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Direct Prediction of Steady-State Flow Fields in Meshed Domain with Graph Networks

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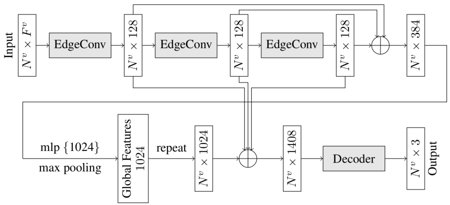
Motivation

Target:

- Modelling fluid dynamical quantities, i.e. velocities $\mathbf{w}_i$ and pressure p_i
- Graph neural network to learn direct predictions of the final steady-state velocity and pressure fields

Given:

- Meshed domain as a bidirectional graph $G = (V, E)$, with Nodes V and Edges E
- Node feature vector $\mathbf{v}_i$=[$\mathbf{u}_i, \mathbf{n}_i$]
  - Mesh-space coordinates $\mathbf{u}_i$
  - Quantities $\mathbf{n}_i$ describing the domain, e.g. angle of attack, Mach number, node type



Model

Edge Function

Local and global feature extraction with EDGECONV as edge function:

$$\mathbf{e}'_{ij} = \mathrm{ReLU}\big(\Theta \cdot (\mathbf{v}_j - \mathbf{v}_i) + \phi \cdot \mathbf{v}_i\big)$$
$$\mathbf{v}'_{ij} = \max \mathbf{e}'_{ij}$$

with Θ and ϕ as a shared MLP and max as aggregation operation

- Local neighborhood information by relative displacement $(\mathbf{v}_j - \mathbf{v}_i)$
- Global shape structure by absolute values $\mathbf{v}_i$

Architecture

- EDGECONV layers as local feature descriptors
- $\oplus$ Concatenation to include multi-scale features
- Global max pooling for global feature vector
- Decoder transforming the latent features to output $\mathbf{p}_i$

Dataset

Three data sets with fluid dynamical simulations to evaluate our method

AIRFOIL

- NACA0012 airfoil for varying angle of attacks α and Mach numbers m
- CFD: Steady-state, compressible, inviscid Euler equation

AIRFOILROT

- Rotation of whole simulation domain of AIRFOIL by angle α

CHANNEL

- Channel flow with varying number of generic objects randomly placed inside the channel
- CFD: Steady-state, incompressible, inviscid Navier-Stokes equation

Results

Comparing with models from literature: Base GCN and MESHGRAPHNETS with two extensions (ABS..Absolute values, POOL..Global Max Pooling)

AIRFOIL

- Same geometry for all samples, solution only depending on α and m
- Low RMSE with all methods

AIRFOILROT

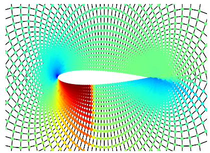
- Sensitive understanding of geometric structure required
- Global information by absolute values $\mathbf{v}_i$ and relative displacement $(\mathbf{v}_j - \mathbf{v}_i)$ necessary
- MESHGRAPHNETS with only relative displacement fails

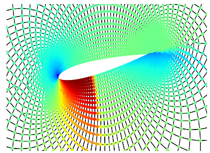
CHANNEL

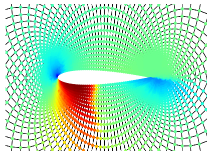
- Strong understanding of complex geometric structure required
- Absolute values $\mathbf{v}_i$ and relative displacement $(\mathbf{v}_j - \mathbf{v}_i)$ together with local and global feature descriptors necessary
- Our methods achieves lowest RMSE
- Generalizes well to new unseen geometric setups of the channel flow

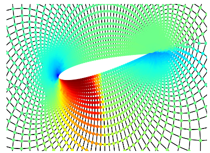
Test root mean square error RMSE$\times 10^{-2}$

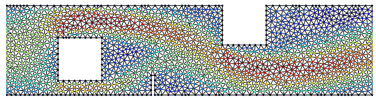
Method	AIRFOIL	AIRFOILROT	CHANNEL
GCN	1.40	-	-
MESHGRAPHNETS	0.95	7.34	13.30
MESHGRAPHNETS (ABS)	**0.73**	1.28	13.04
MESHGRAPHNETS (ABS+POOL)	1.25	0.99	6.58
Ours	1.40	**0.87**	**5.81**

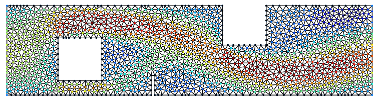

AIRFOIL Ground Truth


AIRFOILROT Ground Truth


AIRFOIL Prediction


AIRFOILROT Prediction


CHANNEL Ground Truth


CHANNEL Prediction

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