SOUND SHAPE MODELLING, INTERACTION AND PROTOTYPING FOR VIRTUAL POTTERY

A thesis submitted in partial fulfilment

of the requirement for the degree of Doctor of Philosophy

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I dedicate my thesis firstly to my **parents** and my sister **Jumanah**, who have always been nearest and gave me love and strength. I also dedicate my thesis to my beloved husband **Ibrahim** and my lovely daughter **Ritall**, who has always believed in me and got me through tough times, giving me the strength to continue. I will never forget my friend **Ashleigh**, who has been the shoulder to lean on. Also, my friend **Vinden** always has a great smile with great talks made me feel fit in the university, welcoming me with a warm heart. Finally, to my supervisor and my friend **Prof. Edmond** who has been there for me from day one, he supported me in challenging times and has always been there for me.

Abstract

Introduction: Virtual Pottery (VP) using creative technologies is a multi-faceted challenge. This thesis addresses the key challenges and makes novel research contributions. This research explores how Virtual Pottery (VP) has evolved and competed with traditional making.

Problem: Traditional research related to Virtual Pottery (VP) shows that the main contribution of applications and 3D modelling software focuses on creating a vessel on a Virtual Reality (VR) potter's wheel or 3D sculpting tools with limitations. Moreover, the available applications may not support the whole experience of traditional making and hold many challenges. 3D modelling is expensive, labour-intensive and time-consuming, especially when modelling in detail on a complex organic object. Some of the available Virtual Reality (VR) applications use a set of unprintable pattern images as a texture. Volumetric pattern modelling with high resolution may affect the application performance and cannot be used in real-time.

Aim: This research aims to overcome the limitations mentioned above, including the following: surface texturing on VP objects, the functionality of 3D modelling tools, physical making experience, organic shape complexity, visual limitations, print limitations and real-time interactivity.

Contributions & Thesis overview: The research aims are accomplished through the innovation of the surface texture of VP and the conceptual design. It is a systematic process demonstrated through a workflow system that employs modelling, interaction and rapid prototyping. The modelling is demonstrated by using VR for base-shape 3D modelling and embedding the detailed sound shape on the base object. The overview of the thesis captures an introduction, literature review, background, methodology, conclusion and future work.

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List of Acronyms

2D Two-Dimensional

3D Three-Dimensional

VR Virtual Reality

VP Virtual Pottery

AR Augmented Reality

VE Virtual Environment

UI User Interface

CAD Computer-Aided Design.

CAID Computer Aided Industrial Design

FDM Fused Deposition Modelling

SLA Stereo-Lithography Apparatus

DLP Digital Light Processing

PLA Poly Lactic-Acid or polylactide, a thermoplastic polyester filament

UV Utilising Ultraviolet

RGB(A) Red-Green-Blue-Alpha

DTRF Domain Transfer Recursive Filter

RBF Radial Basis Function

CSRBF Compactly Supported Radial Basis Function

SRBF Compactly Supported Radial Basis Function

SUS System Usability Scale

DDF Digital Design Fabrication

Chapter 1

Introduction

The fusion of traditional pottery-making and creative technologies produce an innovative path for developing digital artistic creativity as outlined in this chapter. The thesis focuses on the overall aim of developing a novel geometric sound structure texture applied on the surface of a vessel as a big part of the picture. The small part of the novel purpose connects the dots of physical modelling, problem-solving the shortcomings of Virtual Pottery (VP) and prototyping. Furthermore, this research enhances the understanding of the connection between traditional pottery and creative technologies towards Virtual Pottery (VP). Chapter one highlights the aims, objectives, contributions, publication and the thesis structure to maintain the flow for the rest of the thesis. The thesis brings together relative technologies, the tools and devices along with novel experimental approaches to overcome the shortcoming of Virtual Pottery (VP).

1.1 Sound & Creativity

Sound is powerful energy discovered from the ancient cultures and civilisations in history. The geometry formation of sound can be found in nature as unique patterns. The phenomena were used for communication, healing, science, and art. Sound representation in art is a primary medium or material interdisciplinary in nature or can be used in hybrid forms. Sound wave was discovered by **Leonardo Da Vinci** in (1452-1519). He discovered that sound travels in waves. He was a brilliant artist, scientist, and thinker and contributed many discoveries in science. Before his time, he was a man who thought up inventions and ideas that came to be built far later by other engineers and scientists. **Christian Doppler** (1842) later discovered that sound waves could be compressed or expanded, further expanding Da Vinci's theory. Sound waves have been re-analysed by numerous scientists over the past decades. Sound in physics is a vibration that multiplies as acoustic energy waves travel through various materials, liquids, solids, and gases in different ranges. The sound wave can be described by the wave's wavelength, amplitude, time-period, velocity, speed and frequency. The Vibration of sound change the status of a medium and can be seen visually in liquid or solid particles, which is discovered by **Ernst Florens Friedrich Chladni** he was, a German physicist and musician. Chladni plates illustrate 2D standing wave patterns. When a sound of waves vibrates into a plate shape,e.g. square, circular or violin, at a specific frequency of a resonant, the node of 2D shapes will appear in a stationary mode while the plate is vibrating. The power of combining art and science expands both disciplines creating new opportunities, and technology is a branch that facilitates the application of science. The combination of chladni patterns of sound has been researched widely over the past decades, and now with the era of creative technologies, we have the opportunity to expand the discoveries.

1.2 Creative Technologies

Creative technologies provide new tools and techniques to synthesise art and aesthetics to achieve new forms and function. The exploration of cutting edge technology as a creative force helps to unleash the boundaries of imagination. Visualisation towards physicalisation creates a bridge to discover limitless opportunities of existing and emerging technology. The research journey in this thesis searches for immersive and emergent forms through developing novel Virtual Pottery (VP) systems and techniques for materialising deformable shapes of sound-resonance on 3D objects.

Creative Technologies for Cross-Disciplines

Creative technologies create a portal gateway for cross-disciplines to meet conceptually, forming a bridge between science, technology, and art. Over the past decades, innovations in VR technology flourished with creating new experiences, and brought the ability to produce things virtually in sufficient detail, and release imagination of creative power towards real-

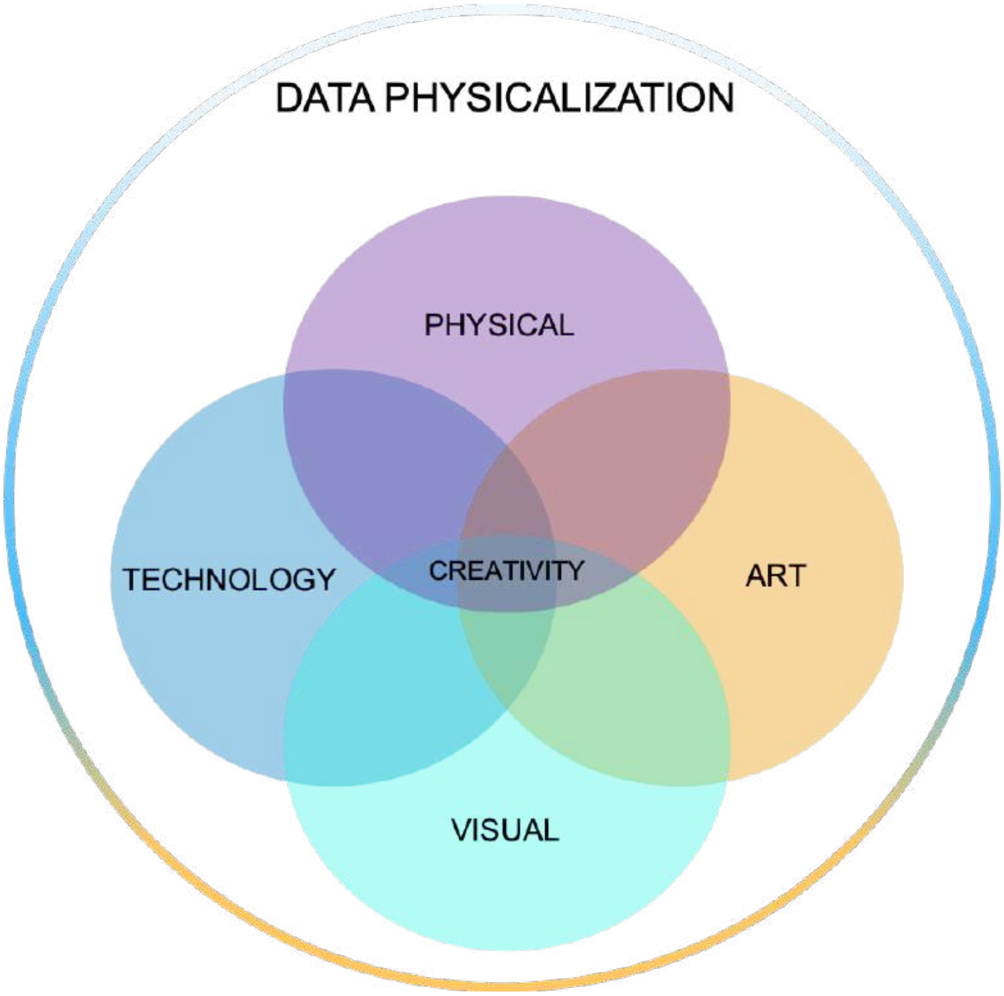


Figure 1.1: Data-physicalisation is a creative approach and currently popular technique of representing an actual data visualisation into a 3D physical data form, breaking the boundaries and enhancing both fields of art and technology .

ity [1; 2]. The thesis pushes the boundary and creates new frontiers of physical pottery by using virtual pottery. The boundaries start from the limitations of traditional pottery of the real-world constraints such as gravity, material properties, capturing patterns from natural phenomena, and tailored support structure for supporting the vessel. As a contribution, the thesis presents methods and techniques for using a multidisciplinary approach. The idea of the thesis is about bringing several fields of science, art and technology, with human interaction, using natural scientific phenomena such as sound resonance (as shown in Fig. 1.2) as a representation of data-physicalisation [1].

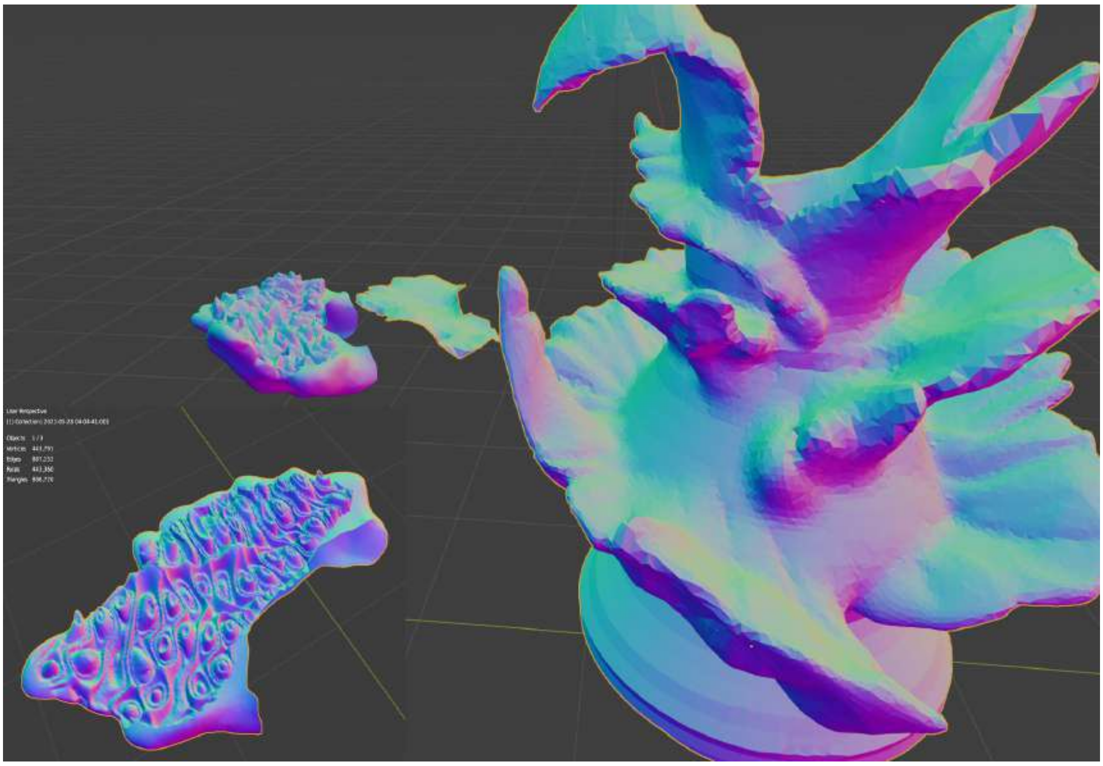


Figure 1.2: VR Pottery Sound Shape Modelling

1.3 Creative Technologies for Virtual Pottery

This research presents the analysis of an alternative to reality in the user's comfort zone while using the existing creative technologies in a virtual space and bringing innovations in fabrication. Due to the pandemics, there is an urgent call to accumulate knowledge, insight and resourceful skills. For instance, it is required that we improve the status of self-produced virtual collaborative work. The ultimate challenge is to determine if the advantages of using these innovations outweigh the traditional method.

Taking the example of pottery modelling, this approach explores techniques to capture the essence of sound energy by trapping sound data and binding it to the digital rendering of deformable shapes. This is to produce transient shapes of sound structures. This perspective improves the framework for virtual and physical ceramics during the process of moulding and manufacturing. It also eliminates the possibility of warping at high temperatures while in the kiln.

Clay as a material poses real-world constraints such as gravity and evaporation that prevent them from fully capturing the visual sound deformation patterns. While using technology such as VR and AR, the research shows that if we cannot obtain the satisfaction of moulding the clay by our hands, we can explore a whole new beginning of pottery with advanced designs and nearly no physical limitations. This interactive virtual clay modelling extends the potter's boundaries and creativity to develop multi-modal objects. Pottery making has been one of the most ancient art forms practised till this date due to its therapeutic and stress relieving qualities, and adding auditory components only heightens the experience of enjoying the art form. Relating audios to emotions and expressing it through pottery makes it an even better means of catharsis. Just as Cymatics is used in fashion to break the barrier between the visible and the invisible, this improved art form reflects patterns common in Cymatics that help find serenity amidst chaos. Connecting the physical output with AR technology allows the viewers to read the sound texture and play the audios or visual animations, which cannot be obtained via conventional methods.

1.4 Creative Technologies - Emerging Areas

This research on Virtual Pottery (VP) can be expanded in many related directions based on creative technologies presented in the literature. Some recent use of creative technologies are highlighted below. Understanding the impact of high-detailed manipulation interference with digital modelling and fabrication would be beneficial for contemporary designs [3], for example, to enable the ceramic artist, product designers, makers and also game designers to produce distinctive immersive deformable shape models. In Art-on-a-Chip [4], the authors present the creation of a prototype for preserving Microfluidic Chips for visualisation and permanent display. As the shapes grow complex, fabrication of the shapes become complex and requires a suitable mathematical representation that acts as the bridge between design strategies and architecture [5]. In addition to visualising sound, emphasis is also made on the feel of sound to be more effective using sonic surfaces [6]. The research can also benefit from newer geometry, fabrication, material of functional art and architecture [7]. Xu et al. [8] make abstractions for digital sculptures, which inherit from traditional art patterns for morphological generation in architecture design. Another possible use of creative technologies by Reki [9] explores new forms and functions through parametric patterns in responsive facades.

1.5 Experimental Approach

The thesis research is an experimental research-based of cross-discipline that integrates computer science and art. It includes a hypothesis and independent variable in a controlled environment, seeking to answer a question and address how to capture sound resonance phenomenon in a novel method with benefits and emphasising the shortcomings of VR as a design medium.

The experimental approach is designed to identify traditional pottery problems and techniques to be resolved using 3D modelling computer graphics tools and devices as one part of determining the research question. On the other hand, using 3D modelling in computer graphics in different novel ways to visualise and highlight the errors and overcome them. All of the small parts creates the big picture of the PhD thesis. This research experiment aims to understand the shortcoming of VR pottery applications using integration of systems as a proof of concept design using off-the-shelf tools for modelling and fabrication.

1.6 Aim and Objectives

The motivation of this research comes from the synthesis of creative technologies and contemporary art. Now artists can experience technology practising their craft in another reality and physicalise their creative imagination crossing reality barriers. Virtual Reality (VR) intensifies interactive physical modelling and fabrication. The understanding of the spatial relationships within a 3D environment, unleashes the creativity of visual and physical interaction. This research explores ways to develop traditional pottery, utilising creative technologies, and overcome real-world physical challenges to create new opportunities.

Research Aim

This research aims to design a VR pottery system for modelling and fabrication. The focus is on object deformation and real-physical object transformations to develop VR interactive physical modelling. The research also includes a novel volumetric sound texture, defying real-world physical constraints with new opportunities.

Research Objectives

The research is, therefore, directed towards achieving the following objectives:

- **Modelling**: To develop and represent a volumetric sound resonance shape surface texture in real-time.
- **User interaction**: To develop a multi-modal interaction that simulates physical-virtual to capture real-world deformable pottery making (addition/subtraction) using tangible hand and finger transformations.
- **Making/ceramics**: The objective is to make physical making central to this process by emphasising the material and the rapid prototyping, which influences the above two objectives.
- **System Refinement:** specification of the system, system integration and functional testing.

1.7 Research Approach

The thesis approach follows an experimental approach plan and procedures. The framework for the study is shown in Fig 1.3 highlights all of the essential elements of the research. The framework establishes a coherent and logical scheme of detailed data collection, analysis, and interpretation methods. The research approach addresses the nature of cross-discipline research problems between artistic creativity and computer graphics.

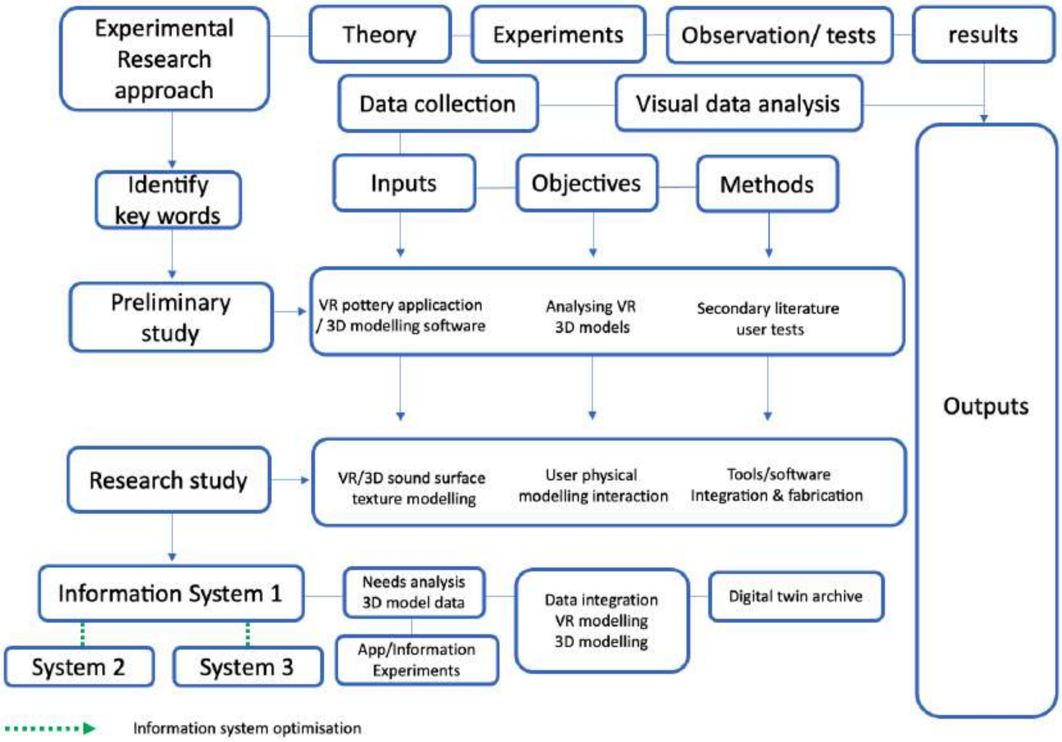


Figure 1.3: Thesis research approach

1.8 Contributions

This research converges on expanding VR pottery modelling and fabrication system methodology, designing a software integration process to advance multi-modal interaction of deformable shape modelling. It begins with designing novel deformable shape modelling specifications, creating a bidirectional fabrication system followed by a volumetric sound texture. The volumetric texture idea uses an image generator for complex geometry patterns with displacement, forming a 3D surface. Other existing VP applications has only texture images without an actual geometry change to the VR object. Then the system progresses towards learning and developing VP skills in a safe environment during pandemics and natural disasters, for example, during Covid-19. The entire design methodology is covered by identifying existing challenges in VP applications. The significant features of this research are:

1.8.1 Modelling Contributions

The crux of the contributions in this thesis is

- The main contribution is the innovation of novel sound resonance surface texture for VP with the conceptual design of the VP pipeline.
- Experiment design for a 3D model representation scheme to seamlessly blend 3D pottery shapes with 3D textures.
- Developed a system and workflow for generating volumetric texture as an extended method of deformable shape modelling for VR/3D objects.

1.8.2 Interaction Contributions

Another main contribution in this thesis is to introduce VR interaction for VP modelling and includes:

- VR visualisation for quality checking in VR modelling systems and validated the implementation of developing techniques as a problem-solving methodology.
- Classified a variety of usability assessment techniques for interactive virtual learning, collaborative work, and edutainment in the VR space.

1.8.3 Prototyping Contributions

To facilitate novel physical prototyping the contributions are:

- Designed and built a 3D printing studio for PLA and ceramic resin prototyping with fundamental compatible tools and applications.
- Produced a customised reusable support structure design, specialised for post-ceramics making during kiln firing.

1.8.4 Systems Integration Contributions

Contributions regarding systems integration included:

- Methodology: The formulation of using off-the-shelf tools to improve and implement deformable shape modelling by novice and intermediate users, specifically tackling VP model problems to simulate traditional ceramics.

- Subsystems: A communication platform group as a learning and gaining skills system for VP. The integration, implementation and system design for a VR/3D/AR interactive physical visualiser, connecting the physical object digitally.
- Systems: The fundamental aspects of fabricating VR/3D and physical tests to evaluate and produce a unique approach for a unified application with simulated traditional potter's experience. A demonstration of problem-solving methodologies by using open source tools in regards to modelling and fabrication process.

1.9 Publications

The following papers have been published as the lead author based on the work presented in this thesis:

- **Dashti, S.**, Prakash, E., Hussain, F., & Carroll, F. (2020). Digital Pottery: Novel Information Systems and Workflow Process for Virtual and Physical Artistic Visualizations of Sound on Ceramics. Advances in Management and Innovation, Cardiff Metropolitan University, 2020.
- **Dashti, S.**, Prakash, E., Hussain, F., & Carroll, F. (2020, September). Virtual Pottery: Deformable Sound Shape Modelling and Fabrication. In 2020 International Conference on Cyberworlds (CW) (pp. 133-136). IEEE.
- **Dashti, S.**, Hussain, F., Carroll, F., & Prakash, E. (2020). Scaffolds for virtual pottery: Design, 3D printing and kiln firing. In the 8th International Conference on RiTA Robot Intelligence Technology and Applications Programme RiTA2020, Three-Minutes Thesis (3MT) Competition. http://dx.doi.org/10.13140/RG.2.2.23405.10722
- **Dashti, S.**, Hussain, F., Carroll, F., & Prakash, E. (2021): Can Virtual Pottery Become The New Norm and Replace The Ceramic Studio?. In AMI 2021 - The 5th Advances in Management and Innovation Conference 2021. Cardiff Metropolitan University, 2021. https://doi.org/10.25401/Cardiffmet.14614209.v1
- **Dashti, S.**, Newball, AAN., Prakash, E., Hussain, F., & Carroll, F. (2021, September). Digital Twin for Virtual Pottery. In the 2nd International Conference of Immersive

Technologies (XR ACADEMIA 2021). Open Press, Tilburg University, The Netherlands.

- **Dashti, S.**, Newball, AAN ., Prakash, E., Hussain, F., & Carroll, F. (2021). Role of Intricate Pottery Visualisation in Ceramic Manufacturing. IEEE Computer Graphics and Applications. Submitted. The Special Journal Issue of on the Role of Visualization in the Manufacturing Industry. Submitted.
- **Dashti, S.**, Prakash, E., Hussain, F., & Carroll, F. (2021, September). Experimental Evaluation of Virtual Pottery Systems. In 2021 International Conference on Cyberworlds (CW) IEEE. ppd. 25-32., IEEE.
- **Dashti, S.**, Dashti, S., Norbert, I., Prakash, E., Hussain, F., Carroll, F., and Newball, A. (2021, September). Creative Technologies-From VR and Art Aesthetics to Form and Function. In 2021 International Conference on Cyberworlds (CW) (pp. 145-146). IEEE.
- **Dashti, S.** and Prakash, E., Imagineering Ceramic Pottery Using Computer Graphics, in Lee., N (ed), Encyclopedia of Computer Graphics and Games, Springer, 2021.

1.10 Thesis Overview

The organisation and structure of this thesis is outlined below and shown in Fig 1.4. After this introductory chapter, the following two chapters provide background on VP modelling and prototyping with a novel information system, a detailed background of literature and an overview of the digital pottery workflow process. The design and implementation of the system module varies from modelling tools, deformable shape modelling aspects and system complexities. These are presented in the sequential order of creation. After the design and implementation sections, the analysis section covers the impact of technology and experimental evaluation of VP systems on visual feedback from users. Conclusions from all these areas of research are highlighted in the final chapter. The contribution in each chapter are described below:

- **Chapter** 2 begins with a brief introduction to the basic concepts of modelling, VP and prototyping. After that, a detailed modelling and prototyping. After that, a detailed background is presented on interactive modelling over the past years with exploration that highlights procedural texture, chladni plate, 3D rapid prototyping and creative technologies. The chapter explores the complexities and challenges of data-physicalisation, represented in an actual data visualisation into a VR/AR/3D physical data form. In this chapter, the focus is on some design tools, for example, Computer-Aided Design CAD and Computer-Aided Industrial Design (CAID) tool showing comparisons and novelty variations of the thesis approach. More so, the focus was on identifying the need for a customised deformable shape modelling approach, creating more natural parameterisation of realistic sound fabricated graphics into interactive physical and 3D shapes. This is followed by an analysis of the requirements for developing VP applications and using the novel sound volumetric texture system for learning and training skills.

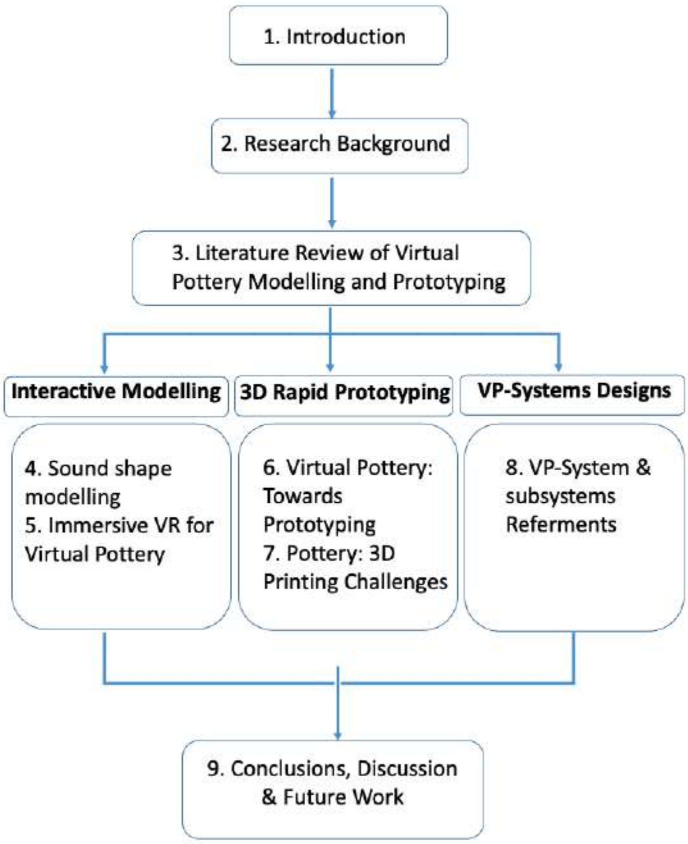


Figure 1.4: Thesis structure. Source adapted (Painkras, 2013)

- **Chapter** 3 The literature review chapter is an overview of the critical literature that's relevant to the thesis discussion of what research has already been done. The integrated review displays the knowledge around deformable shape modelling with sound phenomena. This chapter focuses on the understanding of texture in computer graphics with contemporary designs, revealing the challenges, emphasising sound from as a texture towards fabrication on the shell surface VP model. The journey of the chapter expands with the relation of procedural texture and chladni patterns and what are the related literature that could assist in finding methods to develop a VP model with a refined system. VP systems applications are growing, and this chapter presents some of the top research and game-based VP systems with a demonstration of what tool was chosen for the experimentation stage, also presenting the gap of knowledge. The chapter also presents studies for evaluation methods of the user test to support the idea of the refined system. Finally, displaying studies that help to form the novel information VP system with subsystems that offers more advantages of collaborative learning and Digital Twin technology.

- **Chapter** 4 presents volumetric deformable shape modelling. This chapter introduces a novel system and technique for materialising the deformable shapes of sound-resonance on 3D objects. A technical framework presents a new approach using a series of simple processes to manage complex object transformations that can be used in virtual, 3D modelling and augmented reality (AR) interaction. The research methodology involves the following steps.
  - The first step is on materialising sound resonance images by using a suitable tool such as the Chladni plate software for generating sound resonance shape maps, using bump and displacement mapping.
  - Next, an exploration is made using volumetric deformable shape maps to blend these intricate sound resonance patterns in VP applications.
  - Then the method transforms the resulting complex 3D shape models from the above steps for rapid prototyping using appropriate pre-print tools by remeshing and physics manipulations.
  - The chapter demonstrates the method developed using off-the-shelf tools.

The chapter also examines recent literature and results in a unique texture for interactive modelling towards digital fabrication for basic users, capturing the essence of sound energy creating an object with mixed realities through animated sound texture mapping. The workflow processes have been accomplished using standalone information systems for modelling, deformation, VR, and rapid prototyping.

- **Chapter** 5 discusses the aspects of visual feedback analysis aspects. This chapter presents usability evaluation methods based on research studies related to VR. More so, exploring the multi-display approach for deformable shape modelling, digital twin, edutainment curricula and training skills. VP modelling and fabrication has several opportunities, challenges and desirable properties. More so, the chapter examines the evaluation methods that will advance the research-base using:

  Visual Feedback

  * Gestural Interfaces.
  * Usability factors of 3D modelling in VR.
  * Collaborative Design VR Usability.

  System usability comparison.

  * VR test-bed evaluation.

  Furthermore, the feedback focuses on the usability of integrating multi-disciplinary VR and creative technologies, relying mainly on visual input and image-based studies of VR applications. This approach optimises the results of the novel VP system, configuring traditional pottery modelling, utilising a combination of virtual, 3D modelling and fabrication tools for interactive quality and dynamic compatibility. The usability investigations aim to produce VR usability for novice users. This study provides guidelines on designing and developing applications, utilising VP as an extended version of deformable shape modelling.

- **Chapter** 6 examines layered manufacturing over the past several years of rapid prototyping and tailored manufacturing. It shows the rapid growth of 3D printing pervasive across many fields, including the arts and design. This chapter reveals how visualisation builds a bridge connection between humans and technologies for printed end products.

- **Chapter** 7 explores the challenges and opportunities of VP modelling and fabrication.
- **Chapter** 8 presents an overview of an advanced system and volumetric sound deformation modelling methodology and results. The chapter discusses the outputs of 3D printable objects forms, with high-quality sound texture examples overlayed and blended. The discussion of how to extend ceramic artists creativity of making, up-scaling the boundaries of creative making and develop a multi-modal interaction. More so, showing the significance of simulating physical-virtual, capturing real-world deformable pottery making (addition/ subtraction) using tangible hand and finger transformations. The order of the background overview is set backwards to create a blue print guide map concept, starting from modelling to VP systems and then continuing with the systems as a base construction towards modelling and prototyping.

  The second version of the novel VP system presents a system as a creative technology method for physical activity, training and educational purposes during Covid-19. The new normal era relies on collaboration technologies in the pandemics to develop skills and improve self-production, using virtual collaborative work, such as practising artwork with VP as an example. The idea of a global platform of many sectors have already been implemented. The purpose of using such platforms that initiates during pandemics and natural disasters is to access knowledge base, interaction and creation skills accessibility. This approach shows how practical virtual experience can compete with traditional physical ones as the next best option.

  Finally the third version of the VP system uses the concept of Digital Twin technology to develop human intelligence and performance. The idea of digital twin technology in this chapter shows how it is an applicable concept for VP modelling and fabrication. The system displays the use of 3D model data (such as STL) across multi-application environment, with the growth of organic form made with physical interaction and volumetric texture modelling. This method creates a promising result of tracked deformation across layers of realities, creating a digital twin link between the physical and digital object.

- **Chapter** 9 concludes the uses of the novel VP systems with the sound shape modelling process, in theory, practice and experiments. The chapter summarises how the proposed system model is qualified to develop physical modelling for novice and intermediate users. The contributions of this research are discussed and evaluated in this chapter. The thesis concludes with a discussion of avenues for future exploration and system refinement. Further, it discusses the future step of producing an AR/VR interactive model with extensive usability tests retained due to Covid-19 health restrictions.

In summary, this chapter presented a background of creative technologies and its use in VP. The motivation, aims and objectives were presented. The challenges and novel contributions were explained. The challenges and the novel contributions were highlighted. The outline of the thesis was also presented. The next chapter explains a more detailed background and review of the elements of the VP system.

Chapter 2

Research Background

2.1 Introduction

This chapter provides the background research for VP. Three key background areas are crucial, namely modelling, interaction, and prototyping, presenting this chapter's structure. The first step was to identify several keywords and themes to support this research. One of the keywords was 'sound shape modelling'. The other keyword was 'information systems for pottery'. The review was expanded with more keywords such as modelling, Virtual reality, information system, 3D modelling, displacement, prototyping, deformable shape modelling, interactive texture maps. The structure of the review evolved as a more detailed review was done. Further refinement resulted in crucial searches in 'digital twins' and 'usability analysis'. To facilitate the reading of this chapter, this is also provided as a flow diagram in Fig 2.1.

2.2 Modelling

Computer graphics is a sub-field of computer science that manipulates the displayed visual information. It is a graphical representation technique for images, graphics designs, maps, drawings. Computer graphics is used in UI design, rendering, geometric objects, animation and many more. 3D modelling in computer graphics is about generating digital 3D graphics that can assist in sculpting, texturing, and designing 3D models.

3D modelling in computer graphics is a method that generates a mathematical coordinate-based representation of any surface of an object in 3D specialised software by manipulating

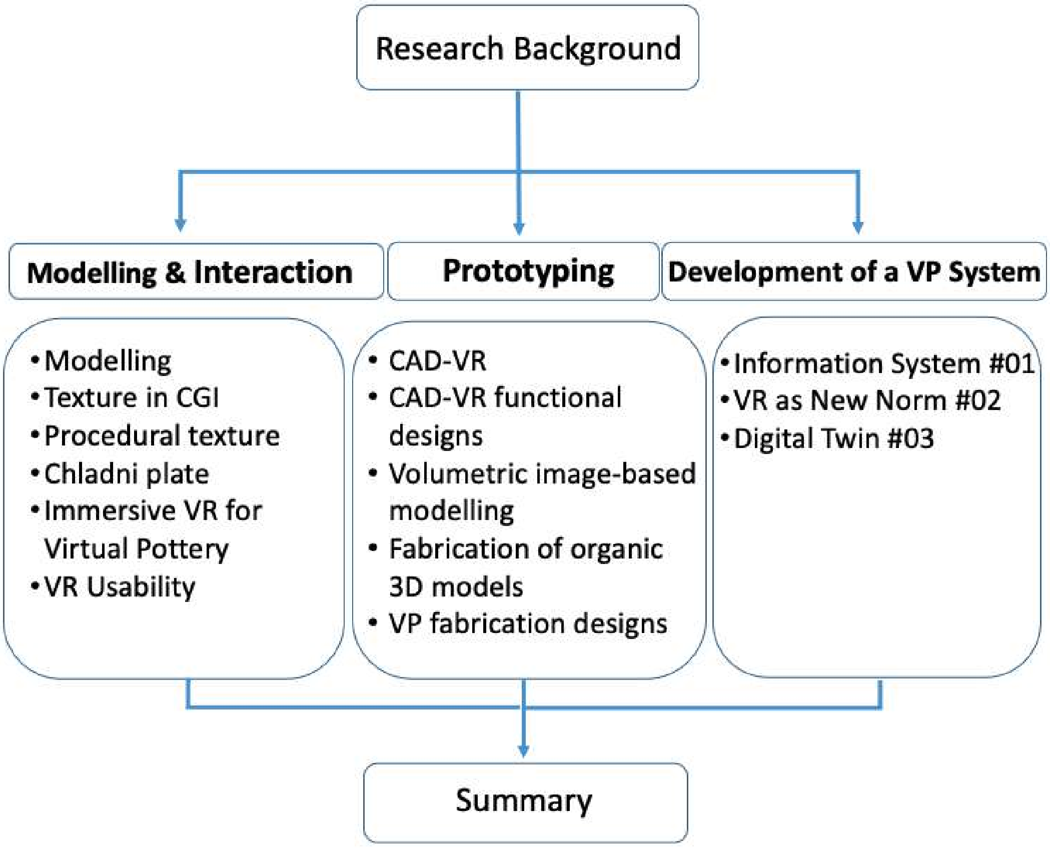


Figure 2.1: Background overview structure

a primitive geometric shape, like a cube, sphere, or cylinder. 3D model components are shaped by edges, faces, vertices, and polygons in a simulated 3D space. The 3D modelling technique is used for producing a 3D digital representation of any object or surface. The thesis uses an advanced type of modelling called deformable shape modelling. Deformable shape modelling is a representation technique towards representing curves or surfaces. The deformable shape modelling captures various external force fields changing the 3D model and internal forces from the model itself computed from the image data. The use of such method is applied in many areas of computer graphics, for example, surgical simulation, character animation, cloth modelling, object, shape editing, and image analysis [10].

2.2.1 Why Deformable Shape Modelling?

Deformable shape modelling is a reliable, functional method in computer graphics for modelling realism and one of the approaches uses a volumetric geometric texture. This approach provides more accurate, pragmatic variable data of deformation behaviour. The technique produces volumetric deformation of, e.g. height, depth, twist, and bend for medical scientists, artists, engineers and can help to enhance their visual graphical understanding, performance and outputs.

2.2.2 Challenges in 3D Graphics Shape Modelling

Computer graphics modelling is considered expensive, labour and compute-intensive. 3D modelling tools mainly create rigid object surface texture deformation and have limitations in the representation of surface details. The challenges in complex modelling objects vary from texturing, topology, long render baking, mesh blending, mesh analysis, 3D object conversion to print. Other challenges are system crash and memory ram capacity while handling larger mesh size of the shape models.

2.3 Texture in Computer Graphics (CG)

Textures are essential for computer graphics, adding surface geometry without modelling any complex surfaces such as wrinkles, scars, cracks, and bumps. It makes surfaces look realistic on computer-generated (CG) 3D models. Textures are one of the seven characteristics of art that guide to a more substantial feeling of an object to the touch or looks as it may feel. Texture basis functions are defined as functions to generate patterns that can be used as a basis for generating textures.

2.3.1 Procedural Texture

The procedural texture is formed by using a computer algorithm for low storage data with unlimited texture resolution and easy texture mapping. Computer graphics have employed the techniques to develop more realistic textures, simulating complex natural models in nature. The Procedural techniques provide multiple advantages for computer graphics applications. There are generally used procedural techniques including: *fractals, L-systems, Perlin noise, cellular and tiling systems*.

Perlin noise: Perlin has developed an evolution method for procedural texture as a type of gradient noise used in computer graphics for realism appearance. The function developed method *Perlin Noise* has a pseudo-random generation of a random numbers computer algorithm with a number called a random seed, yet all of the details are the same size. The function of this method allows it to be readily controllable with multiple transformations duplicates, affecting the object surface used in CGI to make computer-generated visual characteristics, e.g., fire, smoke, or clouds, appear more natural [11].

2.3.2 Sound Relationship with Vibration & Resonance

This section highlights the understanding of sound, vibration and resonance phenomena to understand how it creates the geometric pattern used for the thesis novel sound texture. Sound physics is the vibration that propagates as an acoustic wave through a medium, and the five primary elements of sound waves include frequency, amplitude, time period, velocity and wavelength as shown in Fig 2.2. The origin of science acoustics was discovered by the Greek philosopher Pythagoras (6 th century BC), who worked on experimenting with the properties of vibrating strings that assemble musical intervals. On the other hand, Aristotle (384 BC- 322 BC), a Greek philosopher, suggested that sound waves propagate in air through motion. Galileo Galilei (1564-1642) discovered that sound resonance motion is evaluated by studying vibrations and the correlation with the pitch and frequency of the sound source it produces. He was the first scientist to record the relationship between the wave's frequency to the pitch. Moving on to the Italian philosopher and artist Leonardo DaVinci's movement of sound waves, DaVinci believed that there is no sound when there is no percussion or motion of air [12]. However, Marin Mersenne (1588-1648) is a French natural philosopher as the considered the "father of modern acoustics" he explored how fast sound waves travelled by measuring the velocity of sound by counting the number of heartbeats during the interval occurring between the flash and the perception of the sound mainly. Also, Mersenne independently discovered the complete laws of vibrating strings (completing what Pythagoras and Pythagoreans had started 2000 years earlier). Sound is a tension wave created through a vibrating object, and vibration indicates the periodic back and forth motion of the particles, transporting energy through a flexible body or medium. The vibration then is multiplied as

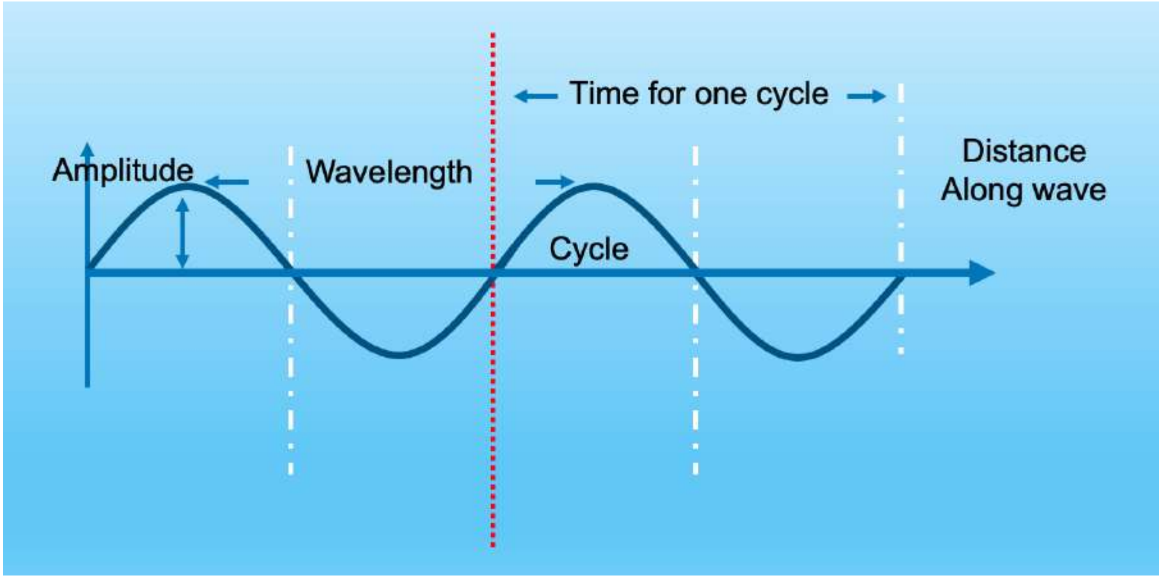


Figure 2.2: Characteristics of Sound Waves.

an acoustic wave via a transmission medium such as liquids, gases and solids. Vibration is simply a mechanical phenomenon via oscillations at a stable point. The vibration of sound leads us to a phenomenon called resonance. Resonance is explained through an object with a natural frequency that receives a forced vibration at the same frequency and it is a non mechanical systems such as electrical, and visual.

There is a difference between vibration and resonance. The vibrations here are called forced vibrations of a medium with an external periodic force of frequency different from the body's natural frequency and types of it can be described as oscillating, reciprocating, or periodic, either harmonic or random. Harmonic vibration emerges when a vibration's frequency and magnitude are continuous and random when the frequency and magnitude vary with time. On the other hand, the vibrations of a body under a periodic external pressure of frequency equivalent to the natural frequency of the body are called Resonant vibrations.

Chladni Plate

Chladni plate is a physicalisation invention of sound motion, vibrating plates made from metal plate surfaces with particles of sand that produced characteristic patterns associated with the physical dimensions of the plate, visualising the effects of vibrations on mechanical surfaces and it was invented by Ernest Chladni. Ernest Florens Friedrich Chladni (1756 -

1827) have accomplished multiple experimentation demonstrated at the *French Academy of Science* in 1808, studying the nodes of oscillation of circular and square plates, typically fixed in the centre and driven with a violin bow. The modes of vibration were identified by scattering sand or salt on a plate, and particles ended up in places of zero vibration. Figure 2.3 shows the drawings from Chladni's original publication [13]. Chladni patterns depend on resonant modes of flat plates. The Chladni patterns are generated by vibrations and can be channelled by fluid channels, as the thesis explores ways to capture and represent the fluidity deformation caused by resonance. The behaviour of the acoustic fluid resonator is numerically predicted by applying an acoustic-structure interaction model to calculate the acoustic pressure distribution at different modes of resonances.

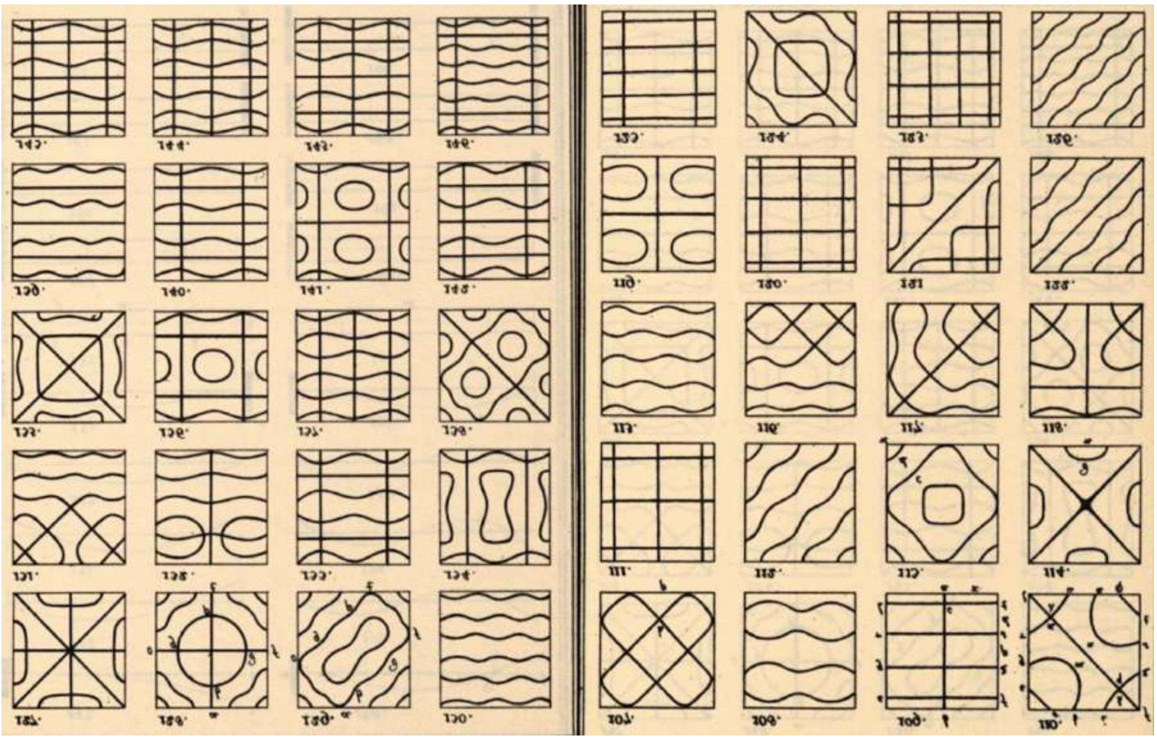


Figure 2.3: Chladni geometry patterns of nodal lines on a vibrating plate. Chladni's Book source.

2.4 Sound Shape Modelling Pipeline in CG

Deformable shape modelling and sound-resonance texture use external data to influence the object shell surface, creating a unique, organic geometric deformation pattern using 2D images of sound fractals as one of the novel approaches. The concept of the thesis's novel approach relay on how the principle of sound resonance affects the medium, as explained in the previous section, using image-based modelling data to deform, visualising the representation of sound resonance on the surface of the 3D object. The approach uses direct internal/external force of sound frequency image on the mesh, changing the mesh position and direction.

2.4.1 Deformable 3D Shape Modelling Using Creative Technology

This section focuses on VP modelling and sharing the diversity of real deformable shape modelling techniques for a geometric-based approach to physical interaction deformation on 3D objects. Computer graphics modelling over the past decades has shown a high demand for sophisticated realism of geometric shapes. Deformable shape modelling assists in designing for various fields, e.g., Art, Medical, Gaming, Engineering and many more. Digital technologies revealed a new path for contemporary art and creation. Today art, science and technology are united by a bridge of creativity, allowing cross-disciplinary fields to meet.

The impact of this bridge created opportunities and challenges for a new innovative approach, enhancing and promoting existing experiences and outputs as explained by Krasteva [14] VR/AR painting and pottery making is the creative beginning of advanced 3D modelling in art practice, opening the imagination to conquer realistic visual and physical real-world reality, to produce, share and enhance skills. Clay Based Modelling is a group of malleable substances used in building and sculpting. It is an ongoing trend for developers of 3D/AR/VR to use the concept in modelling for exploring, expanding methods of development. This method brings realistic deformation, representing natural objects transformations, to the human visual concept that augments a more genuine and actual visual appearance. Clay 3D modelling is a method that integrates digital deformation as simulation upon accurate geometric and physics data. It represents a 3D surface mesh sculpting with tools to push, pull, twist, inflate, surface relief, as well as a voxel-based geometry method to add/subtract.

2.4.2 Mouldable Shape Representations

Mouldable shape representations and research on these models have attracted the attention of several computer graphics researchers and modellers over the past few decades. The research presented some classical representations below as a timeline, showing the impact of deformable shape modelling on computer graphics from primitive to complex objects. The representation mainly is focused on the surface geometry changes of the object The research presented some classical representations below.

1970-1990

In the 1970s early ideas and concepts on digital and graphical Clay Moulding and Sculpting were proposed by Parent [15]. Technology allowed wire-frame shapes to be modelled. Geometric shapes and their interaction led to intersection of surfaces which were addressed to form complex 3D shapes.

Terzopoulos et al. [16] have proposed representations both for elastically deformable objects, as well as objects that exhibit more fluidity and plastic deformation. Coquillart [17] introduced free form surface shape deformation (sculpturing and moulding) and also used the term 'mouldable shapes' based on an extended free form deformation of latices. The article also shows realistic shape changes through a range of examples including cloth.

1991-2000

Szelski and Tonnesen [18] present surface modelling with oriented particle systems. They demonstrate greater flexibility in defining surfaces using particles that facilitates bending, cutting and merging. Gibson and Mirtich [19] present a comprehensive survey of Deformable Modelling in Computer Graphics. This captures a wide spectrum of techniques from the free form to a more physically based deformation representation.

2001-2010

Sourin [20] first demonstrated highly intricate and detailed functionally Based Virtual Computer Art. The examples of carving and embossing highlighted that the time for virtual art has come. Gu et al. [21] demonstrated that geometry could indeed be represented as images. These images enabled to capture geometry as a 2D array of vertex positions, vertex normals and textures. This added a new way of representing shapes and provided avenues for compression, sharing and deformation easier than before.

The approach for surgery simulation uses parametric model by Liu Qiang's Surgery Simulation [22]: Haptics on 3D deformable models is a challenge because of the inevitable and expensive 3D deformation computation. In their paper the authors proposed a technique that extends the conventional rigid geometry images approach. Their approach flattens the geometry, and also helps to accomplish deformation in an effective and efficient manner. They demonstrated their approach is suitable for haptics computing, to perform the deformation on the geometry map itself to avoid the expensive 3D deformation computation. They demonstrated construction of the deformable geometry map representation and its application utilising practical methods for interactive surgery simulation and interactive textile simulation. This parametric approach has potential for the proposed VP application.

Zhang et al. [23] introduced a non-linear multi layered model of the skin where the skin is built as a mass spring network. In Chen Chen's face simulation [24] the authors use an animation system for a personalised human head. The deformation from the template model to the target head is made through adaptation. Both general radial basis function (RBF) and compactly supported radial basis function (CSRBF) are applied to ensure the fidelity of the global shape and face features. Animation factor is also adapted so that the deformed model still can be considered as an animated head. Situations with defective scanned data are also discussed in their paper. This has potential for multi-layered shape modelling for VP.

2011-2020

Follmer et al. [25] presented a system called inFORM that attempts to use shape displays to create physical interfaces and is limited to 2.5D shapes. The physical shapes themselves are captured by using 1-D pins in a 2D array controlled by actuators creating a representation of of object deformation. On the other hand, Weichel et al. [26] a method of modelling clay objects by integrating physical and digital models through a bi-directional fabrication approach. The technique uses scans of a physical object basic shape to be transformed into a virtual model. Then creating natural deformation of hands tangible modelling. This method works through iterative addition/subtraction of material, then it is scanned, and vice versa until the user completes the model.

Arango and Neira [27] use a Unity Procedural modeller for representing deformable meshes in their VP example. They used a Unity Procedural modeller for representing deformable meshes in their VP example. They achieve real-time performance by exploiting the underlying tool features. However reloading meshes are expensive and they use a blending approach to update meshes less frequently to achieve the speed. They also achieved a feedback through synchronised auditive, depth cues and haptic feedback. Arango and Neira also provide an option to export the meshes to an STL mesh suitable for fabrication. The types of mesh deformation involved is quite simple and hence the STL baking seems to work. However, for complex deformations, the STL baking needs more detailed slicing tool.

To summarise mouldable shape representations over the past daces showed a great impact on computer graphics modelling. Interest on clay modelling started in back then in 1970 as realistic object deformation and is still growing to date. In 2007 Liu Qiang's [22] showed a different path for realistic deformation methods. His geometry maps were the most significant concept that helped on shaping the research of the thesis. It shows how to obtain more normal deformable parameters for changes on the surface of the 3D model. The difference between Liu Qiang's approach and the thesis approach is using 2D image geometry patterns that deform the shell surface only, and the basic object deformation is done by physical interaction using physical and virtual VR kit tools. On the other hand, Weichel et al. [26] their proposed method of linking objects in a bi-directional way as a reliable way as a concept to connect objects back digitally. Nevertheless, there are some constraints. The clay as a property as a material will change due to world constraints, air, gravity that may create cracks, and the scans may not be accurate. The thesis approach uses the concept of integrating more than one application, linking the physical object back digitally using the volumetric texture as a tracker QR code, for interactive AR interaction as an audio visualiser.

2.5 Immersive VR for Virtual Pottery

Many industries have integrated various creative technologies, tools, and applications to enhance productivity for optimised outcomes. Two of the common challenging aspects of virtual modelling are the experiences in multi-disciplinary engagement of innovative technologies to fabricate a successful VR object and understanding the aspect of collaborative design and prototyping. The usability of the VR pottery modelling aspects assesses the visual feedback [28] and real object analysis and implementation phases, providing guidelines for designers and developers to improve VP modelling and create a beneficial interaction.

2.6 VR Usability

There has been comprehensive research for VR usability using traditional evaluation techniques for graphic user interfaces [29; 30] and not so much on VP with multi-disciplinary engagement. The methodologies the research seeks can help developers, and users better understand approaches, tools, and application integration.

Pietrowicz et al. [31] explained that virtual worlds are 3D simulations of real or imagined worlds, extending reality by integrating experience between the physical and virtual worlds, implementing even more possibilities. The human interaction in VR is more expressive, more influential, more dynamic human control paradigm. They investigate high-performance interfaces modelled after the techniques of musicians and other performing artists. The developments employ automated learning skills and data mining methods to extract features from multiple data streams: audio, motion capture, etc.

Casu et al. [32] presented RiftArt as development in user hardware that lowers the cost limitation for adopting immersive VR solutions. The RiftArt is a VR tool that supports the teaching and studying of Art History. RiftArt configures virtual museum rooms with artwork models inside, enhancing the experience with multimodal annotation. This approach assists teachers throughout lessons and during students' rehearsals. The study also demonstrates how VR increases the motivation of high-school students' to study Art History.

Huang and Lee's [33] presented an exploration of the learning usability factors of 3D modelling in a virtual reality environment (VRE). The aim at understanding users' 3D modelling usability factors in VR investigated through principal component analysis (PCA). Their studies involved fifty industrial design students who participated in the 3D modelling learning in VR experience experiment. They used System Usability Scale (SUS) scores to assess the user experience for the 3D modelling interface in the VR environment. The results can be provided to 3D modelling software developers as a key reference in VR learning interface design.

De Klerk et al. [34] explained how VR can assist architects at the early stages of creativity and design. They built and explored maquettes at different scales in early design stages. They developed a VR environment where untethered, easy-to-operate peripherals support user interactions, using VR headsets to provide virtual immersion and simplified geometric to model voxel-based maquettes. The show also how usability studies with laypeople suggest that the proposed system is easier to use and more effective than current CAD software to create simplified models rapidly. The results play a visible role in supporting the creative process, allowing architects to become both builders and explore spatial constructs.

Finally, Lteif et al. [35] presented an observational study for the integration of VR technology with art. The study was conducted by replicating an actual museum by a Swiss-Lebanese artist and having the users experience it in an immersive virtual environment. The study collected data was to monitor the user experience and its effects on the emotional and psychological state. Then, the collected data revealed the developments and enhancements, elevating the user experience and possibly improving and enhancing it with more advanced technologies.

2.6.1 VR for Fine Art

VR modelling is one of the cutting-edge creative technologies that supports deformable shape modelling, using physical interaction data to enhance objects by colour and deformation. Kim et al. [36] introduced a high-resolution method of volumetric painting in VR with high depth complexity. The technique consists of digital painting on 2D surfaces extended into 3D volumetric painting.

Pioaru & Ioana [37] examine Tilt Brush, the VR painting application produced by Google as a collaboration between artists and scientists, enhancing creative practice opportunity for users and their 3D artwork created VR space with sharing creations online. More so, turning the 3D VR object into a holographic format for a wider public.

Sener et al. [38] presented a literature review exploration on virtual clay modelling and tools, showing attempts offered on the haptics for force-feedback by Gribnau & Hennessey [39]. More so, highlighting Computer Aided Industrial Design (CAID) is simply the use of computerised software in the industrial design process. The CAID tool grants designers creative freedom, creating a sketch using a stylus, following which, they will generate curves from the sketch and in turn generate surfaces from the curves. Although many CAD tools are good in some ways, the tools shortcoming are about not allowing designers to employ all skills, explaining how 3D modelling is challenging and users must master 3D modelling, to produce sophisticated and complex 3D objects.

As a result, Sener et al. [38] suggested using CAD tools to generate 3D objects using PHANToM haptic devices human-computer interface technology for users to touch and manipulate virtual objects, considering free-form for a better development process. Sener's approach gave a solid ground to develop the concept of VR clay modelling and prototyping. This approach supported the idea of integrating the system method to establish a VP novel system by Dashti et al. [40] .The integrated system of 3D graphics toolkit software showed new opportunities and challenges to enhance both fields of computer graphics and traditional pottery making.

2.6.2 VR in STEM Edutainment and Training

In recent years VR technology has started assisting in transforming our life. VR is now involved in many filed such as education, medical practice, engineering, art, and more, becoming an increasingly valuable tool. Currently, it is considered a tool used in improving skills, entertainment, remote learning, collaborative work and many more. The VR technology now is not only associated with labs; any individual can use a VR kit.

Wang et al. [41] in 2022 presented a method of Edutainment learning using VR technology. During the Covid-19 pandemic, the schools were shut down, and Wang et al. found an extraordinary opportunity to introduce conceptual learning design in VR during the global crisis. The situation was around students who had no access to education. They highlighted findings in an integrated learning design with outcome deficiency. The study potential mainly focuses on the solutions for current educational challenges presenting design the cognitive VR classroom. The design enables students to access rich learning resources within an immersive VR system. The design was based on an amalgamation of brain-based learning theory (BBL) and the cognitive-affective model of immersive learning (CAMIL). They validated the design with a correlation analysis conducted to present the correlation coefficient and the strength of the association. The cognitive VR classroom showed a promising theoretical framework to promote educational diversity and a powerful model to develop innovative classroom learning. Gao et al. [42] propose an interactive installation for VP, which uses motion sensing to understand ceramics art better. Arango and Neira [27] present a VP system that uses affordable (low cost) technology, allowing novices to understand the experience of traditional making as a game and gaining new skills, not as a research-based experience. However, in both systems, the physical feeling of pottery making is absent due to the use of mid-air gestures.

2.7 VP Systems

VP systems include an automated mesh generator and an interactive model editor. The mesh can generate more of a realistic clay in VR, and users can use the concept of deformable shape modelling to shape the virtual object based on real pottery making [43; 44]. In the Wowtao VP system presented by Cai et al. [45], the approach is about creating a topologically equivalent to double-layer of cylinders as a basic vessel, with option to push or pull, without texture relief, mesh growth of a dynamic typology or sculpting tools. The most advanced approach is presented by Dojagi [46], a STEM application that creates more of the traditional experience of pottery making by using a VR kit and real space. The advantage of Dojagi's system relys on the accuracy of pull and push motion on VR objects, with multiple tools to subtract as a Voxel-based modelling.

2.7.1 VR Experimental Evaluation

VR modelling tools are a cutting edge technology with continuous development over the past decade. The exploration of creating 3D objects in VR space with physical interaction, searching for an exceptional opportunity toward contemporary art and design in diverse sectors, e.g. pottery, fine art architecture, interior design, landscape and 3D design. The aim is to understand the spatial relationships within a 3D structure, to unleash the creativity of visual and physical interaction [47].

2.7.2 VR Usability Studies

Zaidi et al. [48] propose a framework for usability evaluation of gamified VR and focuses on how VR could be adopted for different purposes for different users and evidence that VR bring positive emotions. Mäkinen et al. [49] presented a review analysing the usage of different VR technologies in learning and user experiences (UXs) in healthcare practice and education. The survey exploration of different VR technologies used in healthcare education and practice was recognised: haptic device simulators, computer-based simulations, and head-mounted displays (HMDs). The focus of the study was on the user's internal state of mood, expectations or motivation with the characteristics of the system's usability and functionality. The result of the review showed how VR technology enables the innovation of a comprehensive experience for the users. VR technology there led to improved skill development, boosting remote access to training, creativity, training methods and, finally, improving patient safety.

2.7.3 Improving Virtual Prototyping

Müller et al. [50] investigate virtual prototyping guidelines of interaction and visualisation techniques to overcome current limitations, evaluating the user interface concepts in integrating VR in a participatory design process, and introducing agricultural machinery and the automotive industry as application scenarios for VR prototyping, as well as, emphasising how the current technological advancement in virtual prototypes are affordable, quickly realised and easy to modify.

2.8 Prototyping

Prototyping is the development in the arena of advanced manufacturing technologies-the additive manufacturing used for the fabrication of prototypes with a range of materials and devices. The aim is to convert voxel modelling visualisation suitable for product fabrication. Three-dimensional printing or rapid prototyping are computer-process models, selectively curing, depositing or consolidating materials in continuous layers. These essential technologies significantly improve the present prototyping practices in the industry of manufacturing and now by individuals in many fields. This technology have emerged for fast creation of 3D production directly from computer-aided design systems.

This section covers a particular set of essential research regarding modelling to fabricate rapid prototyping methods that have shaped the thesis research project- the idea of prototyping VR objects design, model and analysis. Rapid prototyping over the past years have shown remarkable progress, and the thesis presents a timeline for 3D modelling, visualisation and rapid prototyping. The timeline should give some insights into how the thesis presents the background as a blueprint mind map evolving the concept of visualising VP/3D integration designs towards rapid prototyping. The timeline is highlighted below:

- Free-form prototyping (1992) [51].
- Voxel-based 3D modelling and layered manufacturing (1995) [52].
- Virtual prototyping using CAD-VR data integration (1998) [53].
- Voxel-based terrain modelling (2000) [54].
- Interlocking connections (2006) [55].
- Image based modelling (2010) [56].
- VR voxel-based modelling of line-drawing and volume rendering (2018) [57].
- VR pottery review of modelling tool and applications (2020) [58].
- VR modelling line deformation and fabrication using clay (2021) [58].

Next, the thesis presents some of the important research that helped on shaping the research beginning from VR/3D voxel-based approach for understanding CAD Voxelisation and how it impacted physical modelling designs and materialising methods.

Free-form prototyping:

Catania [51] proposed a prototype method of rough milling free-form mechanical moulds using the NC tool path. The technique system allows direct modelling of the shape of the material to remove the excess areas. The system's technological consideration of the main cutting force resulted in a geometrically evaluated fine tunning milling feed rate. Catania presented algorithms for computing parametric layers and the automatic generation of tool paths with end-mill cutters. *Voxel-based approach:*

Chandru et al. [52] proposed a voxel-based approach for geometric modelling as the new method for rapid prototyping. The proposed method shows resemblance with the voxel model and layer manufacturing (LM) technologies, introducing an interactive environment for voxel sculpting to create a voxel-based geometric STL design.

They designed a method based on a CAD Voxelisation algorithm for layered manufacturing. They proposed that a designer can selectively modify individual voxels using union, intersection and determining layer thickness. Furthermore, the approach shows that the number of layers can define the smoothness. In addition, the author introduced elements of an interactive voxel-based sculpting system for modelling and proposed a design system as a powerful interaction paradigm that gives a designer freedom to realise arbitrary shapes, providing more coherent volume and reducing incremental computations into the unstructured grid in a 3D space.

CAD-VR:

De Sá and Zachmann [53] investigated the steps of applying VR for virtual prototyping to verify assembly and maintenance processes. The proposed method involved CAD-VR data integration in identifying requirements of design quality, showing VR prototyping will play an essential role for VP in the future.

CAD-VR functional designs:

Sass et al. [55] exhibited physical modelling designs and materialising attempts of interlocking blocks, formulating critical aspects for designing a methodological framework of Digital Design Fabrication (DDF). Their approach builds artefacts as part of a creative design process. The assemblies of their method involve creating modules as male or female for interlocking connections, integrating generative computing and rapid prototyping into one process, situated between conceptual design and real-world construction.

Volumetric image-based modelling:

Gilet et al. [56] proposed volumetric image-based modelling using photographs that fit the parameters of a multi-layered noise-based 3D deformation model surface. The deformation occurs only on the shell surface of the object. Ueng et al. [57] showed a fabrication method for prototyping virtual objects that performs line-drawing, animation and volume rendering, using voxel-based manufacturing simulation. The approach focused on detecting printing errors of design with debugging for advanced printing outputs.

VP fabrication designs:

Cao et al. [59] summarised the new cutting edge technologies, tools and applications referring to virtual advantages/disadvantages of pottery interaction making in a cylindrical digital clay volume. They introduced forming and deforming tools with force feedback for the actual pottery production process, enhancing the user's sense of immersion.

Hanssen [58] created a relationship between clay as a material and the prototyping process. They explored ways of layer fabrication using the inner negative space as a creative support structure resembling the Voronoi pattern. He expanded from capturing the designer's hand movement to 3D printing, which is a complex attempt for a physical and parametric model. Also, he used VR layer modelling as pattern-making within the walls of a cylinder shape as an integrated process while building up the object, using a FDM clay printer to prototype the object.

2.9 Development of a VP System

This section aims at a system level view of integrating the various components of VP System including the modelling, interaction and prototyping. Several alternatives exist for building the system. Three such experimental and evolutionary design are presented here.

2.9.1 Design #01: VP Information System

The research background analysis focuses on the representation of data-physicalisation of interactive deformation [25]. Also, the representation of sound deformation exists in both technology and art fields. Not only the importance relays on how to control deformation digitally through creative technology but also on acknowledging the understanding of new patterns in the innovative fabrication of animated designs.

Today, it is possible to represent data artistically as a way of a human connection through creative technologies.Bringing the realistic quality of deformation towards digital objects among physical interaction dominated the field of real-time computer graphics in the past decade. Deformable shape modelling research focuses on producing and generating an illusion of motion with 3D characters and the surrounding environment. Exciting discoveries of deformable models such as efficient modelling for interactive deformation of non-rigid 3D objects, convey a practical method of surgery simulation, helping surgeons and patient, communicating results of how wound healing would happen even before the actual surgery is done [22]. Texture mapping techniques are propagating on vast areas of deformation, allowing 3D object digital- fabrication with high-quality details. More so, texture mapping of volumetric mesostructured explores how a 3D object bends with creating deformation to the surface structure as it would do in reality [60]. The project presented in this thesis investigates tracked sound deformation across realities with clay as a physical and digital medium carrying the physical interaction towards bidirectional digital-fabrication [26; 61], creating a bridge between Art & Technology. Fig 8.2 shows the block diagram of the information workflow.

2.9.2 Design #02: VR as New Norm

The research background on analysis and evaluation focuses on creative technologies such as VR tools/devices and 3D printing creating Art forms during Covid-19. During the last decade technologies have emerged, with art showing how it is starting to catch basic non-professional users' interests. Pottery making is one of the art field that got the attention of games developers to create a simulation of the experience and the output of 3D digital graphics using Rapid Prototyping [27]. This is due to challenges that may occur in the real world, e.g., having a workshop, changing material characteristics, tools and devices. The developers have created a virtual space with sculpting tools and digital clay using real-time physical activity [62; 63], to experience a 3D object making process as shown in Fig 2.4. This method recreates the the physical motion activity in a virtual space allowing virtual positioning of virtual tools and devices to get the whole traditional and physical experience.

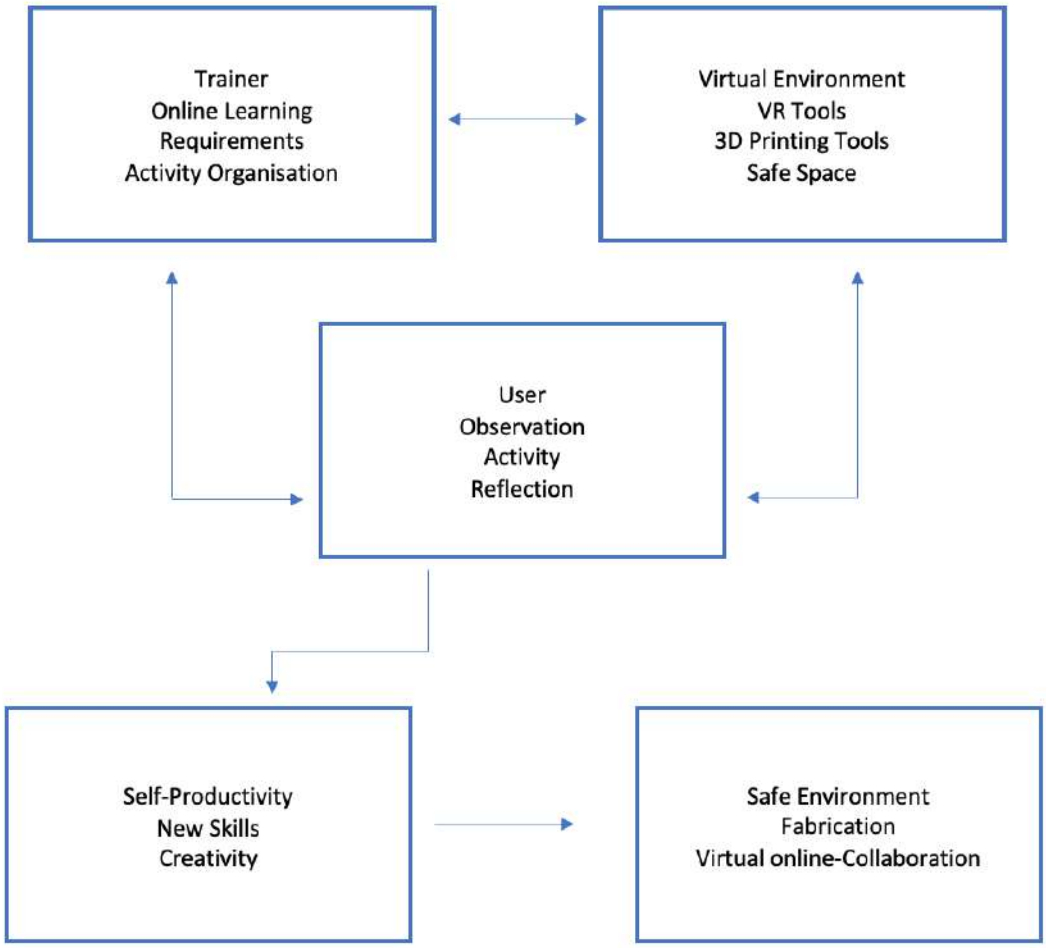


Figure 2.4: Virtual pottery making - the learning and fabrication process.

However, the documentation possibilities of traditional pottery-making for going digital have not been fully explored, to fill the gap of knowledge and apply it as a reliable method for developing real skills through Physical-Virtual learning [64]. The realistic experience and quality of deformation of real clay are the main goal of object digital transformations, among physical interaction remains to dominate the field of real-time computer graphics. The research proposed in this thesis investigates the skills development and the outcome of virtual making and fabrication. Also, it evaluates how stable is this method to be considered a competitive and an alternative tool to traditional pottery making.

In the early 2020, the world was led to a global shutdown, most of the viable sectors faced unprecedented challenges. In response, other than emergencies, training and educational sectors showed a creative growth of using creative technologies in virtual spaces to adapt to the new environment due to the rules and restrictions to safeguard health and to stop the spread of the virus. The global pandemics appears to raise the bar for creative technologies evolving to the maximum limits of physical and learning activities, to show in the short-term to accomplish it in-home space. Individuals are searching for ways to absorb new ways of learning and developing new skills to mitigate this situation.

2.9.3 Design #03: Digital Twin

The integration of VP and digital twins is an ideal perception of object mirroring, having great benefits for manufacturers in advanced production features of complex systems. The realisation of the digital twin creates connectivity between VR and physical objects, producing communications capability using smart production systems [65]. The intent of this concept is mitigating system complexity by providing improved information to the physical twin object. Digital Twin technology is one of the ultimate cutting-edge initially proposed concepts as a centre of attention for industry, representing the benefits of developing virtual and physical objects in real-time, creating a strong link in the manufacturing process. The Digital Twin concept refers to the integration of cyber and physical space devices in a bidirectional way of production [66]. This type of technological concept is used in many applications implemented in diverse industries, including production, product design, health management, and other fields [67].

2.10 Summary

This chapter presented the background research for elements essential for VP. Three key crucial background areas: modelling, interaction and prototyping have been identified. For a VP system, it is essential to integrate the subsystems seamlessly. Furthermore, the chapter gives insights into the flow of the chapters for the rest of the thesis. Next, each section was expanded and explained logically in the thesis in a separate chapter, maintaining the understanding of how to conduct such research. The next chapter discuss VP-systems designs approach and results towards digital twin technology.

Chapter 3

Literature Review

3.1 Texture & Deformable Shape Modelling

This chapter presents literature assisted in developing the novel technique by highlighting the gaps in knowledge and introducing essential information on elements for 3D modelling, Chladni plate, VP systems and systems VP refinements.

The chapter includes a overview diagram shown in Fig3.1 to explore the techniques of integrating deformable shape models with detailed volumetric texture modelling using sound resonance from the Chladni plate [68] software to visual property of a rigid and non-rigid surface [69], also called Cymatics [70], and in comparison with noise texture representing the unique information contained for a better approach for AR/VR applications.

3.1.1 Sound Shape Modelling

In the beginning, the chapter highlights interactive modelling of sound resonance shapes for 3D making several challenges and desirable properties:

- **Labour intensive and Compute intensive:** Sophisticated approaches for 3D deformable shape modelling are available to create realistic output, through 3D data input of deformable physics-based simulation but still considered as labour-intensive and time-consuming [71].
- **Innovative Art Designs for Artists:** Recently, several traditional ceramic artists are engaging with digital modelling, and others of different artistic backgrounds towards creating contemporary innovative art designs [72], using creative technologies and ap-

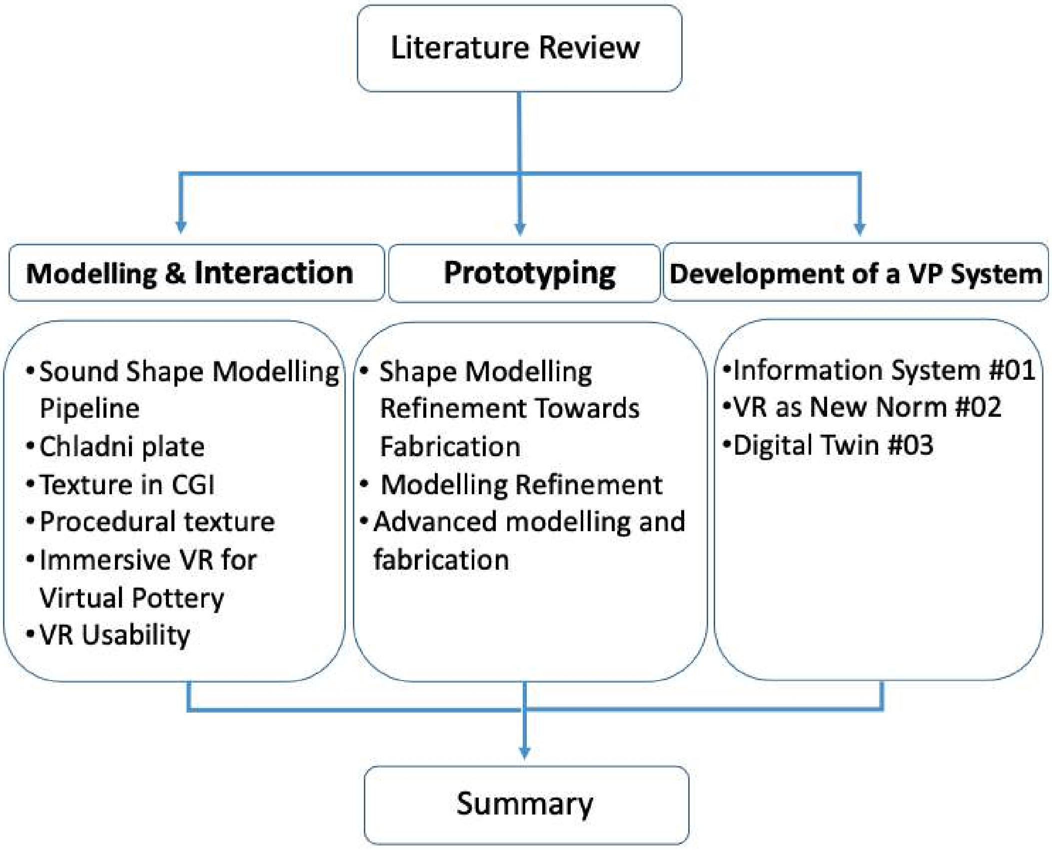


Figure 3.1: Background overview structure

proaches to capture interactive data [73].

- **Fabrication:** The study focuses on assisting users on interactive physical modelling with sound materialised designs as a deformation effect [74; 75] using a virtual modelling application for the basic shape and then creating mesh designs with 3D modelling software, e.g. Unity-mesh [76] and Blender with the ability to export STL files for rapid prototyping using different mediums [77].
- **Capturing Energy Forms on Material:** In the past few years, artists and basic users explored ways of physicalising energy forms as active data, e.g. magnetic energy [78], sound waves.
- **Representations:** Deformable shape modelling uses algorithms and techniques to represent the shape and realistic surface transformations [79]. The proposed new approach incorporates ways to design, develop and demonstrate a simple system and workflow innovation, for art embodiment of physicalised acoustic resonance of 2D sound data through 3D deformable modelling and control [80] to produce textured mesh maps.

- **Blending Sounds in Fluid:** Real physical shapes and textures are the primary sources of information towards deformable shapes of rigid and non-rigid forms [81]. This technique creates low technical user engagement of a digital modelling and fabrication [82], towards creating a natural parametrisation with material manipulation of physical forms and properties [83], e.g., density and viscosity [84], using a series of images and animated graphical sounds exploring volumetric deformable 3D textured shapes [85].
- **Sound as a Volume Texture:** There are many works on creating deformed surfaces using different types of maps and modifiers integration to represent a genuine detailed surface extending the concept of volumetric texture [86], displacement and bump maps [87].
- **3D Fabrication of Sound:** Sound-structure texture explores ways to model and fabricate 2D images [88] using maps with mantaflow physics [89], creating a volumetric surface that generates fine detailed features [90]. The prototypes explore different printable materials, e.g. ceramic resin and PLA.
- **Physical-Simulation:** Object deformation simulating real-physical object flexibility by transforming shells is demonstrated, e.g., bending and stretching [91]. These maps and textures techniques, allow the geometric object of substantial volumetric shapes to produce a real physical simulation for a considerable flexibility [22], having a more realistic prototype of sound resonance textures defying real-world physical constrains [92].
- **Natural phenomenon:** A fundamental reason for traditional and digital artists to consider this novel approach is that it utilises natural phenomenon [93] with creative designs using 3D modelling technology and rapid prototyping, that can communicate digital and sound energy [94]. It allows developing textured forms promoting creativity and productivity by having a functional art embodiment of physicalised data. There are some experimental demonstration of using of sound resonance energy creating sound deformation as a method of Data Physicalisation.
- **Contemporary Designs for Other Applications:** Finally, understanding the impact high-detailed manipulation interference with digital modelling and fabrication would be beneficial for contemporary designs [3] for, e.g., ceramic artist, product designers,

makers and also game designers to produce a distinguished immersive deformable textured shape models.

Furthermore, the thesis presented a novel approach for VP and 3D modelling with augmented reality interaction, delivering a high-quality prototype. The framework offers a simple 3D texture modelling and digital material properties manipulation [27], using sound images to produce a '3D Sound-Structure Texture' exploring new horizons of making, in contemporary ceramic art.

3.2 Chladni Plate

3.2.1 Chladni Plate Patterns in Art & Science

The human being, in life, explores ways to express the aesthetic of emotions, religion and science, using the surrounding of nature with the environment in an artistic vision or in a physical way to complete the image of reality. The creation of images made out of sound is an ancient discovery from many civilisations, called Cymatics. Cymatics can be referred to as the science of visualising audio frequencies. The section explores the integration of art and science, showing the challenges from an artist's perspective, using technology to represent Cymatics's visual and physical aspects. Over the past years, many artists tried to physicalise sound, using clay as a medium with sound energy to deform and reform the medium aesthetically to create a unique texture [95]. In the visual arts, the texture is the perceived surface quality of a work of art & craft. It may be perceived physically, through the sense of touch, visually, or both. The artists involved in CG created labels for their artwork, such as digital art, telematics, generative art, computer art, computational art, process-based art, software art, electronic art, and technological art [96].

3.2.2 Chladni Plate Generative ART

Generative art is still contemporary within the artistic community. Since 1998, there have been conferences about generative art., and Brian Eno [96] has been influential in promoting and using generative art methods. Integrating music and visual art lets a computer system carry over some decision-making, with the artist determining the rules from a step-by-step algorithm. Boden [97] argued that computer art, in general, that art involves creativity and that no computer, irrespective of its observable performance, can be creative. The generative tool is a method to bring out creativity cross-disciplinary. The chladni plate is considered a generative art to create unique, complex textures patterns that can be used visually and on physical objects.

Grzegorz [98] explored generative art using an autonomous system. He explored ways to emphasise generative art algorithmically determined by computer-generated artwork. The artists can use chemistry, biology, and mechanics data and use robotics, smart materials, manual randomisation, mathematics, data mapping, symmetry, tiling, etc. He created an artistic generator tool for an arbitrary number of complex abstract graphics unique artworks, using an integration of a reaction-diffusion system and spatial Chladni figures in numerical simulation. This tool is based on random Chladni patterns and selected 2D space deformations, and both are applied to equation coefficients. The transformation of coefficients of differential equations as a function of space to deliver various non-trivial commands of the reaction-diffusion system. The experiment system output was a unique and non-periodic image representing the result of the Gray-Scott system simulation has been presented. In summary, he managed to implement the following:

- Combination of various patterns in a single simulation.
- Spatial generation of smooth and continuous regions related to patterns using Chladni patterns amplitude functions.
- Deformation of the patterns.
- Perturbation driven by the nonlinear transformation applied to Chladni patterns.
- generates nearly infinite random parameters.

Many artists have experimented with science and technology, testing ways to represent natural phenomena aesthetically. The artists are constantly exposed to visual, auditory, and textual intakes. The expression of each artist is uniquely performed, finding new ways of representation. This section focuses on incorporating sound energy with ceramics as a texture creating unique deformation from sound resonance.

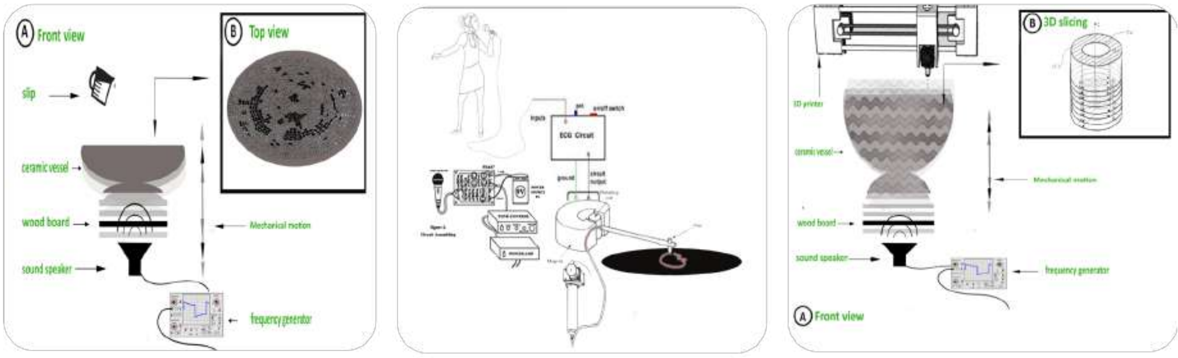
Sidlauskaite [99] is an artist that explored clay with technology with sound resonance phenomena. She created Cymatic patterns using liquid clay with a mix of glazes targeting the surface of a ball. Sidlauskaite used a frequency generator connected to a sound speaker, as represented in Fig 3.2a. She used the mechanical variation motion (up and down) to create Chladni plate patterns on a semi-flat surface and left them to dry. Though there was a visible result, the surface was not flat enough to create an even layer. Also, the properties of clay, glaze, and real-world constraints such as air and gravity didn't preserve the richness of Chlandni's pattern.

Segal and Maayan [100] presented a plate recorder that analogs sound visually and physically. The experiment focuses on decorating and texturing. The experimentation operates on ready-made ceramic plates, used as a medium for recording sounds with real-time printing from printed human vocals, represented in Fig 3.2b. The experiment is established by using an ECG *electrocardiogram* to record the electrical signals. The signal of sound created has a unique texture printed on the surface of the plate, using glaze and clay material to decorate the surface.

Herpt, in 2013 [101] explored unique ways of designing clay, using the technology of 3D printing with sound vibration to deform the layers of the print, creating a distinctive pattern. It is another way of using sound resonance energy to affect the vessel's structure. The design control was by trial and error method in a vertical motion (up and down) with the mechanics of sound speaker represented Fig 3.2c. Though the method is good, this method creates texture using the basic vessel with minimum control and located area of layering deformation. The design details are affected by the properties of the material with the air pump of the 3D printer.

3.2.3 Generating Chladni Patterns Using technology and CG

This section explores the literature on experimentation to generate Chladni patterns and Chladni plate in CG. Over the past decades, the human interest in using sound resonance phenomena, in reality, has shown a significant growth to be perceived in CG as a way of a more precise representation and exploring ways to implement. The idea of using the Chladni



a. Cymatics on Ceramics

b. Physicalising sound with Plate Recorder

c. 3D printing ceramics using Sound Resonance

Figure 3.2: Sound Data Physicalisation Experiments

patterns is to visually create unique geometry textures and interact with a mesh of the object, changing the geometry. Considerable studies tackled the Chladni pattern from different perspectives and functions, generating various representations of the Chladni plate analogy. The following paragraphs show some important literature emphasising experimental resonance patterns using frequency spectrum. The experiments measure vibration mode shapes, formation in liquids and motion of heavy particles, and mathematical functions in processing, besides reconstructed development.

3.2.4 Generating Chladni Patterns

Lévy [102] explored the challenges in geometry processing to rebuild a higher-level representation from raw geometric data automatically using Chladni patterns on an object surface. He examined eigenfunction corresponding to spherical objects used in CG, representing functions of radiance fields, bidirectional reflectance and distribution functions. The eigenfunctions of the Laplace-Beltrami operator define a hierarchical function basis. Laplace-Beltrami in differential geometry generalises the Laplace operator to functions described on submanifolds in Euclidean space and, even more generally, on Riemannian pseudo-Riemannian manifolds.

Schajer & Steinzig [103] explored the classical Chladni method on a saw blade placed horizontally, using the low-frequency vibrations mode with powder to create patterns on the surface in real-time. Their approach aimed to reproduce a series of Chladni's mode shape measurements employing Electronic Speckle Pattern Interferometry (ESPI), captured in a high frame camera. However, their method can be used only for a simulated visual demonstration of measurement on different surfaces by changing the standard plate of a square or circle into a saw blade to create a new deformation pattern on the end of the blade's edges.

Tuan et al. [70] presented a study on Chladni nodal line patterns and resonant frequencies for a thin triangle plate using slat particles. The study experimentally aimed to control the mechanical oscillator measurement. The results indicated that frequencies could be relatively obtained through probing the variation of the effective impedance of the exciter with and without the thin plate. They used the *Helmholtz* equation exploited to derive the response function as a function of the driving wave number for reconstructing experimental Chladni patterns. Tuan et al. results indicated that the objective of the dispersion relationship established the agreement with the formula of the *Kirchhoff-Love* plate theory as shown in Fig 3.3.

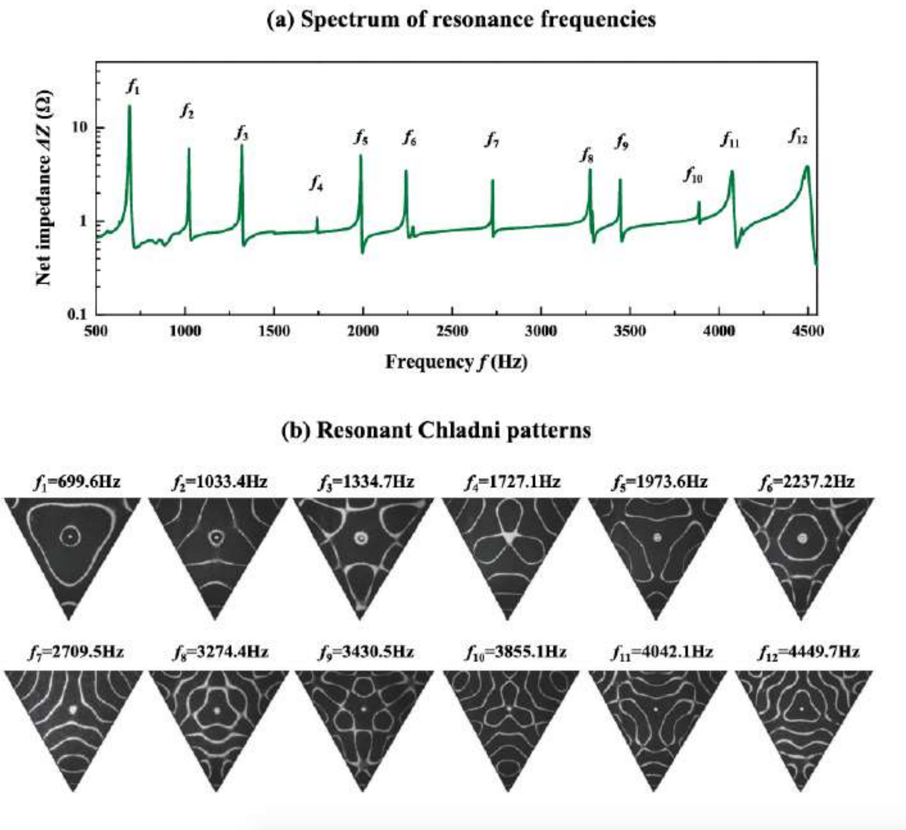


Figure 3.3: Experimentation of Chladni patterns (a) Shows experimental frequency spectrum given by the net impedance of the triangle plate. (b) Shows a nodal line patterns at the resonance frequencies *fi* depicted in (a). Chladni experimental patterns source.

3.2.5 Chladni Patterns Formation in Mediums

Latifi et al. [104] explored manipulation motion techniques with the Chladni pattern, using heavy particles submerging the resonating plate in a fluidic medium. The acoustic radiation force and the effective lateral weight become dominant at the sub-mm scale. They experimented with frequencies in a broad spectrum of resonant and non-resonant frequencies, controlling single particles' motion with a group of particles on the submerged plate.

Lei et al. [105] also experimented with the classical Chladni patterns formed on the cross-section of the fluid channel, using standing bulk acoustic waves. The experimentation presented as an acoustic-fluidic resonator, enabling the visualisation of microparticles in a fluid both on its cross-section and flow direction in a cylindrical wall. The study focuses on the behaviour of acoustic-fluidic resonators numerically predicted by applying an acoustic-structure interaction model to estimate the acoustic pressure distribution at different modes of resonances and the *Gorkov* approach to acquire the possibility of the acoustic radiation pulls that act on suspended particles.

3.2.6 Chladni Plate in CG

Mat Tahir et al. [106] explored Digital Image Correlation (DIC) is a modern non-contact optical techniques measure the static and dynamic displacement problems, material testing, and fracture mechanics. Their paper compared using a digital image correlation method and validated the images with the Chladni plate method. The study aimed to visualisation the experimental Chladni method of vibrating mode patterns to reveal some of the benefits and boundaries of the DIC process for vibration mode shape analysis.

Chladni Surface Texture

Kawai [107] explored mesh design in computer games and animation. The study focused on natural mesh processing and how it often has nontrivial surface shapes and high degrees of freedom. This approach was inspired by the association between fractal biological systems and their underlying *power-law spectra*. The study explained Chladni patterns as a *Manifold harmonics* as a theory of stationary waves. Also, the set of sinusoidal basis functions that

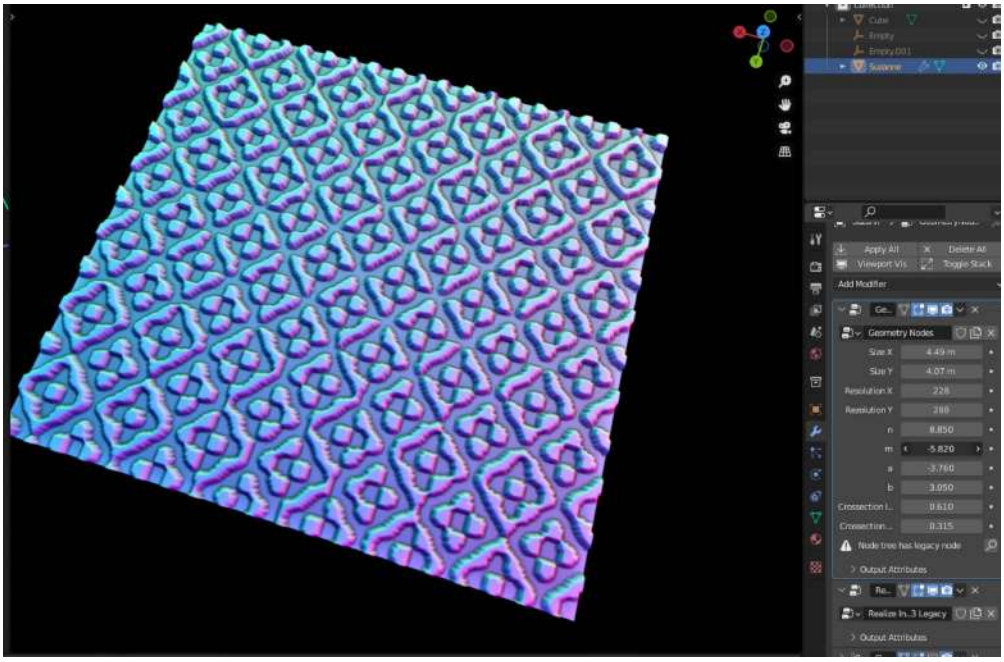


Figure 3.4: Chladni fractal geometry node experiment, using Blender software. Chladni node project source..

emerges in the Fourier analysis can convey by computing eigenfunctions of the Laplacian matrix emanated from a vibrating circle and on a circle graph

Ikpe et al. [108] presented a study of an alternative method of determining the modal shapes on vibrating plate, simulating the modal frequencies and Chladni patterns in thin plates under acoustic excitation. The study showed applications where the displacement or response of components under the influence of vibration is vital. The experiment was performed on a thin plate subjected to acoustic excitation, using fine grain particles such as sugar, sand or salt with the Finite Element Method (FEM). The *HYPERMESH* speeds up CAD to FEM working as an analysis of local structures identification and subtraction of duplicative material generated results relative to the experimental values.

Vladimirovich is an expert digital artist that uses **Blender** tool to illustrate his creativity. In 2021 he experimented with an attempt to implement the Chladni pattern on the infinite plane, using geometry nodes, changing the mesh geometry using metal material. The patterns are controlled by geometric algorithms with selected frequencies showing the *xz* size and resolution with cross-section level and width. The is also a deformation control to curve the plane. Although it is a reasonable approach, it has limited texturing abilities. The texture resolution was low, and the mesh blending or the displacement was not smooth. It is ideal for simple visual demonstration but can't be used for smooth, detailed texture texturing as it shows pixelated texturing. Finally, this approach is for advanced users in 3D modelling. The users of this project must understand how to create a material and change the geometry displacement of an object mesh considering a longer baking time.

Chladni Plate Functions:

Yucel & Yildan [109] proposed an interface of the software that displays Chladni patterns fractals of algorithmic visualisations of mathematical functions and a menu for manipulating variables. The software is called **Cymatify**, and it has seven functions creation of the basic mathematical formula to manage the type of the function allowing the users to generate patterns by modifying mathematical functions and variables in the following:

- Frequency value
- Size of the grid
- Density of the grid
- Colour of the patterns
- Generating and manipulating patterns
- Stroke button
- Export fractals image

The result of the study contributes to the scope of the Chladni plate pattern in CG, discussing the complexity, unpredictability and diversity of the patterns and exploring minimum displacement created visible in particles, liquid or sand. The main goal of displacement understanding is to inform the digital particles by the sound waves coming from preset source points. This information contains the location data designated by the waves for the points. The essential trigonometric periodic functions such as sine, cosine, and tangent simulate sound waves in a digital environment.

Tuan et al. [110] experimented with point-driven modern Chladni systems subjected to the orientation symmetry breaking. They suggested that the plates with square shapes were employed in the exploration based on the property that the orientation-dependent elastic anisotropy is controlled by trimming the sides with a rotation angle matching the characteristic axes of the brass. The driving position of advanced resonant methods can turn into the nodal point, whereas this position is always the anti-node in the isotropic case. The theoretical model has been analytically developed to include a dimensionless parameter. The method was numerically verified by resonant frequencies and Chladni patterns reconstructed with the developed model. The approach shows the feasibility of the produced model to define point-driven Chladni systems with orientation symmetry breaking, also providing a tool to use the analytical model, analysing elastic constants of orthotropic plates.

Tseng [111] explored a truncated basis to analyse the influence of the point interaction on the eigenvalues and eigenfunctions in quantum billiards. He addressed the point of interaction that is numerically confirmed to cause shifting in the eigenvalue. His strategy leads the original eigenfunctions to layover, forming a new eigenfunction. Tseng found that the amplitude and nodal-line patterns of the eigenfunctions vary, especially with the coupling strength. His exploration showed that the point-driven Chladni plates could be employed to analogously embody the apparent reliance of the nodal-line pattern on the coupling strength. His method highlights that the bound between the frequency and the wave number for the flexural wave can be determined explicitly, using the point interaction to model the contemporary Chladni plate patterns.

3.3 Texture Material and Shader

The world is full of rich textures and can be observed both in artificial and natural mediums, visually referring to an immediate tangible feel of surface characteristics and appearance of an object given by the shape, size, density, proportion of its primal part with colour patterns and arrangement. The major goal in computer graphics is realism in most 3D modelling, video games and movies. The relationship of texture, shaders, and material in CG is in the following order:

Shader: shaders are short scripts that include algorithms for computing the colour of individual pixels rendered based on the material configuration and the lighting input ,e.g in Blender shaders are referred to BSDF node, and the nodes are shaders,

Material: is an optical property of an object surface, and a concept in lighting reflected from that surface. The material is a collection of shades that are applied to a model to define the visual appearance.

Texture: the appearance of the material textures is bitmap images. Textures add details at the shader level as an image file or can create a procedural pattern, such as noise, bricks, or gradients. Textures are a generation of a graphical object by programs in the core of image synthesis. The object surface often needs the implementation of texture combination deformation and complex mapping to show 2D/3D visual effects. Also, every position on the object must correspond to a position on the texture. The texture can be raster images, procedural textures or alternative structures. There are types to produce random textures such as: *basic generators*, *noise function*, *Random deformations, and random placement of textural objects* [112].

3.3.1 Texture Functions

The texture function is a method that defines the object's surface details by appealing to the sense of touch, size, shape, density, arrangement, and the proportion of its primal parts. It describes the colour variation in the interior of the 3D polygon for visual realism with shading. Texture in CG is the process of wrapping a 2D image around a 3D model and indicating how light affects it. The texture function indicates how the texture is applied to each pixel, replaced or decal, modulated, and blended. Several methods are involved, e.g., baking, parametrisation, mapping, filtering and are explained in short in the following order:

- Baking: the process of approximating complex surface effects as simple 2D bitmaps and then assigning them to objects.
- Parametrisation: is the parametrisations of the texture map is the integration of geometry with an image with a variety of projections, e.g. plane mapping, sphere mapping, cylinder mapping and cube mapping.
- Texture mapping: is to define high details, surface textures and colour information.
- Filtering: is the method choose the texture colour for a texture mapped pixel, using the colours of the next texels (pixels of the texture).

Various techniques of texture function are used for specific performance, e.g., subdivision perspective, intevese texturing, etc. There are deterministic (regular) as a brick wall in computer CG and statistical (irregular) textures such as grass, wood or grain. Furthermore, the texture mapping application has special applications such as modulation textures, illumination, environment, image-based rendering and non-photorealistic rendering.

Bitmap Texture

The bitmap is a digital image representation of the material, surfaces, and pattern of photos generated by the user designer using a bitmap editor application. It is the most controllable way of adding texture projection to 3D models. Bitmap textures patterns show the simplicity are composed of pixels of two values, 0 or 1, and the dataset consists of 48 different bitmap textures. They are popularly used in Microsoft Windows applications, and it can be easily generated without variation to recreate a rapid image performance [113].

PBR Texturing

PBR stands for Physically Based Rendering, and there are two methods: photoed or procedurally generated. Procedural texturing produces a texture rendered parametrically, using algorithms and a hybrid of texture maps and masks to generate minor details such as wood, fabric, metal, and plastic [114].

3.3.2 3D Texturing

A survey of 3D texturing by Dischler and Ghazanfarpour [115] shows how texture mapping is essential for the realistic rendering to add surface details that are usually too complex to be modelled directly. They explained how the 2D texture mapping is considered most helpful in texturing for real-time applications. Still, there are disadvantages such as distortion, discontinuity of textures, and 3D geometric information that cannot be rendered. On the other hand, 3D texture has solved many issues of CG and is presented into two types: *solid texturing* that defines colour variation in 3D space rather than 2D *geometric texturing* it involves adding 3D data to the surface in the form of more realistic geometry. The difficulty of 3D textures synthesis is explored with specific analytical methods as well as physical-based models providing solutions to this problem.

3.3.3 Texture Mapping

Catmull, in 1974 [116] developed the texture mapping method for 3D models using surface texturing or colour information and high-frequency details realistic and functional 3D scenes. It is a diffuse mapping method of mapped pixels from a texture to a 3D surface, wrapping the object with the image. Several other techniques show complex details, and other methods use material systems to control the texture. Some of the most used texture maps are described in the following:

- Height mapping
- Bump mapping
- Normal mapping
- Displacement mapping
- Reflection mapping
- Specular mapping
- Ambian Occlusion mapping

3.3.4 Procedural Texture

A procedural texture describes the texture mathematically to generate a texture algorithm rather than directly stored data to model surface or volumetric representations of natural elements such as stone, metal, wood, and others. It views areas of 3D work and gaming as more useful for some aspects as a vector graphic is better than a rectangular image pattern and is considered a most consuming aspect. It has infinite resolution can cover any surface with no UV mapping, and you can adjust attributes for different aspects with no limitation in resolution/size and depth. The procedural texture mapping converts input values of a triangle's attributes, such as location, orientation, diffuse and colour.

Ebert et al.[117] explored procedural approaches in texturing, modelling, shading and animation and demonstrated the use in high-quality offline and real-time applications. His investigation also included 2D and solid texturing, hypertextures, volume density functions, and fractals to explore how the procedures are designed to create realistic imagery. Ebert shows methods for a better understanding of how these functions work and how to design complex procedures of textures to produce realistic textures, gases, hypertextures, landscapes, and planets. His book presented controllable implementation techniques interactive procedures that can harness the power of programmable PC graphics to run at real-time rates. The objectives of his research are significantly essential aspects for developing new texturing techniques that help in developing the thesis novel sound texture for comparison to demonstrate the novelty parts, and they are described in the following order:

- Understanding of procedural techniques for solid texturing
- Different design approaches for the procedure
- A toolbox of procedures and basic primitive functions noise with turbulence to produce realistic images
- Understanding advanced procedural approaches for modelling object geometry (hypertextures, gases, fractals)
- Animating these procedural objects and textures
- Understanding of how to adapt these techniques to commodity graphics hardware

He explained the procedural technique as code segments or algorithms that specify some characteristic of a computer-generated model or effect and mathematical functions to determine the colour as an example. He showed the importance of parametric control showing, e.g. smoothness and roughness, and flexibility can represent the qualities of the object, phenomenon, or motion without being constrained by the complex laws of physics. Kelly et al. [118] explored procedural techniques reflected from Ebert et al. [117] book that has been used within computer graphics to create natural textures, simulating special effects and generating complex, realistic models including trees and waterfalls. He has mentioned the texture in the depth of use with function commonly used in the modelling and gaming industries identifying in the following surfaces important features of procedural techniques:
•**Abstraction:** Is a texture and geometric data of details abstracted into an algorithm or set of procedures; the operator can manipulate the model data easily without requiring intimate knowledge of the implementation.
•**Parametric Control:**It is defined as a control algorithm or number of segments for the artist

to operate effectively with the ability to provide data amplification and abstraction of detail.
•**Flexibility**: The procedural models can provide natural essence without explicit linking. The parameters vary to deliver a vast range of outcomes that are not necessarily limited to constraints of the original model.

Procedural techniques

This section present the fundamental procedural techniques and algorithms that have been successfully employed within the domain of computer graphics.

Fractals: conventional geometric methods do not easily describe natural shapes. Natural shapes are complex, irregular, fragmented to regular geometry. Mandelbrot [119] introduced the texture as natural shapes embodied by using fractal mathematics.
L-Systems: Lindenmayer developed L-Systems [120] to study bacteria, and it is being used for computer graphics to visualise and simulate organic growth.
Tiling: The tiling texture can be applied side by side as a copy without a seam, and it can be applied on a large surface by repeating, using images representing the formation of characters, e.g. stone, earth, wood, liquids or gases.
Voronoi Texture Basis: was developed by Worly [121] as a cellular texture basis function. The texture function is calculated by the distance between a lattice and a pixel point for colour control information with randomly distributed feature points in space organised as grid cells.
Perlin Noise: Generates random data, and in order to acquire parametric control from the noise generator, a seeded random function is used typically arranged in a line or a grid developed by Perlin [11].

Procedural Coherent Noise

The noise is formed by using a pseudo-random function to generate a sequence of values which are then interpolated into coherent noise. The pseudo-random function is the key of an input indistinguishable from a truly random function of the information. Several layers of this coherent noise are then composited together using different ratios to create a more natural texture with similar to fractal details [122].

Pattern Generation

Pattern generation is challenging when generating a particular texture pattern procedurally. The shader can call the stored shading language function texture if the texture is simply an image texture. Nevertheless, it is challenging to find particular desired textures that can be executed by locating the material or tacking a photograph to be scanned to produce a unique texture image. Even if flat and smooth, the material of photographic texture images will record variable lighting conditions reflections of the environment also are not infinitely large. The procedural patterns generators are more complex to write, creating a small piece of program code that produces a conceivable representation of a material sample and is still considered as an art form. The real material data are colour variations reflection properties, with surface attributes, e.g. smoothness, roughness, bumpy or hollowed.

3.3.5 Procedural Noise

The procedural noise shows a distinctive texture, adding a type of visual deformation and also can change the geometry mesh of the object by displacement. Perlin [11] developed an image synthesiser through a system algorithm to create a paradigm extremely fast, highly realistic, and asynchronously parallelisable at the pixel level. The system's output creates an effective representation of clouds, fire, water, wood, rock, soap films, stars, marble and crystal. The procedural noise holds many benefits of generating patterns using a very low memory for complex visual details; with a practical set of parameters, procedural noise can easily generate a large number of different patterns. Eventually, procedural noise is randomly accessible to be evaluated independently with the advent of massively parallel GPUs and multi core CPU systems.

Perlin noise types:

- Classic Perlin noise
- Improved Perlin noise: is an improved version of classic Perlin noise.
- Simplex noise: It is a method developed by Perlin [123] same as a Perlin noise based on a simplex grid, generating a smoother pattern of dimensional noise function, and it is comparable to Perlin noise but with fewer directional artefacts and, in higher

dimensions, a lower computational overhead.

- Value noise: this method uses simple values and natural appearance smooth and natural appearance without the block hash pattern, and the noise function produces a continued pattern.

Noise Function

The Perlin noise function generates random data, and for the parametric control, there should be a noise generator and a seeded random function. There are three functions: *fade function*, *hash function*, *gradient function* and *pseudo random function* that are useful for games and other visual media.

Interpolation Function

The interpolation is the process of the curve fitting that intersects through data points and this function. The function uses discrete data set of the function through the provided data points.

Turbulence

The turbulence is more artificial than natural, produced from interpolated noise with random properties. Each layer of noise is called an Octave, and layers are combined with various frequencies and amplitudes. The variety of frequency can and amplitude be expressed as a Persistence value that helps describe the influence successive octaves have on the previous iterations by defining the amplitude with octaves as a fraction. The Perlin noise generated appears smooth with a lower ratio smoothness with very fine detail that with high persistence showing more roughness with more minor fine detail [124].

3.3.6 Volumetric Textures

The volumetric texture is defined in 3D by (x,y,z), and it can be created as a stack of 2D bitmapped textures or as a 3D procedural texture and can be rendered on the inside accurately. The volume rendering represents a method used in CG and scientific visualisation to produce a 2D projection from a discretely sampled 3D data set, e.g., CT, MR, etc. [125].

3.3.7 Interactive Texture

Interactive texture mapping is a tool constructed to manipulate atlases in texture space for pre-defined images onto a surface and improve mapping function. The method measures the deformation energy of an image mapping onto a surface. The function of the technique is used to edit and manipulate atlases and data structures; merging uses segmentation techniques based on curvature and ultrametric [126].

3.4 Procedural Noise Texture VS Chladni Plate

Procedural texturing is computerised software that can texture the 3D object. This technique is used for 3D modelling with duplicative structures, but it is mainly for experts, expensive, and time-consuming. On the other hand, Chladni plate software is straight forwards user-friendly with simple controls as shown in Fig 3.5 with no previous expertise required [127]. The user can run a visual simulation. The chladni resonance fractal is a representation of Cymatics geometry patterns with seconds. The Chladni software functions depend on the image size; the output is a 2D image of a diffuse map with control functions of frequency, amplitude attenuations, material, and scale of the procedural method but with limitations compared to the procedural noise texture method. Table 3.1 with Fig3.7 shows the comparison of Perlin texture and Chladni software, demonstrating the differential functions of each method and how it can be implemented on a 3d model.

3.4.1 Chladni Plate Integration with 3D Modelling Software

The integration of the Chladni plate with Materlize software is to advance the output by using a controllable material function [128]. The tool can be described as a tool that converts the outputs of images to a material that can be used to overcome the shortcomings with attributes such as location, orientation, and diffuse colour. The outcome of the integration of the software creates an adequate control of both baking processes' time of texture map pattern. On the other hand, the Chladni plate method cannot be used for any procedure; conversely, Perlin noise can be any set/range of function/procedures. The Chladni technique could be done as a special Perlin but cannot be used for any Perlin function/procedure.

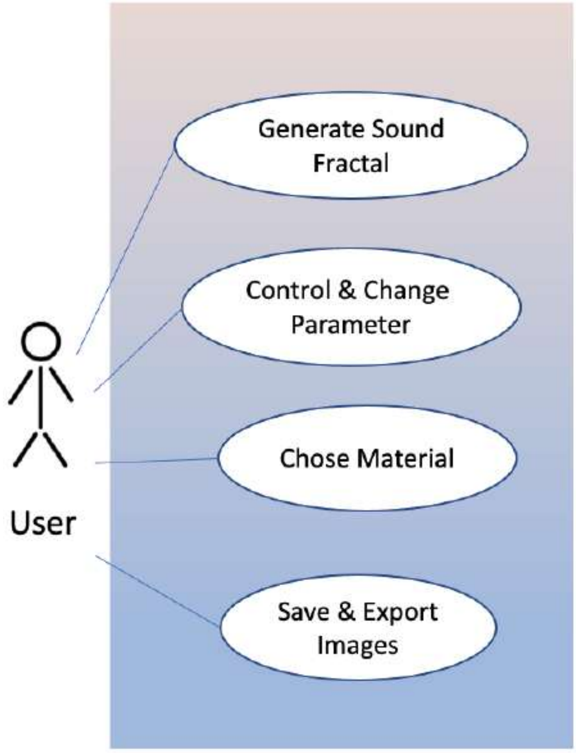


Figure 3.5: Use Case of Chladni software

System Requirement Specification

Requirement specification of real-time integration system with Chladni plate is shown in Fig 3.6. It is essential to acknowledge the time frame of each process and identify each tool and the memory ram. The Chladni plate software can be implemented using software that generates fractal and then converts it to an image. The image then should be converted into a texture map to be displaced in 3D software with retopology. Finally, converting the model into a 3D printable object with slicer software.

3.5 VR Interaction

The previous sections of the literature review were to comprehend and investigate texturing methods to develop the novel sound resonance texture applied to an output model of VP application. This section demonstrates the literature on VP application, interaction, limitations and usability towards fabrication with systems refinements.

Table 3.1: Comparison Functions of Perlin Noise VS Chladni

Functions	Perlin Noise [118]	Chladni Plate [127]
Realism	✓	✓
Periodic Function	✓	✓
Scale	✓	✓
Variation	Limited	✓
Generative	✓	✓
Frequency Value	✓	✓
Geometric Patterns	Gradient vectors	✓
Pseudo-Random	✓	✓
Truncated basis	✓	✓
Material	x	✓
Input	✓	✓
Efficiency	✓	✓
Colour Control	x	✓
Real-time	✓	✓
Render baking	Depend on selected mesh	Fast
User Expertise	Advanced	Beginner

VR gesture interaction is a method for simulating standard communication in human life. The VR gestural devices are classified into wearable interaction devices, touchscreen-based interaction devices and computer vision-based interaction devices. The wearable interaction devices are gloves and sensors that collect the gesture signals and the position information of the user's hand in the 3D space and touch. The touch devices support multi-touch technology in mobile devices, such as phones and tablets, with various applications. On the other hand, computer-vision-based gesture interaction approach does not require additional tools and simulates more natural human-computer interaction gesture devise [129].

3.5.1 VP Gaming and Research Based Systems

The available systems are divided into two sections research and game-based. This section's focus describes a variety of factors, showing the distinctive contribution in each and the shortcomings of the systems. The systems are mainly aimed at novice users with a simulation system of traditional pottery, providing the virtual environments with tools. The methods

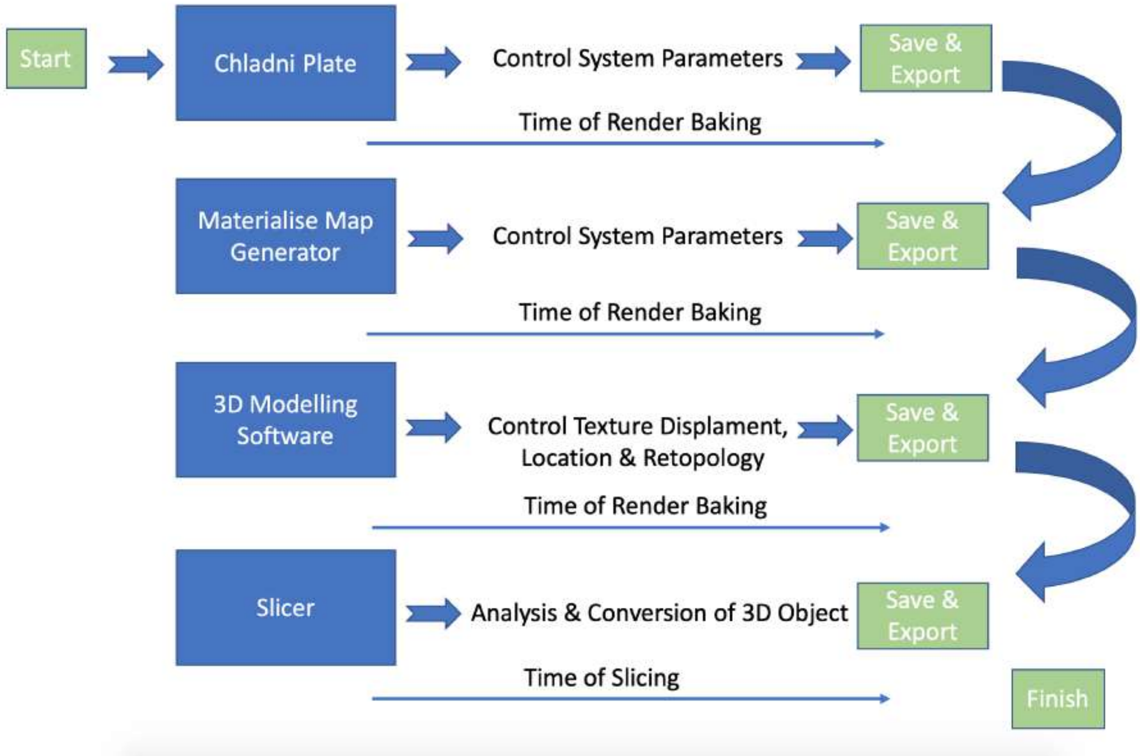


Figure 3.6: Requirement specification of real-time integration system with Chladni plate.

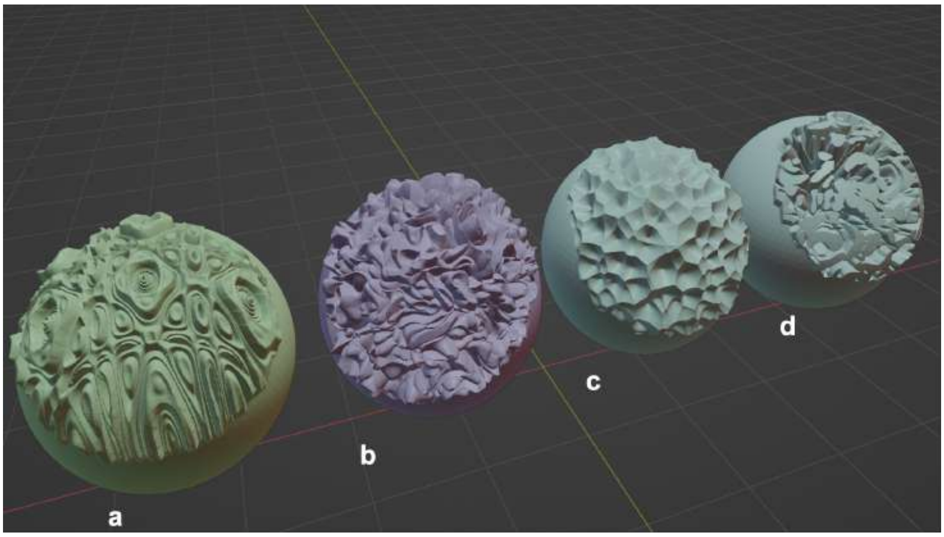


Figure 3.7: Texture example: (a) shows the Chladni texture as a geometry based fractal pattern, (b,c) presents noise textures of Voronoi and (d) is a perlin texture.

vary from VR kit, tools and haptic feedback. This section aims to identify the most helpful tool in the thesis experiments and provide some knowledge of other tools. The systems are explained depth in a variety of tables in chapter 5 in Table 5.2, 5.3, 5.4 and 5.6.

3.5.2 Research Based Systems

The research-based systems background gives more insights into the VP systems application with user usability evaluation, which has been tested but is mostly unavailable as an open-source for users and designed for specific VR kit tools.

POTEL is an engaging VR application that focuses on exploring the art of pottery modelling through virtual reality [27]. The application is designed for novice users. It is an affordable system to model virtual pottery without holding any device to interact with environments and is available as an open-source. Then the system uses an Oculus VR for visualising the world, a LeapMotion for interaction with the environment and an optional Arduino with mobile phone vibrators for haptic feedback. The modelling method is done in real-time deformation by extruding/compressing triangle vertices and interacting by pressing the user's index finger. The users can bake their work, and by baking, it means the process of saving information related to a 3D mesh into a texture file, then export it as an STL file for 3D printing after the experience.

Wowtao is a pottery manufacture system that expands VP creativity simulation [45]. The idea of the system is to design customised pottery virtually on tablets, computers or mobile phones interactively in a short period. The application works with an integrated concept of customer product personalisation, supporting unique designs in the pottery manufacture field. The project developers claim to simulate the entire physical pottery design process, such as modelling, painting, seals, firing. The application provides the ability to have the designed results fabricated by real artists or a 3D printer. The approach of the application imposes some industrial constraints of geometry and decorations. The system focuses on novice users undertaking new skills of VP in the workflow efficiently within 10 minutes.

Furthermore, creating the 3D form in real-time with only visual image patterns with no volumetric texture deformation on the vessel. The Wowtao application can export files for 3D printing. Finally, the easy-to-use application for novice users was relatively similar to those experienced users from visual feedback trials.

PotteryGo is a VP training application system [130]. The application focused on teaching fundamental knowledge and practical techniques in VR environments. The gesture analysis makes it possible to correct the learner's actions by visual feedback. The application is aimed mainly for novice users, for extensive practice and skill gaining of traditional making simulation. The central aspect is creating a deformation by using the physical interaction through the Leap Motion sensor. The user's hand gestures give input data information, making the pull/push effect, creating a mesh deformation. The visual feedback allows user to sync in VR environment by three ways Auditive, depth cues and haptic. The application can export STL files. Scavarelli et al. [131] highlight several ongoing challenges that still exist in virtual systems. VP brings several benefits in terms of experience in real-time rendering, as the PotteryGo application offers deformable modelling to sensitivity to push/pull the virtual clay. The VP system is now scalable, as it is not restricted to a physical space. Several instances of the VP system can be launched simultaneously. The used tools to demonstrate the system uses' subsystems that are not expensive and hence are affordable. With more affordable creative technologies, the thesis project VP system will have wider adoption. Adding multiple users in the system is also feasible, as the users now can access through the virtual environment and need not occupy the same physical space.

3.5.3 VP Game Based Systems

The game-based systems background gives a different type of insight. The accessibility is either open-source or commercial systems available for purchase. The feedback users experience is direct on many websites, for example, Steam-powered.

Dojagi is a VR Korean pottery simulation game with a virtual potter's workshop [46]. It is a game based application for novice and intermediate users with a spinning wheel simulation. The system of this VP application involves creative and training experience, and it is compatible with HTC Vive/ Oculus Rift VR kits. The application has exceptional haptic feedback for a realistic indirect experience. The expertise simulation is made with the famous pottery artist Damggol Kim Jong-young to introduce a highly realistic simulation. The experience involves:

- Immersing hands in clay and developing skills making on VP wheel.
- Glazing.

- Sculpting, vernier calipers, trimming, measuring tools.
- Decorate/furniture of VR space studio.
- Change Visual VR tool.
- 50 pattern stamps.
- Water simulation for VP making.
- Throwing wheel (spinning).
- Export and archive files.
- Tutorials.

The application VR controllers can control the inner and outer side of the VR object, creating a realistic deformation. The main VR object is an empty object with a single coordinate with limited. The vessel starts from a lump basic cylindrical clay model with a set of coordinates for the user choice. The haptic controller feedback shows a reliable simulation of the force of pull/ push in and out of an object. The throwing/spinning wheel has beneficial real-time feedback with the controllers. Adding the water concept significantly impacts the learning skills, an essential part of VP making. The VR sculpting tools help on narrowing down the shape vessel coordinate as an additional deformation method. On the other hand, the application has some errors creating zero faces and seam-line gaps affecting the 3D print file. Furthermore, the holes in the VR object are mainly in the primary object, and the gaps are increased while shaping the object.

Let's Create! Pottery is a VR creative, realistic simulator of an actual pottery workshop [132]. It is a game-based application for novice users. The system of this VP application involves only the training experience, and it is compatible with HTC Vive/ Oculus Rift VR kits. The experience involves:

- Immersing hand in clay and developing skills by shaping.
- Painting various VR clay vessels. (colours are gradient/ translucent).
- Decorating (list of print patterns).
- Firing.
- Curating in a gallery.
- Tutorials.

The application uses one VR controller to create the vessel, starting from a basic cylindrical model. The haptic controller feedback shows a good simulation of the force of pull and push. On the other hand, the application does not export any exchange files for 3D printing. It is a visual/physical training experience with limited haptic controlling actions. The main 3D object is an empty object with a single coordinate point with no additional geometry, so the inner object cannot exceed the empty object inside. It is considered as the negative space of an object. The Use case of the VP system must contain elements as shown in Fig3.8. The use cases in Fig3.8 will allow the user to choose the right tool or integrate tools or, as a game developer, design a system with similar use cases.

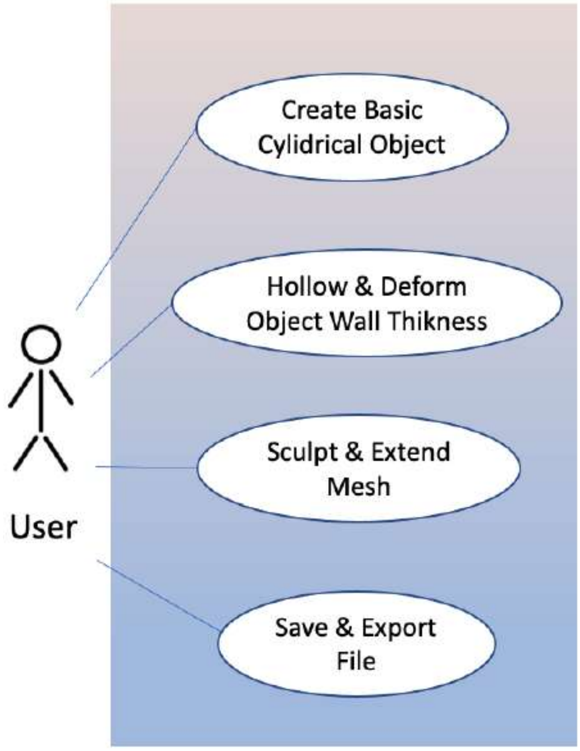


Figure 3.8: Use Case of VP System Application

System Requirement Specification

3.5.4 VP Systems Limitation

Finally, all of the mentioned systems, as shown in Table 3.2 have some knowledge gaps regarding the whole experience of VP skills. The VR applications are limited to a low poly

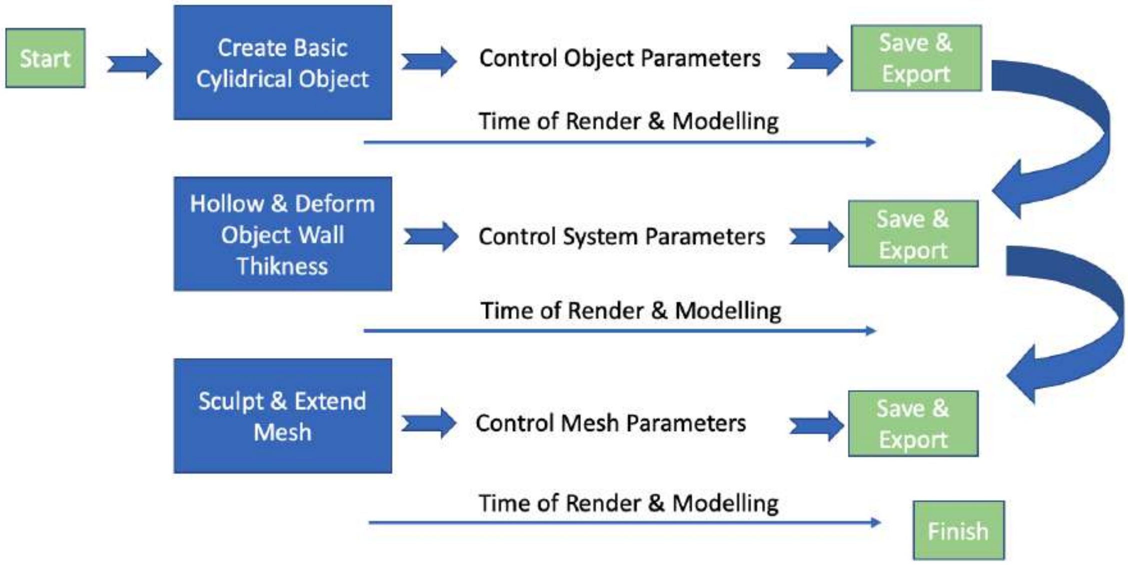


Figure 3.9: VP System Requirement

model, considering the amount of data that increases through physical modelling. The applications mostly lack the essential tools for creating artistic deformation to have a whole, rich experience of traditional pottery simulation. Furthermore, the basic cylindrical object coordinates are fixed and limited, so the user can not exceed them. The basic cylindrical shape has errors, for example, seam-line and zero faces. On the other hand, all applications do not provide volumetric texture patterns. Nevertheless, the limitation of these applications created a good ground for this thesis problem and methods of contributions.

3.6 Proposed Evaluation Methods for VP Systems

3.6.1 Visual Feedback

Fulvio et al. [133] discuss how VR creates a bridge connection of 3D motion between the user development experience, virtual environment and the consequences of their actions, improving performance while maintaining experimental control. The project VP system connects to this concept as the users develop their performance, using multiple applications to create a complex organic model from the visual feedback, improving rapid prototyping with physical/virtual modelling.

Table 3.2: Comparison of VP Systems

Systems elements	[43] Real-pot: an immersive virtual pottery system with hand-held haptic devices	[45] Wowtao: A personalised pottery-making system	[46] UT-PLUS Interactive VR STEAM Application. Dojagi	[44] Turn: a virtual pottery by real spinning wheel	[130] PotteryGo: A virtual pottery making training system	Novel VP System
Game/Research based	Research	Research	Game	Research	Game & Research	Game & Research
System Type	Interactive deformation system	Interactive deformation system	Interactive deformation system	Interactive deformation system	Interactive deformation system	Integrated Interactive deformation system
User Interface	VR UI	smart-phone (tablet computer)	VR UI	computer screen	finger gestures on a tablet PC	•VR UI •PC
Modelling form	basic cylindrical shape	basic cylindrical shape	basic cylindrical shape	basic cylindrical shape	basic cylindrical shape	Cylindrical + Free form deformation
Object co-ordinates	single co-ordinate point with no additional geometry	single coordinate point with no additional geometry	single co-ordinate point with no additional geometry	single coordinate point with no additional geometry	single co-ordinate point with no additional geometry	•Free form deformation •Adding mesh count on basic cylindrical shape
Deformation	Basic deformation	Basic deformation	Basic deformation	Basic deformation	Basic deformation	Basic deformation + free-form deformation
Surface Texture	-	-	-	-	-	Volumetric texture
Mesh count	basic	basic	basic	basic	basic	Increase mesh count
Modelling Tools	Basic	Basic	Advanced	Basic	Basic	Advanced (Integrated VR/3D tools)
Export	OBJ	X-change file	X-change file	-	-	X-change file
3D print output	-	yes	yes	-	-	yes
User Interaction	basic VR simulation interaction	touch-screen based interactions	Advanced pottery making simulation	Kinect sensor based interaction	Leap Motion sensor interaction	Advanced pottery making simulation

Gestural Interfaces

Norman et al. [134] proposed the idea of the importance of the usability of *G*estural Interfaces. The true advantage of the Graphical User Interface (GUI), must focus on controlling the system so the users can understand the connection between the actions and the results of the outcomes.

Usability Factors of 3D Modelling in VR

Huang et al. [33] presents the study to examine learning usability factors that affect the performance of 3D modelling in VR and investigate the ease of use of VR environment, using the System Usability Scale (SUS) for 3D modelling industrial design in VR. The study by Rieuf et al. [135; 136] suggests that VR technology can help industrial designers develop product design concepts. The study shows how the users believe that richer and more convenient functions could improve the usability of 3D modelling in VR. Also, the aspect of how VR assists users to define the state of the virtual object sizes, distances and spatial understanding in VR.

Collaborative Design for VR Usability

Mahdjoub et al. [137] present the collaborative design for usability approach of modifying the virtual prototype of the product or the workplace with VR tools. VR tools are integrated based on a Multi-Agent System for knowledge management in mechanical design projects. The study focuses on developing the knowledge of an engineering system integrated into a Product Lifecycle Management (PLM) linked with VR tools, analysing aspects of the virtual prototype for manufacturing and maintaining a knowledge management approach, improving the collaborative design in industrial areas.

3.6.2 System Usability Comparison

VR Test-Bed Evaluation

Bowman et al. [138] revealed how test-bed evaluation is an improvement for usability testing, suggesting how virtual environments are becoming complex and how the designers are in need of guidance in choosing 3D interaction techniques. Also, how this sort of evaluation is an effective and useful method for the assessment of interaction techniques for virtual environments-focusing on the tasks and interaction requirements for applications. In terms of the performance technique, it requires high levels of spatial awareness and information gathering to improve the experience.

3.7 Shape Modelling Refinement Towards Fabrication

Manufacturing and product design industries have flourished and dominated many fields, creating opportunities for fabrication with new perspectives, coming from the medical, engineering, computer graphics modelling and art sectors. The following section highlights some exceptional research relating to the choice of material, design, fabrication and model refinement.

Modelling Refinement: Bohn [139] presented methods for removing zero-volume parts from CAD models for layered manufacturing by eliminating zero-volume parts. A zero-volume part is any part of a shell that does not enclose any volume. The process of zero-volume part elimination applies to a set of industrial CAD models represented in the .STL file format, reprocessing them to assure complete shell closure. This is done using vertex merging for improved well-shaped triangles, which avoids a significant number of recursive subdivisions.
Ju [140] investigated literature about repairing methods for fixing geometric errors on polygonal models, categorising them by their methodology and capability, offering pointers and directions to resolve them. Their survey focuses on geometric detection and correctness of gaps, holes, non-manifold edges and self-intersections, particularly in engineering, manufacturing and element analysis for actual production, such as rapid prototyping.
Chu et al. [141] presented an approach for completing and reconstructing 3D shapes from incomplete scanned data by using deep neural networks, monitoring the unsupervised shape completion via deep-prior in the neural tangent kernel perspective. The methods included computing methodologies for shape analysis using neural networks, completing and reconstructing 3D shapes from incomplete scanned data by using deep neural networks. They use more efficient design network structures with learning mechanisms for the shape completion and reconstruction tasks.

Advanced modelling and fabrication: Rogers et al. [142] proposed a versatile and scalable method to construct hybrid electrospun scaffolds with tailored three-dimensional micropatterns employing additive manufacturing, and patterning of the fibers during the electrospinning process of fabricating fibrous scaffolds for tissue engineering applications. They showed the 3D directional patterned fibres to reveal the influence of cell behaviour and use to culture cells within a similar 3D micro-topography as experienced in vivo.

Nakano and Ishimoto [143] exhibited a method of powder-based additive manufacturing for the development of tailor-made implants for orthopedic applications, towards rapid prototyping. They illustrate an optical system for raw material production of products made from various materials, from resins to ceramics, metals, and intermetallic compounds. They reviewed the advantage and possibility of AM (Additive manufacturing) in developing functional metallic biomaterials for orthopedic usage described in medical treatments.

Locascio et al. [144] reviewed additive technologies for producing highly porous inorganic materials with a tailor-made morphological architecture for medical purposes. The review discusses methods to manufacture osteoconductive inorganic substances based mainly on calcium phosphates with given macroscopic porosity using rapid prototyping. A requirement for their approach is a composition of morphological architectonic of materials and three-dimensional printing techniques that are most often used to achieve this.

Livesu et al. [145] examined methods of 3D model preparation for fabrication. The report offers an analysis of the state-of-the-art while discussing open and challenging problems from both an academic and an industrial perspective. Also, it discusses pre-fabrication tasks, such as the support structure, multiple materials, building direction, slicing and machine instructions. Also, they present ways for modelling 3D objects in different forms, for example, wire-frames, micro-structures and mixing on multi-filament printers for tone imagery fabrication.

Ievlev et al. [146] proposed a framework for unified analysis, design, and rapid prototyping of small unmanned air planes, creating mission-specific fixed-wing aircraft assets that can be rapidly tailored and manufactured at a forward operating base. The tool-set uses a physics-based analysis model to generate feasible aircraft designs from a family of designs, a decision-making tool to select the optimal design for a mission and to change the parametric architecture of the CAD model.

Chapter 4

Sound Shape Modelling Pipeline

4.1 Introduction

4.1.1 Sound Resonance on Clay

Clay as material presents challenges of preserving sound deformation on a non-rigid liquid form and real-world constraints such as gravity and evaporation prevents the consistent capturing of the dynamic visual patterns created during sound deformation on a ceramic vessel. The innovative deformable shape modelling explores methods of integrating sound data with 3D modelling towards producing a texture mapping technique for a volumetric sound-structure. The shape and texture are the primary sources of information for object recognition, and this approach brings more understanding of how sound travels through non-rigid forms. This technique creates a more natural parametrisation of realistic fabricated graphics into interactive physical and 3D shapes.

Interactive virtual physical 3D modelling is chosen as a way of extending ceramic artist creativity of making, up- scaling the boundaries of creative making and to develop a multi-modal interaction that simulates physical-virtual interaction that captures real-world deformable pottery making (addition/ subtraction) using tangible hand and finger transformations.

This chapter introduces a novel technique for materialising the deformable shapes of sound-resonance on 3D objects with system retirement. First, the chapter will cover some exploration of findings and the suitable tool to use. There are limited tools for creating sound resonance with high details. Secondly, introducing the technical framework based on the logical experimentation sequence related to the research. The framework offers a novel approach using a series of simple processes to manage complex object transformations that can be used in virtual, 3D modelling and AR interaction.

4.1.2 Materialising Sound in Clay

The journey of physicalising sound resonance started with an investigation of using clay as a medium and then Chladni plate tools to test. The interaction of sound resonance mechanics created different patterns while changing the frequency. The frequency ranges are either self-explored or adopted from the research mentioned in the literature chapter 3. The comparison with other research mentioned in the literature chapter was visibly showing some indication of pattern as seen in Fig 4.1; thus, many elements prevented from preserving the pattern or displaying in high detail. The involved constraint of material was viscosity and density with other real-world limitations such as gravity, drying or cracking to use on a surface of the ceramic vessel.

The second approach was on sound resonance simulation, searching for the most helpful tool to understand the Chladni pattern with methods to create a relief showing surface deformation on the vessel. Moving on to technology means that the ceramic artist must have ways to interact with the modelling process, such as VR. The problem with the VP application is that volumetric texture patterns are not available, just limited images that can be applied on the surface of the VP object with no printable features for the texture pattern. The relationship between both problematic issues was connected to complement each other from the novel texture with VP towards prototyping.

4.2 Chladni Plate Experimentation

The Chladni plate exploration started with physical tests towards CG to understand how the different mediums interact with sound vibration and how they can be visualised digitally. The Chladni plate software is an algorithmic visualisation of mathematical functions in a computer programming environment, leading to the quest to create diverse patterns. The mathematical operations of the software are emanated from systematic processes associated with different variables to control patterns. The available Chladni plate software works with

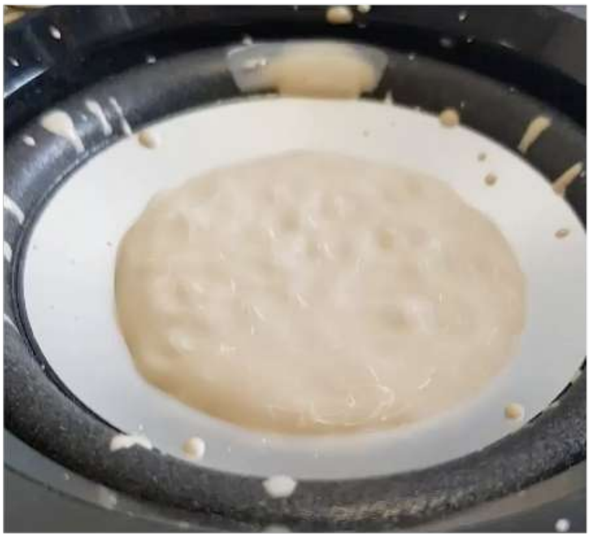


Figure 4.1: Sound Resonance Experiment Using Clay as Medium

mathematical equations. The chladni pattern shows the mode shape, displaying how the vibration amplitude is distributed when a modal resonance occurs. The resonance frequency is defined by the flexural wavelength versus edge reflections, which relies upon the invert of the frequency. The idea of determining the resonance pattern frequency is by trial and error.

4.2.1 Chladni Plate Tools

Nowadays, the Chladni plate is used in presented in CG not only for science but also as an artistic method for a visual unique geometrical pattern representation. Nevertheless, limited Chladni plate tools are available as an open-source, limiting the opportunity for experience non-research based users. The Chladni plate comes in different forms. The acoustic vibration on solid surfaces with mediums such as sand, salt or fluids forms patterns of nodal lines on vibrating plates, and this is the concept of Chladni software.

4.2.2 Nodal Line Overview

The nodal line is the line passing via the ascending and descending nodes of the rotation of a celestial body. The node represents the point with a standing wave where the wave has minimum amplitude, as shown in Fig 4.2. Therefore, the nodal patterns or topology match the shape of the nodal location of finite elements that are developed on a triangle, circle or square plate, as shown in Fig 4.3.

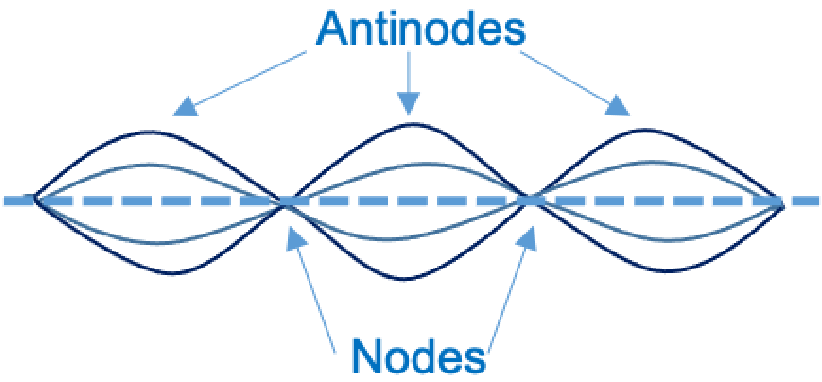


Figure 4.2: Illustration: Nodal Line.

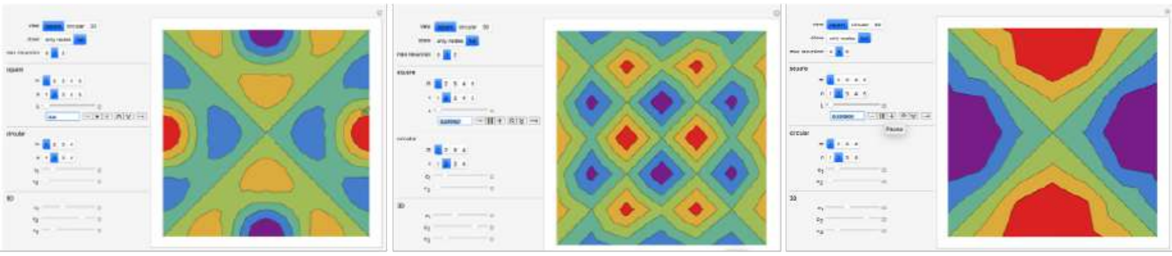


Figure 4.3: Illustration: Chladni figures (nodal patterns) Wolfram source.

4.2.3 Antinodal Overview

Antinodal are points along with the medium, which oscillates between a big negative displacement and a big positive displacement, as shown in Fig 4.4. This chapter aims to find a way to visualise the displacement to be a volumetric texture showing the unique sound resonance pattern and applying it to a VP object. Fig 4.5 shows how the antinodes result from the interference shape of two waves' showing how antinodal positions with a crest meet a crest producing a large positive displacement. Though these tools are good for visualisation, it is still hard for a non-expert to implement with 3D modelling. The aim at this point is to find simplified tools to create the Chladni pattern suitable for 3D modelling.

Therefore the research method involves the following steps:

- The first step is exploring available Chladni plate software with a simplified user interface (SUI).
- Second step consists on materialising sound resonance images by using a suitable tool such as the Chladni plate software for generating sound resonance shape maps which

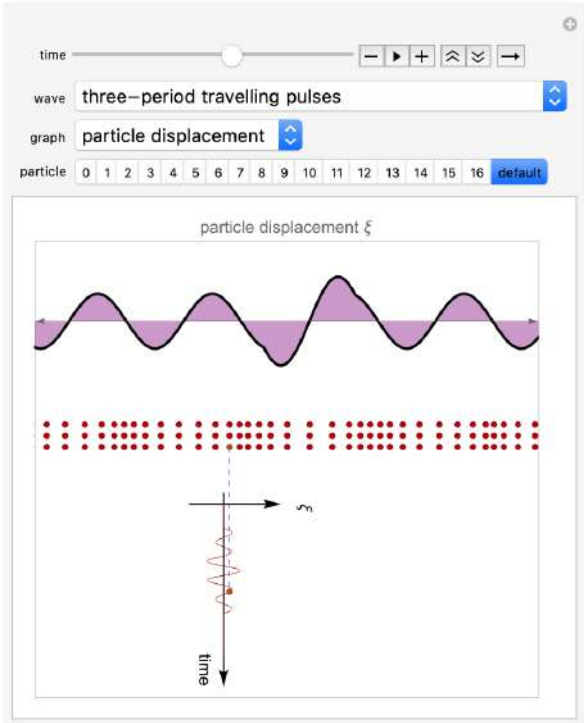


Figure 4.4: Illustration: Antinodal Displacement Wolfram source.

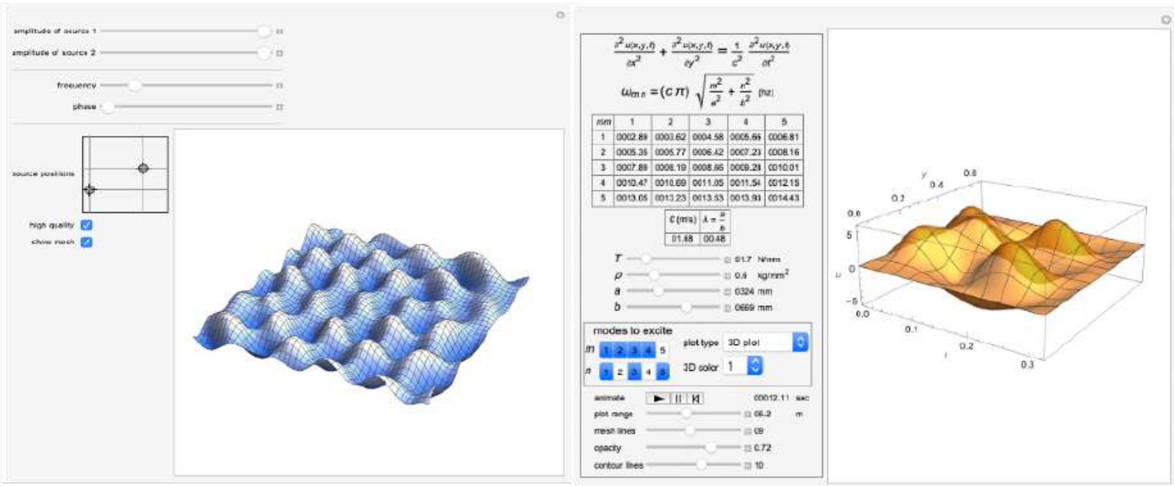


Figure 4.5: Illustration: 3D Antinodal Displacement Wolfram source.

can then be used in bump and displacement mapping.

- Next step is an experiment exploring ways of using volumetric deformable shape maps to blend these intricate sound resonance patterns in VP applications and suitable file format for bidirectional modelling.
- System refinement of integrating tools for bidirectional modelling towards fabrication
- Then the method extends to transform the resulting complex 3D shape models from

the above steps for rapid prototyping using appropriate pre-print tools by remeshing and physics manipulations.

- The result is a 3D printable object form, with high-quality sound texture examples overlayed and blended, that changes the form of underlying 3D objects, demonstrating methods of using off-the-shelf tools.

4.3 Chladni Plate Testing

In the literature chapter 3 Yucel & Yildan [109] presented a Chladni plate fractal generator application called **Cymatify**. The application is straightforward and user friendly, but the output is in a pixels image with low details. On the other hand, there was a recent release of open-source applications in 2019, and Hung-Yi Yeh proposed the algorithms. Fig 4.6 shows test 1 of experimenting by trial and error approach and validating the outputs images of the frequencies was through adapting some frequencies to compare the accuracy from Tuan et al. [70]. Fig 4.7 illustrates the comparison of two outputs with similarities in the nodal-line and antinodal. The Chladni plate software used in test-1 is straightforward and user friendly as well. The software is with similar functions as **Cymatify** such as image properties, frequency value, amplitude, and attenuation. The render baking time is instantly from size image 500x500 as a default setting in the software, and for an image size of 1024x1024, it takes about 3-4 seconds, and it depends on the used device. The export option format varies from, png, jpg, tga, tiff, gif, bmp and wdp.

4.3.1 Materialising Sound

This section talks about converting the exported file from Chladni software in png file as an example to be converted to material in open-source software called **Materialize** [128]. It is is an excellent tool for producing materials for 3D modelling and games from images. You can design a full material from a single image with export and import, controlling many textures functions similar to the procedural texturing to generate, creating the detailed textures you need. This process opens up an extensive spectrum of opportunities to improve 3D designs for additive manufacturing with 3D textures. These maps (see Fig 4.8) can efficiently be

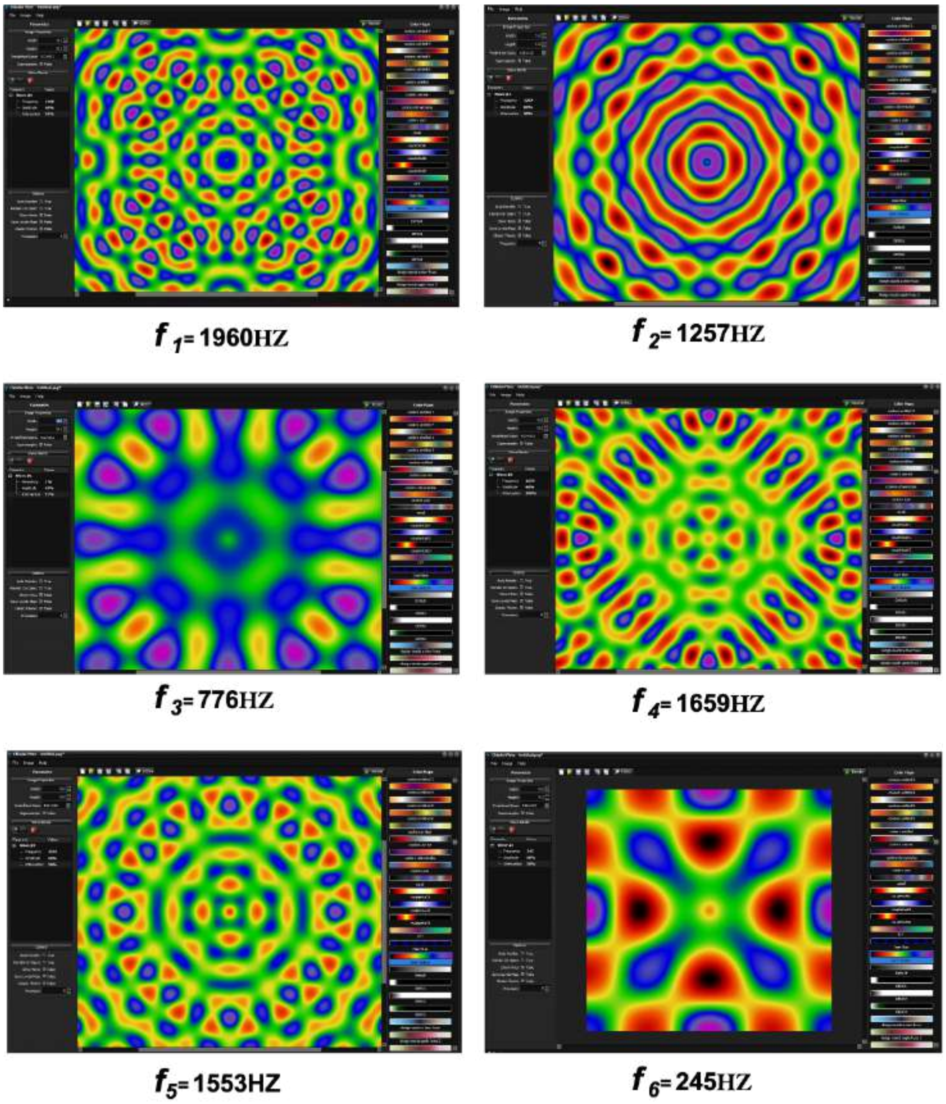


Figure 4.6: Chladni Software Test-1. Chladni Plate software source & Self-experiment (video demo).

generated using the Materialize software employing 2D images with a few simple steps. The render-baking time is instant. The software generates a collection of textures such as metallic, smoothness, occlusion and more textures for most environment materials. It can import and export in many file formats: bmp, jph, png, tga or iff. Finally, the textures collection is saved and exported as a png file as an example in this step to be imported into 3D modelling software.

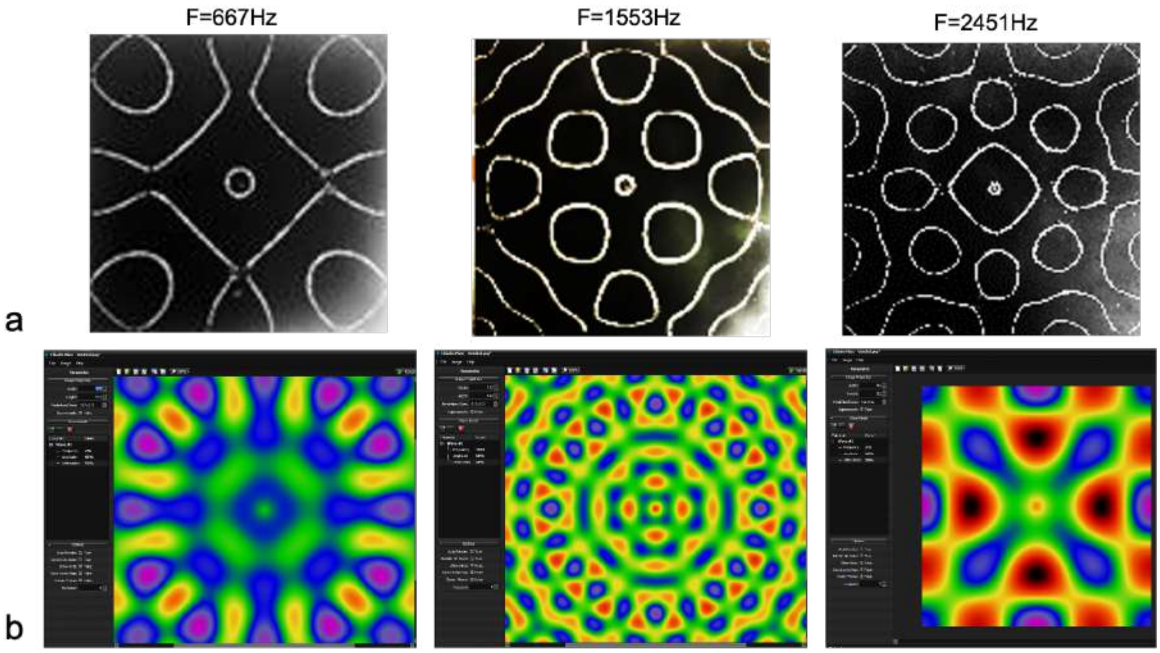


Figure 4.7: Chladni Software Test-1.2 (comparing the outputs) a. source.

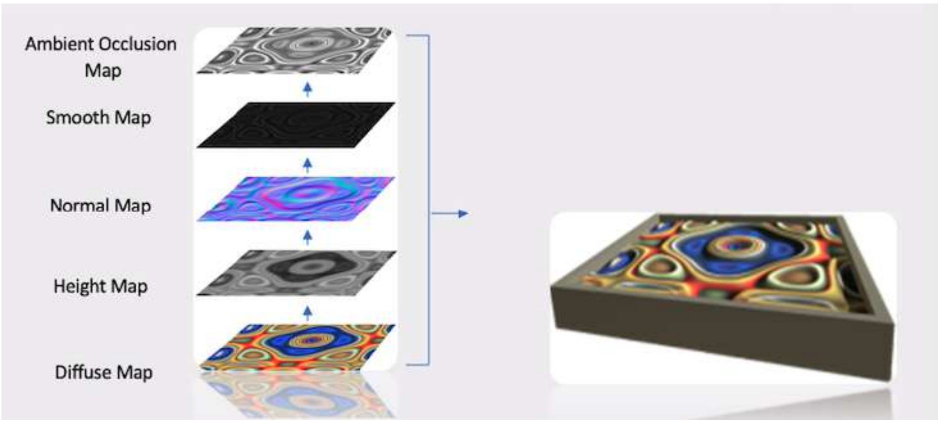


Figure 4.8: Parametric layered sound maps. Source adapted (Liu et al, 2007)

4.3.2 Texture Folder

Next, it is essential to save the collection in a folder while using 3D modelling software such as **Blender**. To archive textures, there is a simple addon that is used for **Blender**, and it is called **Poliigon Material Converter addon**. It provides a folder for PRB texture map by uploading the png files (This addon appear in Blender as a set of visual texture folder, this method can be applied with any 2D texture map image; it adds a set of textures using a specific code name file correct name to work in the nodes as seen in Fig 4.9.

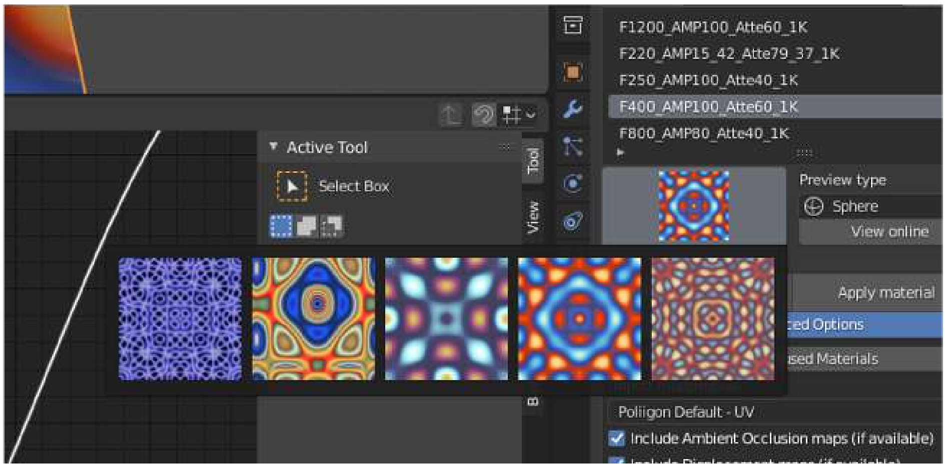


Figure 4.9: Texture Map Folder.

4.4 Chladni Pattern & 3D Modelling Software

4.4.1 Blender Software

After the preparation of Chladni sound resonance patterns converted into texture maps and archived in folders, this step of testing the textures on a 3D modelling object now. This section firstly involves a texture test applied to a 3D object. Secondly, test application of the texture on VP/3D object and finally analyse the VP/3D object mesh and retopologise the mesh using a 3D print tool to close seam-lines and fill zero faces to be prepared for slicing towards 3D printing. The novel volumetric sound resonance texture aims to use in the surface deformation of VP/3D objects showing the diversity of geometric patterns with high quality using 2D images as a minimum effort of texturing a 3D object.

4.4.2 Texture Integration

The user can select the vertex group by changing the weight to be less than the rest of the object, e.g., 0.2. to 1 or select the whole object as shown in Fig. 4.10. Here we can see how fast and easy to choose the desirable texture from the folder and apply the texture on the sphere using a displacement modifier to change the surface of the mesh creating surface deformation. Fig 4.10 also shows how can one image be translated into a different relief, edges, smoothness and can be further manipulated. The Chladni plate, in reality, mainly is physicalised on o flat surface, and the thesis approach shows an advantage of how you can furtherly deform the texture matching the surface of the 3D object, as illustrated in Fig 4.11. There are more tests shown demonstrating how to apply texture on different types of object shapes and how would it interact with them. Fig.4.12 shows texture on curved surfaces shown on the left and on the right uneven block surface. Fig 4.13 demonstrates texture on plane low in thickness and finally in Fig 4.14 texture on layered, complex object on both sides of the object on the left and on the right texture applied on a Stanford Bunny increasing the repeat number of the texture on selected areas. The texture application is applied instantly, but then there are some elements to help on speeding up the process, such as the user device, memory ram setting, level of the viewport, and triangle mesh count. The higher the mesh count, the longer it will take to render bake; also, it may crash the application, so saving the project in each step is advised.

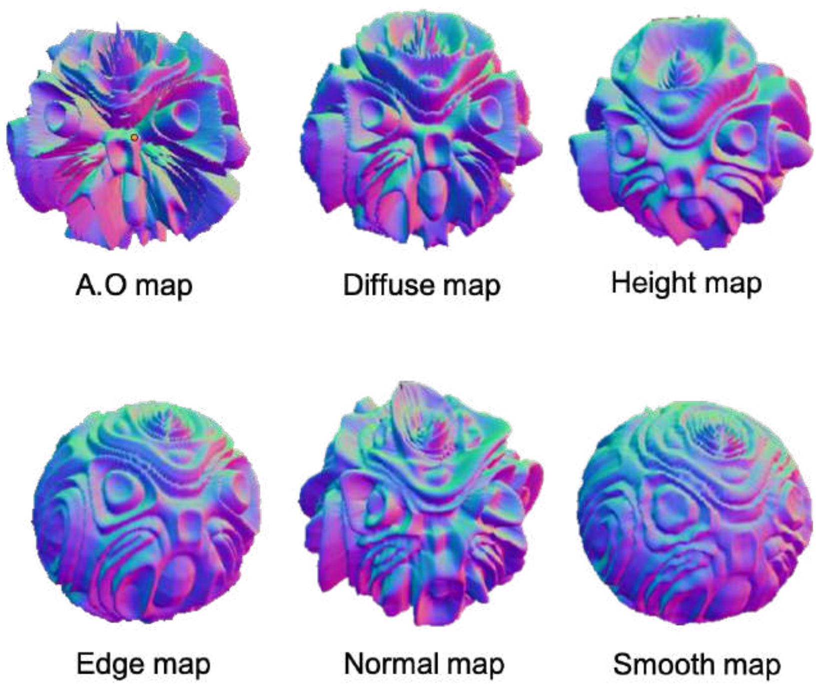


Figure 4.10: Sound Resonance texture on a Sphere

4.5 Sound Texture on 3D/VP Object

The 3D modelling software is essential not only to apply the sound resonance texture on a 3D object. The thesis aim was to apply the texture on a VP object created by physical

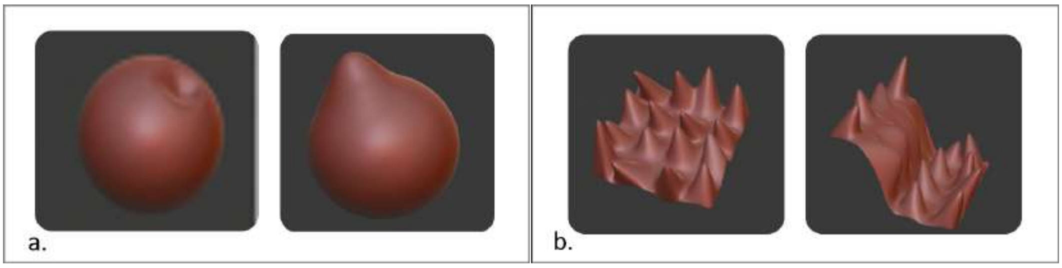


Figure 4.11: Texture Deformation Properties: (a). shows sculpting tool deforming the surface of the sphere, and in (b) a texture deformation shows that textures can be deformed using the existing mesh or manually manipulated.

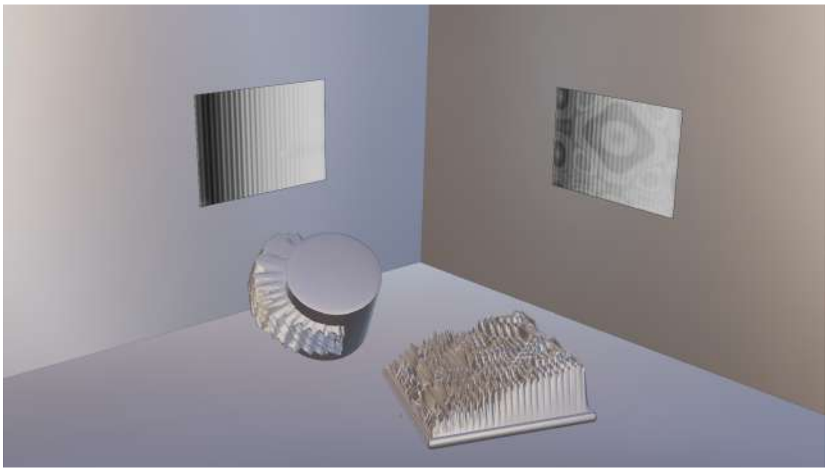


Figure 4.12: Sound texture test 2: integrating sound texture with another texture

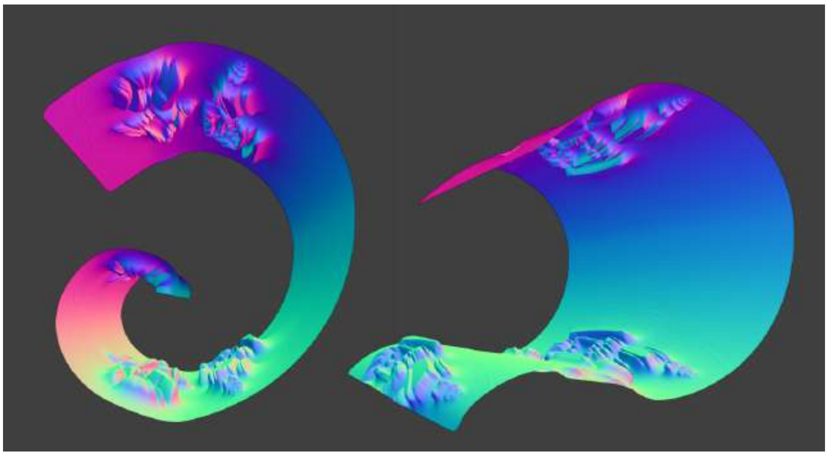


Figure 4.13: Sound texture test 2.1: on a curve plane

interaction using a VR kit tool. This is an integration of VP modelling with 3D texture application and mesh analysis. This step shows how to use the output of a basic VP application as demonstrated in Fig 4.15 to 3D modelling software or advanced modelling with VP sculpting application outputs as seen in Fig 4.16. First, the user should expert the VP object,

Figure 4.14: Sound texture test 2.2: applying texture onto two side on the left and on the right on a Stanford bunny Stanford Bunny source..

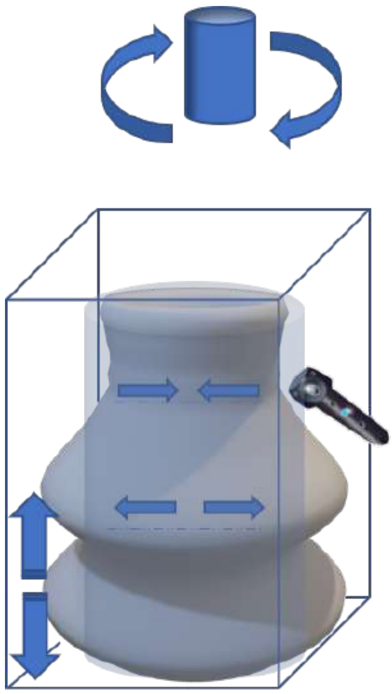


Figure 4.15: VP basic cylindrical shape

for example, an STL file and, critical to a 3D modelling software such as **Blender** or any other software. The user can examine the mesh blending and any errors in the design by retopologising tool called the 3D print tool in **Blender** as seen in Fig 4.17. Finally, in Fig 4.18 we can see an overview of the whole process, starting from basic VP modelling and sculpting towards applying texture and retopologising.

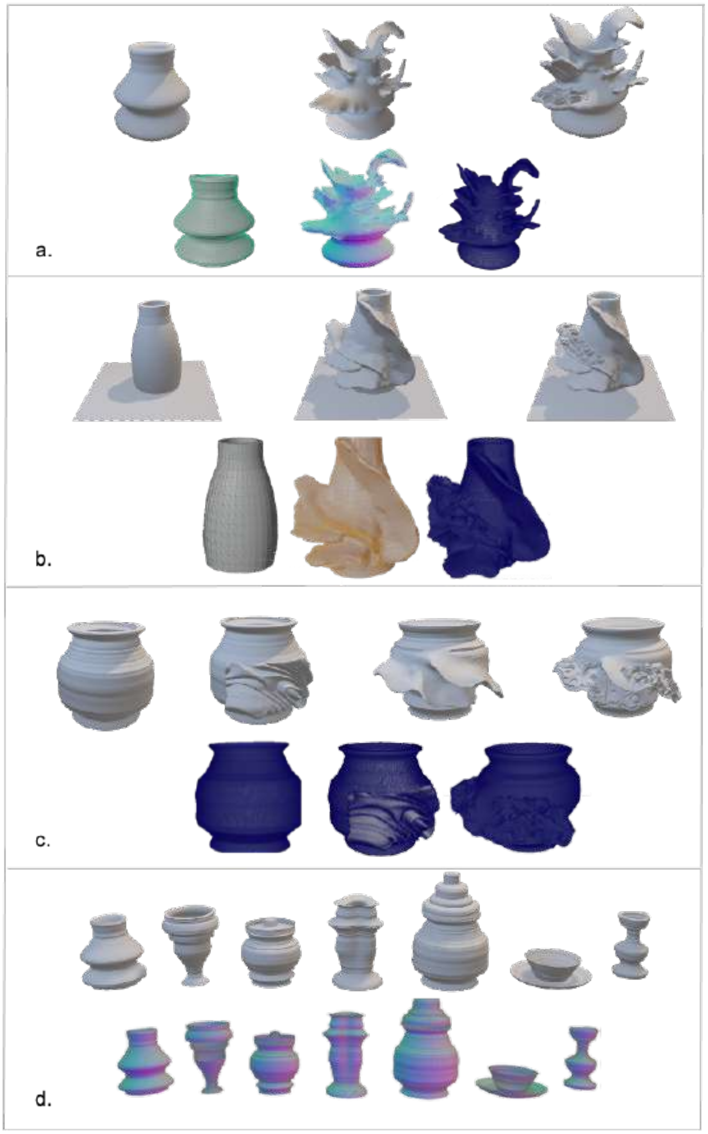


Figure 4.16: VP modeling outputs

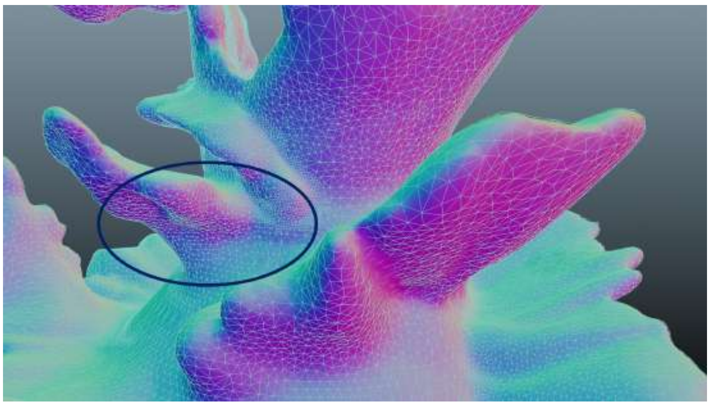


Figure 4.17: Mesh blending

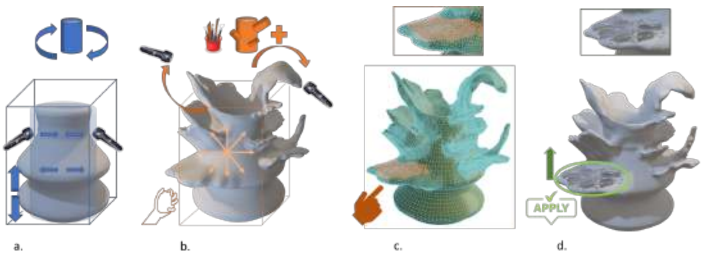


Figure 4.18: Novel VP deformable shape modeling workflow

4.6 Workflow Design

4.6.1 Modelling Pipeline

This research is in physicalising the full effects of sound data on ceramics. To achieve this, the thesis research designs, develops and demonstrates a widely deployable interactive Digital Pottery system as shown in Fig 4.19; and it uses deformable shape modelling to extend physical ceramics. It captures visual sound parameters through creative technologies such as augmented, VR and rapid prototyping.

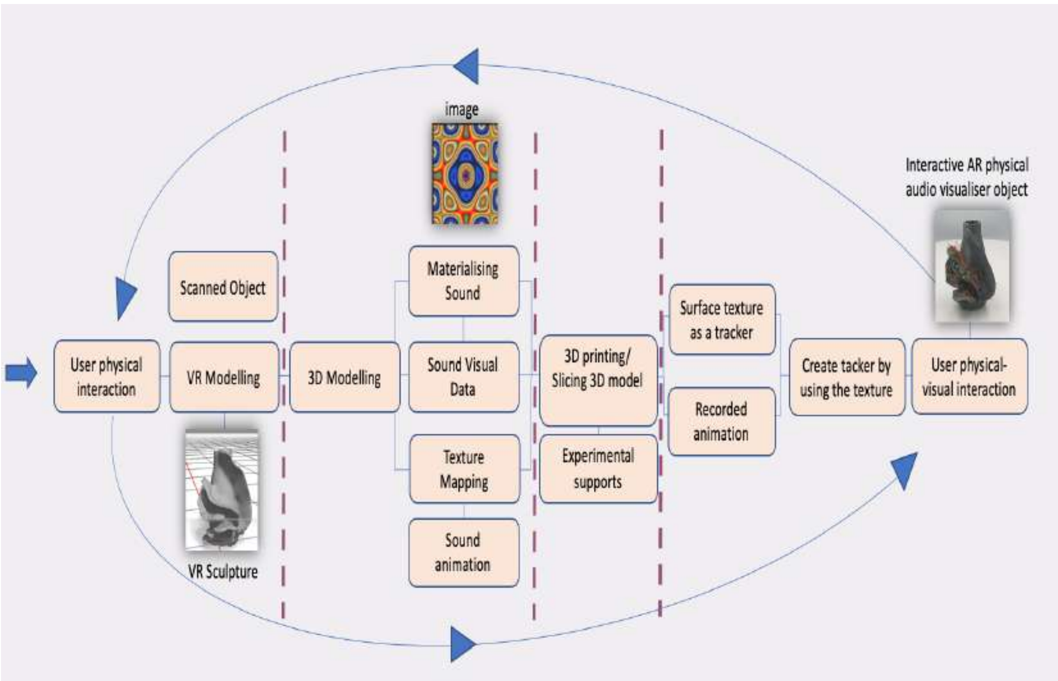


Figure 4.19: Sound Shape Modelling Pipeline.

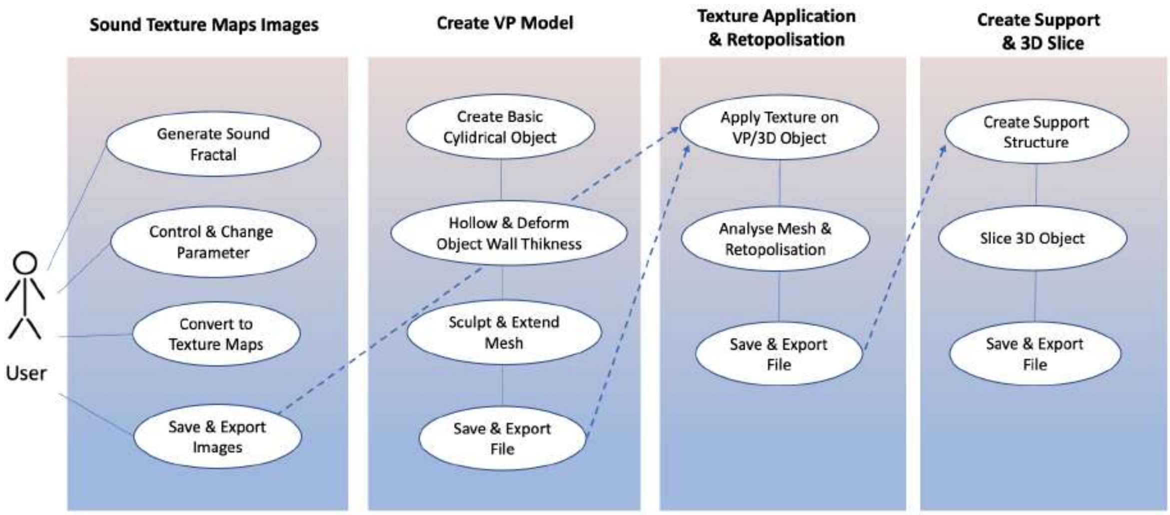


Figure 4.20: Use Case of Integrated Systems Refinements

4.6.2 Workflow

The proposed workflow process of interactive modelling in Fig 8.4 allows the users to detect flaws of the design in different layers of dimensions and realities. With this in mind, the fabrication modelling process would be much easier to generate a volumetric texture for 3D organic forms. Importantly, the deformable models and texture integration may produce some basic errors in 3D modelling software. This method can make the user perception one of the analysis tools for having a high-quality textured organic form with experimental software.

4.7 Self-Analysis

The section presents self-analysis with a case shown in Fig 4.20 to demonstrate the use of the approach and functional testing of the process involved to give some insight and highlight any problematic issues that can be resolved or avoided. The texture function criteria are mentioned in Table 3.1.

Table 4.1: Modelling: Test Criteria/Functionality

Function test	Pros	Cons
Input	Accept input X-change file: JPG,PNG,STL/OBJ.	-
Texture process	Easy/fast in the following: •Subdivision. •Select vertex group. •Apply modifiers (displacement/subdivision)	Crash system/long render baking-time due to the following: •Increasing count of subdivision effect render baking-time. •Increasing level viewport to 5. •Volumetric meshes.
Texture Displacement	•Easy/fast •Changing the geometry with high textured details. •Texture transformation on selected area. •can use 2D texture maps from addon folder	•Using multiple displace modifiers increases mesh count. •longer render baking-time/crash system.
Topology	Detect zero faces	May miss some zero faces and should do it manually.
Render Baking	•Fast & depending on selected mesh count, should do the following: •Free up memory and configure sitting. •Reduce the amount of geometry. •Reduce the amount and size of textures.	Memory ram/crash system.
Export	Depending on the 3D model size and mesh count.	Crash system High mesh count of 3D object export to STL.

4.8 Summary

The research presented a novel 3D sound resonance texture for deformable shape modelling, showing new results to contribute to the knowledge of VP towards digital fabrication for a range of users. Digital fabrication can capture the essence of sound energy by the concept of creating an object with mixed realities through animated sound texture mapping. The workflow processes have been accomplished using standalone information systems for modelling, deformation, VR and rapid prototyping as shown in Fig 4.21. The next chapter introduces VR interactive modelling.

Figure 4.21: Volumetric Sound-structure Texture prototype.

Chapter 5

Immersive VR for Virtual Pottery

VR and creative fabrication tools are still considered a new type of human-computer interface [147; 148]. This powerful technology opens an opportunity for artistic creativity which is easy to use, enjoyable and educational. Today, VP technical developments are more centred around methods supported by interaction devices. VR is evolving the physical / visual interaction concepts as a more reliable robust method, with further advanced visualisation and a complex modelling approach. This approach forms a new art line by contributing to communities, museums, exhibitions, and projects using multiple practice methods and mediums. However, integrating various creative tools such as VR apps, 3D modelling software, or devices suitable for modelling and rapid prototyping applications is becoming more difficult due to the rapid change in the development of the component technologies. This research presents a set of evaluation methods to be considered for the proposed system. The contribution optimises the outcomes in terms of usability for the novel VP system, configuring traditional pottery modelling, utilising a combination of virtual, 3D modelling and fabrication tools.

5.1 Introduction

VR relates to new and varied fields throughout the last decade. Creative interactions engage humans and machines empowering fields of science, art and technology. The new technologies, such as advanced graphics engines, wearable devices, and innovative interface systems, are opening new gateway across disciplines. The concept of VR modelling applications has changed with the growth beyond traditional disciplines, improving the human ability to unify

Figure 5.1: Virtual Pottery Usability.

physical and visual interaction exploration [149]. It is a unique path of creating complex objects in virtually perceived experiences such as VP. From those explorations, the thesis considers it is important, as shown in Fig. 5.1 to perform user studies in VR that include the aspects of Visual Feedback, Gestural Interfaces, 3D Modelling and Collaborative Design. The research investigation contributes to finding the most reliable method for testing VP systems. Furthermore, extending deformable shape modelling for VP making is associated with developing users experience.

This project seeks to address the appropriate evaluation methods, evaluating novel VP system's usability of a multidisciplinary engagement approach as shown in Fig 5.2, e.g., VR 3D modelling and games [150]. The motivation of this system is to encourage using deformable shape modelling in VR with newly developed insights that can help many disciplines [151] e.g., Digital Twins, edutainment curricula and training skills.

VP modelling and fabrication has several opportunities, challenges and desirable properties:

- **VP Usability Evaluation methods:** VP game applications are still in the development stages, filling the knowledge gap to be considered a reliable representation tool of traditional making. The advancement methodology of VP applications is trying to improve user skills, technique, and fabrication for physical/visual interaction modelling. Today's innovation of cutting edge enhanced technology, focuses on developing

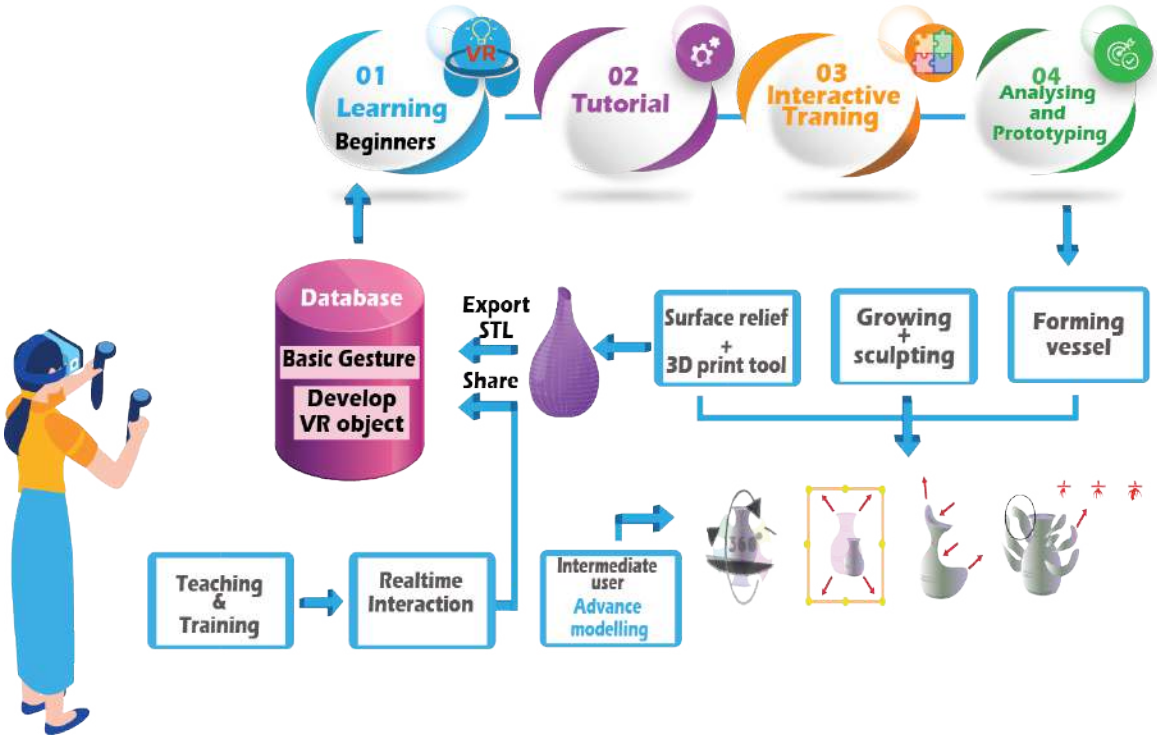


Figure 5.2: Virtual Pottery Workflow System for Learning skills.

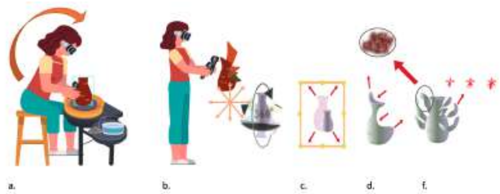


Figure 5.3: vr position

Figure 5.4: Overview of Novel VP System

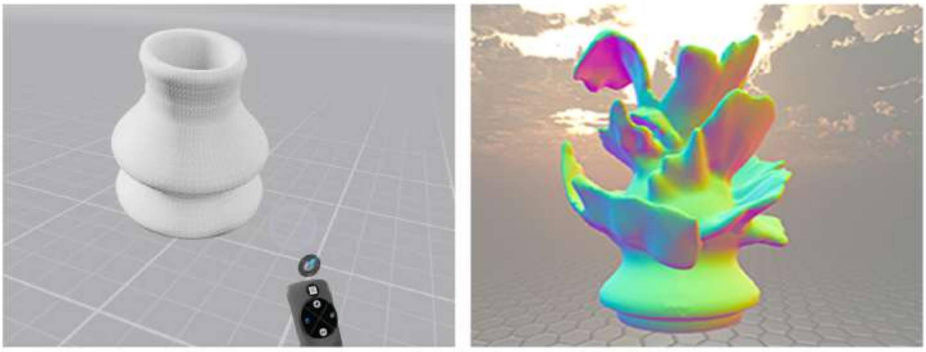
a more reliable sustainable usability evaluation in research.Next, the research present a list of challenges:

- **Labour and Compute intensive:** Many sophisticated methods for 3D deformable shape modelling are available to produce realistic outputs, but they are still considered as labour-intensive, expensive and time-consuming.

- **Creative Technology Integration for VP:** Nowadays, innovative technologies are more involved in the art field of developing human intelligence, performance and fabrication. VP is one of the data physicalisation methods, demonstrating real-time active deformable shape modelling, and it is currently a viable technique of representing an actual data physicalisation. There is a need to create a new form of integration application and tools to perform an improved experience and VP model.
- **VP analysis:** VP is a method that focuses on users physical/visual interaction to create complex VP objects, using digital clay representing the pottery making in real-time. Thus, developers of VP application still lack some knowledge in some areas, from professional makers in developing the virtual clay object for representing the whole traditional pottery making.
- **User manual and teacher/trainer for VP:** VP applications are acknowledged as a game of one player to experience the basic making techniques with some helpful tools. There are no effective communication methods of teacher/trainer to guide users development other than simple tutorials or figures to cope with on-the-go simple instructions.

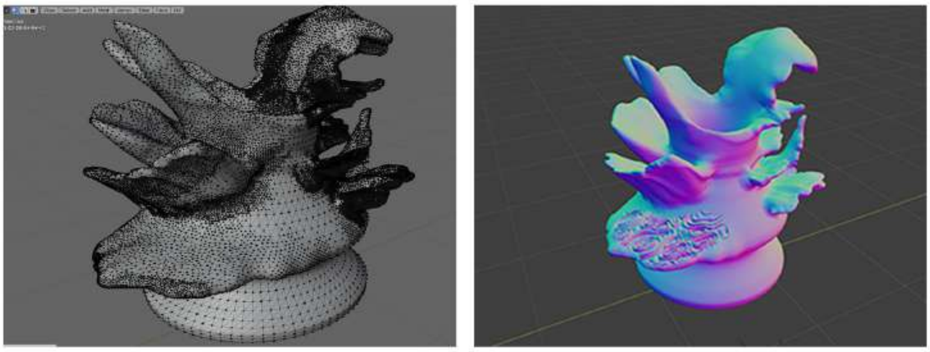
a. Digital clay b. Forming vessel

Figure 5.5: Forming virtual clay vessel.



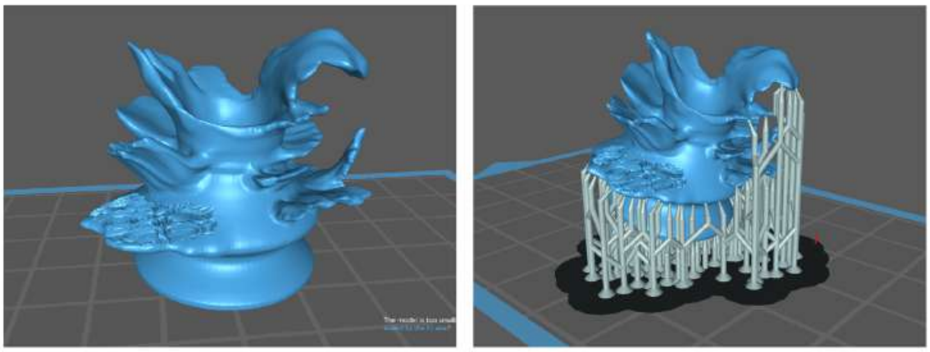
c. Growing d. Sculpting

Figure 5.6: Growing virtual vessel with dynamic typology.



e. 3D print tool f. Relief

Figure 5.7: Adding texture relief on VR/3D object & using 3D print tool.



g. Slicing h. Support structure

Figure 5.8: Slicing 3D model and adjusting structure supports.

5.2 VP System Software and Tools

Although there are several user studies in VR targeting physical interaction, this research aims to find a simple evaluation method as a guideline, targeting usability studies to develop VP systems and application for education and training purposes.

i. Prototype with support j. Final prototype

Figure 5.9: Final prototype outputs using UV resin and DLP 3D printer.

The proposed system is an interactive virtual physical 3D modelling for multi-disciplinary approach e.g, Edutainment and games. [152]. The system is chosen to extend ceramic artist creativity of making, scaling up the boundaries of creative making and developing a physical-virtual experience that captures real-world deformable pottery making (addition / subtraction) using tangible hand and finger transformations.

As shown in Fig. 5.5, 5.6, 5.7, 5.8 and 5.9 the proposed system integrates a chain of VR, 3D and fabricating applications with new techniques to simulate as much as the user would experience in the real traditional making using the novel VP system. The overview of the system usability in Table. 5.3, 5.4 and 5.4 explains the steps from learning to fabricating and how the user would assess the development, and how to evaluate the user's experience.

The evaluation presented in the paper includes (i) visual comparison of relief synthesis compared to other research presented in the literature; (ii) the interaction models proposed and implemented in this research is compared to interaction models used by other researchers; (iii) user studies target creation of simple shape deformation and addition of 2D textures. However, the research prototype uses multiple systems during the modelling stage, which requires sufficient knowledge in the use of the systems to model the shape with sound deformation.

Dojagi and **ShapeLab** are the appropriate applications for the project to support VP. More so, enhancing the ability of basic and intermediate users to analyse VR model errors and extending surface deformation of image-based modelling through using **Blender** software

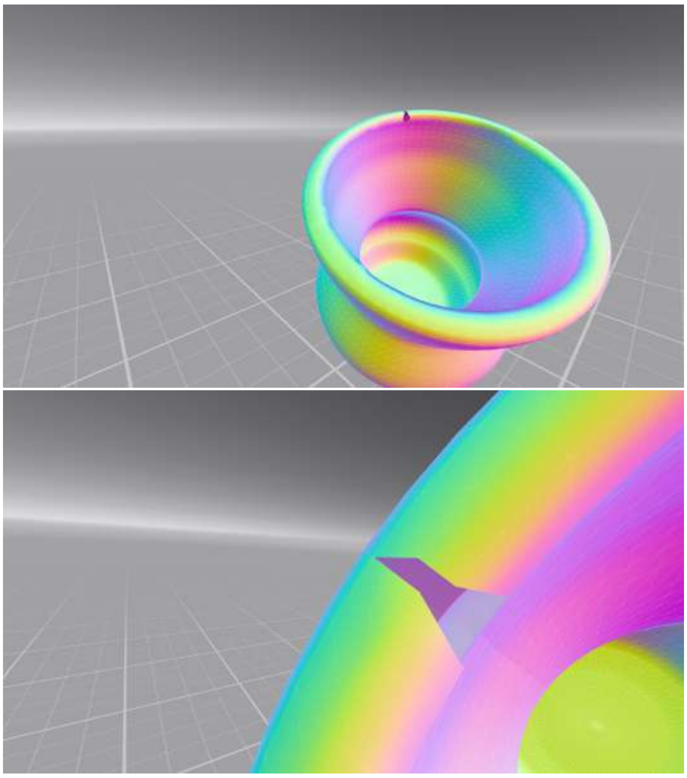


Figure 5.10: Zero-Faces.

and experimental slicer settings. This method enables users to find zero-faces as shown in Fig. 5.10 and other mesh errors and add surface deformation patterns. The project presented a comparison of VP application in Table. 5.2 to explain how the thesis project system is compatible with the **Dojagi** VP application due to the viable elements within the application. The thesis also provides tables of modelling applications comparison and features, as the VP system is not limited to specific applications, as shown in the Table. 5.5, 5.6 and 5.7.

This also facilitates social collaboration, as the VP users can collaborate from any networked location across the globe. The project shows the interplay between the virtual and physical, through 3D rapid prototyping/printing, which is possible through accessible 3D printers. The VP system goes beyond what is done in the physical space. It enhances the capability of the VP learner or user, as the virtual prototype and the physical prototype can be visualised in much less time, than in physical pottery. The VP allows to save snapshots and helps to restore to previous states and recreate the repetitive process easily, instead of starting from scratch every time, if a damage is done to the model. The example including the 3D printed prototype is shown in Fig 5.9 and was done in less than a day, and this can be accomplished once the user has sufficient training and has gained skills to use the system.

5.3 User Studies

The research explores usability studies to enhance the thesis novel VP systems, improving the user's development of 3D deformable modelling for compatibility. Exploring the study methods will set the foundation for future tests to support assessing the evaluation phase. The usability tests approach focuses on the criteria of a multi-disciplinary approach, integrating VR applications for a novel outcome of graphics modelling and rapid prototyping. In the meantime, due to Covid-19 health restriction relying on research related to the field, the research of the thesis could not proceed with the tests. The project created an alternative plan where the project has set a skill Table. 5.1 to develop usability studies, to evaluate the users' performance while experiencing the novel VP system. The system aims to assist novices, practitioners and researchers in improving VP system concepts and applications.

5.4 Self-Analysis

The section presents self-analysis shown in Table 5.8 to demonstrate the use of the approach and functional testing of the process involved to give some insight and highlight any problematic issues that can be resolved or avoided.

User Guide

The thesis evaluates the performance and effectiveness of the thesis VP system with other VP systems to extend the visual feedback criteria of interactive graphics modelling of VP. The investigation approach examines the related user's studies as a blueprint guide for future usability tests and evaluation analysis. The interaction method of graphic modelling delivers more modelling options of texture relief, tools, and problem-solving for complex organic rapid prototyping.

Table 5.1: Skills Table

Skills	Basic	Intermediate	Advanced
e-Learning	Short e-tutorials	e-course learning	advanced self-learning and model development
Gaming	Ability to understand and follow technical soft skills. Create on seat	Ability to recreate objects Set/Walk in VR space	Ability to master control VR kit tools. Function under pressure; Create new models; Set/Walk in VR space
VR Pottery/ making	Under-standing basic pottery making; hand-building	Intermediate - throwing; hand-building; Sculpting	Advanced deformation - Mantaflow; Surface Relief; Design new deformation algorithms. Mantaflow
Creativity	Minimal object deformation on VR object	Creating objects using: Mixed method of VR and 3D modelling	Developing / designing VR application for art output Combination of VR and physical object (augmented-reality)
3D Printing	Use normal settings	Analysing object errors using 3D print tool (changing slicing settings)	Develop new slicing setting Analysing errors in the designs in VR/3D (changing settings)

5.5 Summary

This chapter presented appropriate usability evaluation methods based on research studies related to VR, discussing the evaluation methods that will advance the thesis research based on Visual Feedback, Gestural Interfaces, 3D modelling, and Collaborative Design. The feedback focuses on the usability of integrating multi-disciplinary VR and creative technologies, relying mainly on visual feedback and imaged based studies of VR applications. This approach optimises the outcomes of developing a new VP system, configuring traditional pottery modelling, utilising a combination of virtual, 3D modelling and fabrication tools for interactive quality and dynamic compatibility. The usability studies aim to develop modelling and practices skills, providing guidelines on designing more solid applications, employing VP as an extended version of deformable shape modelling and rapid prototyping.

Table 5.2: VP System comparison and Users Experience Criteria

VP Systems	Wowtao (Training)	PotteryGo (Training)	POTEL (Training)	Novel VP system (Sound Modelling System) Game play / Training
User Interface	Touch / tablet	Gestures / PC	Gestures	tracked motion controllers
Workflow	Includes: Modelling, painting/image pattern, bottom design, firing and final visual image.	Includes: Learning, interactive training, making vessel, surface painting/ free creation and share/teaching.	Creating a vessel in real-time pull/push, brush deformation, bake to STL.	Create vessel in VR space, extend VR object growth, adding sound shape surface texture, experimental slicing, prototype and link physical object with AR
System setup	•Tablet/ smartphone. •Fixed Environment.	•PC Head-set - Room Scale/seated Leap motion hand. •Fixed Environment.	•Tablet PC Head-set- Room Scale/seated Leap motion hand. •Fixed Environment.	•VR kit/ VR space •Dojagi & ShapeLab application features: •Room-Scale/ seated & standing. •VR wheel/ paddle speed controller/ kiln. •VR tools/ Graver, Measurement tool/ Vernier caliper and Brush. •Bucket of water. •Design own workplace and appliances.
Training Module	✓	✓	✓	✓
User Study/ Evaluation of Visual Feedback	Easy-to-use even for novice users were rather similar to those from the experienced users from visual feedback trials.	Strong effect of visual feedback on participants to learn pottery-making skills.	The visual feedback allows user to sync in VR environment by three ways Auditive, depth cues and haptic.	Future research step: the visual feedback may have effect on extending pottery making of creating a complex VR object and developing it in a multiple application with rapid prototyping.

Table 5.3: VP Systems Deformation and Texture Relief Comparison Criteria

VP Modelling Systems	Wowtao	PotteryGo	POTEL	Novel VP system (Sound Modelling System)
Deformation process / Types of gestures	•Real-time rendering •Push/Pull	•Real-time rendering newline •Raise up & top dig	•Real-time rendering newline •Raise up & top dig	•Real-time rendering newline •Raise up & top dig newline •Dynamic typology/Growth newline •Imaged based-modelling relief newline •Free form modelling newline •3D print tool/Fix Non-Manifold mesh newline •Table 3 VP Systems prototyping Criteria
2D Relief Modelling / surface detail	Image pattern (visual)	-	-	Sound resonance fractal images from (Chladni Plate)
3D texture/surface detail	-	-	-	Sound resonance fractal images from (Chladni Plate) + displacement and bump mapping, controlled by normal-map colors for height and depth

Table 5.4: VP Systems prototyping Comparison Criteria

VP Systems	Wowtao	PotteryGo	POTEL	Novel VP system (Sound Modelling System)
✓	-	✓	Xchange STL	Xchange STL/ Obj
Slicing/ support structure	Default FDM slicer	-	Default FDM slicer	Experimental FDM & DLP slicers
Relief prototyping	-	-	-	✓

Table 5.5: Comparison of Virtual Modelling Applications

VR Modelling Applications	Feature Focus	UI experience level	Export Model	Availability	VR Compatibility
Adobe medium	modelling	intermediate / advanced	✓	free	Oculus Rift and Oculus Quest
Gravity Sketch	modelling	advanced / intermediate	✓	free	HTC Vive / Oculus Rift
ShapeLab	modelling	intermediate / advanced	✓	one time purchase	HTC Vive / Oculus Rift
Tvori	modelling / animation	beginner / intermediate	✓	early access	HTC Vive / Oculus Rift
Blocks	modelling	beginner / intermediate	✓	free	HTC Vive / Oculus Rift
SculptVR	modelling	beginner / intermediate	✓	free	HTC Vive / Oculus Rift
Master piece	modelling	beginner / intermediate	✓	free trial	HTC Vive / Oculus Rift / Oculus Quest
Blender XR	modelling	beginner / intermediate / advanced	✓	free	HTC Vive / Oculus Rift

Table 5.6: Comparison of Virtual Pottery Applications

VR Pottery applications	Feature focus	UI experience level	Export model	Availability	Compatibility VR
DOJAGI	gaming / learning	beginner / intermediate / advanced	STL /Obj	one time purchase	HTC Vive/ Oculus Rift
Let's Create! Pottery VR	gaming / learning	beginner	-	one time purchase	HTC Vive Oculus Rift
Potel	gaming / learning	beginner	STL	free	Oculus Rift

Table 5.7: Comparison of 3D Modelling Applications

3D Modelling applications	Feature Focus	UI experience level	Export Model	Availability
Zbrush	modelling	intermediate / advanced	STL/ Xchange file	subscription
Autodesk 3ds Max	modelling	intermediate / advanced	STL / Xchange file	subscription
TinkerCAD	modelling	beginner	STL / Xchange file	free
SketchUp	modelling	beginner /intermediate	STL / Xchange file	free/ subscription
Blender	animation/ modeling	beginner / intermediate / advanced	STL / Xchange file	free
Unity	game development & architecture	intermediate / advanced	STL / Xchange file	Subscription
Houdini	3D animation/modelling (16/17 releases)	intermediate / advanced	STL / Xchange file	subscription
Rhino	modelling	intermediate / advanced	STL / Xchange file	one time purchase

Table 5.8: VR: Test Criteria/Functionality

Function test	Pros	Cons
Input	STL/OBJ.	-
Haptic control	very sensitive & capture deformation in/out of VR object.	-
Virtual clay dimensions.	scalable size.	-
Topology	-	seam-line gap.
Render Baking	fast.	-
Sculpting tools	ShapeLab app: •verity of sculpting tools. •analyse seam-line in VR view.	•limited tools in Dojagi app: •Dojagi app (the sculpting tools creates zero faces).
Slice/Trimming	can caps the object into two with separated control.	-
Texture relief pattern	-	-
Export	STL/OBJ.	-

Chapter 6

Virtual Pottery: Towards Prototyping

6.1 Introduction

Layered Manufacturing has gained international attention and made rapid strides over the last three decades. This chapter presents layered manufacturing from the perspective of the artist, especially for intricate ceramic pottery. Opportunities exist to apply visualisation to the foremost problems plaguing layered manufacturing. The two main conflicting constraints when modelling for VP are the rapid visualisation and accurate rapid prototyping, during the modelling phase and manufacturing phase respectively. The artist needs simultaneous low-poly representation of the shape model for interactive visualisation and at the same time needs an adequate representation to generate an accurate printable model. Two further complexities are also faced by the artist: to add surface details that cannot be achieved by hand and to use material like clay for manufacturing that is used in real pottery. Applications from VP and how visualisation helps in the modelling and prototyping of pottery with intricate shapes and with a range of materials including clay are demonstrated here.

3D printing has started an era of rapid manufacturing, seeking new insights towards the futuristic design and fabrication of voxel-based modelling for layered manufacturing, also known as additive manufacturing technology. The aim is to develop voxel-based modelling using the concept of VR/3D visualisation and a unique high-value 'tailored' 3D printing production process. The approach in this thesis employs the base object made with VR physical interaction and a novel mutable geometry pattern obtained from a volumetric sound resonance texture. In addition, the focus is on the challenges and in resolving issues in the process of modelling towards fabrication as shown in Fig 6.1. In this figure, a voxel-based modelling representation test using Stanford bunny is shown where: (a) shows a method of layering an object with a shell of the main object shape and volumetric texture. (b) presents the process of converting mesh to volume and then volume to mesh to fill holes in the object. (c) is a VR model with volumetric sound texture applied on selective vertex group with high level 'viewport'. (d) is a Voronoi 3D model cell that generates points as an organic form / structure. (e) finally, a voxel model that fills the entire volume.

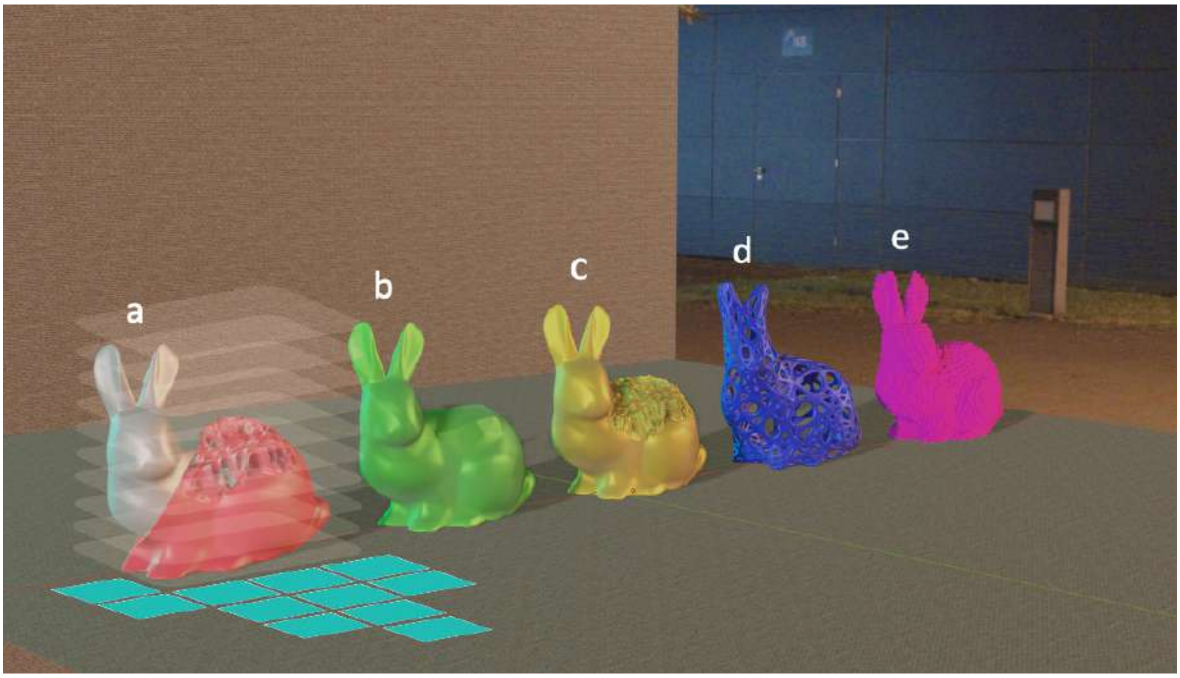


Figure 6.1: Voxel-based modelling test using Stanford bunny - challenges. Stanford Bunny STL file source. .

The special issue on Rapid Prototyping [153] examined the potential of tools, applications, and modelling techniques that assist the fabrication process. Rapid stride in progress has been made over the last 25 years since the first IEEE CG&A special issue was published. Two other CG&A special issues, Volume 33 (6) and Volume 38 (3) which also focused on 3D printing: Computational Aspects of Fabrication: Modelling, Design, and 3D Printing and Computational Design and Fabrication.

With the development of 3D printers, printing technology changed many industries and help both experienced and novice users by giving new insights for application and device development. Furthermore, focusing on objects' visualisation, helps to visually analyse issues with the 3D printing process and enables fabrication based on 3D models in 3D/VR views, including the users ability to convert digital templates into 3D physical objects with customised details aimed at massive production.

The printing process also called Additive Manufacturing, involves slicing digital models into layers, using common affordable printers, and can be achieved even by novice users with limited experience. Printer types include Fused Deposition Modelling (FDM), stereolithography (SLA) and Digital Light Processing (DLP) printers. The materials vary from filaments such as, plastic, clay, metal and nylon for FDM 3D printers; on the other hand, SLA and DLP use resin as a UV-curing plastic liquid cured by a computer-controlled laser.

Clay has been newly introduced as a material in the 3D printing industry, and it is still subject to trial tests. Digital clay modelling is about the simulation of real physical object deformation. This thesis considers developing the visual and physical aspects of fabricating virtual clay pottery.

Recently, there is new development of applications and devices improving prototyping quality with new design ideas. Many applications and printing techniques have been enhanced, motivating non-specialists in customised industries such as artists to work cross-disciplinary. Artists are more immersed in technology, competing with professionals in manufacturing industries. Indeed, their artistic performances are becoming more than exhibiting aesthetics of material and objects; they are now stepping up to help learn and develop the fabrication process and the functionality of the output from a new perspective.

With the new VR creative technology, most modelling specialists recently have adopted using VR applications for physical interaction and more realistic modelling. Artists find that physical interaction can deliver more of the sophisticated fabrication details to be achieved on a 3D physical model. However, challenges are encountered during the fabrication process that arise with more complex and organic forms. This chapter presents methods for fabricating VP objects and extending the process of fabrication using multiple modelling applications.

The approach uses VR Dojagi / ShapeLab and 3D Blender with two slicers Chitubox / Photon S. Furthermore, an SLA printer is used for fabrication to get complete fine complex details, utilising affordable printers. The attempt is to make maximum use of today's tools, integrating multiple tools to address the issues of design and fabrication. More so, it emphasises the distinct physical structural shape data of modelling and visualisation. This research examined method of applying this to VP modelling as a printable volumetric relief, which uses image-based map displacement from sound resonance phenomena that deforms the shell surface of 3D objects.

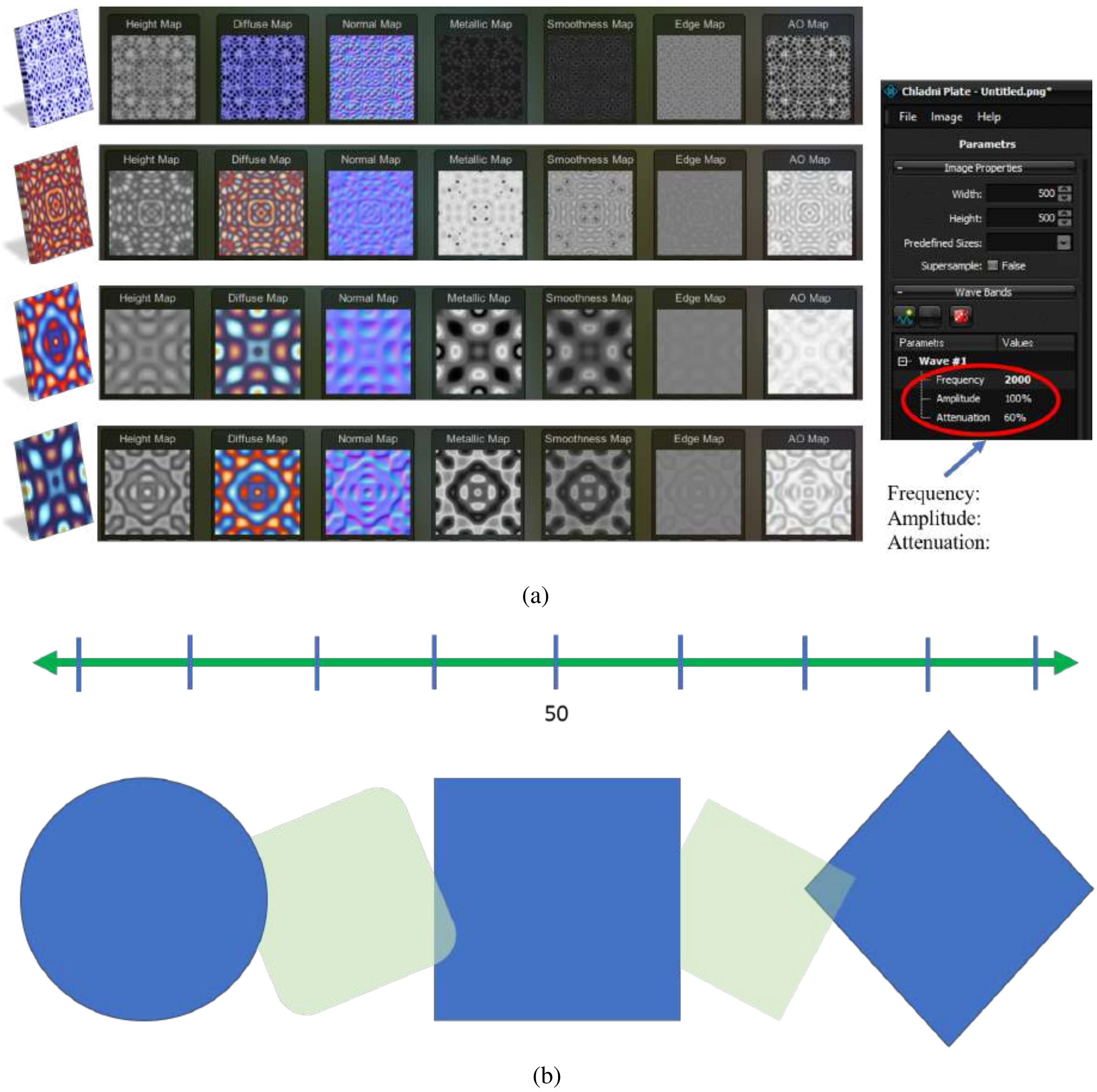


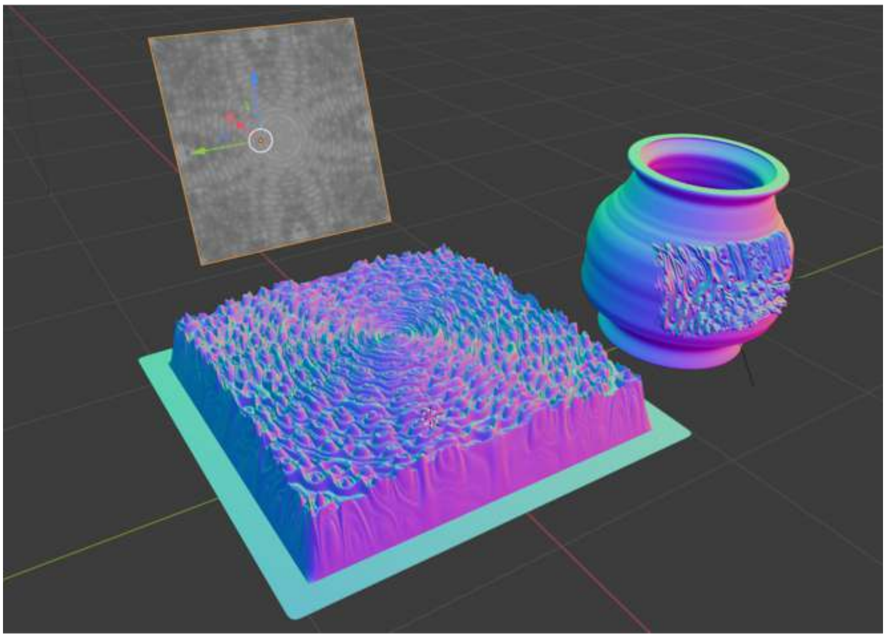
Figure 6.2: Chladni images. (a) Matrix of Chladni images using different input. (b) interactive control for repeatable patterns.

The current VR pottery modelling and fabrication is used to point out the opportunities and challenges for VR pottery developers. This research addresses development of tailored manufacturing and tries to resolve the problematic issue of modelling in VR pottery applications. The current VR applications may have some errors in the 3D models during slicing, creating gaps, thin walls, and some non-manifold meshes. The research relies on a VP application, which uses a cylinder shape. The negative space in the object, shapes the object, using VR controllers with physical interaction. Then the VR object is exported to analyse seam-line position and extend the mesh using dynamic-topology, which VP do not have. Additionally, a novel sound volumetric patterns to apply to the VR pottery model is presented.

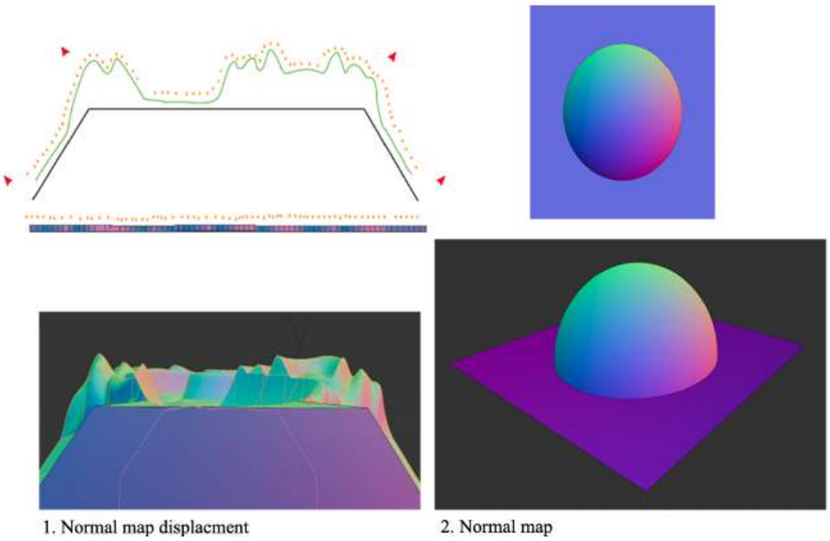
6.2 'Tailored' Manufacturing

The journey of manufacturing revolution in the time of emerging technologies has improved radically together with the variety of today's consumer's needs, changing new service models of digital manufacturing industries. Customised production is now highly demanded, resembling the individual quality of manual human production. With this novel texturing method, VR modelling can help organic object design with various output mappings, while constructing one object which allows deformation control as a state-of-the-art visualisation for a fabrication method of intelligent manufacturing.
The global market growth for sustainable solutions and customised products has resulted in more demand for 3D-printed parts and products. As the 3D printing industry advances, prototyping, mainly supply chains, changed over the past 25 years. During the pandemics of Covid-19, consumer's need for medical protective gears is becoming more popular, impacting large scale customised design production needs on the market. Consumers have been raising the quality requirements and features of the output on demand rapidly. Average massive factory production has not been able to cover the production needs during the pandemics.

This approach can deal with large production of customised designs from internal and external networks worldwide using X-change files. VR fabrication with this system can resolve major fabrication problems with simple steps. One of the objectives is to find new ways of visualising designs before the final output using the Chladni plate software for a geometric complex design generator of 2D images, as shown in Fig 6.2. It explains how Chladni Plate



(a)



(b)

Figure 6.3: (a) volumetric sound structure texture on a plane and a VR model. (b) Integrating Normal images and displacement modifiers to change the location of actual vertices in a mesh.

is used to produce a 2D image of sound resonance fractal controlled by frequency, amplitude attenuation, and colour generator. The second step is to materialise 2D sound fractals images into variant maps as samples and then apply the displacement on a plate using the height-map as an exemplar. The default size setting for height and width is 512 X 512 and can be changed manually. Also, in Fig 6.2 shows the shape orientation control by attenuation change. The X-axis scale of 100% changes the shape by moving to the right or the left, changing the shape's corner from a diamond shape to a perfect circle. The tailored volumetric sound resonance texture is shown in Fig 6.3. This demonstrates how to apply volumetric texture on a flat surface and a curved one. The sound texture is applied to a selected vertex group using a 2D image with a displacement modifier, controlled by a normal map, showing mesh geometry changes as shown in Fig 6.3. Here the mesh geometry point location is changed when applying normal map displacement. Choosing triangles mesh and not quads is essential for blending the detailed texture to the underlying shape/geometry. The interactive modelling creates original organic forms for interactive production, intensifying the path of VR modelling, creating a state-of-the-art for intelligent designs and fabrication.

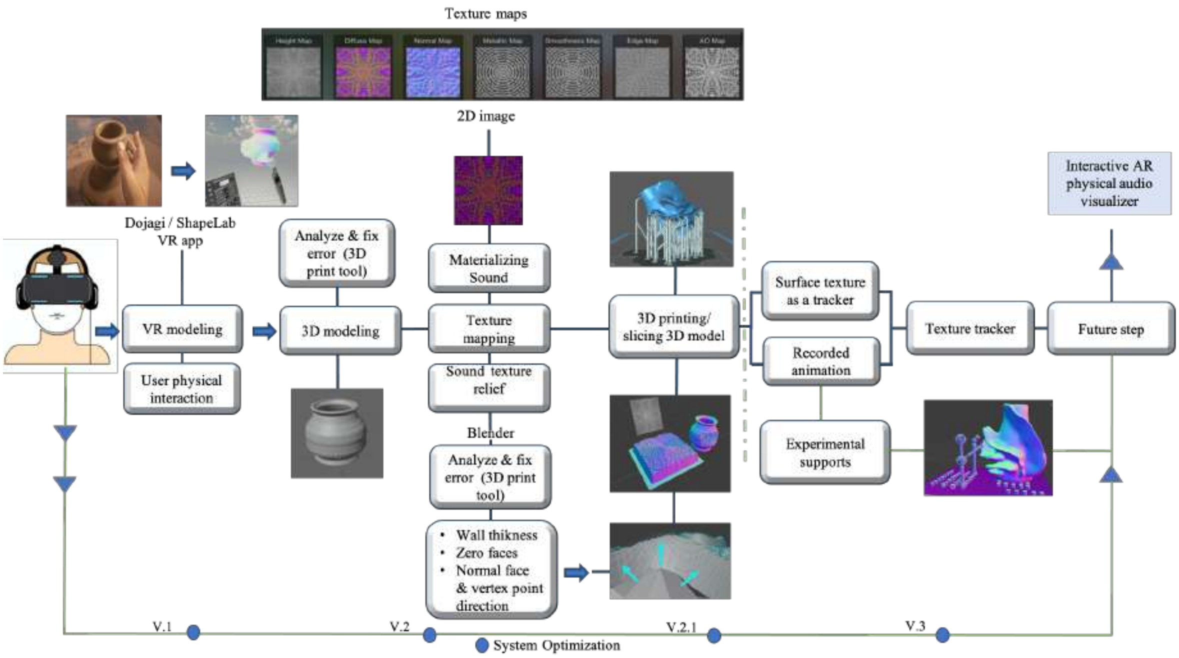


Figure 6.4: Virtual pottery workflow system.

VP is evolving and competing with traditional making, creating new insights to explore. This research developed a system assisting users in creating simply generated sound resonance detailed patterns as a closed-form solution for applying volumetric textures on VR objects as shown in Fig 6.4. The workflow system proposed in the thesis is an integration of novel volumetric sound texture and VR/3D modelling. The method highlights challenges and refinement in four different stages. The method uses the "Chladni Plate software" to produce displacement maps of sound fractals as 2D images, for deforming the shell surface.

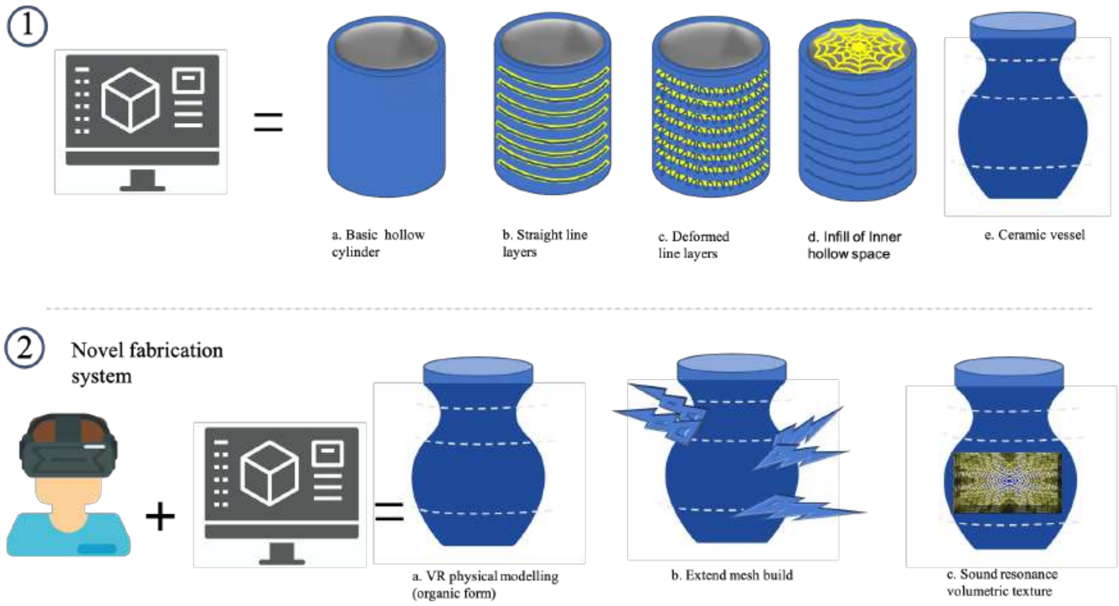


Figure 6.5: VP Modelling system comparison: (1) shows the existing modelling approach of forming cylinder shape.(2) Proposed novel system.

This method propagates a new technique called *volumetric sound-structure texture*, which simulates variables of actual physical object deformation, such as bending, stretching, pull and push.

The constraint of this approach is that it deforms mostly rounded objects as a free form, so the research technique uses' the vertex groups group weight to get seamless details of a deformable shell surface of the selected mesh. Figure 6.5 shows the comparison of fabrication methods in part (1) and the proposed novel method in part (2). Both methods rely on cylinder shape and the negative space to shape the vessel. In Fig 6.5, (1) the top-row shows the control of modelling and fabrication is involved only on layers deformation and infill manipulation reconstruction, while in part (2) the bottom-row shows VR/3D modelling method deforms the surface shape across layers with dynamic topology mesh control deformation, sculpting the shell surface to add and remove details. This method proposes to sculpt a complex shape out of a simple mesh rather than just adding details onto a modelled base mesh.

6.3 Summary

This chapter discussed the evolution of 3D printing and layered manufacturing over the past 25 years. The approach in this thesis is to address tailored manufacturing of shape modelling refinement for complex and organic forms towards the fabrication of VR/3D objects. The importance of 3D printing is now focused on pre-visualisation with a new approach of modelling, including the user's ability to model and interact in a three-dimensional space.

Chapter 7

Pottery: 3D Printing Challenges

7.1 Introduction

Over the years, VR modelling has notably changed and added to computer graphics the viability of interactive virtual/physical making and rapid prototyping, reducing development time while improving prototype accuracy of organic physical modelling. VR technology provides a method for modelling visualisation approaches to create complex 3D models, providing the flexibility of modelling towards the fabrication of physical outputs.

However, there are a limited number of accessible applications. The existing VP applications are mostly gaming based with some learning options. VP applications, in the meantime, create an excellent medium for traditional simulation of pottery making, but on the other hand, there are many challenges with current tools.

The first challenge involves the **wall thickness** of the 3D object. The second challenge is an error of the mesh showing the **seam-line** creating a hole in the mesh, using sculpting tools and in the slicing process. The third challenge is that the user cannot add a **volumetric surface deformation** pattern or add to the mesh count using dynamic topology. The final challenge is **zero-faces** and **non-manifold mesh**, creating an issue to the VR pottery vessel and poses difficulties from being a useful modelling tool for accurate solid prototyping of physical objects.

7.2 Modelling System - Challenges

VP bridges technology and traditional art, using physical making skills in VR space by deforming virtual clay to produce a vessel as a 3D model representation (such as an STL data-structure / file). Therefore, deformation is the key element to extend VR pottery by applying patterns that change the surface geometry, taking the shape of the vessel as a volumetric texture on the shell surface or as a free-form.

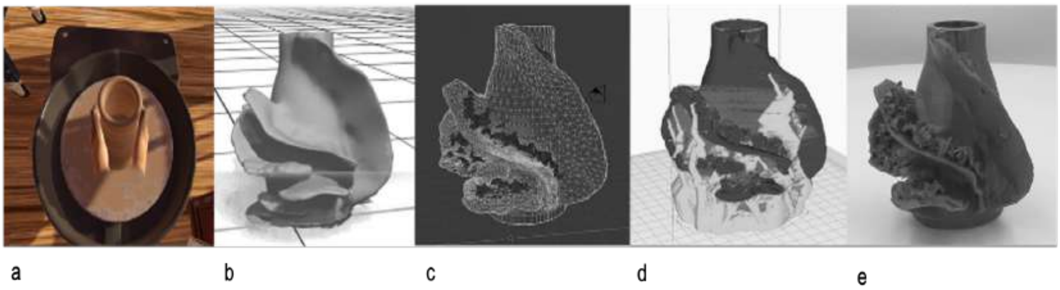


Figure 7.1: Test 1: Pipeline of fabrication, using sound animation texture

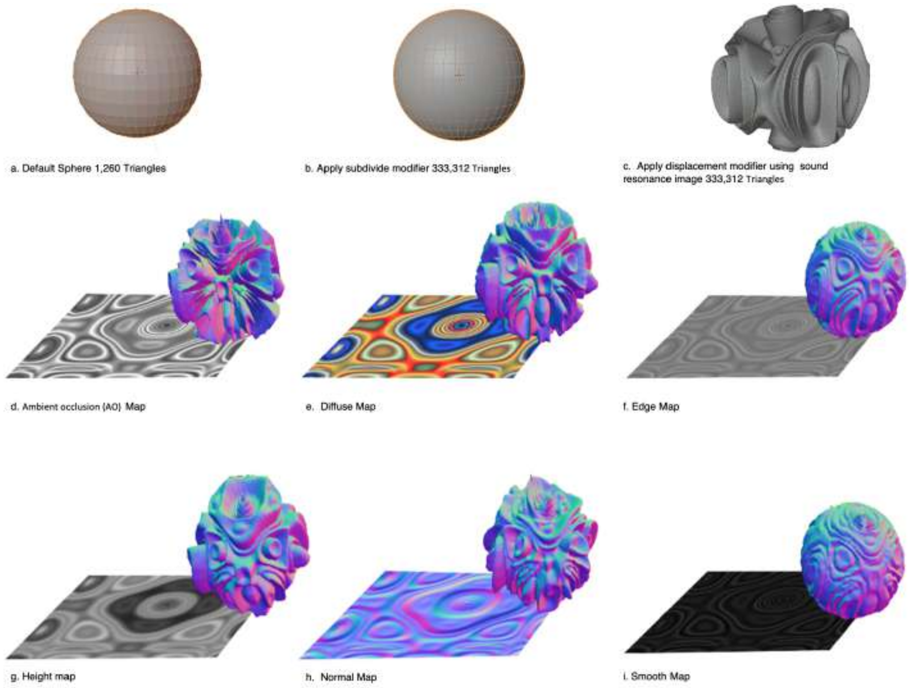


Figure 7.2: Test 2:Displacement maps using sounds

The proposed novel technique that automatically deforms a 3D object shell surface as a free form, using displacement mapping or deforming a complex 3D object. This is achieved by selecting a desirable mesh, creating a variance mesh of a complex object, divided into two vertex groups weight so that the displacement map will be less than the whole weight of the object. Firstly, an interactive mesh is created using a sound visualiser to deform the shell surface of the mesh changing the directions points. Fig 7.1 shows a snapshot of the pipeline workflow fabrication process using sound animation texture. Fig 7.1(a) shows the basic shape making within the VR system. Figure 7.1(b) extends the surface of the basic object, creating curved layers as a part of deformable shape modelling using VR tools. In Fig 7.1(c) the deformation is focused on the shell surface of the object, the wire-frame mesh is selected into vertex multiple groups, interacting with sound, and the extrusion happens along the Z-axis. In Fig 7.1(d), the 3D printing stage is based on slicing the objects and creating supports as scaffolds to ensure a successful print.

The default setting of the support structure may not be the best choice to support organic forms, so the compatible option is to use an experimental tree support for the FDM printer. In Fig 7.1(e), shows final physical prototype object with curve deformation and surface detail obtained from sound texture animation. The test output shows materialising interactive sound animation on a rigid 3D virtual object, using 3D modelling software as a way of capturing the deformation. As a result, the mesh shape was only interacting by extending/extruding the form of the mesh.

Secondly, Fig 7.2 used the Chladni Plate to produce a 2D image of sound resonance from fractal 2D images, producing deformation maps. The normal texture mapping method does not show the geometry of the surface. On the other hand, integrating the 2D image with a displacement modifier can deform a simple 3D sphere shell surface to make it a complex 3D object. The complexity of the object changes by changing the parameter of different maps values with direct pushing, pulling, and strength manipulation, where (a), (b) and (c) represent the visual process of deforming a default sphere in blender software, and the rest are the visual definition of each map:

(d) Ambient Occlusion (AO) is a grayscale map that contains lighting data.

(e) Diffuse Map defines the colour and pattern of the object.

(f) Edge map is an image that indicates where edges are in the image.

(g) Height map Height map: is a grayscale image used in displacement and bump mapping, giving an extra definition to the surfaces, representing the highest point as white and black

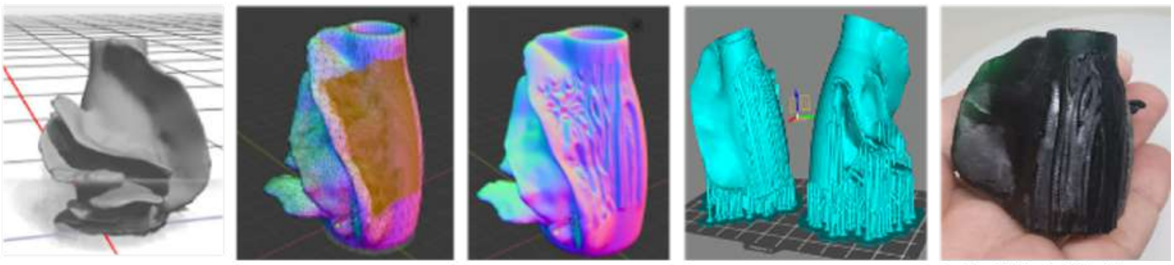
the lowest.

(h) Normal Map adds surface detail, such as bumps, to a model that captures the light as if it represents actual geometry, and it is a mapping technique used for simulating the lighting of bumps and dents.

(i) Smooth Map is a Smooth functions on manifolds.

Thirdly, the result of the Chladni map is used on a sphere, leading to defining new and different types of deformation. The proposed approach is an unique way of pre-visualising texture maps producing different deformation outputs. In Fig 7.3, the user divides the 3D VR object meshes into two groups and applies two modifiers, using subdivision surfaces with displacement and the adjustments of the vertex group selection to create different weights. The displacement should have less weight than the rest of the object, making manipulation adjustments using modifier strength and mid-levels. Each sub-picture shows a different orientation to highlight the straight lines and how the pattern maps in a linear region. It has a combination of a curve (in the neck region) and a straight region below the neck.

The printer used to fabricate the VR/3D object is an SLA printer to show detailed texture. This print has a stretched texture without a repeated pattern, and the texture is applied on a curved shape from a different viewpoint. Finally, Fig 7.4 shows (a) green UV transparent resin as a material that shows dimensions and in (b) the slicer settings. The material viscosity is critical during printing; the higher it gets, the more tension between gravity and support grips holding the object. The SLA machine operates through using a UV laser beam, tends to be slower than FDM in printing time. However, the detail and print outputs are more solid and reliable for complex 3D objects [1].



a. VR model: using VR sculpting application
b. VR/3D model: selecting vertex group
c. applying displacement modifier using 2D image
d. Applying supports and slicing on the VR/3D object with changing the texture orientation.
e. Final UV resin 3D print

Figure 7.3: Test 2.1 - Workflow process of texture application and fabrication.

[a] 

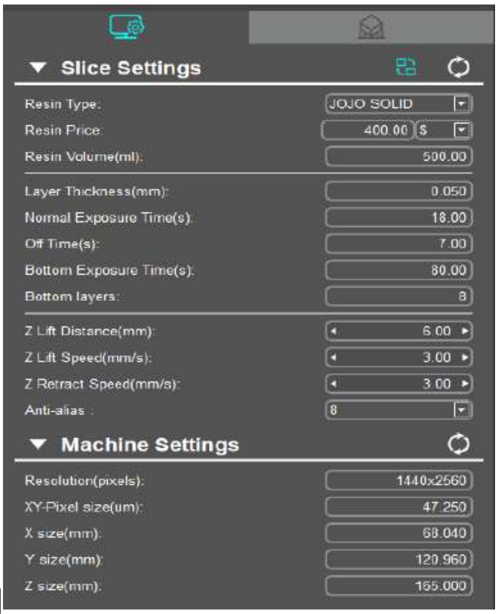
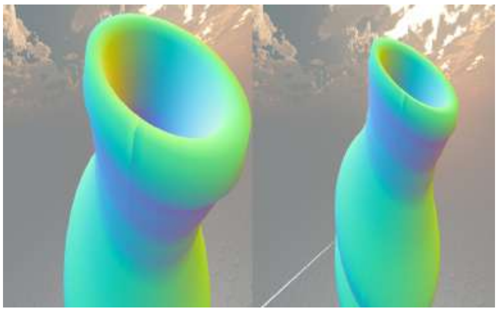
[b] 

Figure 7.4: Prototype information: UV resin with 3D print dimension and weight, (b) slicer settings.

[a] 

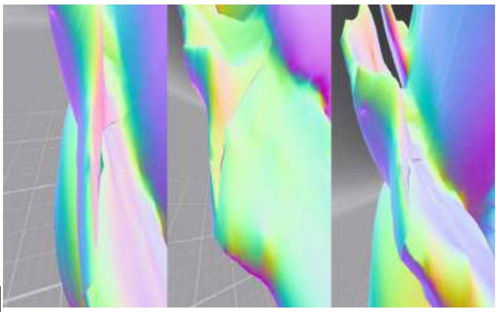
[b] 

Figure 7.5: VR pottery model error mesh analysis: (a) In VR sculpting application, a VR model is imported from the VP application to examine seam-line coordinates. (b) examine the zero-faces form using VR sculpting tools.

7.2.1 Challenge 1: VR Modelling and Problems in Printing

The VR pottery applications are a very good tool to model pottery using physical interaction. However, there are some challenges in the modelling towards the fabrication process:

Modelling problems/challenges: In Fig 7.5 the first fundamental problem of the seam-line and zero-faces that will affect the slicing and rapid prototyping process can be seen. This object is imported from the modelling tool to the VP applications. The second phase in the research system is VR sculpting, using the same object. In this phase, visual analysis of the shape helps to understand the deformation, sculpting boundaries and limitations.

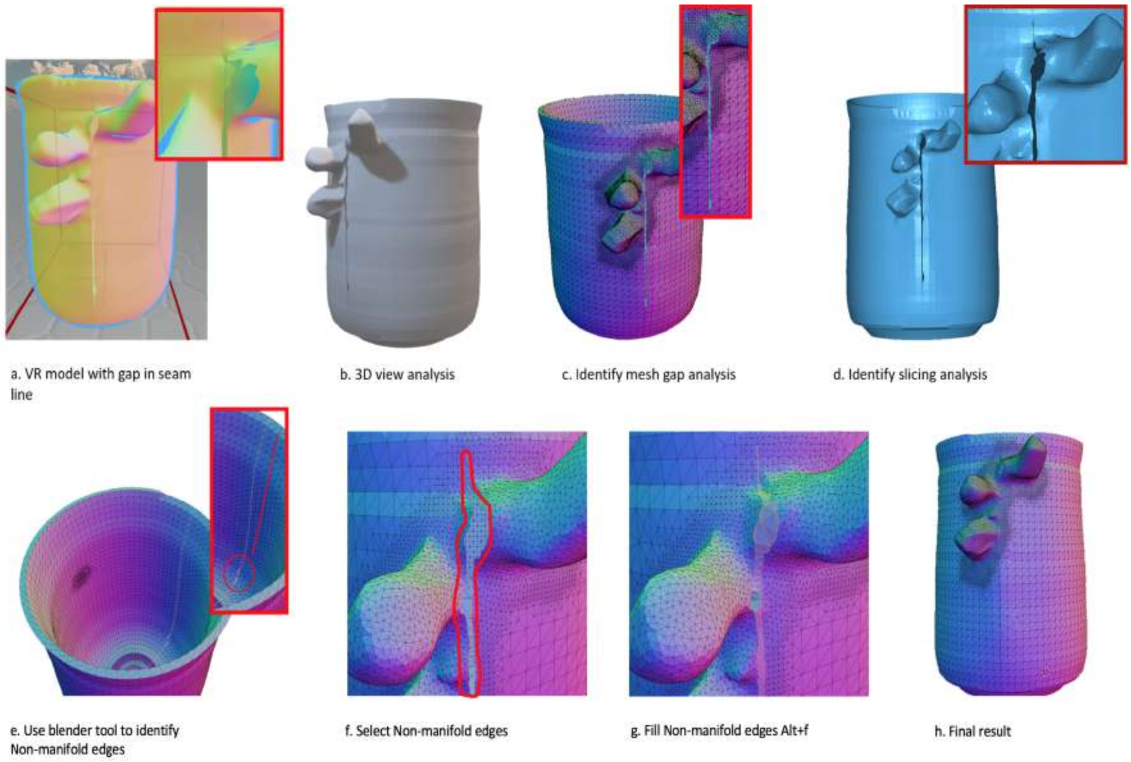


Figure 7.6: Examining VR errors of seam-line and zero-faces

During analysis, it is found that the seam-lines, have issues in fabrication. When using the sculpting tool for stretching/pulling, the model will have zero faces. Zero faces have zero areas and are referred to as a degenerate surface: a triangle will become a line, or a line will become a point. Figure 7.6 shows the hole in the mesh when the user extends the mesh using dynamic topology. The dynamic topology is used for a dynamic tessellation sculpting method, which adds and removes details for sculpting complex shapes out of a simple mesh, rather than just adding details onto a modelled base mesh. This tool is used as a sculpting tool for build-up in the original mesh.

In this phase, it is essential to identify the seam-line. The research demonstrates a method of building the subdivision and making sure the subdivision is done correctly to avoid holes in the object. In this figure, it shows how you can use the technique of examining the error in the design and ways to fix it in the following steps: (a), shows the gap in the seam-line in the VR model through the sculpting phase (b) shows a VR model in a 3D view, (c) helps identify mesh gap in the edge of the seam-lines, (d) shows the gap in seam-line in the slicer, (e) examines how the seam-line gap goes across the wall thickness and then uses a 3D print tool in Blender software to fix, (f) locate the edges and select, (g) fill the selected edges from the seam-lines by using the fill tool, (h) this is the final result of fixing the seam-line gap by filling the gaps, adding extra geometry in the mesh.

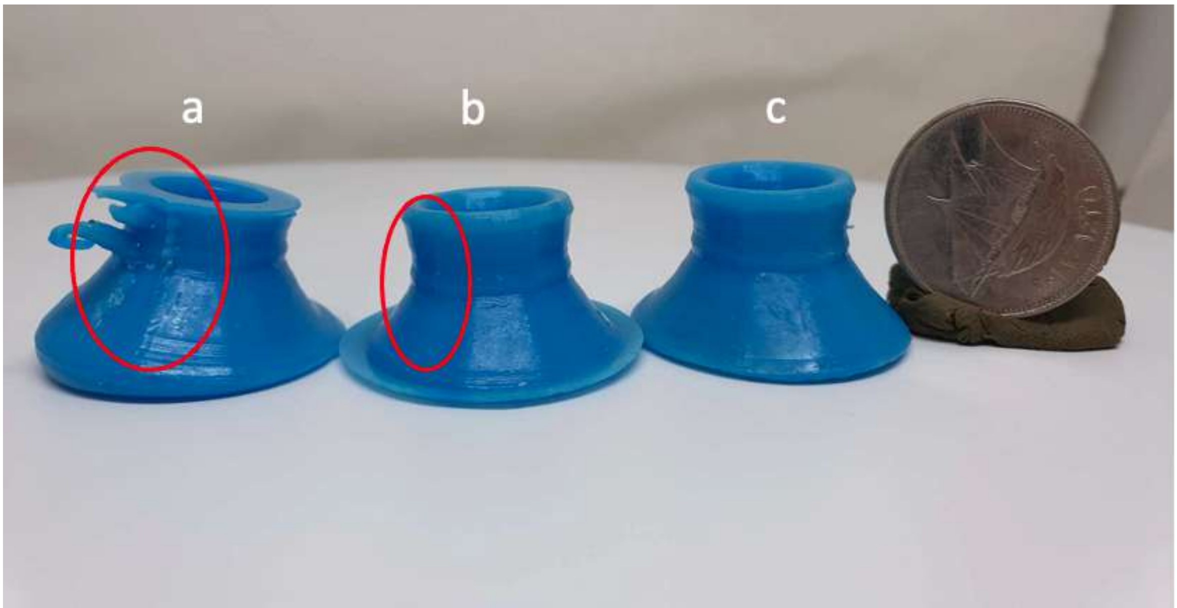


Figure 7.7: 3D printed objects (a) with seam-lines with stretching, (b) middle only with the seam-line, and (c) the right image with the seam-lines fixed.

Prototype problems: Fig 7.7 illustrates a VR model prototype, having the same issues shown in Fig 7.6, focusing on the seam-line and zero-faces in (a) and (b). The gaps are overfilled with resin through the shell surface. This method is a way for automating the software to resolve the errors in the 3D model, trying to fill out the gaps in the seam-line. The blender software has a 3D print tool with features, which helps the modeller interactively fix these errors. The technique is referred to as ’clean print’. There is also manual and automatic features to fix these errors. This approach depends on the model complexity, the complexity of the error, and the modeller’s skill.

Solutions and results: In Fig 7.8, the proposed method analyses the errors in the VR pottery model and finds ways for fixing them. It also presents how to add simple volumetric patterns in complex objects to be fabricated. Here, identifying the seam-line, thickness, and zero triangles is critical to ensure successful slicing. It is essential to ensure that the 3D model has reasonable thickness for better slicing and also for better printing. Without the correct thickness, it won’t print. After fixing the errors with the 3D print tool, we need to select the

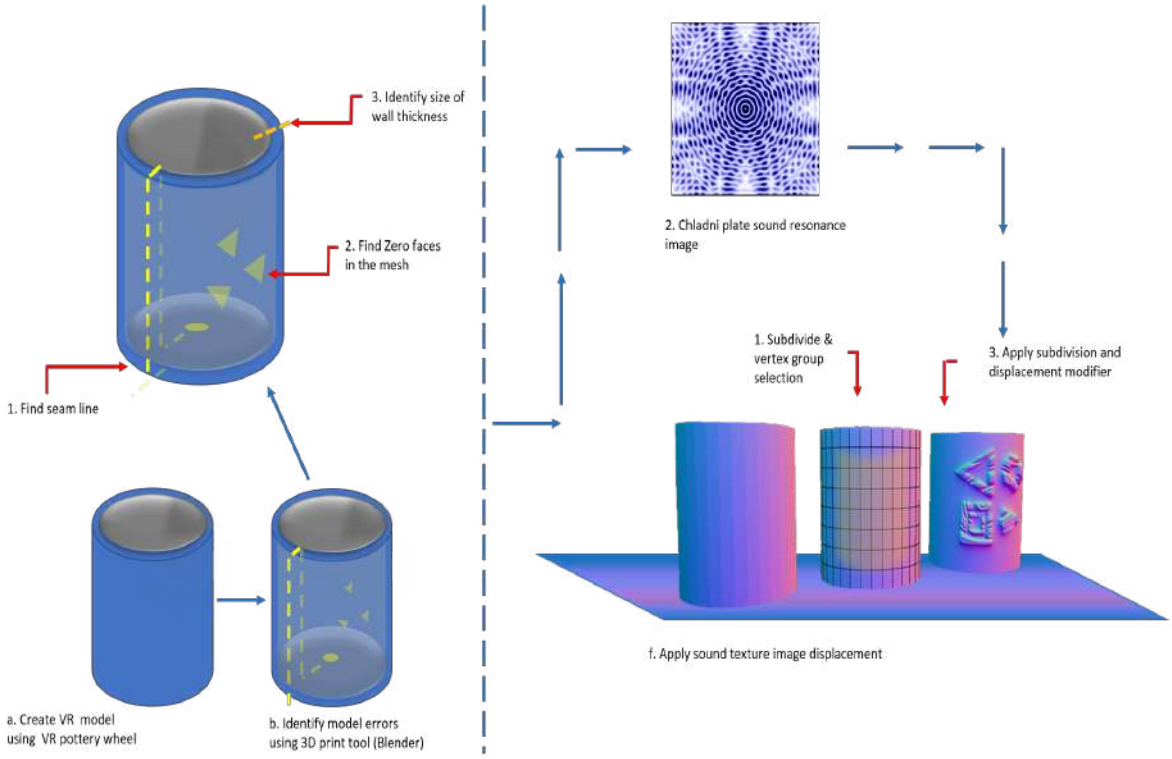


Figure 7.8: Workflow system of analysing errors in the mesh of VR/3D object

vertex to deform the shell surface exterior to the object and not inside the object.

Figure 7.9 shows a VR/3D prototype printed model and reveals the zero faces in the final product. The prototype is fabricated by using an FDM printer with PLA filament. The two red circles highlight zero faces on the surface of the object. This issue arises from the VR sculpting tool. The sub-image shows the zero faces from a different view position. The object is printable but may not be acceptable for commercial print studios, as these models are not compliant with the requirements. These issues will be identified at the pre-print stage and rejected before printing. The inset image is the same object, but the object has been photographed with different lighting. Finally, the object is still printable, as the infill and wall thickness ensures the layer is formed during 3D printing.

7.2.2 Challenge 2: Slicing Tool and Issues

Modelling problems/challenges: It was noticed that the fabrication of volumetric textures is not very clear, and tried to improve the texture depth, increasing the view-port on the selected vertex group. The weight of the vertex group is 0.2 less than the whole object which is 1.0.

Figure 7.9: Prototype VR model with zero-faces mesh.

This method, as shown in Fig 7.10 uses the Utah Teapot test model, shows the increasing amount of triangles.

Prototype problems: In Fig 7.11 it shows a failed print due to the auto default setting in the slicer software. The organic form may need a reset of the settings depending on the organic conditions, wall thickness, hang-overs and the orientation of the 3D model. The image shows a 3D printer where the object is too heavy and object support is thin and not adequately supported. This is obtained using the default setting of the slicer. Holding the heavy object needs more support that can be done manually, so it is required to increase the thickness of the support. This problem could be minimised with a change in orientation. Then place the support at the right places to minimise penetration of the support with the main object.

Solutions and results: Figure 7.12 (a), (b) and (c) shows the solution of VP modelling with 3D printing. The approach of fixing and error analysis of the 3D model with manual alterations of slicing supports settings, using available off-the-shelf tools, indicates where the

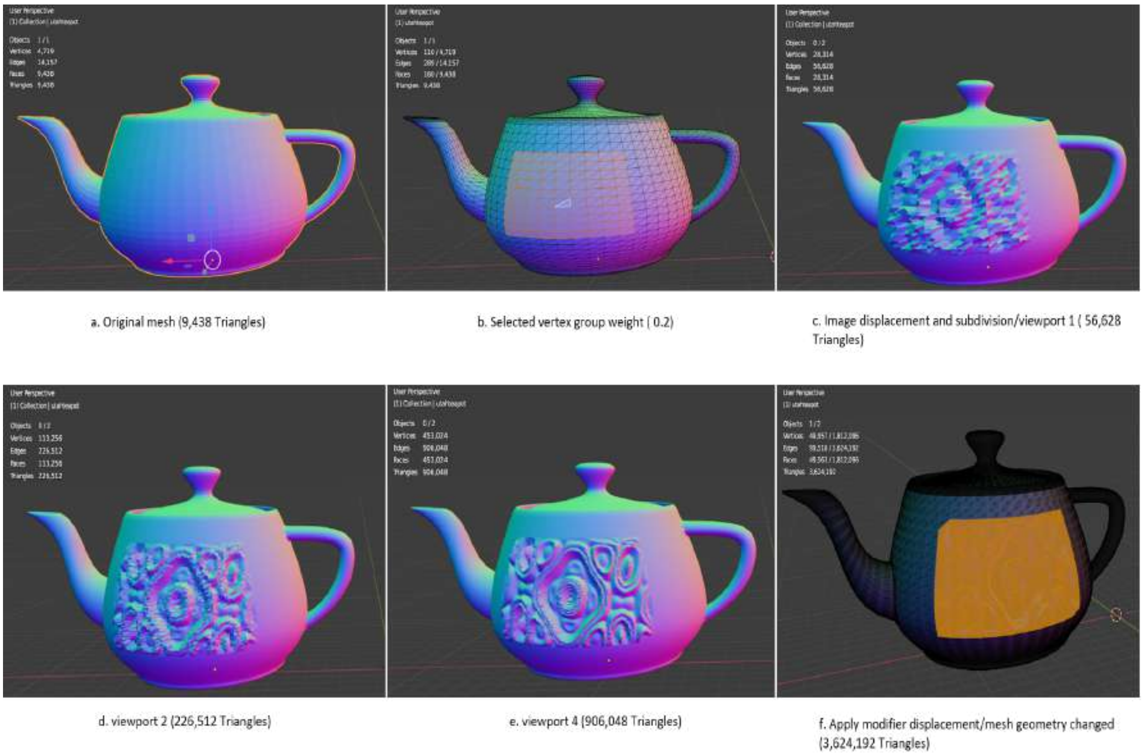


Figure 7.10: Volumetric sound resonance texture modelling using Utah Teapot model

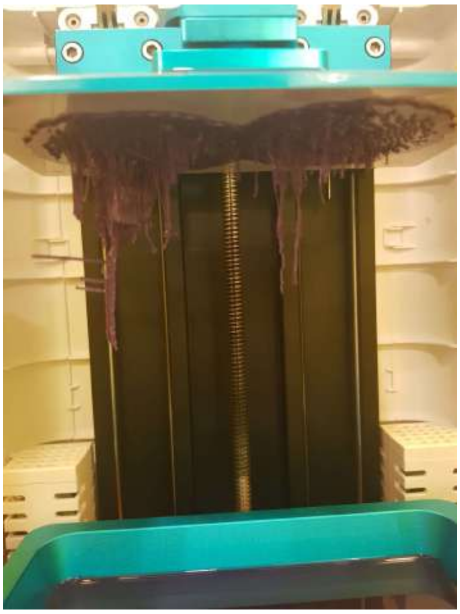


Figure 7.11: Fail support structure test: Slicing 3D model without heavy support and orientation issues.

issues are in the model.

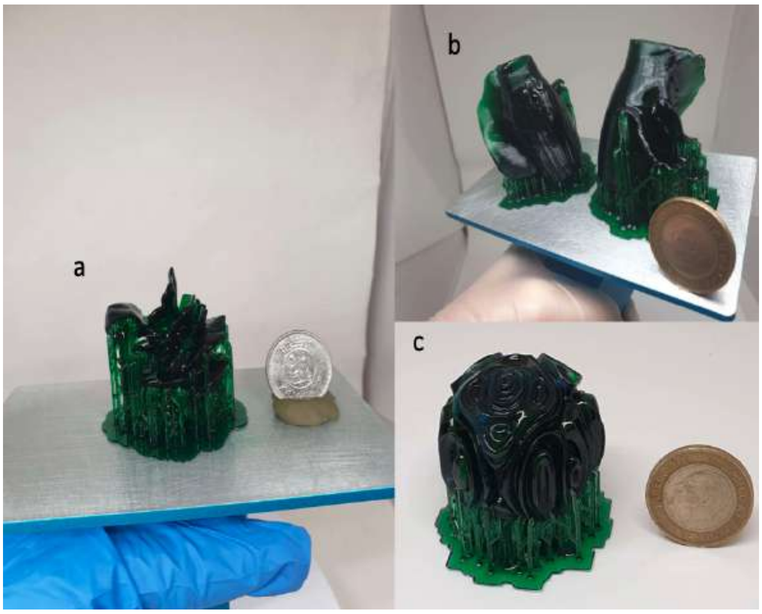


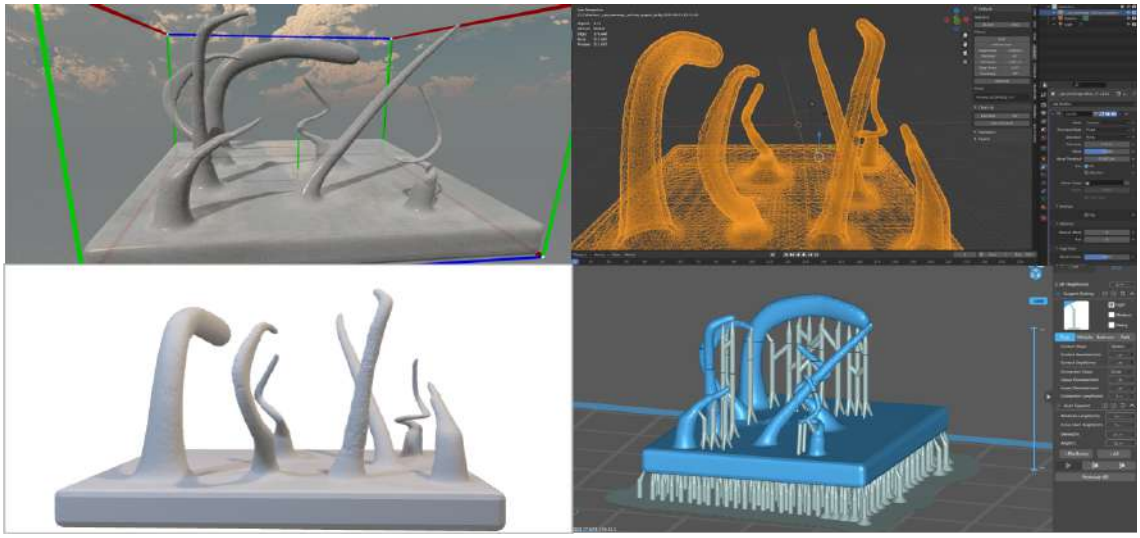
Figure 7.12: Successful print: Slicing 3D model heavy support, hollow and fix orientation position.

7.2.3 Challenge 3: Overhangs and Scaffolding - Pottery Issues

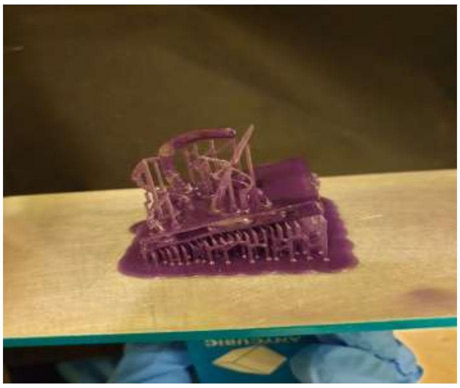
Modelling problems/challenges: An organic model is shown in Fig (a) 7.13 with thin overhung parts, trying to figure how thin to prototype the thickness of overhangs of the objects. Auto-generated settings in the slicer are not accurate for organic forms. The support point size and orientation angle must be manually changed.

Prototype problems: The model produced in Fig (b) 7.13 shows overhung parts with major slicing problems. Even though the easiest solution is to increase the wall thickness, the connection point with the supports might not hold, creating gaps in the model.

Solutions and results: The gap issue in slicing and overhangs problems are overcome by filling the holes in the thin areas in the object. The issue is resolved by converting the inner negative space of the object into a solid volumetric object. The method allows converting the mesh of the object to a volume and then convert it back to mesh. The methodology of this approach fills the gaps by using a volume modifier in Blender. This approach creates a solid object from a volume grid. Also, through research experiments done as part of the thesis now it is possible to add volume displacement on the shell surface of the object as shown in Fig (c) 7.13, deforming the shell surface by using a 2D image.



(a)



(b)

(c)

Figure 7.13: (VR model: (a) with overhangs modelling and slicing, (b) Failed print test: showing thin walls, gaps and missing support structure and (c) Successful print of solid object: using volume modifier (mesh to volume than volume to mesh), also applying volume displacement on the shell surface of the object.

7.2.4 Challenge 4: Material Challenges

Slicing/Prototype problems: Dealing with new experimental materials such as ceramic resin creates some barriers. The ceramic viscosity is higher than standard UV resins. The normal procedural way of printing has been used for typical slicing setting and support and had a failed print halfway as shown in Fig 7.14 (a). There are a couple of issues to be critically considered when using ceramic resin. Firstly, the resin exposure time; bottom layers and normal are facts to be considered. Here it can be seen that the time of exposure was less. The object fell off/split. Secondly, the viscosity of the ceramic resin is thick and has a higher density. The material is experimental, can be influenced by air exposure, in addition to light exposure. Material thickness/consistency also plays a role. This type of material is still considered experimental and expensive, and the cost is £375 pounds for a 1000ml bottle. The time of manufacturing takes a bit longer because of the increasing exposure time.

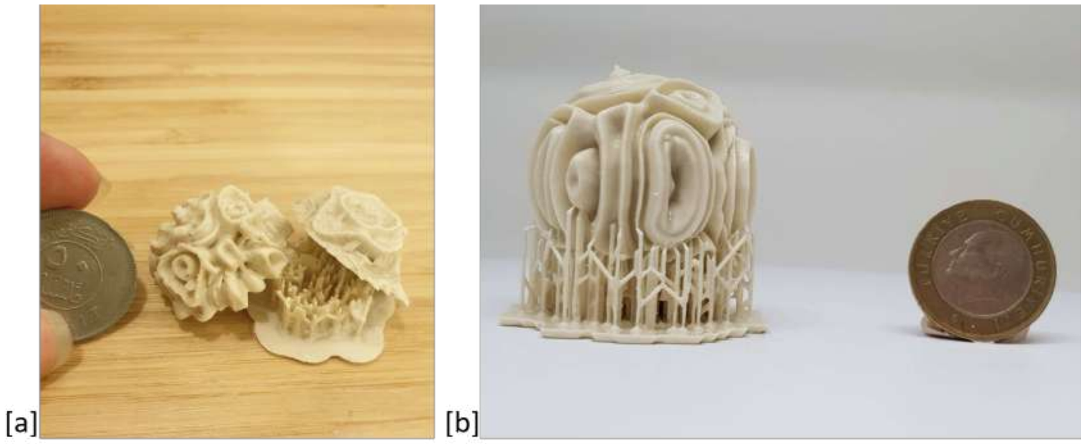


Figure 7.14: Ceramic Resin - material challenges: (a) A failed print halfway due to wrong normals and bottom exposure settings for ceramic resin. (b) A successful print due to increasing the exposure fitting.

Figure 7.15: UV resin materials used in the experiments of the project

Solutions and results: The research at this point resolved the issue of prototyping using UV ceramic resin, by increasing the bottom exposure time to 240 seconds and increased the normal exposure time to 50 seconds as shown in Fig 7.14 (b).

7.3 Summary

Overall, VR technology is a powerful tool for creative modelling to pre-visualise interactive physical 3D modelling. The VR pottery has evolved and can now compete, using the proposed approach, utilising interactive physical activity from traditional making for tailored manufacturing. The focus on resolving the obstacles of slicing and fabrication and adding a volumetric sound texture from the proposed methods, creating an additional tool for complex geometric patterns, which is unavailable in current applications. More so, focusing on the variety of materials that are satiable for showing complex detailed objects as shown in Figure 7.15 and one example of resin's data-sheet in Figure **??**. 3D Printing is undergoing rapid growth and will be used widely for the construction of buildings, structures and products in a matter of hours and seconds, as opposed to the days and months it takes currently. 3D Printing will also be pervasive in newer fields, including the arts and design. Visualisation will continue to be the bridge between the human and the end printed product.

Chapter 8

VP-Systems Design

8.1 Introduction

This chapter focuses on the design of the VP systems and the components: information systems design, design for the new norm and design of the digital twin. The first system discusses the basic plan of advanced volumetric sound deformation in 3D printable objects forms, with high-quality sound texture examples overlayed and blended. This first system works as a blueprint to extend ceramic artists creativity of making, up-scaling the boundaries of creative making and developing a multi-modal interaction. This approach helps is simulating physical-virtual capture of real-world deformable pottery making (adding/ subtracting) using tangible hand and haptic transformations.

The second system exhibits the novel VP platform during Covid-19 as the new norm era for collaborative technologies for physical activity, training and educational purposes. This path works as a gateway for developing skills and improving self-production, using virtual collaborative work, such as practising artwork using VP. The idea of a global platform of many sectors has already been implemented. The purpose of using such platforms that initiates physical access due to pandemic restrictions and natural disasters is to access knowledge, interaction and creation skills. This approach shows how practical virtual experiences can compete with traditional physical ones as the next best option.

The third system presents an innovative VP system concept, using Digital Twin technology to develop human intelligence and performance. The idea of Digital Twin technology relates as the most applicable concept for this research modelling and fabrication process. The system uses an unifying interchangeable modelling representation (such as an STL file) across multi-application with the growth of organic form made with physical interaction and volumetric texture modelling. This method creates a promising result of tracked deformation across layers of realities, creating a digital twin link between the physical and digital object.

8.2 Systems Refinements Designs Background

8.2.1 Virtual Pottery Design 01: Information Systems

Data-physicalisation is a current popular technique of representing an actual data visualisation into a 3D physical data form [154]. This research focuses on physicalising the full effects of sound data on ceramics. To achieve this, the research will design, develop and demonstrate a widely deployable interactive Digital Pottery system in detail; and it will use deformable shape modelling to extend physical ceramics. It will capture visual sound parameters through creative technologies such as augmented, virtual and rapid prototyping [27; 155]. Clay as material presents challenges of preserving sound deformation on a non-rigid liquid form. Real-world constraints such as gravity and evaporation prevent the consistent capturing of the dynamic visual patterns created during the sound deformation on a ceramic vessel.

By sound deformation, the research shows the meaning of deformable shape modelling representing computer algorithms through developing new techniques, that will assist on augmenting realistic shape and surface transformations. The innovative deformable shape modelling explores methods of integrating sound data with 3D modelling towards producing a texture mapping technique for a volumetric sound-structure [156]. The shape and texture are the primary sources of information for object recognition, and this approach brings more understanding of how sound travels through non-rigid forms. This technique creates a more natural parameterisation of realistic fabricated graphics into interactive physical and 3D shapes [157]. More so, the new technique preserves deformation form. Also, the user can display the deformation with AR devices, which act as audio visualisers as an audio visualiser on the interactive prototype surface, which acts as a tracker.

8.2.2 Virtual Pottery Design 02: VR as New Norm

The demand for practising physical activity for training and educational purposes has increased globally. This paper presents the evaluation of using creative technological and fabrication innovation as a fundamental alternative to reality in a safe space. The new normal era is about using collaboration technologies to the maximum [158], by developing skills and improving self-production of virtual collaborative work [159],such as artwork using VP as an example. This is inevitable today and has been introduced as a global platform and as an urgent call that has been initiated during pandemics and natural disasters to access knowledge, interaction and creation skills [160].

8.2.3 Virtual Pottery Design 03: Digital Twin

Digital Twin is one of the concepts driven across creative and problem-solving ontology as a novel approach for human-centred in cyber production [161]. The education sector is also showing great interest in developing educational programs, introducing new ideas and the Digital Triplet concept, advancing the original Digital Twin for more intellectual activity, expanding engineering processes with cyber and physical worlds [162]. Formal and informal education is one of the new norms of learning methods using AR/VR to enhance the learning process. Furthermore, ongoing educational research incorporates digital twins and mixed realities, producing a book that is beneficial for communicating and decision-making [163]. Meanwhile, the VP concept is an extension to VR 3D modelling, representing a real-time solid modelling system, forming digital clay by physical interaction, and applying forces. Mainly, the application allows users to use virtual forces, forming a lump of digital clay to a simple or a complex object [164]. Principally, the pottery modelling system is represented by several circular sectors as a cylinder in layers. The user's physical and visual interaction mostly deforms digital clay in a radial direction due to the potter's wheel [165]. The object represents virtual clay in a horizontal spherical haptic tool, using a VR controlling kit to perform physical interaction pressure on the object. In summary, the design alternatives and the evolution of the systems design is capture and highlighted in Fig 8.12.

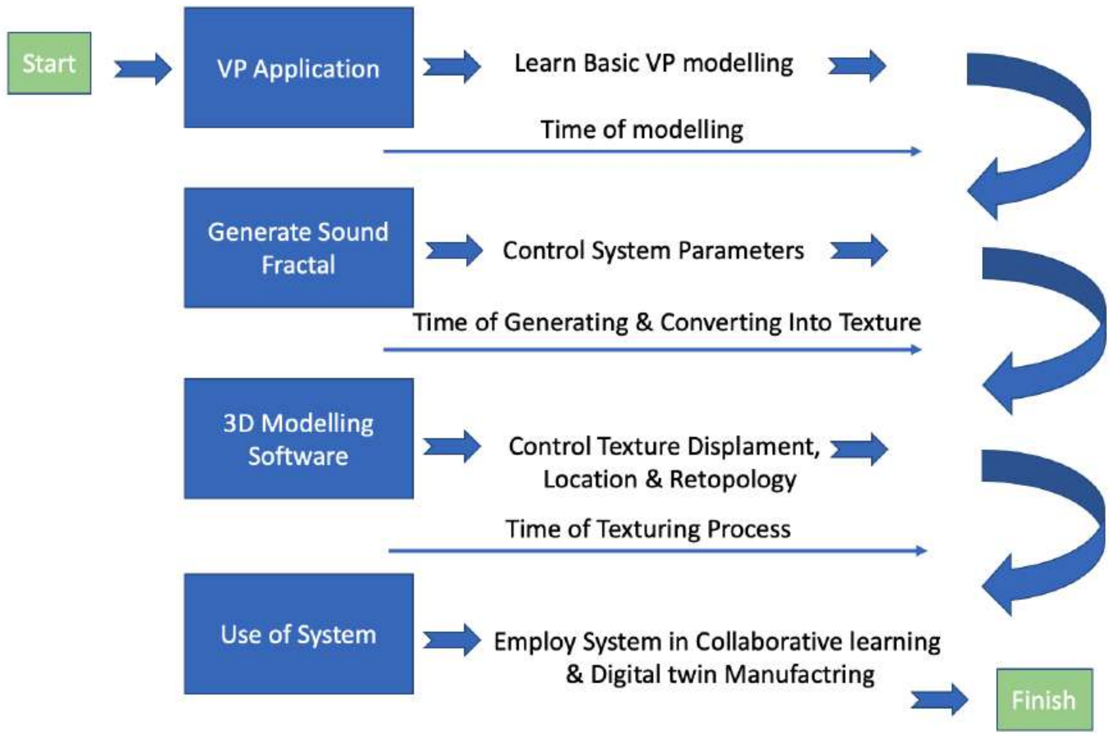


Figure 8.1: Use Case of Systems Refinements Designs

8.2.4 Design Objectives

The ultimate goal is to address the systems complexities and challenges that arise from (i) modelling - the detailed physics-based shape modelling to include sound shape forms as a way of Data Physicalisation with physical ceramic material properties, (ii) interaction - real-time visualisation in AR/VR devices to enable complex virtual and physical interaction, (iii) making - realise it by physical making through ceramic rapid prototyping. To address these challenges, the main objectives are:

• Modelling: To develop a multi-scale representation to model the shape, the physics of audio, surface texture, real-time rendering as well as physical prototyping.

• User interaction: To develop a multi-modal interaction that simulates physical-virtual that captures real- world deformable pottery making (addition/subtraction) using tangible hand and finger transformations.

• Making/ceramics: The objective is to make physical making central to this process by emphasising the material and the rapid prototyping, which in turn influences the above two objectives.

8.2.5 Design Approach

Figure 8.2 shows the block diagram of the information workflow. The research process is in creating data-physicalisation of a tracked deformation data of sound energy with natural clay, nevertheless due to real-world constraints such as gravity and evaporation, the maintenance of the deformed shape is unable to retain the deformed texture. The research is a multidisciplinary case study combining several fields of science, art and technology, highlighting data-physicalisation with human interaction through creative technologies. The project explores new methods of Physical Visualisations of texture mapping techniques for volumetric sound-structure using displacement mapping bumps with sound animation. The data collection is achieved through experiments using physical and digital clay sound interaction, showing the dynamics of motion movement in 3D texture on the surface. Furthermore, developing a visual sound generator and as an example of physicalising sound on the surface of an object done by Segal and Maayan [100] shown in Fig 8.3. The digital pottery system contains design tools, VR and 3D modelling to utilise the proposed texture- mapping representing sound energy travelling in digital form, creating a unique texture deformation. From the research undertaken by Chen et al. [166], 3D printing is the best option for capturing more of an accurate detail on ceramics. The AR technology enhances the clay-sound experience by enabling the audience to explore the mechanism of deformation by a variety of devices such as using tablets, mobile-phones or AR glasses as a way of interactive data-physicalisation of hybrid objects - part physical and part digital of the information workflow.

8.2.6 Design #01 Experimental Results

The experimental trials of each process made the practice more focused on how to create a new texture mapping within 3D modelling software. In addition, the experiments led to categorising sound into two classifications, from audio visualiser and physical visualiser creating a more realistic texture mapping of sound structure. The difficulty arises on collecting the accurate data deformation from clay in different density status from liquid to semi-solid, finding the right mathematical model among frequency generator and oscilloscope, and the best way of conducting the accurate deformation data.

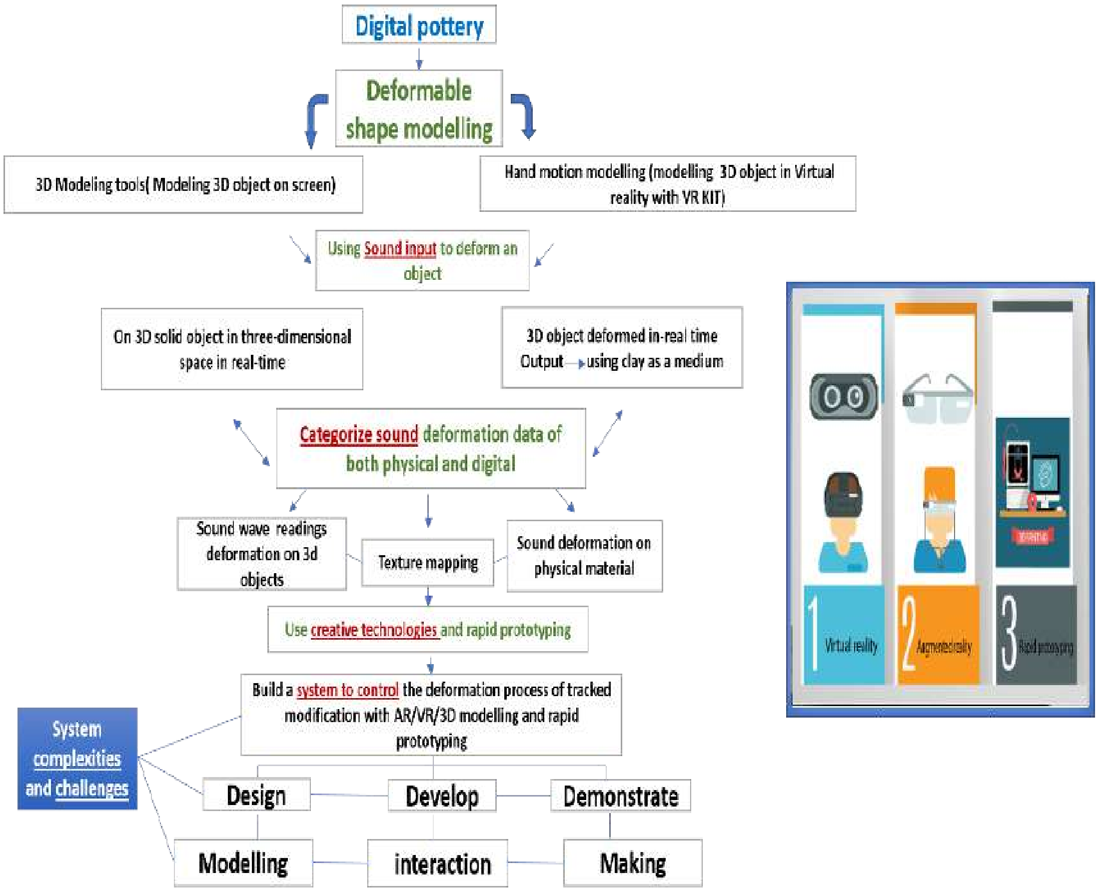


Figure 8.2: Information and Workflow Process in Interactive Modelling.

8.3 Virtual Pottery Design #02: VR as New Norm

8.3.1 Overview & Design Approach

The research approach focuses on creating a learning system, process and an evaluation method for creative technologies tools in virtual spaces, comparing the development of VR and traditional physical skills in a virtual studio, and the access to such experiment is provided in virtual workshops through a group platform using communication models in a large-scale network [167].

For this design, it is choosing to show in this thesis VP as an example for virtual learning and training, replacing traditional making. It is an interactive virtual physical 3D modelling that is chosen as a way of extending ceramic artist creativity of making, scaling up the boundaries of creative making and developing a physical-virtual experience that captures real-world

Figure 8.3: Ceramic plate records using custom-built machine for etching sound waves. Source (Segal and Maayan, 2017) .

deformable pottery making (addition / subtraction), using tangible hand and finger transformations in a safe environment as shown in 8.4.

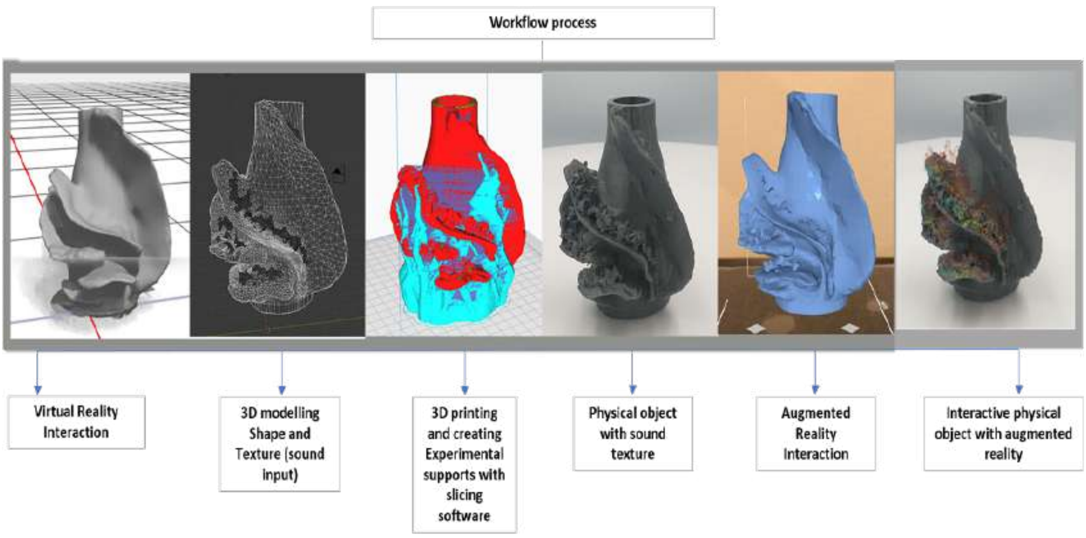


Figure 8.4: Virtual Pottery making and fabrication workflow.

8.3.2 Design #02 Expected Results and Discussion

The experimental system process, in theory, relying on research related to the field, shows a qualified proposed system model to examine the comparative evaluation of the VP practice during Covid-19 and the liability of using this method, not only as a replacement but as a reliable making method of physical and visual modelling in a virtual communication group network. In addition, this approach opens the gates for developing necessary skills in many fields in case of global pandemics and natural disasters with a self-learning tool that is adaptable to environmental changes.

8.4 Virtual Pottery Design #03: Digital Twin

8.4.1 Overview

This section introduces a novel system and fabrication technique for VP towards traditional making simulation, using the concept of Digital Twin technology, integrating cyber and physical spaces. This approach uses creative technologies in the art field to develop human intelligence and performance.

The technical framework presents a novel method, using the user's perception to analyse the virtual model. The process involves deforming a 3D virtual object, using a series of simple processes to manage with tracked transformations across layers of realities. However, at present, no research has focused on simulating all pottery-making skills in one application, e.g., throwing, hand building, sculpting, relief and many more.

The research method uses digital link concept as shown in Fig 8.5 and involves the followings steps: 1) creating a virtual object from digital clay as a file; in STL format; 2) exploring ways of growing a virtual object, using 3D VR application, extending digital clay object deformation; 3) extending the model by using 3D modelling software for surface relief with 3D printing tools to examine the model; 4) examining the model through a slicing experimental setting that will result in a 3D printable prototype.

The thesis present a selected combination of application and shelf tools to simulate the pottery making experience, using a VR application that has been successfully implemented in

Figure 8.5: Crating a link in between the process of Virtual Pottery modelling & fabrication .

the gaming industry, enhancing 3D object modelling and physical/visual skills development. In the future, a Digital Twin in virtual ceramics can contribute to rapid prototyping processes. Fig 8.6 demonstrates ways of integrating both digital skills and pottery making for contemporary design and fabrication methods, utilising the concept of digital twins. This is achieved by using creative technologies to integrate physical and digital objects and fabricate them remotely. Fig 8.6a. shows the first modelling part, using VR kit, 8.6b. object transformation such as scale or rotate for both designer and users from another end to view,8.6c. integrate with interactive texture audio and visual designs, 8.6d. prototype and monitored remotely. Finally, linking the physical object digitally by using the surface texture as a tracker to operate an audio visualiser to see and hear the frequency pattern.

8.4.2 Design Objectives

The research in this thesis presents a novel VP system, exploring the innovation of interactive modelling, with tracked transformations using one object across layers of realities, by the evolving concept of Digital Twin technology. The method in this thesis involves merging creative technologies and tools, producing a new making technique for VP, and developing a complex object. The research system contains a rich representation of simulating traditional

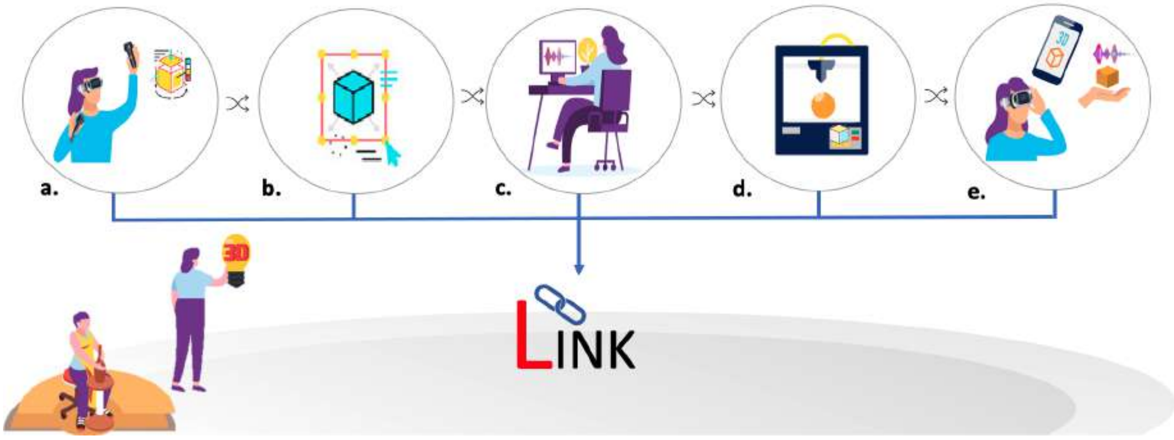


Figure 8.6: Transforming Virtual Pottery with Digital Twin: (a) show VR modelling, (b) object transformation, (c)integrate with interactive texture audio, (d) prototype and monitor remotely, and (e) link the physical object digitally.

pottery skills, using multiple tools and layers of reality. The system works as a bidirectional fabrication method to link physical and digital objects leveraging user's analysis to configure a better prototype.

8.4.3 System Function

The VP system is a method that focuses on exploring ways of integrating creative technologies and the digital twin link concept. In this system, users can create a complex VP object, using digital clay and extending the experience with the aid of using a combination of VR, 3D modelling and slicing. The novel VP experience represents making pottery in the first stage, from forming a vessel in real life located across the growth of the object in a VR space, and screen modelling with slicing, stimulating the creativity of virtual modelling, to finally allowing the creation of complex prototypes (Fig 8.7 a, b, c & d). The available VP applications focus on simply making without using the complete skills and tools due to high processing data, which may overload causing failure and data loss. Complex modelling in VR is one of the leading modelling methods to date. There is not much surface deformation or the ability to grow and extend the virtual object on virtual potter's wheel applications. In such modelling the user creates deformation on the digital clay. It will be hard for the basic user to analyse and evaluate the non-manifold mesh or zero area faces of the virtual model.

The overall goal of the thesis is a novel proposed system is to address the advantages and

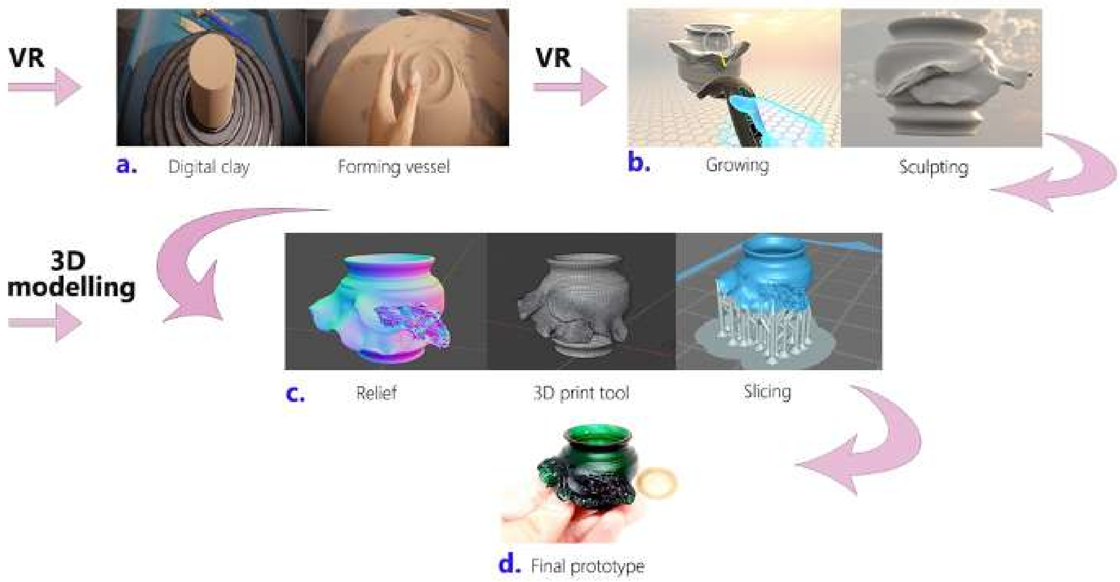


Figure 8.7: Proposed Virtual Pottery System.

challenges of the system that arise from: (i) Modelling - the detailed VR/3D modelling integration as a physics-based shape modelling, using the concept of Digital Twin to create a bidirectional link of data with the physical ceramic material properties. Here, the thesis expands a VP representation of creative deformation models, with the development of the physical virtual force, surface texture relief, real-time rendering as well as physical prototyping. (ii) Interaction - real-time visualisation in AR/VR devices to enable complex virtual and physical interaction. Here, the research shows the development of a multi-modal interaction that simulates physical-virtual that captures real- world deformable pottery making (addition/subtraction) using tangible hand and finger transformations. (iii) Making - realise it by physical making through rapid VP prototyping. Here, the objective is to make physical making central to this process by emphasising the material and the rapid prototyping, which in turn influences the above two objectives.

8.4.4 Design Approach

The research novel approach investigates the link of tracked deformation across realities, using one object of digital clay medium carrying the physical interaction towards bidirectional digital fabrication, creating a bridge using the Digital Twin concept with parallel evolvement between Art & Technology. Fig 8.8 shows the block diagram of developed information

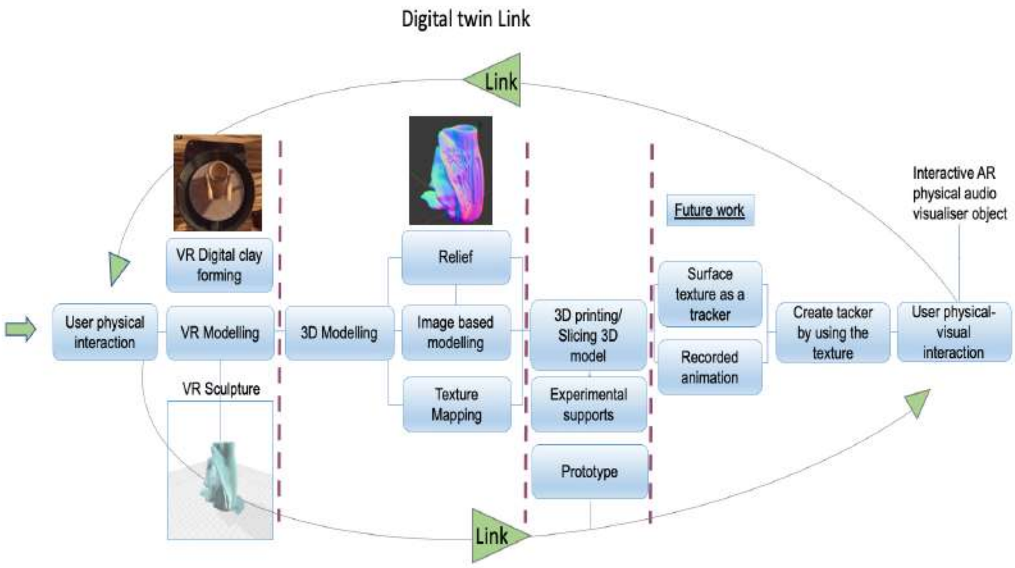


Figure 8.8: VP Information Workflow Using Digital Twin Link Concept.

workflow of the VP system using the Digital Twin Link concept.

8.4.5 Design #03 Expected Results and Discussion

The research approach of a Digital Twin for VP modelling can enhance virtual graphics modelling and rapid prototyping. By introducing this concept, the users can improve self-analysis with improved modelling and fabrication criteria. Nevertheless, the thesis novel VP system has a couple of limitations boundaries for now. First, the system design cannot be tested with real users due to the pandemic Covid-19 health restrictions. The VR kit may be contaminated and could transmit the virus. As a result, the thesis listed experts research findings in VP modelling and publishing papers to support the research. Secondly, the system, for now, defines an integration of several applications. The criterion of thesis future steps is to create a seamless system that allows the user to experience the system without using many applications.

8.5 Self-Analysis

The section presents self-analysis shown in Table 8.1 with use case shown in Fig 8.9 to demonstrate the use of the approach and functional testing of the process involved to give some insight and highlight any problematic issues that can be resolved or avoided.

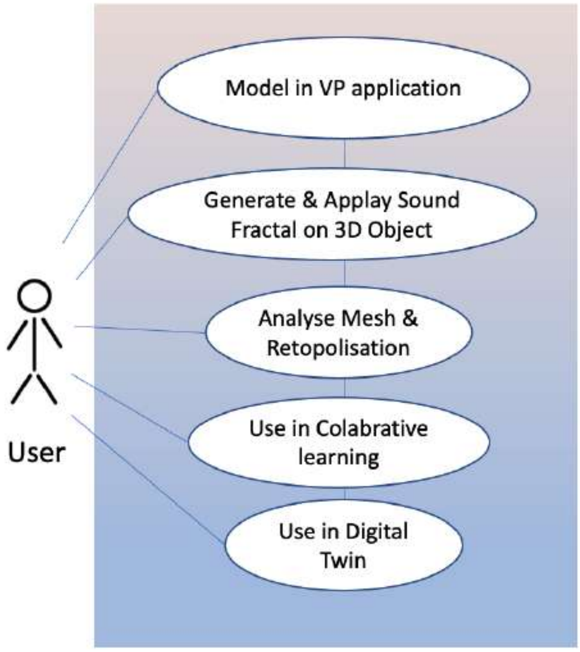


Figure 8.9: Use Case of Systems Refinements Designs

8.6 Summary

This section presents a summary of the VP System Designs shown in Fig 8.12.

Design #01: The results shown Design #01: Is the primary conceptual design system that has been self-tested. The basic information system helped create a closed system for the user to navigate and use modification modelling methods using the X-change file. The results are shown in Fig 8.2, and 8.4 created a new promising path of tracked deformation across realities, creating a link between the physical and digital object as well as designing further use for the system through two subsystems.The workflow processes have been accomplished using standalone information systems for modelling, deformation, VR, and rapid prototyping, which will be integrated seamlessly in future work.

Table 8.1: System: Test Criteria/Functionality

Function test	Pros	Cons
System setup	feasible for basic user	-
Integrating tools	✓	-
Bidirectional modelling	✓	-
User Inter- face	operate with basic user	-
Input	PNG/JPG,STL/OBJ	-
Haptic control	provide very sensitive & capture deformation in/out of VR object	-
Deformation process / Types of gestures	Real-time	-
VR object mesh analysis	VR/3D view	-
Default clay dimensions	scalable size	-
Topology	automatic & manual retopology	-
Render Baking	Fast (depending on used device & object	-
Sculpting tools	VR/3D sculpting tools	-
3D texture/surface detail	high in detail	-
Export	STL/OBJ	-

Design #02: proposed a VP subsystem model for physical-virtual learning in a virtual studio, utilising creative modelling and digital fabrication in a safe environment as we have been through the Covid-19 pandemic. This system can play a suitable role with the innovative technologies that have shown a promising breakthrough to the new norm for the future, significantly impacting the development of physical and visual skills. Virtual space skills can improve learning, compete with traditional methods, and adapt to current health restrictions rules of Covid-19. The thesis contributed to making a short video explaining the whole modelling process at a conference and can be seen in the youtube link provided, starting from VP/3D modelling towards prototyping.

Design #02: The thesis presented a proposed VP system model for physical-virtual learning in a virtual studio utilising creative modelling and digital fabrication in a safe environment. Innovative technologies have shown a promising breakthrough to the new norm for the future, significantly impacting the development of physical and visual skills. Virtual space skills can show novel learning and improvement, competing with traditional methods and adapting to current health restrictions rules of Covid-19. The thesis contributed to making a short video in a conference explaining the whole modelling process, starting from VP/3D modelling towards prototyping. Design #03: The second proposed subsystem focuses on the tracked deformation across realities, creating a Digital Twin link between the physical and digital object. The concept of digital fabrication with multi-users working remotely with real-time tracking for prototyping. The idea is to capture the deformation with mixed realities through VR and multiple tools to improve the VP experience and fabrication. The proposed workflow processes have been accomplished using standalone information systems integrated with Digital Twins, exploring methods of making and relying on the user's analysis to improve the virtual object. Deformable modelling is one of the ways to describe the research project, deform to reform an artistic object. The future steps of the research will include using augmented reality to extend the Digital Twin link.

The next chapter presents Sound Shape Modelling, the pipeline and the novel contributions. The novel approach expands in simple process steps of materialising sound resonance into a textured relief, deforming the shell surface of the VR/3D object. The resulting output produces a relief on the VR/3D model, using the 2D images' geometry to create complex organic textures suitable for modelling and prototyping with high details.

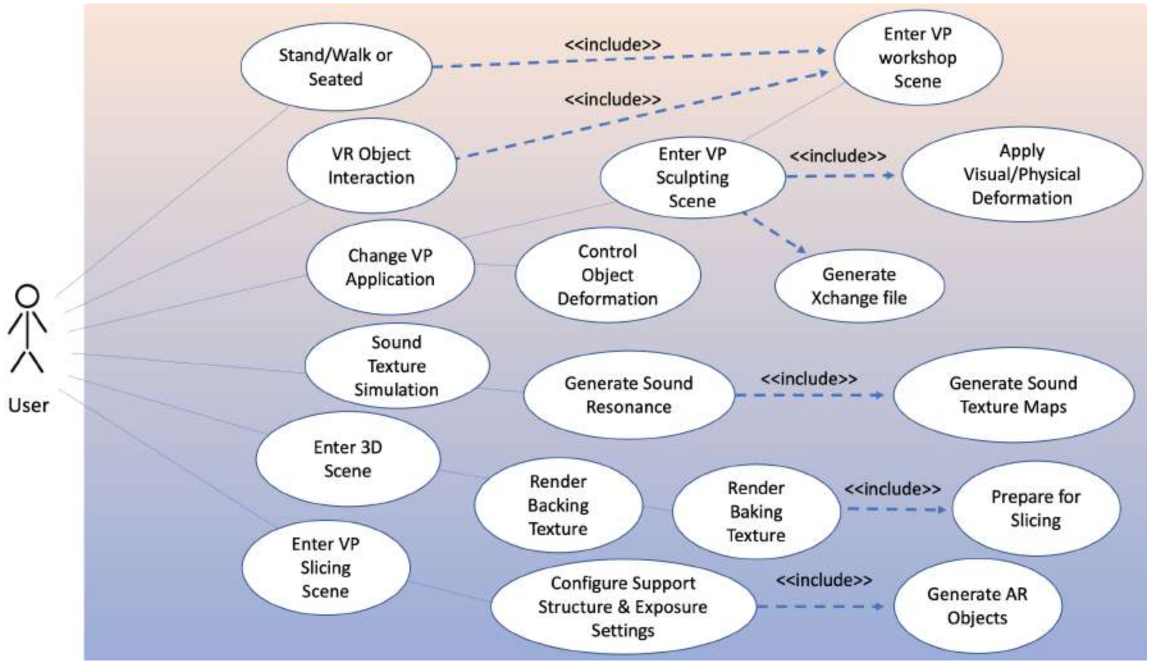


Figure 8.10: Use Case Diagram

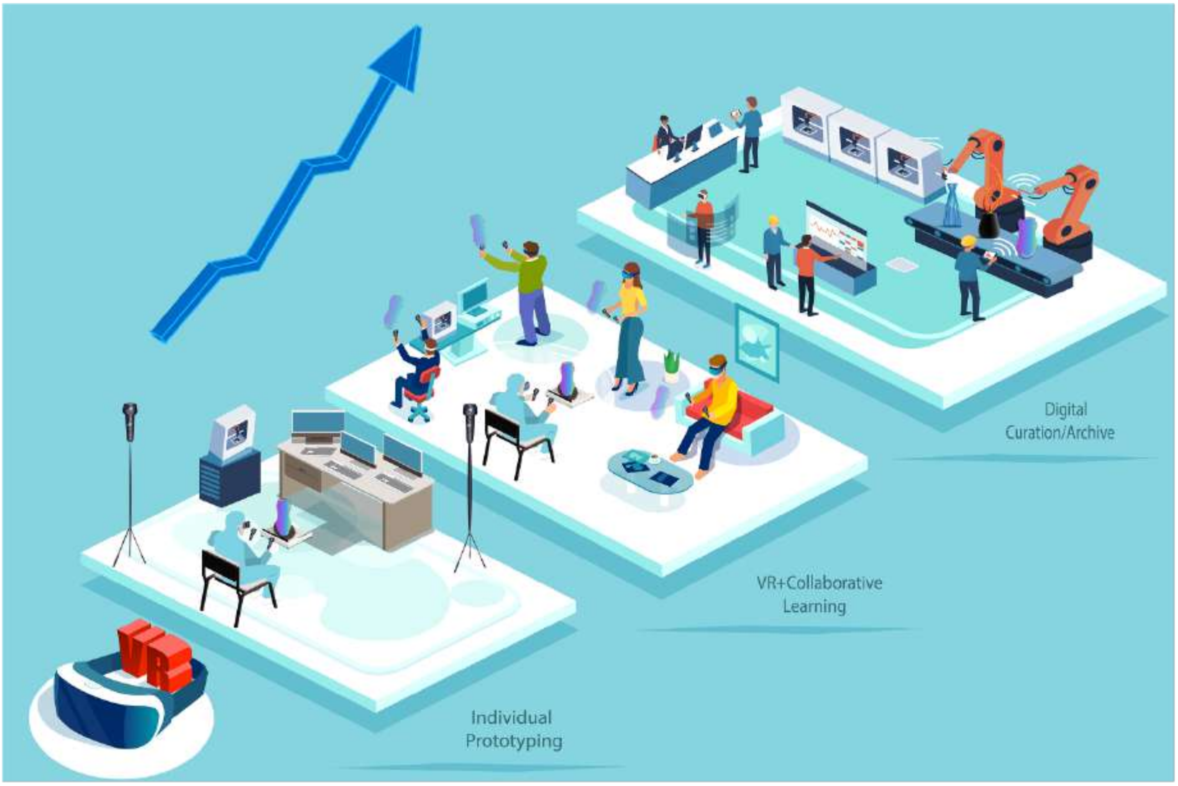


Figure 8.11: vr system and subs

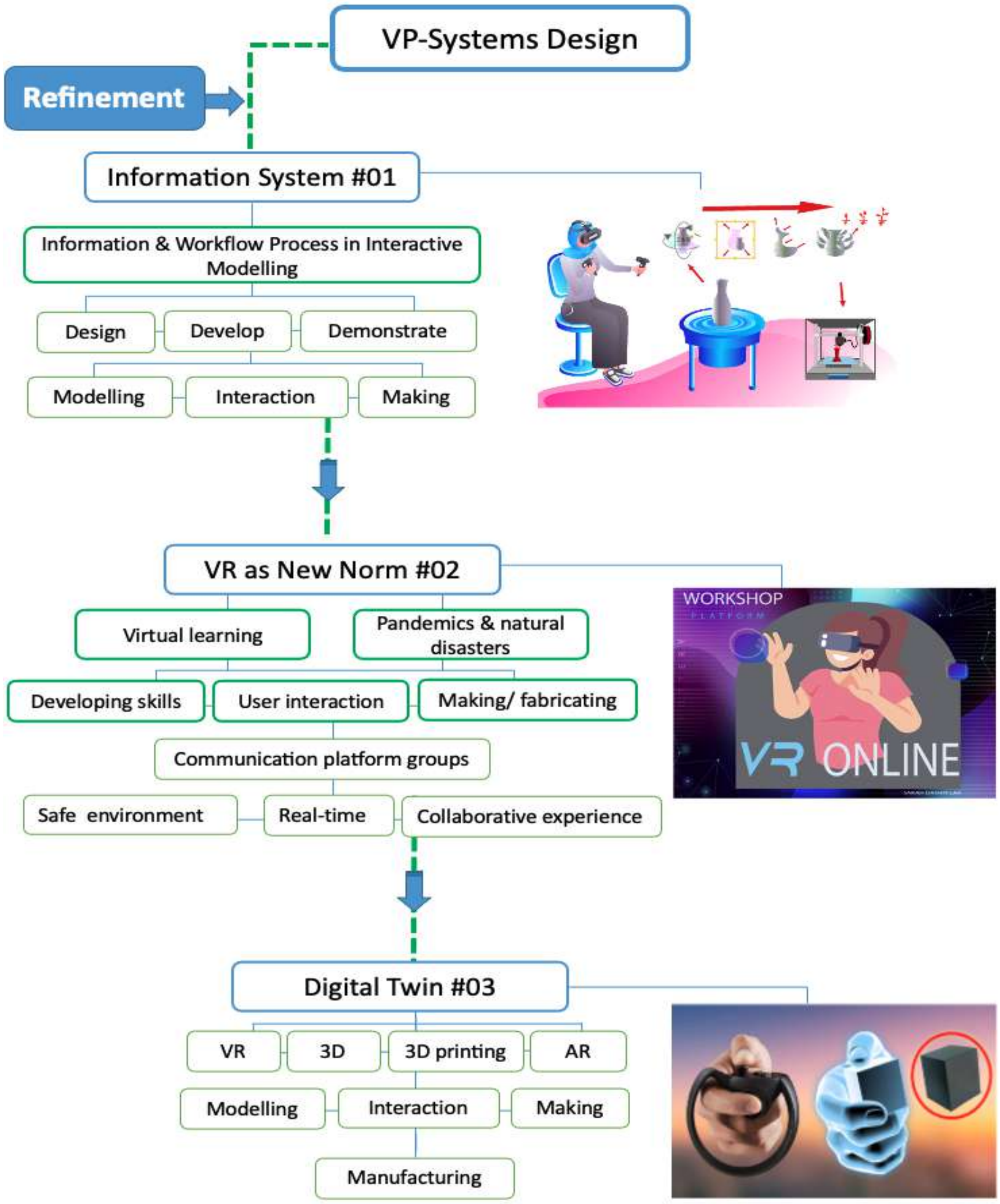


Figure 8.12: VP-Systems Design

Chapter 9

Conclusions and Future Work

This chapter summarises the thesis, and highlights the findings and contributions. It also points out limitations of the current work, and outlines future research directions. The contributions recognise the novel concept of VP modelling towards rapid prototyping. However, many extensions of this research deserve further consideration to create a seamless system for modelling towards fabrication, exploring different types of VR interaction usability studies, improving users experience to develop better VP applications. The chapter is divided into four sections. Section 9.1 is a summary of the thesis. 9.2 presents the Novel contributions of this thesis. Section 9.3 presents the limitations of the current work. Section 9.4 discusses the future work, and finally brings the thesis to a conclusion.

9.1 Contributions of the Thesis

This thesis has introduced a novel VP system design for modelling and fabrication. This research aims to demonstrate the feasibility of the novel VP system by the comparison of the existing systems. More so, highlighting methods on object deformation and real-physical object transformations to develop VR interactive physical modelling. The research objectives' accomplishment was in the modelling process in theory and practice. Using existing tools, it demonstrated the proposed system model to develop physical modelling for novice and intermediate users. Users with artistic backgrounds from other research show with VP systems can use creative technologies to explore physical visualisation. The thesis adds 3D modelling to expand the opportunities of creating complex organic textures on a VR model as part of the first objective.

The second objective contribution is a VP system that enables users to develop a VP experience beyond the VR applications using available tools. The research does not stop at this point. More so, the future steps will involve integrating more than one object. Also, future work can explore ways to connect physical objects digitally, as shown in Fig 8.4. The research outcome's both physical/visual concept and can also be beneficial to educational purposes for children with disabilities as a future collaboration work.

Chapter 2 delivered the background research essential elements for sound surface texture on VP objects. The chapter provides a brief history of texture in CG with challenges. The history of the Chladni Plate is presented as an anker for the texture pattern for deformable shape models used in CG. The chapter then discusses VP in the related fields towards prototyping. Finally, the refinement of the information VP system with the development of subsystems and exploring ways to be used in collaborative learning and the digital twin.

Chapter 3 discussed the literature review of VP by dividing it into three main sections addressing modelling, prototyping and technologies as shown in Fig 2.1. This chapter established studies and systems in a cross-disciplinary practice, transitioning from art aesthetics to science, computer graphics and rapid prototyping. In Chapter 4, presented the innovation on surface texture of virtual pottery and the conceptual design through the computational modelling implementation of the sound shape materialising technique. The first step explored materialising sound resonance images, using Chladni plate software for integrating 2D images with maps and physics manipulation, creating a more realistic texture. Next, the chapter explored ways of using volumetric deformable shape maps to blend these intricate sound resonance patterns in VP applications. Then, the chapter extended the result of complex 3D shape models from the above steps for rapid prototyping using appropriate pre-print tools by remeshing and physics manipulations. Finally, the chapter presented the result of a 3D printable object forms, with high-quality sound texture examples overlayed and blended, that changes the form of underlying 3D objects, demonstrating methods of using off-the-shelf tools.

Chapter 5 examined the VP technical developments and engagement with interaction devices. This chapter emphasised improving the human ability to unify physical and visual interaction. This is presented in a more reliable robust method for the exploration of emerging VR for physical/visual interaction concepts, with further advanced visualisation and complex modelling approach towards prototyping.

In chapter 6, an overview of layered manufacturing, addressed the evolution of 3D printing, 'Tailored' Manufacturing and Shape modelling refinement. The two main conflicting constraints when modelling for VP are rapid visualisation and accurate rapid prototyping, during the modelling phase and manufacturing phase, sequentially.

In chapter 7 the research focused on pottery 3D printing challenges, understanding the visualisation approaches to create complex VR/3D models with applying a volumetric texture. The challenges arise from modelling systems, VR modelling and problems in printing, slicing tool issues, overhangs plus scaffolding pottery issues, and material challenges. This chapter resolved the slicing obstacles, including fabrication and adding a volumetric sound texture from the proposed method.

Finally, in chapter 8 presented VP design refinement as a blueprint guide plan to extend ceramic artists' creativity of making, up-scaling the boundaries of creative making and develop a multi-modal interaction. This chapter focused on the design of the VP systems and the components: information systems design, design for the new norm and design of the Digital Twin. Furthermore, the research contribution are to the gap of knowledge reflected through a range of activities. The experiment outcomes were undertaken and achieved towards providing examples of VP system refinement: (1) Information Systems [40], (2) VR as New Norm [168] and (3) Digital Twin [169].

This thesis has developed traditional pottery by designing VP systems and subsystems for modelling and fabrication, extending VP application with object deformation and real-physical object transformations to create VR interactive physical modelling. The research used creative technologies to overcome real-world physical and fabricating challenges, creating new opportunities. The study's main contribution explored ways of creating a novel sound volumetric texture to develop a VP system of interaction modelling towards 3D prints of rapid prototyping.

More so, the thesis revealed the power of artists physicalisation and interactive modelling using creative technologies and rapid prototyping. The research shows the opportunities and the possible refinement of using existing VP applications and the integration of 3D software. The aims were to create a newly developed VP system towards unique modelling and rapid prototyping for complex organic forms with sound volumetric textures. The research uses an artist background to get new insights to guide the VP applications developer for a more genuine experience and explored tailored manufacturing for individual production.

9.2 Thesis Novel VP Systems Contribution

Finally, Fig. 9.1 captures sound shape modelling in the big picture of the research contributions, using off-the-shelf tools of VP modelling, interaction and prototyping along with the systems design for different functionality. 3D modelling applications are used for fabrication purposes. CAD tools are the most sophisticated tools to be used, but due to the limited time frame of the project, Blender software was good enough to demonstrate and produce a sufficient prototype for the meantime. The future project steps are to develop a new system using an adequate tool such as CAD for more scalable high-end results. However, for the time being, Blender offers good modelling opportunities being under GPL License, allowing customisation, and having a big community.

The research strategy involved designing a system with distinct deliverables starting from managing the integrated modelling software and new methods of virtual learning towards the digital twin concept. The system uses VR/ 3D modelling software with teleportation in between as a bi-directional fabrication approach for developing VR/3D models. The bi-directional fabrication system allows creating of digital clay models using VR and 3D tools, overcoming the shortcomings of the existing VP applications. The existing VP applications have basic tools, horizontal modelling on cylinder vessels without volumetric texture or additive 3D modelling of increasing mesh count. More so, facing some major errors that affect the prototyping process are seam-lines and zero faces.

In the 3D modelling section, the thesis highlights the CAD tool as a more high-end technical approach for industrial designs, rooted in engineering design for product documentation, parametric modelling, simulation and analysis. On the other hand, the CAID tool assists

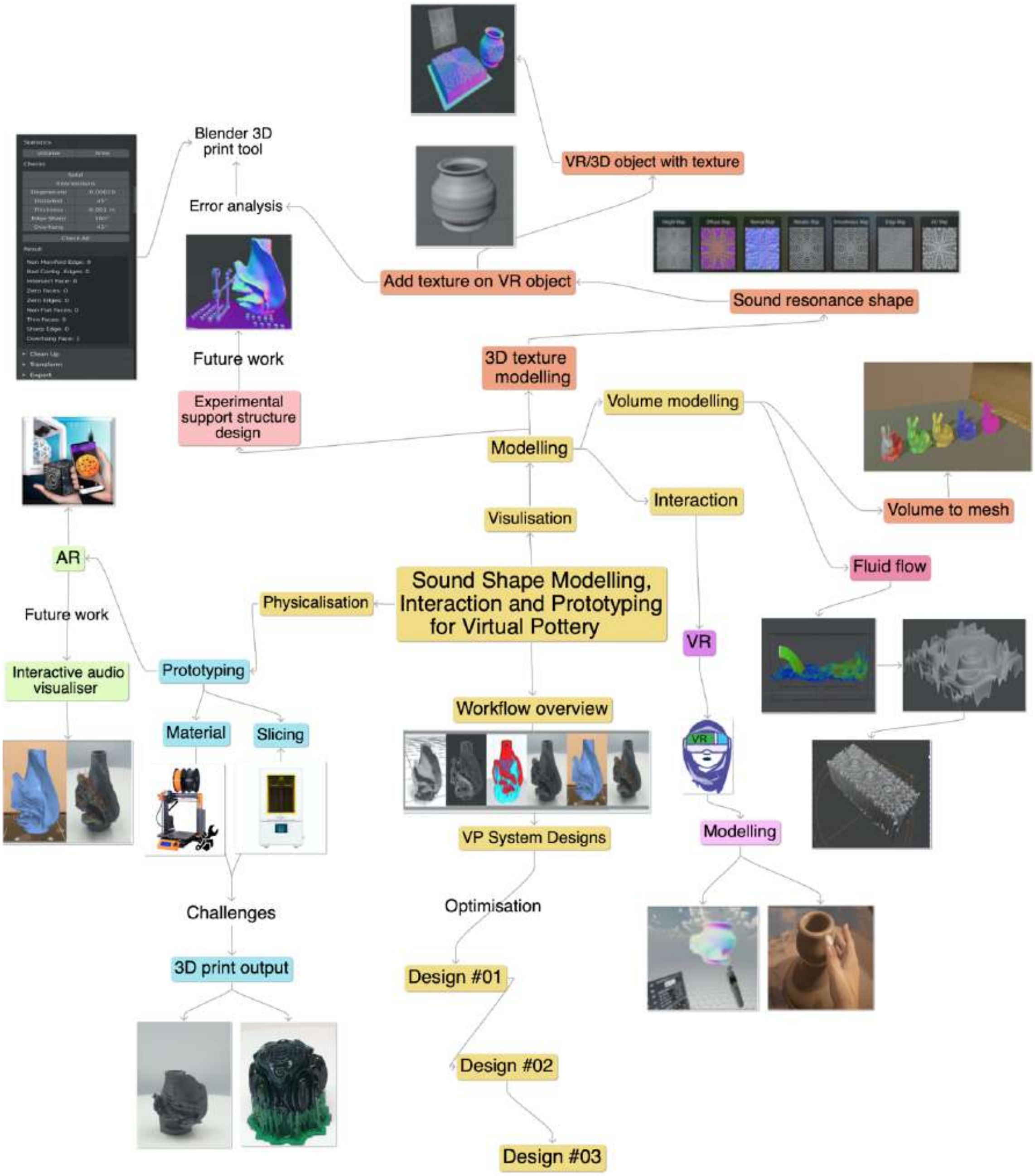


Figure 9.1: Overview contributions of the Thesis

in creating the visual and tangible feel of industrial modelling design features of a product in development. Furthermore, generating curves directly from the sketch generating surfaces directly from the curves. The result is generally a 3D model representing the designer model's primary intent for the physical product. CAID is considered more conceptual and artistic than a CAD tool.

The research shows the importance of CAD and CAID tools, but in the meantime, Blender was feasible to demonstrate the novel VP system of integrating more tools as Sener's concept of integrating CAD and the PHANToM tool [38]. The thesis research provides an integrated development perspective of existing VR/3D tools. The integrated system can be used for artistic designers or computer graphic developers to create organic forms Improving VR/3D ,modelling and tailored manufacturing toward massive production. The VP system simply provides designs for diverse advantages to improve VP application, for example:

- System management of modelling and fabrication
- Object transformations
- Add mesh count
- High volumetric texture details
- Geometric image generator (sound resonance fractal)
- High detail physical organic modelling
- Automated 3D print tool(fix model errors)
- Physical/visual interaction in real space

Also, the system uses more than on-screen modelling; users can interact physically and visually in a VR space. The system's structure is built as operation management and subsystems, providing guidance for modelling, analysing, problem-solving, quality validation and fulfilment of prototyping for the end-user. The research at this point is the first milestone towards infusing CAD with VP applications, improving modelling and fabrication criteria for novice and intermediate users.

9.3 Limitations of the Current Work

A critical characteristic of the research concept is that the research VP system in Fig 6.4 is not entirely seamless. It works as an integrated system of VR/3D and slicer by using off-the-shelf tools to create new opportunities with fewer obstacles and simple steps. The current XR Blender software supports VR modelling as an open free source but needs to be improved to fix errors that occur during modelling and can include a VR throwing wheel to have the whole experience of a seamless system.

However, the novel texture currently uses 2D image-based modelling without actual interactive activity deforming the shell surface as a still surface, such as the interactive audio visualiser experiment. Although the deformable modelling concept had great success, there is a need for the flexibility to explore, expand, or find new alternatives representing sound deformation with user control for sound and shape deformation. Furthermore, this concept can be developed to create an add-on in Blender software as a frequency generator controller for sound as shape deformation simulation. The methodology can allow the user to visualise, hear, and control the deformation much easier, controlling the selected subdivided mesh. More so, the tuning can be a set of 2D images from the Chladni plate with sound, for example, with sound. This approach would be considered as a part of the future research.

9.4 Future Work

While this thesis has demonstrated the potential of the novel volumetric sound texture and VP system with published papers to support it, many opportunities for extending the scope of this thesis remain with the findings of the latest research across disciplines. This section presents some of these directions in the order of chapters. More so, The future work have already a background of relative researches that will help to extend the project as organised into sections. Each of the columns in Table 9.1 presented a blueprint guide map to have one seamless system from VR modelling towards prototyping.

9.4.1 VP - Systems Design

The future work for chapter 8 on Systems Design is to extend the existing system in Fig 8.8 and create an optimised system performance in one or two integrated applications using the component in Fig 9.2 for a better experience. Identifying new ways of modelling and fabrication as a seamless system through using the Digital Twin concept. The study will consider the following research in the field:

Bi-Directional system Liang et al. [170] presented a bi-directional communication bridge between Digital Twin simulations and physical construction robots. This research approach can extend the designed construction models framework for bi-directional communication. The virtual robots receive work tasks and send the commands to the physical robots for ex-

Table 9.1: Developing VP system lined with the objectives for Future work

Future Work		
VP-System Design	Modelling	Prototyping
•Bi-Directional system (Liang et al. [170])	•Relief modelling (Ji et al. [171] and Wang et al. [172])	•Pottery prototyping (Hanssen [58])
•Interactive object management (Kolivand et al. [163])	•Scanned texture relief (Hillary [173])	•Human interaction in the fabrication process (Capunaman et al. [174])
•Digital Twin based system control (Jones et al. [175])	•Interactive edutainment engagement for virtual pottery (Guan et al. [176])	•Deformation: bending, stretching, curves (Ma et al. [177])
•Smart assembly process design (Yang et al. [178], Gulay et al. [179] and Sun at al. [180])	•Interactive VR modelling (Maurya et al. [181])	•Exploring new materials and methods of combining multiple resins (Brunton et al. [182] and Bader et al. [183])
•Pottery product design system (Sun et al. [180])	•Educational modelling skills (Lee et al. [184])	

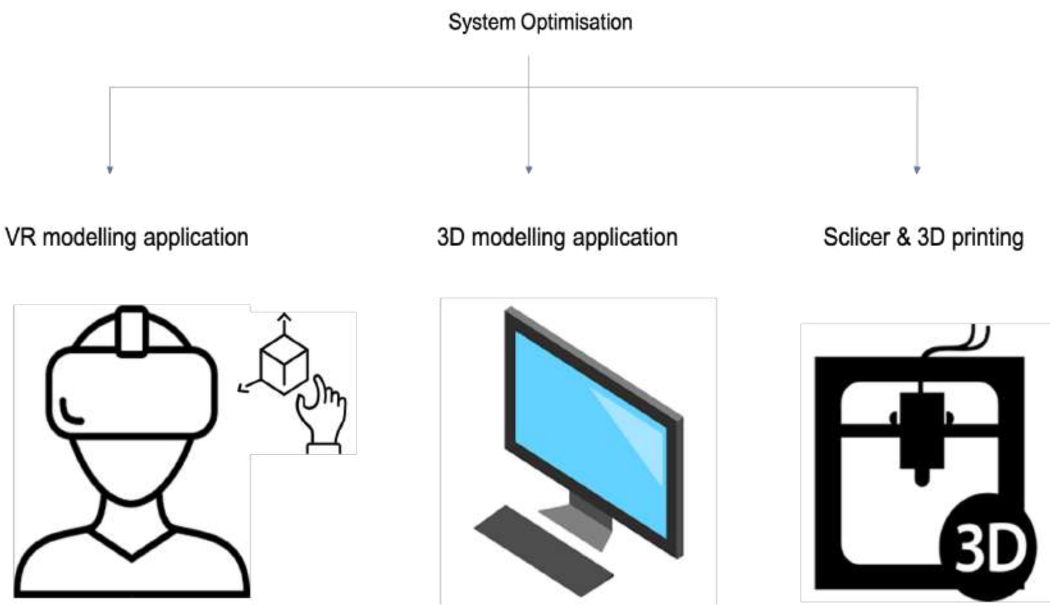


Figure 9.2: Novel VP system components.

ecution. The system is performed with a digital fabrication six-degrees-of-freedom robotic arm mounted on a track system for additional degree-of-freedom, evaluated by comparing the pose between the physical robot and the virtual robot. The results reveal the high effi-

ciency of the pose synchronisation between two robots, allowing further deployment to real construction sites. This research is compatible with the thesis for real-time modelling and fabrication simulating traditional making with a cutting edge approach.
Interactive object management system: Kolivand et al. [163] proposed a smart book as a communication tool that the modernised world requires. The study discusses advanced augmented reality books that integrate the digital twins and the mixed realities to create a book for interacting and making decisions. This project can assist the thesis in creating an integrated system for AR/VR/3D of a physical object.

Digital Twin based system control: Jones et al. [175] introduced an integrated version control of virtual and physical objects, inspired by software engineering and the Digital Twin concept. The study shows modern version control strategies are capable of managing VR objects. The process involves developing new industrial products with virtual and physical objects to refine, examine, and design evaluation. The Digital Twin concept identifies the product life-cycle, evolving the user's medium and maintaining digital/physical synchronicity.
Smart assembly process design: Yang et al. [178] proposed a smart Digital twin-based innovative assembly process design and applications framework for complex products and its case study. This method explores creative assembly, and it becomes a core focus for intelligent manufacturing in the fourth industrial revolution. The research focuses on creating a deep integration between information and physical worlds as a critical phase to develop intelligent assembly process design, creating a bridge between product assembly design and manufacturing. Further, the product assembly station components work on the detailed physical space layer; two main modules, communication connection and the processed data, are introduced in the interaction layer.
Pottery product design system: Sun et al. [180] explored the analyses design of ceramic products using computational aids and used a 3D approach to handle the procedure of fabrication. This research developed a ceramic modelling design framework to use with 3D printing technology and created a fabrication framework. Combined with the advantages of low cost and high plasticity brought by 3D printing technology, digital 3D modelling means to modify into data expression and transfer to 3D printing to achieve the design prototype

materialisation. Furthermore, design a series of ceramic toys with the Changsha kiln ancient artefacts characteristics.

9.4.2 Sound Shape Modelling Pipeline

The future work extends chapter 4 on Shape Modelling and will cover the exploration of developing a method of relief modelling deformation on the shell surface of an object mesh, using interactive image data of sign waves as shown in Fig 9.3. This method will help in developing AR interaction texture on a 3D print physical model. The following research may be developed as the future work of this thesis:

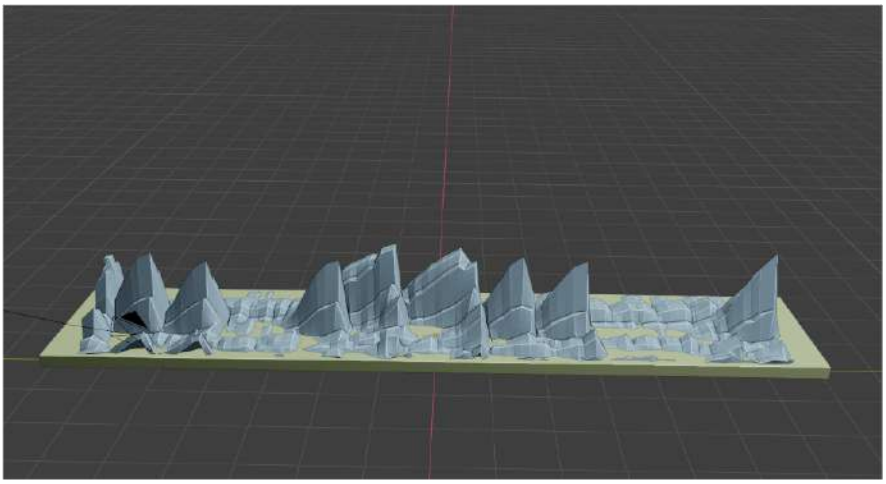


Figure 9.3: Audio visualiser: sound shape modelling and interaction on shell surface of 3D object.

Relief modelling: Ji et al. [171] presented a method of normal mapping manipulation to create deformation on the shell surface, creating a relief. The procedure is based on a normal-based modelling framework for bas-relief generation. The bas-relief is a sculptural relief technique in which the projection from the surrounding surface is slight, and no part of the modelled outline form is undercut. The design elements are just barely more prominent than the overall flat background. These operations treat an average vector as a pixel of a general colour image. This paper extends normal-based methods by processing the normal image from a geometric perspective. The method generates a new normal image by combining various frequencies of existing normal images and details transferring. Also, building a bas-relief from a single RGB image and its edge-based sketch lines. Finally, this approach produces a smooth base surface or generates a layered global shape.

Wang et al. [172] showed another method of mage bas-relief modelling from complex details and geometry with deep normal transfer. This approach introduced a new bas-relief modelling framework for complex detailing, with a visual attention based mask generation and geometry preservation. The project explored a semantic neural network of normal transfer to enrich the texture styles on bas-reliefs. For geometry preservation, they did a normal decomposition scheme based on Domain Transfer Recursive Filter (DTRF).

Scanned texture relief: Hillary [173] presented her thesis on the exploration of visualising Anishinaabe ceramics surface texture as a collaborative approach towards digital archaeology. The project focused on producing a digital model and 3D prints without risking further damage to the original physical object on the shell surface of the object.

A 3D print of a Providence Bay vessel was produced using archaeological illustration methods in a 3D modelling program Blender, creating a model of a pot informed by previous archaeology. This approach resulted in the development of a new methodology (the OCF Aahnkesjihgeh Method).

9.4.3 Immersive VR for Virtual Pottery

For chapter 5, the future work will involve exploring a consistent usability study approach to test the novel VP system by group testing, improving the interactive modelling and fabrication process to compare with existing systems. The following researches can help on designing test to collect usability feedback in-depth, and testing methods:

Interactive edutainment engagement for VP: Guan et al. [176] showed effects of a VR based pottery making approach on junior high school students, examining the creative ability, learning engagement and opportunities in practising new skills. This approach examines students ability to receive VR instruction. It is a meaningful approach to construct observation of physical /visual interaction reflection on the process for students in a pottery making class, promoting their learning experience and performance using VR tools. The study also showed an analysis of group study of VR-based approach had a higher cognitive engagement than other groups of those in the control groups with paper-and-pencil and clay. This approach of VR modelling showed more creativity in VR space and interaction with VR objects.

Interactive VR modelling: Maurya et al. [181] showed the impact of mixed reality implementation on the early-stage interactive product design process. The paper examines the designer's consideration of spatial and behavioural elements besides form/tangible aspects, performing quick validation of the generated concepts through functional prototyping at later design stages of interactive-product behaviours. The design task identifies, create and revise concepts of playful product behaviours was swiftly performed to assess the impact of the implemented method of concept-design behaviour observed throughout the study.

Educational modelling skills: Lee et al. [184] presented a study of how VR design tools can enhance designers' cognitive action and creativity in the design process. The experiments were mainly on the sketch phase early in the design process and selected a 2D digital design tool as shown. This research showed that immersive VR design tools activated physical and perceptual action in design cognition and enhanced flexible cognitive activity amongst different mental action levels compared to the 2D digital design tool. Furthermore, the findings reveal also that the improved flexibility in the cognitive process in VR augmented variant design thinking in design concept generation and connected with creative design outcomes.

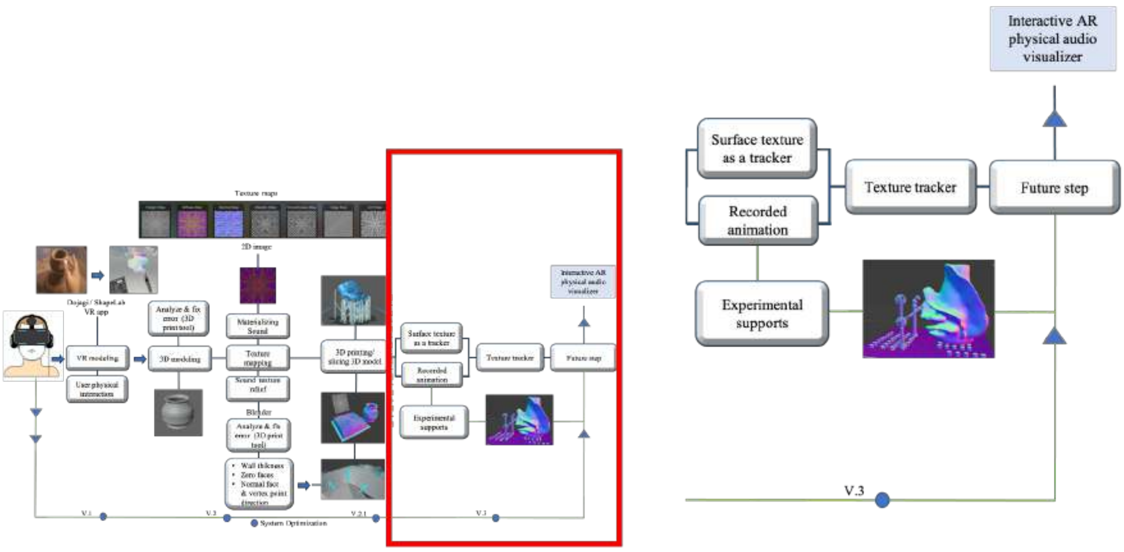
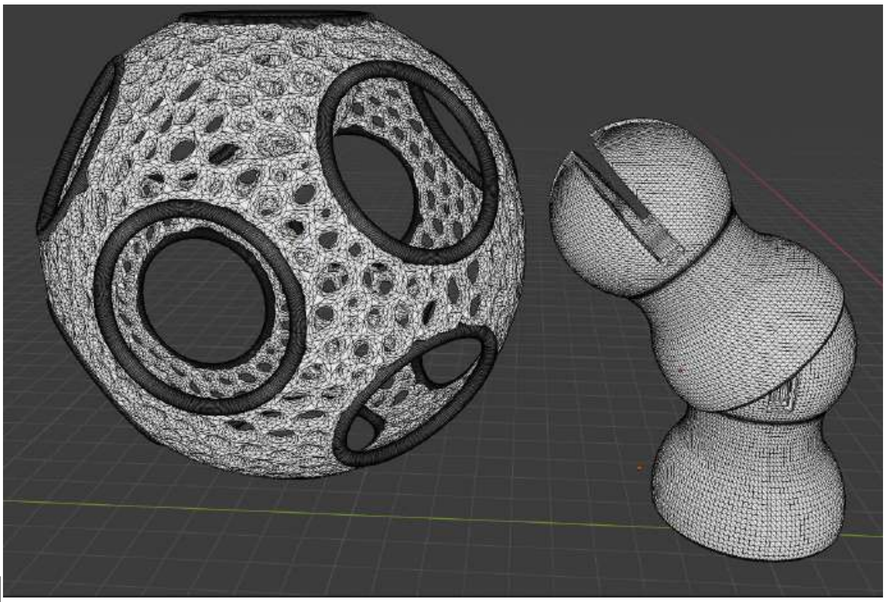
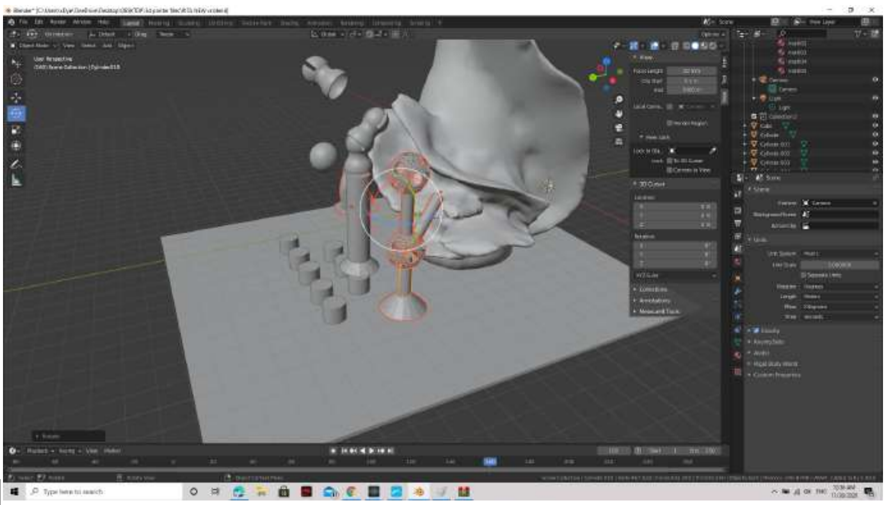


Figure 9.4: VP system future step of AR interaction and reusable scaffolding structure



[a]



[b]

Figure 9.5: Overview of the interlocking support reusable scaffolding structure system

9.4.4 Virtual Pottery: Towards Prototyping

To extend chapter 6 on Prototyping, the future work explores methods of VP modelling with simulating the entire experience of traditional pottery-making in VR in a more conventional approach. Also, the research will explore modelling structure support in Fig 9.4 and 9.5 for VR objects as an analysis in the VR modelling step for better prototype outputs.

Pottery prototyping: Hanssen [58] presented a method of linking the process of throwing ceramic vessels with sculpting tools using a VR kit. The combination technique is about layer modelling, creating a vessel of a thrown object outline and adding weave texture to the layers. This method simulates a 3D clay printer but with the advantage of controlling the modelling process. This approach could support future work for a new modelling methodology in one VR applications rather than throwing and sculpting tools.

9.4.5 Pottery: 3D Printing Challenges

For chapter 7, the future work will explore ways of modelling, prototyping, and the challenges for example, as shown in Fig 7.8 for prototyping complex organic objects with more natural deformation features. Also, future work will consider the following: *(a) Human interaction in the fabrication process:* Capunaman et al. [174] introduced creative method tools for contemporary digital design and fabrication tools. The project is about digital design pre-programmed workflows as a potential for developing a deeper understanding of materials within the process. This project focuses on interactive and adaptive design-fabrication workflow where users can actively take turns in the fabrication process. Furthermore, the proposed experimental setup utilises paste extrusion of clay as additive manufacturing synchronised with real-time control of an industrial robotic arm.
(b) Deformation: bending, stretching, curves: Ma et al. [177] proposed an interactive design system with clay as material that allows users to create sculpting styles and fabricate models using a standard 6-axis robot arm. The design works through a general mesh as input. The user iteratively selects sub-areas of the mesh through decomposition and embeds the design expression into an initial set of tool-paths by modifying key parameters that affect the visual appearance of the sculpted surface finish. The parameters were identified and extracted through a series of design experiments, using a customised loop tool to cut the water-based clay material. Gulay et al. [179] explored a feedback-oriented design process through curved folding. The project works to advance computational design and fabrication technologies, combining physical and digital processes in architecture. This project introduces a feedback-oriented design strategy linking physical models with digital tools to improve processes in architecture.

Sun et al. [185] examined a method for modifying the 3D printed prototype physically. The project presented FlexTruss, a design and construction pipeline based on assembling militarised truss-shaped objects fabricated with conventional 3D printers and assembled by threading. The system design creates an end-to-end approach, a parametric design tool with an optimal Euler path calculation method, which can support inverse and forward design workflow and multi-material construction of modular parts. The FlexTruss extends the design space of 3D printing beyond typically complex and fixed forms. This project also can have great potential for human-object interaction studies.

(c) Exploring new materials and methods of combining multiple resins, coloured core with a translucent vessel: Brunton et al. [182] introduced a method of fabricating an object with multi-material and translucency. The input to the project pipeline is an RGBA signal defined on the surface of an object, making the approach accessible and practical for designers. The project discusses a framework for extending standard colour management and profiling to combined colour and translucency management, a gamut correspondence strategy using opaque relative processing. Finally, an efficient streaming project method is presented for computing voxel-level material arrangements. The study method is achieved for more realistic reproduction of measured translucent materials and artistic effects, involving multiple fully or partially transparent geometries in object fabrication.

Bader et al. [183] presented a way of filling the gap between digital information representation and physical material composition. The projects method is involved in voxel printing for the digital fabrication of data across scales and domains. The process discusses a multi-material voxel-printing method that enables the physical visualisation of data sets commonly associated with scientific imaging. The voxel-based control of multi-material 3D printing. The design allows for additive manufacturing of discontinuous data types such as point cloud data, curve and graph data, image-based data, and volumetric data by converting data sets into material deposition.

The main objectives contribution in result developed modelling of VP objects, ways to extend the physical interaction of using an integrated application, and finally, rapid prototyping. The objectives are focused on developing (a) modelling, (b) interaction and finally, (c) prototyping to overcome the shortcomings of existing VP systems. The novel volumetric sound texture and VP systems are prototype systems and technique for VR/AR/3D modelling that aims to enhance both traditional making and computer graphics modelling. The methodology of this thesis enhances the decision-making process of spatial configuration for virtual clay modelling, transforming the perception of conventional pottery modelling with

VR space and tools. Meanwhile, the thesis also examines the challenges of VR/3D modelling and fabrication, discovering new analysis techniques for novice and intermediate users. Furthermore, finding flaws from artists perspective can help VR applications developers to produce a better simulation of traditional pottery. Future direction has been amended after finalising the thesis to include, (a) user case study to test the system, (b) use Advanced 3D resin printer to compare ceramic resin output, (c) increase subdivision surface. Finally, the project shows new insight into gaining new skills, learning, and tailored manufacturing opportunities for single or massive production compared to other VP systems mentioned in the literature chapter.

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