equation

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

these equations form the basis from which we both interpolate and extrapolate the flow starting from a set of measurements with an array of flow sensors.

2.2. Simulation Environment

The simulation starts from the readings from the array of hair sensors. The sensor values are sampled at a sample rate of 5000 Hz. The samples are buffered and transferred to the simulation engine. Here the data is down sampled to the maximum rate allowed by the used graphics hardware for the real-time flow simulations, i.e. 60 samples/sec. If desired the flow reconstruction can be slowed down to make use of all 5000 samples per second. The reconstruction of the flow can be viewed in fig. 2. The flow reconstruction can be rotated in 3 dimension during the real-time reconstruction of the flow. Multiple snapshots at different time instances from different viewing angles are visualized in fig. 2.

2.3. Discussion

This initial setup shows the feasibility of the idea of combining actual air flow vector measurements and simulations on graphical processing units to process and visualize flow data in real-time. Further tuning and calibration has to be done to guarantee accurate reconstructions of the real air flow patterns. Given the great advancements over recent years in graphical processing unit capabilities and in air flow sensing technology, we believe such a setup will become increasingly interesting as the accuracy of its predictions will further improve.

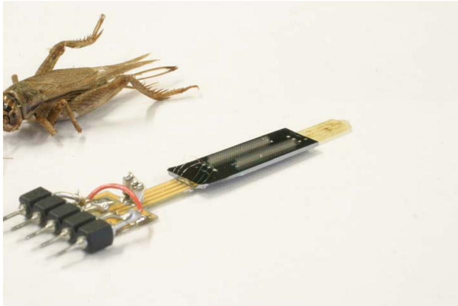

Figure 1: *The cricket and the bio-inspired MEMS hair array sensor.*

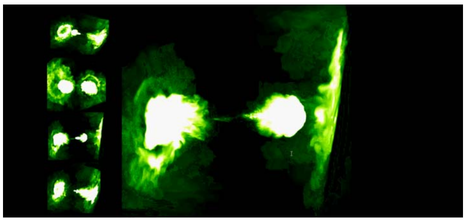

Figure 2: *Multiple snapshots at different time instances of a 3D, sensor based, air flow reconstruction, as seen from different viewing angles.*

References

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