

MeshFL: A Decentralized MeshNet Framework for 3D Brain MRI Segmentation

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Summary

Advancements in federated learning have paved the way for privacy-preserving collaborative training of machine learning models on decentralized datasets. This is particularly relevant in fields like neuroimaging, where sensitive data, such as brain MRI scans, cannot be easily shared across institutions. MeshFL ("MeshFL," 2025) is an open-source framework designed to facilitate distributed training of deep learning models for 3D brain MRI segmentation while maintaining data privacy. Built upon NVFlare (NVIDIA, 2023), MeshFL employs federated learning principles to train MeshNet models (Fedorov et al., 2017) across multiple data sites, enabling high-accuracy segmentation of white and gray matter regions. With Dice scores of ~0.92 for training and ~0.9 for validation, MeshFL demonstrates that decentralized training can achieve performance comparable to centralized setups.

Statement of Need

In neuroimaging, collaborative machine learning is often hindered by the sensitive nature of patient data and the computational demands of training large 3D models. Traditional centralized learning approaches require aggregating data in one location, which is impractical for datasets governed by strict privacy laws. Federated learning addresses this limitation by enabling model training without sharing raw data between sites Rieke et al. (2020).

Existing federated learning frameworks often lack specific adaptations for neuroimaging tasks. MeshFL fills this gap by offering:

- A tailored framework for 3D brain MRI segmentation using the MeshNet model.
- Integration with NVFlare for federated training workflows (NVIDIA, 2023).
- Support for heterogeneously distributed data across sites.

MeshFL provides an easy-to-use yet robust environment for researchers and clinicians, ensuring high model performance while preserving patient privacy.

Implementation

MeshFL leverages NVFlare to implement federated learning workflows, allowing local sites to independently train the MeshNet model on their data and exchange model updates with a central server as shown in ??.

MeshFL key features include: - **Data Preprocessing:** Automated partitioning of MRI scans into training, validation, and testing sets. - **Model Training:** The framework utilizes PyTorch for

38 implementing the MeshNet model and optimize memory usage. Layer checkpointing further
39 reduces memory overhead during training. - **Aggregation Strategies:** Federated averaging
40 of model weights to produce a global model. Initial model weights are shared across sites
41 for consistent training initialization. - **Custom Logger:** MeshFL includes a GenericLogger
42 for detailed logging of training progress, gradient application, and Dice score evaluations. -
43 **Scalability:** Seamless support for multiple sites with varying data distributions and qualities.

44 The architecture of MeshNet, a 3D convolutional neural network, is optimized for volumetric
45 brain MRI segmentation, employing dilated convolutions to capture contextual information
46 while maintaining a compact parameter set (Yu & Koltun, 2016). A CrossEntropyLoss criterion
47 with class weights addresses class imbalance.

48 MeshFL also integrates a learning rate scheduler to enhance training stability. Using OneCy-
49 cleLR, the scheduler gradually increases the learning rate during the initial phase of training
50 and decreases it afterward, ensuring convergence without disrupting the learning process. This
51 approach prevents spikes in the learning rate and supports optimal parameter updates.

52 Validation

53 The performance of MeshFL was validated using the Mindboggle dataset (Klein & Tourville,
54 2012) on 15 MRI samples labeled for white and gray matter segmentation. Using Dice
55 coefficient as the evaluation metric, MeshFL achieved comparable accuracy to centralized
56 training setups while adhering to federated learning constraints. Benchmarks were conducted
57 with uniformly distributed data across sites.

58 Results demonstrated that MeshFL achieved Dice scores of ~0.92 for training and ~0.9 for
59 validation with robust performance comparable to centralized training ??.

60 Code Availability

61 MeshFL is openly available on GitHub at <https://github.com/Mmasoud1/MeshFL>. The
62 repository includes comprehensive documentation, example scripts, and a wiki to guide users
63 through installation and usage. Researchers can reproduce the experiments described here or
64 adapt MeshFL for their applications.

65 Author Contributions

66 We describe contributions to this paper using the CRediT taxonomy (Brand et al., 2015). -
67 **Writing – Original Draft:** M.M. - **Writing – Review & Editing:** M.M., and S.P. - **Conceptual-**
68 **ization and Methodology:** M.M., and S.P. - **Software and Data Curation:** M.M. - **Validation:**
69 M.M., and S.P. - **Resources:** [To be added] - **Project Administration:** M.M.

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