Stochastic Flow Paths for Fast Hazard Simulation

(Masters-level internship)

Guillaume Cordonnier – guillaume.cordonnier@inria.fr
GRAPHDECO, Inria Sophia Antipolis (France) - http://team.inria.fr/graphdeco
http://www-sop.inria.fr/members/Guillaume.Cordonnier/

Figure 1: Floods, debris flows, and landslides have devastating impacts, and no current simulation methods are fast enough to propose emergency scenarios during the event.

Context and goal

Natural hazards such as flash floods, debris flows, or landslides are difficult to anticipate in real time. Existing numerical simulation methods rely on small time steps to guarantee stability, which makes them too slow to cover the large spatial and temporal scales required during emergencies [1]. As a result, decision makers often lack accurate predictive tools when rapid response is most critical.

A promising research direction is to exploit the geometric structure of gravity-driven flows. Instead of simulating the evolution of the entire flow field at small time steps, we can track stochastic flow paths — curves that follow the dominant directions of the fluid over long distance. This idea is inspired by meshless Monte Carlo solvers in computer graphics [2]. By reformulating the shallow water transport equations along these paths, we can design solvers that use very large time steps while preserving essential physical behavior.

The objective of this internship is to develop and evaluate a Monte Carlo flow path solver for fast, uncertainty-aware simulation of shallow flows over complex terrains.

Approach

The internship will focus on the mathematical and algorithmic foundations of stochastic flow path simulation, through the following steps:

- **Flow path formulation:**
  Recast shallow-water transport as implicit equations along flow paths. Represent uncertain flow directions with local probability distributions, and compute upstream

fluxes by sampling these distributions (See the random receiver selection in [3] for a simple example).

- **Monte Carlo solver design:**
  Implement a stochastic fixed-point algorithm that iteratively updates flow thickness and velocity distributions. We will look in particular on how to add a *memory effect* between the iterations to stabilize the convergence.
- **GPU acceleration:**
  Adapt techniques from flow routing and path tracing to efficiently sample and accumulate contributions along flow paths. Explore parallelization strategies to enable large-scale simulations [4].
- **Validation and analysis:**
  Compare the stochastic solver with traditional explicit shallow-water solvers on realistic terrains.

Work environment and requirements

The internship will take place at Inria Sophia Antipolis in the GRAPHDECO group (http://team.inria.fr/graphdeco). Inria will provide a monthly stipend of around 1400 euros for EU citizens in their final year of masters, and ~600 euros for other candidates.

Candidates should have strong programming and mathematical skills with knowledge in computer graphics and experience in Python data science libraries.

References

[1] Courant, R., Friedrichs, K., & Lewy, H. (1967). On the partial difference equations of mathematical physics. IBM journal of Research and Development, 11(2), 215-234.

[2] Sawhney, R., Seyb, D., Jarosz, W., & Crane, K. (2022). Grid-free Monte Carlo for PDEs with spatially varying coefficients. ACM Transactions on Graphics (TOG), 41(4), 1-17.

[3] Jain, A., Benes, B., & Cordonnier, G. (2024). Efficient debris-flow simulation for steep terrain erosion. ACM Transactions on Graphics (TOG), 43(4), 1-11.

[4] A Jain, B Kerbl, J Gain, B Finley, G Cordonnier, FastFlow: GPU Acceleration of Flow and Depression Routing for Landscape Simulation, Computer Graphics Forum, 2024