Dynamic Head Motion Tracking for Precise fNIRS Optodes Localization

Capstone Team: Chau Vuong, Asmaa Afridi, Surhan Nizamani, Rama Abboushi
Faculty Advisor: Dr. Luca Pollonini
University of Houston, Houston, TX

Objective

Develop a data-driven pipeline to accurately estimate and refine the 3D positions of functional near-infrared spectroscopy (fNIRS) optodes on the scalp by integrating inertial measurement unit (IMU) orientation data with geometric constraints and machine learning-based error correction, eliminating the need for repeated digitizer measurements.

Background

- fNIRS is a noninvasive technique that measures brain activity through changes in hemoglobin concentration. Accurate optode localization on the scalp is essential for mapping signals to brain regions.
- In this project, IMUs are integrated into optodes to capture motion and orientation data. However, IMUs provide orientation, not direct 3D position, making localization challenging.
- Traditional 3D digitizers are time-consuming and impractical for real-world use. To address this, we develop a pipeline that estimates optode positions from IMU data, refines them with geometric constraints, and improves accuracy using machine learning, eliminating the need for repeated digitizer measurements.

Methods

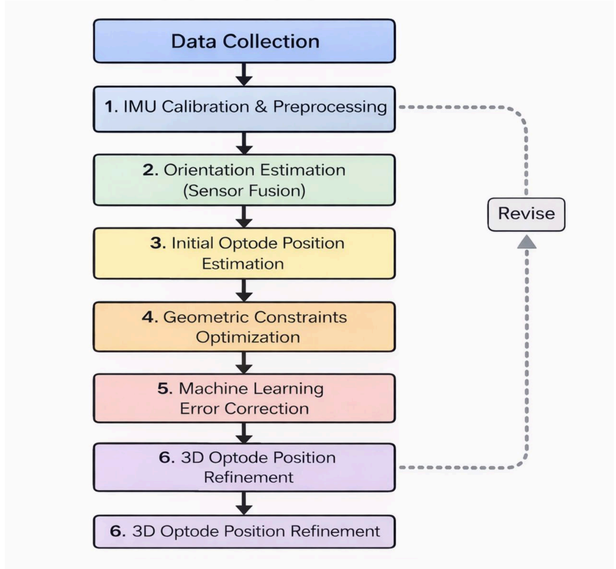

Figure 1. Pipeline for estimating and refining 3D fNIRS optode positions using IMU data

- Orientation was estimated using sensor fusion with an Extended Kalman Filter (EKF).
- Initial optode positions were estimated based on orientation and known cap geometry. Positions were refined using geometric constraints, including head surface projection and neighbor distance preservation.
- Residual errors were corrected using machine learning regression models (Ridge, Random Forest, and Gradient Boosting), with Gradient Boosting providing strong nonlinear error correction

Results

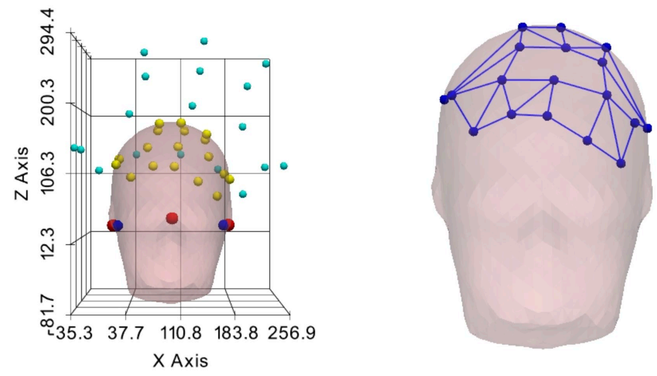

Figure 2. Left (Stage 4) Initial estimate showing ground truth (cyan) scattered off the scalp due to coordinate mismatch between the head mesh and subject data, IMU-based positions (yellow), and fiducials (red/blue). **Right (Stage 5)** Geometry-constrained optimization aligns optodes to the head surface and preserves spatial structure

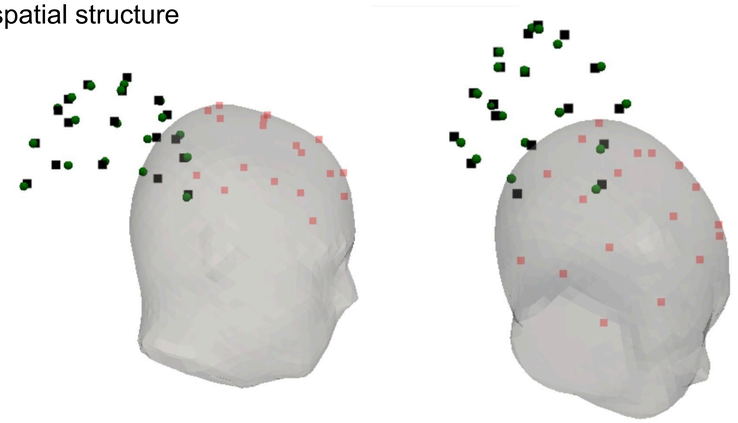

Figure 3. Left: side view; Right: top view. Stage 6 ML results (green) closely match ground truth (black), while Stage 4 (red) shows large error. Despite not being constrained to the mesh, Stage 6 ML result achieves accurate alignment with digitizer data.

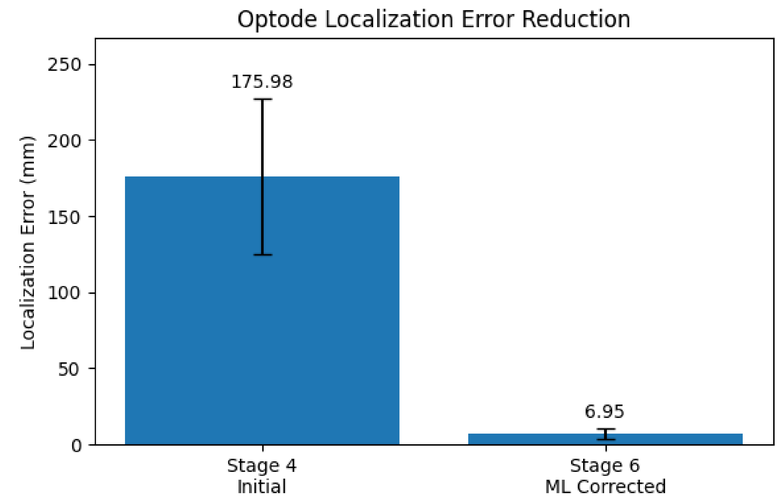

Figure 4. Significant reduction in localization error after machine learning (ML) correction, decreasing from ~176 mm to ~7 mm.

Error Distribution (mm)

Stage	Min	Q1 (25%)	Median	Q3 (75%)	Max
Stage 4 (Initial)	77.84	141.21	176.81	217.39	258.04
Stage 6 (ML Corrected)	1.50	4.79	6.74	8.40	15.90

Table 1. Error distribution across optodes shows a substantial reduction and tighter spread from Stage 4 to Stage 6, indicating improved accuracy and consistency after machine learning correction.

Conclusion

The proposed pipeline integrates IMU-based orientation estimation, geometric constraints, and machine learning to accurately localize fNIRS optodes, achieving substantial error reduction and improved consistency. While the current results demonstrate strong alignment with digitizer measurements, limitations remain due to coordinate mismatches between the head mesh and subject-specific IMU data. Future work will focus on improving mesh alignment and subject-specific modeling to further enhance localization accuracy

Acknowledgements

We would like to thank Dr. Pollonini and Dr. Du for their support throughout this project.