Software Requirements Specification for BrainInsight3D: 3D fMRI Visualization & Segmentation

Nada Elmasry

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Contents

Revision History

Date	Version	Notes
Feb 6	1.0	Intial SRS Document

1 Reference Material

This section records information for easy reference.

1.1 Table of Units

Throughout this document SI (Système International d'Unités) is employed as the unit system. In addition to the basic units, several derived units are used as described below. For each unit, the symbol is given followed by a description of the unit and the SI name.

symbol	**unit**	**SI**
mm	thickness	millimetre

1.2 Table of Symbols

The table that follows summarizes the symbols used in this document along with their units. The choice of symbols was made to be consistent with the heat transfer literature and with existing documentation for solar water heating systems. The symbols are listed in alphabetical order.

symbol	**unit**	**description**
v	-	Voxel
p	-	Pixel

1.3 Abbreviations and Acronyms

symbol	description
A	Assumption
DD	Data Definition
GD	General Definition
GS	Goal Statement
IM	Instance Model
LC	Likely Change
ULC	Unlikely Change
PS	Physical System Description
R	Requirement
SRS	Software Requirements Specification
fMRI	Functional Magnetic Resonance imaging
CNN	Convolutional Neural Network
3D	Three dimensional
2D	Two dimensional
LPS	Left-Posterior-Superior System
RAS	Right, Anterior, Superior System
DICOM	Digital Imaging and Communications in Medicine
NIfTI	Neuroimaging Informatics Technology Initiative
TM	Theoretical Model

2 Introduction

This document provides the software specification requirements(SRS) for the BrainInsight 3D project. The project offers 3D and 2D visualization and segmentation of fMRI brain scans with time and functional activity tracking in 2D through a web application that enables high-resolution visualization and segmentation.

This introductory section explains the purpose of this document, the organization of the document,the project scope of requirements, and the characteristics of the intended reader.

2.1 Purpose of Document

The purpose of this document is to provide the reader with a thorough understanding of what the project does. The document contains all the definitions, theoritical and instance models, inputs, outputs, assumptions, and goals of the project. After reading the document the reader should be able to define the project and have a visual imagery of what the project represents.

2.2 Scope of Requirements

The scope of requirements of the project covers mainly two parts:

- **Visualization**: the project's software will visualize fMRI scans into 3D volumes, and 2D slices representing the anatomical coordinate system used by the fMRI scan.
- **Segmentation**: the project's software can perform anatomical segmentation of 3D volumes into voxels, and on 2D slices into pixels.

The user requirements are to be able to input the correct data type into the project's software, manipulate the user interface to change visualization settings, and to interpret the results of the visualization and segmentation.

2.3 Characteristics of Intended Reader

The readers of the SRS should have taken introductory courses in linear algebra, anatomy, and computer vision to be able to understand the mathematical notations, co-ordinate systems, and instance models provided in the SRS document.It would be beneficial if the reader has a background in software engineering in order to better visualize the project scope and requirements, however, it is not a hard requirement.

2.4 Organization of Document

The organization of this document follows the template for an SRS for scientific computing software proposed by Koothoor (2013) and Smith and Lai (2005). The presentation follows the standard pattern of presenting goals, theories, definitions and assumptions. The goal statements are refined to the theoretical models, and theoretical models to the instance models.

3 General System Description

This section provides general information about the system, identifies the interfaces between the system and its environment, and describes the user characteristics and the system constraints.

3.1 System Context

Figure 1 shows the system context. A circle represents an external entity outside the software, the user in this case. A rectangle represents the software system itself. Arrows are used to show the data flow between the system and its environment.

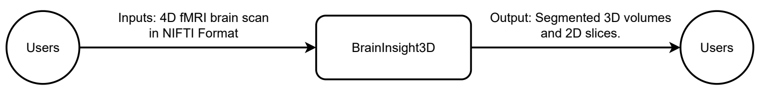


Figure 1: System Context

- User Responsibilities:
  - Provide the correct input data to the program
  - make sure the input meets the required assumptions
  - Verify that the output visualization and segmentation results meet their requirements.
  - Use the provided options in the program to obtain their desired visualization.
- ProgName Responsibilities:
  - Correctly visualize 3D volumes
  - Correctly visualize 2D slices according to the anatomical coordinate system explained in section4.1.1.
  - Correctly perform segmentation of 3D fMRI volumes into the brain anatomical regions explained in section4.1.2.
  - Provide the user input options to be able to choose wether to visualize the complete 3D volume or a sub-volume, and to be able to visualize 2D slices and segemntation results simultaneously across the time frame of the fMRI scan.

3.2 User Characteristics

The intended user of BrainInsight3D should have taken college level introductory courses in Linear Algebra and Anatomy.

3.3 System Constraints

There are no system constraints for BrainInsight3D.

4 Specific System Description

This section first presents the problem description, which gives a high-level view of the problem to be solved. This is followed by the solution characteristics specification, which presents the assumptions, theories, definitions and finally the instance models.

4.1 Problem Description

BrainInsight3D is designed to offer high-resolution visualization and anatomical segmentation of fMRI brain scans, enabling the tracking of changes across various time frames within the scan.

4.1.1 Co-ordinate Systems

the purpose of this section is to provide the reader with the knowledge of the co-ordinate systems required to understand and work with medical images. Nejad (July 2017)

World Coordinate System World Coordinate system is a Cartesian coordinate system in which a model (e.g. a MRI scanner or a patient) is positioned. While each model has it's own coordinate system, all models must be transformed into world coordinate system for accurate model interaction.

Anatomical Coordinate System The Anatomical Coordinate System is a 3D right-handed coordinate system that describes human anatomy through three planes:3D Slicer Community (2022) Nejad (July 2017)

- **Axial/Transverse plane**: is parallel to the ground and separates the head (Superior) from the feet (Inferior).
- **Coronal/Frontal plane**: is perpendicular to the ground and separates the front from (Anterior) the back (Posterior).
- **Sagittal/Median plane**: divides the body to left and right parts.

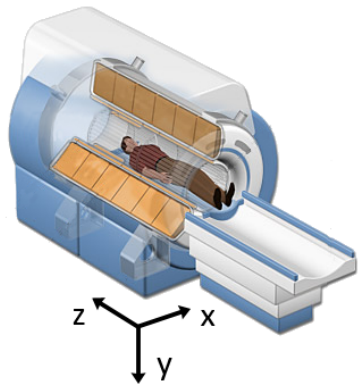
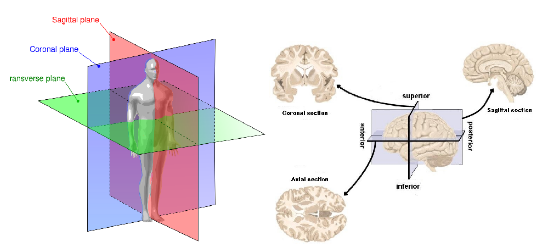


Figure 2: visualization of MRI machine placed in World Coordinate System 3D Slicer Community (2022)



(a) (b)

Figure 3: Anatomical Coordinate System Axes and Planes Asaei (2015)

Medical applications follow an anatomical coordinate system to store voxels in sequences using different definitions. The most common basis are:

- **Left-Posterior-Superior(LPS) System**: In this system, voxels are ordered from left to right in a row, rows are ordered from anterior to posterior, and slices are stored from inferior to superior. LPS System is commonly used in DICOM images.
- **Right, Anterior, Superior(RAS) System**: In this system, voxels are ordered from right to left in a row, rows are ordered from posterior to anterior, and slices are stored from inferior to superior. RAS System is commonly used in NIfTI images and will be used for this project.

Image Coordinate System In our project we will be utilizing the OpenCV Python library.In OpenCV image coordinate system, x-axis increases from left to right, y-axis increases from top to bottom, and z-axis from forward to backward.

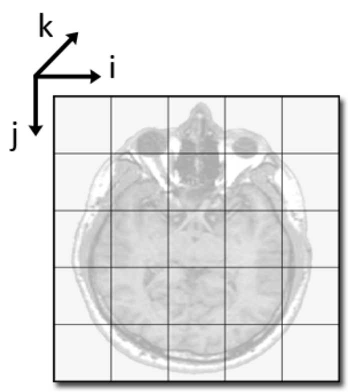


Figure 4: Image Coordinate System used in OpenCV Python 3D Slicer Community (2022)

4.1.2 Brain Segmentation

Segmentation precisely divides an object into related entities, each representing specific locations or meanings. In medical imaging, it's crucial for extracting key data from scans, including organs, tumors, tissues, or nerves. Brain imaging relies heavily on segmentation to gain insight into the brain's structure and function. There are two primary types: functional segmentation, which focuses on brain activity, and anatomical segmentation, which details the brain's physical structure.

Anatomical Segmentation Anatomical segmentation is a crucial process in neuroimaging that consists of dividing the brain into structurally distinct areas based on MRI scans, identifying regions such as gray matter, white matter, and cerebrospinal fluid. This segmentation is essential for a wide range of neuroscience studies, enabling researchers to precisely localize brain activity, assess changes in brain structure over time, or study the anatomical differences between populations. The process of anatomical segmentation has been significantly advanced by the use of deep learning techniques, notably U-Net and Convolutional Neural Networks (CNNs). These methods have proven effective in handling the complexity of brain structures, providing high accuracy in segmentation tasks.

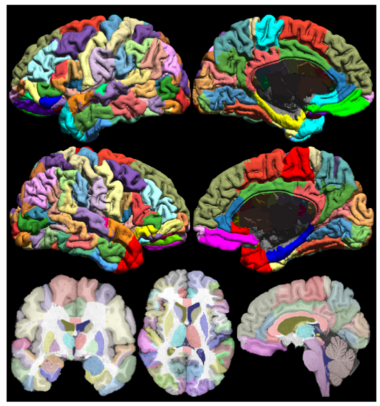


Figure 5: Results of anatomical segmentation on fMRI scan Joshi et al. (2022)

Functional Segmentation Functional segmentation is a process that categorizes the brain into regions that exhibit similar patterns of activity, either during specific tasks or in a resting state. This division is typically achieved through the application of statistical techniques such as Independent Component Analysis (ICA) or through machine learning approaches like K-Nearest Neighbors (KNNs).This approach is crucial for understanding brain connectivity and function, offering insights into neural interactions and the impact of disorders or stimuli on the brain.

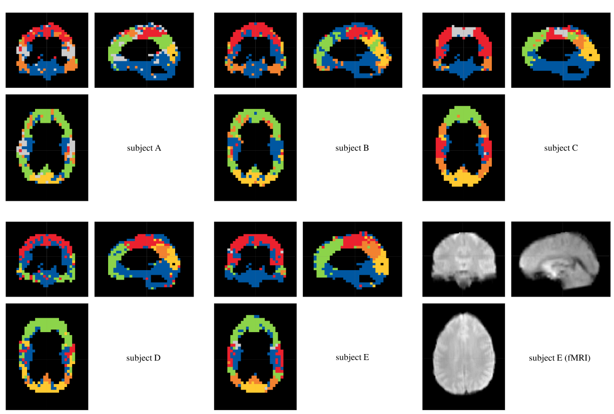


Figure 6: Results of functional segmentation on fMRI scan Schmidt et al. (2016)

4.1.3 Physical System Description

The physical system description of how fMRI scans are developed is outside the scope of the project. We do not need to know the physical system details in order to build the project software.

4.1.4 Goal Statements

Given the 4D fMRI brain scan in NIfTI format which consists of 3D brain volumes across the time span of the scan, the goal statements are:

GS1: Visualize the 3D volume across time.

GS2: Visualize 2D slice views (sagittal, axial, coronal) across time.

GS3: Perform anatomical segmentation on 3D volume.

GS4: Visualize the segmentation results in 2D slice views (sagittal, axial, coronal) across time.

4.2 Solution Characteristics Specification

This section provides the assumptions, data definitions, theoretical models, instance models, and data constraints required for a successful implementation of the project. The information in this section is provided to express the project in clear mathematical and logical terms to remove to prevent ambiguity of the project.

The instance models that govern BrainInsight3D are presented in Subsection 4.2.5. The information to understand the meaning of the instance models and their derivation is also presented, so that the instance models can be verified.

4.2.1 Assumptions

A1: The user provides fMRI scans of the brain and not other organ.

A2: The user provides 4D fMRI brain scans in NIfTI format.

A3: The scans provided are not corrupt.

A4: The metadata of the provided scans is correct.

4.2.2 Theoretical Models

This section focuses on the general equations and laws that BrainInsight3D is based on.

Number	TM1
Label	**Dice Score**
Symbol	DSC
Units	dimensionless
Equation	$DSC = \frac{2\lvert Y \cap \hat{Y}\rvert}{\lvert Y\rvert + \lvert\hat{Y}\rvert} = \frac{2TP}{FP + 2TP + FN} = 2 \times \frac{precision \times recall}{precision + recall}$
Description	Dice score is used in image segmentation to quantify the overlap between the predicted segmentation and the ground truth (actual) segmentation. A Dice score of 1 indicates perfect agreement between the predicted and the actual segmentation, while a score of 0 indicates no agreement. Y is the set of pixels which represent ground truth segmentation. $\hat{Y}$ is the set of pixels which represent the predicted segmentation. FP represents False Positives. The number of pixels that are not part of the segmentation in the ground truth but are incorrectly predicted as part of the segmentation by the algorithm. FN represents False Negatives. The number of pixels that are part of the segmentation in the ground truth but are not predicted as part of the segmentation. TP represents True Positives. The number of pixels correctly identified as part of the segmentation. $Precision$ is the proportion of the predicted segmentation that is correct. It's calculated as $\frac{TP}{TP+FP}$ $Recall$ is the proportion of the ground truth segmentation that was predicted correctly by the algorithm. It's calculated as $\frac{TP}{TP+FN}$
Notes	-
Sources	Fedorov et al. (2017)
Ref. By	IM1, IM2

Number	TM2
Label	**Average Volume Difference**
Symbol	AVD
Units	dimensionless
Equation	$AVD = \frac{2\lvert V_P \cap V_G \rvert}{V_G}$
Description	Average Volume Difference (AVD) is used image segmentation to quantify the overlap between the predicted segmentation and the ground truth (actual) segmentation between volumes of data. V_P is the volume of segmentation predicted by the algorithm. V_G is the ground truth volume of segmentation.
Notes	In the context of this project, AVD can be used to compare volumes of tissues inside the brain.
Sources	Fedorov et al. (2017)
Ref. By	IM1, IM2

Number	TM3
Label	**Convolution**
Symbol	-
Units	dimensionless
Equation	-
Description	A convolution is a method to reduce the image dimensions by extracting relevant information by sliding a kernel (TM4) across the image. A convolution combines information about local pixels such that pixels close to each other in an image are "summarized" by a smaller set of pixels.
Notes	-
Sources	Convolutional Neural Networks
Ref. By	TM4

Number	TM4
Label	**Kernel**
Symbol	-
Units	dimensionless
Equation	-
Description	A kernel is an nxn matrix that performs the convolution operation(TM3) on a mxm image matrix, where $n < m$.
Notes	-
Sources	Convolutional Neural Networks
Ref. By	TM5, TM3

Number	TM5
Label	**Convolutional layer**
Symbol	-
Units	dimensionless
Equation	$W_out = \frac{W-F+2P}{S} + 1$
Description	A Convolutional layer performs a dot product between two matrices, where one matrix is the set of learnable parameters otherwise known as a kernel TM4, and the other matrix is the restricted portion of the receptive field. The Kernel is smaller in size than the receptive field but extends to the depth of the image DD3. If the image is an RGB image, the kernel will be applied to all three color channels. W_out is the width and height of the output volume. W is the width and height of the input volume. F is the size of the kernel FxF. P is the padding around the kernel. S is the stride or jump of the kernel after each operation.
Notes	-
Sources	Convolutional Neural Networks
Ref. By	IM1, IM2

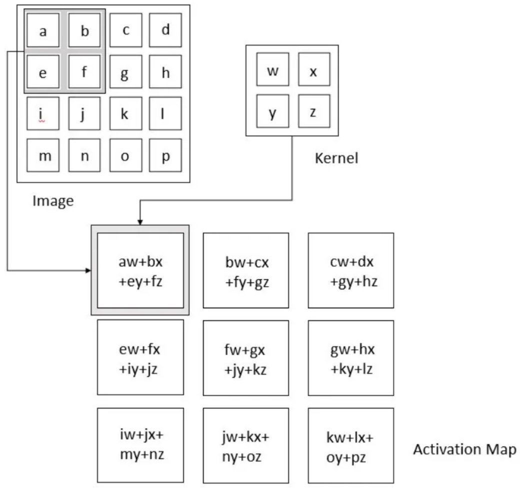


Figure 7: visualization of the inner workings of convolutional layers. The figure shows a kernel performing a convolution operation on a part of an image. Suedumrong et al. (2022)

4.2.3 General Definitions

There are no general definitions in this project.

4.2.4 Data Definitions

This section collects and defines all the data needed to build the instance models. The dimension of each quantity is also given.

Number	DD1
Label	**Pixel**
Symbol	$p : \mathbb{R}$
SI Units	-
Equation	-
Description	A pixel is the smallest programmable color element on a digital screen. Each pixel comprises a subpixel that emits a red, green and blue (RGB) color, which displays at different intensities.
Sources	Pixel Definition
Ref. By	DD3, IM1, IM2

Number	DD2
Label	**Voxel**
Symbol	$v : \mathbb{R}$
SI Units	-
Equation	-
Description	A Voxel is short for volumetric pixel. A voxel is the smallest unit to represent a volume in 3D space. Voxels are expresed using three-dimensional coordinates (x,y,z).
Sources	Voxel Definition
Ref. By	DD4, IM1, IM2

Number	DD3
Label	**Image**
Symbol	$F(x, y) : x \in \mathbb{R}^{m \times n}, y \in \mathbb{R}^{m \times n}$
SI Units	-
Equation	-
Description	An image is a mapping from the continous spatial domain to the discrete digital domain. An image consists of a number of pixels (DD1).
Sources	Image Definition
Ref. By	IM1, IM2

Number	DD4
Label	**Volume**
Symbol	$F(x, y, z) : x \in \mathbb{R}^{m\times n}, y \in \mathbb{R}^{m\times n}, z \in \mathbb{R}^{m\times n}$
SI Units	-
Equation	-
Description	A Volume is a grid based representation of 3D spaces. It consists of an array of voxels DD3.
Sources	-
Ref. By	IM1, IM2

4.2.5 Instance Models

Number	IM1
Label	**Segmentation**
Input	3D volume in 3D segmentation, 2D slice/image in 2D segmentation.
Output	Segmented Volume (Voxels are labeled) in 3D segmentation DD4, DD2. Segmented Slice/Image (Pixels are labeled) in 2D segmentation DD1 , DD3.
Description	Segmentation precisely divides an object into related entities, each representing specific locations or meanings. In medical imaging there exist two types of segmentation: functional segmentation, which focuses on brain activity, and anatomical segmentation, which details the brain's physical structure.
Sources	Joshi et al. (2022), Schmidt et al. (2016)
Ref. By	IM2

Number	IM2
Label	**Anatomical Segmentation**
Input	3D volume in 3D segmentation, 2D slice/image in 2D segmentation.
Output	Segmented Volume (Voxels are labeled) in 3D segmentation DD4, DD2. Segmented Slice/Image (Pixels are labeled) in 2D segmentation DD1 , DD3.
Description	A subset of segmentation IM1. A process that divides the brain into structurally distinct areas based on MRI scans, identifying regions such as gray matter, white matter, and cerebrospinal fluid.
Sources	Joshi et al. (2022)
Ref. By	-

4.2.6 Input Data Constraints

The only input data constraint is that the input data must be in NIfTI format. There will be preprocessing steps in the project's algorithm to resize and resample the scan volume to 256x256x256 volumes with 1x1x1 mm voxels for input to the segmentation algorithm.

4.2.7 Properties of a Correct Solution

A correct solution must provide visually clear visualization of fMRI scans and segmentation results where each brain area is color coded and the colors are visually differentiable. The solution must allow the user to view different 2D slices and 3D volumes and sub-volumes at various time points.

5 Requirements

This section provides the functional requirements, the business tasks that the software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

5.1 Functional Requirements

R1: The system should allow the users to input 4D scans with the associated metadata in the supported formats(NIfTI).

R2: The system should clearly output a visualization of 3D volume and 2D slices in the coronal, sagittal, and axial views of the input fMRI scan.

R3: The system should enable the user to navigate through different time points for 2D slice views and 3D volumes.

R4: The system should provide functionality for users to navigate through time points and view the segmentation results at each point in time

R5: The system should perform all required data preprocessing to accurately visualize input data R2 and perform segmentation IM2 R4

R6: The system should implement an algorithm or set of algorithms capable of performing anatomical segmentation on 3D volumes IM1 IM2.

5.2 Nonfunctional Requirements

NFR1: **Accuracy**: The segmentation accuracy should be comparable with the most up to date benchmarks for brain anatomical segmentation.

NFR2: **Usability**: The system should offer a user inferface that is easy to use with minimal training by both experts and general users.

NFR3: **Maintainability**: The system should be implemented in a manner that enables improvements to current functionality and smooth addition of new functionalities

NFR4: **Portability**: The system should work on any device with modern browser. Users shouldn't have to install any dependencies for the system to work.

Other NFRs that might be discussed include verifiability,understandability and reusability.

6 Likely Changes

LC1: The algorithm used for the segmentation can change after experimentation and evaluation of accuracy and speed of inference.

LC2: The visualization steps order and algorithms can change after experimentation to achieve the best visualization output.

7 Unlikely Changes

ULC1: The project is unlikely to cover functional segmentation.

8 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an "X" may have to be modified as well. Table 2 shows the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 3 shows the dependencies of instance models, requirements, and data constraints on each other. Table 1 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions.

	A1	A2	A3	A4
TM1	X			
TM2	X			
TM3				
TM4				
TM5				
DD1				
DD2				
DD3		X	X	
DD4		X	X	
IM1	X	X	X	X
IM2	X	X	X	X

Table 1: Traceability Matrix Showing the Connections Between Assumptions and Other Items

	TM1	TM2	TM3	TM4	TM5	DD1	DD2	DD3	DD4	IM1	IM2
TM1								X	X	X	X
TM2								X	X	X	X
TM3				X	X			X	X		
TM4			X		X			X	X		
TM5			X	X				X	X		
DD1							X	X			
DD2						X			X		
DD3						X				X	X
DD4							X			X	X
IM1	X	X						X	X		X
IM2	X	X						X	X	X	

Table 2: Traceability Matrix Showing the Connections Between Items of Different Sections

	IM1	IM2	R1	R2	R3	R4	R5	R6
IM1		X	X		X	X	X	X
IM2	X		X		X	X	X	X
R1				X	X	X	X	X
R2	X	X	X				X	X
R3	X	X	X			X	X	X
R4	X	X	X		X		X	X
R5	X	X	X	X	X	X		
R6	X	X	X	X	X	X		

Table 3: Traceability Matrix Showing the Connections Between Requirements and Instance Models

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