Predicting Roughness Effects on Velocity and Temperature in Turbulent Flow - A Data-Driven Approach

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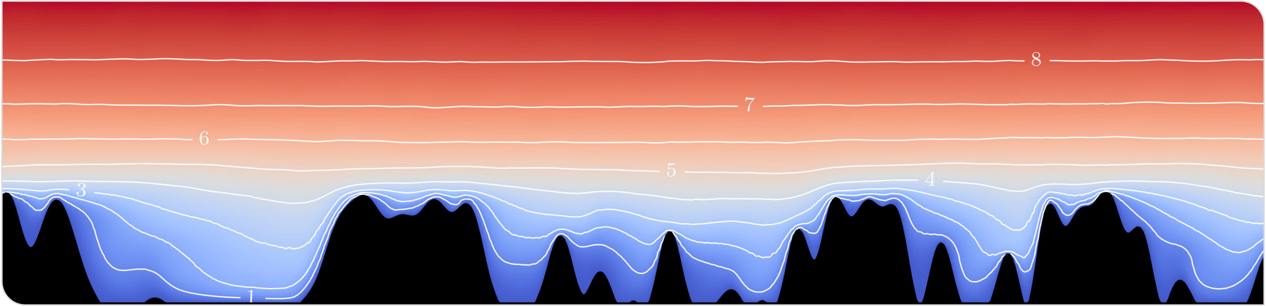
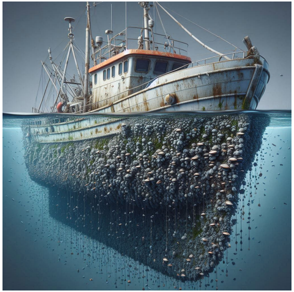


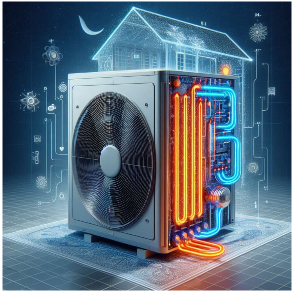
Turbulent Flow above Realistic Roughness

Ship hull[a]



[a] Dall-E 3: "Create a realistic image of a small fishing ship, where small mussels generate a rough and patchy ship surface only on the submerged ship hull below the water line"

Heat exchanger[b]



[b] Dall-E 3: "Create a realistic picture of a heat pump unit for heating a house to visualize the heat flow and transfer from the unit to the surrounding. Show the air flow"

Atmospheric science[c]

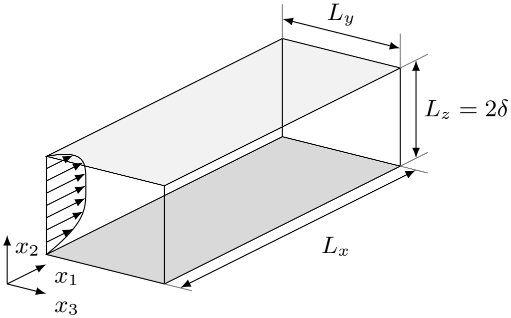
[c] Dall-E 3: "Create a realistic picture of the Austrian alps, where lots of clouds flowing over the mountains showing the turbulent air flow"

Question

- Predict roughness influence to velocity and temperature distribution without costly simulations

Turbulent Channel Flow with Smooth Wall

Simulation Setup



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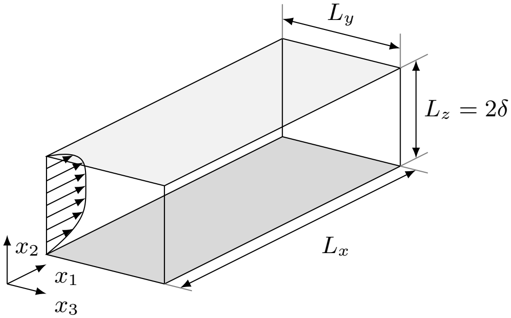
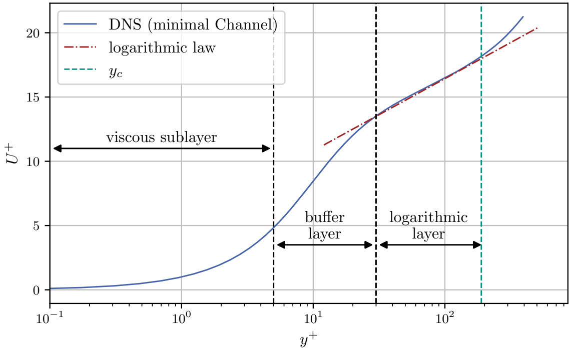
Simulation Setup



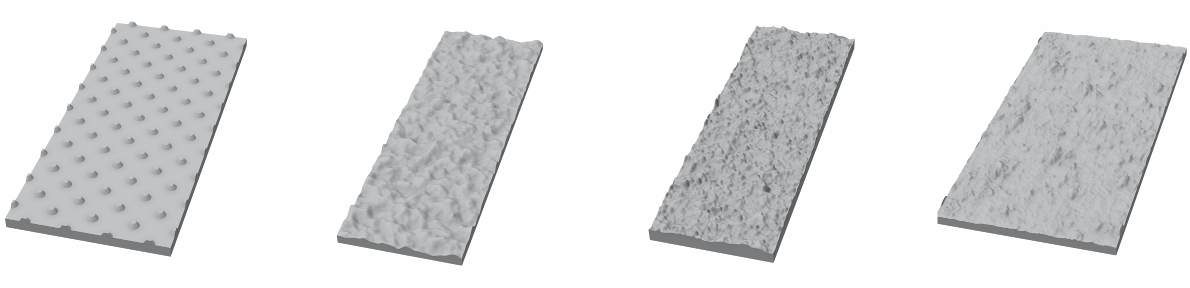
Mean Velocity Profile



Smooth Wall

- Mean velocity and temperature follows distinct profile with known relations (log-law)

Roughness Influenced Channel Flow I

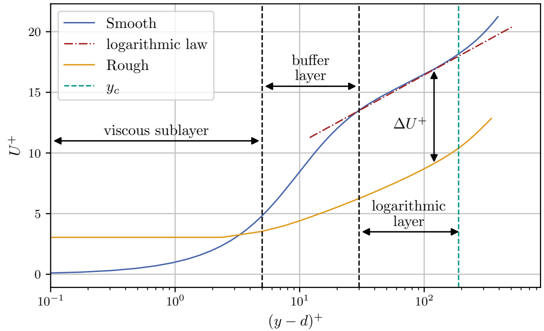


(a) Artificial: Uniform (b) Artificial: Isotropic (c) Real: Sandpaper (d) Real: Turbine blade

Roughness characterization

$\rightarrow$ multiscale phenomenon with diverse subclasses (isotropic, homogenous, patchy, anisotropic)

Roughness Influenced Channel Flow II



Effect:

- Increased friction
- Increased heat transfer

Roughness function ΔU^+, $\Delta\Theta^+$:

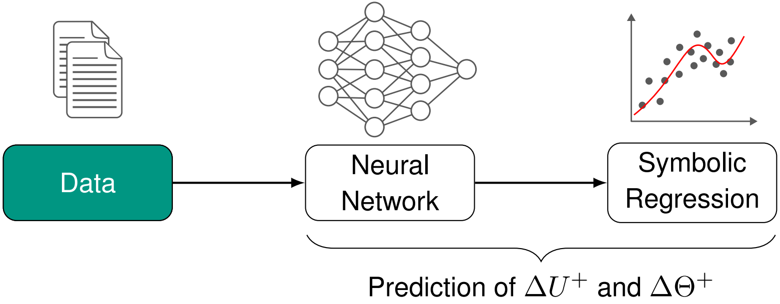
- Characterized shift in logarithmic layer (Hama, 1954; Clauser, 1954)

Research question

$\rightarrow$ Predict shift ΔU^+ and $\Delta\Theta^+$ (and hence C_f and St) given a roughness height profile

Approach

Procedure:

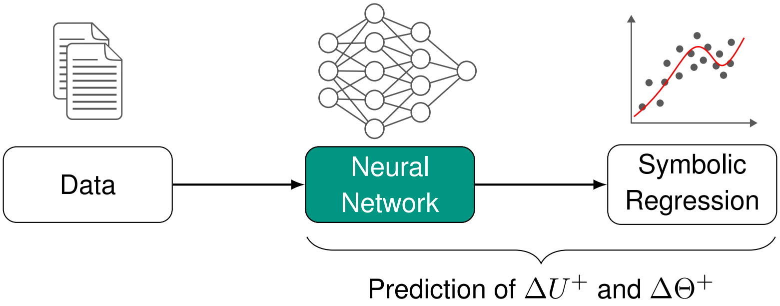


Data:

- 4200 rough surfaces ($\mathcal{S}$) and 93 high-fidelity simulations ($\tilde{\mathcal{S}}$) (Yang et al., 2023)
- External data set ($\tilde{\mathcal{E}}$) for additional testing

Approach

Procedure:

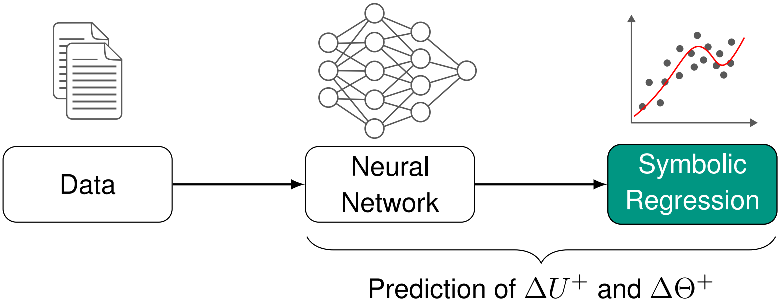


Neural Network:

- Data-driven function approximation given powerful statistical measures

Approach

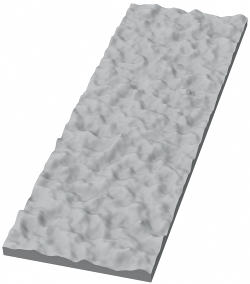
Procedure:



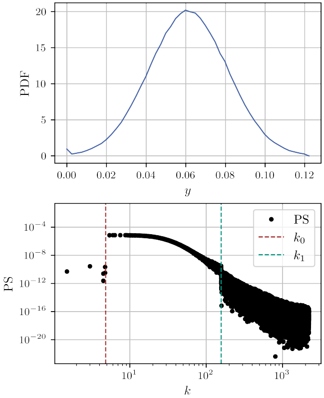
Symbolic Regression:

- Convert hidden function in human-understandable symbolic expression

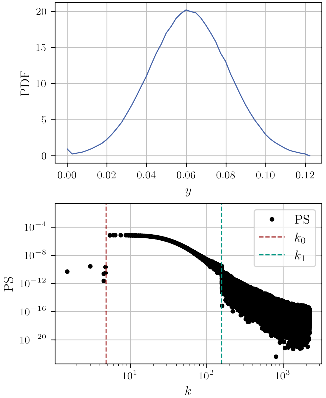
Neural Network Prediction

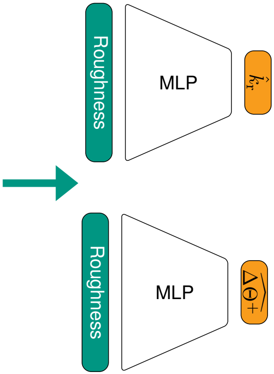


Neural Network Prediction

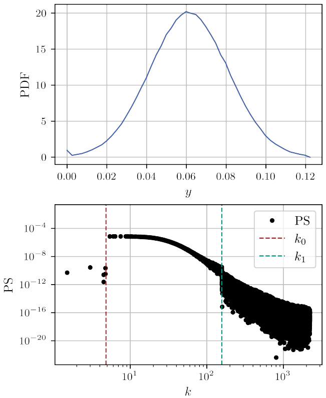


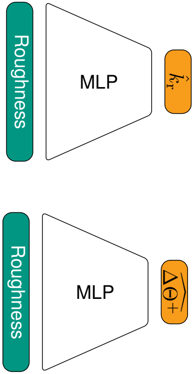
Neural Network Prediction



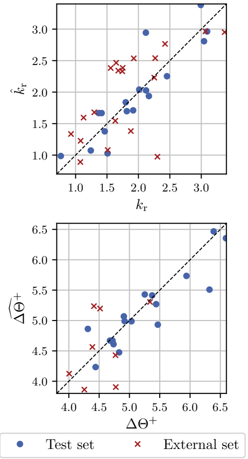


Neural Network Prediction





Results:



k_r:

Set	MAPE
Test	13.41%
External	27.52%

$\Delta\Theta^+$:

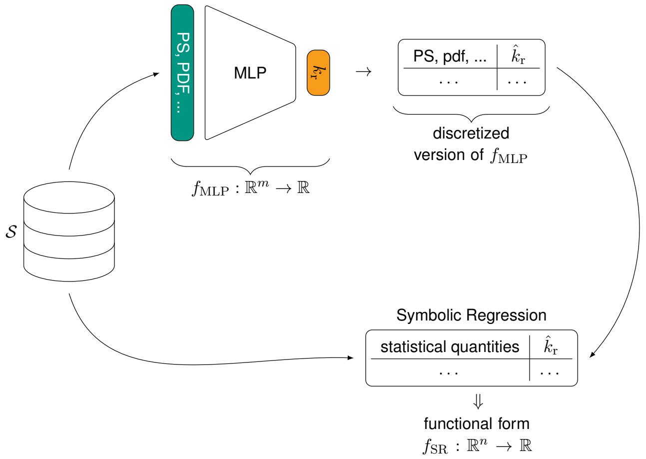
Set	MAPE
Test	4.26%
External	9.5%

Symbolic Regression

Goal

→ Translate network to application-oriented correlation

- Statistical parameters vs. power spectrum & probability density function
- Genetic Programming
- `Python` library `PySR` (Cranmer, 2023)



Symbolic Correlation

Correlation	R^2	Result
$k_\mathrm{r} = \dfrac{k_\mathrm{s}}{k_{99}} = ES_x\,(-ES_x + Sk + 2.37) + 0.77$	0.931	exceed references
$\Delta\Theta^+ = 6.02\left(k_\mathrm{s}\left(-0.18\,Sk + \dfrac{k_\mathrm{z}}{k_\mathrm{rms}}\right)\right)^{0.138}$	0.827	missing Pr

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Measure of Height

- k_{99}: confidence interval
- k_z: mean peak-to-valley
- k_rms: root-mean-square

Measure of Slope

$$ES_x = \frac{1}{A}\int_A \left|\frac{\partial h}{\partial x}\right| \mathrm{d}A$$

- Related to frontal solidity

Measure of Shape

$$Sk = \frac{1}{A}\int_A \frac{h^3}{k_\mathrm{rms}} \mathrm{d}A$$

- Asymmetry in height

Simulation Tool

Demand:

- temperature as **passive scalar**
- fast for database generation $\rightarrow$ **GPGPU**
- arbitrary roughness description $\rightarrow$ **immersed boundary method**

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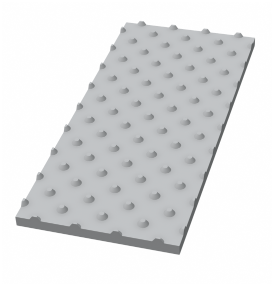
Canonical Navier-Stokes (CaNS) (Costa, 2018)

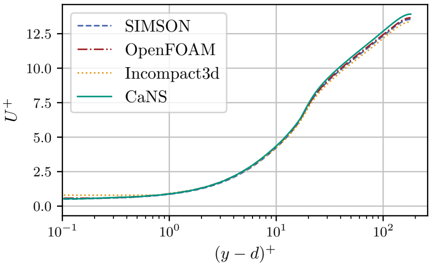
- second-order finite-differences, eigenfunction expansion for Poisson equation
- `Fortran90` OpenACC directives and cuDecomp library
- cuDecomp for hardware-adaptive pencil decomposition
- IBM and passive scalar (Habibi Khorasani, 2024)

Validation at $Re_\tau = 180$

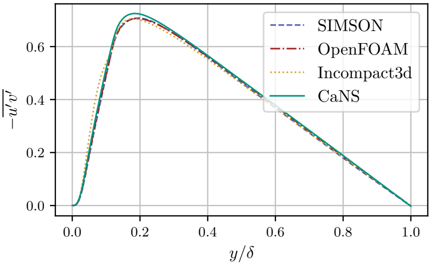
Surface



Velocity



Turbulent shear stress



Conclusion

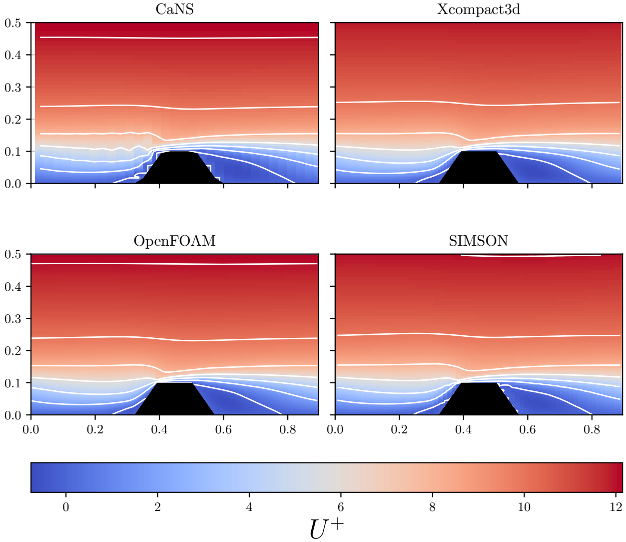
→ GPU code is able to compete with predecessors (Theobald et al., 2021)

→ Successful run on 4 NVIDIA A100 GPUs (1 node) on HoreKa

Preliminary Results

Mean velocity around the truncated cone

- Lack of resolution in CaNS simulation
  - → Enhanced simulation is running
- General trends
  - Recirculation zone
  - increased velocity above element



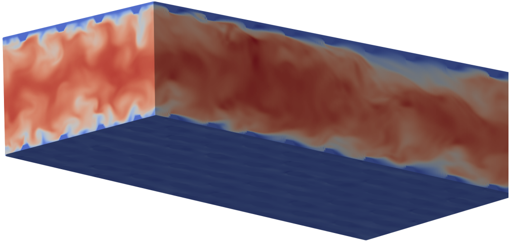
Summary and Outlook

Roughness function prediction

- ✔ Good tools (Neural network, correlation) for velocity augmentation
- ✘ Correlation for $\Delta\Theta^+$ missing Pr number

Numerical tools

- → Passive scalar: Source term problems
- ✔ Significantly faster than predecessors (wall clock time)
- ✔ IBM: Fully working



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