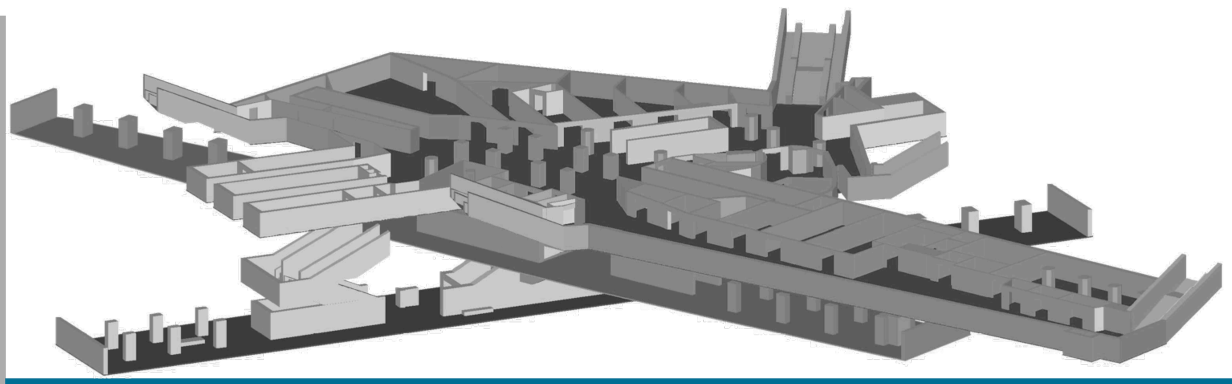

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Real-Time Simulation and Prognosis of Smoke Propagation in Underground Stations: Roadmap

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Motivation

- **Equipment** for smoke extraction is rare in mostly all underground stations worldwide
- Concepts need to be able to adapt to the current situation **dynamically and scenario-based**
- **Simulations in real-time are necessary** due to the strong influence of fire to flow conditions
- To provide for necessary **data processing** and sufficient **computational capacity** in CFD simulations, the computer system needs a minimum amount of **main memory**
- Also **limitations in costs, power, cooling and space** are reasons for installing a small GPU appliance on-site (e.g. in the fire station or truck)

Application

- Predicting the **state of smoke** spread
- **Supporting fire fighters** and technical smoke extraction measures
- **Planning** of rescue work and **development** of control systems for complex smoke extraction via **sensor coupling**
- Dynamic **escape route marking**

Goals

- **Evaluating new models** exploiting modern computer architectures to calculate **smoke propagation in and faster than real-time**
  - **CPU implementation** of a solver for simple 2D geometries
  - **GPU implementation** for complex geometries with dynamical extension of the computational domain
- **Coupling of sensor data** into CFD prognoses

Numerical Models

- **Weakly compressible Navier-Stokes** equations to be solved for a turbulent gas $(\rho = \rho(T))$

$$\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\,\mathbf{u} - \nu\nabla^2\mathbf{u} + \tfrac{1}{\rho}\nabla p = \mathbf{f}(T)$$
$$\nabla\cdot\mathbf{u} = 0$$

- Using **finite differences** in space (2nd order) and time (1st order) due to simplicity and parallelization capability on GPUs results with a **fractional step method** and **Helmholtz-Hodge projection** (cf. [1], [2]) into:
  - Advection: $\partial_t \mathbf{u}_1 = -(\mathbf{u}_1\cdot\nabla)\,\mathbf{u}_1$ (via Semi-Lagrangian)
  - Diffusion: $\partial_t \mathbf{u}_2 = \nu\nabla^2\mathbf{u}_2$ (via implicit Jacobi)
  - Sources: $\partial_t \mathbf{u}_3 = \mathbf{f}(T)$ (via explicit Euler)
  - Pressure: $\partial_t \mathbf{u}_4 = -\frac{1}{\rho}\nabla p$ (via Multigrid + Jacobi)

  Smoke sources:
  - Temperature: $\partial_t T = -(\mathbf{u}_4\cdot\nabla)\,T + \kappa\nabla^2 T + S_T$
  - Smoke fraction: $\partial_t d = -(\mathbf{u}_4\cdot\nabla)\,d + \gamma\nabla^2 d + S_d$
- To include **turbulence** into our model, we apply the **Smagorinsky-Lilly LES** model (cf. [3]) by solving the LES equations for the spatially filtered velocity $\bar{\mathbf{u}}$, temperature $\bar{T}$ and smoke fraction $\bar{d}$ with filter width Δ_f and an effective viscosity of

$$\nu_{eff} = \frac{\mu_{eff}}{\bar{\rho}} = \frac{\mu_{mol}+\mu_t}{\bar{\rho}},$$

where $\mu_t = \bar{\rho} C_S^2 \Delta_f^2 |\bar{S}|$ with Smogorinsky constant C_S (commonly $C_S = 0.2$) and the norm of the filtered stress tensor $|\bar{S}| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}}$ with $\bar{S}_{ij} = \frac{1}{2}\left(\partial_{x_j}\bar{u}_i + \partial_{x_i}\bar{u}_j\right)$.

Goal validation

- **CPU** code validation with simple **2D geometries**; **GPU** code validation with **complex 3D geometries** (e.g. several rooms)
- Validation of **sensor data coupling** with **measured data** provided by collaboration partners

Optimization

- Sensor coupling to **include live data**
- **Ensemble** simulation to optimize prognoses
- **Dynamical extension** of computational domain
- **Multi-GPU** support

Next Steps

- **Verification & Validation** of the CPU implementation
- **GPU implementation** including **dynamical extension** of computational domain and **coupling of sensor data**
- Deep dive into **higher order schemes, Lattice-Boltzmann** & cloud HPC

Literature

[1] Glimberg, Erleben, *Smoke Simulation for Fire Engineering using a Multigrid Method on Graphics Hardware*, 2009.
[2] Chorin, Marsden, *A Mathematical Introduction to Fluid Mechanics*, Springer, 2000.
[3] Smagorinsky, Joseph, *General Circulation Experiments with the Primitive Equations*. Monthly Weather Review 91 (3): 99–164, 1991.

Roadmap