NTNU – Trondheim
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Towards a 3D model of the rat brain in AR as an educational tool

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PROJECT REPORT
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Abstract

Something, something...

Contents

Chapter 1

Introduction

I feel I need the two following sections before the Motivation sections, as they are quick introductions to the basics. But maybe there is a better way?

Augmented Reality

Augmented Reality (AR) describes the use of computer technology to generate an audio-visual experience combining real-world impressions with computer generated graphics, and, *essentially*, the ability to interact seamlessly within both domains. Ever since its infancy medical usage of AR technology has been envisioned as a great potential. The idea of x-ray vision is seen both in science fiction and in genuine research dating all the way back to the 1930s when H. Steinhaus explored ways to visualize metal pieces inside the body (Sielhorst et al., 2008). There is now substantial interest in the use of AR within a wide array of medical fields as well as in industry and education. As an emerging technology there is still much research needed, and great leaps in hardware, software and sensor capabilities are bound to happen in the near future. Already AR shows promising results in both surgical settings and in education (Singh and Kharb, 2013).

Neuroanatomy

The study of neuroanatomy is concerned with the structural organization of the nervous system. This primarily means the brain and its structures, and is what this project will focus exclusively on. Within the study of neuroanatomy, the use of macroscopical brain dissections have long been the conventual practice for teaching the organization of the structures in the brain. Requiring cadavers and the single use of their brain, this method is highly resource intensive and has limited scalability. In addition, there are deeply concerning ethical challenges with the use of animals in research, which will be discussed further in section 2.4.

1.1 Motivation 2

Neuroanatomy is a spatially complex field of study, requiring

1.2 Motivation

In light of the problems with physical brain dissections it is natural that the use of digital tools, three-dimensional modeling and visualization has been seeing growing use for educational purposes.

According to (Dalgarno and Lee, 2010) computer-aided learning generally increases understanding for anatomy. As anatomy in general, and neuroanatomy specifically are highly complex domains both visually and spatially, the ability to use the human senses in a real-world setting could result in greater intuition and understanding. With that in mind the use of augmented reality could be a natural way to virtualize the experience of a brain dissection, and further the unique capabilities of AR could enable innovative ways of learning. (Moro et al., 2017) shows the possibility of greater immersion and engagement while using augmented reality in teaching anatomy to medical students. This has also recently been shown with promising result by (Wish-Baratz et al., 2020), where COVID-lockdown required from-home teaching, and the use of HoloAnatomy, an anatomy application for the HoloLens, performed significantly better than even conventional in-class lectures.

The main problem with most academic implementations, like (Wish-Baratz et al., 2020), of AR in medical education is the use of head-mounted display (HMD) devices like the HoloLens 2 and Magic Leap, which in the near to mid-term future will have limited practical use in education, as a result of the high price-tag, combined with the still inadequate general use-case for these types of devices. This project will try to mend these challenges by having the lecturer using an HMD and having student view and interact with the lecture in an AR-based application running on their smartphone. This is possible because of the great leap in AR-performance seen in recent models of Android and especially iPhones, in combination with development platforms like Unity, Mixed Reality Toolkit and Photon (see section 2.6) which enables multiplatform development and real-time collaboration between devices.

Introduce Nevrolens and WHS brain

The aim of the project will be to create a seamless educational experience in Augmented Reality which can be valuable both on an HMD device and a modern smartphone. The focus will be on investigating its feasibility as an educational tool both in a lecture-type setting and for students to explore the brain anatomy independently.

1.3 Problem Formulation

What Remains to be Done?

1.4 Objectives / Research Questions

What follow are the research questions which motivates this project:

Main-RQ: How can AR support teaching of rat brain anatomy and dissection for medical students?

Sub-RQ1: How should interaction in be implemented in AR to accommodate medical professionals?

Sub-RQ2: How will a collaborative experience shared between an HMD and a smartphone compare to accommodate medical professionals?

Sub-RQ3: Can understanding be increased by integrating microscopical data into a macroscopical model?

1.5 Approach

Research method

The research questions were derived through discussing the needs of the intended users with neuroscientists at the Kavli Institute. It was then narrowed down by a literature review, finding a lack of satisfactory substitutions for real brain dissections and especially finding no attempt at a practical multiplatform application for a more scalable use for students. The

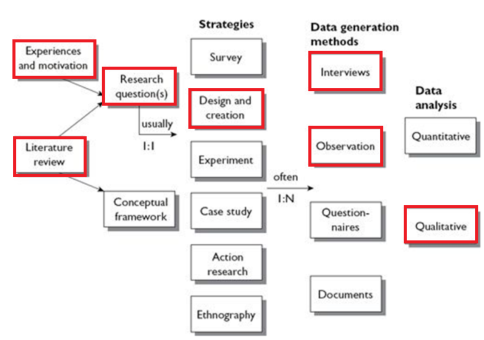


Figure 1.1: Model of the research process as illustrated in Oates (2006)

projects research question falls under the strategy of Design and Creation as the main goal is to develop a useful application for medical education. The focus on a smartphone solution was further motivated by the COVID-pandemic making from-home learning quite essential and making the passing around of HMD devices an unwanted scenario. As part of an agile software development model the gathering of qualitative data from observations and interviews within the scope of user testing will be essential.

Development method

1.6 Contributions

The research product resulting from this project will be a new computer-based software application using augmented reality and running on multiple platforms like HoloLens 1 and 2, Android and more. The aim will be to develop an application that can bridge the gap between expensive head mounted displays and everyday smartphones which you will find in the pocket of any student, and to use this as a collaborative tool for learning neuroanatomy. Throughout the development period we will consult with medical professionals and gather feedback from students on the usability of the application.

Something about macro + micro

1.7 Outline

Chapter 2

Background

2.1 Glossary?

2.2 Augmented Reality

(Jentoft, 2020) AR can be defined as a system that fulfills three basic features: a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects.

Disambiguation of some acronyms

As a new field, this field suffers from naming disagreements. This is a confusing reality which needs to be addressed. There are differing view of what each acronym refers to, and even what they stand for. I will overlook most of this discussion, and simply explain what is meant by each acronym in the scope of this project.

AR Augmented Reality, exercises which implement a see-through effect to display 3D visuals on top of the real-world. The idea of holograms is a good stand-in for the effect of AR. This is the term which will be most used in this project.

MR Mixed Reality, anything within the spectrum between reality and pure visual 3D graphics, which blends computer generated visuals and reality. While the term was not invented by Microsoft[1], it is a term strongly associated with them, and in this project the term MR will generally only be used as a reference to Microsoft's products or concepts.

There term is also used by some as a subset of AR, so in conclusion it is a somewhat controversial term.

XR Extended Reality, much like MR this includes the whole spectrum of experiences blurring the line between the real and the virtual. However it does not have the Microsoft taint, nor the confusion of that term. And thus it is a more acceptable term, and it is what will be used here to describe the spectrum.

VR Virtual Reality, is enclosed experiences which completely surrounds the user within a computer generated world. This is a generally uncontroversial term and will be used for applications running on devices like the Oculus Rift and the HTC Vive.

2.3 Graphics and Rendering

Rasterization, Polygons and 3D models

I feel that there is some misunderstanding about what a 3D model is. Maybe go in-depth about what I mean by 3D model. I have probably already used the term for different things.

2.4 Neuro stuff

Ethics of dissection

The Waxholm Space Atlas of the Sprague Dawley Rat Brain

https://www.nitrc.org/projects/whs-sd-atlas

- What is a atlas
- WHS and ratbrain is open, used and developed by NTNU St Olavs and UiO
- Waxholm Space Atlas of the Sprague Dawley Rat Brain
- Discuss difference between graphical 3D model and 3D atlas

[1] In fact the term was coined by Milgram and Kishino (1994), in this exact meaning.

This project makes use of high-resolution 3D-models of a rat brain. This brain model has been captured and manually delineated[1] by a collaboration between research groups at the University of Oslo and NTNU, and is in fact a highly accurate volumetric representations of the rat brain. This model is an open access community resource, intended as a free tool for education and research[2]. Within the convectional rasterization rendering pipe-line of Nevrolens, a polygonal asset derived from this volumetric model is naturally used.
The model is simply referred to as *The Waxholm Space Atlas of the Sprague Dawley Rat Brain*. What follows is a brief explanation of each confusing part of the this name.

Waxholm Space

Waxholm Space (WHS) is a vector space defined as a standard reference space for the mouse brain and the rat brain (Papp et al., 2013). Its use as a coordinate system simplifies interoperability across atlases. It was developed by International Neuroinformatics Coordinating Facility (INCF) for the mouse brain, and has further been implemented in the rat brain by Papp et al. (2014). The following is the formal definition of WHS:

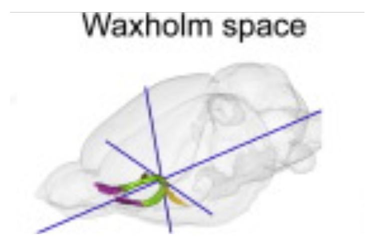


Figure 2.1: WHS (Papp et al., 2014)

> *The coordinate system for WHS is defined as a continuous Cartesian system with the origin in the brain determined by*
>
> - *the anterior commissure (AC) at the intersection between the mid sagittal plane,*
> - *a coronal plane passing midway (rostro-caudal) through the anterior and posterior branches of AC, and*
> - *a horizontal plane passing midway through the most dorsal and ventral aspect of the AC.*
>
> Hawrylycz et al. (2011)

[1] Delineation refers to the process of clearly defining different structures in the brain into separate namable parts.

[2] https://www.nitrc.org/projects/whs-sd-atlas

Figure 2.1 visualizes the axes through origin of WHS in the brain of a rat. Within the scope of this project WHS will be the local space of the rat brain model implemented in Nevrolens.

Brain Atlas

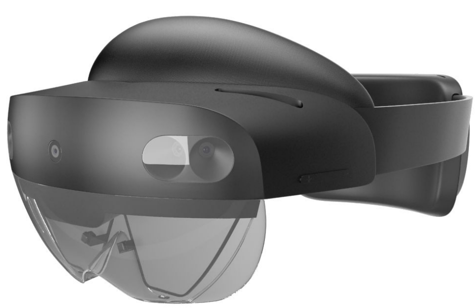
A brain atlas is a composite representation based on one or more datasets of a given brain. An atlas generally has the function of highlighting some specified aspects and relations in the brain, and is a convectional tool in neuroscientific research (Toga and Thompson, 2000). The convectional atlas is based on micrometer scale sliced sections in the brain, effectively creating two-dimensional layers through the brain. While functional, this "turns the brain into a book". Three-dimensional digital atlas are however relative newcomer on the neuro-imagery scene, by employing magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI) the resulting atlases are complete volumetric representation of the subject brain (Papp et al., 2014).
This volumetric model is the basis for the delineated 3D-model used in Nevrolens.

Sprague Dawley

Its a strain of laboratory rat.

2.5 Equipment

HoloLens 2



HoloLens 2 is the second iteration of Microsoft immersive headset line. It uses an ARM-based computing unit, running a custom holographic version of Windows 10 for ARM. This enables the HoloLens 2 to produce high quality graphics while being very power efficient. It was announced in early 2019, with a limited release on November 7, 2019. It is however jet, as of writing, not publicly available and could be considered a limited industrial product.

Display	Optics: See-through holographic lenses (waveguides) Resolution: 2k 3:2 light engines Holographic density: >2.5k radiants (light points per radian) Eye-based rendering: Display optimization for 3D eye position
Sensors	Head tracking: 4 visible light cameras Eye tracking: 2 IR cameras Depth: 1-MP Time-of-Flight (ToF) depth sensor IMU: Accelerometer, gyroscope, magnetometer Camera: 8-MP stills, 1080p30 video
Audio and speech	Microphone array: 5 channels Speakers: Built-in spatial sound
Human understanding	Hand tracking: Two-handed fully articulated model, direct manipulation Eye tracking: Real-time tracking Voice: Command and control on-device; natural language with internet connectivity Windows Hello: Enterprise-grade security with iris recognition
Environment understanding	6DoF tracking: World-scale positional tracking Spatial Mapping: Real-time environment mesh Mixed Reality Capture: Mixed hologram and physical environment photos and videos
Compute and connectivity	SoC: Qualcomm Snapdragon 850 Compute Platform HPU: Second-generation custom-built holographic processing unit Memory: 4-GB LPDDR4x system DRAM Storage: 64-GB UFS 2.1 WiFi: Wi-Fi: Wi-Fi 5 (802.11ac 2x2) Bluetooth: 5 USB: USB Type-C

This project mainly focuses on developing for the HoloLens 2

2.6 Tools

Unity

Unity is a game engine for developing 2D and 3D games. It has grown to become the most popular game engine used by single developers and small development teams because of its ease of use and simple licensing terms for independent developers. Because of its popularity and ease of use Unity has become a platform for 3D development within more widespread fields than video gaming, such as engineering, moviemaking and architecture. Within this project the critical reason for choosing Unity for our 3D development is the exceptional support for the HoloLens product line. As seen in the section 2.6, Microsoft

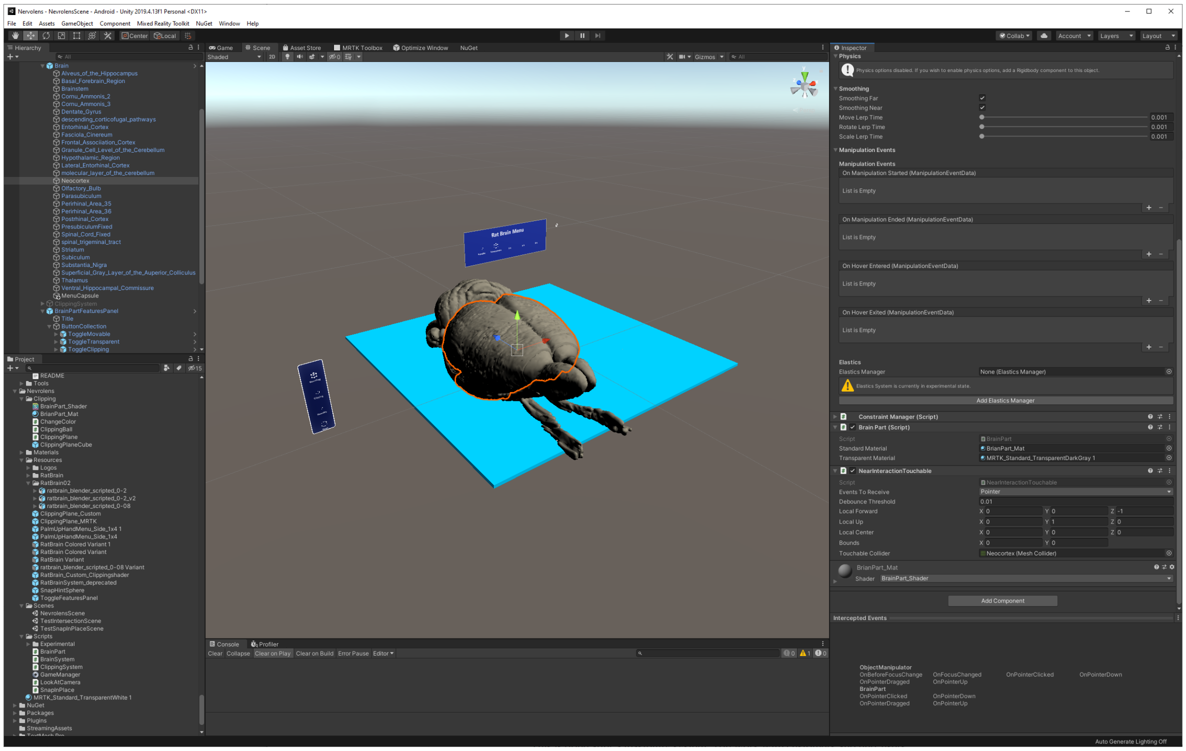


Figure 2.2: Unity 2019.4.13f1 running Nevrolens

has poured resources into developing a "relatively" robust open framework for using Unity to develop for HoloLens. Alternatives to using Unity are slim, but one could be to use Unreal Engine, an 3D game engine with great support for VR and AR in general, however the support for HoloLens specific tools like Mixed Reality Toolkit is limited[2].

Mixed Reality Toolkit

Mixed Reality Toolkit (MRTK) is a open source, Microsoft-driven framework for Mixed Reality (MR) development. In practice it is Microsoft's SDK for HoloLens development, greatly simplifying development related to interaction, user interface and [. . .]. As it is a framework for MR in general, it supports other platforms like Android, iOS and VR devices such as HTC Vive and Oculus Rift with OpenVR. An alternative to using MRTK would be to us XRTK which is a community-driven fork of MRKT. Thought such a choice would be an exercise of free software principles, it also lends it self to better support for some devices, like the MagicLeap.

[2] Microsoft has a version of MRTK for Unreal, called MRTK-Unreal. It seems to be stale however, not having any updates in the last six months in the time of writing.

Blender

Blender is a 3D modeling application, it is free open source software and is has a wide set of functionalities for 3D modeling, animation, rendering and optimization. Till now this project has only made use of one tool in Blender, *decimation*, the process of simplifying the polygon count of a 3D model. This has been done by scripting, simply because Blender does not have a built-in way to apply a modifier on multiple objects[3]. Listing 2.1 showcases my use of Blender in its entirety.

```python
import bpy # importing the blender python library

def decimate(ratio, replace = True):
    # Finds all objects and filters irrelevant objects from the FBX
    brainparts = [n for n in bpy.data.objects \
        if n.name not in ("Camera", "Light")]

    for part in brainparts:
        mod = 0
        # Finds all decimate modifiers on each brainpart
        decimate_mods = [n for n in part.modifiers \
           if n.type == 'DECIMATE']
        if decimate_mods and not replace:
            mod = decimate_mods[0]
        else:
            if replace:
                # Removes all decimate modifiers from the brainpart
                for m in decimate_mods:
                    part.modifiers.remove(m)
            mod = part.modifiers.new(type='DECIMATE', name='Decimate')
            mod.decimate_type = 'COLLAPSE'
        # Sets the specifies strength to the decimate operation.
        mod.ratio = ratio
# Calls function with given decimate strength.
decimate(0.08)
```

Listing 2.1: Blender script applying a decimate modifier to all relevant objects in a scene.

Photon

Photon is the state of the art networking library for Unity. It can manage everything from voice chat to interaction over network. This has not jet been used in the project, but will

[3]Or at least I didn't find any such solution.

be referred to in Further Work.

Git

Git is a distributed version control system. Together with hosting on NTNUs self-managed GitLab it enables version control and cloud back-up of the project. While this is the most conventional version control system for any software project, using Git with Unity can be frustrating. Git is design for projects with only (mostly) small, human-readable text files, like a code base. A Unity project often as huge files, which Git does not support, and relevant changes can happen in binary files, which makes merging impossible. Git LFS, gitignore and setting in Unity to disable binary files...

GitKraken

Kanban and such
Used both / separately for Nevrolens and Project thesis.

2.7 Related work

VRVisualizer

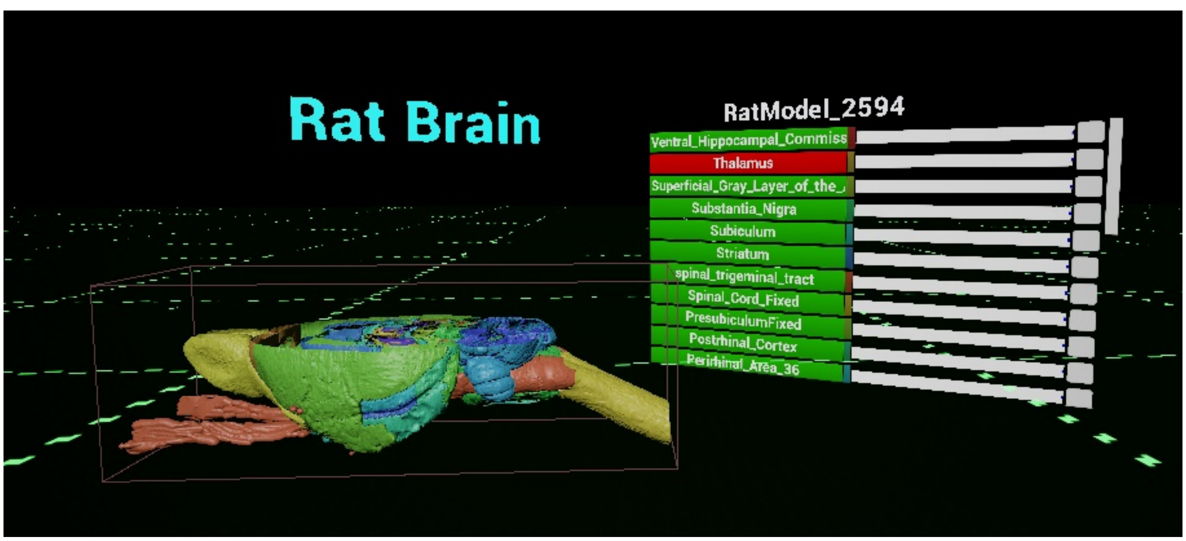


Figure 2.3: Cutting operation in VRVisualizer on HTC Vive

VRVisualizer is the name of the research product from the master thesis Elden (2017). It is a VR application running on the HTC Vive. While its features are similar to the goals of this project, the focus of Eldens project was to develop universal guidelines for scientific visualization in VR. That is far from this projects goals and thus its feature set, relating to interaction and exploration, is quite superficial.

HoloAnatomy

Insight Heart

SphenoBlock?

Noe HoloCare stuff?

Chapter 3

Implementation

3.1 Requirements

The first meeting initializing the project took place at VRLab Dragvoll in early September, here I was introduced to the general background and the problem description of how Witter and others envisioned the use of AR for neuroanatomical education. It was explained how cadavers for education are difficult to acquire and [...]. Another problem we discussed was related to the difference in medium between VR and AR. While the application VRVisualizer did have many of the features envisioned, and could have been a basis for further development. The fact that is was implemented in VR was problematic for the envisioned use cases. Being completely enclosed visually limits its use case in lectures and in any use case with collaboration in a physical space. Generally the loss of spatial awareness and eye contact as a result of using VR headsets was though of as an impediment for using VR for such an application. Thus, we had an outline of a neuroanatomical education tool in AR using the HoloLens 2 and concluded with some questions and requirements for the project:

1. Can the current VR dataset[1]be used in the HoloLens 2 AR environment?
2. If not, which steps need to be taken to use the segmented WHS rat brain to develop a suitable 3D model that can be used in AR?
3. Develop an optimal user interface for a single person to explore the rat brain as if the user is doing a dissection of a real brain.
4. Develop/test ways to make this a multiuser/shareable tool adequate in a teaching environment.

5. Explore ways to integrate microscopical data into the AR representation.

6. Describe/explore the feasibility to implement the system for Human neuroanatomy education.

Here items 1-4 were deemed critical for the project, while 5 and 6 were dependent on the progress made.
This meeting together with the list formed a clear problem description and can be seen as the initial discovery process of the project. Though the following period of exploring the newly arrived HoloLens 2 and its capabilities, we formed a set of *system requirements*. System requirements are descriptions of how a system should operate, what it should be able to do and the constraints of its operation. The requirements must reflect the stakeholders needs for the system (Sommerville, 2011). System requirements are generally split into functional requirements, which describe specifics of what the system (and its subsystems) should do, and non-functional requirements, which generally are descriptions of the user experience of the system as a whole. What follows are the system requirements decided on for the application:

Functional Requirements

1. **Implement a brain dissection tool in AR.**
   The app should render a brain at sufficient quality for educational use, and have the tools for creating a dissection experience in AR.

2. **The application must run in HoloLens 2 and at least one mobile platform**
   The ability to run a version for the app on multiple platforms is essential for the purpose of this project. While the main platforms are HoloLens and mobile, others may also be implemented in the future.

3. **Implement cross-platform collaboration over network**
   For the application to have value above a single user it is important that it can be used with a HoloLens and a more accessible platforms in a collaborative manner.

Non-Functional Requirements

1. **Medical students should find educational use for the app.**
   It is critical that there is educational value in the application.

[1] Referring to VRVisualizer.

2. **The application should be usable without outside guidance.**
   The app should have a clear and understandable design, such that a new user should be able to navigate the app by them self, even with minimal experience with AR.

3. **All relevant usability criteria for a mixed reality app should be met.**
   We should work to not fall under the 'meets' criteria on any relevant metric in the App quality criteria[2]. This includes criteria on; FPS, spatial anchoring and view comfort.

3.2 Software Process

Even though I have developed the Nevrolens application by myself, I have strived to use best practices for a software development workflow. These practices have generally grown out of the the needs of a multi-developer setting, enabling simpler use of collaboration and version control. Though their value possibly increases exponentially by the number of team members, I have found value in the structure and clarity I find in the workflow.

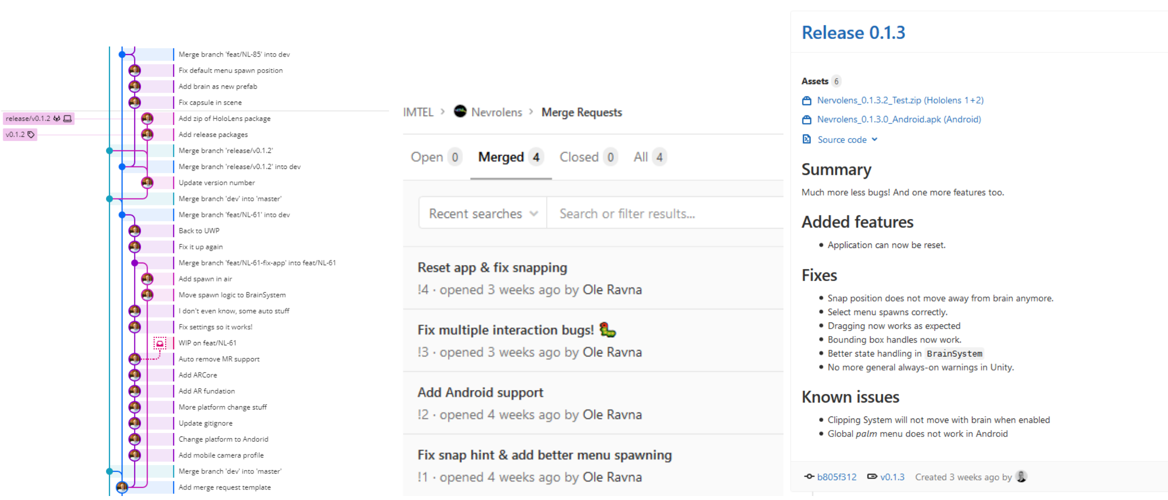


Figure 3.1: Feature branches, merge requests and releases.

My workflow is based on *Gitflow*, a workflow framework optimized for continuous software development. In short, this is just a very basic rule set for branch-naming and the sanctity of the master-branch (requiring merge requests of only product ready code), within the version control system Git. It does however act as a fundament which enables practices like rapid release cycles, because of the clearly define production ready state, and the

[2]https://docs.microsoft.com/en-us/windows/mixed-reality/develop/platform-capabilities-and-apis/app-quality-criteria

integration with lean development technics like Kanban. This stems from the parallels between feature-branches in Gitflow and the *ticket* in Kanban. In practice, this means that tickets, with issues or new features for the app, are created on in the *Backlog* column of the Kanban board and are then moved to *Doing* column simultaneously as a feature-branch is created with the ID of the ticket, e.g. `feat/NL-42`. All of this is automated in the Git management tool GitKraken, which manages both the git-repo and the Kanban board.

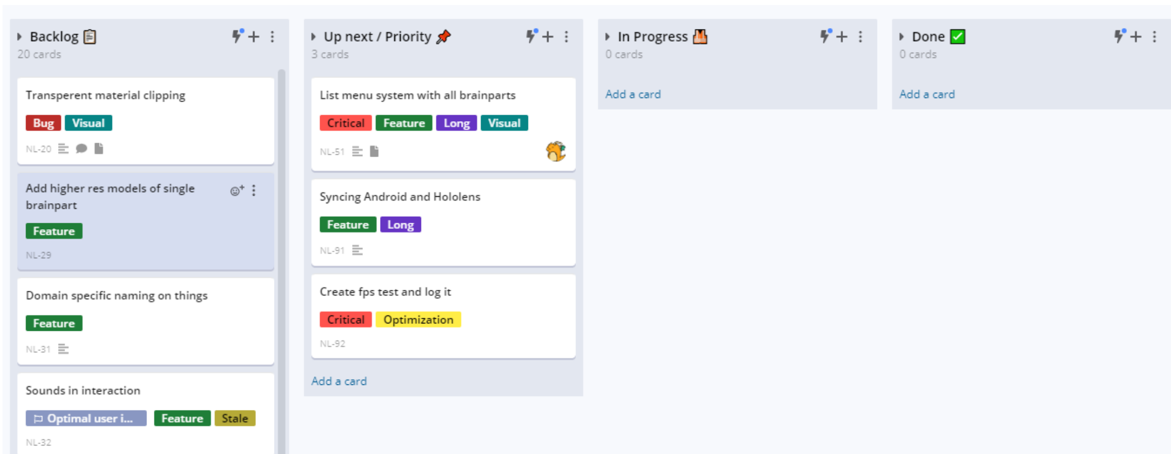


Figure 3.2: A snapshot of the Kanban board in GitKraken, after a development sprint, when completed tickets are archived (closed).
Note: *Priority* acts as pined tickets on *Backlog*, as the backlog tends to sizeable.

This workflow, by design, supports an agile development process. Agile approaches to software development are generally human-centered, valuing individuals and interactions over processes and tools[3], and focused on iterating rather than upfront planning. This is ideas which are beneficial for single-developer or small teams especially when developing for new platforms like the HoloLens 2. While the project aims for an agile approach, the feedback cycle[4] core to the agile development, where stakeholders are involved for regular feedback, has only really been done for one cycle

3.3 Validation / Testing

[3]The Agile Manifesto https://agilemanifesto.org/
[4]General term; release cycle in XP, sprint cycle in scrum. All are some sort of feedback cycle.

Chapter 4

Results

Chapter 5

Conclusions, Discussion, and Recommendations for Further Work

5.1 Limitations

5.2 Summary and Conclusions

5.3 Discussion

5.4 Further Work

- Collaboration, Networking
- Macro+micro implementation
- Importing new models
- Look into volumetric rendering

Appendix A

Acronyms

NTNU Norwegian University of Science and Technology

AR Augmented Reality

MR Mixed Reality

XR Extended Reality

VR Virtual Reality

FPS Frames per second

HMD Head-mounted display

WHS Waxholm Space

GPU Graphics Processing Unit

SDK Software Development Kit

MRI Magnetic Resonance Imaging

DTI Diffusion Tensor Imaging

Appendix B

A geometric model of the rat brain

This is a section from Elden (2017), the master thesis about VRVisualizer the VR application this project is loosely inspired by. The section explains how Elden extracted a geometric model of the rat brain from the medical models which is high fidelity volumetric data.

5.2 Exporting segments of a rat brain atlas as geometry for the Rat Brain model

The geometric meshes used for the rat brain model were extracted from a volumetric and segmented atlas. IKT-SNAP was used to export each segment of the brain as an STL file. These geometric meshes were then opened in Blender3 to be converted to OBJ or FBX files. 3DS Max imported the models and performed all modifications made to the geometry and structure. ITK-SNAP requires three files to segment and label the models; the atlas and a segmentation file, both stored as NII files, and a LABEL file for the labels. When all files are loaded the program lets the user select a segment to export and generate a geometric hull along the boundary of the segment. Due to instability experienced with 3DS Max using all 16 GB of RAM available on the computer used for development, Blender was used to first convert the files to FBX files. These FBX files caused no issues when imported into 3DS Max. Since these meshes were too detailed, they needed to be reduced and transformed in 3DS Max. The meshes were reduced such that the entire model consisted of 4.5 million triangles. Most of the meshes had to be transformed such that each segment was where it should be inside the model. For some reason the exported meshes were of several relative scales and heights and a lot of manual work went into moving and scaling the meshes to match the volumetric model seen in ITK-SNAP. Properly processed, the model was exported as an FBX file and sent to UE4.

Bibliography

Dalgarno, B. and Lee, M. J. W. (2010). What are the learning affordances of 3-d virtual environments? *British Journal of Educational Technology*, 41(1):10–32.

Elden, M. K. (2017). Implementation and initial assessment of vr for scientific visualisation: Extending unreal engine 4 to visualise scientific data on the htc vive. Master's thesis, University of Oslo.

Hawrylycz, M., Baldock, R. A., Burger, A., Hashikawa, T., Johnson, G. A., Martone, M., Ng, L., Lau, C., Larsen, S. D., Nissanov, J., Puelles, L., Ruffins, S., Verbeek, F., Zaslavsky, I., and Boline, J. (2011). Digital atlasing and standardization in the mouse brain. *PLOS Computational Biology*, 7(2):1–6.

Milgram, P. and Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Trans. Information Systems*, vol. E77-D, no. 12:1321–1329.

Moro, C., Štromberga, Z., Raikos, A., and Stirling, A. (2017). The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education*, 10(6):549–559.

Oates, B. (2006). *Researching Information Systems and Computing*. SAGE Publications.

Papp, E., Kjonigsen, L., Lillehaug, S., Johnson, G., Witter, M., Leergaard, T., and Bjaalie, J. (2013). Volumetric waxholm space atlas of the rat brain for spatial integration of experimental image data. In *Front. Neuroinform. Conference Abstract: Neuroinformatics 2013*.

Papp, E. A., Leergaard, T. B., Calabrese, E., Johnson, G. A., and Bjaalie, J. G. (2014). Waxholm space atlas of the sprague dawley rat brain. *NeuroImage*, 97:374 – 386.

Sielhorst, T., Feuerstein, M., and Navab, N. (2008). Advanced medical displays: A literature review of augmented reality. *Journal of Display Technology*, 4(4):451–467.

Singh, V. and Kharb, P. (2013). A paradigm shift from teaching to learning gross anatomy: meta-analysis of implications for instructional methods. *Journal of the Anatomical Society of India*, 62(1):84 – 89.

Sommerville, I. (2011). *Software Engineering*. Pearson Education, Inc., 9th edition.

Toga, A. W. and Thompson, P. M. (2000). 40 - image registration and the construction of multidimensional brain atlases. In BANKMAN, I. N., editor, *Handbook of Medical Imaging*, Biomedical Engineering, pages 635 – 653. Academic Press, San Diego.

Wish-Baratz, S., Crofton, A. R., Gutierrez, J., Henninger, E., and Griswold, M. A. (2020). Assessment of Mixed-Reality Technology Use in Remote Online Anatomy Education. *JAMA Network Open*, 3(9):e2016271–e2016271.