High–Fidelity Haptic Rendering through Implicit Neural Force Representation

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Introduction

The **refresh rate requirement** for haptic rendering is very tight (1kHz).

This is an issue for the haptic rendering of complex meshes.

Analytic methods struggle to meet the refresh rate requirement while *approximate methods* can't maintain the right level of detail.

We would like to create a fast and scalable method, that is mesh-agnostic and produces high-fidelity results.

Methods

Idea

Represent the mesh implicitly using a distance function (SDF) and respective normals (UNF).

Why

SDF: force magnitude

UNF: force direction

How

Neural networks utilizing sinusoidal activation functions have shown potential in representing various signals[1].

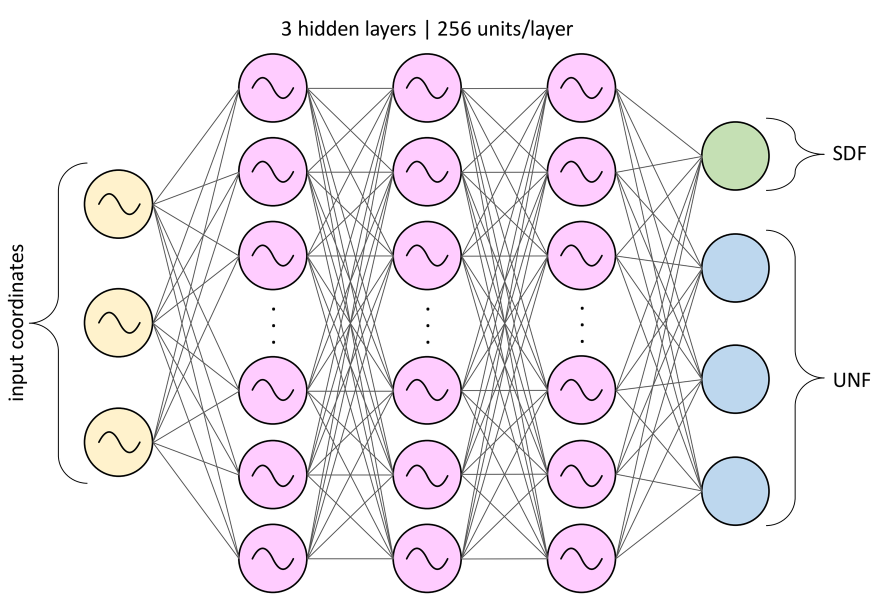


Fig.1: The architecture of our proposed method.

- Pose the SDF and UNF calculation as a Boundary Value Problem in order to construct the loss function.

Results

1. Calculate forces that would be generated (for validation).

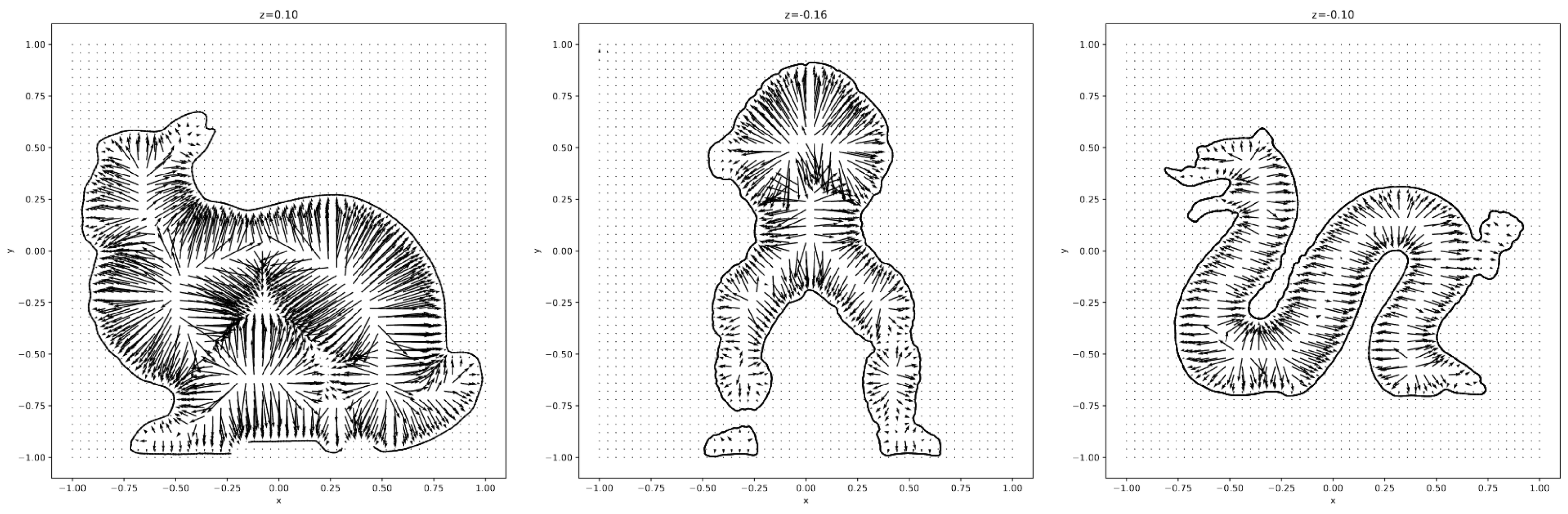


Fig. 2: Forces according to Hooke's Law, as obtained by our method (we're calling it **PANDIS**).

2. Implement haptic rendering pipeline.

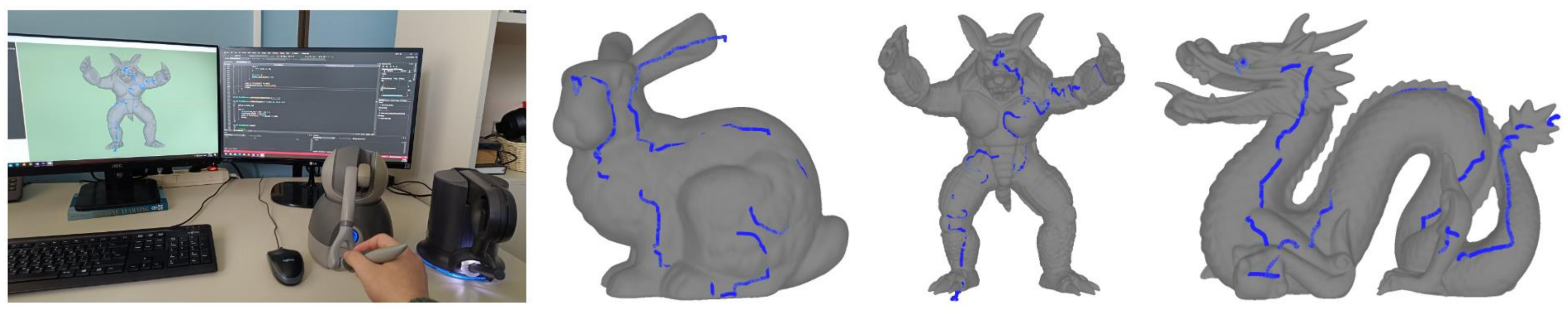


Fig. 3: Experimental setup and probe trajectories that were used for testing.

Setup time and storage space: Comparable to calculating forces on a 32^3 grid and interpolating.

Update rate: ~1.3 kHz (97% of frames above 1kHz) **independent of mesh choice**.

Quality:

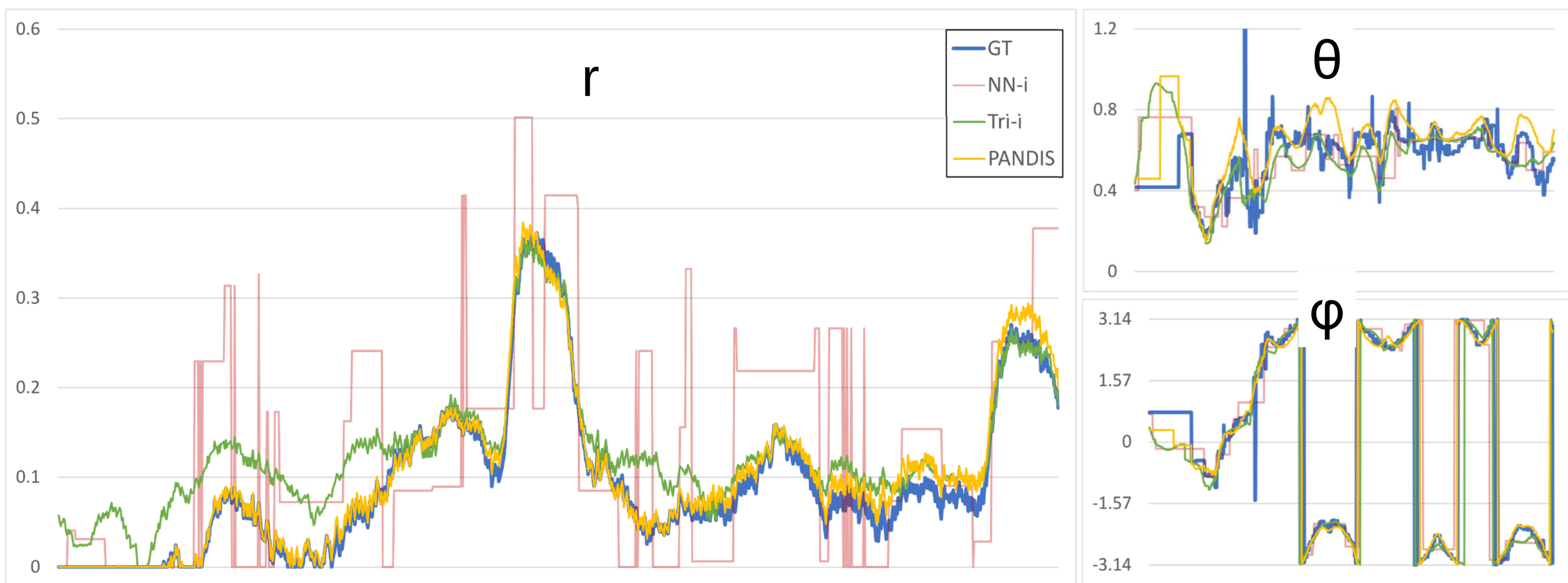


Fig. 4: Response force of NN-i (Nearest Neighbor interpolation), Tri-i (Trilinear interpolation) and **PANDIS** compared to GT (Ground Truth).

Quantitative Results:

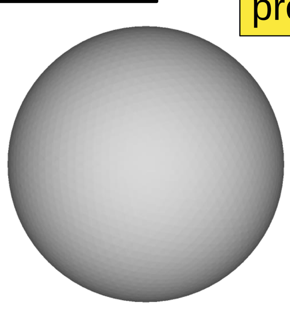
Average Error	GT	NN-i 32^3	NN-i 64^3	Tri-i 32^3	Tri-i 64^3	PANDIS
Bunny	0	0.086	0.031	0.057	0.026	0.006
Armadillo	0	0.139	0.081	0.099	0.046	0.022
Dragon	0	0.176	0.054	0.171	0.041	0.068

$$\text{Average Error}_i = \sum_j \frac{1}{j}\left(\|\text{force}_{i,j} - \text{force}_{\text{GT},j}\|\right),\; i = \{\text{GT, NN-i, Tri-i, PANDIS}\}$$

Loses only to 64^3, which use way more storage space and preprocessing time.

3. Further validation (theoretical).

The SDF and UNF of a sphere can be calculated analytically.



Method	GT	NN-i	Tri-i	Salisbury & Tarr [2]	Kim et al. [3]	Moustakas [4]	PANDIS
Average Error	0	0.097	0.082	0.083	0.367	0.296	0.162

Conclusion

We have successfully:

- embedded both the SDF and the UNF into a Neural Network.
- created and implemented a method of **fast, accurate,** and **highly scalable** haptic rendering.
- validated the results against ground truth data and other state-of-the-art methods and found PANDIS to be on par or better than the competition.

Discussion

While the groundwork to support machine learning – based haptic rendering is there, some issues still exist that should be researched further:

- The inability to effectively model non-linear mesh deformations in a robust manner, avoiding the current necessity to re-train the neural network.
- The very nature of the SDF as a mathematical distance function and its innate crudeness in representing non-watertight meshes.

References

[1]: Sitzmann, V. et al.: Implicit neural representations with periodic activation functions. NeurIPS 2020, 7462–7473

[2]: Salisbury, K., Tarr, C.: Haptic rendering of surfaces defined by implicit functions. ASME IMECE 1997. 61–67.

[3]: Kim, L., et al.: A haptic-rendering technique based on hybrid surface representation. IEEE CG&A 24(2), 66–75.

[4]: Moustakas, K.: 6dof haptic rendering using distance maps over implicit representations. MULTIMED TOOLS APPL 75(8), 4543–4557.

Acknowledgments

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Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN

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Further information

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