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# **FINITE ELEMENT MESH GENERATION FOR A MULTI-COMPARTMENT HEAD MODEL IN ZEFFIRO INTERFACE**

Bachelor's Thesis  
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# ABSTRACT

Lassi Rissanen: Finite element mesh generation for multi-compartment head model in Zeffiro Interface  
Bachelor's Thesis  
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Modelling the human brain and simulating its functionality with computer programs introduces a great number of applications. These applications include for example applying finite element method for optimizing injection currents in transcranial direct electrical stimulation, a form of treatment used for example in depression and Parkinson's disease, or localizing brain activity in different scenarios such as during an epileptic event to pinpoint the causing tissue in the brain.

Zeffiro Interface is one software representing recent advancement in finite element-based forward and inverse modeling of brain activity. It is an open-source software built for multidisciplinary GPU accelerated finite element method based forward and inverse computations for intricate geometries in Matlab environment. Zeffiro Interface originally started as a project for enabling the use of finite element method in electro- and magnetoencephalography (EEG/MEG), but its modular parameter structure allows applications in other fields as well.

Finite element mesh generation is an essential step in finite element method. This thesis is a literature review about the finite element mesh generation process for a multi-compartment head model in Zeffiro Interface. As background information, the thesis also introduces the finite element method, its applications in brain modelling, and related technologies such as EEG and MEG. In addition, the thesis introduces computing examples of mesh generation using Zeffiro Interface along with documented procedure for both user interface and script.

Keywords: Zeffiro Interface, finite element mesh generation, brain modelling, EEG, MEG

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

# TIIVISTELMÄ

Lassi Rissanen: Finite element mesh generation for multi-compartment head model in Zeffiro Interface (suom. Elementtiverkon generoiminen moniosaiselle pään mallille Zeffiro Interface ohjelmistossa)

Kandidaattitutkielma

Tampereen yliopisto

Tietojenkäsittelytieteiden tutkinto-ohjelma

Elokuu 2023

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Aivojen mallintaminen ja niiden toiminnan simuloiminen tietokoneohjelmien avustuksella tarjoaa lukuisia mahdollisuuksia ja soveltamisen kohteita. Näihin kuuluu muun muassa elementtimenetelmän hyödyntäminen injektiovirtojen optimoimiseksi transkraniaalisessa suorassa sähköstimulaatiossa, hoitomuodossa, jota käytetään esimerkiksi masennuksen ja Parkinsonin taudin hoitamiseen, sekä aivojen aktiivisuuden paikantaminen erilaisissa tilanteissa, kuten epilepsia kohtauksen aikana sen aiheuttavan aivokudoksen paikallistamiseksi.

Zeffiro Interface on yksi ohjelmisto, joka edustaa viimeaikaista edistystä aivojen mallintamisessa elementtimenetelmän avulla. Se on Matlabilla rakennettu avoimen lähdekoodin ohjelmisto monitieteellisten elementtimenetelmään pohjautuvien laskutoimitusten ratkaisemiseksi monimutkaisissa geometrioissa GPU kiihdytetysti. Zeffiro Interface alkoi projektina, jonka tarkoitus oli mahdollistaa elementtimenetelmän hyödyntäminen aivosähkökäyrä- ja aivomagneettikäyrätutkimuksissa, mutta sitä on mahdollista hyödyntää myös muilla soveltamisen aloilla.

Elementtiverkon generoiminen, tai diskretisointi, on olennainen osa elementtimenetelmää. Tämä tutkielma toteuttaa kirjallisuuskatsauksen elementtiverkon generoimisprosessista moniosaiselle pään mallille Zeffiro Interface ohjelmistossa. Taustatietona tutkielmassa perehdytään elementtimenetelmään ja sen sovelluksiin aivojen mallintamisessa, sekä aiheeseen läheisesti liittyviin teknologioihin, kuten aivosähkö- ja aivomagneettikäyrätutkimukseen. Lisäksi tutkielma esittelee esimerkitapauksia verkon generoimisesta Zeffiro Interface ohjelmistossa käyttöliittymän ja skriptin avulla.

Avainsanat: Zeffiro Interface, elementtiverkon generointi, aivojen mallintaminen, EEG, MEG.

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

# TABLE OF CONTENTS

1.INTRODUCTION .....	1
2.MATERIALS AND METHODS .....	2
2.1 Research method.....	2
2.2 Zeffiro Interface.....	2
2.2.1 basic workflow .....	2
2.2.2 hardware requirements .....	3
2.2.3 GPU acceleration.....	4
2.3 EEG/MEG .....	4
2.4 Finite element method.....	5
2.4.1 Applications in brain modelling .....	5
2.5 Mesh generation process in Zeffiro Interface .....	6
2.5.1 Mesh generation .....	6
2.5.2 Post processing .....	8
3.MESH GENERATION IN ZEFFIRO INTERFACE: COMPUTING EXAMPLES.....	9
3.1 Mesh generation using the user interface.....	9
3.2 mesh generation using a script .....	13
4.CONCLUSIONS.....	17
REFERENCES.....	19

# 1. INTRODUCTION

The application of advanced computational techniques has revolutionized our ability to understand and simulate brain activity. Among these techniques, the Finite Element Method (FEM) has emerged as a powerful tool for modeling electromagnetic fields within the complex and multi-layered structure of the human head. Its applications in brain modelling include for example localizing brain activity in electroencephalography (EEG) and magnetoencephalography (MEG) to pinpoint the causing tissue of epileptic event (Brette & Destexhe, 2012), and optimization of injection currents in transcranial direct electrical stimulation (tDES), a form of treatment used for example in depression and Parkinson's disease (Galaz Prieto, Rezaei, Samavaki, & Pursiainen, 2022). One essential part of FEM is the process of generating a finite element mesh, also referred to as discretization/meshing, for the related problem domain (Liu & Quek, 2014).

Zeffiro Interface is one software representing recent advancement in finite element-based forward and inverse modeling of brain activity. Built as an open-source software package for Matlab, ZI seeks to offer a platform for multidisciplinary FEM based forward and inverse computations and constructing volumetric finite element meshes for intricate geometries like the human brain. Until recently, FEM has been seen as computationally heavy method for discretizing the intricate geometry of the brain and the predominating method used in EEG and MEG has been the boundary element method (BEM). To mitigate this issue, ZI takes advantage of GPU acceleration. (He;Rezaei;& Pursiainen, 2020)

The goal of this thesis is to conduct a comprehensive exploration of the process of finite element mesh generation for multi-compartment head model within the framework of the Zeffiro Interface software. As background information, the thesis first introduces Zeffiro Interface along with related technologies, such as the finite element method and its applications in brain modelling, EEG and MEG. Introducing these topics is necessary for understanding the field of research as they are likely not familiar to readers coming from background of computer science. The thesis then proceeds to explain the finite element mesh generation process applied in Zeffiro Interface. Finally, the mesh generation in ZI is explored by using ZI to generate meshes for a multi-compartment head model with different parameters and examining the results. Furthermore, the steps for generating the mesh using the user interface and script are explained.

## 2. MATERIALS AND METHODS

### 2.1 Research method

This bachelor's thesis was done as a literature review. The primarily used research papers cited were gathered from "related papers" part in Zeffiro Interface GitHub repository and citations of those papers. Further gathering of material for background information was done by conducting searches to Tampere University Andor library database with search phrases such as "'finite element method' OR 'FEM'" and "EEG OR MEG". In addition to literature review, an empirical study was conducted by using Zeffiro Interface to generate meshes with different parameters for multi-compartment head model and comparing the resulting mesh products and their generation time. The process was documented for both user interface and a script.

### 2.2 Zeffiro Interface

Zeffiro Interface (ZI), introduced in He, Rezaei & Pursiainen (2020), is an open-source software package built for Matlab. It aims to offer an accessible multipurpose finite element method (FEM) based forward and inverse modelling platform with GPU acceleration. Using ZI, one can create a volumetric finite element mesh for complex realistic geometry such as the human brain. ZI provides functionality for constructing a head model consisting of multiple compartments, evaluating a lead field matrix for the generated model, and analyzing and inverting given set of results, for example, localizing the originating source of brain activity based on data obtained from EEG or MEG recordings. In version 2.2 of ZI, forward solvers for EEG/MEG and electrical impedance tomography (EIT) are included along with inverse solvers based on hierarchical Bayesian model. In addition to brain modelling, Zeffiro Interface can also be applied to implementing other FEM based models that can be formulated as a product of a lead field matrix and potential solution vector. Zeffiro Interface is currently only to be used for research purposes, not in clinical applications.

#### 2.2.1 basic workflow

The basic workflow in Zeffiro Interface consists of three phases. The first phase is defining the head model using segmentation tool. Second phase is finite element mesh and lead field matrix generation using meshing tool. Third phase is applying inverse tools to analyze the results. (He;Rezaei;& Pursiainen, 2020)

In the first phase, segmentation tool is used to define surface segmentation for describing different properties and tissue structures such as scalp, skull, and grey matter. Triangular surface meshes for different tissue types are imported as ASCII files. Furthermore, a complete head segmentation consisting of multiple compartments can be imported at once by defining a single initialization (.INI) file. While the default set of compartments consists of white matter, grey matter, cerebrospinal fluid, skull, and scalp, in version 2.2 of ZI, up to 27 different tissue compartments are supported. Each compartment can be defined as active or inactive. Furthermore, in EEG/MEG the direction of the activity can be set as constrained or unconstrained. (He;Rezaei;& Pursiainen, 2020)

In the second phase, based on the surface segmentation done in the first phase, uniform tetrahedral mesh is generated for each compartment from innermost to outermost. Parameters, such as resolution of the mesh can be defined in the mesh tool. The mesh generation process is explained in greater detail in chapter 2.5. After generating the mesh, a lead field matrix can be computed regarding selected imaging modality e.g., EEG or MEG, and given number of degrees of freedom (DOFs) which represents the possible sources of activity. Lastly, to enable inversion of measurement data in the third phase, interpolation process connecting the DOFs and mesh nodes needs to be performed. (He;Rezaei;& Pursiainen, 2020)

The third phase consists of importing the measurement data from e.g., EEG, and applying inverse tools for solving the inverse problem i.e., reconstructing the unknown active source within the brain based on the EEG measurements. (He;Rezaei;& Pursiainen, 2020)

### **2.2.2 hardware requirements**

Because FEM is considered as computationally heavy method for discretization of such a complex geometry as the human brain, ZI is meant to be used with a high-end computer having tens of gigabytes of RAM, one or more GPUs and a multi-core CPU. For reference, a finite element mesh of 1 mm resolution will consist of 20-30 million elements and 3-4 million nodes taking up to 64 GB of motherboard RAM and 2-4 GB of GPU RAM allocation in the generation process and leading to 0.5-1 GB project size when stored on a hard disc. (He;Rezaei;& Pursiainen, 2020)

### 2.2.3 GPU acceleration

ZI takes advantage of GPU acceleration to speed up its processes e.g., mesh generation, forward and inverse computations, 3D visualizations and searching and sorting operations. A GPU is a parallel processing unit which excels in effectively executing computationally intensive operations. However, memory intensive computations should be avoided since GPU has limited RAM compared to motherboard RAM. GPU acceleration is necessary for accomplishing about 1 hour computing time for generating a finite element mesh with 1 mm resolution which is a necessity to achieve physiologically accurate inverse results. (He;Rezaei;& Pursiainen, 2020)

## 2.3 EEG/MEG

Neural activity and communication within the brain is associated with minimal electric currents that generate electrical potentials on the scalp which can be measured in EEG and magnetic fields outside the head which in turn can be measured in MEG. EEG and MEG are noninvasive neurophysiological methods, meaning that body or body tissues are not penetrated or disturbed in the process. They are used for studying brain dynamics and changes in activation patterns and sequences over time. EEG and MEG recordings can be done at the same time given that EEG electrodes and wires are not magnetic and small enough for the head of the subject to fit in the MEG device simultaneously. The data attained from EEG and/or MEG measurements can be used to solve so called inverse problem i.e., locations and strengths of the originating source of activity in the brain can be estimated. (Hari & Puce, 2017)

MEG recording is done in a way where the subject is sitting with their head placed in a MEG device containing hundreds of highly sensitive magnetic-field detectors. The magnetic fields generated by the brain are so small,  $10^{-8}$  times the strength of earth's steady magnetic field, that MEG recording is conducted in magnetically shielded room to mitigate or eliminate magnetic disturbances. Even then, the magnetic fields can be picked up by the most sensitive sensors. The most used sensors in MEG are superconducting quantum interface devices (SQUIDS) that are not in direct contact with the head since they are contained in an insulated liquid-helium-containing dewar. The magnetic fields coming from the brain activate a current flow in the SQUID sensor, from where a circuit attached to the sensor works as a flux-voltage amplifier, converting the flow to a voltage that can be read by a computer. (Hari & Puce, 2017)

In EEG recording, the subject is wearing an EEG hat or elasticized net containing electrodes attached to the scalp of the subject. The electric potentials on the scalp are measured between two electrodes at a time. The electric potentials measured in EEG are also



so small that they need to be amplified and filtered before they are digitalized for further analysis in computer. (Hari & Puce, 2017)

The spread of electrical potentials measured in EEG is more widespread than the corresponding magnetic field measurements done in MEG. This is because the structure of the head and varying electrical conductivities in different parts of the head causes the spread of the electric potentials in EEG measurements, while the spread of magnetic fields measured in MEG is only dependent on the distance between the sources and sensors. This EEG's sensitivity to varying electrical properties makes solving the inverse problem more complicated since assumptions about conductivities of different parts of the head are required. (Hari & Puce, 2017)

## **2.4 Finite element method**

Finite element method is widely applied in solving complex engineering analysis problems in various application fields. It is a mathematical procedure that can be used for calculating approximate solutions to distribution of field variables within a given problem domain. In FEM the geometry of the original problem domain is divided into smaller parts that are called finite elements (FE). The finite elements are represented in simple geometrical shapes such as quadrilaterals or triangles for 2D elements and tetrahedrons or hexahedrons in 3D elements. The elements are connected to each other at points that are called nodes. This process of dividing the original problem domain into smaller elements is referred to as discretization or meshing. After dividing the domain into elements, physical and mathematical rules are applied to establish equations for each element. The collection of solutions to those equations within each element is then used to represent the distribution values in the domain. This is done because the solution to the problem at hand is expected to be complicated and unpredictably varying when using functions over the whole domain. However, it is relatively simple to calculate an approximate solution within a single element. (Liu & Quek, 2014)

### **2.4.1 Applications in brain modelling**

FEM is a robust tool for brain modelling, and it is extensively used to model electromagnetic fields in the brain. It can be used to accurately represent tissue parameter distribution values such as electrical conductivity in anisotropic tissues like white matter and skull and complicated internal boundary layers of the brain (Rullman, et al., 2009). FEM can be applied to modelling an electromagnetic source in the brain to solve a forward

problem where electric potential field is calculated based on known source current, domain geometry and conductivity within compartments of the head such as skull, scalp, and gray-/white matter. Furthermore, FEM can be applied to solving inverse problems e.g., localizing brain activity in EEG/MEG. (He;Rezaei;& Pursiainen, 2020) Solution to such inverse problem can be used for example to localize generators of epileptic events, to conduct presurgical mapping of cortical areas, or to study which brain areas are active while performing different tasks such as language processing. (Brette & Destexhe, 2012) Further applications of FEM include mapping of electrical conductivity distribution or its disruption within a given domain in electrical impedance tomography (He;Rezaei;& Pursiainen, 2020) and optimization of injection current patterns in transcranial direct electrical stimulation, which is an established form of treatment in neuropsychiatric disorders and brain illnesses including migraine, depression, epilepsy, Parkinson's disease, tinnitus, alcoholism, and stroke conditions. (Galaz Prieto, Rezaei, Samavaki, & Pursiainen, 2022)

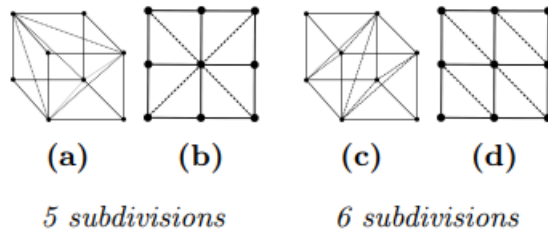
## **2.5 Mesh generation process in Zeffiro Interface**

Generating a finite element mesh for human head can be considered as a difficult task because of the various internal layers with complicated geometrical properties. The approach used in Zeffiro Interface for generating a tetrahedral finite element mesh for multi-compartment head model is introduced in Galaz Prieto et al. (2023). The realistic human head model used in the research, was attained from an openly available MRI dataset of real human head. Before generating the mesh, surface segmentation for the head model was constructed using FreeSurfer software, which is a suite of tools that can be used for neuroimaging data analysis to evaluate key features of the human brain such as functional, connective, and structural properties (Fischl, 2012). It is shown that the approach used can generate a finite element mesh with precision higher than 1.0 millimeters, which is a "significant milestone for 3D structure discretization and EEG source localization estimation". The approach consists of two stages, mesh generation and post processing. (Galaz Prieto, et al., 2023)

### **2.5.1 Mesh generation**

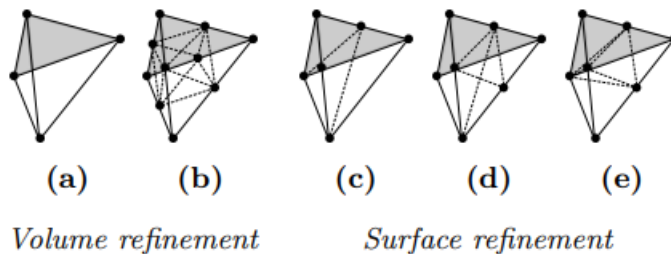
The first part of mesh generation is regular meshing. Here, the domain is first discretized into a mesh consisting of elements represented as hexahedrons. The hexahedrons are then further subdivided into five tetrahedral elements. Implementing the subdivision like this establishes an altering direction in diagonals that are subdividing the edges of the hexahedron, when in comparison, subdivision to 6 tetrahedrons would lead to non-altering diagonal directions as can be seen in picture 1. Advantage of this subdivision pattern

is that it mitigates possible geometrical bias in mesh manipulation done in later stages. Furthermore, five being the lowest possible subdivision of hexahedron to tetrahedra, it also minimizes the computer memory used to support the dataset. (Galaz Prieto, et al., 2023)



Picture 1. Example hexahedra subdivisions (Galaz Prieto, et al., 2023)

A subdomain in the mesh can be further refined in respect to its volume or boundary. In volume refinement each tetrahedron in the given subdomain volume is subdivided into eight tetrahedral elements as depicted in b of picture 2. In surface refinement, elements at the subdomain boundary are subdivided into one to three depending on the number of edges shared with the boundary resulting in c, d, or e of picture 2. (Galaz Prieto, et al., 2023)



Picture 2. Volume- and surface refinement illustration (Galaz Prieto, et al., 2023)

For establishing what compartment, e.g., skull or gray matter, an element belongs to, solid angle labeling method is used. In this process, solid angle is calculated for each node in each tetrahedron in the mesh. By comparing the solid angle to a threshold value, it can be established whether the node is inside the compartment. Elements with four nodes inside the compartment surface are labeled as belonging to the compartment. The labeling process is performed recursively for the tetrahedra at the boundaries. This re-labeling possibly changes the labels of the elements, which changes the boundary. The process is iterated until the boundary remains unchanged between two iterations. (Galaz Prieto, et al., 2023)

### 2.5.2 Post processing

After completing the first stage, i.e., creating the mesh, labeling, smoothing, and re-labeling, the mesh is further processed in post processing stage. This post processing stage consists of smoothing, inflation, and optimization of the mesh. The goal is to accurately fit the compartment surfaces in the mesh with the complementary closed segmentation boundaries. (Galaz Prieto, et al., 2023)

The mesh can be smoothed in postprocessing. For smoothing the mesh, and to minimize shrinkage a method called Taubin's method with altering forward and inward Laplacian smoothing steps is used. The smoothing process continues until smoothness given as a parameter by the user is reached. (Galaz Prieto, et al., 2023)

After completing the labeling process in the first stage, all tetrahedra at the boundary have their nodes inside the segmentation boundary. In post processing those tetrahedra are then inflated, meaning that they are lifted to better fit the segmentation boundary. The inflation process is conducted by first identifying edges intersecting with the segmentation boundary and establishing their intersection points. The nodes and their complementary edges at the boundary are then moved towards these points. (Galaz Prieto, et al., 2023)

The post processing stage is concluded with optimization done in two phases. The goal is to make sure the elements are valid. In the first phase of optimization, inverted tetrahedra having negative determinant, i.e., the element has nodes outside the surface of its super node consisting of adjacent tetrahedra sharing an edge with the element. This is fixed by bringing the outside nodes back inside the super node. This fixing of inverted elements is repeated recursively until no inverted elements are found. In the second stage of optimization, Delaunay turns are done for all pairs of neighboring tetrahedra where in either of the elements the element volume divided by its longest edge is less than a given threshold value. (Galaz Prieto, et al., 2023)

### **3. MESH GENERATION IN ZEFFIRO INTERFACE: COMPUTING EXAMPLES**

This section introduces computing examples for generating a finite element mesh for a multicompartment head model using Zeffiro Interface. The computer used was a laptop with AMD Ryzen 7 PRO 4750U CPU with 16 GB RAM and 512 GB SSD memory and no GPU, so the GPU acceleration feature was unavailable.

The multi-compartment head model used in these examples is the one that can be found in the Zeffiro Interface repository's example projects. The model is from an openly available MRI dataset that provides the geometric information by level-sets for each tissue boundary. (Piastra, et al., 2020) The surface segmentation for the model in the ZI example is attained using FreeSurfer software.

To use Zeffiro Interface, one must have Matlab with Signal Processing Toolbox, Optimization Toolbox, Parallel Computation Toolbox and Statistics and Machine Learning Toolbox installed in their computer. The instructions for installing Zeffiro Interface can be found in the GitHub repository.

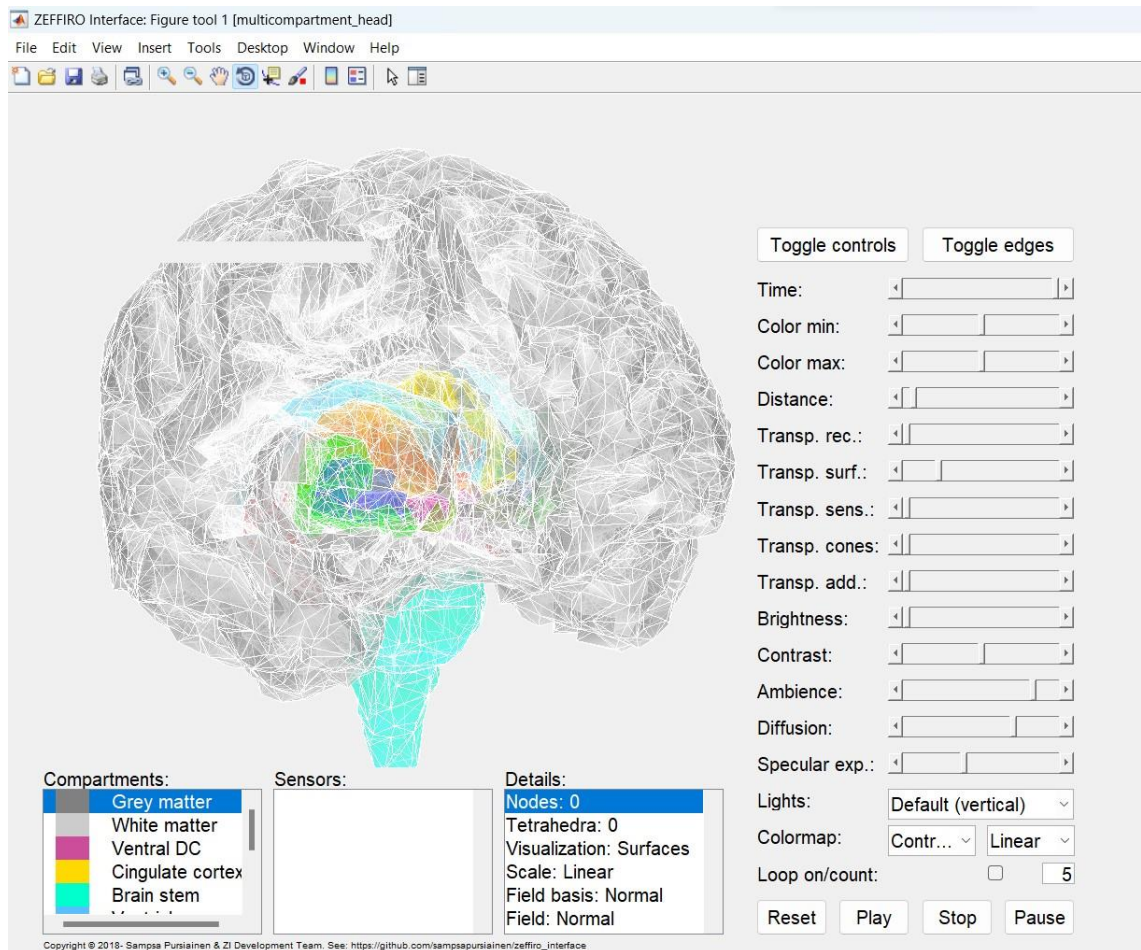
#### **3.1 Mesh generation using the user interface**

After opening ZI, one must first obtain the model to be meshed. The model used in these examples is found in the multi compartment head example project available in the ZI repository. The first step is to open the project from "open project" under "project" tab in ZI menu tool.

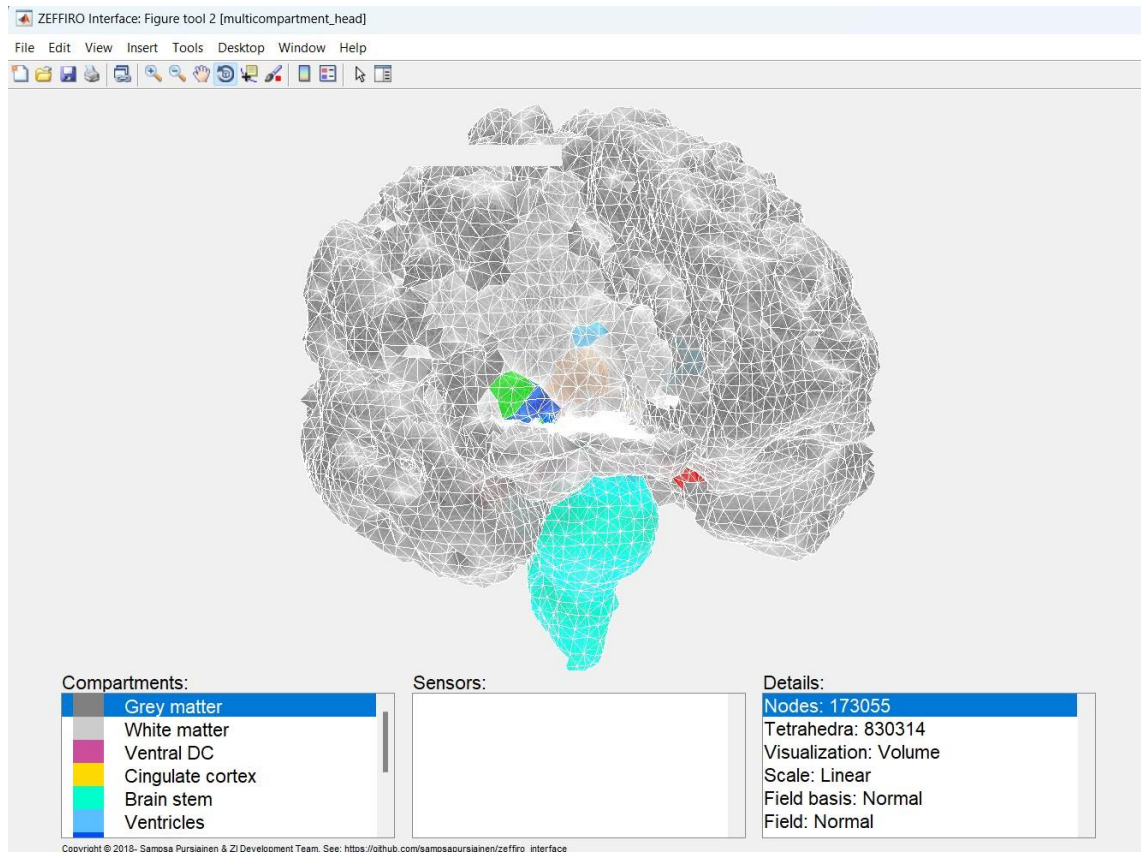
Once the project has been opened, the initial model can be observed by clicking "Visualize surfaces" button in ZI mesh visualization tool. The surface discretization can be observed by clicking "Toggle edges" button in ZI Figure tool. The surface discretization of the head model is shown in picture 3.

Parameters for the mesh generation, such as mesh resolution and enabling refinement and smoothing, can be adjusted from the Mesh tool. More options for both mesh generation and optimization, such as selecting compartments to be refined, can be adjusted from forward and inverse processing options which can be opened from "settings" under menu tool. Generating the mesh is done from the mesh tool by clicking the "Create FEM mesh" button.

First, a mesh with 3 mm resolution and no refinement was created. The mesh generation took 17 minutes and 34.2 seconds. The resulting volumetric mesh can be visualized by clicking “Visualize volume” button in mesh tool. The generated 3mm resolution mesh is shown in picture 4. As can be seen when comparing the generated mesh to the plain surface discretization, in the mesh the volume of each compartment is discretized into tetrahedra, and the surface discretization is of higher resolution.

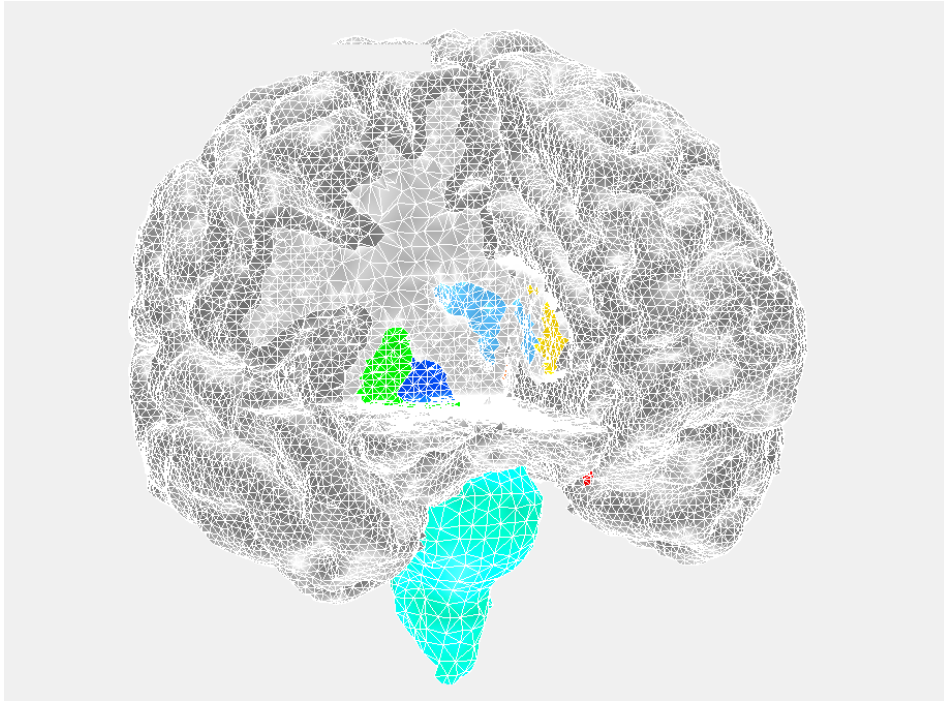


picture 3: multi compartment head model surface discretization

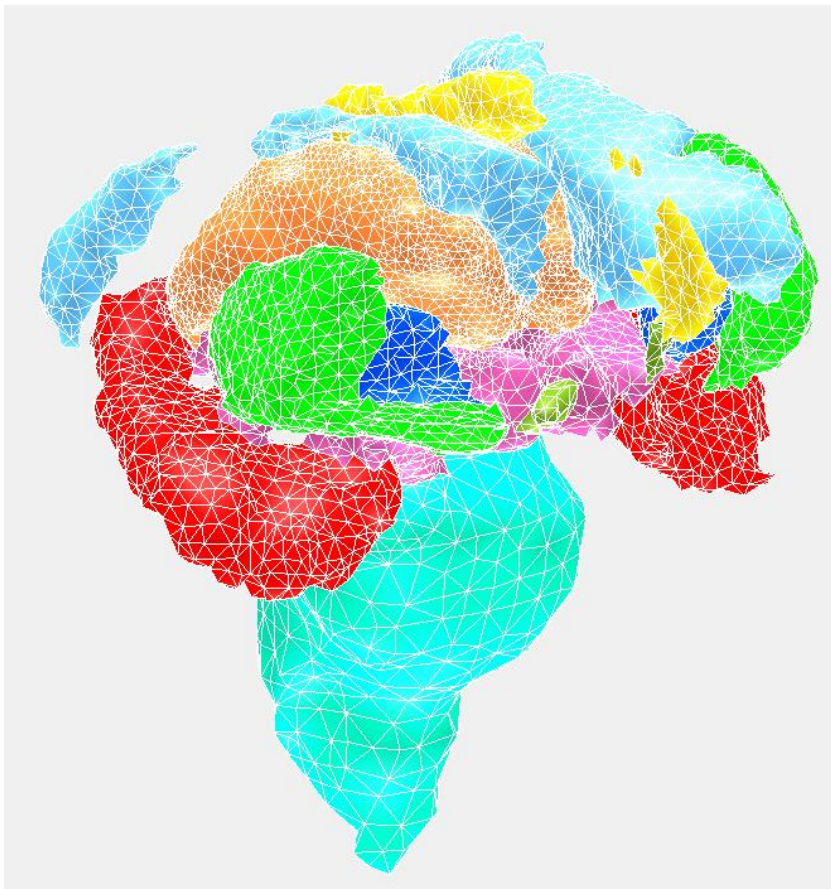


picture 4: multicompartment head 3mm mesh

As a second example, a mesh with 3 mm resolution and surface/volume refinement to thalamus and surface refinement to grey- and white matter was generated. The compartments for surface- and volume refinement can be selected from a list in forward and inverse processing options which can be opened from “settings” under menu tool. In this case thalamus was selected for both surface- and volume refinement and grey- and white matter was selected for surface refinement. Respectively, the refinement could be done for all other compartment by selecting different compartments in the settings. Generating the mesh in this case took 47 minutes and 27 seconds, so adding the refinement noticeably increased the computing time. The resulting mesh is shown in picture 5. As can be seen from the picture, the surface refinement on grey/white matter (dark grey and light grey compartments) increases the number of elements making the mesh denser on the surfaces on those compartments. Picture 6 shows the effect of surface/volume refinement on thalamus (the orange compartment) which clearly has finer discretization compared to adjacent compartments.



picture 5: multicompart ment head 3mm mesh with grey/white matter surface refinement and thalamus surface/volume refinement



picture 6: multicompart ment head 3mm mesh with grey/white matter surface refinement and thalamus surface/volume refinement (grey/white matter removed)



### 3.2 mesh generation using a script

The mesh can also be generated using a script. Program 1 shows an example Matlab script that can be used for generating a mesh in Zeffiro Interface. The script is run in the root of ZI directory. The script defines a function named “zef\_meshing\_example\_thalamus\_refinement”. In the function, the project structure is initialized and assigned to “project\_struct” variable by calling “zeffiro\_interface” function with the given parameters. The “zeffiro\_interface” function with the given parameters starts the ZI in a no display mode and imports the surface segmentation of multi-compartment head model generated by FreeSurfer to the workspace. After initializing the project structure, the parameters for the mesh generation and all other settings that can be modified in the user interface can be configured by modifying the properties of the “project\_struct” variable. The script sets on the smoothing and surface/volume refinement, specifies the compartments for both surface- and volume refinement as vectors and sets the mesh resolution and surface triangles. The surface triangles parameter represents the resolution of the initial surface segmentation, 2 being twice as dense as default. The mesh is generated by calling the “zef\_create\_finite\_element\_mesh” function with the “project\_struct” variable as a parameter. Finally, the project is saved by calling “zef\_save” function with the “project\_struct” variable and path where the project is saved as parameters.

The mesh generation with the script took 49 minutes and 53 seconds. The resulting mesh can be examined by opening the saved project in ZI. The resulting mesh is depicted in pictures 7 and 8.

```

% This script example generates a tetrahedral mesh for the multi-
2 % compartment head model and refines the thalamus compartment. Surface
% refinement is also done for active compartments and grey matter.
4 % Running the script generates 'example_project_thalamus_ref.mat'
% project under data/ folder which can be opened in Zeffiro Interface.
6 % The script can be run with Matlab in the Zeffiro Interface repository
% root folder
8
function zef_meshing_example_thalamus_refinement
10
% initialize project structure
12 project_struct = zeffiro_interface('start_mode','nodisplay','im-
import_to_existing_project','scripts/scripts_for_importing/multicom-
14 partment_head_project/import_segmentation.zef');

16 % set smoothing and refinement on
project_struct.mesh_smoothing_on = 1;
18 project_struct.refinement_on = 1;

20 % set surface/volume refinement on
project_struct.refinement_surface_on = 1;
22 project_struct.refinement_volume_on = 1;

24 % Set the number of refinements
project_struct.refinement_surface_number = [1];
26 project_struct.refinement_volume_number = [1];

28 % set the compartments for surface refinement
% -1 = active compartments, 7 = thalamus, 14 = grey matter
30
project_struct.refinement_surface_compartments = [-1 7 14];
32
% set compartments for volume refinement
34 project_struct.refinement_volume_compartments = [7];

36 % set mesh resolution and surface triangles
project_struct.mesh_resolution = 3; % millimeters
38 project_struct.surface_triangles = 2; % twice the default

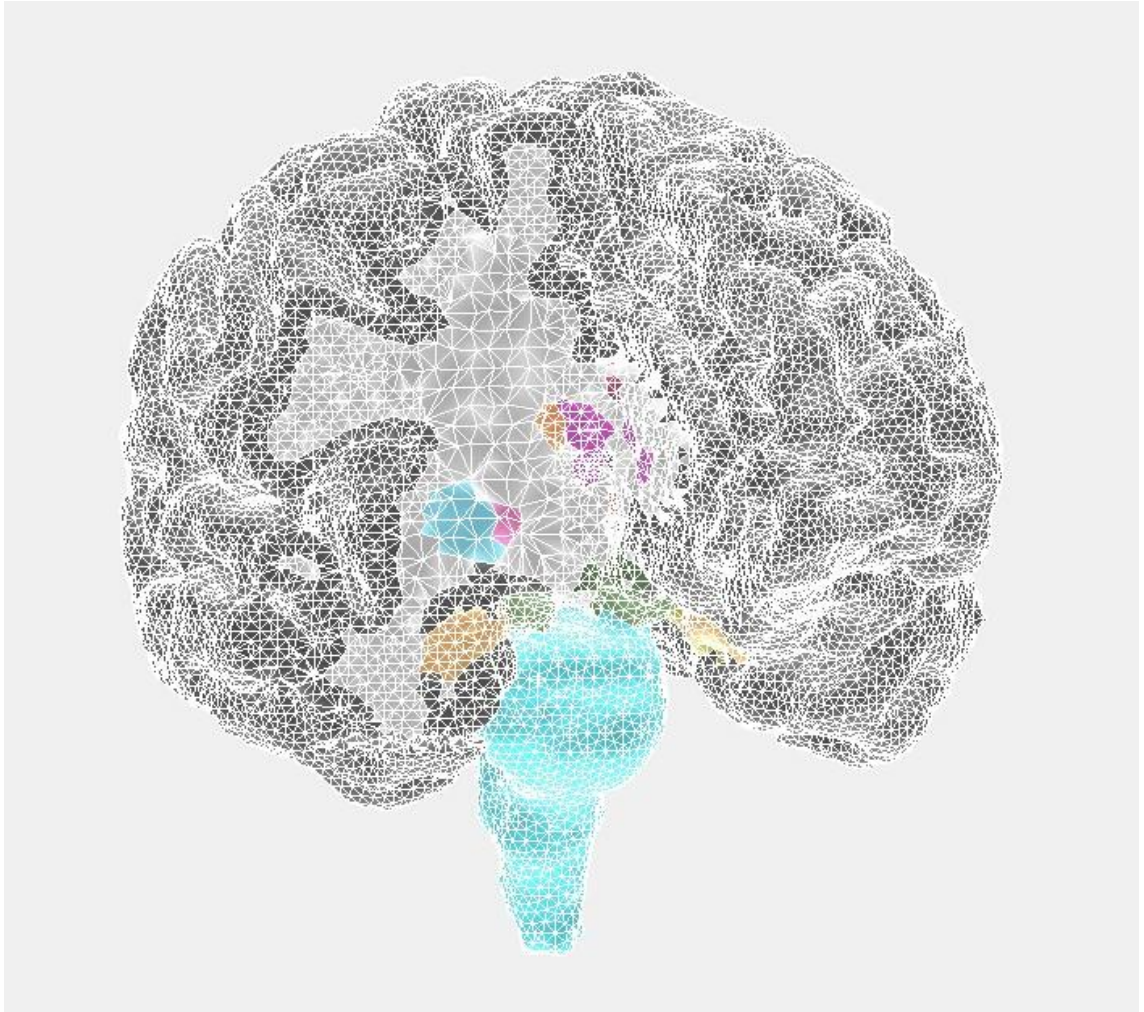
40 % use GPU acceleration
project_struct.use_gpu = 1;
42
% create the mesh
44 project_struct = zef_create_finite_element_mesh(project_struct);

46 % save the project as example_project_thalamus_ref.mat
zef_save(project_struct,'example_project_thalamus_ref.mat','data/');

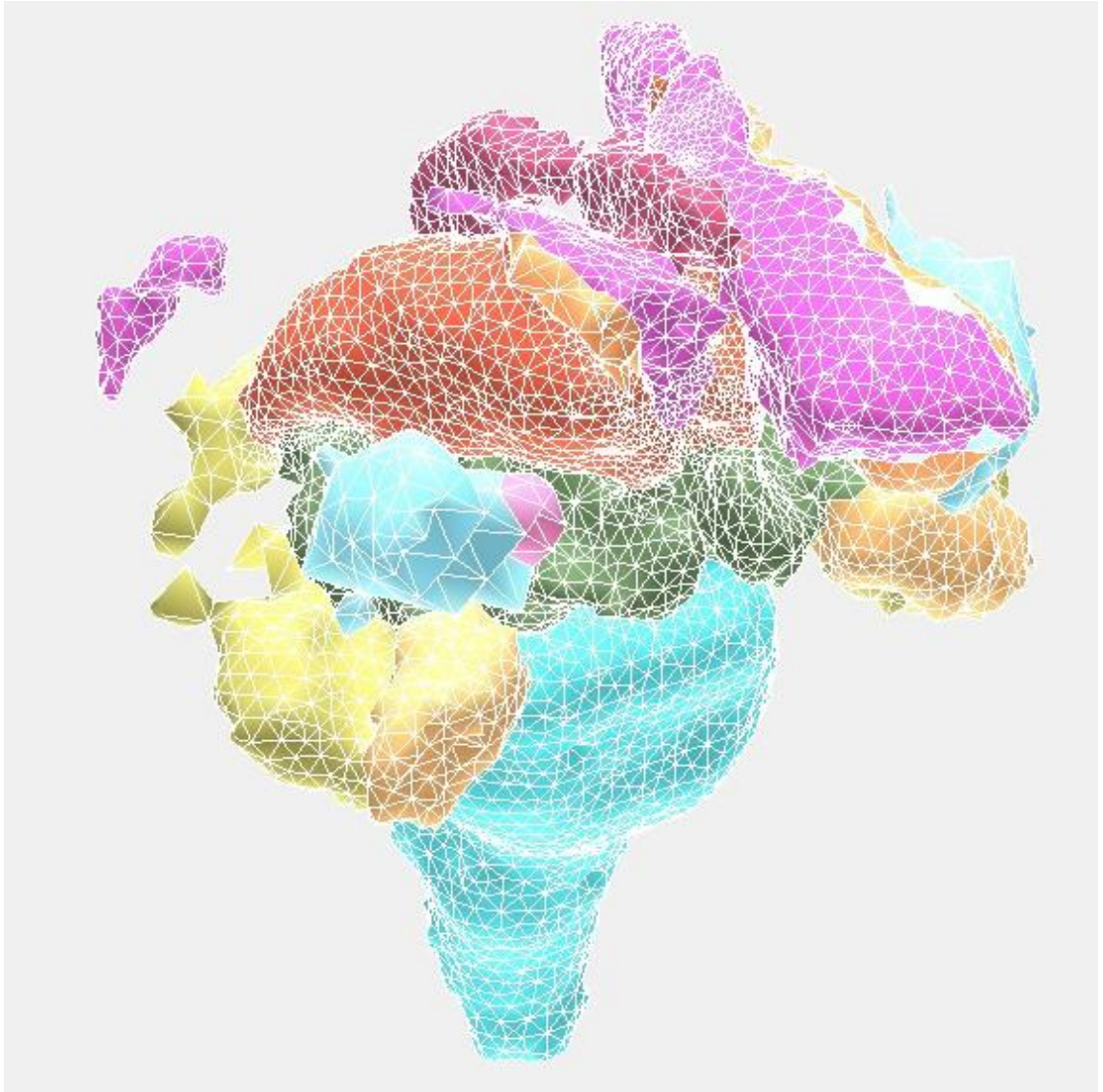
end

```

**Program 1. Example mesh generation script**



**picture 7.** mesh generated via script.



**picture 8.** mesh generated via script (grey/white matter removed)

## 4. CONCLUSIONS

The purpose of this thesis was to research the finite element mesh generation process for a multi-compartment head model in Zeffiro Interface software. It also introduced the Zeffiro Interface software along with FEM, EEG and MEG as related technologies. Furthermore, the thesis introduced computing examples of mesh generation for a multi-compartment head model in ZI using the user interface and a script.

The mesh generation process in Zeffiro Interface is shown to be capable of generating a finite element mesh with an accuracy greater than 1 millimeter resolution for multi-compartment head model, which is a significant milestone for 3D structure discretization and EEG source localization estimation. The process consists of two phases, mesh generation and post processing. The mesh generation is further divided into regular meshing, refinement, and labelling. Respectively, the post processing is divided into smoothing, inflation, and optimization. The advantage of the mesh generation in ZI compared to alternative mesh generators such as TetGen (Hang, 2015), NetGen (Schöbler, 1997) and Gmsh (Geuzaine & Remacle, 2009) is its robustness for intersecting surfaces. Furthermore, the recursive labelling applied in the process along with GPU acceleration capability makes the mesh generation in ZI highly effective by decreasing the computational cost. (Galaz Prieto, et al., 2023)

Alternatives tools for ZI include for example Duneuro (Schrader, et al., 2021), SimBio (Fingberg, et al., 2003), Brainstorm (Tadel, et al., 2011), Fieldtrip (Oostenweld;Fries;Maris;& Schoffelen, 2011) and MNE-Python toolbox (Gramfort, et al., 2013). Brainstorm and Fieldtrip are alternative packages for Matlab, while Duneuro and SimBio are similar open-source FEM libraries for EEG and MEG applications utilizing C++ language and MNE-python toolbox is the most established option for python. The advantage of ZI compared to these alternatives is its support for advanced GPU and FEM computations, as none of the alternatives currently support both. For example, the core forward modelling approach used in Brainstorm is BEM. FEM has at least two advantages when applied in EEG/MEG compared to BEM. Firstly, BEM solvers are slower when the surface mesh resolution or the number of surfaces grows, while FEM is virtually independent of these factors. Secondly, in FEM the conductivity distribution can be anisotropic which is the case for some tissues of the brain, e.g., white matter. (He;Rezaei;& Pursiainen, 2020)

Future research could include approving the use of these technologies for clinical applications as they are currently only to be used for research purposes. Furthermore, the computational performance of these technologies is likely to improve in the future along with advancements in computer hardware and technologies like quantum computing. The related computational methods can also possibly be applied into development of brain-computer interfaces (BCIs), as for example EEG data can be used as BCI input (He, Yuan, Meng, & Gao, 2020).

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