STIMULATING THE GROWTH OF A CALADIUM PLANT FOR A WEB-BASED METAVERSE ENVIRONMENT

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2024

STIMULATING THE GROWTH OF A CALADIUM PLANT FOR A WEB-BASED METAVERSE ENVIRONMENT

A Thesis Submitted for the Degree of Master of Computer Science

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University of Colombo School of Computing
2024

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ACKNOWLEDGEMENTS

I would like to take this opportunity to express my sincere gratitude towards my supervisor Dr. K. D. Sandaruwan for the continuous support of my master's research. Without his patience, guidance, and motivation this thesis would not have been possible. Special thanks to my co-supervisor Dr. KAKT Karunanayaka for supporting my research and taking valuable time to share their insights and for always being there to assist on any course-related matters as the research module coordinator.

I would also like to thank Ms. R. Achchudha for participating in the research evaluation despite their busy schedule.

I would like to thank my beloved family and friends for their continuous support, love, and encouragement during my study. Finally, I would like to thank the people not mentioned here, who helped me whether directly or indirectly are gratefully acknowledged.

To my family

ABSTRACT

Studies on object realism in virtual environments are abundant, but tree growth stimulation in VR spaces like the Metaverse remains largely unexplored. This technology has the potential to significantly enhance the user's sense of realism within an immersive VR experience. Applications range from creating aesthetically pleasing virtual spaces to developing VR environments for scientific studies, designing realistic game scenes, and even constructing immersive virtual environments for disaster control and simulation training.

This thesis presents a feasibility study on incorporating tree growth stimulation modeling into a web-based virtual environment to improve object realism. The approach focuses on a specific plant, Caladium Bicolor, and aims to model its growth stimulation using WebGL for a web-based VR environment.

The evaluation involves three parts: a qualitative user test comparing the created model against an actual Caladium plant growth stimulation, a statistical analysis of data collected from the Caladium growth model, and a performance evaluation of the WebGL implementation.

The results suggest that the proposed web-based approach to the metaverse that uses less computational resources, has significant potential as a foundation for a proper growth stimulation model. This thesis presents the proposed proof of concept and the evaluation results as its key contributions obtained from a simulated environment. Additionally, the thesis discusses the limitations of the created model and provides insights into aspects that require further focus when extending and implementing the approach for a real use case in an immersive virtual reality environment.

Keywords: Computer Graphical Simulation, Realistic Growth Stimulation, Modeling and Simulation, Virtual Reality

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ABBREVIATIONS

AR	Augmented Reality
VR	Virtual Reality
2D	2-Dimension
3D	3-Dimension
HMD	Head Mounted Device
IVE	Immersive Virtual Environment
VE	Virtual Environment
IE	Immersive Environment
WebGL	Web Graphics Library
OpenGL	Open Graphics Library
GLGS	OpenGL Shading Language
CPU	Central Processing Unit
GPU	Graphics Processing Unit
VRML	Virtual Reality Modeling Language
LiDAR	Light Detection and Ranging
VFX	Visual Effects
JS	JavaScript
API	Application Programming Interface
JSON	JavaScript Object Notation
WebVR	Web Virtual Reality

CHAPTER 1
INTRODUCTION

1.1. Motivation

Within the realm of virtual environments (VEs), a distinct phenomenon emerges regarding user priorities. Unlike traditional media, where the primary focus rests upon the depicted environment or narrative, users within an immersive virtual environment (IVE) often prioritize the aesthetics and customization of their character models, particularly their user avatars. This prioritization stems from the unique characteristics of IVEs, which allow users to embody a virtual representation – their avatar. Upon entering the VE, users are immediately confronted with this digital manifestation of themselves, prompting an initial focus on its appearance and potential for customization. This emphasis on the self, facilitated by the immersive nature of VEs, transcends concerns about the surrounding environment, leading to a higher perceived importance placed on the character model's aesthetics compared to the supporting objects within the virtual world. Consequently, the initial user experience within VEs is often characterized by an exploration of and investment in personalizing the avatar's appearance, reflecting a fundamental human desire for self-expression and control within digital spaces.

A changing environment brings dynamic perception to the user, rather compared to a statically modeled rock and a puddle of water which does not follow the fundamental properties of physics. A tree is a key component in the natural environment, and it is sensible thinking to bring a similar experience in a virtual environment as well. (Ruoxi Sun et al., 2009) This study tries to amplify the values and perception of the aforementioned factors, by drawing out the growth stimulation of a simple plant model. A niche area to be exact, in the world of object realism in the scope of immersive virtual reality.

1.2. Statement of the Problem

1.2.1. Metaverse – The VR Digital World

Metaverse is an immersive digital environment which is accessible through virtual reality environment. The term was coined in the late 90’s where a virtual reality world where people could be able to access and interact with each other via a creative embodiment of the user - an avatar. Metaverse has become a buzz word in the field of ubiquitous computing in the recent years, due to the technology advancements and the hyper growth of social digital experiences.

(Lee et al., 2021) Since the metaverse is an open concept, not just the big leaguers like Microsoft, Meta (Priorly known as Facebook), Epic and Niantic but also few too many smaller groups are also contributing on shaping up the metaverse. (Jungherr and Schlarb, 2022)

Hence it is being open, metaverse opens too many ways to be acknowledged and highly interoperable in the non-computer science fields as well. Collaborative and creative process is a fitting example in this case. With the platform agnostic approach, metaverse can be accessed through various devices, from phone, computers and highly perfected virtual reality headsets or head mounted device (HMD) giving a much seamless experience to interacted with the virtual world.

The growth of VR devices results in affordability as well. Low-cost virtual reality devices are getting better over time and adopting more cost-effective solutions to bring out a fully immersive system. Because of that, the commercial usages for VR devices has increased and becoming inexpensive to own one too. (Hilfert and König, 2016) Most virtual reality systems have skewed their interest to build less hardware cost devices with adequate technical components to capture the mainstream gaming community. (Hilfert and König, 2016) Hence the VR HMD devices are considered to be commercially used devices. User can easily get into a one of vendor metaverse using their proprietary VR headsets to access the virtual realistic world, mimicking not only just the known universe of objects but also expanding the limits of accessible knowledge which used to be a complicated due to various many reasons. Digital avatars are the primal mode of accessing the environment. (Wang et al., 2023) Each avatar is a unique user who is logged in to the metaverse, and their actions, movements, and gestures are portrayed using the specially designed handheld sensors which comes with the VR headsets. Now a representation of a user – the digital avatar could play games, interact with the environment models, attend online meta-concerts and even do social dating. (de la Fuente Prieto et al., 2022)

Metaverse is supposed to be a medium of relying on all things- everything related to XR (Extended Reality). Encapsulating everything from Augmented reality, virtual reality, mixed reality and in between. Extended reality supports more enhancement to the existing models of 3D entities in a more detailed manner. (Arias et al., 2021)

Web based metaverse experience is another faction in the world of metaverse. It is targeted towards the basic principle of inclusive and available to all. Accessibility with web-based environment is a lower barrier to enter since browsers have become a mainstream user tool in any medium to access the interconnected web, from anywhere and anytime. (Ritterbusch and

Teichmann, 2023) Thus, the idea of stereotypical metaverse accessibility through HMD based VR devices are changing over time in the industry. Additionally, since the web-based metaverse environments run in a web browser they typically have lower hardware requirements to compute compared to a typical dedicated VR device platform. (Choi et al., 2022)

1.2.2. Object Realism in XR

Metaverse is evolving day by day with the achievements from the conducted proper research. More user crowd is expected to be absorbed in the Metaverse in the upcoming years. In ten years,' time, human-computer interaction and social media will have undergone a major transformation. We will have moved away from 2D applications (Lee, 2021) Though, there are some challenges to imitate a near-real environment due to the limitations in the few too many areas. Maintaining a high dynamic range to simulate real-life like experience while also maintaining the luminance level within the headset is a challenging process in the current state. (Matsuda et al., 2022) With the longevity of the metaverse usage, maintaining an evolutionary feel with their own digital realism is another area which has not been covered with active studies in recent past. Virtual realism is not only dependent on the object modeling but also how an object model's attributes change over time in a specified environment.

Object realism is a philosophical study on how to determine whether an object you see is real or not. Regardless of the concept of metaverse, in virtual reality technology, as discussed with the exposition given, an object is real only if it's interactive and able to manipulate its qualities. The more realistic the object is, the more immersive the experience becomes for the user in a metaverse. (Terashima, 2002) Whilst the user does have the freedom to customize their own virtual realism with a one-to-one depiction of their own real-world surroundings, they should also have the sense of realism over-time with the manipulation of the object attributes regardless of whether it is a tree, a fruit or rather their own avatar.

1.2.3. Why Trees are Important in VR?

The tree is a key component when it comes to natural environments. (Ruoxi Sun et al., 2009) In virtual reality environments, the inclusion of trees serves a crucial purpose beyond mere aesthetic appeal. Trees are essential elements that contribute to the immersive experience and realism of the virtual world. Beyond their visual impact, trees provide a sense of scale, depth, and environmental context that enhances the overall user experience. Their presence creates a sense of naturalism and tranquility, fostering a connection with nature that can positively influence the user's emotional state and well-being during VR experiences. (Batistatou et al., 2022)

Moreover, trees can serve as landmarks or navigational cues, aiding users in spatial orientation and exploration within the virtual environment. (Wöbbeking, 2022) From a technical perspective, gaming trees play a significant role in optimizing performance by serving as occlusion objects, helping to manage rendering costs and improve frame rates.

Emerging VR use cases and studies focus on natural disasters for deeper understanding of the context and prevention management needs a more realistic environment with a proper indicator of the impact of the said natural disaster. The scale of the tree damage or destruction provides a valuable visual clue to the user on understanding the severity of the disaster. A fitting example for this would be wildfire studies and storm severity tests. Users will be able to grasp the fundamental severity of the scale of such a high-scale natural disaster by immersing themselves into a simple VR HMD. (Dhunnoo, 2023; "Virtual reality forests could help understanding of climate change | Penn State University," n.d.)

Thus, integrating trees into VR environments is not only aesthetically pleasing but also functionally important for enhancing immersion, guiding navigation, and optimizing performance, contributing to a more compelling and enjoyable user experience.

In conclusion, object realism is still an in-development field of topic in the world of virtual realism. Metaverse is in a mature state compared to its inception. Object modeling and the immersiveness of their presence in the digital world has come a long way. User avatars physical existence, and their motions are capable of bringing out the human interaction. Yet the environment does not seem to be dynamic enough because of the lack of focus of realism in the other day-to-day life entities in the environment.

As a summary, this research focuses on the narrowed background of the problem, on identifying the stimulation of tree models' growth in a metaverse virtual realistic environment. Object realism of plants and trees in a metaverse environment is not an actively researched area. Secondary factors like the surrounding environment and their dynamicity to changes over time bring out the adequate sensory perception of an immersive virtual realistic environment. Hence this study focuses on the viability of stimulating a growth of a plant in the metaverse environment.

1.2.4. Research Questions

Q: How to stimulate a plant growth stimulation in a web-based environment?

> Q1.a: What type of technology is to be used to achieve the realistic modeling that is expected by the main research question?
>
> Q1.b: How to realistically model the plant in a low resource web-based graphical model?

1.3. Research Aims and Objectives

1.3.1. Aim

To narrow down the research problem, this study will be performed with a selected species of plant – Caladium Bicolor, which is a tropical plant known for their big foliage, good yield of leaves and having the easier growth stimuli with the perfect time range to sync with this research work. (Deng, 2012). Focusing on a single vegetation plant (caladium) instead of considering a broader "tree" perspective, yields a more rigid research gap and the proof of concept resulting in a much more statistically accurate evaluation.

The project aims to enhance the aesthetic appeal of the metaverse by stimulating the growth of virtual Caladium plant–tree. The project intends to create a realistic low-poly model and immersive simulation of caladium's growth in the metaverse, using advanced techniques such as procedural, biophysical modeling and the fundamental study of metaverse.

1.3.2. Objectives

The objective of this current study is to give an overall comprehensive review of bringing behavioral realism to the metaverse with a simple caladium growth stimulation model. As the secondary sub-objectives,

- Conduct a critical literature study on the topics of tree stimulation models in VR, object realism in VR and other related areas along with a brief study on how existing model creations are done with the tools.
- Develop a dataset on Caladium tuber growth for further study.
- Evaluate the proposed approach with qualitative and quantitative methods and finally a computer performance-based evaluation.

- Demonstrate the potential benefits of the project for e-learning, entertainment, and research purposes.

1.4. Scope

The study of this work is within the scope of realistic tree simulation modeling and virtual reality environments aspects especially focusing on Caladium bicolor plant and its attributes. Existing modeling techniques and algorithms will be taken into study. For the extent of proving in metaverse, the scope is also extended up to the related characteristics of a browser-based virtual realistic environments. Assumption, for simulation, and modelling the Caladium tree model, it will be following the actual controlled environment such as sun-light density, water level, wind, humidity level etc. to be equivalent and no factor is to be an outlier.

1.5. Structure of the Thesis

This thesis aims to cover the milestones and the process it had followed up on in the following structure.

Chapter 2, the literature study discusses the existing selected paper studies on the most recent, relevant works on the field of object realism in metaverse and realistic tree stimulation models. Furthermore, it gives a comprehensive overview of the work that has been done and deriving the identified gap to confirm the research question and the objectives.

Chapter 3 covers the flow on the journey of data collection procedure and the implementation of the expected conceptualized design solution followed to attempt on bringing the expected low-cost realistic tree stimulation model work. The methodology of this research adopts the constructive research method. The solution design for Caladium growth stimulation is implemented with the aid of realistic growth pattern data obtained from a Caladium live plant subjects are analyzed and discussed.

In chapter 4, the evaluation of the conceptualized design solution is deeply analyzed. Evaluation techniques being followed for the performance and usability testing is discussed. Finally, the results are discussed based on research questions and its objectives.

Chapter 5 concludes with the summary of the research and a brief pointer on future work is discussed.

CHAPTER 2
LITERATURE REVIEW

Metaverse is a virtual reality escape from the real world, providing ubiquitous computing features and providing the ultimate bridge between the digital world and real world. Realism is one of the important pillars of the virtual reality world. As the factor of realism is already being focused on the area of human visualization, not much active research is done for tree growth stimulation nor plant models on the basis of virtual reality. Therefore, this thesis will contribute to the identified gap and the research question is well constructed based off of this reasonings.

The technological world revolves around new discoveries and research in every field. Even though the selected study follows a novel approach, there are a few related studies found in this particular field. Follows a comprehensive detailed analysis of the research and implementations found and selected based on our selected study.

Focusing on realistic 3D models of virtual environments has been an active research area since recent past. Various fields are trying to push the boundaries in this area for a more realistic entity modeling and real life like experience. The biggest factors of the entertainment fields, both cinema and gaming, actively working in a way to bring out more immersive experience and reality by not just focusing on main model but also in simulating the perfect realistic environment. With that follows a brief literature study on existing work and their key areas.

2.1. Inducing Realism in Current State of Virtual Reality

Virtual reality has become a widely used technology in recent times. Growth in VR and mixed reality fields improves the experience to be near realistic. Going beyond, levels of reality is being defined in multiple ways nowadays bringing a blend of AR and VR characteristics to bridge between digital world and the natural world around you. (“Apple Vision Pro,” n.d.)The 2024 launched, VR HMD Apple’s Vision Pro excels in this technology by reimagining the boundaries of VR HMD by bringing high resolution display, spatial sound engines, user centric-design and more overall immersive AR overlay for object engagement and interactivity. (“Introducing Apple Vision Pro: Apple’s first spatial computer - Apple,” n.d.)

Hence the trend of VR HMD priced lower by year, the usage of VR is being increased in many fields. Such as gaming, agriculture, auto engineering, electrical and electronics and user engagement. (Hilfert and König, 2016) Social interaction platform is an up bringing trends in the world of VR. Virtual reality being an individual experience is not anymore, but more of collective experience interconnecting more people at once. Numerous web based metaverse already exists. The approach of open metaverse applies to

2.1.1. Realistic User Avatars in VR social Interaction Platforms

One of the trendier implementations of VR are chat rooms applications. Mozilla's Hubs application – creates a session based virtual hangout room for all your needs like to host a friendly chat with your close circle, a family re-union or even a funny turn to have your work meetings with all your co-workers. The people or users in this context are represented in a digital animated portrayal of your clone. The importance for better user avatar in virtual realistic environments has been increasing lately. The avatars bring out the feeling of being together in this digital meta-playground. (Kim et al., 2023) Even though early era of virtual reality systems had the user depicting in a simple object representation later on more impactful representations for users was expected.

Avatars in VR environments have become the medium to interact with the environment. Avatar brings out the self-perception depth to the VR world where everyone can engage digitally with one another. (Latoschik et al., 2017) People can not only just interact with each other, but now they can also host parties and virtual events. Most special feature would be the multiplayer gaming, where users can immerse themselves by interacting with each other and engage with environment models, and score some points based on the VR-game design. (Visconti et al., 2023) Avatars plays this huge role in current state of the art in VR world. Being a dynamic character model would be an important part of an Avatar design. Sense of realism comes from the innate features of the character model. Motions, expressions, and feelings need to be represented in the digital avatar model to bring out a fully connected experience. Users tend to feel the reduced psychological distance between the users by interacting with the avatars. This brings a more real feel of presence and increased sense of social presence as well. Embodiment and social presence heavily rely on the degree of immersion that avatars achieve within the realm of virtual realism.(Visconti et al., 2023) Microsoft brought the avatar making feature to its Office 365 products, especially in Microsoft Teams to have a more fun-filled meeting session. ("Avatars for Microsoft Teams," n.d.) Extended customizable options for avatar build and more importantly, eye-tracking and movement tracking for facial expressions were introduced within the feature pack. Even though Teams is not a part of a VR based application, still the implementation of a such intelligence is being added to a simple desktop application is appreciated.

2.1.2. Realism in Virtual Reality Gaming and Realistic Animal Modeling

The VR experience flows ahead on this trend for bringing realism in other areas too. Applications of VR in gaming are a huge area.(Dani, 2019) Current generation HMD based VR devices are shipped with motion tracking controller for ease of access, but highly focused in the area as precise gaming joysticks. PlayStation VR and current generation Meta Quest are a few of the examples for gaming focused HMD devices which also comes with a proprietary peripheral controller for gaming. As the industry of gaming in other devices and consoles, the VR based games and gaming developers also push towards the next generation of realistic graphics and character models in their games. (Bergmann et al., 2017) Being in the virtual reality field, immersion is also a high priority necessity to be focused. Animal Jigsaw on Steam is an upcoming 3D puzzle game that invites players to assemble realistic animal models. Additionally, the game also focuses on immersive story telling with respective backgrounds of said animals in their habitat – realistic natural environment modeling for deeper understanding of the plot and aesthetic value point. ("Animal Jigsaw VR on Steam," n.d.) Following table stated under Chapter 2 Table 1 summarizes the gaming in VR and its features.

Feature of VR Gaming	Description	Example
Realism	Focus on realistic graphics, character models, and natural environments	Animal Jigsaw VR - Players assemble realistic animals in realistic habitats
Immersion	Prioritizes user feeling of being "in" the virtual world	Motion tracking controllers for ease of use

Chapter 2 Table 1: Features of VR Gaming

2.1.3. Object Realism in VR Environments

Lahner et al. with Facebook Reality Labs did a study based on how realistic cloth modeling with accurate fabric wrinkle pattern yielding a high frequency detailed 3D space model in a for a AR/VR experience. (Lähner et al., 2018) Existing methods for realistic cloth modeling often rely on computationally intensive physics-based simulations, which involve many heuristic parameters. Models reconstructed from visual observations tend to lack geometric details. Thus, study proposes high-quality rendering of clothing deformation sequences, including fine wrinkles observed in high-resolution data. This innovative method promises to enhance the realism of virtual clothing, benefiting fields such as animation, virtual reality, and more.

2.2. Applications of Modeling of Trees in Virtual Reality

Bringing a serene environment and adapting the user slowly into the ecosystem would minimize the effects on the user perception. In the study by Batistatou et al, the importance of the color design and their beneficial aspects to the users were deeply analyzed. Behavioral measures, combining psychological measures resolve the beneficial factors of nature on human motor behavior and wellbeing. (Batistatou et al., 2022) Trees play a huge role in natural environment modeling.

2.2.1. Sense of Realism and Avoiding VR Sickness with VR Trees

Trees in virtual reality are an important feature. Plant models bring out the natural feel and instincts to the user when they are using the virtual reality system. A major issue in VR HMD is, the HMD disconnects the outer world experience completely after wearing them. Thus the user gets a confusion in sense of realistic feel because, the actions that they do is in outer word, but their clone in digital world ("Barriers to mass consumer adoption of VR worldwide 2019," n.d.) The lag between sensory inputs of what your brain receives majorly causes this confusion, as a result, nausea, dizziness, profusely sweating and sometimes headaches too. Repeated use of HMD and gradual increase in VR usage session lengths might help overcome this problem. Although one other method suggested to overcome this to give more realistic feel of the environment so that the user can immerse themselves a bit easier and to focus on a fixed object models in a typical VR environment. (Wöbbeking, 2022) One other suggestion was to induce natural colors in the viewport to adjust their perception, especially green colored objects. (Batistatou et al., 2022) Consequently, adding a tree model to the VR model resolves the early level issues in the field of VR sickness or simulator sickness.

2.2.2. Trees for Immersive VR based Learning Environments

Since VR has been commercialized in the recent years, not just only for gaming, VR devices are being used for the educational purposes too. (Hilfert and König, 2016) VR for education brings so much of importance to the plate, considering the immersiveness and the interactive nature brings the knowledge more in an accessible way compared to the traditional methodical approach. The learning environment in VR has become a revolutionized way of teaching-learning approach in recent times. Unity Engine is a powerful real-time virtual reality development platform to create VR experiences. Unity 3D supports all the mainstream vendor specific VR devices and their HMDs like, PlayStation VR, Samsung Gear VR, Meta Quest VR (priorly known as Oculus Rift devices) Unity comes with their own asset marketplace to be used in the developing VR experience, and such use cases do have static tree models which can be straight away added to your current VR project. (Nguyen and Dang, 2017) The variety of vegetation models are huge including typical tree models like coconut tree, generic tree structures with dense branching, seasonal tree models like fall season twig-based tree trunk selections and much more. On the other hand, these models are still a static model asset which doesn't bring the realistic perception for the user over the time. Yet, still accomplishes for an aesthetically adequate natural live looking environment which fulfills the purpose of a simple VR learning environment.

2.2.3. Forest and Tree Generation Libraries and Plugins

There are various plugins and libraries in the market to generate graphical models which can be used in application, game designing and development. These plugins support a quick model generation for their specific needs instead of working on the object model spending time and effort. With that, there are a few libraries offered by several vendors which do object model generation for trees and forestation scenarios. The plugins which are to be discussed in this specific section of the study are within the application of computation graphic modeling, 3D objects for web VR and other VR based usages.

SpeedTree is a feature rich 3D plant modeling tool. This software provides virtual foliage models that are highly customizable for specific needs. They are prominently used in the field of computer graphics, animation, movie industries and game developing as well. Additionally, this specific tool is owned by the parent company of the Unity Engine, and therefore a seamless integration is proven to be used in a Unity based VR environment as well.

Babylon JS is a web-based 3D rendering library with HTML5 and JavaScript. One of the industry's leading game designers, open-source 3D game engine. TREEGEN is an online tree and forest mesh generator for exporting random tree mesh for the use of assets for web-based 3D scene designing. ("TREEGEN.IO - An Online Procedural Mesh Generator for Forests and Trees," n.d.) TREEGEN follows a simple procedural-based approach to create a randomized tree mesh model with Babylon.js mesh modeling features with the user given parameters from leaf count to bark texture. Nevertheless, the option for visualizing growth stimulation modelling is lacking in the feature set.

2.2.4. Realistic Trees in Metaverse

TreeXR by NatureXR ("TreeXR," 2022) is another collaborative project done by the Non-profit organization, Unique Places to Save, brings the natural conservation techniques to a whole another level. Using combinations of technologies like, high-definition photogrammetry, 360-degree video with scanning, they are achieving this realistic tree modelling for VR environment. TreeXR also extends its applications for realistic disaster preparedness and risk perception specific to wildfire scenarios. The user can easily immerse themselves in a scenario like a scorching wildfire environment and what are the impacts on the environment and more importantly the realistic changes that happen with the disaster. (Carey, 2020; "NatureXR," n.d.) This industry standard toolkit also powers the mission and vision of the TreeXR project.

Modeling trees in a virtual realistic environment could be a complex task. Various software tools are available in the modern technology world. Virtual Reality Modeling Language (VRML) provides a means of rendering 3D worlds from mathematical equations or descriptions. VRML used to be a standardized way of creating VR scenes and object modeling computer graphics and web-based modeling. ("The VRML 2.0 sourcebook (2nd ed.)," n.d.) New discoveries in the field of 3D modeling and object modeling, newer updated tools and libraries sooner started to evolve in the field and people started to adopt them to be the new standards. OpenGL became the new age modeling toolkit and natively supported to run 2D 3D graphics on any cross platform. The study by Yao Li and Chen Yu is about a comparison study between modeling and rendering tree objects for VR environments using OpenGL and 3D Max as the test toolkits. For real-time rendering of large, forested scenes, choosing the optimal tree representation method boils down to a balance between speed, ease of use, and visual fidelity. Using 3D Max's Contour Tree method stands out for its blistering speed and tiny model size, where if the lack of realism is tolerable. If photorealism is crucial, SpeedTree reigns supreme, but the intricacies of its plugin system and limited development options make the process a bit tedious. OpenGL offers a model-free approach with equally fast rendering, but the coding burden and lack of realism might be up to a satisfactory level but not fully photorealistic. (Li and Yu, 2010)

2.3. Tree Modeling

Plants have always been the active attraction of human interest. Evolving plant studies have always supported intelligent studies not just from the computer science field but from various other departments.

Evolving plant structures requires a proper study of the specific plant family, the environment, different scales of space and time. Coming up with a one-true model for a tree is a rather tedious process and the uncertainty of the plants needs to be properly analyzed. Experimental based stimulation and model-based studies can be helpful to tackle such instances.

There are many studies that have been conducted in the field of computation geometry and object modeling. These were brought out to be focused in the early 80s and late 90s where many papers seemed to be written on the topic of real-world tree-object modeling with computational graphics to mimic the real-world entities in the digital world. Although virtual reality comes later in the picture, these studies paved the path to the current state of virtual reality systems.

2.3.1. Fractal Trees

The study conducted by Peter E. Oppenheimer on the “Real Time Design and Animation of Fractal Plants and Trees” (Oppenheimer, 1986) is one of the important studies in the field of the computational graphics. The vision of the study was to understand how the logic of nature can be precisely captured in a computer simulation. The essence of real-life natural entities is unpredictable and non-linear. Hence capturing them in a digital sphere is also a challenge. Oppenheimer’s study encapsulates a fundamental study on branching objects with stochastic fractal model to achieve this. If an object’s large-scale sample resembles the earlier smaller scale sample of that natural entity, the object is said to be self-similar. (Oppenheimer, 1986) This became true in the case of modeling a vegetation model. These fractal models are not only being used in tree modeling but also in other fields of computational fields as well. The advantage of a fractal model solution architecture is that a simple kernel structure can provide a complex structure model for a tree model.

2.3.2. The Mighty Maple Study

“Modeling the Mighty Maple” (Bloomenthal, 1985) is one of the prominent researches in the field of Computational Geometry and Object Modeling, done by Jules Bloomenthal of New

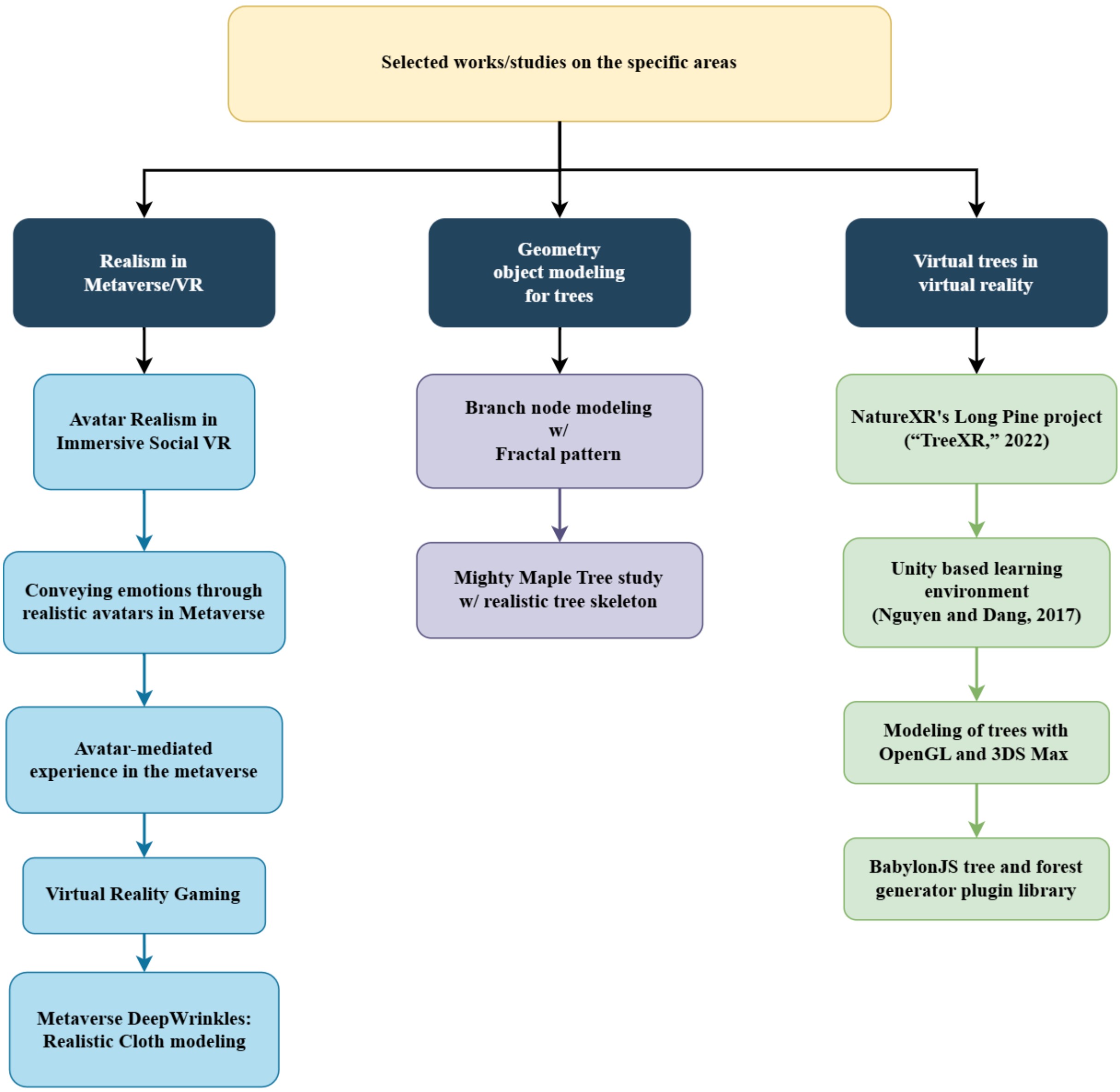
York Institute of Technology. A contemporary to Peter E. Oppenheimer, Jules's study also revolved around the three-dimensional computational graphics and realistic object modeling and simulation. The Mighty Maple study delves around the more realistic tree modeling considering tree ramiform, limb surface, trunk surface, bark visualizations and even a more realistic tree skeleton modeling and visualization of tension physical properties. The separation of concern is a more viable solution since each individual parameter is considered in an isolated manner. Tree features like branch twig angles, leaf angles, branch ramiform shape and trunk's amorphous index. The importance of geometry modeling in trees is discussed later in the dissertation as the ideology of geometry modeling is followed in the proof of concept.

2.3.3. Procedural Trees

There is no one true solution or a formula to represent a tree model or its growth pattern. Depending on numerous factors, the growth pattern changes vastly. Procedural trees are one of the easiest ways to demonstrate or simulate the forecasting of a plant model with parameters and computations. In a typical virtual scene, a procedural tree can be modeled with various input parameters such as age, height of a stem, leaf pattern, texture of the bark etc. to generate a variety of trees, to be placed as realistic placement of trees. TreeSketch is a system for modeling complex trees that look natural yet are creatively designed. The interface is slick and intuitive, with gesture- and sketch-based controls. (Longay et al., n.d.)

Based on the technical feasibility focused on creating such models yield a hyper realistic procedural tree, or even less accurate low poly procedural trees too. Domains like gaming, computer animation computer assisted landscape design are a few of the areas where procedural modeling is involved extensively. To access a said system, the users do not need to have a sound knowledge in the field of computer science or botanical studies. The models can easily be interacted with and modelled by the defined modelers. (Longay et al., n.d.)

The taxonomy in Chapter 1 Figure 1 summarizes the selected works on metaverse, object realism and virtual reality-based tree modeling areas.



Chapter 2 Figure 1: Taxonomy of selected works on object realism, and VR based tree modeling studies

To summarize the detailed literature study, metaverse refers to a collective virtual shared space, of converging multiple digital platforms, where users can interact with computer generated environment and other users. The metaverse's approach in bringing object realism is an actively engaged area. From the accurate depiction of human models to the lifelike representation of animals within their natural habitats, the breadth of realistic object modeling within immersive VR environments is widely recognized and valued. Though there have not been many attempts on exploring realistic tree growth stimulation in this focus area. A tree is one of the vital parts of a realistic natural entity. To bring the essence of realistic feel to a VE should focus more on proper realistic 3D modeling of trees. In recent literature, approaches on modeling realistic trees have been explored regards to various aspects of VR use cases like e-learning, disaster control IVE, etc. Whilst realistic tree modeling, studies have focused on conceptualizing randomized tree generation patterns but only limited focus on bringing realistic stimulation of a plant's growth model according to the related recent literature. This indicates a gap in the knowledge in terms of a realistic tree growth stimulation in VR applications. Therefore, this is the basis for the main research question.

Most conducted studies and applications of modeling in VR use more resource heavy tools and software solutions for this purpose. Regardless of the type or mode of accessing VR environment, gaps on identifying a low-cost alternative for the growth stimulation modeling would be discovered with the sub question (a) and (b). Hence, this research delves in the region of web-based VR environment for a simplified and narrowed approach.

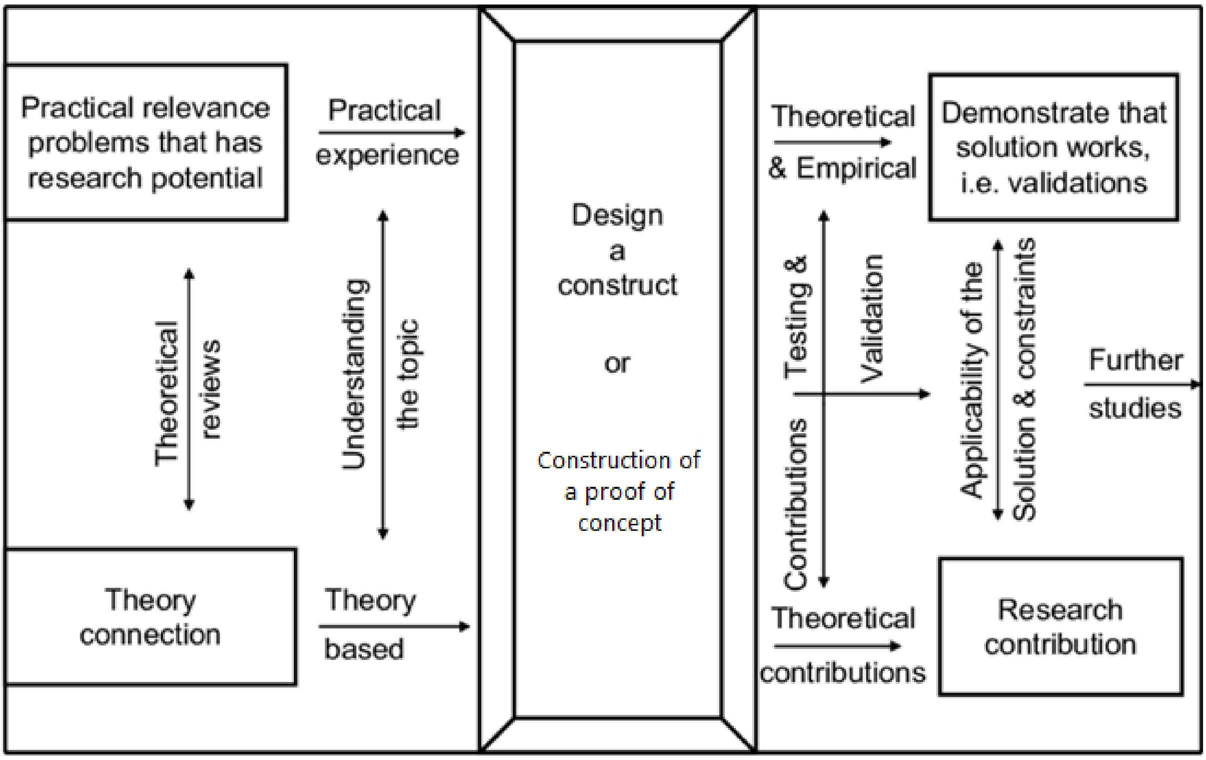
CHAPTER 3

METHODOLOGY

In this chapter, the author explains the methodology followed in order to find the answer for those aforementioned research questions. The descriptive chapter will analyze the process and journey went ahead on finding and implementing a potential proof of concept, find and plan a rudimentary solution architecture, obtaining supporting dataset collection, methods to achieve it and problems faced in data elicitation techniques, technological design and obstacles faced and so on.

3.1. Research Approach and Journey Map

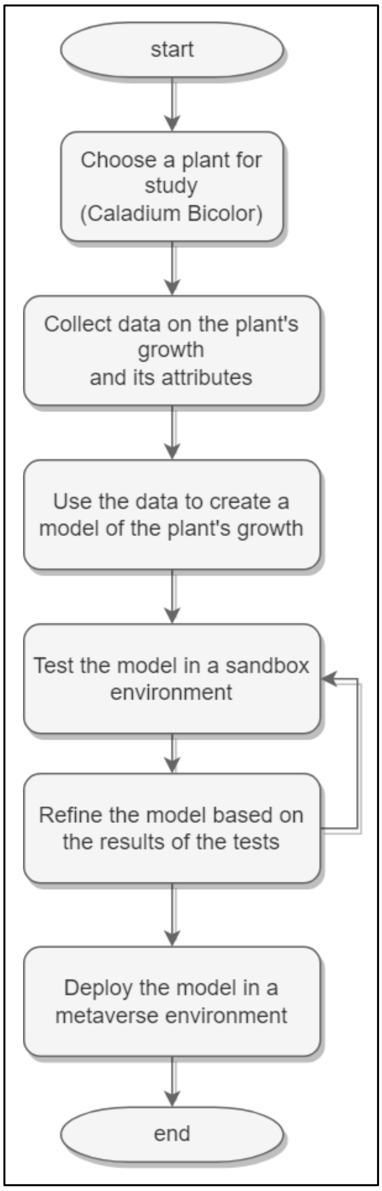
Following figure (Chapter 3 Figure 1) illustrates a brief flow architecture in constructive



Chapter 3 Figure 1: Constructive research approach features (Oyegoke, 2011)

research approach.

One of the common research approaches in the computing research domain is the constructive research method. This approach involves designing, developing, and implementing a novel system within a controlled virtual world and evaluating its effectiveness through data collection and analysis. Therefore, adopting constructive research approach for the methodology of this study was most suitable, since the properties of a typical constructive research approach consists of iterative concept modeling and evaluation, mixed-method validation and most of all, the design oriented solution basis. (Knauss, 2021) Hence, this dissertation employs a constructive research approach to investigate the efficacy of utilizing a web based metaverse environment for stimulating caladium plant growth. Following Figure 2, illustrates the derived approach for this specific research methodology.



Chapter 3 Figure 2: Proposed methodology to find realistic stimulation growth pattern with constructive research method

3.2. Selection of Plant Subject and Setup for Data Collection

3.2.1. Determining the Optimal Plant Subject

Stimulation for plant growth is wide scope. Trees and plants follow different growth patterns, under various levels of stimuli. Considering all those at once would be a huge overhaul. Not all the vegetation follows a similar pattern of growth. Environmental factors like light, temperature, humidity and availability of water are a few of important stimuli to be considered while considering a solution architecture for identifying growth stimulation a plant.

Thus, the research scope was defined to cover only a selection of plant family or a cultivar. Isolated focus towards one single plant is the optimal solution since the research focus was much easier to target towards that specific stimulation and the related stimuli. Additionally, this was the way forward as the tenure for this study was also limited.

Firstly, the selection of plant for this study was the pine tree, also scientifically known variation of "*Pinus Caribaea*" due to its slender looking growth and individual branch with grouped twigs with long leaf structure. Even though it was a perfect candidate for this study, there were several issues identified while the preliminary study was done on the pine tree basis. Primarily, due to the limited time for this specific research, trees like Pine do not reflect a variance of morphology to continue with the study which will probably be applied to this expected graphical study as well. The significance of slower growth stimulation is not a suitable subject for such short-term studies. Moreover, regarding the variances of visual indicators which would be the key area in this study, pine tree's less visual identity in its earlier growth stages is less frequent to be measured. Lastly, even though pine trees are susceptible to grow in Sri Lanka, to grow a sample plant would take an immense effort of care including specified nutrient, soil quality, and most of all, natural environmental factors like temperature, humidity and levels of light. The final part was a considerable factor in this study, since for more rigid evaluation and supporting study subject, a live plant study was necessary to understand and get the realistic, natural growth stimulation with looks and feel, sensory perception.

Consequently, the Caladium plant was selected as the test subject. Caladiums are known for their bright display of colors in the leaves with variant pattern and the variably shaped leaves. Thus, they are commonly sold as ornamental aesthetic plants. Caladiums are made with hybridization of breeding techniques to produce less disease susceptibility and as for the main attraction with the vibrant, uniquely looking leaf structure. (Deng, 2018) So, most cultivar under the Caladium genus share a similar characteristic, except for the unique properties which distinguish different than the other breed in the same genus.

The specific plant taken for the research purpose is closely resembled botched fancy leaves of "White Queen" – Caladium bicolor, also commonly referred as Elephant's ears or Heart of Jesus which is scientifically identified as genus of *Caladium* of family *Araceae*. White Queen is a common variant available in most florists in Sri Lanka. Unlike the pine tree, Caladium has the flexibility to grow in a high humid area, with adequate light level. Caladium cultivars' growth habitats change from variants to variants. Subsequently the White Queen variant follows a terminal dominance growth rate according to the biological studies where under ideal conditions, including warmth, humidity, and appropriate light exposure, tubers can sprout within a swift 1-2 weeks. Even more impressively, full maturity and the iconic white and green leaves can be achieved within a mere 2-3 months from planting. During its active growing season, this fast-growing plant can even produce new leaves at a remarkable rate of 1-2 per week, offering researchers many opportunities to see and measure the effects of various stimulation techniques. However, it is crucial to remember that this rapid growth depends on providing an optimal environment. (Parrish et al., 2023) (Deng, 2018) The tuber growth stimulation is prominent with the specified limited time and unlike the genus of *Pinus* trees the tuber transformation is less complicated too.

Leaf spotting and color blotches in *Caladium* genus is another standing out feature of this plant. As mentioned earlier, each hybrid cultivar is prominently segregated based on the display of the leaf's features and the pattern it contains. The length and width of mature leaves can vary from several centimeters to over 30 cm among cultivars (Deng, 2018) With the age, the leaf's transformation can be noticed in both the color pattern, and the leaf's shape from the initial budding stage to the matured broaden state. In addition, most caladiums have heart-shaped (triangular- or round-ovate) leaves, with three main veins on each leaf arranged in the form of an inverted letter Y. (Deng, 2012)

Therefore, Caladium plants have been selected as the plant study for this specific methodology. The fast-growing nature and clear visual indicators of Caladiums make them ideal subjects for rapid data collection and analysis within the partial controlled environment. As for constructive research validation, (Knauss, 2021) control group of caladium plants grown in a traditional physical environment will be used to establish a baseline for comparison and assess the relative effectiveness of the virtual environment.

3.2.2. Preparation of Subjects for the Study

Chapter 3 Figure 3: Caladium "White Queen" Plant

As mentioned, in the above section, the Caladium – white queen plants were obtained for the live subject study. (Refer Figure 3) To get an initial understanding of the plant's growth stimulation in the initial phase itself, two subjects were prepared to be grown in a partial controlled environment. Each selected plant was at a different growth rate and age as one of them was a little bit over 2 weeks old and the next subject was chosen in a bit of a matured state where already a couple of tubers were already grown. For clarity in the context of this methodology, the two distinct subjects investigated in this study will be designated as Subject A and Subject B, respectively. Each plant subject was obtained in a different time period. So, the data collection process includes both the plants in various timelines, though the collected data reflects the same behavior and timely plant-basis properties. Both plants were grown in a partially shaded area, with adequate space, and constant care of watering and pest controlling. Since the growth was recorded in a household, this practice cannot be considered to be a fully controlled environment, but rather a partially controlled environment. The following Figures 4-6 show the early budding shooter growth with days. Displacing the plant pot is avoided to an extent. Follows the Table 1 of Chapter 3, details the list of regulators for this setup.

Light	Grown under a bright but partially shaded area to avoid full face open to the sun. Caladium can be grown under minimal levels of light intensity.
Temperature	Not regulated as this was complex stimuli to precisely regulate in a non-fully controlled environment. Though, Caladium can perfectly sustain in a warm area like Colombo.
Humidity	Not regulated and sustainable in a warm humid environment.

Water	Adequate water supply was needed. Mostly watered in the rhythm of 2-3 days of interval. Depending on the level of warmth, temperature, and factors like if it rains or not also decided the further watering cadence.
Nutrients	Blue granular fertilizer was used once within the test growth period. This is an all-purpose granular compound fertilizer which is a type of blue fertilizer that contains nitrogen, phosphorus, and potassium in a 12-12-17 ratio, with added magnesium and trace elements. It's a general-purpose fertilizer suitable for various plants and soil types. (Naqqiuddin et al., 2014)

Chapter 3 Table 1: Regulators for selected plant subject

Chapter 3 Figure 6: Caladium – Day 0

Chapter 3 Figure 5: Caladium – Day 5

Chapter 3 Figure 4: Caladium budding tuber shoot

3.3. Monitoring and Data Collection

Accordingly, the plant subjects A and B eventually reach the certain state to be analyzed and ready for data collection phase. Since there are few acknowledged research papers on Caladium growth dataset or growth stimulation is available, this manual data collection helps the process of building the accurate graphical model. Regardless of when the plant subjects were obtained, the monitoring procedures and the data collection process were similar.

The Caladium bulb subjects were monitored from the day it was obtained. Following preparation setup in the flowerpots, the plants were left undisturbed for two or three days to assess the success of their preparation. Once a proper growth pattern is indicated, the data collection phase is begun. Typical data collection phase begins from the leaf budding stage. Unlike other plants the budding in Caladium are tuber shoots which are also dormant growing points. The prominent light green tuber shoots slowly bud from the main bulb stem in a sharp pointier tightly furled manner. This stage is considered to be day 0 in the monitoring phase. The shooters slowly unfurl into traditional caladium leaf shape. This early-stage leaf will consist of specific cultivar characteristics, such as the pattern of blotches, and a bright indicator of veins. These traits do not change over time, yet the shape tends to expand, and the leaf gets its distinctive Caladium genus specific properties. The tuber growth varies between each cultivar. The monitoring phase will continue until day 60 or until 60th reading of the plant during the timespan. The analysis is based on data collected within the first 60 days or first 60 readings, as further data collection was not feasible within the defined scope and timeframe. Subsequent updates and indicators are therefore not included in this iteration. This approach ensures we address pressing issues without overextending our effort and resources.

Chapter 3 Figure 7: Measuring tuber shoot with measuring tape

Chapter 3 Figure 8: Measuring tuber shoot with the standard ruler

3.3.1. Tools Used in Data Collection Processes

During the data recording phase, three essential tools played crucial roles in capturing valuable information: smartphone cameras, measuring tape, and standard measuring rulers.

Smartphone cameras - These ubiquitous devices served as the primary tool for capturing live model data in the form of photographs. Their portability and ease of use allowed for quick and efficient documentation at various points throughout the study. Moreover, these images served as valuable reference points when working on specific parts of the model later on, ensuring accuracy and consistency in the data recording process. Additionally, smartphone cameras provided a convenient way to track progress over time by capturing images at regular intervals, allowing for visual comparisons and analysis of changes in the model.

Measuring tape and standard measuring ruler: These traditional tools played a vital role in quantifying the tuber growth, providing precise and objective measurements. The measuring tape offered flexibility for capturing larger dimensions, while the standard ruler ensured accuracy for smaller, more intricate details. Please refer figure 7 and 8 in the previous section.

Overall, the combination of these three tools – smartphone cameras for capturing visual data and measuring tape/ruler for quantitative measurements – created a comprehensive data recording system, ensuring both qualitative and quantitative information was collected effectively throughout the study. This approach allowed for a holistic understanding of the model's development and provided valuable data for further analysis and interpretation.

3.3.2. Quantitative Data Collection

The plant’s tuber growth height was picked as the primary quantitative measurement record. There are several reasons for choosing the tuber growth property to be identified as a candidate. First, it’s a simple factor to measure. Measuring tuber height is a simple task compared to other tedious measurements like finding the tuber volume, girth etc. With the limited timeline and scope restrictions, measuring tuber height seemed a better candidate overall. Considering from the stimulation point of view, tuber growth is one of the main properties that reflect growth in the selected genus of plants. The vertical expansion and slender increasing height property indicates a reliable resource accumulation for this work. In the evaluation and results chapter, the collection of standardized data is used for robust analysis of the model.

By quantifying tuber growth height alongside the number of tuber shoots, you gain a comprehensive understanding of the caladium's growth dynamics. While the number of shoots indicates potential for new plantlets and future propagation, tuber height provides insight into the overall growth potential and resource availability, making it a valuable metric for the research on modeling caladium growth stimulation.

Moreover, on the technical part of the measurement, the growth is identified from the ground level. Measurement will have a slight adjustment of margin of error in identifying the precise tuber length due to the measuring tool need to be adjusted on the soil level to measure the object. Hence, this margin of error is ignored in further investigation and implementation.

The readings are noted in a Google spreadsheet along with a snapshot of the plant on that specific session. Most recorded days, only the measurement is obtained.

3.3.3. Qualitative Data Collection

Additionally, a qualitative analysis is employed through photographic documentation of the caladium plants. Standardized general plant images captured at specific time points serve as a baseline reference and enable comparison across taken past and future readings. Detailed aerial photographs of leaves and zoomed-in images of tubers facilitate qualitative assessment of potential changes in leaf morphology and tuber texture, respectively, providing further insights alongside the quantitative data retrieved with the detailed plan stated in previous section.

Chapter 3 Figure 9: Detailed top-level picture of a Caladium leaf

Capturing the plant growth from each reading provides a baseline comparison analysis of the stimulation rather than looking through quantitative readings. The subjects are maintained in a fixed state of position, avoiding displacement to ensure a consistent growth formation of snapshots. The top-level detailed snap of leaf offers a closer look at the change of pattern in the leaf, the shape changes, unfurling rate of the leaf and clearer vein patterns. On the other hand, the zoomed pictures of tubers offer the clear view of texture pattern changes over time. While tuber texture analysis was incorporated, its value as a primary measure was limited due to the absence of visually discernible changes in texture patterns or attributes over the observed period. Figures 9-10 shows the detailed top level pictures of the Caladium leaf.

Chapter 3 Figure 10: Detailed top-level pictures of mature Caladium leaf shape and blotch pattern

3.3.4. Data Cleanup and Refinement Steps

Each data point collection was done repeatedly to ensure the obtained data is correct. Measurement is taken in centimeters since the tools which are used for this case are calibrated for either meter or centimeter. Although during the data collection phase, importance was given to correctly measuring the point, decimal millimeter measurements too.

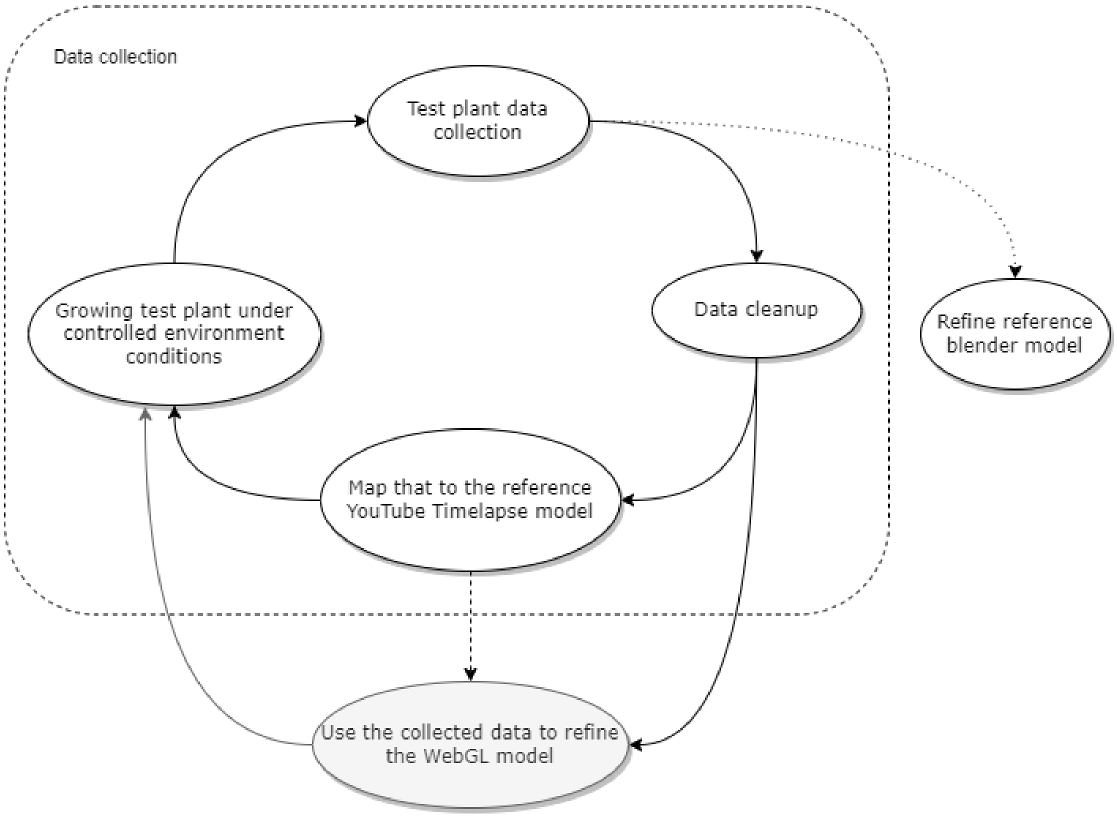
The readings are documented in a Google sheets document. Dataset is reviewed once or twice a week to see if there is an inconsistency with the trend obtained. Chart visualizations are used for a quick analysis on data accuracy and data trend over the time. Moreover, in the cases where a missing data is identified or in a case of identifying an outlier, Google sheet's autofill is used to fill the missing value with the series of previously obtained data, as the data imputing method. The deviation is comparatively low, and it did not affect the trend of the growth model dataset. (Hellerstein, 2008)

The qualitative data – snapshot collection of the plant's growth model, tuber and leaf's texture stimulations are labeled by date and stored under the Google Photos cloud application. If the captured photo seemed to be blurred, or shaken, carefully reviewed to obtain a clearer picture.

In summary, obtaining precise growth data in a plant environment is a tricky area. A margin of error may occur in the data gathering phase in such domain, and necessary actions and precautions were taken as much as to attain a less-noisy data collection.

3.3.5. Caladium Growth Timelapse Videos

Although the data collection will be done extensively, there was a need for pre-study on the Caladium growth model was needed to get an idea before starting the next phase – the design implementation of the model. Therefore, a couple of timelapse videos on Caladium genus plant growth were used as a reference to get a pre-study understanding of the expected growth stimulation. These resources were found on the social video sharing platform, YouTube. The channel which uploaded the videos was reviewed briefly to validate the content accuracy of the specific videos which were chosen for the pre-study. To conclude on the data collection and refining section, the below figure 11 states the diagram of the process which was followed in the research.



Chapter 3 Figure 11: Diagram of process of data collection and model definition process

3.4. Plant Simulation Modeling

3.4.1. Polygon Mesh Study and Reference Model in Blender

Since the proof of concept will focus on to more low-cost visualization with the graphical model, low polygon modeling was preferred for the solution design. Low-poly designs are pretty common in contemporary designing, arts, video game designing and animations. A model is determined whether a high-poly or a low-poly is based on how many polygons were being used to create a specified graphical model. The more the polygon mesh, the more realistic and life-like. Fewer the counting, less detailing in the end product.

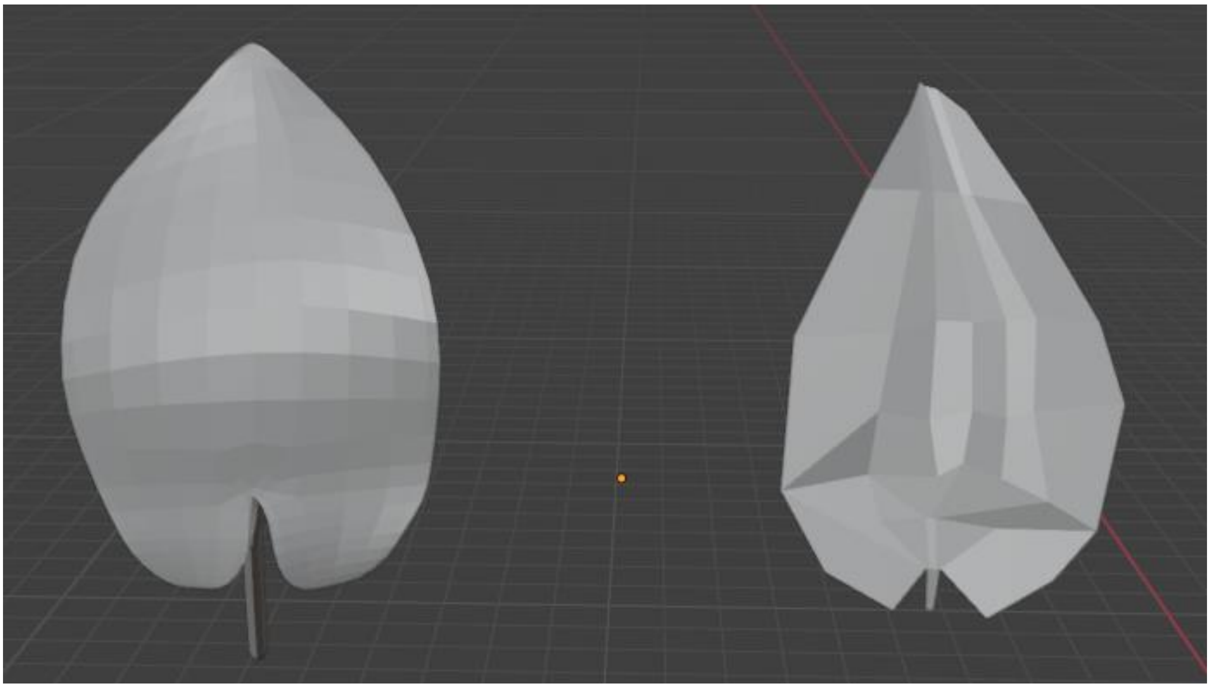
Though low poly designs are considered to be less detailed, still the market for using low poly designs is more prominent in most fields. In game design, low poly designs are an important part of the game environment level designing, since environmental features are a big part of the area which boosts the storyline and background to the characters. (Amarasinghe and Parberry, 2011) While designing environmental models, developers need to only develop or design the models in high poly mesh which are mostly interactable by the player or the things which are near to his viewable area to bring the realistic looks. (Kang et al., 2006) Otherwise, the distant objects and environmental features are always modeled in the low poly way to minimize the resource load, and the purposeless effort.

The aesthetic which is conveyed from the low poly designs is a trendy design style in most areas. Low poly modeling creates a distinct visual language with an interesting design thinking. Typical usages of geometric shapes like triangles, squares, and circles add a unique appeal to the viewers which eventually generates a series of patterns and textures to the overall design.

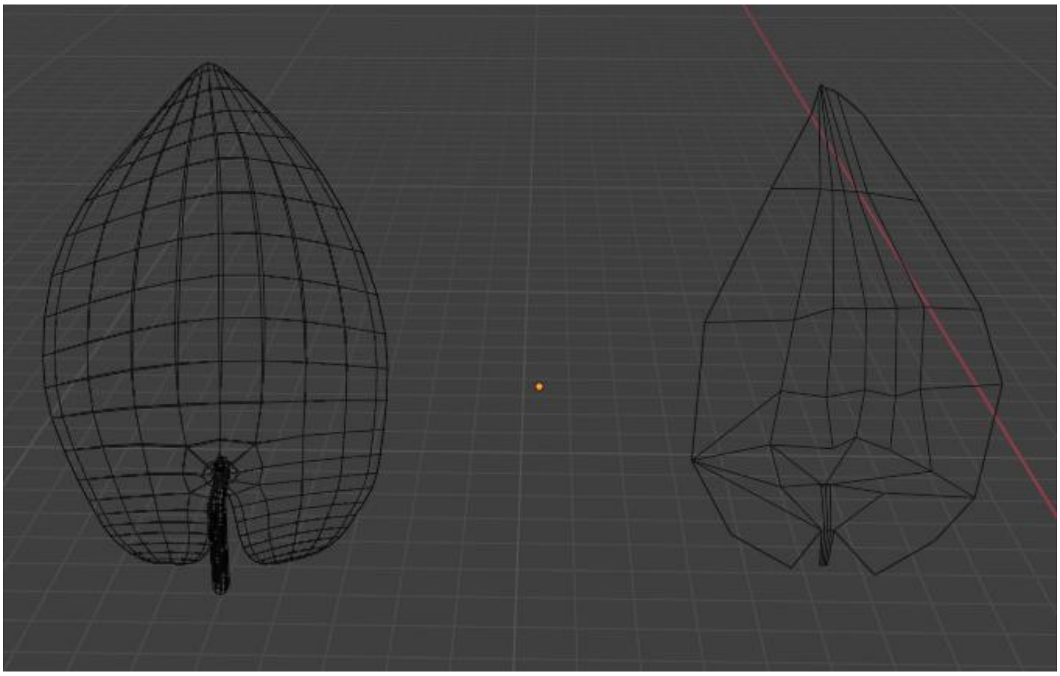
Consequently, technical efficiency is a noteworthy key pointer of low poly designing, since the fewer number of mesh generation is not a high computational factor. It requires less processing power compared to generating a similar design in a high poly mode. (Harrington et al., 2022) Hence, the render time is quicker, and saves time and computation resources too. That makes low poly design the most suitable technique for real time 3D applications like games and simulations.

Blender is a free 3D creation software which is a powerful tool for modeling detailed object modeling. Blender is one of the most widely used 3D creation tools amongst designers and animators for its ease of use, less complicated flow, and intuitive User Interface (UI) for people to get used to this very easily. With the gathered data from the plant studies A and B, along with the YouTube reference thumbnails, an initial pilot study was done to get an understanding on how low poly design can be used for the realistic plant visual modeling, and how does Caladium plant modeling can be abided to the ways of low-poly mesh design language.

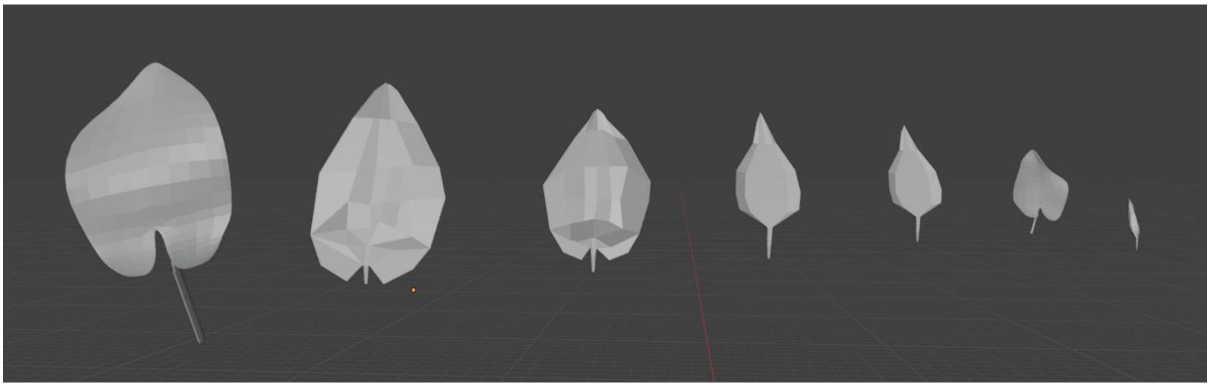
Therefore, Blender was used to create a series of growth stages of pattern of White Queen Caladium, in a low poly, less-complex modeling to get an initial exploratory design study on the outcome of the expected proof of concept experiment. Illustrations covered the milestones of visual indicators of the plant's leaf that changes over time. Since the pilot study was only to get an understanding of low poly mesh models, the illustrations covered the leaf's asymmetric proportional margin, the depth of the leaf or the shape and the base where stems are connected to the leaf. The following Figures 12-15, shows the created blender model and the detailing of the expected low poly model of Caladium plant.



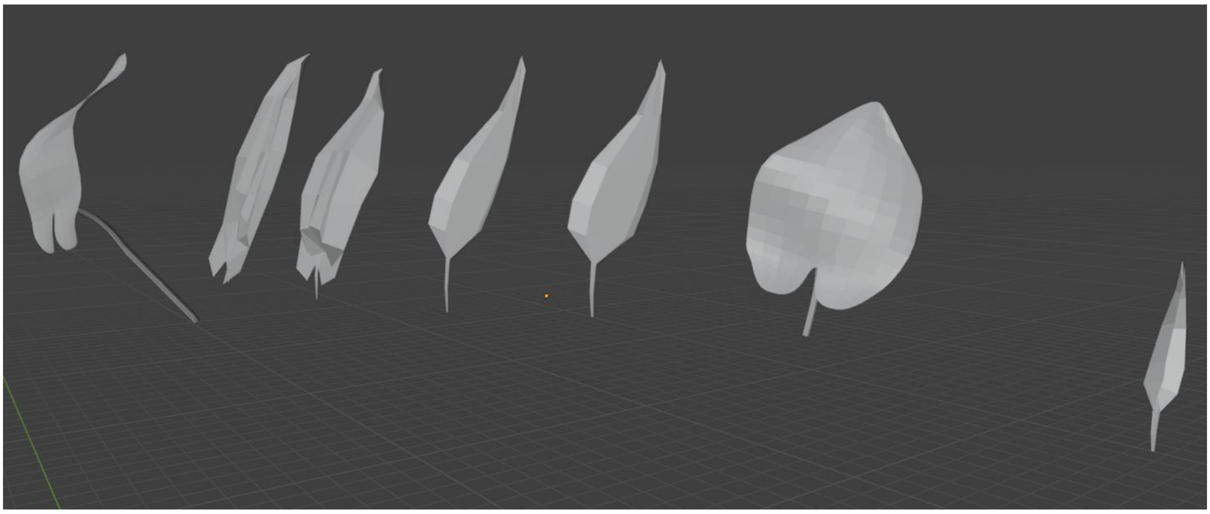
Chapter 3 Figure 12: High-poly reference model vs Low-poly Blender reference model in solid view



Chapter 3 Figure 13: High-poly reference model vs Low-poly Blender reference model in wireframe view



Chapter 3 Figure 14: Growth series modeling in Blender



Chapter 3 Figure 15: Side view of growth series' models

Mesh modeling is the tool which is primarily used to create the base model. Primitive plane mesh is added to the canvas and using the subdivide option to add more vertices to the plane for smoother sculpting. By splicing and translating the vertices to the required space of position in the canvas, low poly material rendering was added to make it low-poly style. Fine tuning by rotating and adjusting the vertices brings the Caladium distinct triangular-ovate shape.

As a result, a series of fine-tuned mesh models of growth stages of Caladium plant was created in the Blender tool. The low poly style addition was successful and did not lack any actual feature representation or far too skewed to the realistic look. Therefore, the blender model was used as a reference model for the further implementation of the proof of concept.

3.4.2. Technical Feasibility Study on Trending Tools

According to the studies detailed in the literature review, for tree modeling in virtual realistic environments, a few researchers have preferred the widely used computer graphical modeling software tools - 3D rendering software which supports high fidelity object modeling and realistic simulations based on hyper realistic physics engine that is built into the core of the tool. Recent advancements in modeling tools have seen a significant rise in features that enhance the creation process. This includes the ability to generate highly realistic 3D models, establish interactive workflows, and simulate realistic physics behaviors. Leveraging hardware acceleration through Graphics Processing Units (GPUs), the software utilizes the device's computational resources for efficient model creation, rendering, and real-time property-based simulations. Accordingly, taking into consideration the recent works in this area, most researchers have preferred widely used modeling tools like Unity 3D, Blender, and SpeedTree Library. Each of these tools have their own unique strengths and weakness over the other tools or even similar to them in most cases.

Unity 3D, also commonly known as Unity, is one of the powerful 3D game engine tools. (Evgeniya, 2016) This is primarily used for game development and for 2D and 3D interactive modeling as well. This real-time engine has powerful toolsets to create realistic immersive object modeling which can be interacted with and adhered to real-life physics. VR and AR experiences are another branch of feature set of Unity engine. Unity is a well-known virtual realistic environment building software out there. Experimental learning and training simulators can be built by Unity platform.

The VR based learning educational environment research done by Nguyen and Dang (Nguyen and Dang, 2017) uses a Unity based environment modeling. The objects and assets used in those environments were obtained from the Unity assets store. The Unity assets store holds a vast collection of 2D, 3D environments and models which are ready to be used in an instant with the click of a button. An initial feasibility study was done in Unity to select this tool for modeling the growth stimulation proof of concept.

A pilot study with Unity's stock 3D GameObject asset, Tree object is used. Simple fundamental stimulation by changing the parameters branch, trunk, growth angle and growth scales and simulated to the needs for showing the growth stimulation. Additionally, the options to additional shaders and additional meshes usage were available too. Though the rudimentary study yields a reasonable POC (Proof of Concept) still porting directly to a web-based VR environment is not straightforward. The online community based alternate suggestion for this case, was to use the 3D rendering web based graphical libraries like BabylonJS and Three.js to port the modeled game scene or the simulation assets to be rendered in a web-based environment. In contrast, this method might not yield the same level of details and advanced features offered by the Unity 3D output.

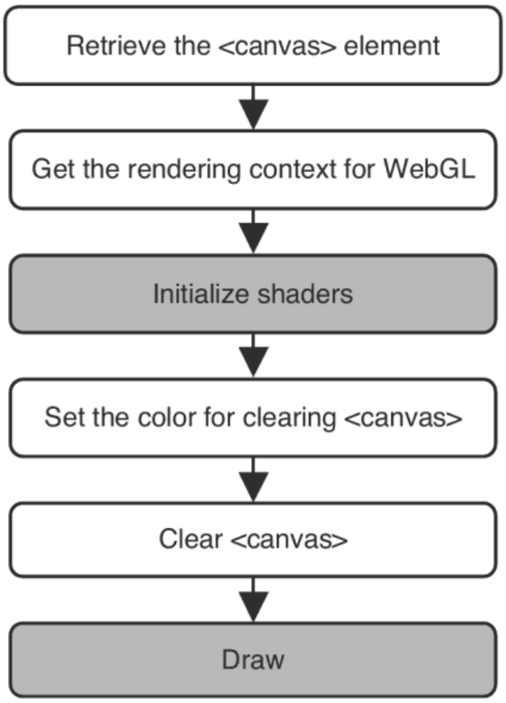
While Blender, another powerful 3D animation and modeling software, offers realistic simulations using a precise real-world physics engine, similar to Unity simulations, it does not directly support porting them to web environments. As with Unity simulations, a preferred alternative involves exporting Blender-created models to web-based JavaScript rendering engines to create simulations.

SpeedTree is a realistic procedural based vegetation modeling tool. Following the generic modeling software tools, SpeedTree also provides assets library, generation editor and model view designing for realistic foliage models. Additionally, SpeedTree exported models can be directly used in a Unity based environment as well. The generation editor is SpeedTree provides a highly customizable tree generation modeling, procedurally changing the isolated structure of each tree components. While SpeedTree excels in creating near photorealistic models, its intricate detail may be unnecessary and even counterproductive for simpler, cost-effective stimulation modeling projects. (Bai and Huang, 2010; Xiong and Huang, 2010)

3.4.3. 3D in Web - with WebGL

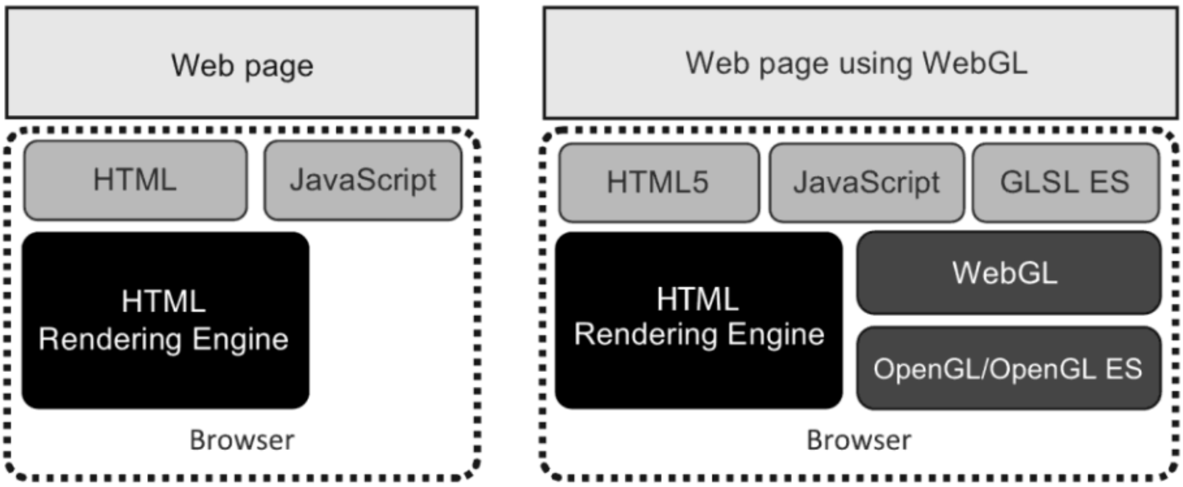
WebGL is hardware accelerated standard for 3D scene creation inside browser window. It uses the native browser JavaScript API for real-time 3D graphics without the use of any 3rd party plugins nor libraries. (Parisi, 2012) Made on the fundamentals of the OpenGL ES, the browser community made the push towards the innovation to the WebGL, for bringing browser-based 3D graphical rendering technology along with utilizing the device's GPU capabilities. (Angel and Shreiner, 2014) From being able to run a simple animation to play browser-based 3D games without any recompilation across platforms, WebGL has a lot to offer in the modern browser culture.

VRML and X3D are prominent predecessors of WebGL for modeling 3D assets for virtual objects. HTML5's initiation opened new possibilities for visualizing 3D objects with the built-in WebGL integration, native JS support for handling the Canvas features and OpenGL shader features. (Matsuda and Lea, 2013)



Chapter 3 Figure 16:WebGL drawing on canvas rendering steps. (Matsuda and Lea, 2013)

While JavaScript handles application logic and interacts with the HTML5 canvas element for rendering, the actual WebGL code is downloaded from a server (local or remote) and compiled by the browser's JavaScript engine for execution on the user's system, utilizing both CPU and GPU resources for optimal performance. Thus, WebGL is platform independent and can be loaded from any server. (Angel and Shreiner, 2014) Following Figure 17 explains this process in a simple diagram.



Chapter 3 Figure 17: Traditional web pages vs. WebGL based web pages rendering. (Matsuda and Lea, 2013)

WebGL is a well-known technology for web based simulations. (Rego and Koes, 2015) With the additions of 3D rendering packages like Three.js and Babylon.js, the process of modeling such intricate objects have become an effortless task. Consequently, a pilot study for the growth stimulation was done in the WebGL APIs. Publicly available open-source, generic plant models made with WebGL were used to simulate a simple environment scene. An initial rudimentary study was able to achieve by changing the parameters with JavaScript. The potential for building a design solution for this thesis was identified.

Furthermore, the WebGL low poly has got drastic performance upgrade compared to using the Unity or Blender 3D engines. (Hamid et al., 2021) This is the ultimate key-pointer in the decision-making process since the focus of the POC also revolves around building a low-cost nature model suggestion for a web friendly environment.

3.4.4. Design Assumptions

The realistic nature of building this model is to mimic the realistic growth stimulation of the plant. The design architecture focuses on an isolated tuber growth modeling since growth modeling shares the same behavior in branched twigs and tuber shoots. External weather, wind and related stimuli related changes are not considered in the methodology as it needs further effort. The solution design might go through changes in aesthetic feels to overcome the performance-based vulnerabilities, if there needs to be arisen at any point.

In conclusion, this research focuses to bring a realistic growth stimulation model of an actual plant study which can be further associated with immersive web based virtual environments. Hence, hyper-realistic feature modeling and environment realism are less focused in the research.

3.5. Implementing the Solution Design for Proof of Concept

Going forward with WebGL as the technical foundation for building the proof of concept, the next phase is focused on the implementation of the proof-of-concept solution design.

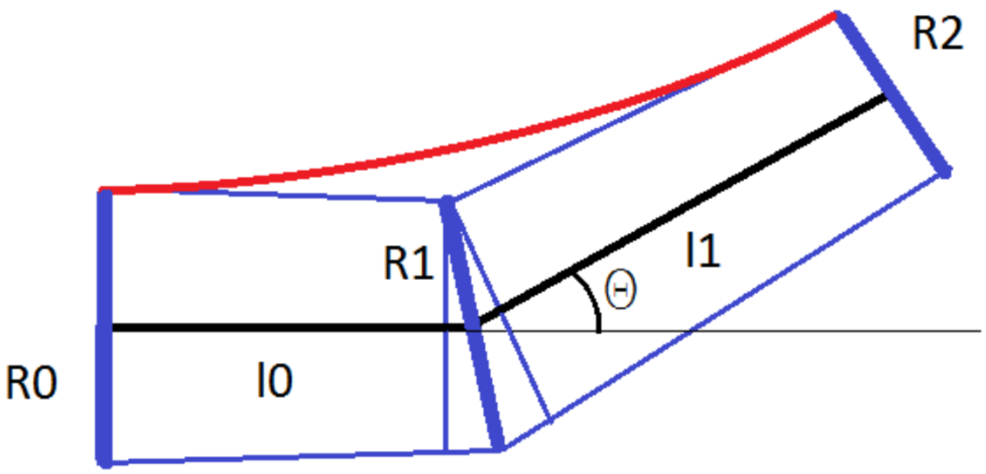
3.5.1. Accumulated Existing Model and Brief of the Study

Though they lack realistic growth stimulation, this study's proof of concept will evaluate the effectiveness of the approach. Building a model from scratch could be a risk that needs to be addressed before starting the work. L-System based procedural tree generation are widely used in tree and forest generation libraries. (Longay et al., n.d.; Meˇch et al., n.d.) Hence, a preliminary search for the existing model was done. Consequently, an existing working model of maple tree growth stimulation was found. ("Modeling the Mighty Maple for Web," n.d.) This model is built with WebGL and follows the study of procedural based tree growth simulation. This was authored by Evgeny Demidov and found on an online digital library and archive forum - ibiblio.org. ("The Public's Library and Digital Archive," 2024) The resources it hosts are open sourced, free to obtain and extended for their own usage for research and product development. In the interest of brevity, we will adopt the designation "MT" (shortened acronym form for maple tree) to represent the found maple growth stimulation model throughout this section. Moreover, investigating the model thoroughly, MT follows the proposed study of Jules Bloomenthal's work – "Modeling the Mighty Maple" (Bloomenthal, 1985) Bezier splines polynomial and Bezier cylinders are primarily used to generate the isolated components of the tree structure.

3.5.2. Adopting the Model

As mentioned in the previous section, the found model is conceptualized based on the original idea proposed by Jules Bloomenthal's work on his paper study "The Mighty Maple" (Bloomenthal, 1985; "Modeling the Mighty Maple for Web," n.d.) which deeply involves the technical aspect of the usage of Bezier cylinders and the spline modeling.

In the realm of virtual environment creation, the utilization of Bezier cylinders, specifically constructed as tensor product patches combining circular cross-sections with quadratic Bezier splines, represents a fundamental technique for crafting intricately detailed structures such as twigs and tuber shoots. (Fernández-Jambrina, 2007) These Bezier cylinders are meticulously designed to emulate the natural curvature and form of organic elements, lending a lifelike quality to virtual foliage and other botanical elements within the VE. As linear Bezier splines is based off two different controlled fixed linear interpolation points, on the other hand, the extended de Casteljau proposes the quadratic spline modeling to evaluates Bezier curves at any point in a repeated linear interpolation scale. ("De Casteljau's algorithm," 2023) With that, the cubic Bezier spline is derived and influences four different control points in a series, which offers a practical advantage to model smooth curvature-based modeling in a given object. This is achieved by translating and adjusting the tangent of the mentioned control pointers. Figure 18 gives the brief technical aspect of creating the spline modeling. Therefore, the said technical aspects ensure the creation of smooth and natural contours and shapes to mimic the realistic features of a typical plant model. The twig skeleton modeling follows a similar approach here to get the realistic angular shape features of a natural tree. Continuous patching and the addition Bezier semi-cylindrical structure then afterwards brings the smoother ramiform of continuous twig formation. (Zakharov and Zakharova, 2020)



Chapter 3 Figure 18: Tensor products of control circle and quadratic Bezier Spline to form curved Bezier spline

The expected model of the proof of concept for Caladium modeling extends the fundamental approach said here to mimic a similar growth perception identifying the twig formation to be used for the basis of natural tuber shoot characteristics along with minor substitution and in some cases a remodeling is anticipated. ("An Interactive Introduction to Splines," n.d.)

3.5.3. Use of Obtained Caladium Growth Dataset and Control Application Changes

Collected dataset from the actual plant growth was used as the basis for the incremental procedural growth parameter. The existing MT model has a fixed number of uniform incremental steppers from 1-9 as the age parameter to obtain the stages of the plant and visualize based on the selected age in the control application.

The obtained collection of datasets is fed to the model using a JSON file. In this JSON file, there is a single object that holds one property: height. The height property is an array of float numbers being the collected measurement of the height of the Caladium shooter tuber. For the convenience of the ascending growth model visualization, the height array values have to be added in an ascending increasing way which suggests that they represent progression and a sequence of measurements taken at various times. Consequently, now in the model, age varies depending on the number of values given to the height array and to obtain the specified height value of a particular age, index of age value is used to access the height array.

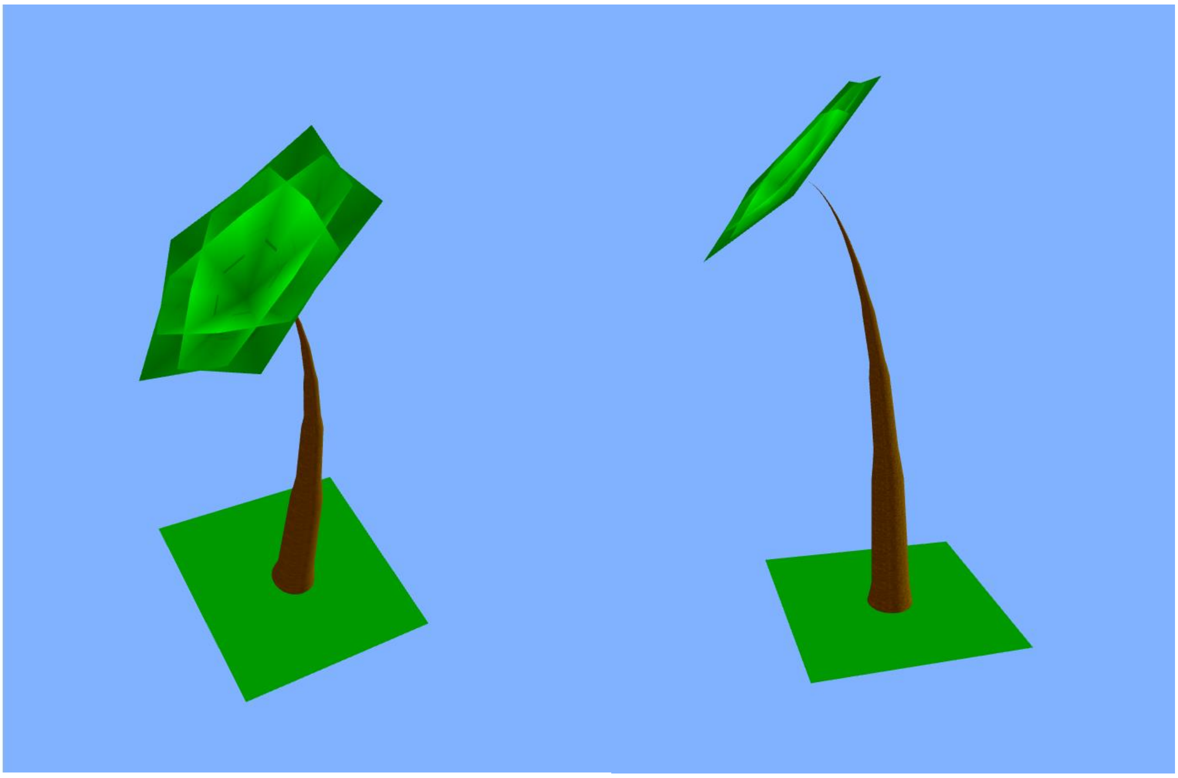
```
     If height = [1,2,2.5,3,4,5];
The age is mapped around the length of the array.
     console.log(age); // 3
     console.log(height[age-1]); // 2.5
```

The controlled application which is used to manipulate and simulate the procedural parameters, is changed respective to the aforementioned use case to indicate the age parameter to be dynamic, based on the given number of inputs. To avoid any asynchronous issues for missing out the initialization of age parameters to the model, JavaScript's async-await synchronous behavior is attached. Hence the Web GUI waits until the data feed phase is completed.

3.5.4. Modeling of the Tuber Growth Stimulation

The maple tree follows the generic tree structure with a base, trunk, branches with twigs. In the case of Caladium, the plant simply has shooter tubers and leaves. Extending the MT model was a bit challenging since the conversion from the higher model structure to get to a lower-end model structured stimulation where the plant has a tuber shoot growth instead of twig-based pattern. The approach followed for the tuber growth is proceeded in the model was to equate the growth pattern of the twig model to the tuber growth model. Therefore, in the retrieved maple tree model's twig model is substituted to simulate the properties of Caladium's growth perception. This research focuses on an individual tuber growth pattern, even though the actual plant growth model consists of branching. The constants which are being used in the segment are added to mimic the nature of Caladium tuber and its growth perception. Unless specifically mentioned, consider the twig as the Caladium's tuber shoot in this section.

Twig shape is further controlled by parameters like lengths, bending and rotation angles, influencing aspects like taper, curvature, and twisting relative to previous segments.

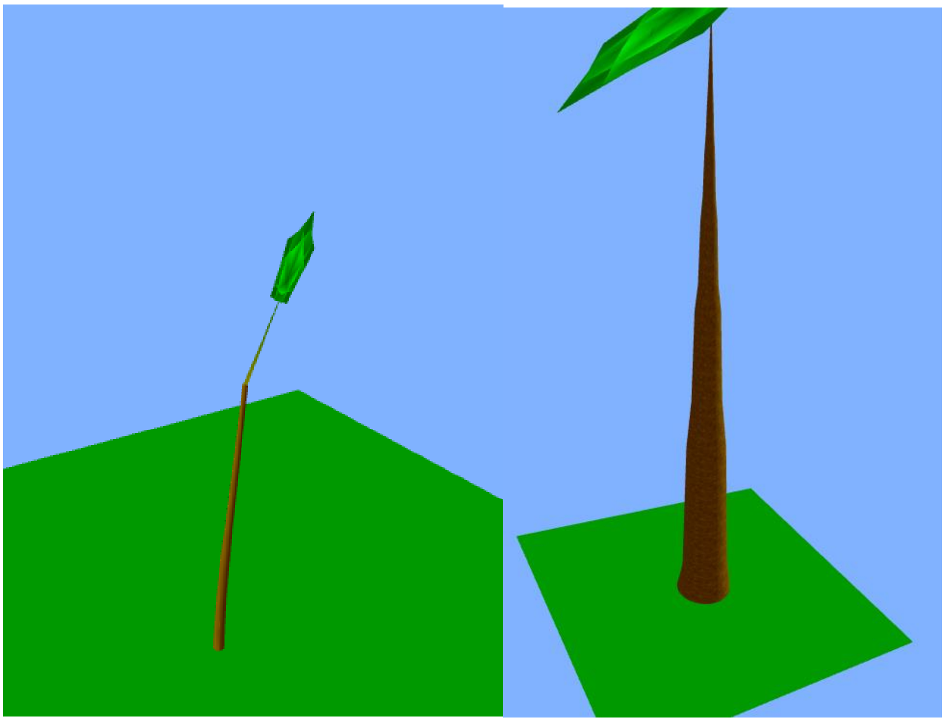


Chapter 3 Figure 19: Tuber shoot growth model

The written twig function generates a 3D WebGL model of a twig using a combination of Bezier splines and cylindrical coordinates. (Zakharov and Zakharova, 2020) Here is a breakdown of the function model.

The function uses a quadratic Bezier spline to interpolate between three points: the base of the twig, the middle of the twig, and the tip of the twig. The Bezier spline is defined by the parameters B0, B1, and B2, which are calculated based on the variable t, representing the position along the length of the twig ("Composite Bézier curve," 2024). For the cylindrical coordinates, Math.pi function along with sine and cosine of the angle around the cylinder were used. The radius of the twig's cylindrical shape along the base middle and tips are also represented within the function to get that uniform shape of a Caladium tuber shoot.

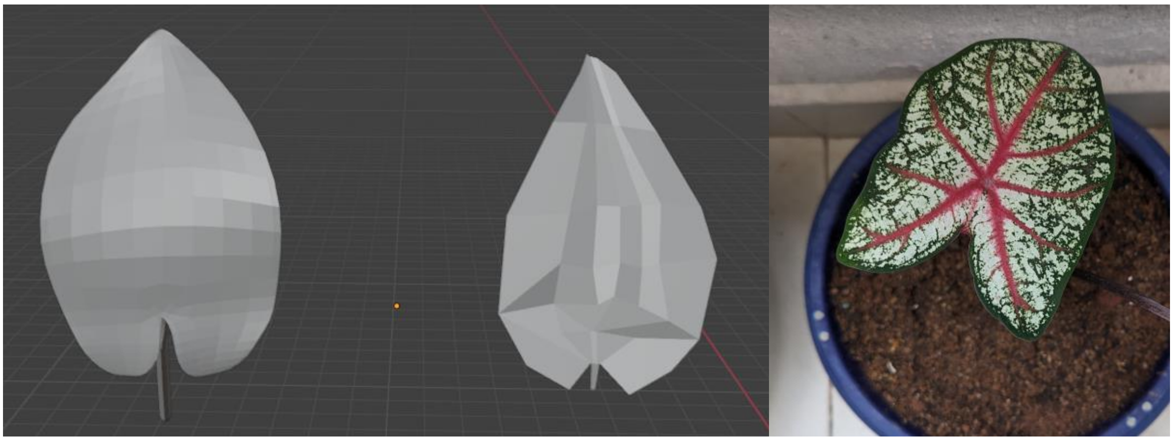
The model changes the growth perception based on the height array of inputs given through the JSON file and the respective age slider in the GUI control. Following, in figure 20 the disparity between early-stage tuber model and matured tuber model is shown.



Chapter 3 Figure 20: Side by side visualization of early-stage growth and matured tuber growth

3.5.5. Modeling of the Leaf Shape and Leaf Pattern Stimulation

The behavior of the leaf's anatomy is one of the key factors in graphical simulations. The morphology of the leaf is an important part of a tree growth simulation and factors like shape of the leaf, color, blotches and spots, surface texture and tropism are some of the key factors that need to be prioritized. The model MT for a generic maple tree follows a flat 3D based model leaf with generic vein. Though for Caladium, the shape of the leaf and the visual identifier patterns are the unique properties of the genus of the plant. To ease the flow, as stated in Figure 21, aforementioned blender based low-poly model and relative real life subject snapshots are taken as a reference object, regardless of feasibility to resolve this with the expected model.



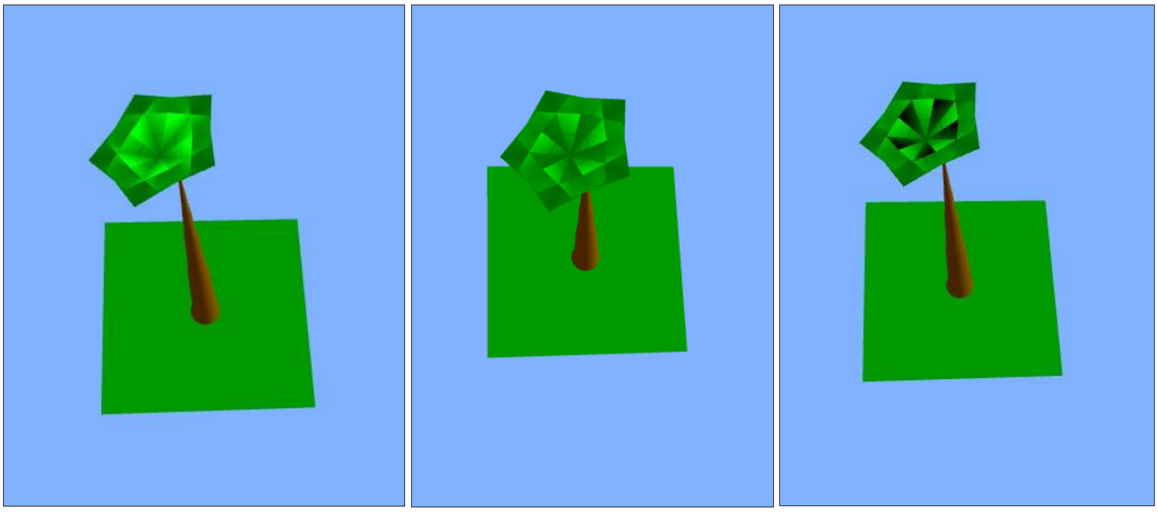
Chapter 3 Figure 21: Reference models: Blender based high-poly, low-poly rendering and top-level detailed Caladium snapshot

Separation of concern is a good implementation model. Fewer coupling between the dependencies brings a simpler, maintainable codebase. With that, the method for leaf stimulation is segregated as positioning and another one for leaf model designing and stimulation properties.

The positioning method takes the parameters of the base point for the leaf/leaves group and the stem model radius. The base point is shown by a Float32 Array, a transformation matrix, set of vertices for the 3D leaf model. After that, the created vertices array is passed to the leaf creation model method. The age parameter passed down from the GUI control is also passed along from the base method.

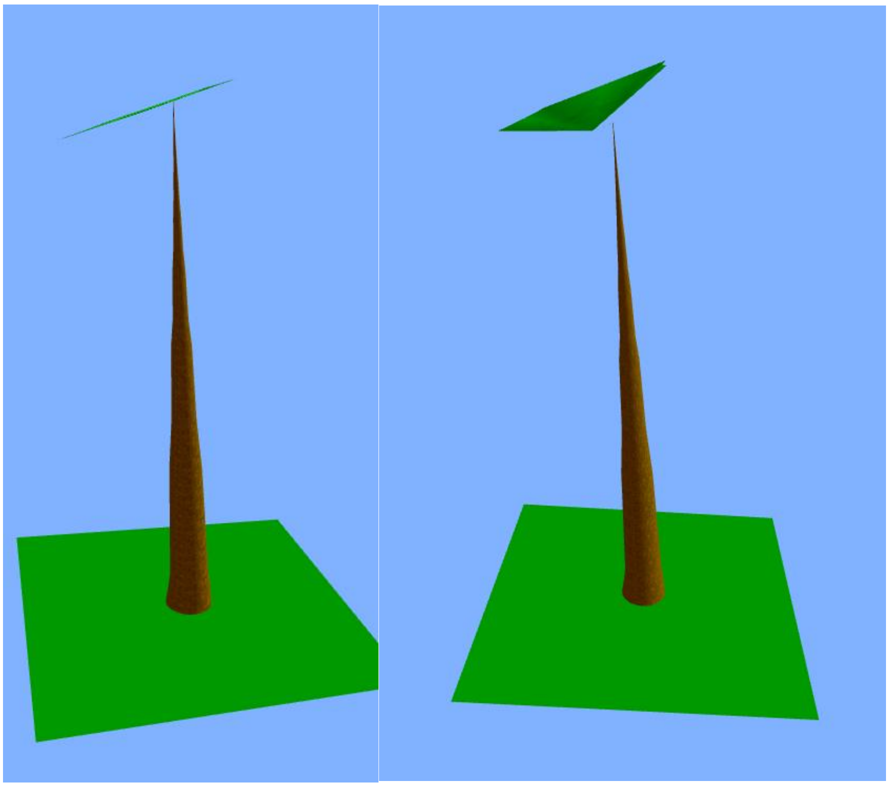
The leaf modeling method takes the parameters leafPropertiesArray, leafRadius, leafLength, leafYCoordinate, leafAngle, and the age of the plant from its parent to identify the supporting base model of the leaf structure. For the ease of creating the Caladium leaf model, a five-faced generic leaf model is created and then used the angular sine and cosine values along with Math.pi method to twist from the inward base anchor point to make the shape a bit elongated and sparse.

The leaf pattern is an important characteristic of a Caladium genus plant. Each cultivar of Caladium uniquely distinguishes by their prominent leaf pattern and the vein of the leaf. With that the attempt to bring those features to the simulation had its fair share of complications and success. Leaf blotching enlarges with the age of the plant. The simulated leaf in this model tries to attain an equivalent properties of blotch pattern using changing each face's partial pointer vertices to lighter shade of green, making the final model with natural blotch pattern of a caladium leaf. In figure 22 the tried approaches of blotch pattern are stated.



Chapter 3 Figure 22: Different botch pattern highlighting with shaders

Furthermore, the Caladium leaves contain a visually distinguished, depth pattern in their round-ovate shaped leaf. To attain the said behavior in the model, repeated sandbox simulation testing was used to identify the correct range of values. With that, 3.75 is an optimal base nominal value found for the depth effect and the age value is involved to extend the model with the time series. (Fig 24)



Chapter 3 Figure 23: From 2D looking leaf model to ovate depth leaf model definition.

Tropism is a noteworthy feature of a generic leaf and with the Caladium, this is uniquely exceptional. With the qualitative photographic data gathered from the first data collection process, the tropism of the leaf is clearly visible from the day 0. To mimic this characteristic, tropism angle calculation function is used. This method takes in the Caladium's height at the point in procedural step. With the data, a mere constant value of 11cm is when the unfurled leaf started to bend outwards to receive more sunlight and act like an antenna. Hence, the process called the tropism, more precisely, "phototropism" in this scenario. (Liscum et al., 2014)

The pseudocode for the respective method is as follows.

```
Function calculateAngle takes in parameter heightValue

  If heightValue is less than or equal to 11
    Calculate and return the maximum of 0 and (1.5 -
(heightValue - 5) * 0.15)
  Else If heightValue is greater than 11
    Calculate and return the maximum of -1.5 and (-0.15 -
(heightValue - 11) * 0.15)
  Else
    Return 1.5
  End If

End Function
```

The identification of the range -1.5 to 1.5 is through repeated sandbox simulation testing and the provided range brings the more realistic leaf bend of naturalistic tropism features of a Caladium. Hence, based off the height change of a selected tuber with leaf model, the linear reduction of the value is calculated by the given number of height inputs in the simulation model.

The leaf shape and the vein design are not hyper-realistic and precisely modeled within the given period. Though the overall model designing is passable as delineated in the design assumptions, the equations and methodologies introduced in this proof of concept possess inherent limitations and are solely applicable within the simulation environment conditions outlined in the study. A detailed pseudocode model of the leaf stimulation and growth modeling is appended in Appendix A for further reference.

3.5.6. Modeling of Textures in Tuber

Textures bring realism to the object's depth and their actual surface type. In the field of foliage, barks differ from trees to trees. Some are plain and shallow, and some textures consist of rugged and brittle structure. Caladium has a fairly rough textured, soft, and squishy tubers which also has this vibrant texture of color. Therefore, a texture generation method is used for this purpose.

The proposed function to be created uses noise generation to create a procedural bark texture. The texture is stored in a Float32Array and can be used in a 3D graphics context to texture a tree model. The Diamond-Square algorithm is often used in terrain generation for video games and other 3D graphics. (Wang et al., 2010) Natural patterns of a trees can be simulated perfectly with this method. A heightmap is created with the given constant of k=512 determining as the size of texture is transformed in to a Float32Array. The identified step counter is looped within the height map context, calculates a new value for the new surroundings. This is the form of noise generation this method creates for an indeterministic texture generation. The absolute value of the noise data is taken, and then a sine wave is added to it. This sine wave creates the vertical striations typical in bark textures. The final texture is a grayscale image, where each pixel's color is determined by the corresponding element in the *img* array which is a raw binary data consisting of an array holding the RGBA values for a $k * k$ image, where every four elements represent the RGBA values of a pixel.

3.5.7. Tools Used in the Implementation Phase

The choice of integrated development environment (IDE) is Visual Studio Code (VS Code). Local server testing is hosted through an integrated extension of the IDE – Live preview. As for version controlling and code maintenance, Git and to keep a copy in remote, GitHub is used as the remote repository handler. Finally for the purpose of post-implementation user study evaluation and testing in other devices including mobile, the created model study was deployed through a static website hosting via Microsoft Azure Storge.

CHAPTER 4
EVALUATION AND RESULTS

In this chapter, the author will present the protocols of evaluations which were conducted and the background to conduct the said evaluation techniques.

4.1. Evaluation Protocol

An empirical approach of validation is brought to assess the outcomes and validate the proof of concept works. The proof of concept of this dissertation mainly covers the aspects of the study of realism and the philosophical approach on the importance of the realistic entity modeling in virtual realistic environments like metaverse.

Evaluation strategy covers three different areas in this dissertation. Primary focus is towards the primary outcome of this research – the Caladium model visualization with growth stimulation. Secondary evaluation consists of establishing delineation of the dataset accuracy derived with the tuber growth prediction statistical analysis by identifying the margin of error and accuracy of the data. A brief tertiary performance-based evaluation will be performed with the WebGL model memory consumption performance against a browser-based environment. Therefore, the evaluation protocol aims to cover all three perspectives of this research – data analysis and data accuracy, growth stimulation modeling and finally finding the optimal solution for a low resource metaverse virtual realistic environment.

4.2. Results

4.2.1. Stimulation Evaluation Scenario

There is no widely accepted benchmark on evaluating such 3D models nor realistic plant growth models. Graphical modeling evaluation goes through a similarity check in case they are based off an actual real model or pre-planned structure which was used as the foremost idea to model it in the first place.

In the field of Mechanical and Automobile Engineering, Computer-Aided-Design models (CAD) are often used to create high precision realistic models. These models help modeling further component buildings, related engineering simulations, parts designing and many other applications. Industrial-level laser scanners are used to create the replicate model in their respective software by creating a digital copy of the scanned item. (Bourdot et al., 2010) These objects are high precision and accurately measure models. Studies and projects on integrating CAD and VR is an emerging topic in the field of virtual reality and most vendor specific HMD already provide similar CAD based applications in their IVE. (Raposo et al., 2006) On other hand, laser scanning is an expensive piece of technology which also needs proper handling and good knowledge on their usages to operate them. ("How to Evaluate the Quality of a 3D Model for Parts & Products | Cad Crowd," 2021) Though in our scenario unfortunately, a scanned model for the taken plant study – Caladium Bicolor is not available in any botanical based web indices or on Internet archives.

Model accurate detailing and representation in the real-world covers the initial impression for the evaluation, compared to the advanced statistical based evaluation. Thus, evaluation of a 3D modeling can be pointed at 5 different key aspects. Scale and dimension, lighting and texture materials, realism and sensory perceivability. ("How can you evaluate 3D model accuracy?," n.d.) Consequently, we can further breakdown our model evaluation with technical aspects, model features (characteristics of the body of model), interactivity and the subject measures like, perceived realism, usability and the aesthetic features. Use of proper quality metrics elevates the model's accuracy and the realism factor more. ("How do you measure and evaluate the impact and effectiveness of 3d models for immersive media?," n.d.)

When it comes to evaluating a web-based 3D tree model with growth stimulation, growth model realism is a critical area to be discussed. The model of Caladium visualization is the primary outcome of this research. Validating a 3D plant model should consider numerous factors. In a real-world scenario, determining the efficiency of the growth or the growth pattern of a selected plant model is unattainable work. Also, the technologies which are being used to make this application of model have to be evaluated as well. The proceeding section presents the details of the case study.

4.2.2. Questionnaire Based Qualitative Analysis

The post study questionnaire was administered to the participant to get subjective feedback. The questionnaire is the selected evaluation tool for this user study. A supporting reason to consider questionnaire-based user study along with qualitative evaluation is to get the user behavior on perceiving the emotion by using such model. Tracking the user behavior by making them use this model can help with more thorough evaluation on the user behavior on how proposed stimulation model attracts the audience and engages them in the process. This is a key point to consider while building a dynamic object modeling for an interactive environment like metaverse or any other virtual realistic environments.

This questionnaire aims to collect information from the selective sample of participants on their experience with the created growth stimulation model for the Caladium plant. This facilitates subjective judgments about the strengths and weaknesses of the model, enabling the user to provide qualitative feedback on the proof of concept's usability and effectiveness. The questionnaire used for this research is attached with this dissertation, in the section of Appendices under Appendix-A. Furthermore, the questionnaire strictly follows the methodological framework aiming to measure the user experience in an immersive virtual environment point of view. Formulated questions encapsulate the skill of the user and the gain, flow state on using the model and the emotion perceived by using the demo. Adoption to technology is another motivational factor in finding how welcomed are these changes to an IVE. Likert scale and comment type of questions are primarily used for their justification for their pragmatic thinking. (Tcha-Tokey et al., 2016)

The questionnaire has three sections excluding the demographic questions. Demographic questions were selected based on a several related past works and similar approach was adopted by few other non-related research areas too. (Avenash, 2022)

The initial section focuses on general perception of such models. This section measures if the users have experience with computer modeling based stimulation models and any other plan simulation models. Moreover, in the next section, the evaluation of our stimulation model is focused on comparing the plant stimulation model created in WebGL with a normal plant model of the Caladium plant. A few sub sections were added to categorize the focus of questions. The sub-section – Realism, expects a response to a Likert scale type of question for a subjective measurement on how realistic the created model is. These discrete data points are further used in statistical assessment. Furthermore, interactive experience sub-section focuses on how engaging was this model compared to static based models and the additional importance of values it brings to the table as educational research value point of view. (Tcha-Tokey et al., 2016) The Growth Factor - sub section, measures the behavior of the growth stimulation pattern of the Caladium comparing it to its actual natural growth model.

Finally, the "Application of mode" covers the value of bringing such growth stimulation models to a virtual realistic environment/metaverse. The importance of realism and supporting factors like visual fidelity and growth stimulation models are prioritized.

At the end of the questionnaire, an optional section is provided to get additional feedback to improve the current growth stimulation model and any other comments that need to be raised.

The type of rating scale used for each question was a 5-point Likert-type scale. The digital version of the questionnaire was created using Google Forms and shared with the participants through email and social media apps like WhatsApp.

Participants and Apparatus

Instead of a more generalized response from a random sample, for this specific evaluation, only a selected number of users were picked as the questionnaire participants.

Common traits on identifying sample of participants:

- Have a sound knowledge in botanical studies or priorly involved in a botanical based study earlier in their academics.
- Have experience in working in the field of botanical studies.
- Have experience in modeling/Visual Effects (VFX)/designing or worked with CAD graphics.
- Users who own/have experience in VR HMD

As a result, the user study was conducted with 5 people user-group, ranging in different levels of expertise in the field of botanical studies to computer science and graphical background. One of the selected participants, who has 9 years of collective experience in both botanical studies, and in working in the field of Bio food industries. Similarly, another participant is a veteran VFX artist who has experience in WebGL modeling, and modeling with 3D engines like 3D Max and Maya. The evaluation was done individually on their preferred workstation web browsers and parallelly getting a feedback response with their thoughts and actions via a Google meet call session. User test can be done remotely since the proof of concept is hosted in an

Azure static web host resource. (“Caladium,” n.d.) (“Static website hosting in Azure Storage | Microsoft Learn,” n.d.)

Data Collection

As stated in the previous section, a hosted demo site with pre-defined dataset configuration was sent out to the participants and the questionnaire reflects upon the experience gained from that demo. Google forms was used as the main surveying tool for these questionnaire assessments to obtain their responses and feedback. An automated sync within the Forms tools was used to access all the response synchronized to a spreadsheet for more convenience.

Additional comments from the participants were noted for this evaluation as well. Some input on extending this model for the future works were also recorded and taken into consideration.

User Study Results

The study involved five participants using the Caladium growth stimulation web demo and participated in a qualitative analysis. The analysis identified three key themes related to the object realism, importance of growth stimulation in VR, and how immersing was this work of proof of concept, which will be discussed in detail throughout this section. Refer the Appendix B and C sections for questionnaire related survey and response stats.

Each participant was asked to get around the given hosted demo link to familiarize to the environment first. They were easily able to understand the model and the visualization of it. The mouse is the primary mode of user input and possible interaction modes were explained just in case the participant is not aware of the interactions. With that, they were asked to answer the questionnaire as the next phase.

The general perception results yielded a sparser demographic sample. Most participants have said they are occasionally involved in botanical based simulation models. The computer graphics-based simulation is also somewhat new for the participants. For some participants, this has been a rare experience and one of the participants has actually worked around with the computer graphic based simulation. This data is an eye opener, since it is assumed, botanical studies highly involve graphical based simulations.

Considering the questionnaire section of the realism of the created plant model, most participants have said that they are interested in the created model. About 40% of the participants have given they have perceived almost near realism for the visual representation of the created plant model and another fraction of 40% of the participants have given a neutral response. With this we can acknowledge that most users have accepted the model to mimic the realistic features of the Caladium to some extent. Moreover, the similarity of the natural plant model against the virtual model is about the same for most of the participants.

Getting into the growth stimulation pattern of the created model, participants have shared that the growth simulation around the bracket of moderately accurate considering that one of the participants have shared their concern around the growth stimulation is little less accurate.

Furthermore, when asked for their feedback on which characteristics of the given virtual model feels more realistic or unrealistic, most feedback comments were around the area of the Caladium leaf model. The feedback suggests a virtual Caladium model with promising elements of realism, particularly in capturing the growth patterns and number of leaves. However, there are areas for improvement, especially in animation, texturing, and color accuracy. One of the strengths suggested was these lays off a good fundamental study for an improved immersive experience in the future. The ability to leaf model variation against the age is another praised factor with regards to the growth factor realism. Although, one of the participants have shared their feeling around less realistic leaf model in the animation due to the absence of vein and pattern identifiers of a typical caladium model. The highlight suggested afterwards on, for this being a low poly proof of concept which was worked within a brief time span.

With that, an overall analysis of interactive experience is obtained. An equal number of people found the interactive features to be more engaging (40%) and about the same (40%) compared to a static model. A fifth of the respondents (20%) found the interactive features less engaging. No one found them much less engaging or much more engaging.

Overall, the survey suggests that the interactive features of the Caladium plant simulation model hold promise for engaging users, with nearly as many people finding them more engaging as finding them about the same as a static model.

Furthermore, on the aspect of interactivity of the dynamic model helps in educational and research proposition, the most striking aspect of the results is the unanimous agreement (all five responses) that interactivity significantly increases the educational and research value of the caladium plant simulation model. This strong consensus highlights the model's potential as a powerful learning and investigative tool.

Concluding on this questionnaire segment, the results from the participants reveal that the interactive features of the caladium plant simulation model are not just supplementary, but rather a cornerstone of its educational and research value. By enabling active engagement, exploration, and real-time data collection, the model fosters a deeper understanding of plant growth processes and empowers users to conduct meaningful research.

Next, the applications of the virtual stimulation model were taken into consideration. All the participants were strongly backing on the fact that such virtual models are important for a VR environment and from a botanist's perspective, this was a huge benefit for their field as well. Further analyzing the key pointers mentioned, one response highlights that VR can improve accessibility compared to physical research environments. This is because VR can potentially be accessed from anywhere with the right equipment, eliminating geographical limitations.

Multiple responses mention the immersive and interactive nature of VR as a benefit. For example, one response talks about users being able to engage with the model in a more realistic way, fostering a deeper understanding through firsthand exploration and observation. This resonates with the concept of "learning by doing" where users can learn from actively interacting with the simulation. Another response points out the collaborative nature of VR. This means that people in separate locations could potentially work together on experiments or educational projects within the VR environment. Imagine researchers from various universities working on the same simulated plant growth experiment despite being physically distant. A response discusses the scalability and flexibility that VR offers. This refers to the ability to easily adjust the simulation parameters to experiment with various conditions. For instance, researchers could assess how a plant grows in different climates or soil types by virtually modifying the environment within VR.

Talking on this during the questionnaire, the selected veteran botanist mentioned such an instance where this could be really helpful as well. Considering a specific example of how a VR plant growth simulation model could be used for collaborative research. A team of researchers from different countries is interested in studying the effects of light intensity on plant growth. They can use the VR model to design a virtual experiment where they can manipulate light variables and observe the plant's response in a controlled VR environment. This would allow them to collaborate virtually, share data and observations easily, and potentially accelerate their research process.

Continuing, when the next question asked on the scale of realism for such visual growth stimulation models, most of the participants responded supported such realistic approach is welcomed but doesn’t have to be hyper realistic mimicking one-to-one of a natural life model. Engagement should be prioritized, nevertheless. Growth stimulation should achieve near realistic modeling but doesn’t have to focus on depending on stimuli-based stimulation to bring a hyper-realistic growth stimulation.

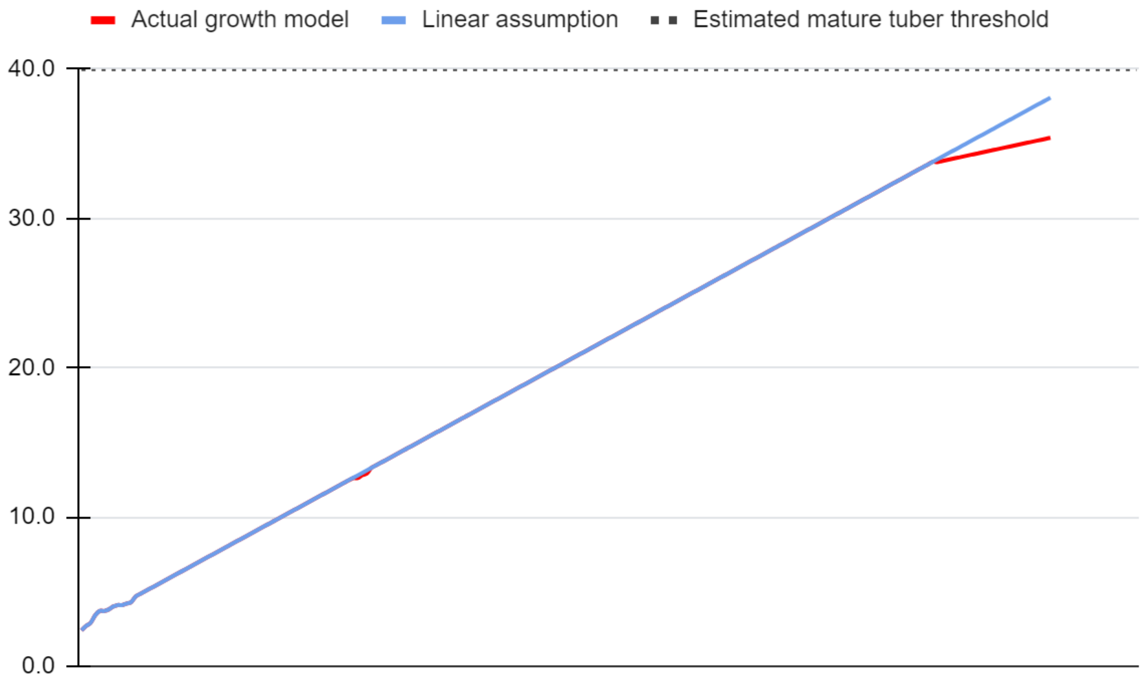
The survey ended with an additional commentary-based questionnaire, requesting additional features or improvements or feedback suggested for enhancing the realism and growth factors of plant simulation models given in the demo and feedback. The feedback suggests that the plant simulation model could benefit from improvements in texturing, animation, and the incorporation of external factors to make it more realistic and representative of actual plant growth. Climate and environmental condition were requested for more realistic approach. The feedback received from the veteran VFX artist suggested adding textures, increasing polygon count, and fine-tuning anchor points and colors for a more realistic appearance. Another valuable feedback from the veteran botanist suggests incorporating dynamic environmental factors like sunlight and wind, as well as seasonal variations and genetic diversity for a more realistic experience. Additionally, interactive features like pruning and pest interactions are seen as valuable for a more hands-on learning approach. However, limitations exist in color accuracy, vein detail, and environmental responsiveness. Future iterations should integrate dynamic environmental factors, genetic diversity, and interactive elements to enhance realism and create a more comprehensive representation of natural Caladium growth.

The user study offers valuable insights into the model's limitations and areas requiring enhancement. Participants' confidence suggests that, once the identified limitations are addressed, the proposed virtual growth stimulation model has the potential to yield expected outcomes. The results are likely less biased as they were obtained from individuals within the relevant scientific field, making them pertinent for future endeavors as well.

4.2.3. Statistical Evaluation of the Model’s Growth Stimulation Rate Against Realistic Growth Pattern

The created stimulation model follows a simple growth pattern stimulation. The algorithmic approach visualizes the plant model based on the given inputs. Though considering the actual growth model from the taken subjects, the tuber growth displays a stabilized growth around the 30cm threshold. Likewise, the cultivar specific height threshold was identified to be 12-30 inches of the threshold range in the botanical based web resources. (“Caladium | Home & Garden Information Center,” n.d.)

The projection of the actual dataset and an assumption of the model yields shows that the data points of the actual dataset get its mature growth stability around 30-40cm threshold range. Though the created model is not bound to the actual growth representation. Even though model creation relies on the given height parameter, a mechanism to validate the stimulation to visualize the precise growth pattern needs to be implemented.



Chapter 4 Figure 1:Actual tuber growth height (cm) data against the data reading points

The linear assumption trend was retrieved with the usage of Google Sheet’s series pattern data imputation.

4.2.4. Performance Evaluation by Analyzing Run Time Performance of the WebGL Model in a Browser-based Environment

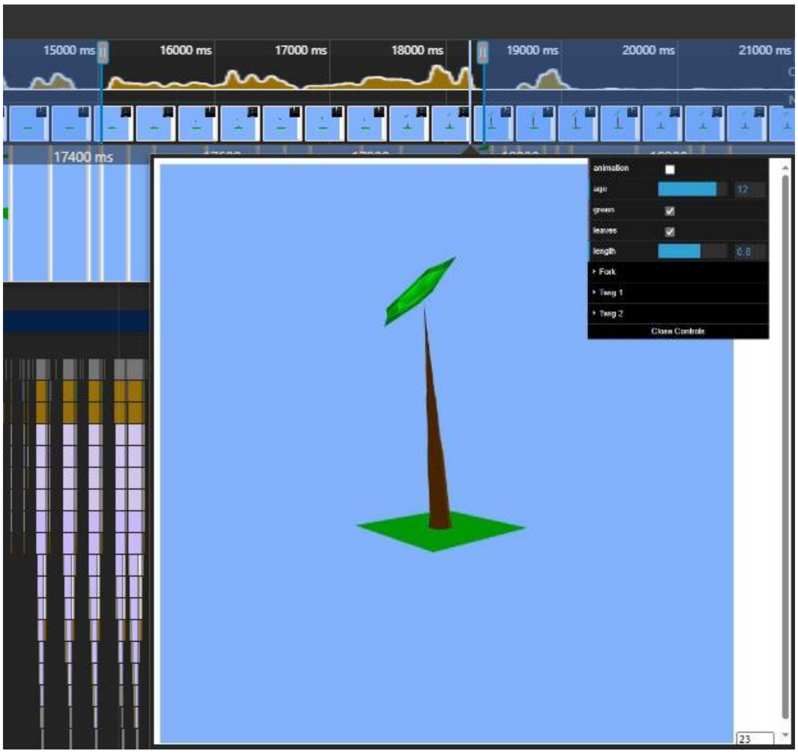
WebGL or Web Graphical Library is a JavaScript API which is used for creating 2D and 3D graphics that can run on any web browser. As a result of using such native support JavaScript API, there is no need for any extra plugins, library or even third-party tools to run it on a web browser and easily accessible on any kind of device. Hence, WebGL is being used in a wide range of possibilities in modern-day web applications. Although it can run on the browser environments, with the use of device's GPU (Graphical Processing Unit) leveraging, WebGL can easily, and quickly render any visualization assets. With this brief evaluation, we are assessing the performance of the model ("Performance features reference | DevTools | Chrome for Developers," n.d.) along with other factors like frame drop rate and FPS counters.

The selected scenario for this evaluation was changing the leaf's age from least to the highest with a brief half a second interval. Following figure (Chapter 4 Figure 2) depicts the specific scenario being tested in the Chromium based, Edge web browser and the relative evaluated results on the dev-tools window (Developer tools). ("Analyze runtime performance | DevTools | Chrome for Developers," n.d.)

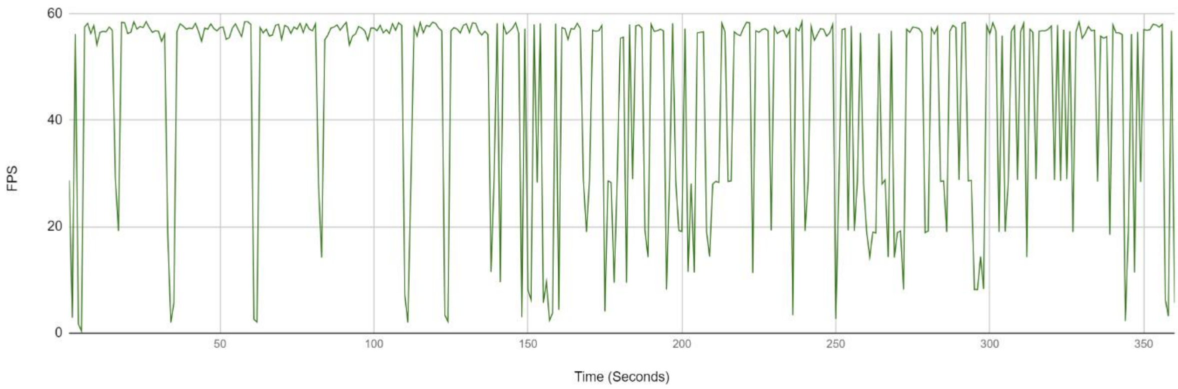
The CPU time is consistently around 9.0 ms or lower for most measurements. This suggests that the CPU is not a bottleneck in the rendering process, as it is completing its tasks relatively quickly. Hence, the focus of the evaluation deeply involved in the areas of GPU and FPS. The GPU time varies but generally falls within the range of 1.2 ms to 4.1 ms. This indicates that the GPU is doing the bulk of the rendering work and is responsible for most of the frame time. There are occasional spikes in GPU time, such as the measurement at 14683.8 ms, where the GPU time is significantly higher (14674.6 ms) compared to the average. These spikes could indicate rendering operations that are particularly complex or resource intensive.

The GPU was active for a relatively short duration compared to the total time elapsed (327 ms out of 4823 ms), indicating that the rendering workload may not have been very heavy during this period. Similarly, while comparing the memory usage of the selected Edge web browser also yielded a comparatively normal memory usage with the hardware acceleration feature is on.

While comparing the frame rate/FPS (frames per second) properties, we could be able to see some interesting patterns of frame rendering sequence. The following chart depicted in Chapter 4 Figure 3 visualizes the frame rate received for 360 seconds (360 frames) with relative to our selected use case scenario on testing the ascending growing stimulation model.



Chapter 4 Figure 2: CPU usage with running the WebGL model in the browser developer console

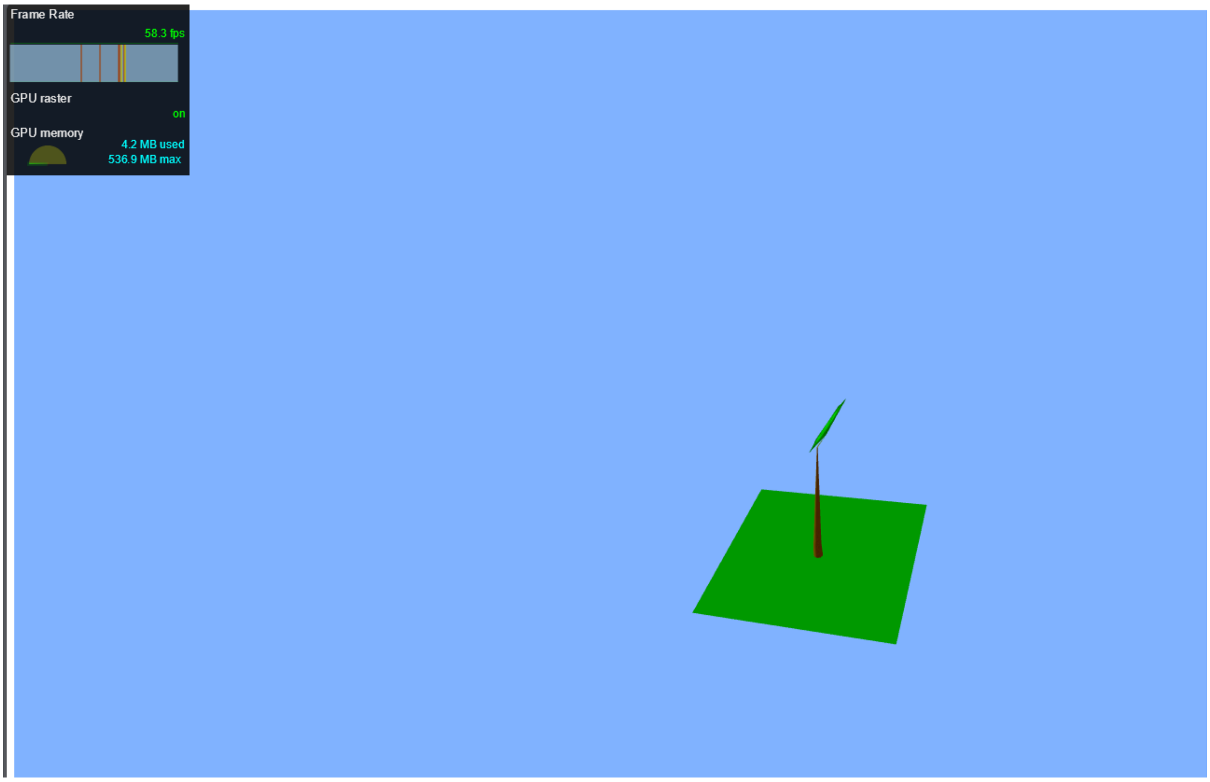


Chapter 4 Figure 3: Rendered FPS against time

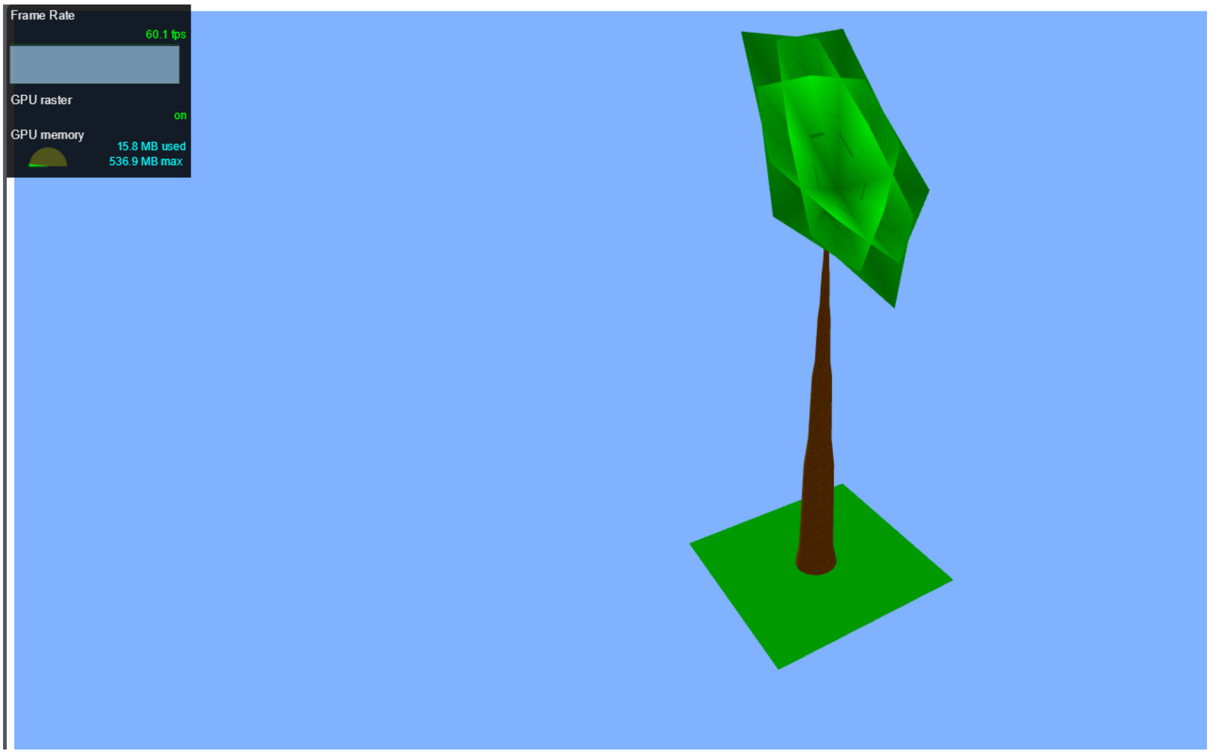
- The FPS values vary over time, ranging from as low as around 0.4 to as high as around 58.5.
- There are fluctuations in FPS, which is normal in dynamic scenes or during rendering-intensive operations.
- The majority of the FPS values fall within the range of 55 to 58, indicating relatively smooth performance for the WebGL application during those periods.

- There are occasional drops in FPS to lower values, such as around 0.4 or 2, which may indicate moments of increased rendering complexity or processing load.
- Some FPS values are repeated, suggesting that the performance during those moments remained relatively stable.

Overall, the data suggests that the WebGL application's performance varies over time, but it generally maintains a relatively high FPS as calculated to have around 44.9 Average FPS but mostly keeping around the 60.1 mark, which indicates smooth rendering and interactions.



Chapter 4 Figure 4: The spikes in the Frame rate monitor tool indicates change in the model and with that the change in FPS rate



Chapter 4 Figure 53: A constant 60 FPS framerate is maintained when the model is not being changed with the parameters

To further analyze and optimize performance, the focus should be shifted to GPU-specific optimizations such as reducing the complexity of shaders, optimizing texture usage, minimizing overdraw, and batching draw calls. Additionally, identifying and addressing any specific rendering operations causing spikes in GPU time could help improve overall performance consistency. According to the study by Toasa G et al. the usage of WebGL performs stably but not more efficiently than WebXR (Previously known as WebVR) based on the results obtained in the tests performed in his work. Since FPS performances are also in a more stable manner this stimulation model seems to be proper functioning state for a web based metaverse environment. (Toasa G et al., 2019)

4.3. Discussion

The proposed proof of concept involved in the investigation and implementation of a low-resource growth stimulation model for a web based virtual realistic environment. Gained the understanding of the domain of multiple studies whilst working on this research. Botanical studies on the growth patterns, stimuli and stimulation process, realistic plant modeling and low resource object modeling for WebVR are few to be mentioned. Considering the user-based questionnaire study results, most concerns are towards the positive results and feedback in the terms of answering the main research question of this research. Supportive quantitative results of the performance-based evaluation support the user study results. The collective results give the confidence to continue this study and extend the scope as a part of future work. The proposed model has the potential to be pilot study for further research reference models. The usage of simple WebGL modeling is extendable to the need-specific plant-based models.

Further discussing the user study results, the growth factor realism that the proposed virtual Caladium model shows potential for achieving high realism, especially considering the positive feedback on growth features. Focusing on improving animation, texturing, and color accuracy will enhance the overall authenticity and immersive experience. The participants' feedback emphasizes the benefit of active engagement. Unlike static models, the interactive features allow users to manipulate variables, observe the plant's response in real-time, and experiment with different scenarios. This active participation fosters a deeper understanding of plant growth processes compared to passive observation. The dynamic nature of the model encourages exploration and inquiry-driven learning. Users can ask questions, evaluate hypotheses, and discover cause-and-effect relationships between a range of factors impacting plant growth. This promotes a more engaging and effective learning experience compared to traditional methods. The ability to manipulate variables in real-time makes the model valuable for research purposes. Users can simulate different environmental conditions, observe plant responses, and collect data efficiently. This facilitates hypothesis testing and experimentation, leading to a richer understanding of plant behavior.

On the other hand, there were a couple of concerns about bringing improvements to the model as well. The texturing incorporates the leaf vein pattern, more detailed blotches and more precise leaf shapes can be focused on to bring more realism to the model definition. The realistic appearance ensures the initial understanding of the application itself. Hence, perfecting the plant model would be a good fit for the upcoming future works based on this research. Proposing an alternative algorithmic approach for isolated leaf component modeling and introducing a separate vector base blotch pattern with realistic randomized pattern of display would be a good addition for future work to improve the realism of the leaf model. Consequently, with the results, the participants accepted the growth stimulation model simulation provided through the proof of concept. Yet, a few concerns were raised about bringing more dynamicity to the stimulation model. Impact of environmental factors to the plant seasonal variations, interactive features like, pruning, and the involvement of pesticides and pests are few of the top-level identification of the feedback. These are a really valuable addition to the model and can be worked towards in the near future.

Even in data collection, the measuring can be done in a methodical botany-based approach. Use of hydroponic growing technique can be beneficial with precise measurement and controlled environmental assessment to see the change in stimuli resulting in a variety of results.

Use of WebGL as the tehcnical foundation, brought an immense upgrade to the performance based approach on applying such models to an immersive virtual environments. A constant 60 FPS frame rate was achieved on a computer browser base evaluation. The model's resource consumption and execution in a browser based environment, resulted a satisfactory level response from both the performance based evaluation mentioned above and the user study results. Though this only evalutes a single, isolated tuber growth model stimulation. An elaborated test plan might be needed if the model is to be extended to show further growth pattern and behavioral realism.

The brief statistical analysis of the model stimulation and actual plant stimulation brings a key factor of the model accuracy. According to the current graphical stimulation model, the simulation works based on the inputs fed into the logic. Hence, it operates with endless options to simulate based on the range of inputs provided. This has to be validated in the further studies on the related research where a machine learning model can be introduced to achieve the correct growth pattern similar to the actual model. This can be used as a basis to identify more rigid, deterministic pattern of growth stimulation for the selected plant study as well.

Looking on overall, realistic simulation part of the evaluation, as in the yield of results, the need for hyper-realistic modeling is not expected unless the application for the specified model is clearly focused on realistic educational studies on botany or for the usages of life-like immersive experience which is not targeted in a commercial grade virtual reality experience currently. The proposed model can be improved a bit further to achieve the benchmark for the necessity of near realistic projection in VE. Frustum culling, a technique done in computer graphics and game development to hide the level of details and reduced object build volumes to increase the rendering performances. While trees being an important part of environmental design build, showing the dynamicity of a tree growth over timeseries is a complex task. The proposed model brings a lightweight solution to show a generic tree growth stimulation with an expenditure of a marginal computational resource. (Parisi, 2012)

The effort that has been put into making this proof of concept is appreciated in the user study responses. While the observations identified areas to improve the model's accuracy and usability, the evaluation results support the research's sub-questions. The study also highlighted limitations in the current approach. However, participant confidence suggests the solution aligns with expectations, which is a positive finding.

This thesis explores a low-resource web-based approach to the metaverse, acknowledging the limitations of high-fidelity models that necessitate specialized hardware and restrict accessibility. The design presented here serves as a proof-of-concept, successfully functioning within the specific simulated environment established for this study. However, further research is necessary to determine the generalizability and applicability of this approach in real-world metaverse contexts.

CHAPTER 5
CONCLUSION AND FUTURE WORK

5.1. Conclusion

This thesis presents a low-poly growth stimulation web model which can be imported to a web based virtual realistic environment. This low-cost solution brings a simple procedural-based visualization of a realistic Caladium genus of plants or the cultivars' growth pattern which is created using WebGL – web-based 3D rendering JS API. Actual plant study of a specific Caladium cultivar helped to refine this model as the supporting data collection for obtained since inception. The core stimulation growth pattern is identified with the prominent indicators of a real, typical Caladium plant model, which are the tuber growth and the leaf. Bezier quadratic splines and Bezier cylindrical core concepts were highly involved in the tuber growth modeling. The tuber modeling shows a realistic tuber shoot with a natural curve and smooth bending around each cylindrical model being used to model the tuber part. Changing the age parameter brings a timeseries of growth stimulation of the tuber with the provided height data in the supporting JSON file. A similar time series-based approach is followed with respective to change in age, to model the leaf of Caladium. The shape of the leaf, depth of the ovate leaf model, natural blotch pattern and tropism are a few realistic natural leaf model attributes which were focused for the developing the design model. Up to some extent the low-poly growth stimulation model achieves the realistic actual plant growth stimulation model.

The importance of bringing a realistic growth stimulation model to the metaverse is not actively considered in the existing approaches in the realm of tree growth stimulation for VR, better yet, a lower cost resourced way. Upon completion of this dissertation, the proposed low poly, low-resourced, realistic growth stimulation, especially scoped for Caladium plant model, for a web-based IVE metaverse environment is the main contribution of this research.

The proposed approach undergoes evaluation through user perception validation tests, statistical model analysis, and performance-related evaluations based on the model. The responses and results obtained from this research demonstrate the significant potential of this model, which can be effectively employed to simulate realistic growth in a virtual environment (VE). The evaluation results, including those from the case study, are recognized as key contributions of this work, highlighting the potential for expansion and adaptation to other similar use cases beyond the scope of this thesis.

5.2. Future Work

The results of the research promote and prove that the proposed graphical stimulation growth model does work in the context of web-based environments. However, there is more room for improvement to extend the model a bit further accurate and immersive in the region of plant growth stimulation model for virtual realistic environment. To maximize its potential for educational and research applications in web-based VR environments, several key areas warrant further investigation.

Prior to implementation, the data collection process can be addressed in a more methodical approach. The marginal errors faced in acquiring data can be reduced and precise measurements can be obtained. The collected data can be further studied to get a standard growth perception of a selected plant using advanced techniques like data analysis processes and machine learning. Plant model observation is important for extending this study. Clearer picture of the study is obtained while working with the definition of model.

Enhancing model realism can be achieved through improved plant modeling techniques like alternative algorithmic approaches for leaf components, separate vector-based blotch patterns, and detailed textures. The addition of polygons can bring a slight difference in viewing experience. 3D point cloud technology can be used to digitally scan a plant to get the data points in a XYZ based vertices graph map to obtain an accurate model to be worked on. (Reisner-Kollmann et al., 2011) The consideration of stimuli-based growth stimulation was not under the scope of this research. The environments stimuli can be proposed in future iterations of this study. Additionally, increased dynamicity can be introduced by integrating environmental factors and interactive features like pruning, pest infestation, and pesticide application. Other anatomy of the plants should be focused. Tuber shoots branching, tuber bend proportion to weight of the leaf, dynamic rotation for phototropism effect does bring more plant like feature in a typical virtual environment.

The use of WebGL facilitates the necessary use cases of the growth stimulation modeling. Though using a third-party library like Three.js, or Babylon.js might be a better fit for simpler modeling with less complex scripting, maintainable code and most of all – improved readability. A deeper pilot study can be done to find the most suitable packages for this case.

Moreover, for scalability and generalizability, a comprehensive test plan assessing diverse growth patterns and behaviors is necessary. Additionally, model expansion beyond tuber growth to encompass a wider range of plants should be explored.

Finally, user experience considerations include conducting further user studies to refine the experience and integrating educational elements like quizzes and tutorials. By systematically addressing these future research directions, the low-resource growth stimulation model can evolve into a robust and versatile tool for education, research, and potentially, metaverse applications.

APPENDICES

Appendices A. Implementation – Pseudocode

a. Leaf generator function

```
Function leaf takes in parameters: leafPropertiesArray,
leafRadius, leafLength, leafYCoordinate, leafAngle, leafColor,
leafAge


    Set initialOffset to off divided by 8

    Set ageRadius1 to 0.25 times leafAge

    Set ageRadiusMid to 0.39 times leafAge

    Set ageRadius2 to 0.5 times leafAge

    Set sinAngle to sine of leafAngle

    Set cosAngle to cosine of leafAngle

    Set fi to undefined


    Set temp to leafPropertiesArray[0] times cosAngle minus
leafPropertiesArray[2] times sinAngle

    Set leafPropertiesArray[2] to leafPropertiesArray[0] times
sinAngle plus leafPropertiesArray[2] times cosAngle

    Set leafPropertiesArray[0] to temp

    Increase leafPropertiesArray[1] by leafYCoordinate


    Create a new Float32Array named leafNormalArray with size
6

    Set normalMagnitude to square root of
(leafPropertiesArray[0] squared plus leafPropertiesArray[2]
squared)

    Set leafNormalArray[0] to leafPropertiesArray[2] divided
by normalMagnitude

    Set leafNormalArray[2] to negative leafPropertiesArray[0]
divided by normalMagnitude

    Set leafNormalArray[4] to 0.05 times (leafAge times 3.75)


    For each element in leafPropertiesArray from index 9 to 11
```

```
        Set pt[off] to leafPropertiesArray[index] plus leafLength times leafPropertiesArray[index - 9]
        Increase off by 1

    Set leafIntensity to 0.02 times (1 minus absolute value of leafPropertiesArray[1])

    Set pt[off] to 0
    Increase off by 1
    Set pt[off] to 0.4 plus leafIntensity
    Increase off by 1
    Set pt[off] to 0
    Increase off by 1
    Set pt[off] to 0
    Increase off by 1
    Set pt[off] to 0
    Increase off by 1

    Set tempOffset to initialOffset plus 1
    Set sinDelta to sine of (PI times 0.3)
    Set cosDelta to cosine of (PI times 0.3)
    Set sinAngle to 0
    Set cosAngle to -1
    Set temp to undefined

    Repeat 5 times
        For each element in leafPropertiesArray from index 9 to 11
            Set pt[off] to leafPropertiesArray[index] plus leafLength times leafPropertiesArray[index - 9] plus leafNormalArray[index - 6] plus leafPropertiesArray[index - 9] times (ageRadius1 times cosAngle plus 0.1) plus leafNormalArray[index - 9] times ageRadius1 times sinAngle
            Increase off by 1

        Set pt[off] to 0
```

```
        Increase off by 1
        Set pt[off] to 0.9 plus leafIntensity
        Increase off by 1
        Set pt[off] to 0
        Increase off by 1
        Set pt[off] to 0.125
        Increase off by 1
        Set pt[off] to 1
        Increase off by 1

        Set temp to sinAngle times cosDelta plus cosAngle
times sinDelta
        Set cosAngle to cosAngle times cosDelta minus sinAngle
times sinDelta
        Set sinAngle to temp

        Repeat the above steps with ageRadiusMid and 0.15
instead of ageRadius1 and 0.1
        Repeat the above steps with ageRadius2 and 0.2 instead
of ageRadiusMid and 0.15
        Repeat the above steps with ageRadiusMid and 0.15
instead of ageRadius2 and 0.2
        Repeat the above steps with ageRadius1 and 0.1 instead
of ageRadiusMid and 0.15

    Repeat 5 times
        Repeat 4 times
            Set ind[pi2] to initialOffset
            Increase pi2 by 1
            Set ind[pi2] to tempOffset
            Increase pi2 by 1
            Set ind[pi2] to tempOffset plus 1
            Increase pi2 by 1

        Increase tempOffset by 1
```

```
    For each element in leafPropertiesArray from index 9 to 11

        Set pt[off] to leafPropertiesArray[index] plus
leafRadius times leafPropertiesArray[index - 6]

        Increase off by 1

    Set pt[off] to 0.5

    Increase off by 1

    Set pt[off] to 0.5

    Increase off by 1

    Set pt[off] to 0

    Increase off by 1

    Set pt[off] to 0

    Increase off by 1

    Set pt[off] to 0

    Increase off by 1


    Repeat the above steps with leafPropertiesArray[index - 3]
instead of leafPropertiesArray[index - 6]

    Repeat the above steps with negative
leafPropertiesArray[index - 6] instead of
leafPropertiesArray[index - 3]

    Repeat the above steps with negative
leafPropertiesArray[index - 3] instead of negative
leafPropertiesArray[index - 6]


    Set ind[pi2] to initialOffset

    Increase pi2 by 1

    Set ind[pi2] to tempOffset

    Increase pi2 by 1

    Set ind[pi2] to tempOffset plus 1

    Increase pi2 by 1


    Repeat the above steps 3 more times with tempOffset
increased by 1 each time and tempOffset minus 3 in the last
step


End Function
```

Appendices B. Questionnaire

Botanical Study Evaluation: Caladium Plant Stimulation Model vs. Normal Plant Model

Dear Participant,

Thank you for agreeing to participate in this dissertation evaluation of plant stimulation models. Your feedback is valuable in assessing the realism and growth factors of the Caladium plant model created in WebGL compared to a traditional plant model. Please provide your honest opinions and insights.

Before answering the questionnaire, please open the following website containing the live demo of the plant model.

Caladium (windows.net) (Web-link)

Instructions to use web demo.

- Model camera perspective is changed by moving with mouse cursor.
- Pressing shift / mouse wheel can be used to zoom in and out the model.
- Changing the parameters in the panel on the right top corner of the screen changes the model.
    - Change **only** the age slider to see the growth model of the Caladium Bicolor plant.

Instructions on writing answers for the questionnaire.

- Please state your general information with your consent. Otherwise, its optional.
- Give your relevancy to the field by answering the rest of the questions.
- For choice questions, just underline them by selecting the option and add underline from toolbar or pressing CTRL+U
- For comments and discussion like answers write them underneath the relevant questions.

Thank you and good luck!

Section 1: Participant Information (Demographic questions)

Name: [Optional/Anon]

Affiliation/Institution:

Years of experience in botanical studies:

Section 2: General Perception

1. How frequently do you interact with plant simulation models in your research or studies?
    a. Rarely
    b. Occasionally
    c. Frequently
    d. Regularly

2. How would you rate your familiarity with WebGL-based plant simulation models?
    a. Not familiar
    b. Somewhat familiar
    c. Moderately familiar
    d. Very familiar
    e. Expert

Section 3: Evaluation of Plant Models

For the following questions, please compare the plant stimulation model created in WebGL with a normal plant model.

1. Realism:
    a) On a scale of 1 to 5, how realistic do you find the visual appearance of the Caladium plant model in WebGL?
        i) 1 (Not realistic at all)
        ii) 2
        iii) 3
        iv) 4
        v) 5 (Highly realistic)

    b) How does the realism of the Caladium plant model in WebGL compare to a traditional plant model?
        i) Much less realistic
        ii) Less realistic
        iii) About the same
        iv) More realistic
        v) Much more realistic

2. Growth Factors:
    a) How accurately does the growth pattern of the Caladium plant model in WebGL simulate real-world growth patterns?
        i) Not accurate at all
        ii) Slightly accurate
        iii) Moderately accurate
        iv) Very accurate
        v) Extremely accurate

    b) Are there any specific growth features or behaviors of the Caladium plant model in WebGL that you find particularly realistic or unrealistic? Please elaborate.

3. Interactive Experience:
    a) How engaging do you find the interactive features of the WebGL Caladium plant stimulation model compared to a static, traditional plant model?
        i) Much less engaging

ii) Less engaging
iii) About the same
iv) More engaging
v) Much more engaging

b) Do you believe the interactivity of the WebGL Caladium plant stimulation model enhances or detracts from its educational or research value? Please explain your answer.

Section 4: Additional Comments

1. What additional features or improvements would you suggest for enhancing the realism and growth factors of plant simulation models in WebGL, particularly in the context of the Caladium plant?

2. Any other comments or feedback you would like to provide regarding the comparison between the WebGL Caladium plant stimulation model and traditional plant models?

Thank you for your participation in this evaluation. Your input is greatly appreciated!

Appendices C. Questionnaire Results - Likert-based Questions

On a scale of 1 to 5, how realistic do you find the visual appearance of the Caladium plant model in the given graphical demo?

5 responses

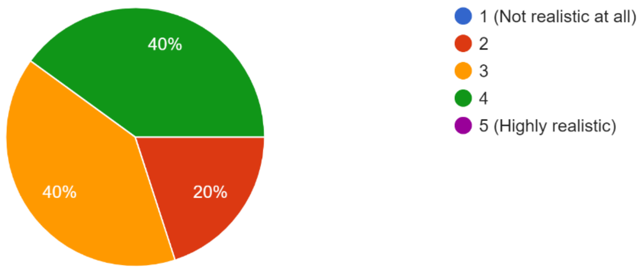


Figure C 1: Likert-based question response statistic on getting user's opinion plant's graphical model realism factor

How does the realism of the Caladium plant model in the given model compared to a natural plant growth model?

5 responses

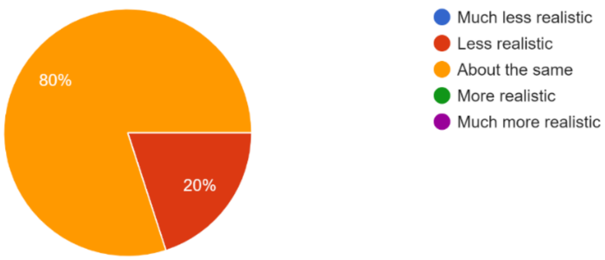


Figure C 2:Likert-based question response statistic on getting user's opinion plant's realism compared to the graphical model prototype

How accurately does the growth pattern of the Caladium plant model in the given model simulate real-world growth patterns?

5 responses

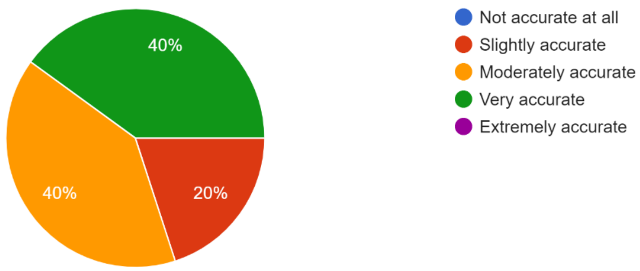


Figure C 3: Likert-based question response statistic on identifying the prototype growth pattern similarity to real-world scenario

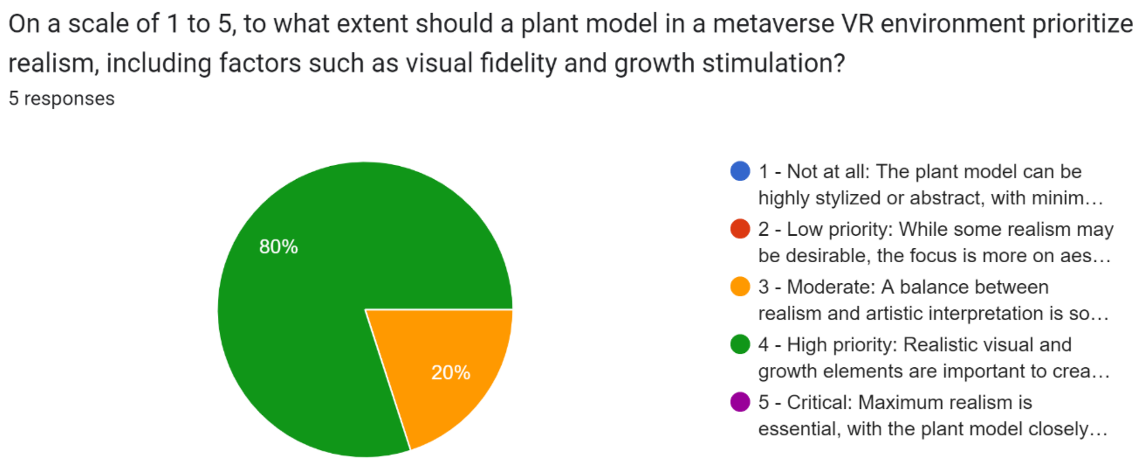


Figure C 4: Likert-based question response statistic on understanding user perception on creating realistic plant model in metaverse mimicking to the level of realistic growth stimulation and modeling

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