

Ph.D. Thesis

A Study on Interactive LOD Control of  
Image Triangulation and Its Effect for  
Entertainment Game

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# Abstract

This research explores an effect of combining “generative art” on “interactive installation” and puzzle game - “Hidden Object Game”. Generative art is an art style in which an artwork is generated automatically by a rule such as an algorithm of computer program and a mathematical autonomous process. This art style attracts artists and researchers due to its power to effectively generate unique and sophisticated artworks. Interactive installation is an art style in which an artwork, such as an image projected by a projector, an object, and a material, is shown to a participant and it changes attractively so as to react to the participant’s interaction. It can be said that generative art is related to how to “generate” an artwork while interactive installation is related to how to “show” an artwork. This research takes up image generation caused by “triangulation” as a subject of generative art and studies its effect in interactive installation. Specifically, the LOD, namely, level of detail of the triangulation is controlled by the participant’s interaction. In order to investigate the effect of this LOD control, interactive artworks were developed and evaluated. Through this research, it is expected that the difference between generative artworks and other kinds of artworks, such as abstract artworks, used in interactive installation is clarified.

This thesis firstly presents the background of generative art and interactive installation, which includes their definitions and the comparison between typical examples of artworks in which artists combine them. It also reports how generative art is useful in various kinds of fields, such as architecture, graphic design, and advertisement. Especially, lots of artworks show that generative art is greatly usable to give fascinating visual effects on images. Besides, it is clarified that interactive

installation can help help artists to show their artworks and participants involved in the artworks and to understand their concepts.

In this research, two major artworks related to generative art and interactive installation are proposed. In both artworks, the core idea is “interactive image triangulation”, in which a given image is triangulated interactively by the hand movement of a participant. The triangulation is a well-known method. This research uses the triangulation as a method of generative art and investigates how it works in interactive installation. The interactive triangulation is realized by two Delaunay triangulation algorithms, which play the most important role in this research.

The first artwork proposed in this research is “triangulation-based image emergence”. It has three types of applications, that is, one basic application and two extended applications. In the basic application, an arbitrary image is used as an original image that is unknown to a participant. The original image is triangulated and shown to the participant by projecting it onto a large screen or a wall with a projector. The triangulated image works as an approximation of the original image and makes the participant enjoy imagining the content of the original image. Initially, the triangulation is too rough to imagine the content. The LOD of the triangulation becomes finer and rougher by the hand movement of the participant in front of the projected image. This LOD control changes the difficulty of the participant’s imagination. The LOD becomes finer on the image area near the hand movement. Consequently, the participant intends to move hands near the area where the participant wants to see the detail as if to wipe a misted glass window to see an outside scene. In order to realize the finer and rougher LOD change, two Delaunay triangulation algorithms are used. One is an incremental algorithm to add new points to triangulate, and another is a decremental algorithm to delete existing points. The two extended applications are based on the basic application; each application is given a kind of dynamics by giving a random movement to a triangulation. In the first extended application, each point of a triangulation, that is, each vertex of triangles moves slightly around its initial position in the 2D image space. In the second extended application, each triangle moves slightly in the 3D space. The three applications were played by participants and evaluated by a questionnaire.

We suggested a wiping operation for the second research to accelerate human activities in the Hidden Object Game. We implemented two types of games: a game with a wiping operation and one without a wiping operation, to measure the efficiency of the wiping operation. In this game, a participant is given a task to find queried target objects from a triangulated image whose LOD is changed by the participant's movement. We installed our game on the wall and the computer. On the wall, the player will play their hand movement. On the computer, players use a computer mouse. We measured the players' brain activity and took the survey from the players to measure game enjoyment after gameplay. Based on both results, the wiping operation made the Hidden Object Game more enjoyable.

This thesis concludes that the interactive LOD control of image triangulation proposed in this research works effectively as a tool in generative art for an interactive installation. Moreover, the visual effect of the interactive triangulation has the power to attract many participants. From this result, generative artworks realized using interactive triangulation could also be practical in various entertainment fields, not only in the game. Finally, there are some problems to work on in the future. In order to realize smooth interaction even for triangulation with a vast number of points, the Delaunay triangulation algorithms should be improved to work robustly.

On the other hand, our proposed methods should be installed on various devices such as tablets, smartphones, and other display systems. A limited number of participants did the current evaluations for the proposed artworks. Therefore, obtaining various evaluations from more participants is also vital to improve our research.

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# Chapter 1

## Introduction

This thesis explores the combination of “generative art” and “interactive art”. The generative art explored in this thesis is focused on exploring usability in interactive installation. Generative art is related to both of “programming” and “art”, which are considered to have opposite properties each other in general. Programming is an interface between man and machine; it is clean, logical discipline, with clearly defined aims. On the other hand, art is an emotional subject, highly subjective and defying definition. Generative art is the meeting place between the two things: it’s the discipline of taking strict, cold, logical processes and subverting them into creating illogical, unpredictable, and expressive results. The interactive art is commonly associated with virtual reality in that it attempts to induce a state of presence where the participants may believe that they are inhabiting some other virtual environment. In an interactive entertainment, its contents are changed by user’s interaction in real time. A user can enjoy the involvement to the contents by feeling the sense of immersion. However, in order to achieve real-time interaction, the contents have to be generated efficiently in limited computation time while acquiring the user’s interaction accurately. In such cases, the development of appropriate algorithms is important.

The practice-based research proposed in this aims to explore the usability of generative art in interactive installation. This thesis first provides a fundamental interactive installation, which contains three types of applications. In this

installation, the most important process is the triangulation of a given image. The triangulation is achieved by using Delaunay triangulation as a generative artistic algorithm. Then this thesis provides another interactive installation based on the first installation. The second installation is an entertainment interactive game by using improved Delaunay triangulation.

Measuring game enjoyment is a challenging task in the game research field nowadays. However, researchers proved that if the user or participant's brain is active during the gameplay, they mostly enjoy the game. As we got this idea, we used a brain activity measuring device to measure our game's enjoyment along with the models which measure the game enjoyment.

Overall, this thesis aims to explore the combination of interactive installation and generative art. Specifically, we will explore the Delaunay triangulation algorithm's usage on several entertainment applications.

In order to achieve our goal, the following tasks have been identified:

- To create an interactive installation whose content is created by generative artistic algorithms
- To examine the effect of combining generative design for entertaining contents

## **1.1. Background**

As this dissertation is a combination of generative art and interactive installation, there is a need to define these important terms and explain how these seemingly disparate fields may be combined.

### **1.1.1. Generative art**

This study begins by defining generative art. Its history starts from the late 1950s by some of artists and designers begin to experiment with mechanical devices and analog computers. This served as a precursor to the work of the early digital pioneers who were not artists or designers but engineers and scientists. A number

of definitions of generative art have been proposed [1, 2] which attempt to situate it within a wider range of artistic activity, and to classify it according to media, methodologies or approaches (e.g. interactive art, algorithmic art, software art, artificial life art). Additionally, each of generative art does not involve digital computers at all. To fully understand computational generative art, we must take into account this rich and insightful non-computational work. But the computer and its associated technological progress bring new ideas and possibilities that have previously been impossible or impractical to realize. This makes generative computer art different from its non-computational counterparts.

In essence, all generative art focuses on the process by which an artwork is made, and this is required to have a degree of autonomy and independence from the artist who defines it. Moreover, generative art involves procedures (rules, formal instructions, algorithms) created by the artist, that are enacted with varying degrees of autonomy. Many generative artists concur that they are programming a computer to perform the desired result is challenging.

Generative art is a method whereby we use an algorithm to generate an image. The design is controlled by a set of rules that determines its outcome. Therefore, generative design is used in a various kind of fields. Even for visualizing a vast and complex data information as well. Figure 1 is showing the “Taxi, Taxi” which in a digital installation featured within some events in Manhattan. It uses NYC Open Data taxi data plotted against routes created with Open Street Map which is displayed within a 3D model of New York City. It is designed to run in real-time which can give a true information in an aesthetic way.



**Figure 1: “Taxi, Taxi”, Robert Hodgin [3], 2016**

Thus, a generative design approach is a useful addition to a designer’s toolbox. By using a generative design, designers or artists can reach their goal efficiently and create a new aesthetic artwork self-reliantly.

### **1.1.2. Interactive installation**

In order to understand the interactive installation, it raises some relatable questions: What form the interface can take and what interaction design can stand out for interactive installations? Is its purpose for more practical reasons such as selling and marketing a product for educational or research purposes or for physical and emotional engagement? Is it extension of participatory design? Is its purpose to improve the effectiveness of interactive design or to illustrate a new wave that reflects recent transitions among science, technology, and society?

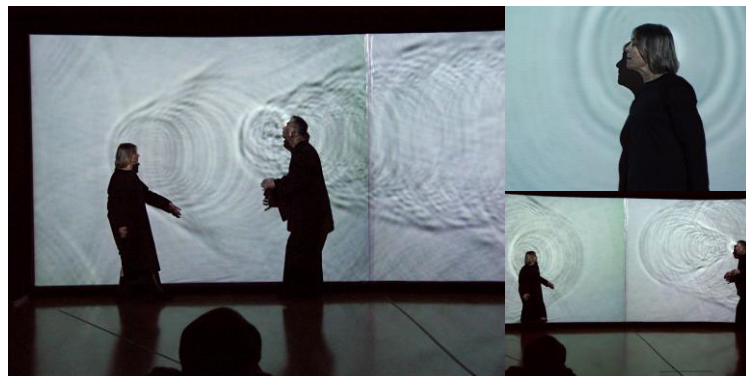
Interactive installation is an interdisciplinary subset of digital media and digital art. Interactive art installations are generally computer-based and frequently rely on sensors, which gauge things such as temperature, motion, proximity, and other meteorological phenomena that the maker has programmed to elicit responses based on participant action. In interactive artwork, both the audiences and the machine work together to create a unique artwork for each audience to observe.

According to an art critic Michael Rush [4], as example of interactive installations, which are “beyond the ‘clicking’ and ‘surfing’ activities of the Web, which are, indeed, forms of interaction with computer technology, several contemporary artists have created works, often on a large scale, that are truly participatory”. He

emphasizes the importance of both the digital process, which is the use of computational systems, and the scale of the physical interface, which usually triggers participants' whole-body movements. His perspective explains the role of digital interaction and the scale of a physical interface.

## 1.2. Motivation

The motivation for this research originated from Golan Levin and Zachary Lieberman's "Placing the voice" [5] which is an audiovisual performance. In this performance, speech, shouts, and songs produced by two abstract vocalists are radically augmented in real-time by custom interactive visualization. The sophisticated and playful contexts are showed abstract communication as getting a sound and body positions of the vocalists as shown in Figure 2. In this work, the creators used many physical elements and cartoonish, visual effects.



**Figure 2: "Ripple", a section of "Placing the voice" in which the performers' voices affect a water-ripple simulation. [5]**

An artist's goal was to make human sound visible. For their goal, they used physical elements as integrating real-time computer vision and speech analysis algorithms. Specifically, a computer uses a video camera to track the locations of the performers' head. Creating elements from performers' head is shown as they talk or creating sounds visible. Figure 3 shows one section of solo performer's performance.





**Figure 3: Performer emits stream of bubbles by making a special cheek-flapping sound. As his sounds grow more vigorous, his bubbles fill up the screen. But the resulting cloud of jostling sound-bubbles is unstable. [5]**

As watching Figure 3 and other sections of this work, I really deepening into how those elements working physically and lively. Moreover, I amazed at how those elements create randomly but also could expressing the artist's expression.

For creating those elements of artworks, they used autonomous and mathematical system which are used in Generative Art or Design and Creative coding. The autonomous system can be a computer, but more broadly an autonomous system is non-human and can independently determine features of an artwork that would otherwise require decisions to be made directly by an artist [6]. Those video arts [7, 8], music shows [9, 10], and dance arts [11, 12] are not only types of interactive installations artworks, but also each of them has their own meaning and narration. Most of them used computer technology on its contents with a cycle of interaction that fully integrates audiences and performers. Then each of them is expressing unique, playful, and sophisticated meanings those all are included in this interactive installation. In most cases, both artists and audiences do not know the outcome. Which may make their work flexible and unique.

Generative art is not usually used in goal-oriented entertainment applications even though it is efficient way to create unique artworks and can express the artist's concept. And we observed the most of used methods chosen by artists are mostly expressed their works in an abstract way. Through the definition of generative art (Section 1.1.1), a generative art is rule based which are set by artists or creators. Then we propose the rule based on original image and use generative art as an image

effect likely created by traditional tools such as Photoshop. Thus, we propose to use those effects on interactive entertainment application.

The goal of this work is to devise a goal oriented interactive entertainment application using a generative art. We divided our goal into the following tasks:

- To create an entertainment application based of the concept of generative art
- To measure the user enjoyment based on game enjoyment model which is widely used for games or entertainment applications

### **1.3. Proposed idea**

In many works such as [13, 14, 15, 16, 17, 18], artists and researchers use generative art to express their artworks and let users involve and feel the artworks by themselves without any thoughts. From those works, it is evident that most of their works express the artist's concepts well even if the works are abstract. While generative art is used in less amount of game, it is used in many photo applications, each of which transforms an original image into another image.

Then we chose Delaunay triangulation algorithm. Jonathan Puckey et al [19] used it for changing original raster image into formed vector image. Aesthetically, the resulting image is recognizable as an original image which makes the result unique. Comparing with the computer visionary image changing algorithms, it can create vector image as well as it works efficiently and fast.

We proposed an entertainment application and the wiping operation on Hidden Object Game based on the concept of generative art according through our motivation. We planned the aims of our research works as follows.

1. A user is entertained visually
2. A user has a sense of achievement.
3. A user has concentration and a sense of immersion

To demonstrate the user's satisfaction, we aimed to measure enjoyment of the application. Thus, we set the 2<sup>nd</sup> aim for our research and implemented our application by combining it with 1<sup>st</sup> aim. Finally, we implemented our application

and proposed the wiping operation by measuring enjoyment on the Game Experience Questionnaire [21].

As we aimed to create a real-time interactive installation and the wiping operation on Hidden Object Game, we used Delaunay triangulation to change images constantly. According to the references (Chapter 2), a Delaunay triangulation is researched for various purposes depending on the usage.

## 1.4. Thesis overview

Chapter 2 begins by examining and comparing each related work of generative art and interactive installation. Then, as we took experiments based on Generative art, we highlighted more results that used interactive installation. Finally, we introduced measurement methods for defining game enjoyment.

Chapter 3 introduces the methods we used in our interactive installations. Briefly, we used a Delaunay triangulation algorithm. As we described in this chapter, we used other improved Delaunay triangulation algorithms compatible with our application to use in our last experiment. Thus, Delaunay triangulating with incremental insertion and point removal in Delaunay triangulation are presented in this chapter.

Chapter 4 presents our 1<sup>st</sup> experiment in detail. First, we let participants play with our application, then took the survey. Finally, we implicated the study with questions and highlighted its results. From the result using the idea from current research, we understood that we needed more research results to implement our research idea. So then, we planned to experiment next time.

Chapter 5 provides a piece of detailed information about our last game application. As we told, on each installation, we took surveys to measure the enjoyment of participants and measured brain activity while playing. In this game application, we explained how we organized a questionnaire based on the Game Experience Questionnaire [21]. Also, the results we got are explained in particular.

Chapter 6 summarizes and concludes the thesis and suggests directions for future research. Since the thesis aims to provide the usage of generative art in interactive entertainment applications, the thesis highlighted its use application and game.

# Chapter 2

## Related works

In this chapter, we are going to reveal considerable research around interactive immersive technologies. There was, however, a relative scarcity of information to be found at the intersection between a generative art and an interactive installation.

### 2.1. Generative art

Generative art is art or design generated, composed, or constructed through computer software algorithms, or similar mathematical or mechanical autonomous processes. The most common forms of generative art are graphics that visually represent complex processes, music, or architectural design which are driven by a set of rules. Here we compare some usage of generative art in various kinds of fields. Recently, a generative art is used for creating context by a whole and



Figure 4: Side table, table and bench design – Jane Kytanen (2014)

In this case, an artist observed generative design's unique possibilities and used its uniqueness on his works [22]. He creates design of furniture, accessories and industrial tools using a generative design which makes his works unique and modern. Automatically created design not only in a life related tools but also used in architectural and out-doors' design [23].

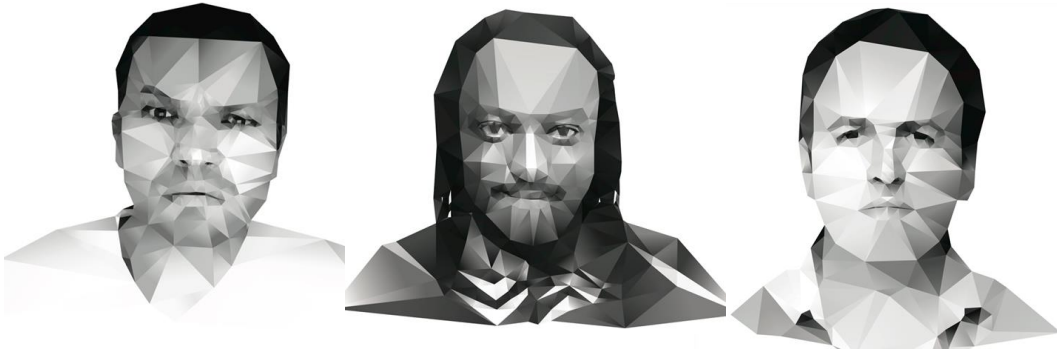
Artists tend to use generative art in their artworks depending on their unique concept. Evidently, artist created contents using physical, autonomous algorithms which users or participants easily involve with their works and feel artist's idea what they wanted to tell and express from those works [13, 14]. In those installation works a user's and performers contact and create their feelings interactively in Figure 5.



**Figure 5: "Seventh Sense" -2011. Performers easily show their impressions with dance movement through this interactive environment.**

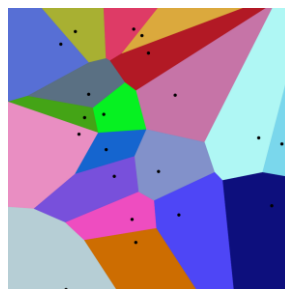
In many cases, even if the artists know the rules and understands how they are executed, they could have not foreseen the outcome. In other words, the outcome is often unpredictable. That why some researchers hypothesized combination of a generative art and interactive installation give audience much enjoyment. In this way, a user can enjoy the direct involvement to the content and feel the sense of immersion. However, to achieve real-time interaction, the content must be generated efficiently in limited computation time while acquiring the user's interaction accurately. In such a case, it is often so important to develop appropriate algorithms [16, 17] for efficient computation.

As we chose a Delaunay triangulation, it is the one kind of autonomous algorithm which is used in generative art. In digital media, a Delaunay triangulation algorithm is used for modeling 3D efficiently and low costs. In the digital world where computer efficiency is a crucial topic nowadays, it is well suited for saving memory and loading complex 3D models robustly at a low cost in many kinds of areas.



**Figure 6: Portraits for Esquire Russia. [19]**

Jonathan Puckey et al [19] proposed an image filtering tool which makes an original image into a triangulated image. In the traditional printing process, the computer rasterizes an image automatically. It is a deterministic process that is always executed in the same manner; for example, a user can change some parameters when applying an image filter, but the consequences are always predictable. In contrast, their program permits the intervention of the human hand. After scanning the image, the user sets grid points on the image by clicking the mouse and, in so doing, learns how the tool works, since its effects are immediately visible. This feedback allows the user to respond to changes in the image and influence the process directly. The resulting image will vary according to how the points are set; hundreds of quick user decisions determine the result. This tool is based on the Delaunay triangulation and creates a set of optimal triangles out of a group of points.



**Figure 7: 20 points and their Voronoi cells**

On the other hand, Aleksandar Čučaković et al has highlighted the importance of generative design by their biomimetic approach which is for create 3D model based on the natural elements by using a Voronoi diagrams. A Voronoi diagram is a partitioning of a plane into regions based on distance to points in a specific subset of the plane in mathematics. That set of points is specified beforehand, and for each seed there is a corresponding region consisting of all points closer to that seed than to any other. These regions are called Voronoi cells. The Voronoi diagram of a set of points is dual to its Delaunay triangulation. In their approach, they created 3D architectural model which is inspired by nature elements such as flowers. They highlighted importance of the creation of the geometric structure of the flower using Voronoi diagram especially for 3D printing. However, they have investigated that for the structure of more complex objects, it is necessary to continue the research.

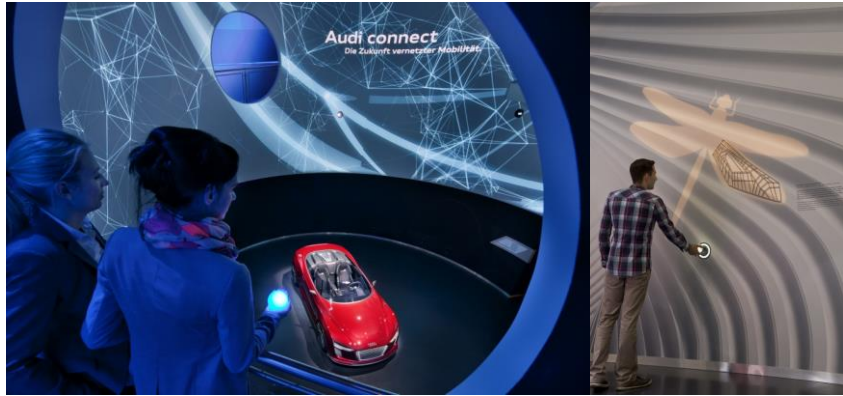
## 2.2. Interactive installation

In recent years, an interactive installation is tended to use in a variety of artistic fields. Those kinds of artworks emerged from new computer technologies and digital tools such as cameras, sensor, and projectors. Some installations are displayed on monitors, some are projected on the walls [11, 18], and some performed by humans on stages [12, 24] using computer controlled devices. From some other pre-prepared dance shows [24], artists could use any other graphical software to generate effect which is created by generative algorithms easily.

In their work, Mayumi et al. [12] used generative art algorithm in their context to create dance effects such as lightening and flashing. For creating those effects, they basically used randomized particle algorithms. From their work, it is obvious that generative art can be used substantially.

Interestingly, using interactive immersive technologies in an advertisement is giving chance to increase sell marketing of any product company. Evidently, interactive immersive technology allows brand to create completely unique stories and environments and offer something new. In the Audi's pavilion's [25] (Figure 8) special highlight is an interactive ball, the "Audi Sphere", which visitors use as a personal companion on their tour of the pavilion.





**Figure 8: Audi created its brand pavilion in Auto City Wolfsburg with a remake of its permanent exhibition, which showcases Audi’s current technologies and innovations.**

[25]

From such kind of works, many marketers and producers are finding that using interactive immersive technologies allows users and visitors to engage with the pieces and “feel a connection with products and artists”. From the references, we observed the possibility of generative art algorithms usage on interactive installations.

## **2.3. Measuring Game Enjoyment**

Defining game enjoyment is challenging in the game research field cause of its subjectiveness. Therefore, researchers are measuring game enjoyment in two ways: subjectively and objectively. Now we will demonstrate those ways in this chapter.

### **2.3.1. Subjective measurement**

Subjectively measuring a game's enjoyment is one of the easiest ways. However, because of its low-tech method, these measures consist of questionnaires and surveys. Moreover, the drawback of those kinds of measurement is the reliance on self-reflection from the participants. And its questions are not strictly defined in any game. Nevertheless, some researches relate to measuring the enjoyment of the game, such as the Game Enjoyment Model [20] and the Game Experience Questionnaire [21]to measure game enjoyment etc.

The Gameplay Enjoyment Model is a theoretical framework that seeks to explain and predict the enjoyment of playing games. The model suggests that enjoyment is a function of several key factors, including challenge, control, competence and immersion. It suggests that enjoyment in playing games is a function of several key factors, including:

1. Challenge – The degree of difficulty in a game and the player’s ability to overcome it.
2. Skill – The player’s level of ability and competence in the game, which influences how they respond to challenges.
3. Control – the player’s sense of agency and control over the game and their actions.
4. Competence – The player’s perception of their skill level and their ability to achieve their goals in the game.
5. Immersion – The player’s sense of being fully immersed in the game world and losing track of time and the real world.

These factors interact with each other to contribute to the player’s overall enjoyment of the game. The model suggests that players enjoy games that are challenging but not too difficult, in which they feel in control of their actions and decisions, feel competent, and experience a high degree of immersion in the game world.

In sum, the Gameplay Enjoyment Model is a theoretical framework that seeks to explain and predict the enjoyment of playing video games.

Based on our first experience, we proposed using our newly created operation, which's name is the wiping operation on Hidden Object Game. To measure the efficiency of this operation, we selected the Game Experience Questionnaire (GEQ) [21]. It is another research tool used to measure the subjective experience of playing a game. The GEQ consists of standardized questions that ask players to rate their experience in various areas. The GEQ is a multitude of 5-point scaled questions within various categories. The categories are in three modules:

- Core Module (33 items): test on seven components of the game experience:

1. Challenge – The degree to which the game provides an appropriate level of challenge to the player.
  2. Competence – The degree to which the player feels that they are making progress and improving their skills in the game.
  3. Sensory and imaginative immersion – The degree to which player enjoys the visual, auditory, and other sensory aspects of the game.
  4. Flow – The degree which the player feels absorbed in the game world.
  5. Tension/annoyance – The degree to which the player feels nervous or anxious while playing the game.
  6. Negative affect – The degree to which the player feels negative while playing the game.
  7. Positive affect – The degree to which the player feels negative while playing the game.
- Social Presence Module (17 items): questions pertaining on the behavioral model of the player when another entity is present.
  - Post-Game Module (17 items): questions to assess how the player feels after they finished playing.

The in-game version of the core module is also available, which is a more concise version for multiple/frequent in-game testing stops containing fewer items per component. We used the in-game module on our game, as shown in Chapter 5.

The GEQ has been used in numerous studies to investigate the impact of different factors on the player's experience, such as game mechanics, graphics, sound, and story.

It is important to note that both of these models are still a subjective measure of enjoyment, and the results can vary significantly from person to person. However, they can provide valuable information about the player's experience and help identify areas for improvement in video game design.

### 2.3.2. Objective measurement

Objective measurements, such as temperature, brain activity, or time, are not subject to personal bias. Physiological measurements are commonly used in game research to measure game efficiency.

There are two common categories based on the controlling nervous system. The Central Nervous System (CNS) controls measures like Electroencephalography (EEG), Event-Related Nervous System (ERP), and Electrooculography (EOG). The Peripheral Nervous System is the nerve system beside the brain and spinal cord. They rely on the information between the brain and the rest of your body. These measurements' ambiguity makes it difficult to draw on them as stand-alone measurements. However, a few studies have verified them as stand-alone measurements by validating them with subjective measurements.

Researchers are measuring the enjoyment of a game using brain sensors such as Electroencephalography (EEG), Functional Near-Infrared Spectroscopy (fNIRS), or Functional Magnetic Resonance Imaging (fMRI). These techniques can provide information about brain activity and blood flow patterns in response to various stimuli, including games.

For example, EEG can measure brain activity in real time and show increased activity in areas of the brain associated with pleasure and reward in response to enjoyable stimuli. fMRI can reveal changes in blood flow to specific brain regions and provide information about which areas of the brain are active while playing a game.

Based on our research purpose, we aimed to use a cheaper and easiest way to measure during the gameplay. As we compared the ways to do it, we used the devices used for fNIRS, despite the difficulty of using fMRI's large, stationary imaging machine known as a whole-body magnetic resonance imaging scanner and usability and EEG. We suggested using a device for fNIRS along with the Game Experience Questionnaire (CEQ) in our research.

We used a fNIRS device for following reason:

1. Mobility

2. Price
3. Simple management system

### **2.3.3. Summary**

Both subjective and objective measurements cannot imply game enjoyment separately. So that we used those measurements together in our experiment, as shown in Chapter 5. To implement, we selected the GEQ as a subjective measurement and used the fNIRS device to measure brain activity as an objective measurement.

# Chapter 3

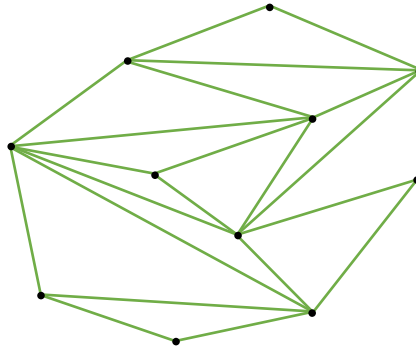
## Fundamental methods

In this chapter, the fundamental two methods we used in the proposed installations are explained. One method is “triangulation”, which plays an important role by working as a generative artistic algorithm, used in both proposed two installations. It is used for an effect which changes an original image into a transformed image. The proposed installations use well-known Delaunay triangulation. For the interactivity of the proposed installations the Delaunay triangulation algorithm to use needs to work in real time. Thus, some Delaunay triangulation algorithms are compared with each other.

### 3.1. Triangulation

Before we talk about the Delaunay triangulation algorithm, we should demonstrate triangulation and mesh. In trigonometry and geometry, triangulation is the process of determining the location of a point by forming triangles to it from known points. In order to explain the triangulation, firstly it must be identified what is a triangulation of points and initially what is a cloud of points which are known. In a simple way, it is possible say that a cloud of points is simply a set of points distributed in a space region, at this space of two dimensions. One of the forms in which a set of points can be triangulated is randomly. For it, an algorithm that tries to be most randomized possible has been used. The ideas are simple: (1) A points

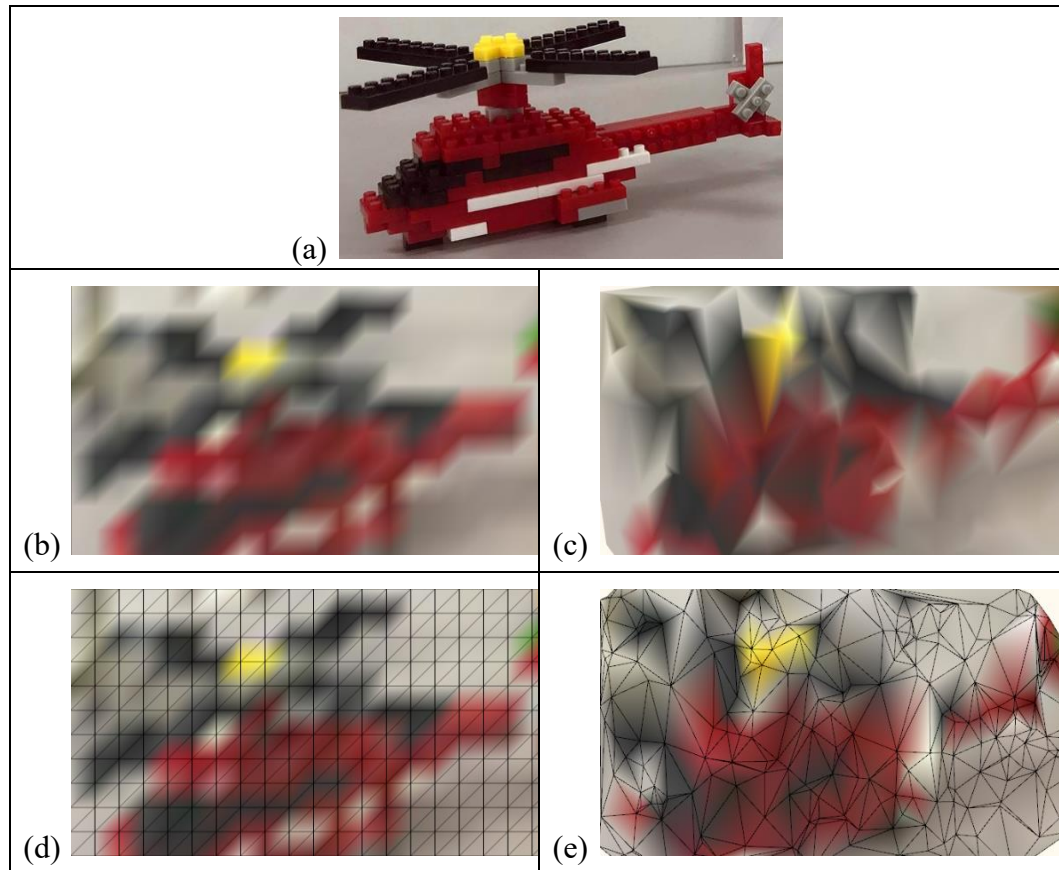
of the set that can be connected to another point is obtained at random, (2) then looking for the points which can be connected to that points and one is obtained at random, (3) the pair of points is connected by means of a new edge and (4) the process is repeated until they are no points with which to be able to connect left.



**Figure 9: An example for a random triangulation**

Meshes composed of triangles or tetrahedra are used in applications such as graphics, interpolation, surveying, and terrain databases. Numerical methods such as the finite element method and the finite volume method are an irreplaceable means of simulating a wide variety of physical phenomena in scientific computing. They place particularly difficult demands on mesh generation. If one can generate meshes that are completely satisfying for numerical techniques like the finite element method, the other applications fall easily in line. Historically, the automation of mesh generation has proven to be more challenging than the entire remainder of the simulation process.

Meshes can be categorized as structured or unstructured. Figure 10 illustrates an example of each. Structured meshes exhibit a uniform topological structure that unstructured meshes lack. A functional definition is that in a structured mesh, the indices of the neighbors of any node can be calculated using simple addition, whereas an unstructured mesh necessitates the storage of a list of each nodes' neighbors.



**Figure 10: An original image (a), structured (b), structured with wireframe (d), unstructured (c), and unstructured with wireframe (e) meshes**

The generation of both structured and unstructured meshes can be surprisingly difficult, each posing challenges of their own. This thesis considers only the task of generating unstructured meshes, and furthermore considers the Delaunay triangulation for movable points. Because of our applications' 'challenge' factor which we described it based on Garris's [26] and Malone's [27] work, we aimed to use unstructured meshes. Because our points we used are changeable and not stable. Which means during the deletion of the points, new points are added which are executed by the participants. If we use a structured point, they should be more stable, and it became harder to delete or add points. However structured image that is triangulated using structured points easier to recognize, seeing from the characteristic of our application it was not compatible to use those points. On the other hand, unstructured points are fulfilled our applications' 'challenge' characteristic.

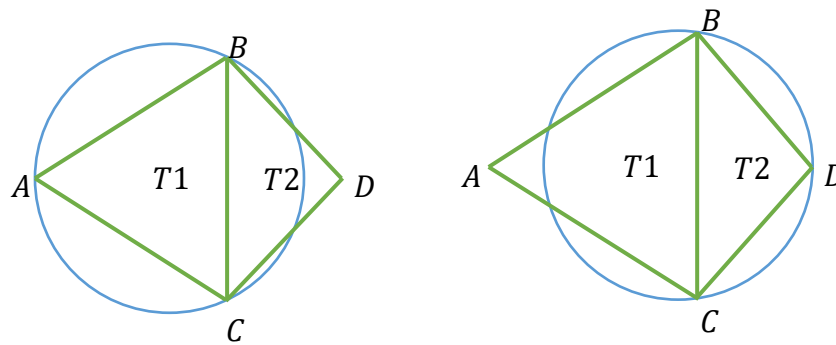


### 3.1.1. Definition of Delaunay triangulation

The Delaunay triangulation is a geometric structure that has enjoyed great popularity in mesh generation since mesh generation was in its infancy. This triangulation gives as result a uniform triangulation, obtaining a set of the equilateral triangles possible and works in any dimensions. However, we used it in two dimensions due to our applications working process. In two dimensions, it is not hard to understand why: the Delaunay triangulation of a vertex set maximizes the minimum angle among all possible triangulations of that vertex set.

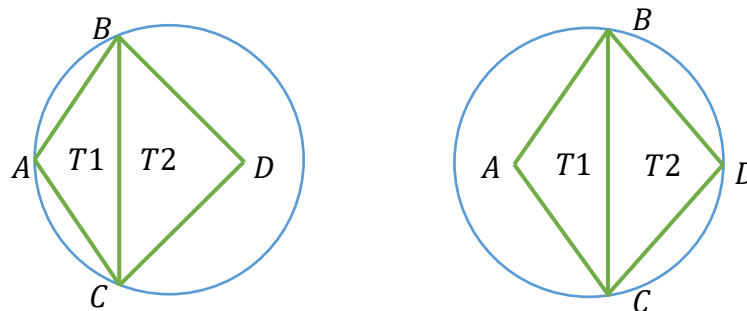
In mathematics and computational geometry, a Delaunay triangulation for given set  $P$  of discrete points in a plane is a triangulation  $DT(P)$  such that no points in  $P$  is inside the circumcircle of any triangle in  $DT(P)$ . Delaunay triangulations maximize the minimum angle of all the angles of the triangles in the triangulation; they tend to avoid sliver triangles. The triangulation is named after Boris Delaunay [28] for his work on this topic from 1934.

The fundamental property is the Delaunay criterion. In the case of 2D triangulations, this is often called the empty circumcircle criterion. For a set of points in 2D, a Delaunay triangulation of these points ensures the circumcircle associated with each triangle contains no other point in its interior. The property is important. In Figure 11, the circumcircle associated with  $T1$  is empty. It does not contain a point in its interior. The circumcircle associated with  $T2$  is empty. It does not contain a point in its interior. This triangulation is a Delaunay triangulation. On the other hand,  $BC$  edge is called ‘legal’ when starting from the edge in question and the two triangles which it belongs to, the circumscribed circumference to one of the triangles does not contain the remaining point that belongs to the other triangle, and vice versa.



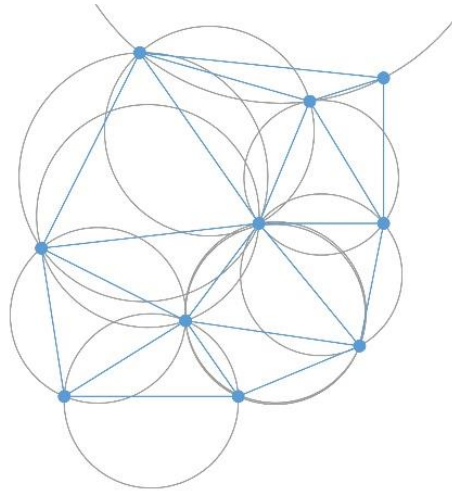
**Figure 11: Example of triangulations that fulfilled the criterion**

On the other hand, Figure 12 shows the reverse example from the previous one. The circumcircle associated with  $T1$  is not empty. It contains  $D$  in its interior. The circumcircle associated with  $T2$  is not empty. It contains  $A$  in its interior. This triangulation is not a Delaunay triangulation.



**Figure 12: Example of triangulations that could not fulfill the criterion**

Delaunay triangles are said to be “well shaped” because in fulfilling the empty circumcircle property, triangles with large internal angles are selected over ones with small internal angles. The triangles in the non-Delaunay have sharp angles at vertices  $B$  and  $C$ . If the edge  $\{B, C\}$  were replaced by an edge joining  $A$  and  $D$ , the minimum angle would be maximized, and the triangulation would become a Delaunay triangulation. Also, the Delaunay triangulation connects points in a nearest-neighbor manner. These two characteristics, well-shaped triangles, and nearest-neighbor relation, have important implications in practice and motivate the use of Delaunay triangulations in scattered data interpolation. In our applications, while refining image by adding a new point, because of well-shaped triangles, the refined image became more recognizable and accurate.



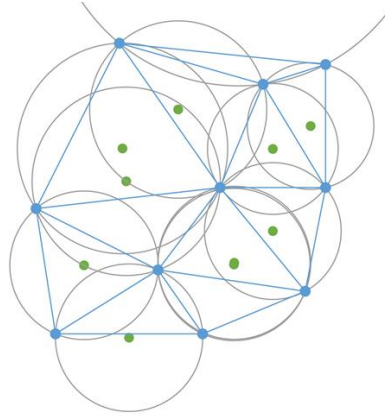
**Figure 13: A Delaunay triangulation in the plane with circumcircles shown**

For a set of points on the same line there is no Delaunay triangulation. For four or more points on the same circle (e.g., vertices of a rectangle) the Delaunay triangulation is not unique: each of the two possible triangulations that split the quadrangle into two triangles satisfies the “Delaunay condition”, i.e., the requirement that the circumcircles of all triangles have empty interiors.

By considering circumscribed spheres, the notion of Delaunay triangulation extends to three and higher dimensions. Generalizations are possible to metrics other than Euclidean distance. However, in these cases a Delaunay triangulation is not guaranteed to exist or be unique.

### 3.1.2. Voronoi diagram

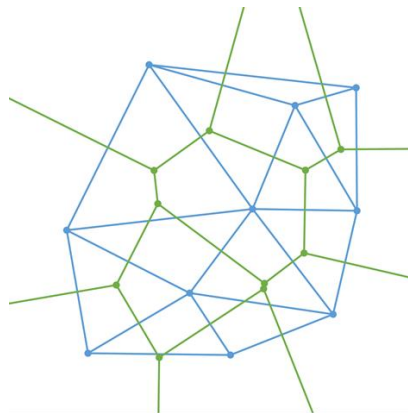
The Delaunay triangulation of a discrete point set  $P$  in general position corresponds to the dual graph of the Voronoi diagram for  $P$ . The circumcenters of Delaunay triangles are the vertices of the Voronoi diagram. In the 2D case, the Voronoi vertices are connected via edges, which can be derived from adjacency-relationships of the Delaunay triangles: if two triangles share an edge in the Delaunay triangulation, their circumcenters are to be connected with an edge in the Voronoi tessellation.



**Figure 14: The Delaunay triangulation with all the circumcircles and their centers (in green).**

Special cases where this relationship does not hold, or is ambiguous, include cases like:

- Three or more collinear points, where the circumcircles are of infinite radii.
- Four or more points on a perfect circle, where the triangulation is ambiguous, and all circumcenters are trivially identical.
- Edges of the Voronoi diagram going to infinity are not defined by this relation in case of a finite set  $P$ . If the Delaunay triangulation is calculated using the Bowyer–Watson [29, 30] algorithm then the circumcenters of triangles having a common vertex with the "super" triangle should be ignored. Edges going to infinity start from a circumcenter and they are perpendicular to the common edge between the kept and ignored triangle.

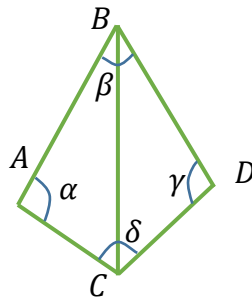


**Figure 15: Connecting the centers of the circumcircles produces the Voronoi diagram (in green).**

### 3.1.3. Flipping operation

From the above properties an important feature arises: Looking at two triangles  $ABC$  and  $BDC$  with the common edge  $BC$  (Figure 16), if the sum of the angles  $\alpha$  and  $\gamma$  is less than or equal to  $180^\circ$ , the triangles meet the Delaunay condition.

This is an important property because it allows the use of a flipping technique. If two triangles do not meet the Delaunay condition, switching the common edge  $BC$  for the common edge  $AD$ .



**Figure 16: This triangulation does not meet the Delaunay condition (the sum of A and D is bigger than  $180^\circ$ )**

This operation is called a flip, and can be generalized to three and higher dimensions. In this way, if a triangle is non-Delaunay, we can flip one of its edges. This leads to a straightforward algorithm: construct any triangulation of the points, and then flip edges until no triangle is non-Delaunay. Unfortunately, this can take  $\Omega(n^2)$  edge flips. While this algorithm can be generalized to three and higher dimensions, its convergence is not guaranteed in these cases, as it is conditioned to the connectedness of the underlying flip graph: this graph is connected for two dimensional sets of points but may be disconnected in higher dimensions.

The Delaunay triangulation can be generated by several different algorithms found in the literature, each one with a specific approach. Some of these algorithms are: Bowyer-Watson [29, 30], Incremental [31, 32], Divide-and-Conquer [33], Fortune [34] and Brute Force [35]. This work describes the Incremental algorithm, which presents a time complexity of  $O(n \log n)$  as an upper bound for the running time of the algorithm with an input dataset of size  $n$ .

### 3.1.4. Incremental Point Insertion in Delaunay triangulation

The incremental Delaunay triangulation computes the triangulation building an initial triangle with three points of the triangulation and then adding the remaining points. When adding a new point new triangles are created and it is necessary to check if those new triangles fulfill the Delaunay triangulation conditions; if they do, then it continues inserting the next point; if not, it is necessary to flip some edges of the triangulation and then continue with the next point. Because of our applications' changeable property, we used a Delaunay triangulation algorithm with incremental insertion. This algorithm's computing time makes our application work robustly in a real-time.

#### Point Location

Two general approaches to point location techniques are most widespread and the performance of the incremental insertion algorithm strongly depends on the used point location technique. The more complicated one uses sophisticated data structures and usually achieves better results in the field of time complexity and overall performance (in 2D we can expect time complexity of  $O(\log n)$  per point and memory complexity of  $O(n)$  where  $n$  is the total amount of points in the triangulation). On the other hand, these structures are not very well suited for time-dependent triangulations because changes in the tree-like (or even more complicated) hierarchies are nontrivial. For this reason, it will not be described. Details on these data structures may be found in [32, 36] and many others.

The walking algorithms represent an easy-to-implement and very popular way of point location. Because they do not depend on any additional data structures, the modification of the triangulation as a result of the movement does not represent a problem. The principle of walking algorithms is that the triangle containing the searched point is found by visiting a random triangle at first and then searching for which of the neighbors of the currently visited triangle is nearest to the searched point. The search may be performed in various different ways, which may be found for instance in [36]. Depending on the strategy for searching for the first random triangle and the used walking strategy, the point location may vary from  $O(n^{1/2})$  to  $O(n^{1/3})$  per point location in 2D case.

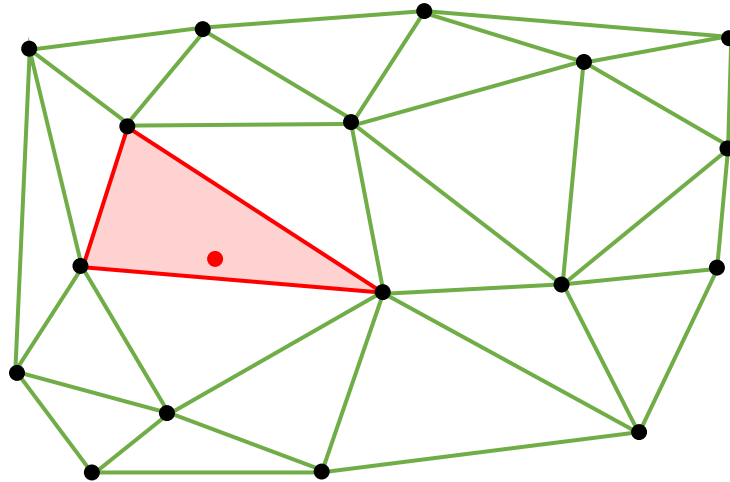
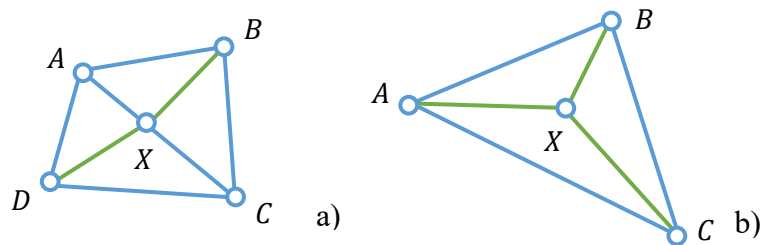


Figure 17: Point insertion

### Point Insertion and Edge Legalization

When a point is inserted into the triangulation, two cases may occur in 2D. It is either inserted into an interior of a triangle or on an edge (we will further ignore the singular case, where two points are identical and thus the inserted point lies on a vertex of the found triangle). Figure 18 shows both cases (with  $X$  being the inserted point).



**Figure 18: Triangle splitting in the creation of Delaunay Triangulation via incremental insertion. Case a) shows the situation when the inserted point lies on an edge common to two triangles, case b) shows the way of splitting a single triangle that contains the inserted point.**

There exist more cases in 3D, which are generally more complicated to handle. These cases include the point being inserted on an edge or face of a tetrahedron and are described for instance in [37].

As displayed in Figure 18, if the point is being inserted into a single triangle, this triangle is split into three triangles by connecting the newly inserted point to each

of its three vertices, thus creating triangles  $ACX$ ,  $CBX$  and  $BAX$ . If the point lies on an edge adjacent to two triangles, then it is connected to their vertices which are opposite to the edge that contains the inserted point. Note that the inserted point may never lie on an edge of the convex hull of the triangulation structure, because the initial triangle created at the start of the algorithm contains the whole triangulation area and is thus equal to the convex hull of the triangulation.

The newly created edges may not be locally legal in the sense of Delaunay condition, so a legalization step is conducted upon them, which is based on a very similar idea as the Local optimization algorithm above.

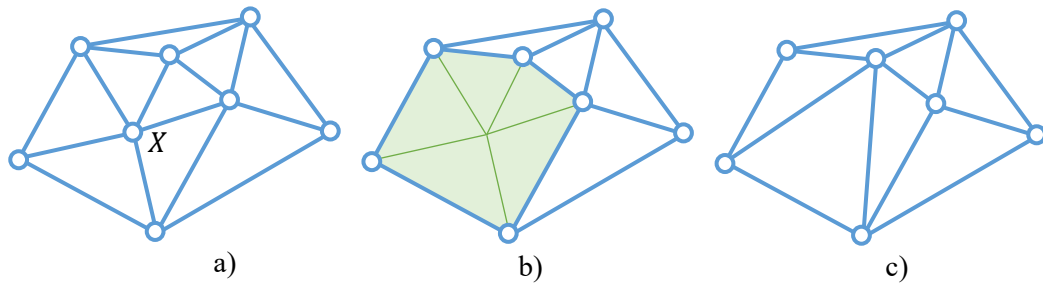
### **3.1.5. Decremental Point Removal in Delaunay Triangulation**

The computation of the Delaunay triangulation of a set  $S$  of  $n$  points in the plane is one of the classical problems in computational geometry. Many structures and algorithms have been proposed in the past to compute Delaunay triangulations. Some of these algorithms have the two following properties: they are incremental, and they do not use complicated data structure in addition to the triangulation itself. Among these algorithms we can cite the historical algorithm of Green and Sibson [38] or some other variants [39, 40, 41]. All walk in the triangulation to accelerate point location.

The advantage of that category of Delaunay incremental algorithm is that they can be easily turned in fully dynamic Delaunay algorithm. Since there is no complicated data structure for point location, the deletion of a point is reduced to the deletion in the triangulation itself.

Due to the fact that some of the algorithms for the kinetic Delaunay triangulation directly use a removal of points from the triangulation, and other may take advantage of this possibility, it will be useful to describe one version of this algorithm (proposed by Devillers in [42]).





**Figure 19: Removing point P from the triangulation.**

Let us have Delaunay triangulation  $DT(P)$ . If we want to remove the point  $X$  from the triangulation, we have to remove all the triangles sharing this point as a vertex. By removing these triangles, a hole is created in the triangulation. This hole defines a star-shaped polygon, which has to be retriangulated (the changes in the triangulation are strictly local and limited to this polygon, no other triangles in the triangulation will be affected by the point deletion). The whole process is illustrated in Figure 19.

Using this test, we are able to determine if the three tested points lie on a line, are oriented clockwise or are oriented counterclockwise. Details of the test and the priority function may be found in [42]. Briefly, he optimized small degrees when deleting points from triangulation to make this process fast in this work.

### 3.1.6. Summary

The literature provides numerous definitions of the Delaunay triangulation algorithm. Most Delaunay algorithms work robustly. However, in order to delete and add a certain amount of points in real time, it is crucial to select a potential algorithm. We demonstrated the basics of the Delaunay triangulation algorithm, incremental point inspection, and decremental point removal algorithms.

## Chapter 4

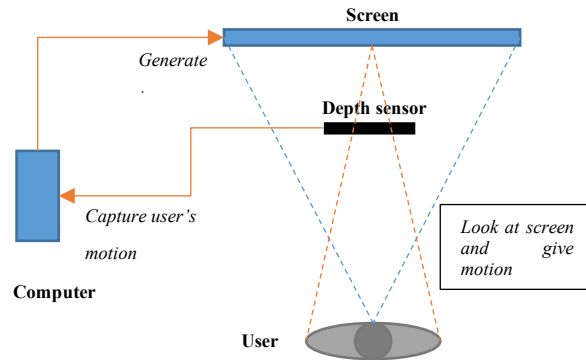
# Triangulation-based image emergence

This chapter presents a brief overview of an interactive entertainment by triangulation-based image emergence. We created this installation to measure the effect of the Delaunay triangulation algorithm on image application. It was our 1<sup>st</sup> attempt to show a possibility of a generative art algorithm. This entertainment application gives a user an enjoyment by showing a triangulation-based changeable image that approximates an original image using a Delaunay triangulation algorithm. The detail of the original image gradually emerges in the triangulation-based image interactively by the user's body motion. The user can enjoy it by imagining what the original image contains. We propose three types of applications. Generally, a depth sensor captures the motion of a user. Then, a triangulation-based image is generated from the original image according to the user's motion and projected onto the screen in front of the user by a projector. We used a Kinect sensor as the depth sensor (Figure 20).

### 4.1. Overview

In this work, an original image is approximated by a triangulated image, whose LOD (Level Of Detail) is controlled by the motion of a user's hands. The user can interactively enjoy imagining what the original image contains. The LOD control

of a triangulation is done by incremental and decremental Delaunay triangulation algorithms. We have developed three types of applications, that is, a basic application, an extended application with moving points, and an extended application with moving triangles. Each application has LOD and it is controllable by hand movement. Those applications' preparation process is the same but is shown to the users differently.



**Figure 20: Triangulation-based image emergence system**

In all of these applications, the user interacts with the screen to make image finer on the screen. Each application, we used one original image, and participants are given tasks to refine the coarser image until it becomes recognizable in a certain time. In real-time, because all of those images are changeable, participants have to move fast to know the real image. Each application looks different cause of its effects. And then they had to judge which is good or bad. We aimed to know this kind of changeable concept is useful or not in the interactive installation. Moreover, we wanted to know whether the generative artistic algorithm: Delaunay triangulation is usable on this kind of application or not useful.

#### 4.1.1. Preparation stage

In this stage, we generated points using the original image before Delaunay triangulate them. When we used a randomly generated image it looked coarser. We inspected that a triangulated image used random points is hard to recognize and understand the goal of this application. Thus, we decided to give slight information about the original image. To give the information, we used an edge detection algorithm [47] to generate points. After we detect the edges from the original image,

we converted to points which able to be triangulated (Figure 21). Each of our parts of this application has this preparation stage, even though these are different from each other. As shown in Figure 21, Delaunay triangulated image looks more recognizable. When system is decreasing the points from the edge of the image, those points able to adjustable. On the other hand, we can change the points' count as we want.

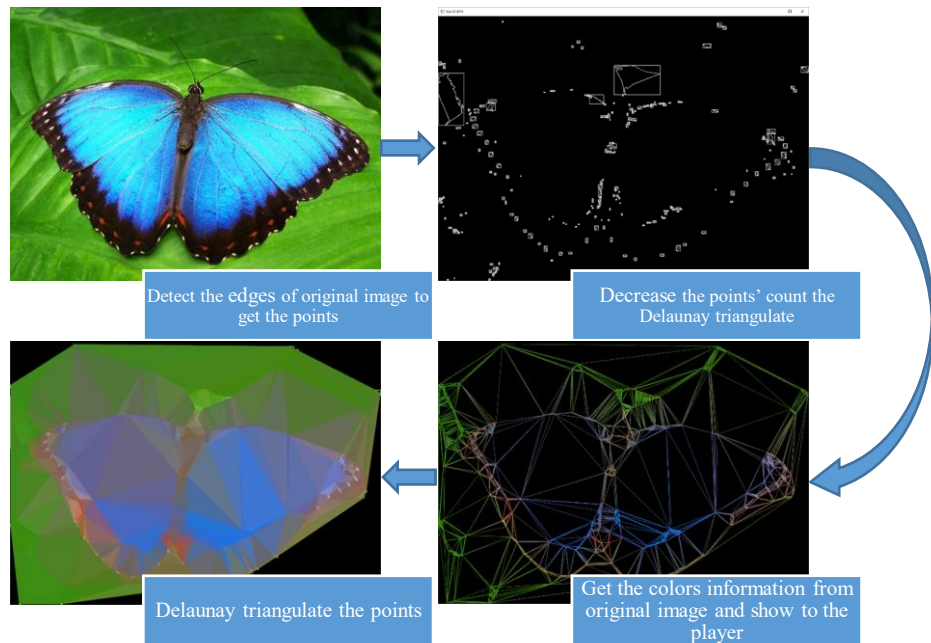
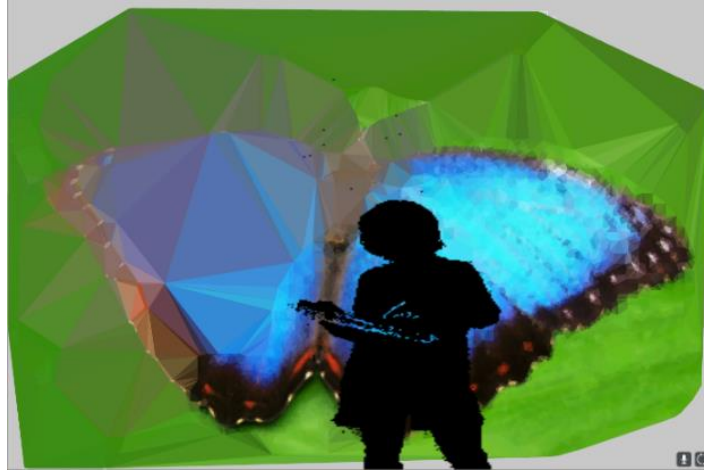


Figure 21: A preparation stage from an original image to a triangulated image

#### 4.1.2. Interactive LOD control of triangulated image

In the interaction stage, first, the initial triangulated image is shown to a user. Then, the interaction by the user starts. The motion of the user's hands captured by a depth sensor changes the triangulated image, which results in controlling the level of detail (LOD) of the image interactively, as shown in Figure 22, as follows.



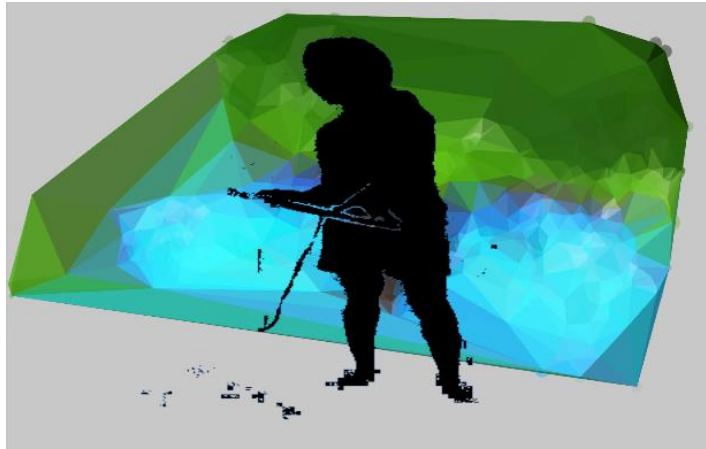
**Figure 22: Interactive LOD control in our basic application.**

The image plane of the sensor is mapped to the image plane of the triangulated image. Thus, the position of the hand captured by the sensor is mapped to the position on the triangulated image. The user moves the hand in the region of interest on the triangulated image. Then, new points are added in the region, and the triangulation is updated to be finer locally around the region by the incremental Delaunay triangulation algorithm. This results in making the triangulated image finer so that the user can obtain more detailed information to imagine the original image. As more points are added, the triangulated image approaches the original image. However, each added point has a lifetime, and the point is deleted after the time. This makes the triangulated image coarser, and makes the user's imagination for the original image harder. The shorter the lifetime is, the sooner the triangulated image returns to the initial one. Thus, the user cannot keep a detailed triangulated image, which makes our application interesting. The user can enjoy imagining what the original image contains by moving hands all over the triangulated image as if to wipe a misted glass window to see an outside scene.

### **4.1.3. Triangulated image with moving points**

This application makes each point added by the user's interaction constantly move slightly around its initial position. This makes an active impression such that a resulting triangulated image seems as if it were alive. An execution example is shown in Figure 4. In this example, each triangle is given the average color from its

three points, which makes the user feel the activeness more effectively. As shown in this example, the silhouette of the user can be optionally displayed.



**Figure 23: Our application with moving points**

This application has a serious problem, which is caused by the high computing load of the Delaunay triangulation algorithm. In order to realize the above, a triangulation has to be always updated for new positions of constantly moving points. This consumes lots of computing time. The update speed gets lower as the number of points increases. This makes the motions of the points slow, which results in degrading the attractiveness by moving points. To make matters worse, the increase of points delays the addition of new points by the user's interaction. This results in degrading the interactivity and the real-time performance of our application. Afterward, we fixed this problem by improving point deletion algorithm (Chapter 3.1.5).

#### **4.1.4. Triangulated image with moving triangle**

The third application produces an impressive 3D effect. In this application, an initial triangulation made in the preprocessing stage is kept in the interaction stage without updating it by adding and deleting points. In the preprocessing stage, each triangle in an initial triangulated image is given 3D coordinates to become a 3D triangle. At the beginning of the interaction stage, all the 3D triangles constitute a plane and are displayed in gray color on the screen. This gives a user a feeling that there seems to be nothing. Afterwards, when the user moves hands over the screen, the 3D triangles touched by the hand appear in their own colors obtained from the original

image as described in section 3.3. Besides, the colored 3D triangles move with 3D rotation in the direction of the hand motion. An execution example is shown in Figure 5. In this example, each triangle is also given the average color from its three points, and the user's silhouette is optionally displayed. This application gives the user an impressive 3D feeling.



**Figure 24: Our application with moving triangles.**

If possible, it is desired that this application updates the triangulation to be finer and coarser by the user's interaction as well as the previous applications. As a result, the visual effect caused by the interactive LOD control of 3D triangles with 3D rotation arouses the user's great interest. Nevertheless, it is practically difficult because of its time-consuming computation. In our next application, we improved this problem.

## 4.2. Questionnaire

As our aim was to measure effectiveness of Delaunay triangulation on other application, we implemented a three kind of applications. Through the implementation of those applications, we were able to measure its effectiveness.

The participants were asked questions we prepared. From the first experiment, we aimed to measure possibility of generative algorithm which is the Delaunay triangulation. Our three-application result are demonstrated in chapter 4.3.

Q1: “How interesting were these applications?” - Score 5 means “interesting” while score 1 means “boring”

Q2: “After finished playing the applications, how tired were you?” - Score 5 means “tired” while score 1 means “not tired”

### 4.3. Result of questionnaire

The result of the questionnaire survey is shown in Figure 25. From the result of Q1, most participants felt that all of the three applications were interesting. In particular, they felt that the third application “triangulated image with moving triangles” was the most interesting. On the other hand, they felt that the first application “interactive LOD control of triangulated image” was less interesting than the others. The first application provides the most essential property realized by the update of the LOD of a triangulated image. However, in the first application, the elements of the image, that is, points and triangles do not move. Therefore, most of the participants might have difficulties to understand the essence of the application.

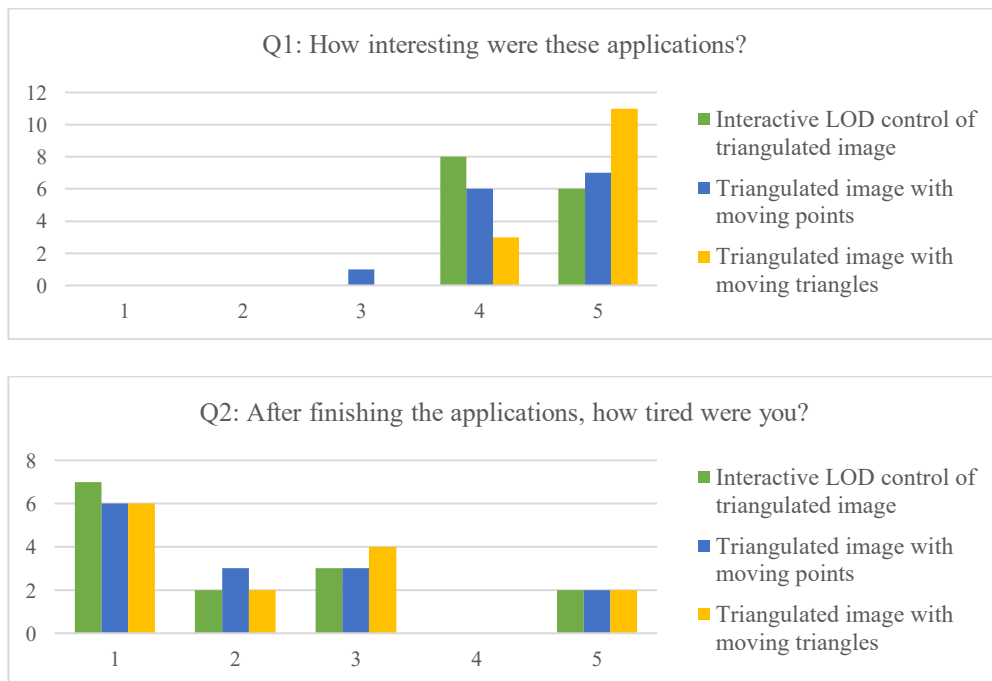


Figure 25: Result of questionnaire survey

On the other hand, the third application provided enjoyment by not only the movement of elements but also an impressive 3D effect. The main purpose of Q2



was to measure how much a participant felt interesting and concentrated upon the applications. The result of the questionnaire does not show clear differences for the three applications. However, the third application gave slightly more tiredness than the other applications. Based on this result, we developed our next game application which works in a real-time. Next chapter, we will explain our last application more.

## Chapter 5

### Object identification in a triangulated image

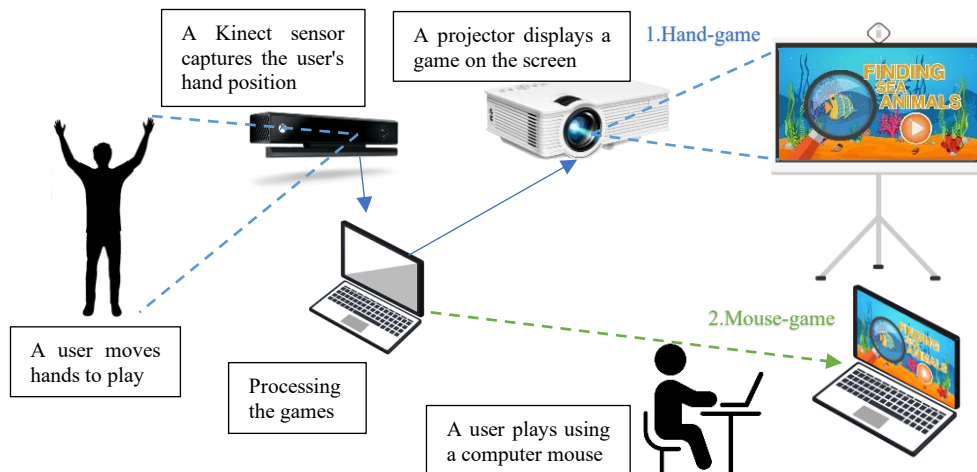


Figure 26: Application environment

Here we demonstrate the "Study on Wiping Operation to Accelerate Human Activities on Hidden Object Game," our last experiment. We proposed a wiping operation on the Hidden Object Game. We took this experiment based on our previous experiment (Chapter 4). In order to improve our application, we made some comparisons between the existing Delaunay triangulation algorithms. Thus, in this work, we expanded our application into the interactive game installation on the wall and personal computers. In the hand game, participants are given a task to find an object using their hand movement. To find the given items, they must move their hands to refine the triangulated image. In addition, participants must move the

mouse on the computer screen in the mouse game. We measured the wiping operation's efficiency both objectively and subjectively. Furthermore, this chapter will explain our entertainment game applications in detail.

## **5.1. Overview**

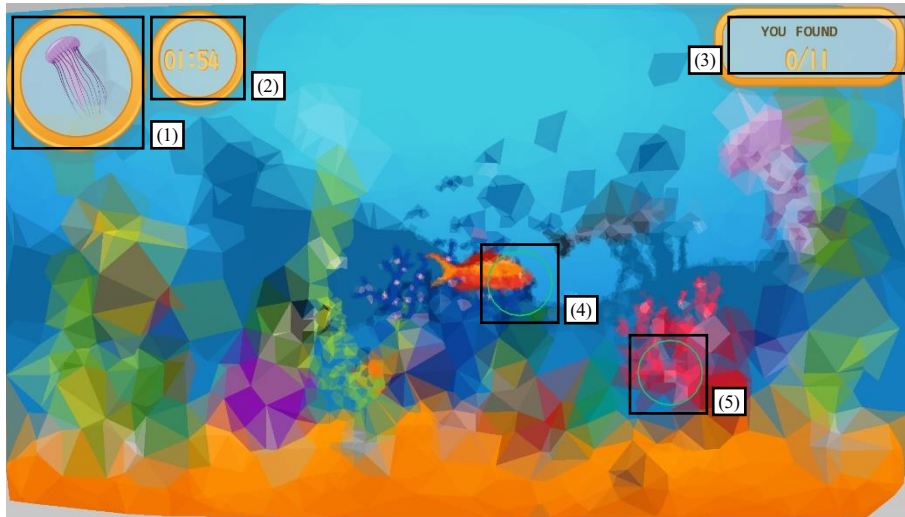
Hidden object games (HOG) are a subgenre [43, 44] of casual gaming. In HOG, a player must find objects that are hidden within a scene by a given hint. The hint is often the names of the objects. The games have a repetitive play, predictable storylines, enjoyments, etc. Aesthetical image composition and mysterious stories are used to make an HOG enjoyable. Therefore, exploring the efficiency of game effects on HOG is required to make an enjoyable HOG.

Measuring game enjoyment is a complicated task in the game research field. Some researchers correlated brain activity data and questionnaire data [45, 46]-to measure game enjoyment. Thus, using brain activity data by electroencephalographic (EEG) system proved to evaluate a game enjoyment. If player's brain is active, the game enjoyment is higher [45]. Then, if some human operation to accelerate brain activity is able to introduce on HOG, its operation becomes effective operation to enjoy HOG.

In this work, we proposed a new wiping operation on an HOG. The wiping operation is applied to a triangulated scene image in which a player finds objects. This operation activates human brain and gives a player great enjoyment. To verify the effectiveness of the wiping operation, a brain sensor is used to measure a player's brain activity.

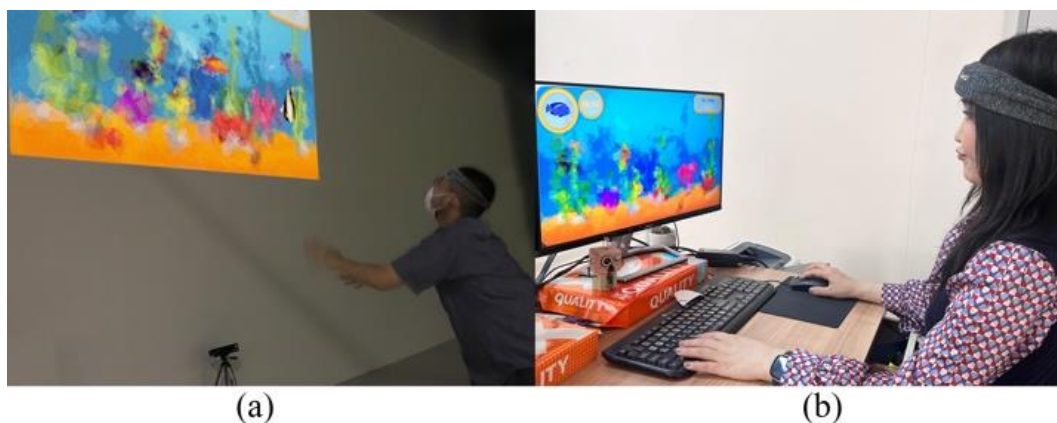
We implemented an interactive entertainment application based on the concept of generative art (Chapter 2.1). Our application showed a user a triangulated image generated from an unknown original image, which gives the user an enjoyment to imagine what the original image contains. The triangulated image is becoming finer and rougher by the user's hand motion interactively using efficient Delaunay triangulation algorithms. The user can see the detail of a desired area on the image by moving hands over the area as if to wipe a misted window to see an outside scene

clearly. We enhance its “game” enjoyment by making the user find queried target objects from the triangulated image. The triangulation process of our game is shown in Figure 33. Our main playing interface has 4 main components: time indicator, object counter, hand position coordinates and target image as shown in Figure 27.



**Figure 27: Game interface (1) A target object to find (2) Time indicator (3) Counter of found objects (4) and (5) represent left and right hands respectively**

We developed our game in two environments: *hand-game* and *mouse-game*. In *hand-game*, an image is projected on a wall, and a player plays by moving hands in front of the wall. The player's body movement is captured by a Kinect sensor, as shown in Figure 28(a). In *mouse-game*, a player plays a game on a personal computer by holding a computer mouse, as shown in Figure 28(b).



**Figure 28: Game environments (a) Hand-game (b) Mouse-game**

To measure brain activity, a player wears a headband with a brain sensor, XB-01 sensor, during game play, as shown in Figure 29. We will describe it and compare both games' results in section 5.2.



Figure 29: XB-01 brain sensor in a headband. A sensor must be placed in the upper area of the left eye.

### 5.1.1. Preparation procedure

To realize the wiping operation, we develop an HOG using a triangulation algorithm [41, 42] on our game as follows:

1. An original image is first transformed into an initial triangulated image. As each triangle is large in the initial triangulated image, it is difficult for a player to distinguish each object clearly.
2. If a player moves hands over the triangulated image during gameplay, the triangulation is refined in real time. Then, it becomes easier to distinguish each object. We call this effect by moving hands *wiping operation*.
3. If the player stops moving hands, the triangulation returns to the initial state gradually.
4. After a certain period, the refined part returns to its initial state. Then, it becomes harder to distinguish each object again.
5. The above 2 and 3 are repeated by the player's hand movement everywhere on the triangulated image.

### Game without wiping operation

In order to evaluate wiping operation, we developed other two games for comparative experiments to the hand-game and mouse-game with wiping operation.

These games also use triangulated images generated from an original image and reconstruct the triangulation. However, the way of the reconstruction is completely different. In these games, the game screen has a refine button. If a player presses the button, the triangulation is refined globally by adding new points randomly over the whole image. After starting from an initial triangulated image, the player can press the button anytime in the playtime and several times. Every button press adds new points, and the triangulation is refined gradually. One button press reduces 5 seconds from the remaining time. The local reconstruction of the triangulation by wiping operation is replaced with the global reconstruction by button press, and other game features are the same as the hand/mouse-games explained previously.

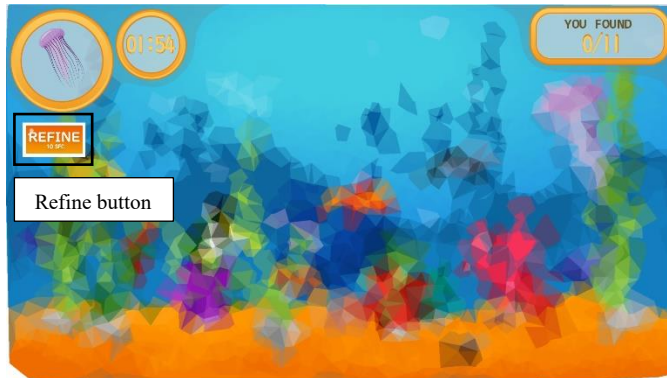


Figure 30: Game interface with a refine button

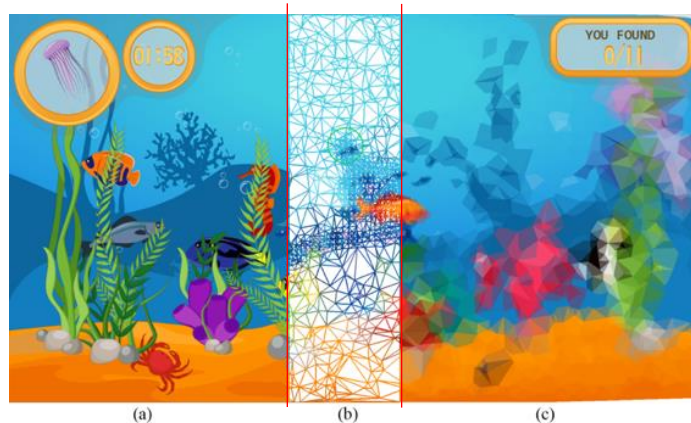
### 5.1.2. Wiping operation

The wiping operation accelerates human activity on HOG. This operation refines the level of detail of a triangulated image by moving hands over the image, that is, wiping the image as if to wipe a misted window to see an outside scene clearer through the window. The refinement is locally applied to only the image part, which a player wiped. If a player moves hands over the image, triangles increase. Then, increased triangles decrease after a certain time. The demonstration of the game process is shown in section 3.2. In the increasing and decreasing progresses, we use incremental and decremental triangulation algorithms that reconstruct triangulation locally in efficient ways.

### 5.1.3. Triangulation procedure

We used triangulation because of the low-cost as compared with other methods such as the blur effect. In other words, when using a blur filter, scaling the area takes more time than the Delaunay triangulation algorithm.

After the game starts, a player first sees the initial triangulated image generated by a Delaunay triangulation algorithm. The positions and kinds of existing objects are not recognizable in the initial triangulated image. During the game play, triangles are increased and decreased in real-time. The color of each triangle of a triangulated image is given by averaging the colors of the positions of the three vertex points on the original image. In Figure 31, (a) represents an original image, (c) shows a triangulated image, and (b) shows the wireframe of the triangulated image.



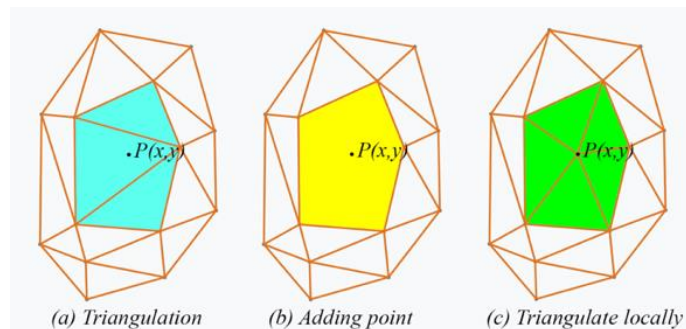
**Figure 31: The triangulation of our game. (a) original image (b) wireframe of triangulation (c) triangulated image after filled triangles**

The initial triangulated image is made using randomly generated  $p=2000$  points. In the image, the position where each object is located is unknown.

If a player moves a hand, basically, 20 points are added in a hand circle, whose center is the position of the hand, in each frame. For example, if the updating rate is 30 frames per second, 600 points will be added per second. If a new point  $P(x,y)$  is added to the triangulation, as shown in Figure 32(b), the triangulation is reconstructed locally, as shown in Figure 32(c). We used an incremental Delaunay triangulation algorithm in this process. Particularly, the simple stochastic walk algorithm [41] is used to obtain the location of the point in the triangulation. If the point already exists on the pixel coordinates  $(x,y)$  where a new point  $P(x,y)$  will be

added, the new point is not added. In this case, less than 20 points are added. If all pixel coordinates in a hand circle are occupied by the existing points, any new points are not added.

The added points have lifetime during which they remain. The added points are deleted after 0.3 seconds from the time when the points were added. In the deletion process, the triangulation is reconstructed using the remaining points by the decremental Delaunay triangulation algorithm, which makes the triangulated image unrecognizable again. When the point  $P(x,y)$  is deleted, shown in Figure 32(c), from the triangulation, the triangulation is reconstructed using local points around the deleted point [42], as shown in Figure 32(a). The efficient local reconstruction in adding and deleting points makes our game lively in real-time.



**Figure 32: Local reconstruction of triangulation**

More points are added if the player moves hands faster. As a result, the player sees a more recognizable triangulated image. In other words, the triangulated image works as an approximation of the original image. The detail of the original image gradually emerges by the player's hand motion, while the detail disappears after the lifetime of each point.

The triangulation is reconstructed repeatedly in real-time whenever points are added and deleted during the gameplay. The initial points are not deleted, which means that the initial triangulated image is recovered after adding no points for a longer time, as shown in Figure 33(c). An example of rough and fine triangulated images is shown in Figure 33(d). The wireframes of (c) and (d) are shown in (a) and (b), respectively.



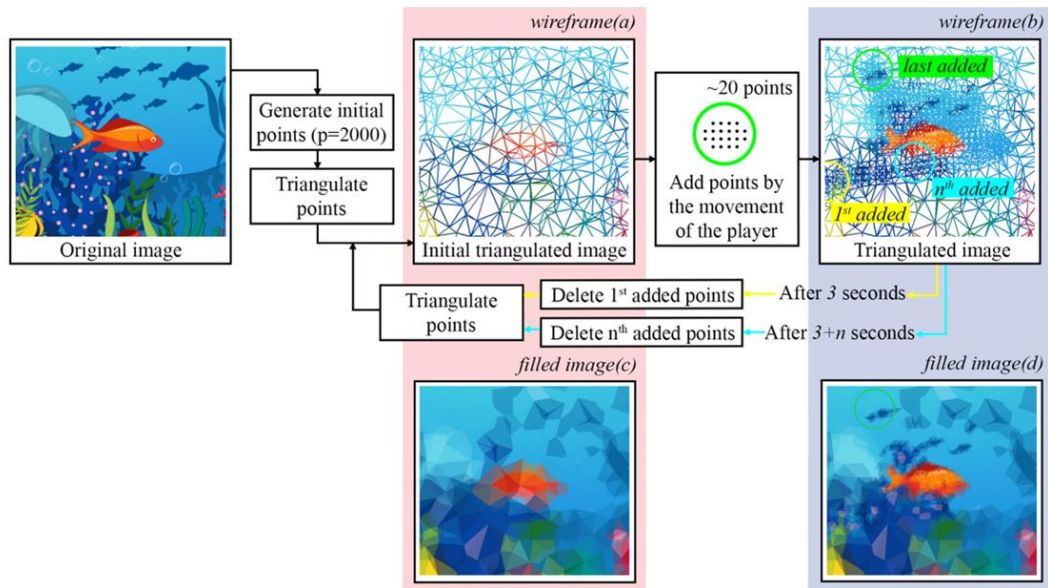


Figure 33: Triangulation process. (a) wireframe of a rough triangulated object (b) wireframe of a fine triangulated object (c) a rough triangulated object (d) a fine triangulated object.

## 5.2. Interface

Generally, we used 2 original images for our game application. Our game application has two levels which are: “with wiping operation”, and “without wiping operation”. The participants can interact with the game with their hands or a computer mouse.



Figure 34: Game starting interface

In the hand game, as grasping their hands, they able to choose a level they want. In the mouse game, they simply click the mouse whichever level they want to play.

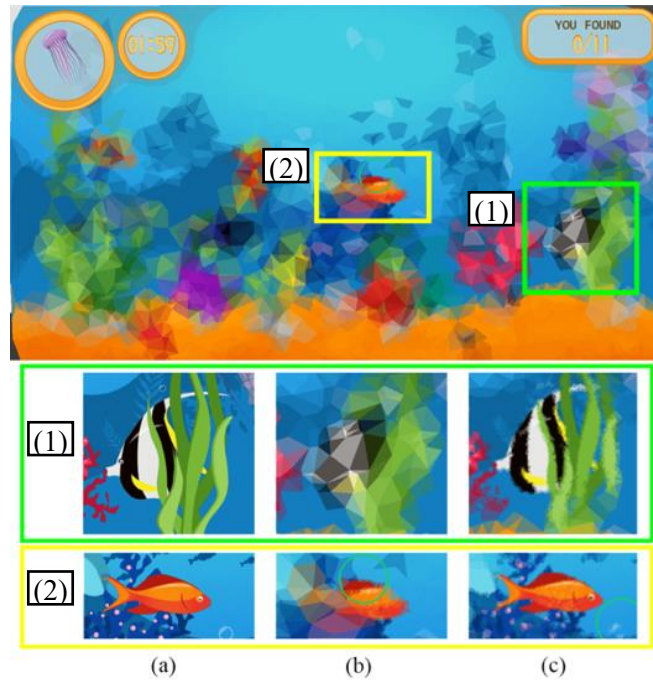
After participants choose the level, they would be given the task to find the object. After they find the object, next task to find the object has given.



**Figure 35: Task window**

After the task had given, they will move as fast as they can to find the objects.

As we demonstrated in chapter 5.1.3, a player first sees the rougher triangulated image where the positions and kinds of objects are unrecognizable. When the player refines the triangulated image, the player can see where and what objects exist. The finer and rougher changes in the level of detail of the triangulation are repeated by the wiping operation of the player during gameplay. Triangulation with fewer points looks rougher and makes objects more unrecognizable. Therefore, a player needs to move hands more quickly to find objects fast. As shown in Figure 36, a finer triangulated image (c) looks more recognizable than a rougher triangulated image (b).



**Figure 36: An example of rough and fine triangulated images. (a) An original image. (b) A rough triangulated image. (c) A fine triangulated image.**

As participants watching target object image, they will find the object to find. Because if object become coarser, the objects would be recognizable for system to identify. For example, from Figure 37 (a) we can see coarser triangulated image.



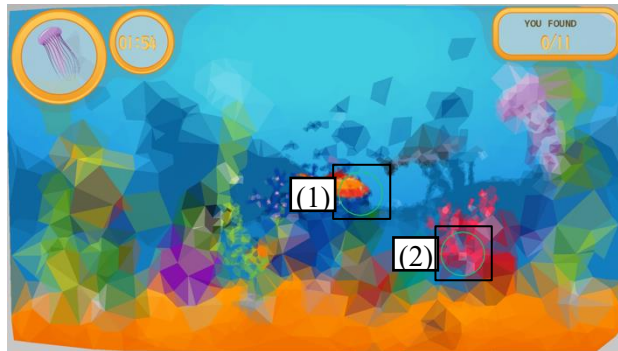
**Figure 37: Playing window. (a) Coarser triangulated image, (b) denser triangulated image.**

### 5.2.1. Hand-game

The game screen is projected on the wall by a projector, as shown in Figure 28(a). A player interacts with a game to find each object, fish, by moving both hands in front of the projected game screen.

First, if a player wants to find an object, fish, the player must refine the image to know where it exists. The player moves hands on a specific image area where the object to find seems to exist, which results in refining the triangulation of the area. The Kinect sensor captures the hands' motion, and approximately 20 points are added to each hand position as described in Section 3.1. In the game screen, the positions of the hands are represented by green circles, as shown in Figure 38. If the player wants to find an object, the player needs to move hands faster and not stop.

Second, if the player thinks that the object has been found on a certain position, the player grips a hand on the position as if to grab a real fish. The player can grip each hand.



**Figure 38: Interface of hand-game. Green circles (1) and (2) represent left and right hands respectively**

### 5.2.2. Mouse-game

The game is playable by a mouse on a computer screen, as shown in Figure 28(b). The green circle represents a mouse position, as shown in Figure 39.

First, if a player cannot recognize the object to find, the player moves the green circle by moving the mouse over the image area in which the object seems to exist. While the player moves the green circle, approximately 20 points are added around the green circle.

Secondly, if the player thinks the object has been found on a certain position, the player clicks the left button of the mouse on the position. If the object does not exist in the position, 5 seconds are reduced from the remaining time.

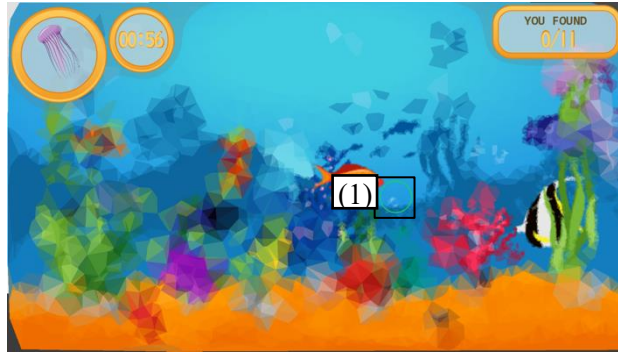


Figure 39: Interface of mouse-game. Green circle (1) represents a mouse position

### 5.3. Experiment

We did an experiment to investigate the performance of our new action, wiping operation, by showing how it accelerates human activities on our hidden object game.

We did a survey for 26 players after playing the game. Among them 16 players played the mouse-game while 10 players played the hand-game. 22 players were students aged between 16 and 25, and 4 players were aged between 25 and 36.

We asked the following questions to measure the player's gaming skills. Table 1 shows that 22 players answered they play games frequently: a month (7), a week(10), and daily(5). Approximately 84% of the players have game enjoyment in daily life.

Table 1. Result of the Question “How frequently do you play games?”

Frequency of playing game	Player
Daily	5
Several times a week	10
Several times a month	7
Several times a year	2
Not at all	2

Table 2 shows the players' desire for game playing. 21 players, that is, approximately 80% of the players like to play games. This result implied the players have a taste of game to measure its enjoyment.

**Table 2. Result of the Question “Do you like to play video and/or computer games?”**

	Very much	Somewhat	Not really	Not at all
Players	7	14	4	1

The last question was asked to measure the player’s experience in a hidden object game. Only 2 of the players had never tried this type of game before.

Overall, the above results showed 26 players had any experience in any type of game, which means they can value game enjoyment.

### Questionnaire

Enjoyment is a commonly stated reason why people play games and why people are active. Therefore, we did a survey using game experience questionnaire, GEQ [21], to measure the enjoyment.

Immediately after the game play, all players completed the GEQ. The questionnaire has 7 factors: *negative affect*, *tension/annoyance*, *competence*, *challenge*, *sensory and imaginative immersion*, *flow*, and *positive affect*. Each factor connected with emotions while players paying the game.

- ***Negative affect***: shame and guilt
- ***Tension/annoyance***: irritation, disappointment, ignorance, and anger
- ***Competence***: accomplishment, euphoria, and pride
- ***Challenge***: challenge, pressure arousal hoping to win
- ***Sensory and imaginative immersion***: sensory immersion, presence and how they absorbed in story, empathy, and identification
- ***Flow***: concentration, being absorbed, flow, loosing track of time, and detachment
- ***Positive effect***: accomplishment, pleasure and relaxation

Each factor consists of 2 questions and there are totally 14 questions as we mentioned in Appendix. The questions measure the player’s feeling statement by five-point scores ranging from 1 (not agreeing) to 5 (strongly agreeing).

**Table 3: Game experience questionnaire**

	<b>Questions</b>	<b>Game factors</b>
1	I was interested in the game's story	<i>Sensory and Imaginative Immersion</i>
2	I felt successful	<i>Competence</i>
3	I felt bored	<i>Negative affect</i>
4	I found it impressive	<i>Sensory and Imaginative Immersion</i>
5	I forgot everything around me	<i>Flow</i>
6	I felt frustrated	<i>Tension/Annoyance</i>
7	I found it tiresome	<i>Negative affect</i>
8	I felt irritable	<i>Tension/Annoyance</i>
9	I felt skillful	<i>Competence</i>
10	I was fully occupied with the game	<i>Flow</i>
11	I felt content	<i>Positive affect</i>
12	I felt challenged	<i>Challenge</i>
13	I had to put a lot of effort into it	<i>Challenge</i>
14	I felt good	<i>Positive affect</i>

## 5.4. Result of questionnaire

Figure 40 shows the questionnaire result of the mouse-game. Each player played both of the mouse-games with and without wiping operation. Then, the player filled in the questionnaire for each game. In Figure 40, for each factor, the scores of all questions of the factor for all players are averaged. As a whole, “negative affect” and “tension/annoyance” are given low scores, which means that the games are given good evaluation. Other factors are given high scores, which are higher than 3. This also means good evaluation. After this, we consider 5 factors other than “negative affect” and “tension/annoyance”. The game with wiping operation is given higher scores than the game without wiping operation for all factors. Especially, “competence” has larger difference, which is approximately 0.66, than

as comparing other factors. The scores of “competence”, “sensory and imaginative immersion”, “flow”, and “positive effect” are more than 4.

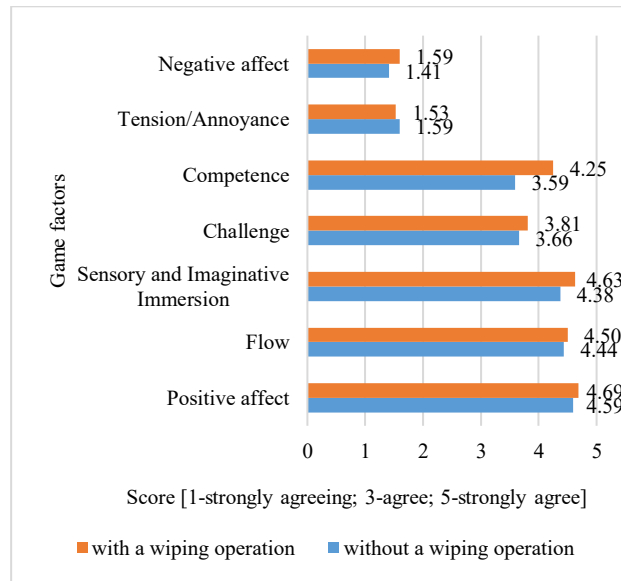


Figure 40: Questionnaire result of mouse-game

Figure 41 shows the questionnaire result of the hand-game. The questionnaire was filled in after the gameplay in the same way as the mouse-game. In the same way as the mouse-game, “negative affect” and “tension/annoyance” are given low scores and other factors are given high scores. This means that our games are given good evaluation. After this, we consider 5 factors other than “negative affect” and “tension/annoyance”. The game with wiping operation is given higher scores than the game without wiping operation for all factors. Especially, “challenge” has larger difference, which is approximately 0.65, than other factors. In the hand-game, the player moves hands actively when moving their body parts. Thus, this play style might make the player improve the challenging spirit [47, 48]. The scores of “sensory and imaginative immersion”, “flow”, and “positive effect” are more than 4.



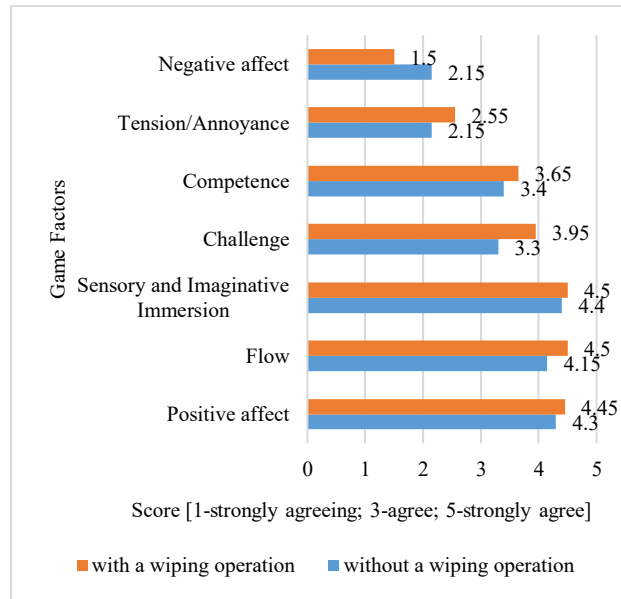


Figure 41: Questionnaire result of hand-game

Comparing Figure 40 with Figure 41, the score of “tension/annoyance” in the hand-game is much higher than that of the mouse-game. In the hand-game, players need to move not only hands but also other body parts. We consider that some players felt tense. Besides, the hand-game uses a Kinect sensor and it sometimes fails to capture a player’s hand motion exactly. In such a case, we consider that the player felt annoyed. In addition, the score of “competence” of the mouse-game was much higher than that of the hand-game. The questions of “competence” ask the players whether they felt skillful and played the game successfully. Considering the play style of the hand-game by capturing the player’s hand motion using a Kinect sensor, the hand-game must be difficult to play successfully than the mouse-game which is controlled easily by a mouse.

To examine the game factor differences between the game without wiping operation and with wiping operation, we conducted the Wilcoxon signed rank test, which is a non-parametric statistical hypothesis test. Test results are shown in Table 4. For the Wilcoxon test, a p-value is a test statistical probability that implies a difference in the data distribution. If the probability is below 0.05, it is indicated that there is a significant difference in data.

Table 4 reveals a significant difference between the game with wiping operation and without wiping operation,  $p = 0.031$ , for the mouse game. This means players

were more likely to enjoy when they were playing a mouse-game with wiping operation. On the other hand, the p-value,  $p = 0.156$ , for the hand-game does not show a significant difference. When some players played the hand-game, the Kinect sensor was out of control when they went far from the play space. We consider that, in such a situation, the players must have been frustrated or irritable. Thus, we infer that the Kinect sensor's response problem was one serious reason for the high score of tension/annoyance factor and made p-value high.

**Table 4. The probability result of questionnaire result**

	Mouse-game	Hand-game
	<i>p</i> value	
Without wiping operation	0.031*	0.156
With wiping operation		

$p < .05$

## 5.5. Brain activity result

During the gameplay, the player wore a headband with a XB-01 brain sensor over the left eyebrow on the forehead. The sensor was connected to an iPhone using Bluetooth for data collection. XB-01 measures real-time brain activity, by blood flow volume during the exercise program. After the gameplay, the application of XB-01 gives us one brain activity value by the score from 0 to 100; 100 means brain activity is the highest while 0 is the lowest.

Figure 42 and Figure 43 show the brain activity result of the mouse-game and hand-game. The horizontal value represents the players' numbers while the vertical value represents their brain activity values. In Figure 42, the game without wiping operation has the maximum 53 and the minimum 18, and the game with wiping operation has the maximum 70 and the minimum 29. Among 16 players, 4 players have higher values for the game without wiping operation, 7 players have higher values for the game with wiping operation, and 2 players have the same values. Among 10 players with higher values for the game with wiping operation, the player 13 has the highest score, 70, in the game with wiping operation, and also has the largest difference, 36, between the games with and without wiping operation. The

player 2 has the second highest score, 62, in the game with wiping operation, and has the second largest difference, 29, between the two games. Among 4 players with higher values for the game without wiping operation, the player 8 has the highest score, 52, in the game without wiping operation, and also has the largest difference, 10, between the two games. As a whole, large number of the players tend to have higher scores in the game with wiping operation, and some players have large differences between the two games.

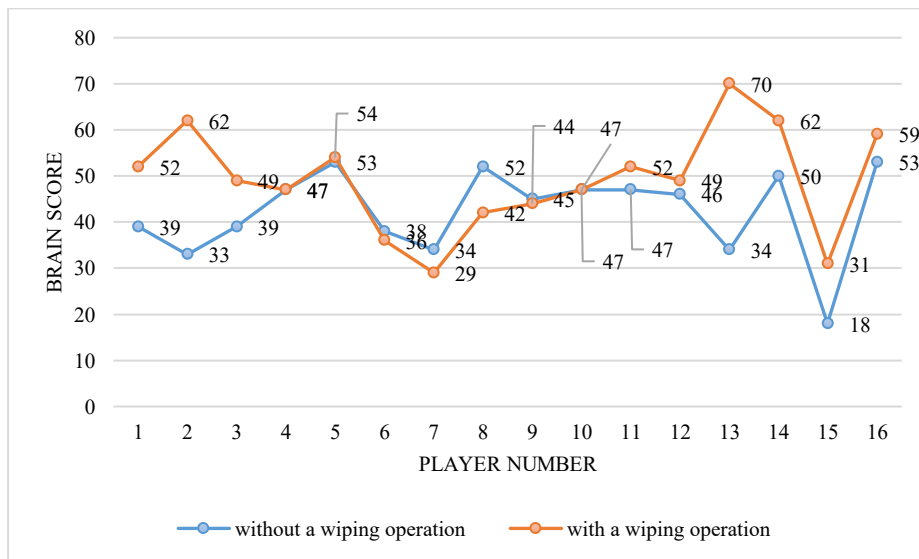
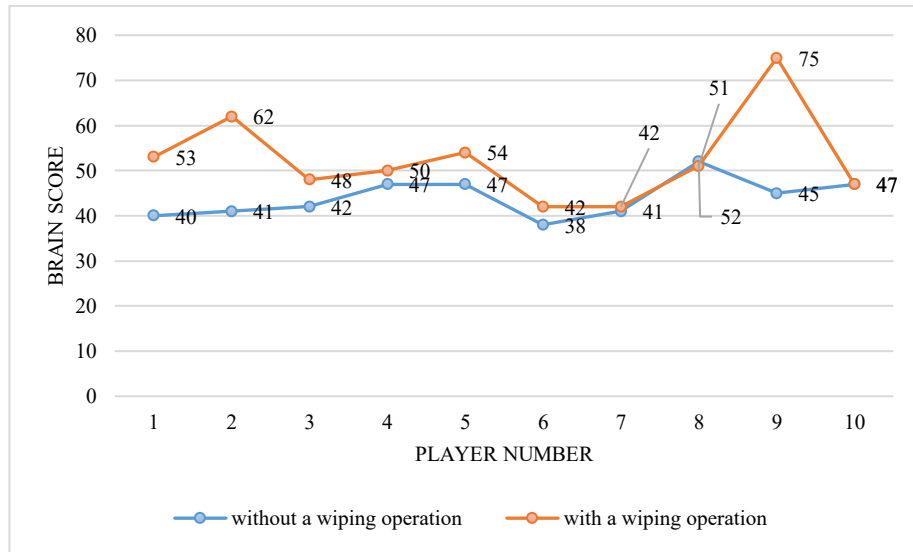


Figure 42: Brain activity result of mouse-game

In Figure 43, the game without wiping operation has the maximum 52 and the minimum 38. The game with wiping operation has the maximum 75, and the minimum 42. Among 10 players, 1 player has higher values for the game without wiping operation, 6 players have higher values for the game with wiping operation, and 1 player has the same values. Among 8 players with higher values for the game with wiping operation, the player 9 has the highest score, 75, in the game with wiping operation, and also has the largest difference, 30, between the games with and without wiping operation. The player 2 has the second highest score, 62, in the game with wiping operation, and has the second largest difference, 21, between the two games. The player 8 is the only player who has higher score, 52, in the game without wiping operation, and the difference between the two games is only 1. As a whole, most of the players tend to have higher scores in the game with wiping operation, and some players have large differences between the two games.



**Figure 43: Brain activity result of hand-game**

Table 5 provides the probability result of the Brain activity. The differences between the game without wiping operation and with wiping operation on both mouse-game,  $p = 0.035$ , and the hand-game,  $p = 0.015$ , are significant because the  $p$ -values are lesser than 0.05. As a result, the wiping operation gave more enjoyment to players while they were playing the game with it. From the questionnaire and brain activity results in the experiment, the wiping operation accelerates human activity and gives more enjoyment to players in hidden object games.

**Table 5. The probability result of brain activity**

	Mouse-game	Hand-game
	$p$ -value	
Without wiping operation	0.035*	0.015*
With wiping operation		

$p < .05$

# Chapter 6

## Conclusion

In this thesis we explored generative art algorithms usage on interactive game. Briefly, we predicted that generative art algorithms help artists and researchers make unique artworks in a real-time application. Both of our works gave a significant result.

We proposed a generative artwork “triangulation-based image emergence” through our first experiment. In this work, an original image is approximated by a triangulated image, whose LOD is controlled by the motion of a user’s hands. The user can interactively enjoy imagining what the original image contains. The LOD control of a triangulation is done by incremental and decremental Delaunay triangulation algorithms. In the first experiment, we have developed three types of applications. This includes a basic application, an extended application with moving points, and an extended application with moving triangles. The second and third applications had a common problem caused by the time-consuming computation needed for our Delaunay triangulation algorithms. Then we aimed to improve deleting amount of points when triangulating the points. From the 1<sup>st</sup> results we understood we can use a Delaunay triangulation algorithm like computer visionary algorithm. Furthermore, we also observed some possibilities of a Generative art algorithms from this work. We also highlight its usage is robust and we can create unique images with generative art algorithms.

In our second game application, we presented the wiping operation to accelerate human activity on a hidden object game. In the games to find objects in a triangulated image by mouse and hands, the wiping operation works well to activate human brain efficiently. By the Wilcoxon test analysis, the brain activity data showed significant differences between both of the mouse and hand games without and with wiping operation and the effectiveness of wiping operation. In addition, the questionnaire result of the mouse-game also showed the effectiveness of wiping operation. However, the questionnaire result of the hand-game was not an expective result mainly due to the limitation of the Kinect sensor's sensing range. Overall, the wiping operation is highly effective on HOG as we hypothesized. In the future, we need to investigate the effect of the wiping operation more. In addition, we are planning to apply the wiping operation to other types of games.

## **6.1. Future works**

Our work clearly have some limitations that when we are working with the vast of points, any kind of operations can take much more time and showed it in Chapter 5.1. Depending on the contents developers or artists should use any other efficient algorithms for improving Delaunay triangulation related contents. On the other result was the study that only 24 subject participated with our study. In the future, we believe that we can get more a precise result by increasing the number of users who play and take a survey.

To further our research, we will take research on the Delaunay Triangulation algorithm's possibility that can work with a vast of points. Moreover, we will consider more algorithmic art usage at the computer visionary fields.

On the other hand, the interactivity of our application is degraded as the number of points to triangulate increases. In order to solve this problem, we need to improve the Delaunay triangulation algorithms and the feature point matching algorithm. The parameters of the automatic object identification have to be given optimal values empirically according to an original image. An efficient way to select the optimal values should be considered. We proposed our application as an entertainment in a large space by projecting the game screen on a large surface such

as a wall. However, our application can be also enjoyed in a small space such as a smartphone and a tablet PC. In such a case, an appropriate interface should be proposed. We are planning to improve our application from the above viewpoints.

Moreover, we predicted more possibilities of generative art algorithms for any kind of entertainment applications. Also it is important to improve user enjoyment for interactive installation games. The enormous variety of generative art algorithms are suitable for any kind of performance genres, interaction aesthetics and immersive technologies provide almost endless potential for creativity and research in future explorations. While examining only a small portion of this intersection, I hope that this research can inspire others to creatively explore the boundaries between generative art and interactive installations.

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