MATHEMATICAL METHODS FOR TEETH DETECTION IN ORAL CAVITY PHOTOGRAPHS

SAKDINEE RATTANA

A Thesis Submitted in Partial Fulfillment of the Requirements for the

Degree of Doctor of Philosophy in Applied Mathematics

Suranaree University of Technology

Academic Year 2021

วิธีการทางคณิตศาสตร์เพื่อการตรวจจับฟันในภาพถ่ายช่องปาก

นางสาวศักดินี รัตนา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต

สาขาวิชาคณิตศาสตร์ประยุกต์

มหาวิทยาลัยเทคโนโลยีสุรนารี

ปีการศึกษา 2564

MATHEMATICAL METHODS FOR TEETH DETECTION IN ORAL CAVITY PHOTOGRAPHS

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Thesis Examining Committee

(Assoc. Prof. Dr. Anirut Luadsong)
Chairperson

(Asst. Prof. Dr. Jessada Tanthanuch)
Member (Thesis Advisor)

(Assoc. Prof. Dr. Eckart Schulz)
Member

(Asst. Prof. Dr. Benjawan Rodjanadid)
Member

(Dr. Amornrat Suriyawichitseranee)
Member

(Assoc. Prof. Dr. Chatchai Jothityangkoon)
Vice Rector for Academic Affairs
and Quality Assurance

(Prof. Dr. Santi Maensiri)
Dean of Institute of Science

ศักดินี รัตนา : วิธีการทางคณิตศาสตร์เพื่อการตรวจจับฟันในภาพถ่ายช่องปาก (MATHEMATICAL METHODS FOR TEETH DETECTION IN ORAL CAVITY PHOTOGRAPHS) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.เจษฎา ตัณฑนุช, 57 หน้า.

คำสำคัญ: ตัวพรางสังวัตนาการ/การวิเคราะห์ภาพทางทันตกรรม/การจำแนกชนิดของฟัน/ขั้นตอนวิธีสันปันน้ำ

วิธีการวิเคราะห์ภาพดิจิทัลหลายวิธีถูกนำมาใช้ในการจำแนกชนิดของฟันมนุษย์ในภาพเชิงทันตกรรม แต่งานเหล่านั้นกระทำบนภาพถ่ายภายในช่องปากที่มีการใช้เครื่องมือช่วยเก็บภาพโดยเฉพาะ หรือภาพเอกซเรย์ฟันเป็นส่วนใหญ่ วิทยานิพนธ์นี้เสนอวิธีการจำแนกชนิดของฟันมนุษย์บนภาพถ่ายช่องปากที่ถ่ายด้วยกล้องโทรศัพท์มือถือสมาร์ทโฟน ขั้นตอนเริ่มจากการถ่ายภาพแบบจำลองทันตกรรมของชุดฟันแท้ Simkit ด้วยสมาร์ทโฟนรุ่น iPhone 7 และได้คัดเลือกมุมถ่ายของแบบจำลองที่เหมาะสม คือกึ่งด้านหน้า-ด้านในของแนวฟันล่างของแบบจำลอง ไปเป็นภาพต้นแบบสำหรับทำการจำแนก จุดประสงค์คือต้องการจำแนกฟันในภาพออกเป็น 4 ชนิด ได้แก่ ฟันหน้า ฟันเขี้ยว ฟันกรามน้อย และฟันกราม ในขั้นตอนการเตรียมภาพ ได้ทำการแยกส่วนของฟันออกจากส่วนอื่น ๆ ของช่องปากที่ปรากฏในภาพถ่าย โดยใช้การวิเคราะห์สีและการดำเนินการเชิงการเปลี่ยนแปลงรูปร่าง จากนั้น ระบบจำแนกฟันอัตโนมัติจึงถูกนำมาใช้ โดยระบบประกอบด้วยสองส่วนคือตัวพรางสังวัตนาการจำแนกฟันกรามน้อยและฟันกราม และขั้นตอนวิธีสันปันน้ำจำแนกฟันหน้าและฟันเขี้ยว ยิ่งกว่านั้นได้มีการแนะนำวิธีการวัดผลการทำงานวิธีใหม่ ใช้ชื่อว่า “อัตราส่วนการคลาดเคลื่อน” ผลลัพธ์แสดงให้เห็นว่าระบบจำแนกฟันอัตโนมัติที่นำเสนอ สามารถตรวจจับและจำแนกฟันทุกชนิดที่อยู่ในแนวฟันได้

สาขาวิชาคณิตศาสตร์	ลายมือชื่อนักศึกษา_______________
ปีการศึกษา 2564	ลายมือชื่ออาจารย์ที่ปรึกษา_______________

SAKDINEE RATTANA : MATHEMATICAL METHODS FOR TEETH DETECTION IN ORAL CAVITY PHOTOGRAPHS. THESIS ADVISOR : ASST. PROF. JESSADA TANTHANUCH, Ph.D. 57 PP.

Keyword: CONVOLUTION MASKS/DENTAL IMAGE ANALYSIS/TEETH CLASSIFICATION/ WATERSHED ALGORITHM

Several methods of digital image analysis are applied for human teeth classification in dental images, but most of these operate on dental mirror intraoral images taken by specialized equipment or on dental x-ray images. This thesis proposes a method for human teeth classification working on images captured by a simple smartphone. The process started from taking pictures of SimKit, the dental model of permanent teeth, by iPhone 7. A suitable view point of the oral cavity model picture, lower arch by frontal-occlusal view, was selected to be the prototype image of the work of classification. The purpose was to classify 4 types of teeth; incisor, canine, premolar, and molar, from that image. First, preprocessing was applied to isolate the teeth parts by image processing techniques, color analysis and morphological operations. Then, an automated system of teeth classification was applied. It consisted of 2 parts: the convolutional masks for inner teeth like premolars and molars, and the watershed algorithm for frontal teeth like incisors and canines. Moreover, a novel accuracy measurement method was introduced, called the "missing ratio". The results show that the proposed method is able to detect and classify all types of teeth in the arch.

School of Mathematics | Student's Signature ____________

Academic Year 2021 | Advisor's Signature ____________

ACKNOWLEDGEMENTS

Years of the Doctorate Degree are full of difficulties and uncertainties. I would not finish them without support from some people. These are people I would like to express my gratitude to, for that they are a part of my thesis completion;

- my advisor Asst. Prof. Dr.Jessada Tanthanuch, for all the advices, helps, and patience,

- people of the School of Mathematics, Institute of Science, Suranaree University of Technology, for their academic support,

- my family - mom Chan and brother Golf (Mei$^+$), for the cheer and faith they have on me all these years,

- also, I wish to send my thank you word to everybody whose path has crossed mine at any points, for the lucks and lessons they shared to me.

Lastly, I highly appreciate the kindness of Her Royal Highness Princess Maha Chakri Sirindhorn, for the scholarship I have been receiving to finish my higher education.

Sakdinee Rattana

CONTENTS

CONTENTS (Continued)

Page

CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

CHAPTER I

INTRODUCTION

1.1 Statement of the problem

Oral health is one of the crucial parts of living a healthy life. We obtain essential nutrients for our bodies by eating everyday, which means we use our mouths every day. Parts of a mouth: teeth, tongue, gum, blood vessels, nerves, etc., can get damaged in several ways such as decay, accidents, or some diseases. One of the most frequent oral problems is the dental caries. It is often suggested that one should go to see the dentist to check the oral health every 6 months. However, checking oral health is a huge workload for dentists. Moreover, with difficulties of access to health checks, especially for people in rural areas, only a small number of people get their oral health checked properly.

Recent technology innovations like digital cameras in smartphones have shone some light on solving accessibility problems. Many models of smartphones have affordable prices to the point that they can be owned by almost everybody, while embedded cameras in them are becoming better day by day. We wished to apply this technology to improve the chance for people to get their oral health checked, by exploring the possibility to work on images obtainable by smartphone.

1.2 Accessibility to medical care/services in Thailand

Pictures of hospitals being overcrowded and stories of someone not seeing their doctors because the hospitals are too far have been a familiarity to Thai people for years. The InfoCenter of National Health Commission Office states at least 3 obvious problems in Thailand's public health system; too many patients in state hospitals, high pricing in private hospitals, and hospitals/healthcare facilities being poorly distributed especially in remote areas (Pinprateep, n.d.). The root of these problems is complicated and it requires solving problems from many ends. One of the proposed ends is the information and communication technology. In fact, the rise of smartphone ownership in Thailand today offers a new way to ease up on the situations in hospitals - telemedicine, with applications designed by hospitals (Donchalermpak, 2020). The problems with telemedicine in Thailand are that

1. it is still a new idea that is not yet well-established,
2. it needs much effort to keep the database in order, and
3. hospitals still develop their applications separately.

1.3 Smartphone technology

A smartphone is a portable device that combines mobile telephone and computing functions into one unit (“Smartphone.”, 2021). The era of smartphones began when the hardware components of both mobile telephones and computers became small enough to be put together into one piece with hand’s size. The term “smartphone” was coined in 1995, but the first model that could ever be called a smartphone is the IBM Simon Personal Communicator, developed by IBM in 1991. The first smartphone designs were heavily influenced by PDAs. Only in the late 2000s did the touchscreen phones emerge. The legendary iPhone was first introduced in 2007 by Apple Computer, and that model has made a huge change on how smartphones look like. Since then, smartphones featuring touchscreens, and also third-party applications, or simply “apps”, have become the standard of smartphones as used today.

1.4 Smartphone cameras

Mobile phones featuring cameras started with a camera phone model Kyocera Visual Phone VP-210, released in 1999. Cameras became popularly integrated into smartphones only around 2010s, but the built-in camera technology has been improving very fast. Smartphone cameras work basically like stand-alone digital cameras, but mostly they improve in the direction of daily-life usage such as capturing human faces, specific object focusing, and landscape light/color adjustment. The recent direction is to work with apps. Some applications require access to the phone cameras to obtain images as data. Examples of these apps are banking apps, text-reading apps, and Google Lens.

1.5 Smartphone ownership in Thailand

ICT household survey reports by National Statistic Office show that the percentage of Thai population aged 6 year-old up (approx. 60-70 millions people) who own smartphones increases almost every year, from 8.0% (5.0 millions) in 2012 to 50.5% (31.7 millions) in 2016 and 69.6% (48.3 millions) in 2018 (National Statistic Office, n.d., Prachatai, 2021). Smartphone technology and quality have improved all the time while also have become more and more affordable. One can find smartphones even cheaper than 3,000 Thai Baht which still support necessary apps like messaging and video-calling apps, state service apps, banking apps, delivery apps, and many other apps which can also include medical service apps in the future.

1.6 Dentistry and teledentistry

Dentistry, also known as dental medicine and oral medicine, is a branch of medicine that consists of the study, diagnosis, prevention, and treatment of diseases, disorders, and conditions of the oral cavity, commonly in the dentition but also the oral mucosa, and of adjacent and related structures and tissues, particularly in the maxillofacial (jaw and facial) area (American Dental Association).

Teledentistry is a combination of telecommunications and dentistry involving the exchange of clinical information and images over remote distances for dental consultation and treatment planning (Jampani, Nutalapati, Dontula, and Boyapati, 2011).

The use of smartphone cameras in dentistry is still rare. To the best of our knowledge, there are no common instructions on how to analyze photographs of the human oral cavity. In fact, the kind and quality of information always depend on those who do the analysis. In this thesis, we began with fixing the kind of information we wanted, to be the types of teeth. Then, we searched for and modified some tools in digital image processing that can classify teeth in the photographs. We wished our proposed system of image analysis to improve the efficiency of dental care with helps from computers in the future, which could especially decrease human workload in image analysis.

1.7 Objective of the study

To survey various tools in digital image processing and develop an image analysis system that can detect and classify individual teeth in photographs of human oral cavity.

1.8 Scope and limitations

1. The image used in this thesis is a photograph taken from a permanent teeth model provided by Institute of Dentistry, Suranaree University of Technology.
2. The photograph used in this thesis is a colored photograph taken by a smartphone model iPhone7.
3. The main objects of interest are teeth on the lower dental arch.
4. Teeth are to be classified into one of four types; incisors, canines, premolars, and molars.

1.9 Expected result

A system of digital image processing tools for teeth classification on the photographs of human oral cavity.

CHAPTER II

LITERATURE REVIEW

2.1 Teeth

2.1.1 Human oral cavity

The oral cavity (mouth) includes the lips, the inside lining of the lips and cheeks (buccal mucosa), the teeth, the gums, the front two-thirds of the tongue, the floor of the mouth below the tongue, and the bony roof of the mouth (hard palate). The area behind the wisdom teeth (called the retromolar trigone) can be included as a part of the oral cavity, but it is often thought of as part of the oropharynx (throat) (The American Cancer Society medical and editorial content team, 2018).

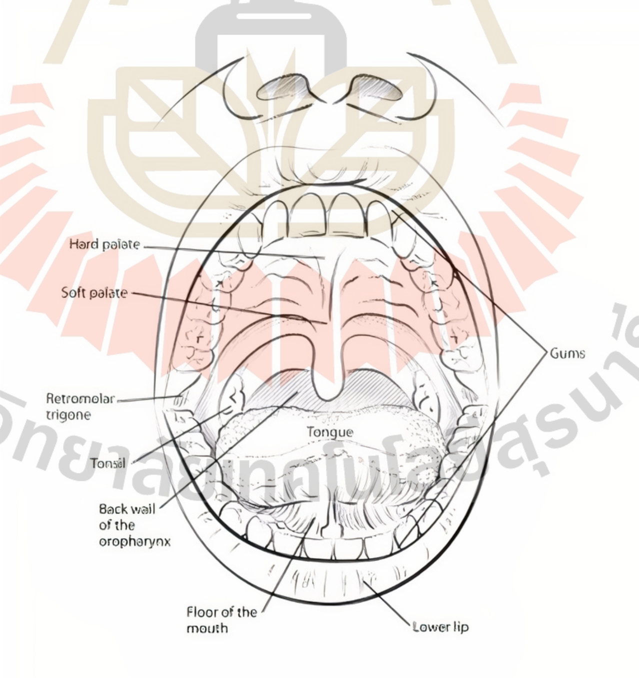


Figure 2.1 Oral cavity.

Source https://www.cancer.org/cancer/oral-cavity-and-oropharyngeal-cancer/about/what-is-oral-cavity-cancer.html.

Oral cavity is the part that intakes food, and the beginning of digestive system. Teeth are the main structure that break down food into smaller particle which are to be digested by the next parts of the system.

2.1.2 Human teeth

Humans have 2 sets of teeth: primary teeth and permanent teeth.

- **Primary teeth** are found in children age from 6 months old to 12 years old. The set consists of 20 teeth.
- **Permanent teeth** are found in people of older age. The set consists of 32 teeth. Usually, permanent teeth appear to be more yellowish than the primary teeth.

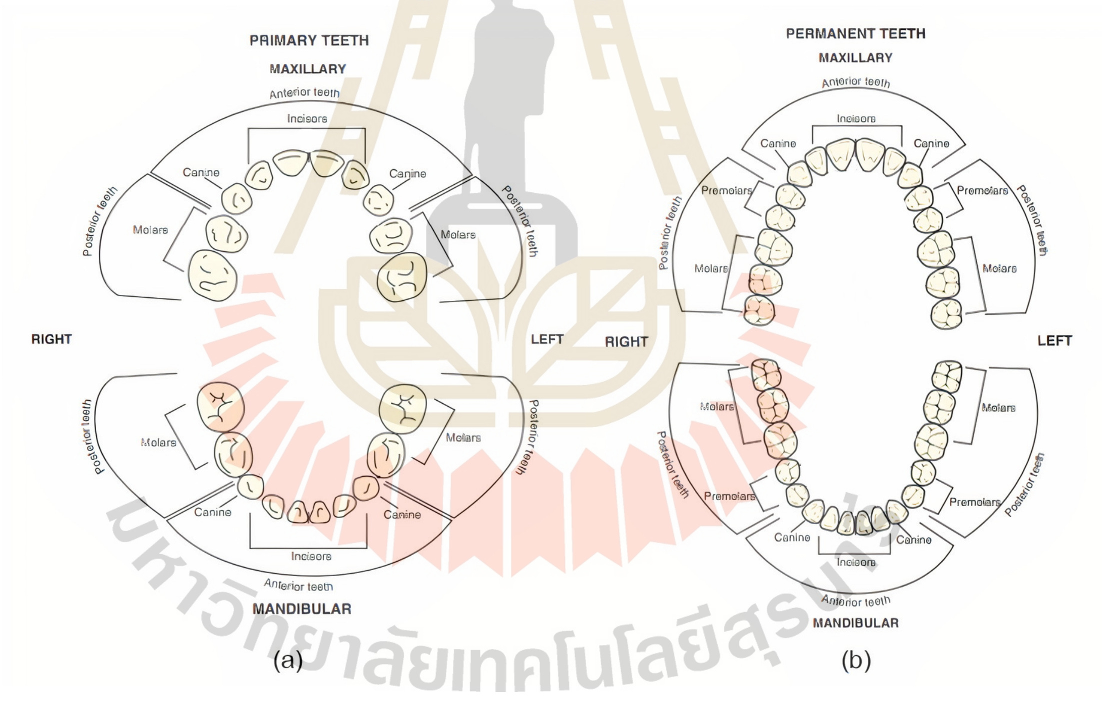


Figure 2.2 Charts of (a) primary teeth, (b) permanent teeth.

Source Woelfel's Dental Anatomy 8^{th} Edition (5-6), by Scheid R.C., 2012, Philadelphia: Wolters Kluwer Lippincott William & Wilkins.

2.1.3 Types of teeth and their functions

Within the set of teeth there are teeth with different shapes that function differently, to break down large food pieces into small enough particles that can be process further by the inner organs in the digestive system. They are

1. **Incisors**: Incisors are the front teeth with thin and flat shape. There are eight of them - four upper and four lower. Their function is to bite into a food piece.

2. **Canines**: Canines are located next to incisors. They shape is sharp like a spike or a cone. There are four of them - two upper and two lower, at the ends of the incisors rows. They tear a food piece apart.

3. **Premolars**: Premolars are located next to canines and can be counted as inner teeth. Each of them has two cusps so they can also be called bicuspids. There are eight of them - four upper and four lower. They help both canines and molars, to tear a food piece and grind it.

4. **Molars**: Molars are at the deepest of the dental arches, next to premolars. Their faces are flatter than premolars' faces and each of them has four or five cusps. They grind food pieces. There are twelve of them - six upper and six lower. Recently, in human evolution, our jaws have become shorter since the food has become softer and the third molars or the wisdom teeth (the ones at the four ends of the dental arches) have become less necessary. People often find that the third molars cause problems and decide to have them extracted or they fall out by themselves.

Figure 2.3 Shapes of teeth.

Source https://www.tindaledental.com.au/the-4-unique-types-of-teeth.

2.2 Photographs in dentistry

In this section, we first survey the use of images in dentistry or dental images, advantages and disadvantages of different types of images, then we look at the possibility to exploit photographs in dentistry.

2.2.1 Dental images

Dental images are images of human oral cavity. There are many types of dental images, from different imaging methods (image sensors). Shah, Bansal, and Logani (2014) gather the imaging methods used in dentistry as follow,

- X-ray
- Cone Beam Computed Tomography (CBCT)
- Magnetic Resonance Imaging (MRI)
- Ultrasound or ultrasonography (US)

These types of dental images are usually obtained by specifically-built devices present only in some healthcare facilities. Their main advantage is precise diagnosis, since the devices can scan through to the underneath tissues and structures. However, their disadvantage is that the devices are difficult to be moved around and they are expensive. This disadvantage suppresses accessibility to the treatment for impoverished people in remote areas, and it leads to the use of the alternative type of dental images - photographs.

2.2.2 Photographs in dentistry

Photographs are mostly used in aesthetic dentistry to track changes of smiles. Photography in dentistry has its own name “dental photography”. Dental photography deals with issues like (digital) camera settings, light settings, view settings, and images as data for further use (consent from patients is needed) (Haddock, Hammond, and Romero, 2018). In dental photography clinics still use stand-alone digital cameras and there is no purpose of image analysis on the images.

2.2.3 Photo views in dentistry

Estai et al. (2017) study the use of smartphone cameras to take photographs of human oral cavity. They make up the list of possible dental views of the oral cavity that can be obtained by smartphone cameras without any helping tools such as retractors and dental mirrors then compare the efficiency of via-photo and face-to-face oral health assessments. The possible dental views they list are

1. Front view
2. Upper occlusal view
3. Lower occlusal view
4. Left lateral view
5. Right lateral view

Further, we will use the same terms in this thesis.

2.3 Image processing

2.3.1 Digital images

A **digital image** is a representation of a real image as a set of numbers that can be stored and handled by a computer ("Digital images." Computer sciences., 2020). In order to translate the image into numbers, it is divided into small areas called pixels (picture elements). For each pixel, the imaging device records a number, or a small set of numbers, that describes some properties of this pixel, such as its brightness (the intensity of the light) or its color. The numbers are arranged in an array of rows and columns that correspond to the vertical and horizontal positions of the pixels in the image.

Mathematically, an image may be defined as a two-dimensional function $f(x, y)$, where x and y are spatial (plane) coordinates, and the amplitude of f at any pair of coordinates (x, y) is called intensity at that point (Gonzalez and Woods, 1992).

Figure 2.4 Digital image, pixels, and intensities of three color-components in a pixel.

2.3.2 Image analysis

Digital image processing is the study of manipulating digital images by computer. Tools in image processing are sets/orders of mathematical operations on the numbers stored in pixels of the images. To obtain meaningful information from the images, ones need to define precisely what kind of information they want from the images, then choose to suitable tools to process the images. The act of obtaining meaningful information from the images is called image analysis. Some of the frequent tasks in image analysis are

1. **Classification** Classification mostly is to tell what objects are present in the images.

2. **Object detection** Object detection is to detect the presence of targeted objects.

3. **Segmentation** Segmentation is to label pixels in the images what object they belong to.

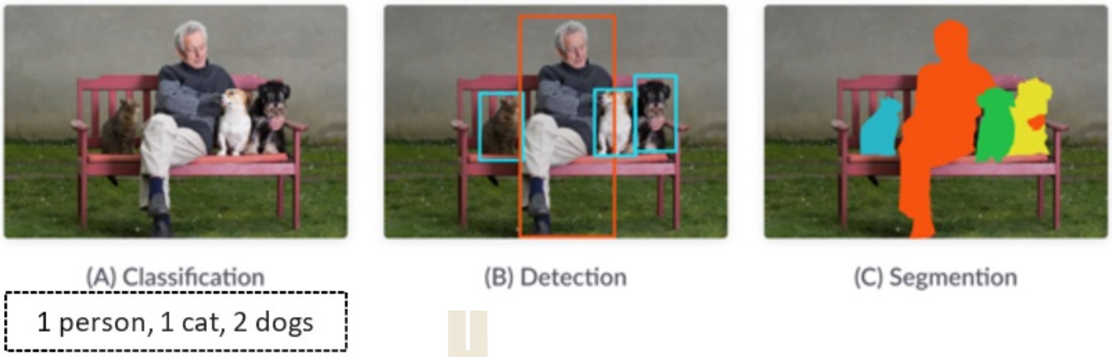


Figure 2.5 Image analysis.

Source https://missinglink.ai/guides/computer-vision/image-segmentation-deep-learning-methods-applications.

2.3.3 Image features

When ones try to explain an object to someone else without telling exactly what the object is called, they use visual details such as shapes, colors, sizes, patterns, textures, etc. Image processing goes the same way since computers do not understand objects in images. They only know the numbers contained in pixels. In order to analyze the images using computers, ones detect the visual details of the objects of their interest. Visual details in image processing are called **image features**. Image features have their mathematical interpretations, thus there are tools that can detect them in the images. Please notice that sometimes the words “numbers (in pixels)” and “intensities” can be used interchangeably.

Examples of image features and their brief mathematical interpretations

As a digital image can be defined as a 2-dimensional surface or a function of 2 variables, image features can be defined mathematically too. Some of the most used image features used in image processing are as follow;

- **Edge** is where the huge difference of intensities in the neighboring pixels occurs. In real applications, it can be either a line/curve or a single point.
- **Corner** can be defined as an intersection of two edges (lines/curves).

- **Blob** is a region of an image in which some properties are constant or approximately constant. It can also be defined as a group of neighboring pixels which contain the same set of numbers or the intensities within close range.

- **Ridge** of a smooth function of two variables are a set of curves whose points are, in one or more ways, local maxima of the function in at least one dimension.

(a) (b) (c)

Figure 2.6 Detection of (a) corner, (b) blob, and (c) ridge.

Source (a) https://medium.com/swlh/harris-corner-detector-an-overview-of-the-original-paper-cf20c502ab0f,

(b) https://scikit-image.org/docs/dev/user_guide/tutorial_segmentation.html,

(c) - (MATLAB generated).

Other features such as colors, textures, shapes, and even coordinations can be interpreted mathematically too. In fact, interpreting objects in images into mathematical definitions is an art and it often depends on ones' creativity and the images themselves. This also happens to the methods or algorithms used to analyze images. The next section reviews some that are applied in this thesis.

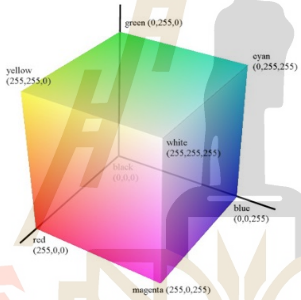
2.4 Image processing tools used in this thesis

2.4.1 Color components and morphological operations

Color system RGB

In the process of image obtaining, colors in each part of the images are recorded by corresponding color codes. As colored digital images can be represented by 3 layers of colors; red, green, and blue. Red, green, and blue are primary colors of light. Since image sensors sense light that reflected from objects, red, green, and blue become the main color system that represents colored digital images, called RGB.

Most of the colors human eyes perceive can be composed of different “intensity” values of red, green, and blue. Basic digital cameras including ones built in smartphones have the levels of intensity run from 0 to 255 for each of the three colors. 0 means lacking of the light in the color, and 255 means strong colored light. Pure red has RGB code (255,0,0), pure green - (0,255,0), and pure blue - (0,0,255). Pure white has (255,255,255) and pure black - (0,0,0). The RGB color system can also be depicted by an RGB cube.



Color	RGB code
	(192, 0, 0)
	(255, 203, 153)
	(128, 128, 128)
	(153, 255, 153)
	(254, 255, 153)
	(102, 0, 205)
	(153, 205, 255)

Figure 2.7 RGB cube and examples of RGB codes for some colors.

Source https://3dwarehouse.sketchup.com/model/f28fa4312fc010f1c7ecd65c510d37b4/RGB-Color-Cube?hl=sv.

Grayscale images and thresholding

Grayscale images are represented by only 1 layer of light intensity. The levels run from 0 to 255 like each layer of colored light intensity in colored images. Grayscale images can be created in a number of ways. They can be made from colored images, calculating from the three color values in each pixel by some formula. The software we used uses the formula to transform colored images to grayscale as below,

$$0.2989R + 0.5870G + 0.1140B,$$

where R, G, and B are red, green, blue intensity values of each pixel.

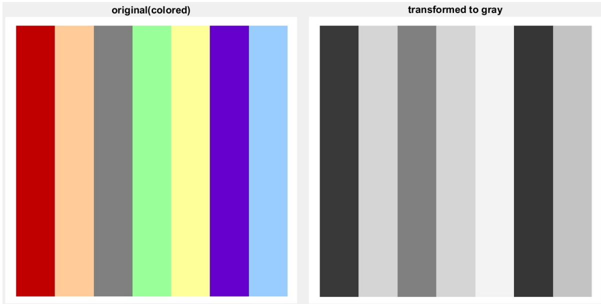


Figure 2.8 Colored image transformed to grayscale image.

Grayscale images can also be made by picking one of the three color layers and take it as grayscale.

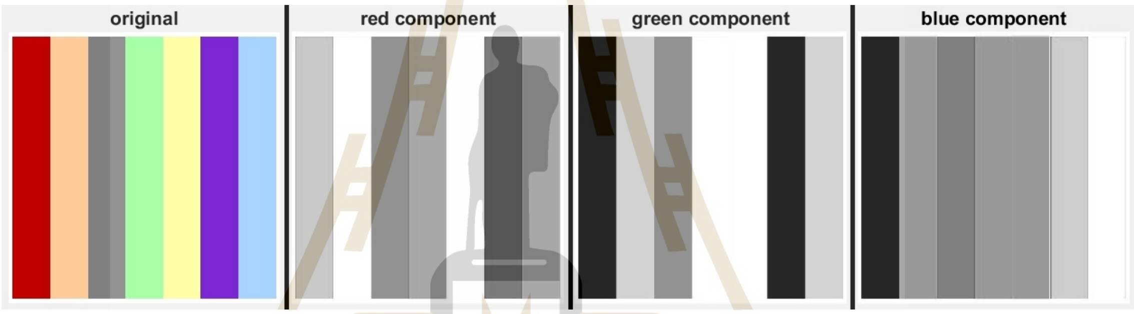


Figure 2.9 A set of different colors and their red, green, blue intensity values.

Different objects have different colors, hence different color codes. The difference between color codes can separate wanted objects from the unwanted ones. For example, if we want to keep objects with red color, the R value should be high while the G and B values should be low.

Figure 2.10 Keeping red band using color value conditions $R > 170, G < 20, B < 20.$

Another example, to keep objects with yellowish colors, the ratio $R:G$ should be approximately 1.00 (yellow = red + green) and $B:G < 0.30$.

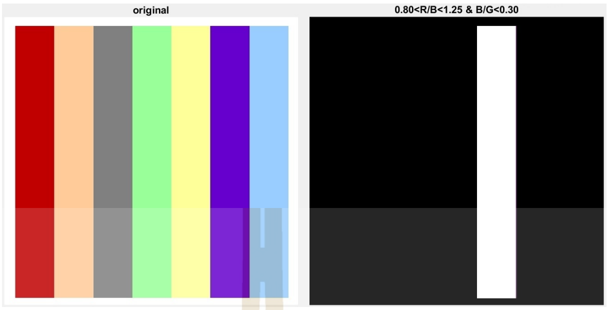


Figure 2.11 Keeping yellow band using color value conditions $0.80 < R/B < 1.25, G/B < 0.30$.

These processes are called thresholding. Each condition comes with calculation on the R, G, B values and its threshold, thus gives a binary image that contains logical values 0 and 1, where pixels following the condition contain 1 (true, white), and the others contain 0 (false, black). Binary images can operate with each other logically and yield more precise results in selecting wanted objects in images.

Since the photograph we work on is a colored photograph, we use the color system RGB to extract the dental arch or the teeth region from the other parts in the image – the background and then the gum. The background was eliminated by thresholding the red color component, then the gum part was removed by thresholding the green color component.

Morphological operations

Morphological operations slightly change shapes of objects in binary images for better analysis using object shapes. There are many of such operations. Using morphological operations, the first step is always labelling "objects" - groups of connected pixels of the same color, automatically. Then other morphological operations follow. The figures below explain the selected morphological operations. They are used to do the clean segmentation. Apart from labelling, there are counting areas (pixels) of individual objects, which helps keeping the largest object that was expected to be the teeth region, and filling holes, which fills the holes within the object that was kept.

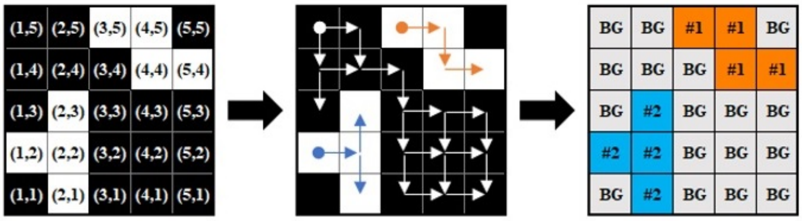


Figure 2.12 Object labeling.

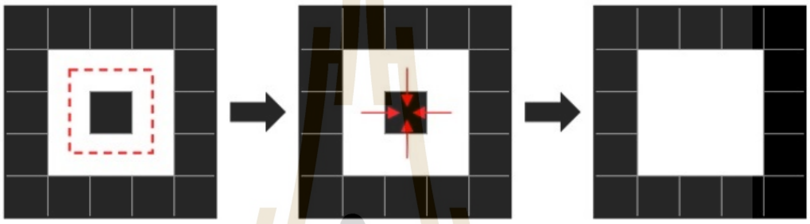


Figure 2.13 Filling hole(s).

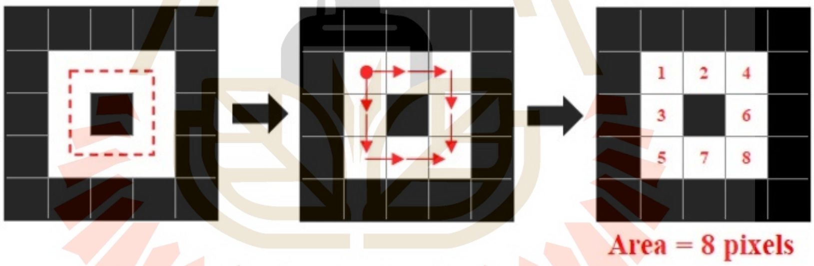


Figure 2.14 Counting area (pixels) of an object.

There are many more morphological operations. Some are compositions of others. Labelling objects is always the first operation done before any others. Then there are properties of each object that can be called such as area, centroid, and location. The object shape-changers start with dilation and erosion of objects in binary images. These two, and other more complicated operations involve another kind of pixel sets called structuring elements.

Dilation

Objects in binary images are dilated by

1. Put the center of the structuring element at each border pixel.

2. Within the area of the structuring element, if pixels with value 0 are found, change to value 1. Leave pixels with value 1 unchanged.

3. Repeat 1.-2. to every border pixel.

The bigger the structuring element is, the larger the objects are dilated from their borders.

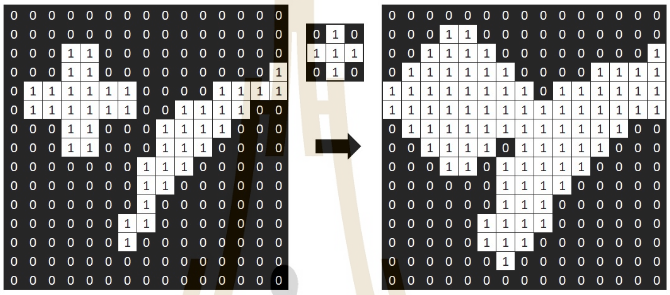


Figure 2.15 Dilation.

Erosion

Erosion has the similar process to dilation, but only differs by changing pixels of value 1 to 0 and leaving pixels with value 0 unchanged in the step 2.

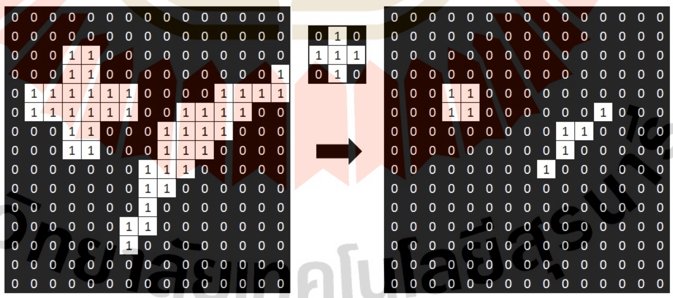


Figure 2.16 Erosion.

Opening and closing images are two different compositions of dilation and erosion. Opening is erosion followed by dilation. It makes objects less spiky (smoother at the borders) and erases the narrow shapes.

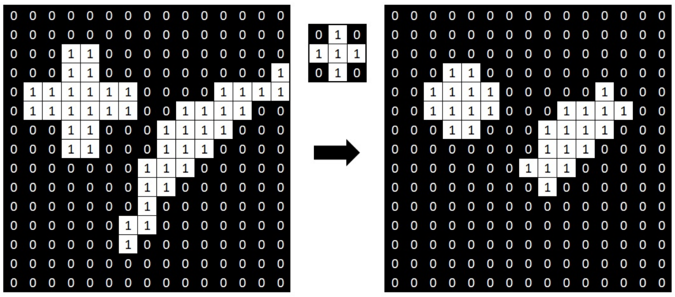


Figure 2.17 Image opening.

Closing is dilation followed by erosion. It makes objects less spiky and fills some small holes within the objects.

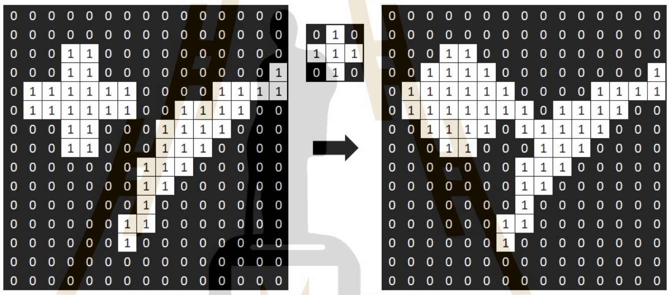


Figure 2.18 Image closing.

Other more complicated operations can be composed by these operations.

2.4.2 Convolution masks for shape detection

Image convolution, or simply convolution, is a mathematical operation used wildly in image processing, especially to detect edges or to blur (smoothen) images. It is a way of multiplying two matrices. The process is almost the same as dot products, where two vectors pair their corresponding values, multiply within the pairs, and then sum up the products to be a number. In convolution, grayscale or binary images can be taken as matrices of intensity values. Another matrix is built to suit the purpose of convolution, so it contains a specific set of entries. This other matrix usually is smaller than the image matrix. It is called a kernel or a mask. When doing the convolution, the mask is run through the image. At each pixel of the image, the entries in the mask multiply with the corresponding intensity values, the products are summed up to a number and the number is put in the result matrix at the same location of the pixel. This operation gives a new matrix as a result, as shown in figures below.

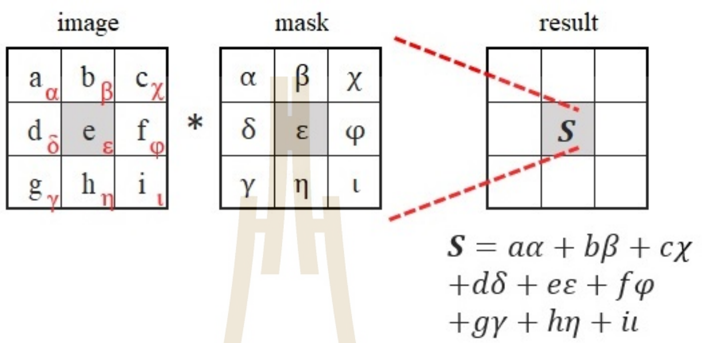


Figure 2.19 Convolution - calculation the value of each cell in the result matrix.

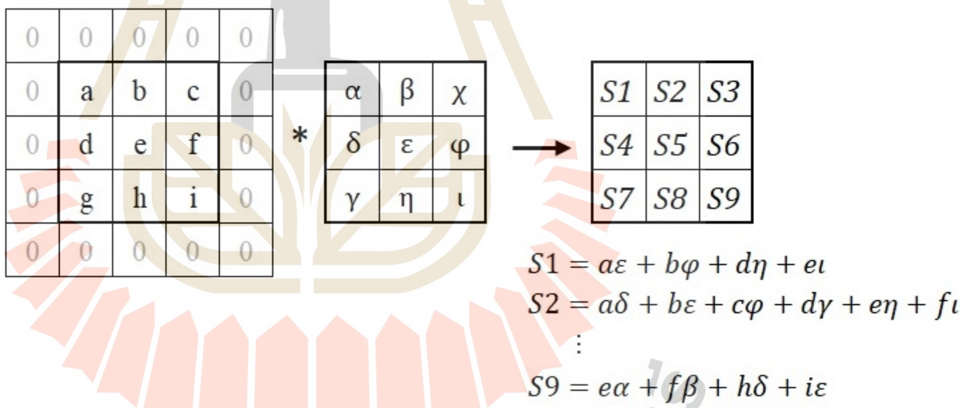


Figure 2.20 Convolution - samples of result values.

In this work, masks are designed to be matrices of the patterns of the cusps and grooves. They can be created by just copying the patterns. It came from our observation, that when looking at the photographs of human oral cavity, there exist patterns of cusps and grooves of the inner teeth like molars and premolars, which are specific to the teeth positions. These patterns are composed of irregular curves. We adapt the concept of the technique “Optical Character Recognition (OCR)”, which uses a finite set of letter templates, to read texts from images by template matching. We build templates for the patterns we observe in the form of matrices, and apply the image convolution.

Initially we followed the Cauchy-Schwarz inequality:

$$\left| \sum_{i=1}^{n} u_i v_i \right| \leq \sqrt{\left(\sum_{i=1}^{n} u_i^2 \right) \left(\sum_{i=1}^{n} v_i^2 \right)}$$

where where u_i and v_i are real numbers.

In the convolution, where the convolution mask has the dimension of $M \times N$, let

$i = 1, ..., M \times N,$

u_i be the i^{th} entry of the convolution mask matrix,

and v_i be the intensity value at the corresponding pixel i^{th} of the image,

where u_i are any real numbers, and $v_i \in \{0, 1, 2, ..., 255\}$, which are the possible intensity values or gray levels in each pixel.

The convolution operates in the same way as dot product of two vectors, where one vector contains intensity values of images, and another contains coefficients from the mask matrix. The inequality becomes an equality if the two vectors are linearly dependent, which includes the two images being similar to each other. Also, since u_i or the convolution mask is fixed, when the inequality becomes an equality, it reaches the maximum.

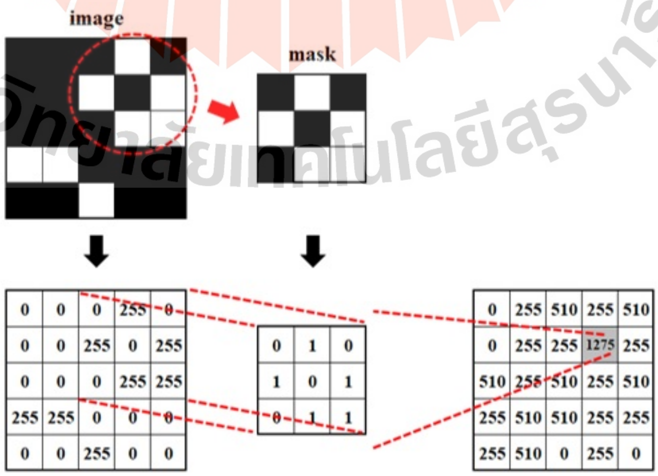


Figure 2.21 Convolution for shape detection.

2.4.3 Watershed algorithm

The watershed algorithm is one of the tools for image segmentation. The concept is to take objects in images as “water basins” and flood them up, then count the number of water bodies found. To mark the water basins, there are processing steps that assign “depth” to each pixel. Depth can be stimulated by various methods. The one we used in this work is a function “distance transform” (MathWorks, n.d.). It calculates the distance between the pixel within an object and the nearest border pixel of the same object.

Suppose that we have a picture of different objects.

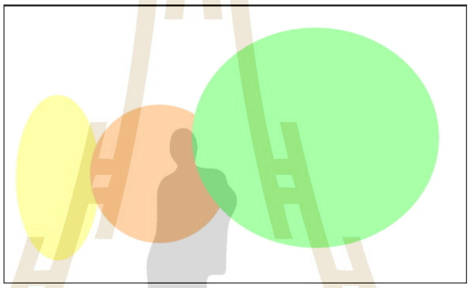


Figure 2.22 An image of different objects slightly overlapping each other.

First, we change it to a binarized image.

Figure 2.23 Binarized image of connected objects.

Then, apply a distance transform. A distance transform is a function that calculates the distance between a pixel inside an object and the closest border pixel of the object.

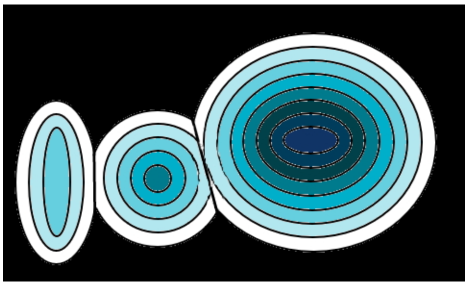


Figure 2.24 Distance transform - depth of water basins.

The distance given to each pixel within objects becomes depth of a water basin. The deepest point of each basin is counted as the center of the object. This gives a number of local maxima, from which groups of pixels are labelled as different objects and the objects are recognized by computer.

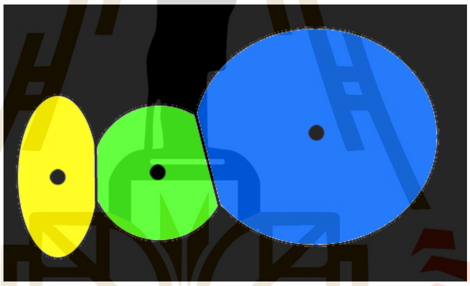


Figure 2.25 Watershed algorithm applied.

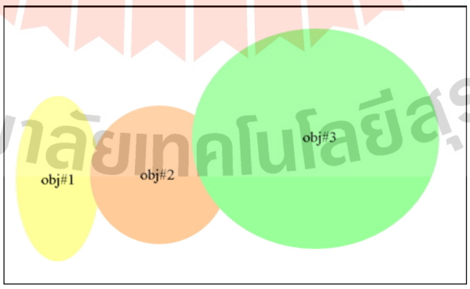


Figure 2.26 Objects individually labelled.

The watershed algorithm is chosen in this thesis because it suits detecting objects with convex shapes that do not overlap each other too much. The shapes of frontal teeth like incisors are almost convex. With a few more commands added to the algorithm, the watershed algorithm is a promising tool to detect the teeth.

2.5 Related works

There is no universal method for all dental (medical) images and purposes of analysis. The following researches are done independently from each other.

Kang X. et al. (2017) use thresholding to detect metal implants in gray-level dental photographs. This is the simplest method to detect an object in the images. The main disadvantage is that it only detects odd objects; it does not distinguish objects of the same class like teeth piece by piece.

Kang H.C. et al. (2015) use global thresholding to extract teeth from mandibular bone in dental CT images. The method used to detect teeth is simple and detects teeth separately. However, the image type in this research plays a large role in the simplicity of the chosen method.

Lins et al. (2017) use watershed to segment teeth in occlusal intraoral digital photographic images and classifies teeth by their type. Comparing with the previous research, the method used for teeth detection in this research is more complicated, but it does not require expensive image acquisition like CT scanner.

Kumar, Janardan, and Larson (2012) use watershed-based segmentation to detect tooth features such as grooves and cusps in dental meshes (3-D simulation of dental arch). Both the method and the image acquisition are complicated, but more information about human teeth are found and this method can be used for more efficiency in teeth detection.

Rad, Rahim, and Norouzi (2014) use integral projection technique to detect lines that separates teeth in X-ray dental images. The X-ray dental images are the most used for image analysis by dentists/experts from dental area since they show the inside of teeth. The shape of an individual tooth shown in X-rays images is not regular, and the teeth positioning in the images can cause more difficulties in segmentation. The 90% accuracy claimed in this research shows that the method might be a suitable teeth detection methods for this type of dental images.

Yadollahi et al. (2015) use region growing and convex hull to segment the teeth in the dental arch, together with Hough transform to detect teeth centers in digital records of illuminated plaster casts. The method consists of many steps therefore it cannot be classified into any of three generations. The teeth detection via Hough transform is interesting since it detects teeth separately by details of one whole tooth, which almost imitates the way human recognize objects.

Zheng, Zhang, and Ding (2010) develop the technique called Hybrid Differential Method or HDM with Turn-point analysis to detect molars in the grey photographs of occlusal view of teeth images.

Amer and Aqel (2015) divide x-ray panoramic images of teeth into parts to extract the wisdom teeth (the third molars) from the whole images.

These researches employ different methods with different goals, some even develop their own methods. The methods we use in this thesis are explained both in the previous section and the next chapter.

CHAPTER III

METHODOLOGY

There are roughly 4 steps outlined as follow:

1. Taking a photograph of human teeth;
2. Pre-processing;
3. Detecting molars and premolars using convolution masks;
4. Detecting incisors and canines using watershed algorithm.

3.1 Taking a photograph of human teeth

A colored photograph was taken from a model of permanent teeth “SimKit”. The smartphont model in use was iPhone 7, with camera mode “Photo” (default mode).

Figure 3.1 Photo shoot setting.

3.2 Computer and program in use

Hardware usage:

- Model: HP ProBook 430 G4

- Processor: Intel(R) Core(TM) i5-7200U CPU 2.50 GHz (4 CPUs)
- Memory: 8192 MB RAM
- Operating system: Windows 10 Pro 64-bit

Software usage: MATLAB R2020b, The MathWorks, Inc., Natick, Massachusetts, United States.

MATLAB was the main image processing software in this thesis. It is a computational program with friendly user interface. The advantage of this program is that it comes with matrix-based calculation, which reduces processing duration when working with images as matrices, and provides ready-to-use image processing tools without reprogramming.

3.3 Pre-processing

In this step, color components and morphological operations were applied to extract the dental arch in the image.

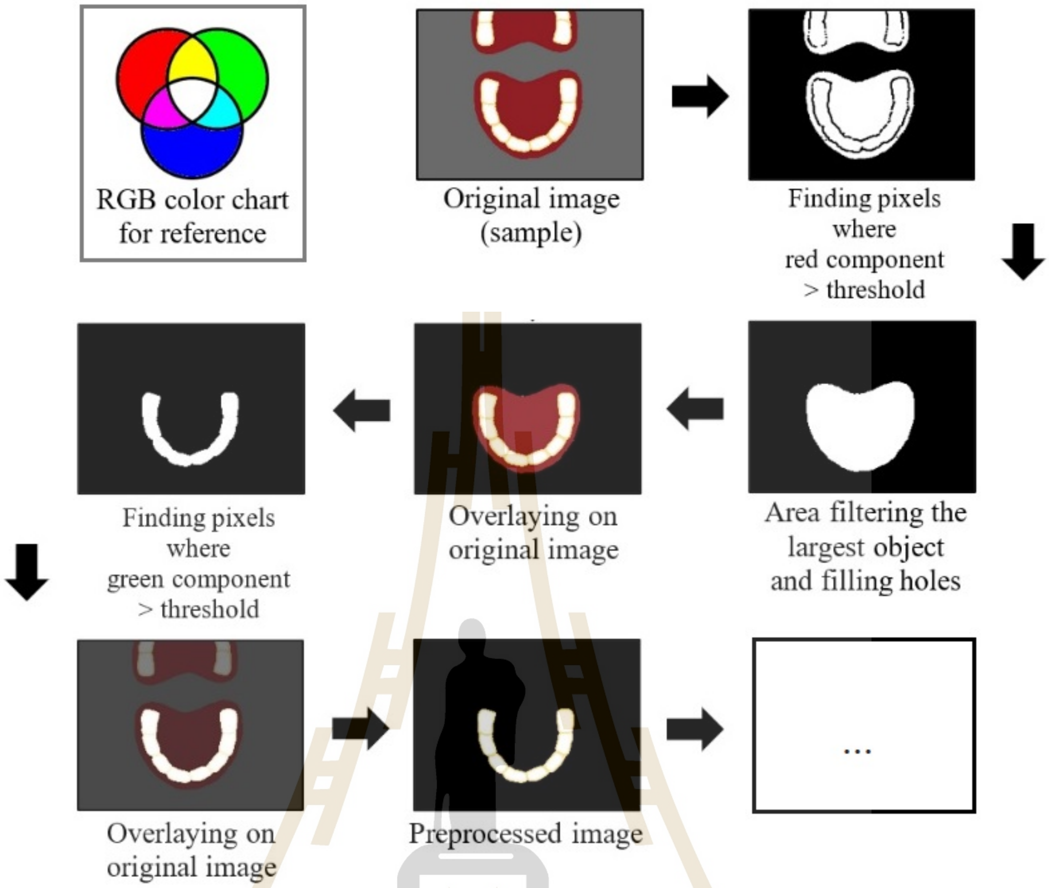


Figure 3.2 Pre-processing flowchart.

3.4 Detecting molars and premolars using convolution masks

The convolution masks were used in this step. The 4 masks for the 1^{st} premolar, the 2^{nd} premolar, the 1^{st} molar, and the 2^{nd} molar on the left side of the arch were created, simplified and flipped horizontally to get other 4 masks that detected the same types of teeth on the right side of the arch. The masks detected all 8 different positions in the image. The masks are shown in the figures below, noting that the parameter c of each input mask was set to be 0 for convenience when designing, and automatically computed and substituted by program.

3.5 Detecting incisors and canines using watershed algorithm

The watershed algorithm was used to detect the incisors. The algorithm detected all 4 incisors. Then, their centroids were found by the program, and 2 of them; the leftmost and the rightmost, were taken to plot a line that predicted the locations of the 2 canines at the ends of the frontal teeth row.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Outlook of each step

4.1.1 Taken photograph to be tested

The photograph was of dimension 4032×3023, with resolution 72 dpi and saved in the format JPG. The view obtained was between frontal and lower occlusal views.

Figure 4.1 The photograph (image) to be tested.

4.1.2 Pre-processing

The photograph from the previous step was cropped and resized to the dimension 256×192, then pre-processed by colors and morphological operations so that it kept only the dental arch.

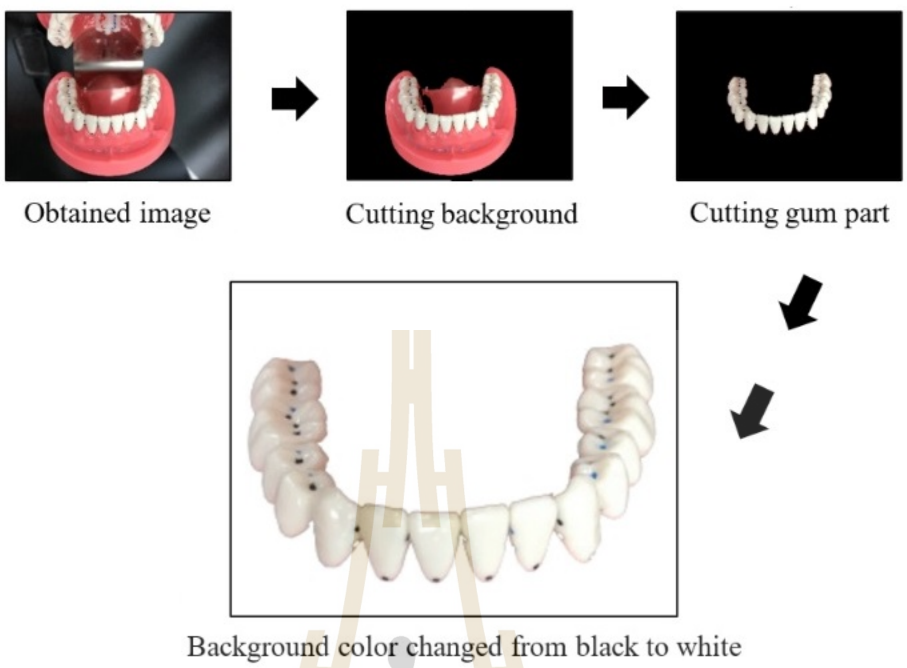


Figure 4.2 Preprocessing the image.

4.1.3 Detecting molars and premolars using convolution masks

The theory for convolution masks in section 2.4.2 is true for binary images but not always the case for grayscale images. The large range of intensity values in grayscale images affects the result. The designed shapes in the masks alone could not tolerate the variety of intensity values and mistook other objects for the targeted ones. More precisely, even though the masks were of the pattern of the targeted objects, they could catch other objects of absolutely different patterns if the intensities of those objects were higher than the intensities of the targeted objects.

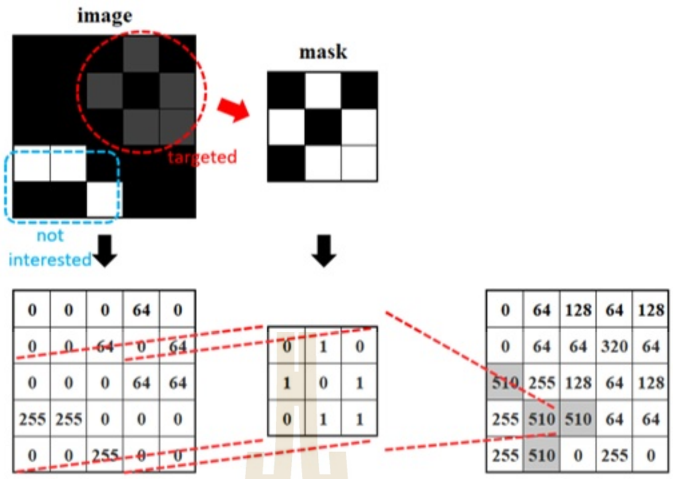


Figure 4.3 Incorrect shape detection.

This problem was caused by the coefficients 0 in the mask matrix. By the fact that any number multiplied by 0 gives the result 0, this process loses the information about the relationship among intensity values in pixels. The coefficients 0 had to be substituted by other values. One of the possible ways to calculate new coefficients was to set up the convolution between the matrix containing the pattern of the targeted object and the mask matrix, changing the coefficients 0 in the mask matrix to the unknown value c.

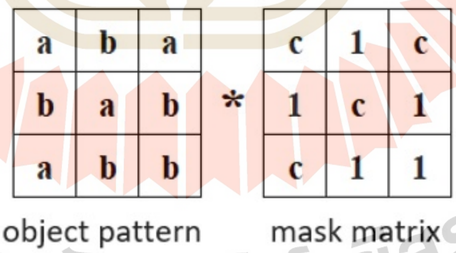


Figure 4.4 Setting up to calculate the parameter c.

Then calculate the convolution. Let the number of the entries in the mask be D, the number of the entries with value 1 be w, then the number of the entries with value 0 is $D-w$. Since this sample uses 3×3 matrices, we have $D = 3\times3 = 9,\ w = 5,\ D-w = 4$, and the result of convolution is $5b + 4ac$.

Next, we want the result to stay the same, no matter how much the intensity values in the targeted object change. Let f be a function (a real-valued function with range $R_f = \{0, 1, 2, ..., 255\}$) that transforms the intensity values in the targeted object. Set the convolution up again.

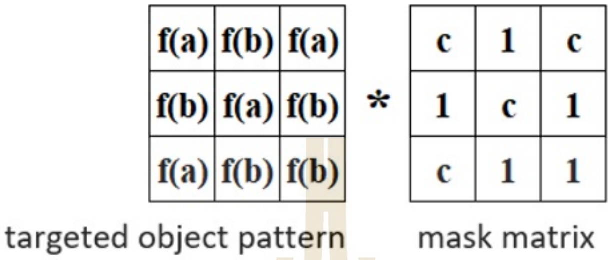


Figure 4.5 Setting up to calculate the parameter c (continued).

Calculate the convolution. The result is $5f(b) + 4f(a) \cdot c$. Then, calculate c:

$$5 \cdot f(b) + 4 \cdot f(a) \cdot c = 5b + 4ac$$
$$4 \cdot f(a) \cdot c - 4ac = 5b - 5 \cdot f(b)$$
$$4c(f(a) - a) = 5(b - f(b))$$
$$c = \frac{5}{4} \cdot \frac{b - f(b)}{f(a) - a} = -\frac{5}{4} \cdot \frac{f(b) - b}{f(a) - a}$$

We want c to be fixed for the pattern, which means $\frac{f(b)-b}{f(a)-a}$ is a constant. Let

$$\frac{f(b) - b}{f(a) - a} = k$$
$$f(b) - b = k(f(a) - a)$$
$$f(b) - b = k \cdot f(a) - ka$$
$$f(b) - k \cdot f(a) = b - ka$$

Since a and b are arbitrary $(a, b \in \{0, 1, 2, ..., 255\})$, substitute them with some possible numbers to find k. The pair $(a, b) = (0, 0)$ gives $k = 1$, as shown below:

$$f(0) - k \cdot f(0) = 0 - k \cdot 0 = 0$$
$$(1 - k)f(0) = 0$$
$$1 - k = 0$$
$$k = 1$$

Other pairs do not give constants. Hence, take $k = 1$ and calculate backward to find c.

$$\frac{f(b) - b}{f(a) - a} = k = 1$$

$$c = -\frac{5}{4} \cdot \frac{f(b) - b}{f(a) - a} = -\frac{5}{4} \cdot 1 = -\frac{5}{4} = -1.25$$

Change c with -1.25 in the mask matrix and convolve again. The result is shown below.

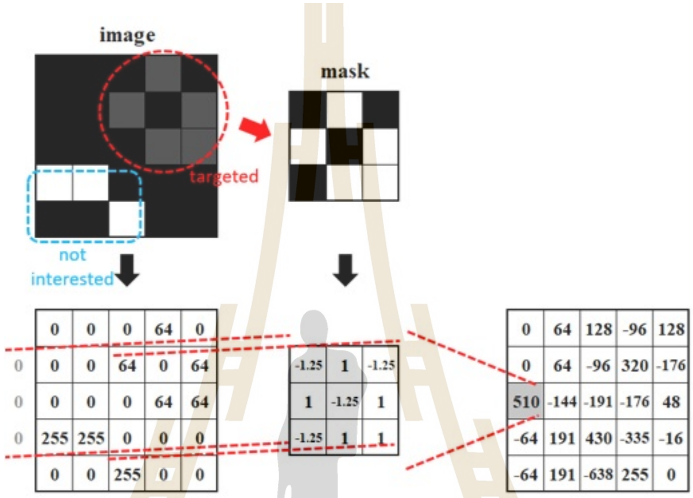


Figure 4.6 Improved shape detection.

The result shows that the improved mask still does not work well enough. The brighter object still gets detected instead of the targeted one. However, the number of pixels containing maximum values outside the site of targeted object decreases (from 4 to 1, shown with grey pixels). This is not a good example, since the patterns are too simple, so that the intensity values still play a more important role. However, in real application to this thesis, this conception was shown to work better; it detected the targeted objects. The formula for c can be generalized as follow,

$$c = -\frac{number\ of\ mask\ cells - number\ of\ cells\ with\ value\ 1}{number\ of\ cells\ with\ value\ 1}$$

The parameter c is computed after the mask is created and it is done automatically by the program.

The figures below are of the designed masks that were run through the tested image, and an example of the 1^{st} molar mask run through the image.

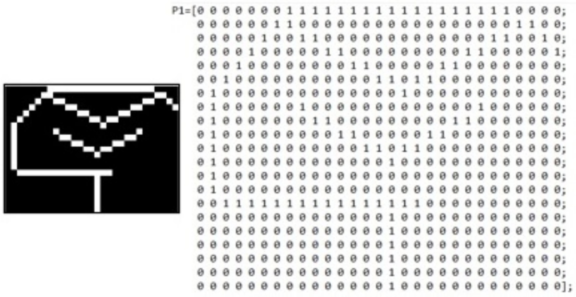


Figure 4.7 The 1^{st} premolar mask.

Figure 4.8 The 2^{nd} premolar mask.

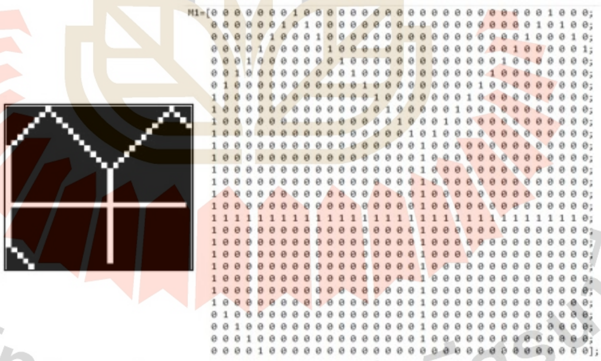


Figure 4.9 The 1^{st} molar mask.

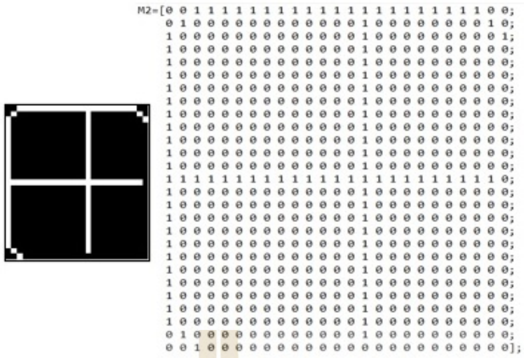


Figure 4.10 The 2^{nd} molar mask.

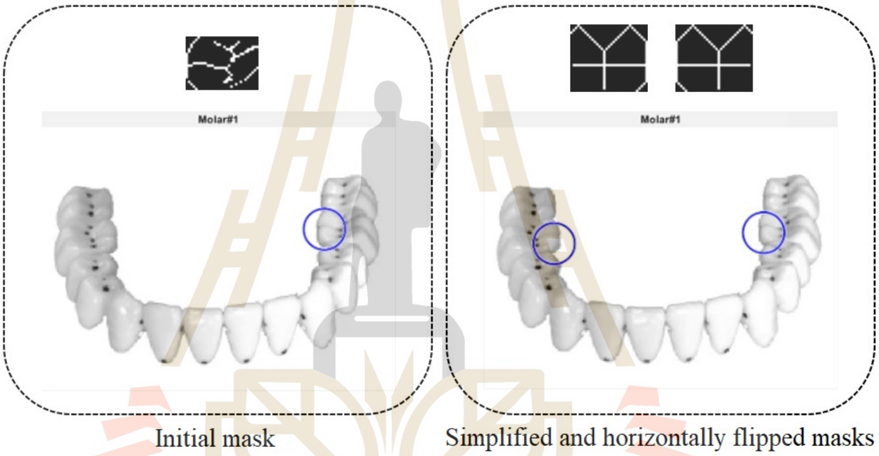


Figure 4.11 Running the mask through the image.

4.1.4 Detecting incisors and canines using watershed algorithm

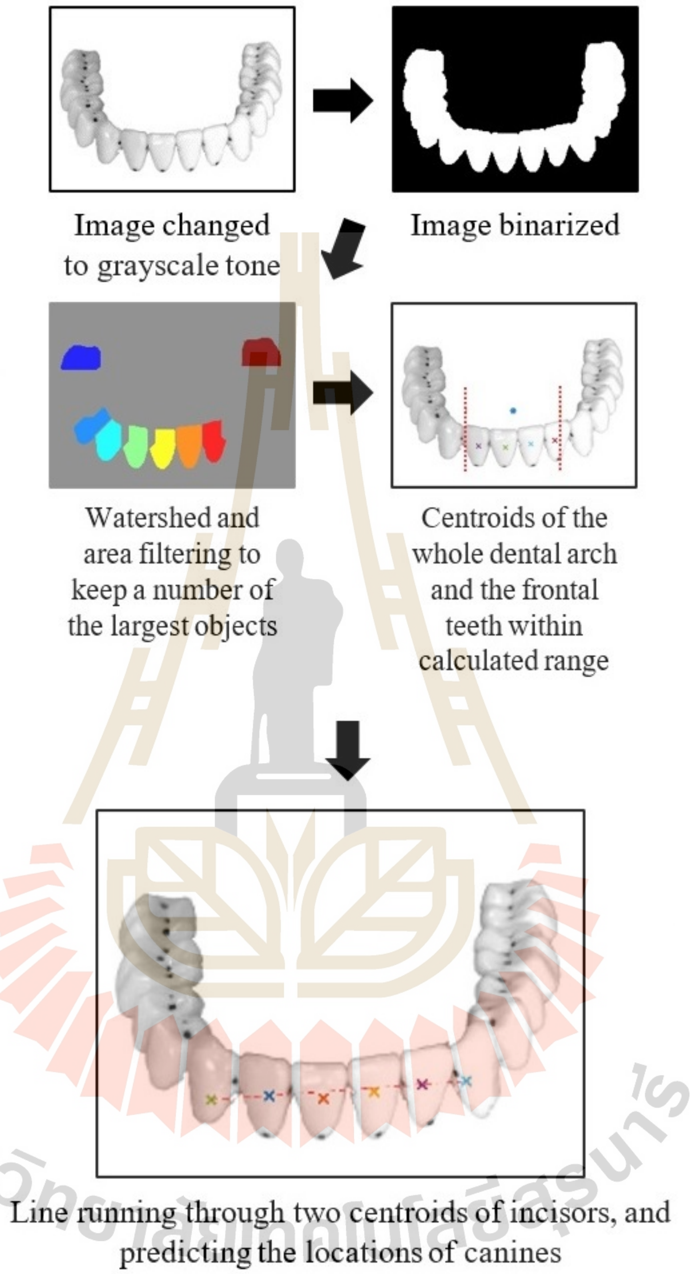


Figure 4.12 Detecting incisors and predicting canines.

4.2 Accuracy assessment: Missing ratio

By the system of image analysis we proposed, almost all the types of teeth were detected. However, there were errors with the detected locations. We measured errors and accuracy by the newly introduced "missing ratio". Missing ratio is the ratio of the distance between the expected position and the detected position of each tooth, over the radius of the smallest circle circumscribing the tooth. High accuracy is when the ratio converges to 0.00. The criterion for "detected" / "missed" is when the ratio is less than / exceeds 2.00 respectively. This measurement shows how much the detected results miss the expected results, compared to the size of the targeted objects themselves.

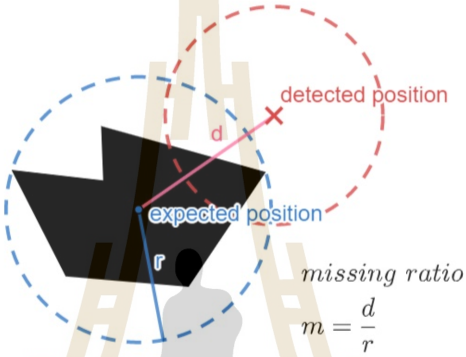


Figure 4.13 Missing ratio.

4.3 Detection results

The detection results are shown in figures below, and the accuracy assessment by missing ratio is shown in table 1.

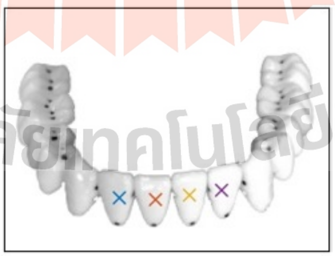


Figure 4.14 Result for incisors.

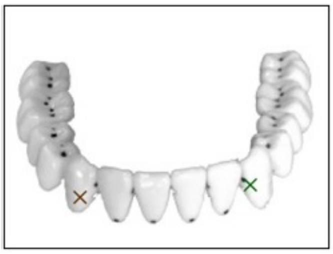


Figure 4.15 Result for canines.

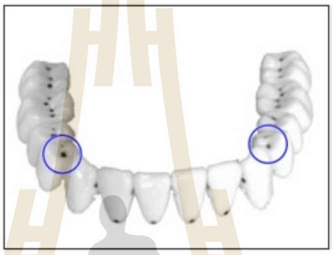


Figure 4.16 Result for the 1^{st} premolars.

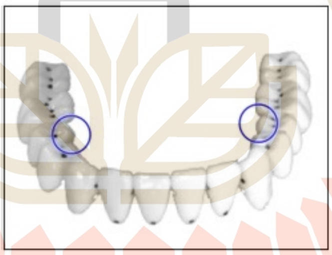


Figure 4.17 Result for the 2^{nd} premolars.

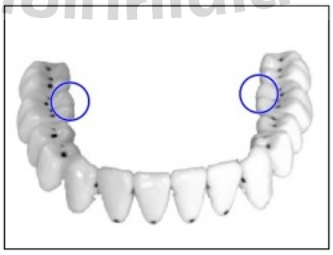


Figure 4.18 Result for the 1^{st} molars.

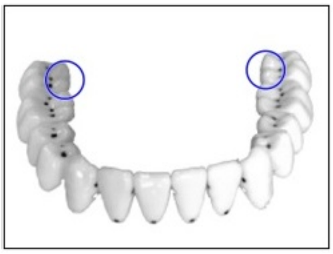


Figure 4.19 Result for the 2^{nd} molars.

Table 4.1 The accuracy of the proposed system.

Tooth	Missing ratio	Tooth	Missing ratio
2^{nd} left molar	0.66	1^{st} incisor	0.09
2^{nd} right molar	0.60	2^{nd} incisor	0.09
1^{st} left molar	0.75	3^{rd} incisor	0.09
1^{st} right molar	0.70	4^{th} incisor	0.12
2^{nd} left premolar	0.88	1^{st} canine	0.31
2^{nd} right premolar	1.00	2^{nd} canine	0.36
1^{st} left premolar	0.12		
1^{st} right premolar	0.17		

CHAPTER V

CONCLUSION

5.1 Discussion

The accuracy recorded in table 1 shows that the proposed system detected 12 teeth by type and predicted the other 2 teeth correctly. The proposed system can be divided into 2 main parts; the convolutional masks and the watershed algorithm.

The Watershed algorithm obviously worked well detecting incisors and helped predict the locations of canines by a line equation. The line equation predicting the canines locations can be substituted with other kinds of equations, considering that the dental arch is not a straight line.

The convolutional masks part still needs to be improved even though the masks worked. The high missing ratios suggest that illumination conditions in the image still affect the results. The problem can be fixed with a few additional commands in the program, together with the photo shoot setting being adjusted.

The proposed system of image analysis is the expected result of this thesis. The system works with colored photographs, which are not yet widely integrated into diagnosis and treatment in dentistry, compared to X-ray images, which are the most frequently used. Also, when compared to other researches reviewed, the dental view of the teeth model in our photograph is different from the views they use. While our view is between frontal and occlusal, most researches on dental photographs use either frontal or intraoral occlusal views. Overall, the photo shoot setting in this thesis is considerably new, and the proposed system tends to work with this new way of obtaining dental images.

5.2 Summary

The entire process of this thesis can be summarized by the scheme below,

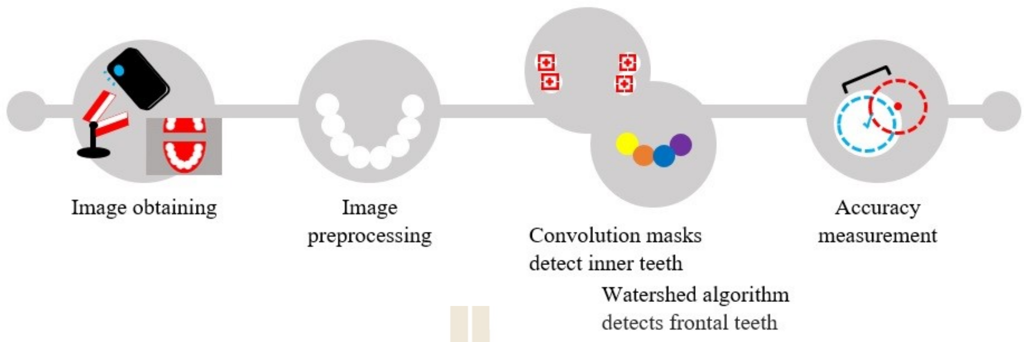


Figure 5.1 Brief scheme of the thesis.

5.3 Conclusion

This thesis proposed a system of image processing tools to detect and classify human teeth in a photograph. Teeth classification can be counted as the beginning of the process to obtain data from human teeth photographs by computer. It shows the possibility to work on photographs, which are easier to collect than other types of dental images such as X-ray and CT scanned images. Obtaining data by the proposed system can also decrease human workload on analyzing the images and provides more space for healthcare personnel to put on more patients.

The idea of using smartphone cameras to obtain photographs that are to be used as medical images is still new, hence not many researches on this topics can be found. The benefit of using photographs is the convenience for both sides of healthcare system; doctors and patients. The disadvantage is that photographs do not reach the inner sides of organs/structures, so that their usage might have to be limited to only some cases of disease assessment, such as caries. Also technical problems around photographs such as illumination conditions and image distortion have to be accounted for.

5.4 Suggestion

To reduce the effect from illumination condition, well-set image acquisition is primarily suggested. In the future, the proposed system could be improved also by computer vision machine learning networks such as CNNs if the data for training&testing can be provided. More types of teeth can be added including damaged teeth, to directly detect them.

REFERENCES

REFERENCES

Amer, Y. Y., and Aqel, M. J. (2015). An efficient segmentation algorithm for panoramic dental images. *Procedia Computer Science, 65*: 718-725.

American Cancer Society medical and editorial content team. (2018). *What are oral cavity and oropharyngeal cancers?* [On-line]. Available: https://www.cancer.org/cancer/oral-cavity-and-oropharyngeal-cancer/about/what-is-oral-cavity-cancer.html. (Retrieved 29/10/2020)

"Digital images." Computer sciences. *Encyclopedia.com* [On-line]. Available: https://www.encyclopedia.com/computing/news-wires-white-papers-and-books/digital-images. (Retrieved 31/10/2020)

Donchalermpak, P. (2020). Telemedicine for Thailand. *BOI e-Journal, 3*(6): 12-17.

Estai, M., Kanagasingam, Y., Huang, B., Shiikha, J., Kruger, E., Bunt, S., and Tennant, M. (2017). Comparison of a smartphone-based photographic method with face-to-face caries assessment: A mobile teledentistry model. *Telemedicine and e-Health, 23*(5): 1-6.

Gonzalez, R.C., and Woods, R.E. (1992). *Digital Image Processing*. Massachusetts: Addison-Wesley.

Haddock, F.J., Dds., Hammond, B.D., Dmd., and Romero, M.F., Dds. (2018). *Guide to dental photography* [On-line]. Available: https://decisionsindentistry.com/article/guide-to-dental-photography. (Retrieved 29/10/21)

Jampani, N.D., Nutalapati, R., Dontula, B.S.K., and Boyapati, R. (2011). Applications of teledentistry: A literature review and update. *Journal of International Society of Preventive & Community Dentistry, 1*(2): 37-44.

Kang, H.C., Choi, C., Shin, J., Lee, J., and Shin, Y.-G. (2015). Fast and accurate semiautomatic segmentation of individual teeth from dental CT images. *Computational and Mathematical Methods in Medicine. 2015*, article ID: 710896

Kang, X., Xu, J., Zou, D., Wang, X., Wan, L., Hu, G., Zhen, T., Zhou, L., Lei, H., Lei, Z., and Leng, Y. (2017). Dental bio-metrics information used for binary image processing, segmentation and matching. *Journal of Clinical and Medical Case Studies, 2*: 22-30.

Kumar, Y., Janardan, R., and Larson, B. (2012). Automatic feature identification in dental meshes. *Computer-Aided Design & Applications. 9*(6): 747-769

Lins, R.A.S., dos Santos, K.E.A., Dória, A.D., Neto, Noro, L., Roncalli, Â., dos Santos Medeiros, M.C.M., de Souza, P.H.S., and da Silva, S.M. (2017). Use of support vector machine for teeth recognition from occlusal intraoral digital photographic images. *XIII Simpósio Brasileiro de Automação Inteligente*, Porto Alegre, Rio Grande do Sul, Brazil, 1747-1752.

MathWorks (n.d.). *Watershed transform – MATLAB watershed (R2021a)* [On-line]. Available: https://www.mathworks.com/help/images/ref/watershed.html. (Retrieved 29/06/2021)

National Statistic Office. (n.d.). *Increasing smartphone usage among Thai people* [in Thai] [On-line], Available: http://www.nso.go.th/sites/2014/Pages/ActivityNSO/A24-05-60.aspx. (Retrieved 29/10/2021)

Pinprateep, P., Dr. (n.d.). *Inequality in Public Health* [in Thai] [On-line], Available: https://infocenter.nationalhealth.or.th/node/27630. (Retrieved 29/10/2021)

Prachatai, (2021). *ICT Household Report 2018, 56.7 millions Thai people own mobile phones, only 69.6% are smartphones* [in Thai] [On-line], Available: https://prachatai.com/journal/2021/02/91540. (Retrieved 29/10/2021)

Rad, A., Rahim, M., and Norouzi, A. (2014). Level set and morphological operation techniques in application of dental image segmentation. *International Journal of Computer and Information Engineering, 8*(4): 182-185.

Shah, N., Bansal, N., and Logani, A. (2014). Recent advances in imaging technologies in dentistry. *World Journal of Radiology, 6*(10): 794-807.

“Smartphone.” (2021). *Wikipedia* [On-line]. Available: https://en.wikipedia.org/wiki/Smartphone. (Retrieved 29/10/2021)

Yadollahi, M., Procházka, A., Kašparová, M., Vyšata, O., and Marík, V. (2015). Separation of overlapping dental arch objects using digital records of illuminated plaster casts. *BioMedical Engineering OnLine. 14*(67)

Zheng, X., Zhang, Y., and Ding, H. (2010). The teeth image recognition using HDM and the turn point. *2010 International Conference on Optoelectronics and Image Processing*, Hainan, China, 645-648.

APPENDICES

APPENDIX A

MATLAB CODES USED IN THIS THESIS

A.1 Image pre-processing

read-in original image

```
I=imread(image of the teeth model);
```

cutting background

```
Ired=I(:,:,1);
Inbg=(Ired>=128);
Inbg=bwareafilt(Inbg,1);
Inbg=imfill(Inbg,'holes');
Imasked=bsxfun(@times,I,cast(Inbg,'like',I));
```

cutting the gum

```
M=Imasked;
Mgreen=M(:,:,2);
Mng=(Mgreen>128);
Mng=bwareafilt(Mng,1);
Mng=imfill(Mng,'holes');
Mmasked=bsxfun(@times,M,cast(Mng,'like',M));
```

A.2 Applying convolution masks

call mask matrix, get size, calculate c

```
A=[]; <- matrix from separated file
[ro,co]=size(A);
S=sum(A,'all');
K=S./(S-ro*co);
A(A==0)=[K];
```

grayscale image

```
I=imread(image of the teeth model);
I=rgb2gray(I);
Iconvert=255-I;
```

original mask

```
C=filter2(A,Iconvert);
Cgray=mat2gray(C);
M=max(Cgray,[],'all');
[a,b]=find(Cgray==M);
```
horizontally-flipped mask
```
B=fliplr(A);
D=filter2(B,Iconvert);
Dgray=mat2gray(D);
N=max(Dgray,[],'all');
[c,d]=find(Dgray==N);
```
show results
```
imshow(I), title('Result')
viscircles([b,a],15,'Color','blue');
viscircles([d,c],15,'Color','blue');
```

A.3 Watershed algorithm and line equation

grayscale image
```
I=imread(image of the teeth model);
I=rgb2gray(I);
```
get the 1-piece dental arch
```
Iin=(I<250);
Iin=imfill(Iin,'holes');
Iout=imcomplement(Iin);
```
find dental arch centroid
```
Ic=regionprops(Iin,'centroid');
```
watershed by distance transform
```
D = bwdist(Iout);
D = -D;
L = watershed(D);
```

```
L(Iout) = 0;
```

keep large pieces

```
Lout = (L =0);
Lpis = bwareafilt(Lout,8);
```

work with centroid to keep incisor

```
stat = regionprops(Lpis,'centroid');
```

plot on original image

```
imshow(I); hold on;
kount = 0;
xmin = 0;
xmax = 0;
for x = 1: numel(stat)
if (stat(x).Centroid(1)>=Ic(1).Centroid(1)-50)
&&(stat(x).Centroid(1)<=Ic(1).Centroid(1)+50)
kount = kount + 1 ;
plot(stat(x).Centroid(1),stat(x).Centroid(2),'x','LineWidth',2,'MarkerSize',20);
if (kount==1)
xmin = stat(x).Centroid(1);
ymin = stat(x).Centroid(2);
end
if (stat(x).Centroid(1) >= xmax)
xmax = stat(x).Centroid(1);
ymax = stat(x).Centroid(2);
end
end
end
```

predict the position of canines using line equation

```
wid = (xmax-xmin)./(kount-1);
xi = Ic(1).Centroid(1) - 2.5*wid ;
xt = Ic(1).Centroid(1) + 2.5*wid ;
```

```
coefficients = polyfit([xmin, xmax], [ymin, ymax], 1);
a = coefficients (1);
b = coefficients (2);
yi = a*xi + b;
yt = a*xt + b;
plot(xi,yi,'x','LineWidth',2,'MarkerSize',20,'Color',[0.4,0.2,0]);
plot(xt,yt,'x','LineWidth',2,'MarkerSize',20,'Color',[0,0.4,0]);
m = [xi xt];
n = [yi yt];
line(m,n,'Color','red','LineStyle','–');
```

APPENDIX B

PROBLEMS AND SOLUTIONS ALONG THE WAY

This part records successes and failures in the survey of image processing tools that could work on our images, and the explanation why some conceptions work and some do not.

B.1 Problems

Here are main problems encountered with teeth classification:

1. Teeth look very similar to another. They have almost the same color and shape. It is the problem of having more than 1 object of the same kind in an image.
2. The edges of each tooth are not strong enough to separate adjacent teeth from another. Also, the edges are very similar to the patterns of cusps and grooves.
3. The shapes of teeth are irregular.
4. In images from real humans, the position of each tooth is not fixed as shown in the diagram.

B.2 Order of attempts to apply various tools in the study

1. A photograph of human oral cavity was taken without any helping tools such as retractors, dental mirrors, and special cameras.
2. The dental arch (the teeth region) was separated from other parts of oral cavity, using color components and morphological operations.
3. The watershed algorithm was applied, but some teeth are not of convex shape.
4. Edge detection did not work, because of the problem #2.
5. There is a survey paper that categorizes image analysis tasks on medical images into classification/detection/segmentation/registration/etc. Most of the tools we tried belong to the segmentation category.

6. There is a survey paper on segmentation methods in medical image analysis. It classifies the methods into 3 classes of complexity, and also identifies them as automatic/semi-auto works.

7. Usually, the more manual input, the more efficient the methods are. The semi-auto methods of segmentation work better than automatic methods on average. However, this does not serve the effort to decrease human workloads as we want.

8. There is a survey paper on atlas-guided segmentation with CT-scanned images of human brain. The atlas-guided segmentation is a method that combines segmentation and registration. It is an automatic work. Could this concept work, the edge detection would be avoided.

9. Registration was applied but did not work well. The computations involved in this method are huge and the program ran very slowly. Also, the accuracy was too low.

10. There are 3 kinds of registration; landmark-based, segmentation-based, and voxel (volume&pixel) based. The landmark-based choice is a semi-auto work, so it was not considered. The voxel-based choice was time-consuming, with low accuracy. The only choice was segmentation-based, which relies heavily on image features such as edges.

11. The basic image features are edge/blob/corner/ridge, as shown in the Literature Review. Other features such as texture and color can also be considered for use.

12. There is an interesting conception - interpretation of digital images in other "spaces" than intensity values in each pixel. Direct calculation on every pixel is a huge work and it is slow. A number of new tools are developed from this conception, for examples - Fourier transform and wavelets.

13. From #12, there are spaces specifically developed for digital images. "Curvelet", "shearlet", and "ridgelet" came from images being 2-dimensional objects and they emphasize the 2D features such as directions of edges and shapes.

14. There is a space named MCA (morphological component analysis), in which curvelets, shearlets, and ridgelets are included, possibly with other features especially textures and patterns. Unfortunately, there were problems; the toolbox installation was complicated, the theory behind this conception was found only in a few places, and there is too little information of its usage.

15. However, the turning point came after looking at MCA being used in a research. The research used different image features to separate components in the images of eyeballs, using MCA. This provided us the brief outlook of the solution to our work - we needed to pick the feature(s) that actually "differentiate" teeth in the image for this thesis, not to find the common features among them.

16. As shown in the previous parts of this thesis, template matching was selected to differentiate the inner teeth; premolars and molars. Also, the work was divided into two parts, since the frontal teeth incisors and canines do not have patterns like the inner teeth do.

17. For frontal teeth, Gabor filters were tried first. They did not work because they are still based on edge detection. They did not catch frontal teeth like blobs as expected.

18. The watershed algorithm was reconsidered. It worked catching all incisors because of the shape, but did not do well with canines. Then the canines' location were predicted instead of directly detected. The centroids of incisors and a line equation were used in the prediction as shown in Methodology.

CURRICULUM VITAE

NAME : Sakdinee Rattana

EDUCATION BACKGROUND:

- Bachelor of Science (Mathematics), Suranaree University of Technology, Thailand, March 2019

SCHOLARSHIP:

- Under Her Royal Highness Princess Maha Chakri Sirindhorn

EXPERIENCES:

- Teaching assistant at the School of Mathematics, Institute of Science, Suranaree University of Technology, from trimester 3/2018 to 3/2020: Calculus III, Foundation of calculus, Numerical methods for computer, Analytical calculus II, Complex variables, Differential equations II, Differential equations for civil engineers, Calculus III (international program), Principles of mathematics
- Teaching substitute for Mathayom 4 at Surawiwat School, Nakhon Ratchasima, July-September 2019
- Research assistant in the project "Analysis and Classification of Teeth from Mobile Phone Photographic Image" 2020-2021

CONFERENCE:

- The 4th PIM International Conference "Globalization Revisited: Building Organization Resilience with Digital Transformation", March 3rd, 2021