AI-Based Surrogate Modelling for Incremental Sheet Metal Forming

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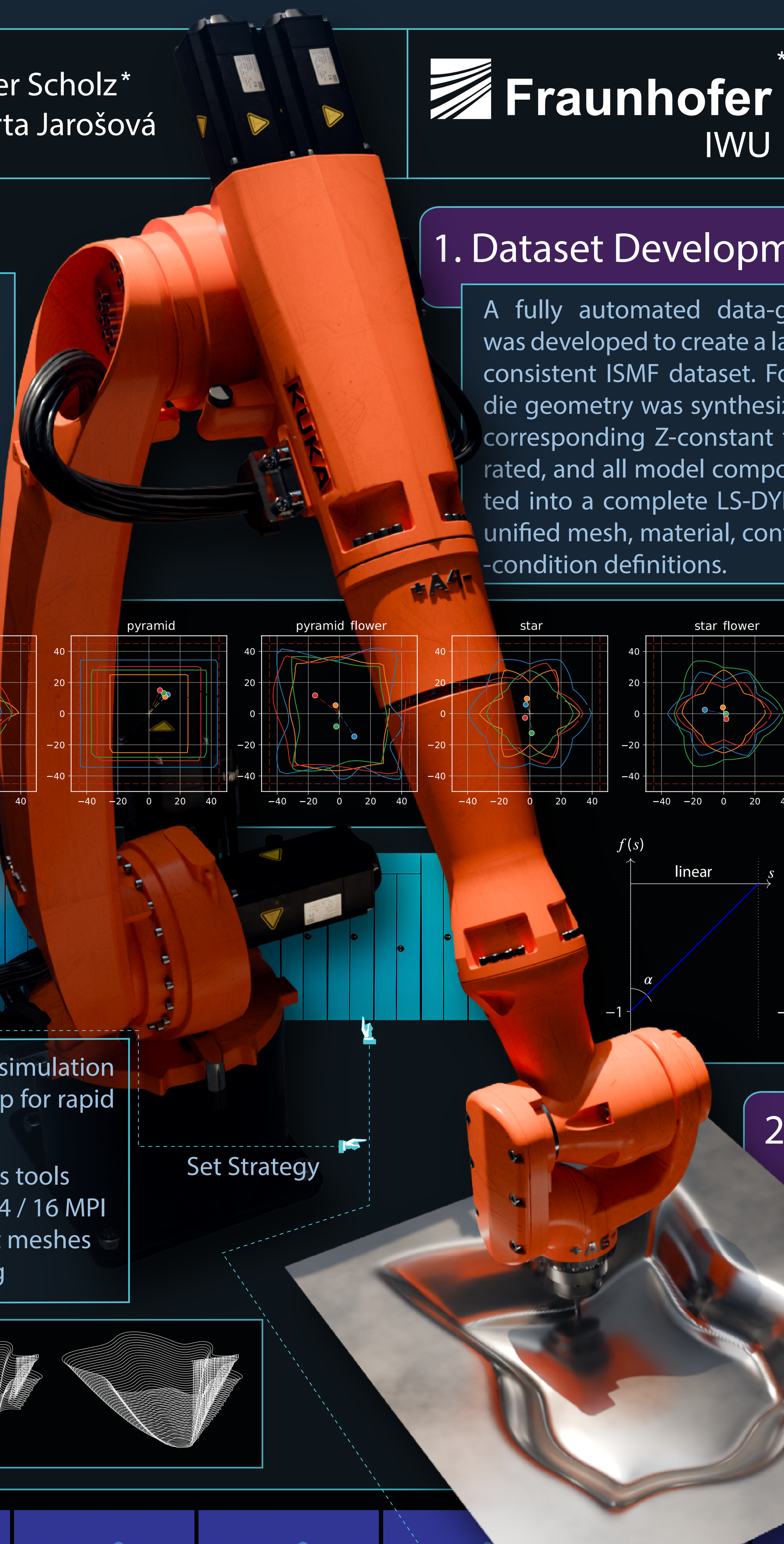
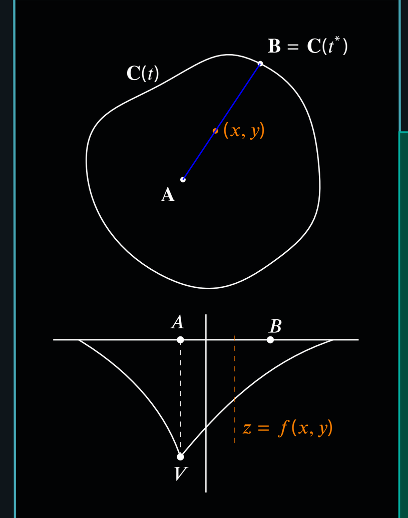


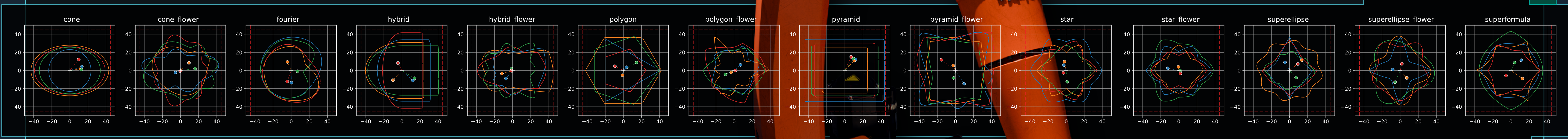
Problem and Motivation

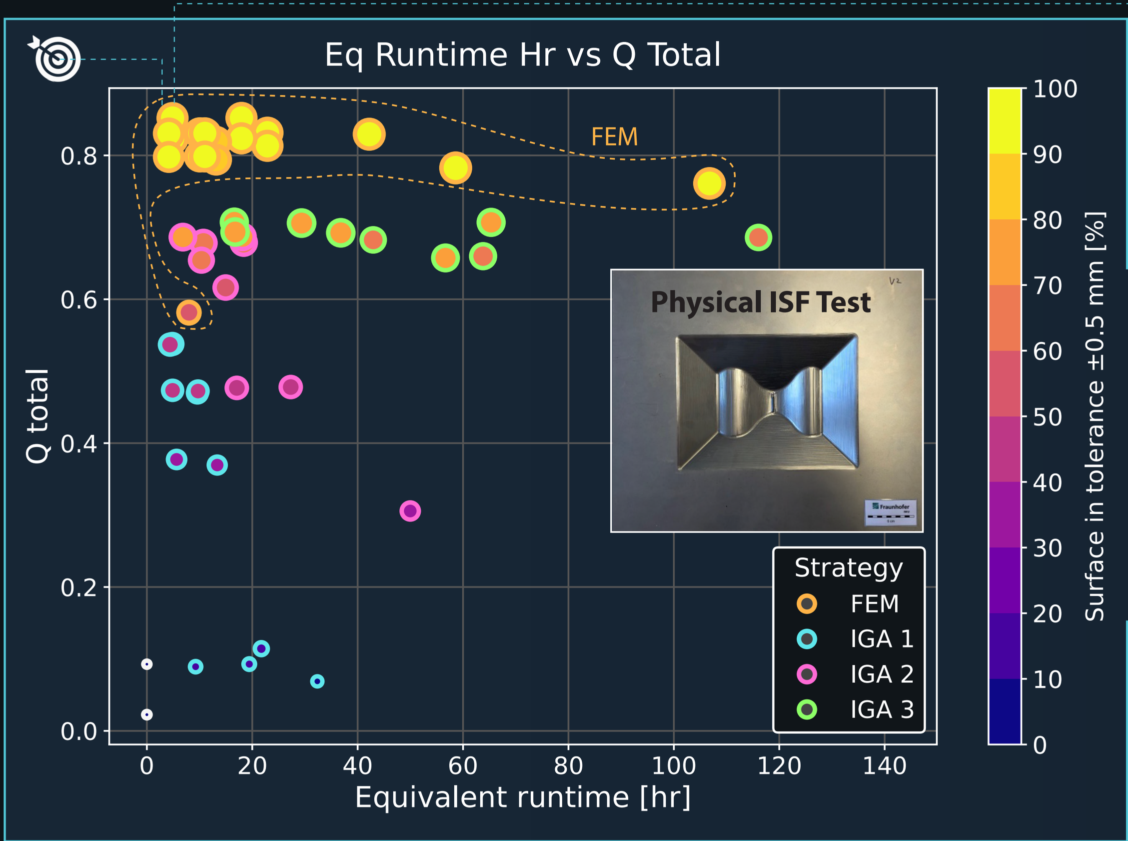
Incremental Sheet Metal Forming (ISMF) offers a flexible way to manufacture complex and customized metal parts without dedicated tooling, which is especially attractive for small-batch production and hybrid tooling concepts. However, the process is difficult to predict accurately because it involves strong nonlinear deformation, complex contact, material anisotropy, and springback. High-fidelity finite element simulations can capture these effects, but they are computationally too expensive for tasks that require evaluating many forming scenarios, such as toolpath optimization, process design, or die-shape compensation. This motivates the development of fast AI-based surrogate models trained on large-scale simulation data, enabling rapid prediction of sheet deformation while preserving the essential physical trends of the forming process.

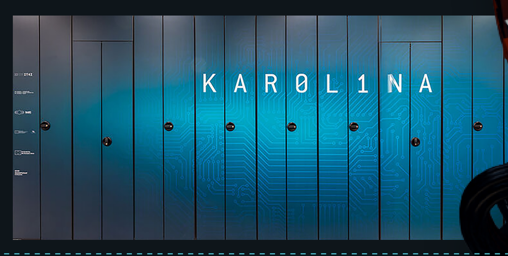
1. Dataset Development

A fully automated data-generation pipeline was developed to create a large and structurally consistent ISMF dataset. For each sample, the die geometry was synthesized automatically, a corresponding Z-constant toolpath was generated, and all model components were converted into a complete LS-DYNA input deck with unified mesh, material, contact, and boundary-condition definitions.





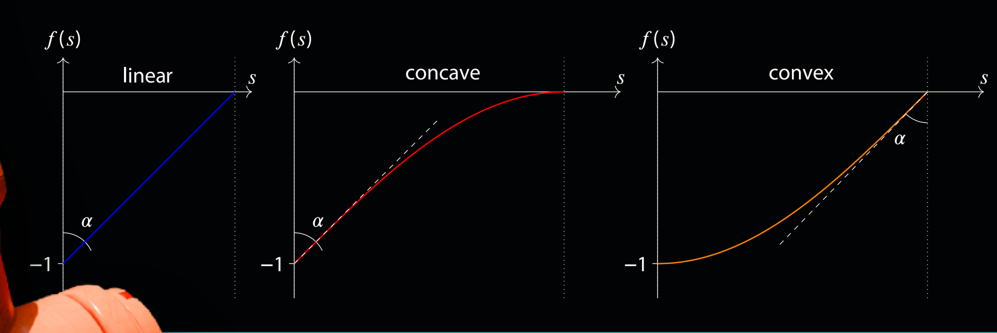


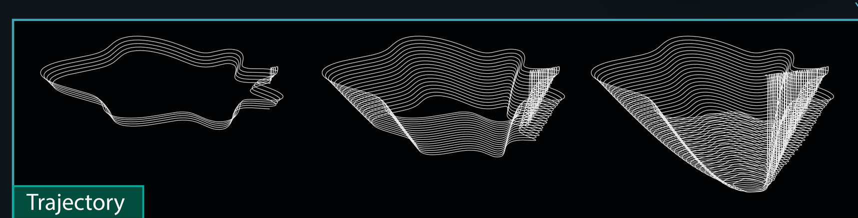


Strategies for acceleration of ISF simulation to identify the most efficient setup for rapid dataset generation.

- Multiple-tool: 1, 4, or 8 fictitious tools
- Parallelization setup: 4 SMP, or 4 / 16 MPI
- FEM or IGA with three different meshes
- Tool acceleration - mass scaling

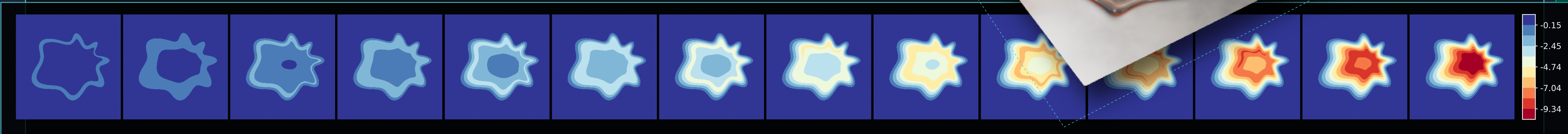
Set Strategy



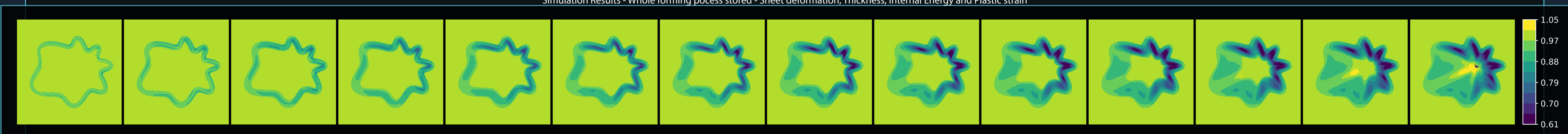


2. FEM Data Generation

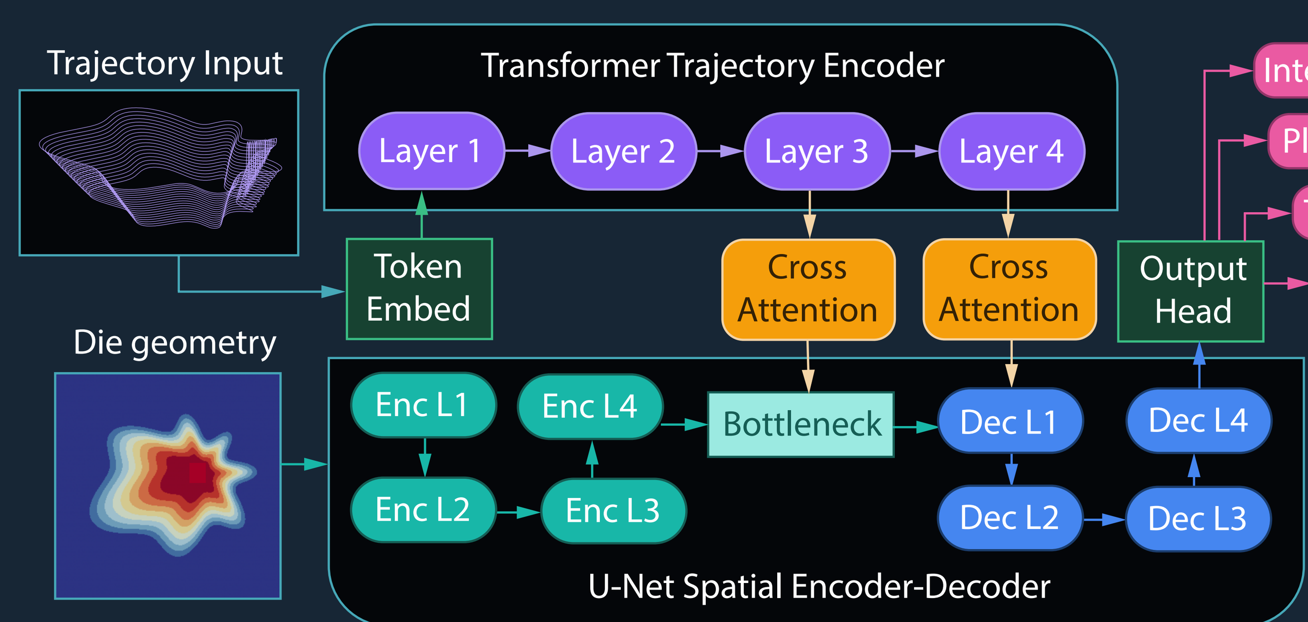
The generated models were solved using high-fidelity explicit FEM simulations to capture the deformation of the sheet during forming. Automated post-processing then extracted intermediate and final geometries in a uniform format, producing a large-scale dataset suitable for training and validation of the surrogate AI model.



Simulation Results - Whole forming process stored - Sheet deformation, Thickness, Internal Energy and Plastic strain



Transformer Cross Attention U-net



Model Generalization

The surrogate was trained on the full dataset containing both flat-bottom and wavy-bottom geometries

Training the surrogate only on samples with flat-bottom geometries and evaluating it on unseen wavy-bottom cases.

The dataset consists of 4,517 FEM simulations, of which 1,975 correspond to geometries with a flat-bottom die. The FEM simulations were performed on the Karolina cluster, while surrogate-model training was carried out on LUMI up to 160 GPUs.

TCAU variant model	Train dataset	Validation dataset	Test dataset	Total dataset
Final-time	4117 (91.14%)	200 (4.43%)	200 (4.43%)	4517 (100.00%)
Fully time-resolved	15045338 (90.93%)	729681 (4.41%)	771047 (4.66%)	16546066 (100.00%)

Dataset split used for training, validation and testing.

TCAU variant model	Number of GPUs	Peak VRAM [GiB]	Disk size [GiB]	Samples/s	Epoch time [min]	Epoch at target	GPU hours [h]
Final-time	1	48.23	5.76	11.1	7.23	481	57.96
Fully time-resolved	160	64.02	7407.1	201.5	986.38	5	13151.73

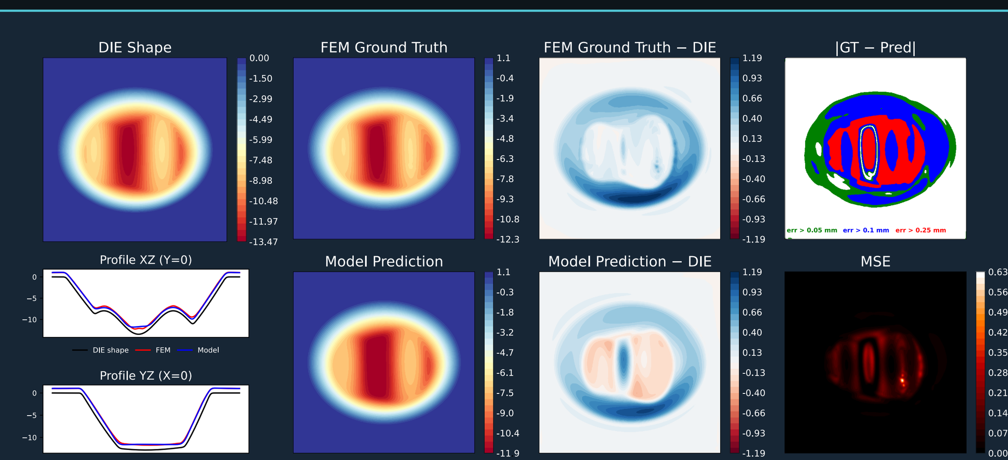
Training-time memory usage, storage requirements, and computational cost of TCAU.

Perfor. metric	MSE	RMSE	MAE	MaxAbs	RelL2	PSNR [dB]	SSIM	|e|<0.1	|e|<0.25
Local (final step)	1.1e-03	3.3e-02	2.2e-02	4.1e-01	7.2e-03	52.12	0.99	98.89%	99.96%

Inference metric	N	T_N [ms]	Throughput [/s]	#GPUs
Value	1	54.92	18.2	1

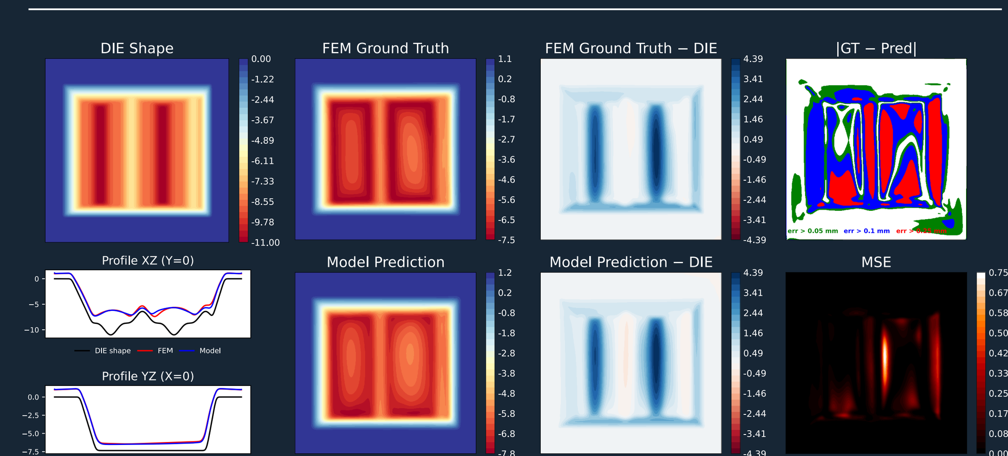
Perfor. metric	MSE	RMSE	MAE	MaxAbs	RelL2	PSNR [dB]	SSIM	|e|<0.1	|e|<0.25
Local (final step)	4.8e-03	6.9e-02	4.1e-02	4.3e-01	1.6e-02	41.91	0.99	90.55 %	98.42%

Inference metric	N	T_N [ms]	Throughput [/s]	#GPUs
Value	1	50.9	19.6	1



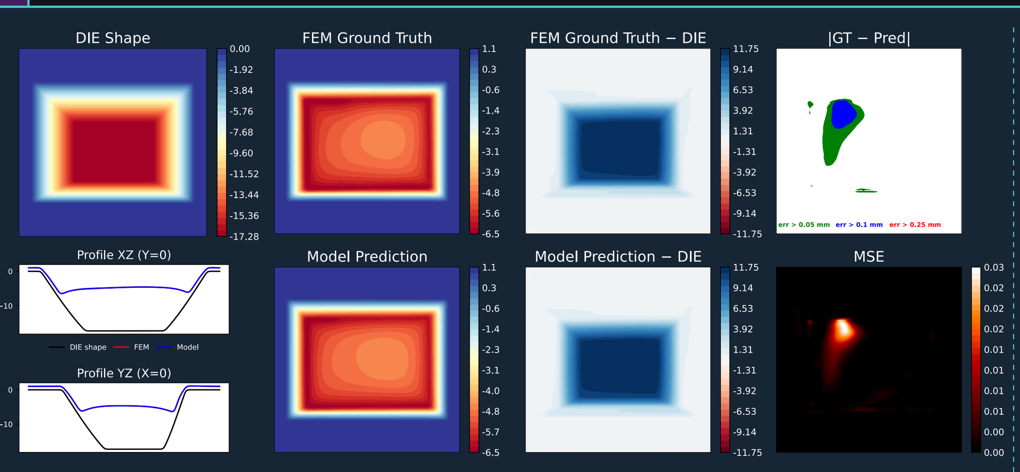
Perfor. metric	MSE	RMSE	MAE	MaxAbs	RelL2	PSNR [dB]	SSIM	|e|<0.1	|e|<0.25
Local (final step)	1.9e-02	1.4e-01	8.5e-02	7.9e-01	3.0e-02	39.68	0.99	70.30%	88.74%

Inference metric	N	T_N [ms]	Throughput [/s]	#GPUs
Value	1	54.99	18.2	1

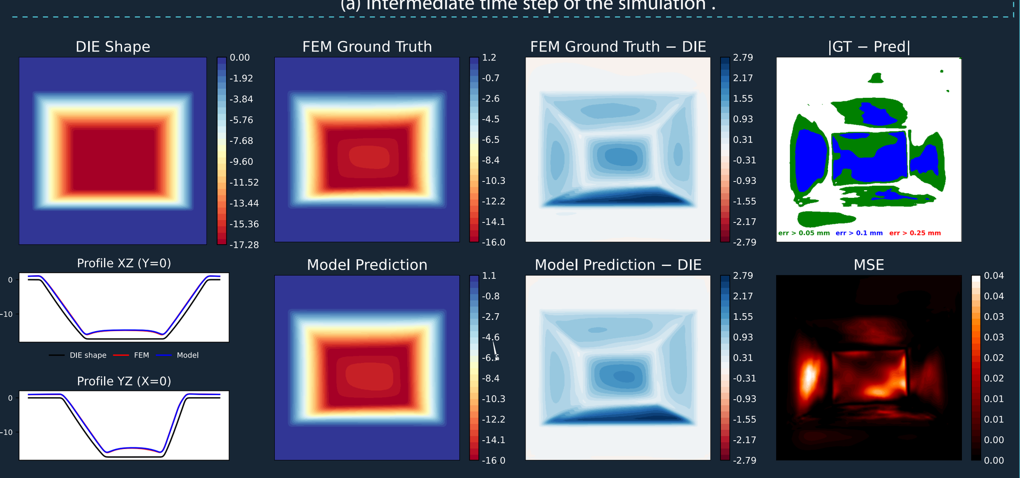


Perfor. metric	MSE	RMSE	MAE	MaxAbs	RelL2	PSNR [dB]	SSIM	|e|<0.1	|e|<0.25
Local (final step)	3.2e-02	1.8e-01	1.5e-01	8.7e-01	4.2e-02	33.68	0.98	63.40%	85.98%

Inference metric	N	T_N [ms]	Throughput [/s]	#GPUs
Value	1	50.96	19.6	1



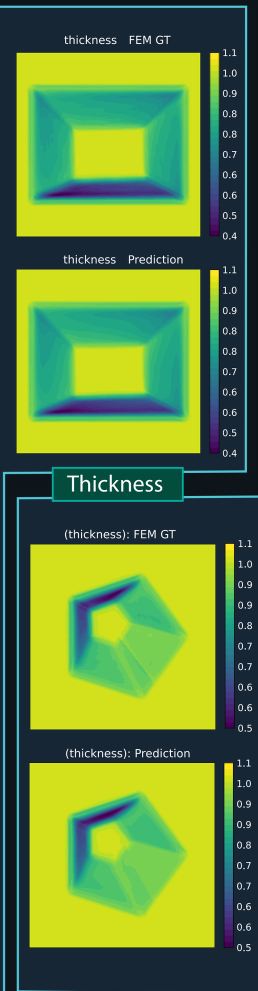
(a) Intermediate time step of the simulation.



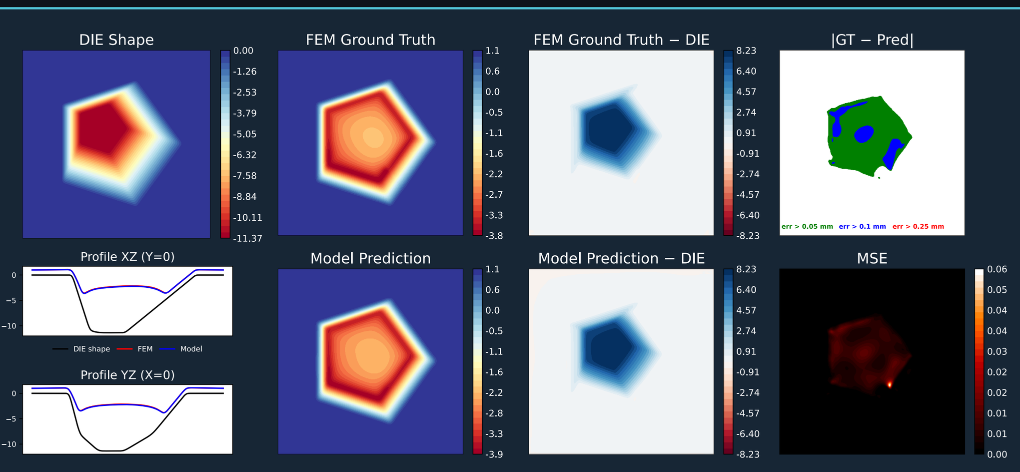
(b) Final time step of the simulation.

Perfor. metric	MSE	RMSE	MAE	MaxAbs	RelL2	PSNR [dB]	SSIM	|e|<0.1	|e|<0.25
Local (mid step)	6.1e-04	2.5e-02	1.4e-02	1.6e-01	7.1e-03	49.74	0.99	98.4%	100%
Local (final step)	4.4e-03	6.6e-02	5.0e-02	2.7e-01	8.8e-03	48.31	0.99	84.9%	100%
Global (all steps)	1.8e-03	4.3e-02	2.6e-02	3.7e-01	1.0e-02	52.22	0.99	95.1%	99.9%

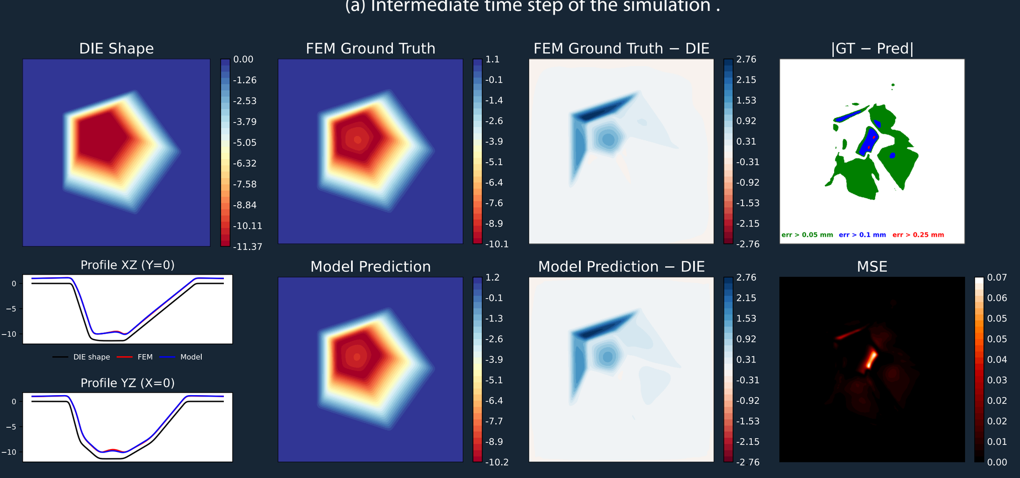
Inference metric	N	T_N [s]	T_i [ms]	Throughput [/s]	#GPUs
Value	5193	265.0	51.04	19.6	1



Thickness



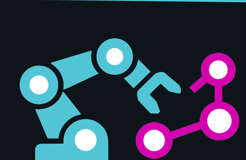
(a) Intermediate time step of the simulation.



(b) Final time step of the simulation.

Perfor. metric	MSE	RMSE	MAE	MaxAbs	RelL2	PSNR [dB]	SSIM	|e|<0.1	|e|<0.25
Local (mid step)	1.2e-03	3.4e-02	1.9e-02	2.4e-01	2.2e-02	43.17	0.99	97.5%	100%
Local (final step)	1.2e-03	3.5e-02	2.6e-02	2.6e-01	1.1e-02	50.13	0.99	98.9%	99.9%
Global (all steps)	1.2e-03	3.4e-02	1.9e-02	5.2e-01	1.8e-02	50.45	0.99	96.6%	99.9%

Inference metric	N	T_N [s]	T_i [ms]	Throughput [/s]	#GPUs
Value	2386	54.43	22.83	43.8	1



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