DEVELOPMENT OF AN ACQUSITION AND IMAGE ENHANCEMENT PLATFORM FOR DIGITAL DENTAL IMAGING

by

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DEVELOPMENT OF AN ACQUSITION AND IMAGE ENHANCEMENT PLATFORM FOR DIGITAL DENTAL IMAGING

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ABSTRACT

DEVELOPMENT OF AN ACQUSITION AND IMAGE ENHANCEMENT PLATFORM FOR DIGITAL DENTAL IMAGING

With technological developments in X-ray imaging, digital systems started to replace analog systems. Principle advantages of digital X-ray imaging are; it has lower cost (in the long run), is ready to be processed with a computer, could acquire 3D images and has better imaging quality even at low radiation doses. Usage of digital technology in dental imaging is also increasing rapidly. Although, dental dose levels are significantly less than other X-ray imaging techniques, its cumulative effects could be harmful in the long term. Main aim of this thesis is to set up a digital dental imaging system and to implement its image processing software. A digital dental X-ray system consists of three of the shelf components; a digital intraoral X-ray sensor, a portable X-ray tube and a computer. The new digital system and its acqusition software are tested on phantom and cadaver tests. Furthermore, effects of several image enhancement techniques on low dose dental radiographic images are examined.

Keywords: dental, X-ray imaging, image enhancement

ÖZET

DİJİTAL DİŞ GÖRÜNTÜLEMESİ İCİN GÖRÜNTÜ KAYDETME VE İYİLEŞTİRME PLATFORMU GELİŞTİRİLMESİ

Teknolojinin gelişmesiyle birlikte, analog X-ray görüntüleme sistemleri yerlerini dijital sistemlere bırakmaya başladı. Uzun vadede gerçek maliyetlerin düşük olması, 3 boyutlu görüntülemeye izin vermesi, görüntülerin bilgisayar ortamında işlenebilir olması ve düşük dozlarda dahi istenen kalitelerde görüntü elde edilebilmesi dijial teknolojinin avantajları arasındadır. Diş hekimliğinde de dijital sistemlerin kullanımı gün geçtikçe artmaktadır. Her ne kadar diş hekimliğinde kullanılan doz miktarları diğer X-ray görüntüleme yöntemlerine göre az olsa da, uzun vadede insan vücuduna zarar verebileceği unutulmamalıdır. Bu tezin hazırlanmasındaki öncelikli amaç dijital bir diş görüntüleme sisteminin kurulması ve ona uygun bir imge işleme yazılımın geliştirilmesidir. Basit bir dijital diş röntgen sistemi başlıca üç komponentten oluşmaktadır; diş sensörü, portatif X-ray tüpü ve bilgisayar. Kurulan görüntüleme sistemi ve geliştirilen yazılım fantom ve kadavradan alınan görüntüler üzerinde test edilip sonuçları anlatılmıştır. Ayrıca güncel görüntü iyileştirme teknikleri arasından bazılarının özellikle düşük doz diş radyografileri üzerindeki etkileri araştırılmıştır.

Anahtar Sözcükler: diş X-ray görüntülemesi, imge iyileştirme

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

$R_i(x, y)$	Retinex output
$I_i(x, y)$	Image distribution in the i^{th} spectral band
$F(x, y)$	Gaussian function which equals to $Ke^{-(x^2+y^2)/c^2}$
K	Constant value which is determined by $\int\int F(x, y)dxdy = 1$
c	Gaussian surface surround constant
h(x)	Histogram function
N	Number of scales
ω_n	Weight associated with n^{th} scale

LIST OF ABBREVIATIONS

kv	Kilovoltage
kVp	Peak kilovoltage
ma	Milliamper
mAs	Milliamper second
CT	Computed tomography
AC	Alternating current
DC	Direct current
CCD	Charge coupled device
CMOS	Complementary metal oxide semi-conductor
PSP	Photostimulable phosphor
TMJ	Temporomandibular joint
CBCT	Cone beam computed tomography
SSR	Single scale retinex
MSR	Multi scale retinex
HE	Histogram equalization
CLAHE	Contrast limited adaptive histogram equalization
API	Application programming interface
OS	Operating system
MFC	Microsoft foundation classes
OpenCV	Open computer vision
BSD	Berkeley software distribution
DBMS	Database management system
ODBC	Open database connectivity
MSVC	Microsoft visual studio C++
PGC	Pixel gain correction
PDC	Pixel defect correction

1. Introduction

Dental radiographs are important in dental examinations for many reasons. They can expose hidden tooth decay; reveal a tooth abscess, cyst or tumor; show impacted or extra teeth; and also help to determine the condition of dental fillings, tooth crowns, dental bridges and root canals. These are just some of the many reasons why dentists rely on dental X-rays.

Once photographic film has been exposed to X-ray radiation, it needs to be developed. Traditionally, this is done using a process where the film is exposed to a series of chemicals in a dark room, as the films are sensitive to normal light. This can be a time-consuming process, and incorrect exposures or mistakes in the development process can necessitate retakes which expose the patient to additional radiation. Digital X-ray imaging, which replaces the film with an electronic sensor, address some of these issues, and is becoming widely used in dentistry. It requires less radiation and allows acquired images to be processed much quicker than conventional radiographic films. Acquired images are instantly viewable on a computer. However digital sensors used to be extremely costly and had relatively poorer resolution, both are much improved currently in modern sensors.

Digital imaging is being used more and more in place of analog imaging, because digital technology is cheaper, images can be processed directly with computers and can be stored easier than analog ones. Modernization and digitization of old systems are rapidly spreading [1].

When working with dental radiographs, one of the most important thing is dose level that a patient is exposed to. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report [2], dental radiology is the most frequent X-ray examination. In addition, majority of dental radiology investigations is performed in dental clinics where there is neither any routine quality assurance programme nor proper operator training. Patients may be subjected to unnecessarily high-radiation doses due to unsatisfactory equipment or inadequate techniques which requires many repeat exposures.

Main objective of this thesis is to set up a digital dental imaging system and develop a suitable image processing software with a focus on dose reduction in digital systems compared to analog ones. In the next chapter, background information about digital dental systems and digital image processing is given. In the third chapter, development of a digital dental X-ray system is explained in detail. In the last chapter, initial tests on phantom and fresh cadaver of our dental imaging system are presented and discussed. In addition, information on the newly developed image acquisition plugin and Ipad client application can be found at the end of the last chapter. User manuals of the developed software are given in the appendix section.

2. Background

In this chapter, brief background information about digital X-ray imaging and image processing methods will be given. In order to understand our in-house developed digital X-ray imaging hardware and software, X-rays and image enhancement algorithms will be introduced first.

2.1 X-ray

2.1.1 History of X-ray

Earliest invention of X-ray dates back to year 1895, when German physicist Wilhelm Conrad Röntgen decided to work on cathode rays in his laboratory. Cathode rays are invisible stream of electrons and cause flourescent atoms to glow when they hit them. On the evening of November 8, 1895; Röntgen realised that even when he enclosed the crooke's tube, which is used to produce cathode rays, with cardboard, there is shimmering on the paper plate covered with barium platinocyanide which was two meters away from the tube. This observation made Röntgen realize that there should be invisible penetrating rays produced by crooke's tube. During several experiments, he found that if he put different objects in front of the tube, the amount of shimmering changed. Those changes pointed out penetrating ratio depended on type of objects. Röntgen called these new rays as X-rays because of their unknown nature and the name is still in use today. By replacing paper plate by photographic plate he succeeded to record the first X-ray image. This was a new type of imaging never seen before. The first image was his wife's hand (Figure 2.1) where the bones of Röntgen's wife and ring on her finger is clearly seen. In further experiments, Röntgen showed that the X-rays are produced by the impact of cathode rays on a material object. Later, Max von Laue showed that they are of the same electromagnetic nature as light, but differ from it only in their higher frequency of vibration.

Figure 2.1 Radiography of Röntgen's wife's hand which is known as the first radiography ever taken [3].

2.1.2 X-ray Production

X-ray tubes are used to produce X-rays. Simple diagram of an X-ray tube is shown in Figure 2.2. In a typical X-ray tube, there is a cathode which emits electrons and an anode which collects electrons coming from the cathode. High voltage source is applied to anode and cathode in order to accelerate electrons. Accelerated electrons come off from the cathode and hit the anode. X-rays come out because of the atomic processes induced by this electron shot on the anode. According to the production mechanism, there are two types of X-rays which are called bremsstrahlung and characteristic.

Bremsstrahlung is also called "breaking radiation". In this type of X-ray production, the energetic electrons loose their kinetic energy while passing near the target atom's nuclei. This loss of kinetic energy appears as X-rays (Figure 2.3). A low-energy bremmsstrahlung X-ray is produced when an energetic electron slightly effected by nuclei's electrostatic field which causes the electron to slow down and change its direction. A high-energy bremmsstrahlung is produced when electron looses its all energy.

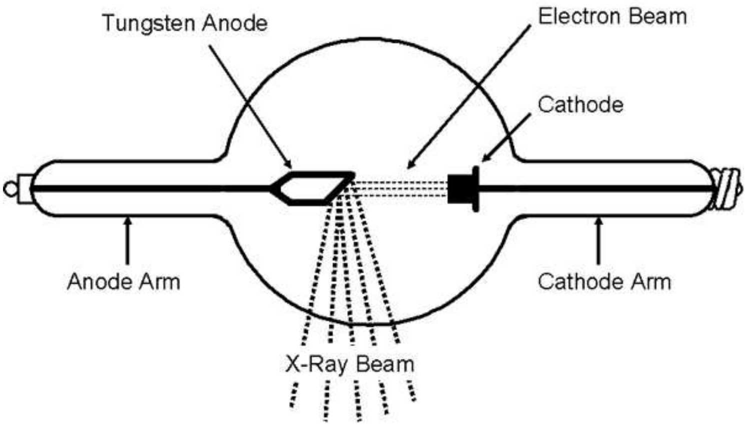


Figure 2.2 Schematic view of typical X-ray tube [4]

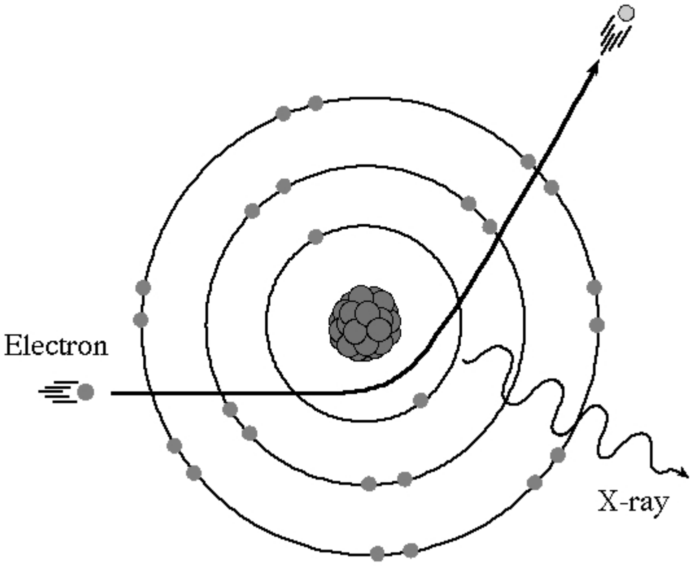


Figure 2.3 Production of X-rays by bremmsstrahlung radiation [5].

Second type of X-ray is called characteristic X-ray. When electrons bombarded to a target atom, they may hit energy shell of the target and excite an electron. The excited electron moves to the upper shell or leaves atom which resulting in a vacancy in the atom's shell. An electron from the higher shell with higher energy fills this vacancy. As a result of this relocation, intermediate amount of energy which is equal to energy difference between excited electron and incoming electron is released. This released energy produces X-rays (Figure 2.4).

Quality and intensity are two main parameters to classify X-rays. Quality is

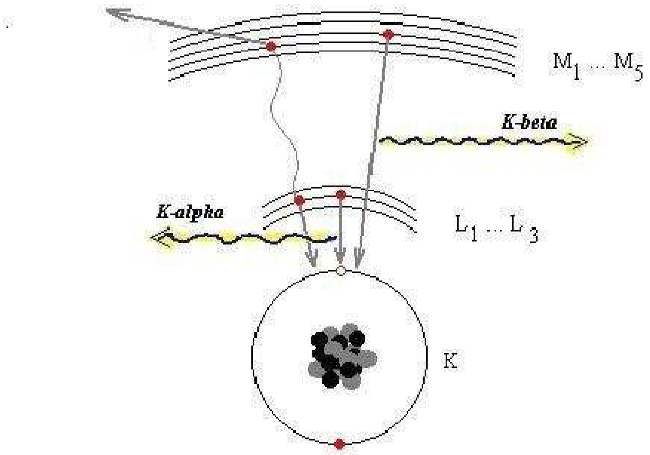


Figure 2.4 Production of X-rays by characteristic radiation [6].

penetrating power of X-ray photons and intensity is X-ray energy passing through unit area per unit time. Both quality and intensity can be changed by voltage, current and operation time on the X-ray tube. Their effects on the produced X-ray radiation are described below.

2.1.2.1 Effect of Voltage. Voltage between cathode and anode affects both quality and intensity of produced X-rays. Either characteristic X-rays or bremmsstrahlung X-rays can have photon energy up to the maximum kinetic energy of bombarded electrons. The higher voltage is applied, the higher maximum energy of photons are generated. This causes quality of spectrum to increase. When it comes to intensity, it is directly proportional to voltage change as well (Figure 2.5).

2.1.2.2 Effect of Current. Current is nothing but total number of electrons passing through unit area per unit time. The higher current, the higher number of electrons that hit anode. Therefore, the area under the X-ray spectrum, which shows intensity, increases with increasing current or viceversa. On the other hand, current has no effect on quality of X-rays.

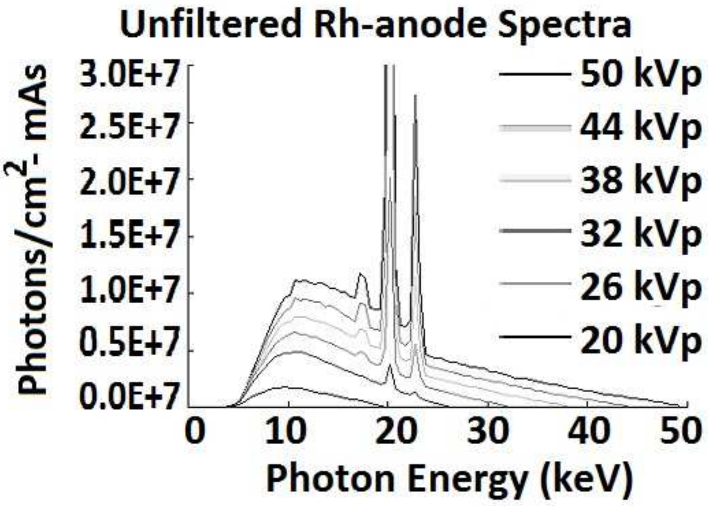


Figure 2.5 Effect of voltage change on the generated X-ray's energy spectrum [7]

2.1.2.3 Effect of Duration. Time parameter in X-ray production is important as well. Due to the fact that total amount of electrons passing towards anode increases proportionally by the operation time, it has the same effect as the current. Therefore, it is very common that duration controller and current controller are combined and used together as mAs, which stands for combined current and time.

2.1.3 X-ray Detectors

2.1.3.1 Photographic Film. Photographic film is a sheet of plastic which is coated with a material sensitive to light. When it is sufficiently exposed to X-ray it holds a latent image. After applying chemical processes (film development), the film is converted to a visible image.

2.1.3.2 Proportional Detector. Proportional detectors are designed to count particles of ionizing radiation. In this type of detectors there are two electrodes seperated by special gases. X-ray particles make these gases ionized while passing through them. This ionization results a current between electrodes. X-ray quaintity is calculated by measuring this current [8].

2.1.3.3 Microchannel Plate. Microchannel plate is formed by locating small channels, called electron multipliers, together with parallel orientation. When X-ray particle comes and strikes atoms on the inner channel surface, it causes electrons to be emitted. Emitted electrons are accelerated due to electrical field driven by voltage source. While these electrons are moving towards the end of electron channel they hit the inner surface again, ending up with new electrons. This process goes on until enough number of electrons are collected. X-ray level is measured by looking at the total number of collected electrons [9].

2.1.3.4 Semiconductor Detector. Semiconductor detectors are designed to detect particles by using semiconductors like silicon and germenium. When X-ray hits the surface of the detector, it produces free electrons and holes on the electrode surfaces. The number of electron-hole pairs on these surfaces is directly proportional to the total radiation energy. X-ray amount is calculated essentially by counting these holes.

2.1.3.5 Scintillator. Scintillator detector is made by combining a scintillator material and a photomultiplier tube. It emits very low visible energy when exposed to high-energy charged particles. When X-ray particle strikes the front side of the detector, the scintillator material absorbs it and scatters photons. This process creates current which is very low to detect. Photomultiplier tube at the back of the scintillator detector, multiplies this low current to make it detectable. The amount of radiation is determined by measuring this amplified current.

2.1.4 Health Risks and Shielding

X-ray became very popular right after its discovery. It was considered to be safe until it was shown that it has a potential to cause cancer. Researches showed that X-ray radiation can have several destructive effects for living objects: It can cause DNA mutations which result in apopitosis (cell suicides), random cell divisions and malformations. In addition, it can affect white blood cell production so that the immune system gets weaker making us more susceptible to diseases. Red blood cells could be affected as well, increasing the risk of anemia. If the subject is a pregnant woman, her fetus may be affected dramatically. It is also important to note that not only the patient exposed to X-rays but also the unprotected operators and healthcare professionals are under the radiation risk [10].

In order to reduce the risks of the radiation, precautions should be taken. There are three issues that need to be considered here.

1. Duration of the operation
2. Distance to the X-ray source
3. Shielding

X-ray operation should not last more than necessary, because the produced X-ray amount is directly proportional to the duration of the process. The distance to the X-ray source is important as well, since exposure is inversely proportional to the square of distance. Staying away from the source as far as possible reduces harmful effects dramatically. Last but not least precaution is the shielding, which refers to covering someone or something with material to protect from radiation. The most commonly used shielding material is lead. Due to its atomic properties lead can stop alpha rays, gama rays and X-rays. It is used extensively to shield X-ray imaging rooms. In addition, operators should wear lead glasses or lead aprons to protect their body [11].

2.1.5 Clinical Use of X-ray

Since Röntgen discovered that X-rays could identify bony structures, they have been utilized extensively in medical imaging. Radiology is a specialized field of medicine where the X-ray radiography was used almost exclusively to acquire diagnostic images until few decades ago when MRI imaging became available for routine clinical use. X-rays are useful in detection of the pathologies in the skeletal system as well as detecting diseases of the soft tissue. The most common example for clinical usage of X-ray can be the chest X-ray, which is used to identify lung diseases like pneumonia, lung cancer or pulmonary edema as well as fractures of the rib.

2.1.5.1 Plain X-ray.

Plain X-rays are used for diagnosing internal injury and pathology of the skull, face, spine, bony thorax and upper and lower limbs. Simple X-ray system consists of X-ray tube, collimator and X-ray film. Collimator is an aparatus which limits radiation exposure to only area of interest. Generated X-ray passes through subject and hits the film that is sensitive to X-ray and light. In order to prevent overexposure, film has to be enclosed in a cassette which does not allow light to come in. After developing film with chemicals, X-ray generated shaded image of the interested area is obtained (Figure 2.6).

Figure 2.6 Plain X-ray radiography [12].

2.1.5.2 Computed Tomography.

Until 1970's, plain X-rays were used in medical applications. There were several disadvantages of using plain X-rays, where we project a three dimensional object onto a two dimensional image plane: some anatomical structures could overlap and interfere with other structures. These problems were resolved by the invention of computed tomography(CT). CT uses a fan type X-ray source beam and array sensors which image slices of body by rotating around it (Figure 2.7). These slices when combined with the help of a computer give the full volumetric data of a subject. Although CT is one of widely used examination type for diagnostic purposes, its overall exposure dose could be significant (much higher than direct X-ray imaging) and should not be overlooked.

Figure 2.7 Computed tomography scanner [13].

2.1.5.3 Fluoroscopy. Fluoroscopy is used when it is necessary to screen internal structure of a patient in real-time. It is not only good for diagnosis but also suitable for real time operations performed on cardiac and brain vessels. Fluoroscopic system consists of X-ray tube and intensifier where a patient is placed inbetween. Tube produces X-rays continuously and as they pass through the body, they are attenuated with different ratios according to internal structures they hit and cast shadow of the impermeable structures on the final intensifier screen. Intensifier captures the image and sends it to the computer screen (Figure 2.8). The operation goes on continuously until it is terminated.

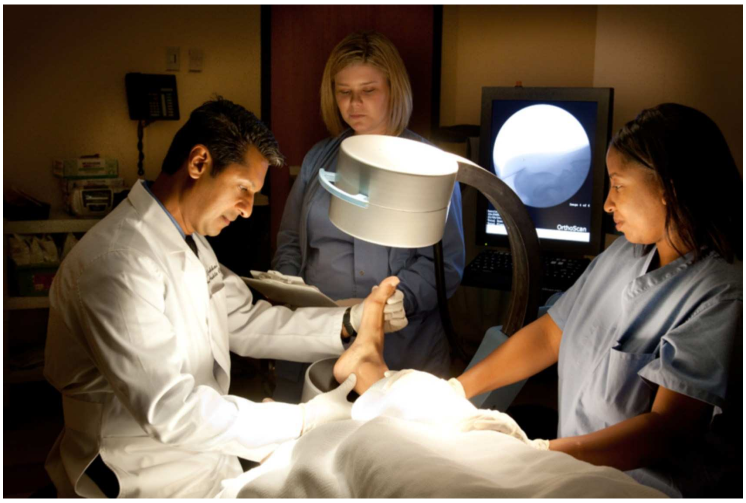


Figure 2.8 Typical flouroscopy which is used in an ambulatory surgery for foot treatment [14].

2.2 Dental X-ray Imaging

X-ray imaging is widely used in dentistry. Dental radiographs can show teeth, bones and soft tissues around them. Therefore they are useful for diagnosis, treatment planning and following outcomes of treatment. Almost all topics in various dental subdisciplines benefit from dental imaging: caries, periodontal diseases, endodontics, orthodontics, dental and maxillofacial traumas, implantology, temporomandibular joint disorders and jawbone or sinus lesions [15]. For each diagnosis or treatment, appropriate X-ray imaging technique should be used. These techniques will be described later.

Although dental exposures are less than most of the other medical exposures, its cummulative effect should not be overlooked. Furthermore, with the advent of three dimensional imaging techniques in dentistry, the amount of exposure increases gradually. It should also be noted that exposures in dental examinations can reach sensitive tissues such as thyroid and salivary glands easily.

2.2.1 Dental Tubes

In all dental X-ray examinations tube positioning is important. In order to adjust its position easily and to reduce the raditation dose, specific modifications are done on dental X-ray tubes; aliminium filtration, longer cones and rectangular collimators are some examples of these modifications. Simple view of dental X-ray tube can be seen on the Figure 2.9. X-ray voltage for these tubes is around 60 and 70 kV and both AC and DC are used.

Figure 2.9 Example of a dental X-ray tube [16]

2.2.2 Dental Sensors

2.2.2.1 Traditional Films. Traditional dental films are film based X-ray imaging systems. X-rays interact with electrons on the film and this produces a latent image. After applying chemical processes this latent image is converted to a gray shaded visible image. This technique is also referred as analog imaging. Sensitivity of the film determines the amount of dose that needs to be exposed for a good quality image. One drawback of this technique is its processing step. Once the film is processed by chemicals, there is no way to manipulate it again. Furthermore, if there is a problem during the processing, it needs to be retaken. Another disadvantage is that it usually needs more dose than digital sensors. Dose reduction can only be achieved by using high speed films.

Although traditional films have disadvantages discussed above, it is the most commonly used dental imaging technique today. The main reason is that dentists are accustomed to use these films for dental imaging and the cost of the film is very low. In addition placement of the film is easy for dentist and comfortable for patient due to its flexible structure [17].

2.2.2.2 Direct Digital Sensors. Direct digital sensors are solid-state detectors. Charge Coupled Device (CCD) is the earliest type of these detectors. Inside the CCD there are silicon crystal array which converts photon energy to electrons. Outer surface of CCD is covered with a scintillator screen. When X-ray hits this surface, it glows and CCD captures these photons. Captured photons are converted to electrons. Then, these converted electrons are transferred to common output source in order to be converted to digital data. Other type of digital sensors is Complementary Metal Oxide Semi-conductor (CMOS) based dedectors, which are invented later than CCD based sensors. Externally, CMOS appears identical to CCD, but it is using active pixel technology which means conversion of electrons to digital data takes place at each pixel. Cost of CMOS sensor is less than CCD sensors and it needs less voltage to operate. On the other hand, noise artefacts are more pronounced with CMOS sensors. Both CCD and CMOS based sensors have thick and rigid external housing structure.

2.2.2.3 Indirect Digital Sensors. In direct imaging, original image is captured in digital format whereas in indirect imaging, image is first captured in analog format and converted later into digital format. Indirect digital sensors use photostimulable phosphor (PSP). The image is captured on a phosphor plate as analog information and is converted into a digital format when the plate is processed. PSP radiographic systems were first introduced in 1981. The PSP consists of a polyester base coated with a crystalline halide emulsion that converts X-radiation into stored energy. The energy stored in these crystals is released as blue fluorescent light when the PSP is scanned with a laser beam. The emitted light is captured and intensified by a photomultiplier tube and then converted into digital data. Its resolution is less than traditional films but it is at a level compatible with around normal human visual perception. In addition, its cordless housing structure makes it more comfortable than direct digital sensors.

2.2.3 Dental Imaging Types

Dental imaging can be grouped into two main topics: intraoral imaging and extraoral imaging. Intraoral imaging refers capturing small areas of dentoalveolar process while extraoral imaging refers craniofacial complex. Intraoral imaging is most common imaging technique in dental imaging. There are three types of intraoral images: bitewing X-rays, periapical X-rays and occlusal X-rays. All these three X-ray techniques use two dimensional imaging. On the other side, extraoral imaging aims to examine larger areas and could uses three dimensional imaging techniques as well. It has four types: panaromic, cephalometric, sialography and CT scan.

2.2.3.1 Intraoral Imaging. As it is stated above there are three types of intraoral imaging techniques: periopical film, bitewing film and occlusal film. Anatomy of a typical tooth is showed in Figure 2.10.

Periopical Film: Main objective of periopical film is to show the apex of tooth and its surrounding bone. Entire crown needs to be imaged. Parallel technique is used for this type of imaging; sensor and tooth are aligned parallel to each other and X-ray is projected perpendicular to the sensor. In parallell technique projected geometry shows minimal distortions. Example of a periopical film is shown in Figure 2.11.

Bitewing Film: Bitewing radiographs only image the teeth crowns and alveolar

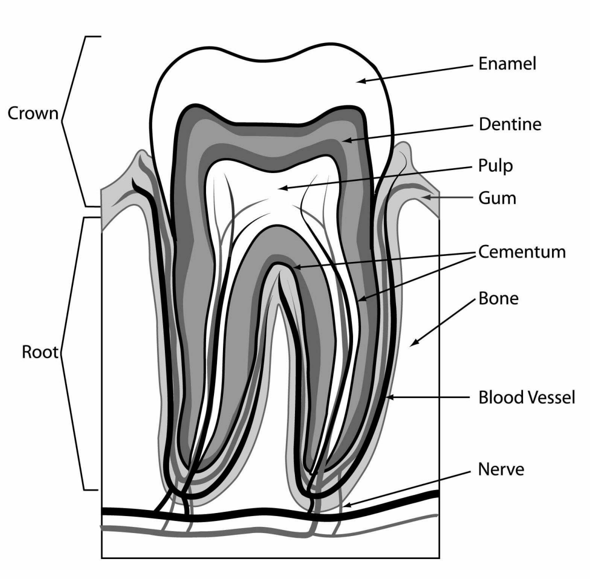


Figure 2.10 Anatomy of a typical tooth. Detailed explanations of these structures can be found at appendix B.

Figure 2.11 Sample periapical dental radiography

crest from both upper and lower teeth which makes them most suitable for visualisation of interproximal areas and associated carious lesions. As in periopical film paralleling technique is used. Example of bitewing film is shown in Figure 2.12.

Occlusal Film: The objective of occlusal film is to show large area of maxillary and mandibular arches, parts of the maxilla and the floor of the mouth. This type of film is larger than the periapical film. Patient bites on the entire film between the

Figure 2.12 Sample bitewing dental radiography

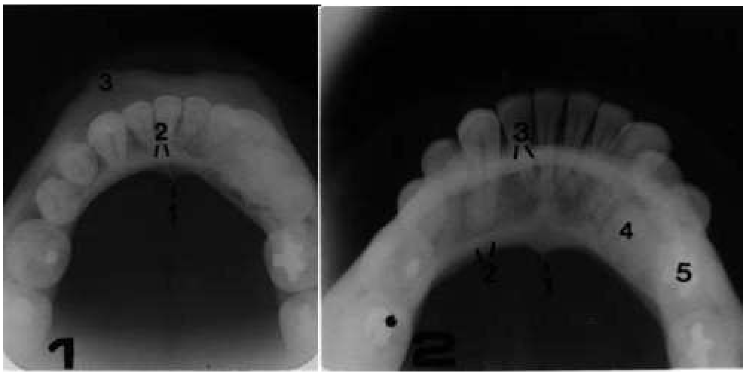


Figure 2.13 Sample occlusal radiography

occlusal surfaces of upper and lower teeth. Example of occlusal film is shown in Figure 2.13.

2.2.3.2 Extraoral Imaging. Extraoral imaging is used when dentist want to see the structures outside of the mouth. The reason why it is called extraoral is that the sensors are placed outside the mouth. Panaromic, cephalometric, sialography and CT scans are main types of extraoral of imaging.

Panaromic: Panaromic radiographs are one of the most used extraoral imaging technique. Captured radiographs are not detailed as much as intraoral images but cover a larger area and give information about mandibulofacial structures including jaws, teeth, sinuses and temporamandibular joint (TMJ). Furthermore, exposure dose used in panaromic examinations are optimized such that it is lower than the corresponding dose when mouth is fully scanned with intraoral images. Major disadvantage of panaromic imaging is geometric distortions and overlaps due to the projection of a three dimensional structure onto a two dimensional plane. Example of a panaromic film is shown in Figure 2.14.

Figure 2.14 Sample panaromic dental radiography

Cephalometric: This type of extraoral examination is used by orthodontists for diagnostic purposes. It is a projection X-ray image of the entire head from right or left side. According to measurements with several landmarks, cephalometric analysis is done on the film. Cephalometric analysis has contributed to the analysis of malocclusion and it has become standardized diagnostic method in orthodontic practice and research. Example of cephalometric film is given in Figure 2.15.

Sialography: Sialography is used for examining salivary gland problems. Dentists rarely use this type of film. In this examination, medium contrast is injected to the duct of the salivary gland of the patient by inserting a catheter through the mouth. Ordinary X-ray imaging techniques are applied with the aim of visualizing these glands.

CT Scan: Computed Tomography (CT) is used for creating three dimensional

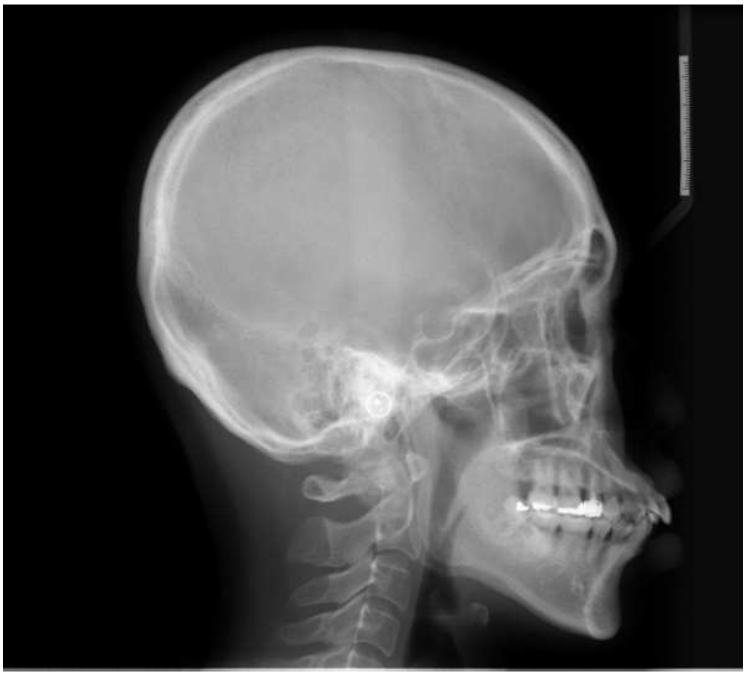


Figure 2.15 Sample cephalometric dental radiography

model of the head. It can be divided into two categories based on X-ray beam type: fan beam and cone beam. Their schematic view can be seen on Figure 2.16. Fan beam scanners scatter X-ray in a fan shape in order to acquire data slice by slice. Dentist could later use these slices to form the exact three dimensional model of the jawbone.

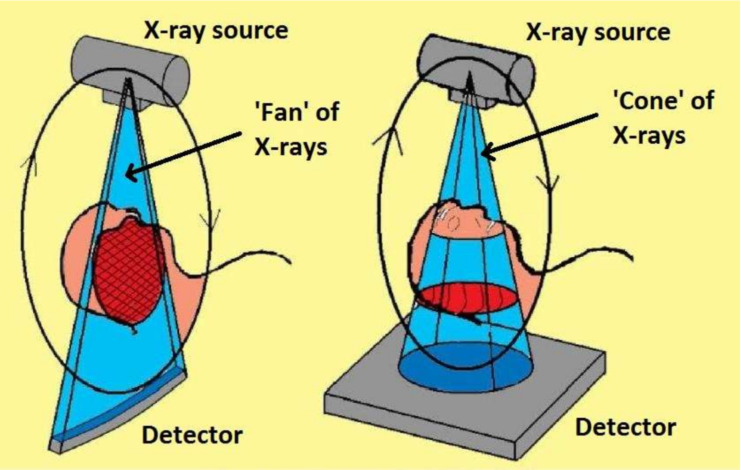


Figure 2.16 Left side and right side show schematic view of fan beam imaging and cone beam imaging respectively [18].

Cone Beam CT (CBCT) uses area detectors and X-ray source that is rotating around the head synchronously. At a particular vantage point, it acquires a two dimensional projection image. After all acquisitions are completed, a full three dimensional model is constructed using specific computer applications. CBCT is well suited for imaging the full craniofacial area. It provides clear images of highly contrasted structures and is extremely useful for evaluating bones. Published reports indicate that effective dose of radiation is lower than both fan-beam CT and panaromic images. On the other hand, CBCT has routinely more visible image noise.

2.3 Digital Image Enhancement

Digital images are nothing but two dimensional integer matrices, containing red, green, blue values for each pixel. Actually, it is not necessary for an image to contain three color information. Most of the medical images such as X-ray radiographs have only gray scale values.

Image enhancement can be explained as improving the perception of an image so that it becomes more suitable for a specific task. During this process one or more attributes of the image could be modified. Methods used for image enhancement can broadly be divided into two categories:

1. Spatial domain methods
2. Frequency domain methods

In spatial domain techniques, enhancement algorithms are applied directly to the image pixel values whereas in frequency domain methods, image is transformed to frequency domain first via Fourier transform and then enhancement operations are performed there. At the end, the image is transformed back to the spatial domain (using inverse Fourier transform).

2.3.1 Noise Reduction

Image noise could be described as "unwanted" fluctations on the brightness values of an image. As an example, the lena image (Figure 2.17) and its noisy version (Figure 2.18) which is created by adding salt and pepper noise are shown. Image noise can be caused by a wide range of sources: sensor calibration errors, environmental variables, quantization errors, etc. According to the type of the noise, it can be removed or reduced by applying appropriate denoising filters.

Figure 2.17 Lena image is one of the most widely used standart image in image processing algorithms.

Denoising an image before applying post-processing methods is important due to the fact that most of the post-processing methods either introduce additional noise to the image or amplify the existing noise. The more initial noise, the more noise in the resultant image. First of all, it would be better to keep noise as low as possible while acquiring the image. There are several algorithms used in digital image noise reduction. Three of the most basic algorithms are mean filtering, median filtering and gaussian filtering and they are described below.

Figure 2.18 Left image is original lena image. The image on the right shows salt and pepper noise on the lena image.

2.3.1.1 Mean Filtering. Mean filter is a very simple convolution filter; it works by calculating the mean value of a pixel's neighbours and replacing itself with this mean value. Typically, a NxN size kernel is passed over the image and new intensity values are calculated for each position. It is most commonly used as a simple method for denoising, but it does not preserve edges. Sample kernel for 3x3 kernel is shown as:

$$\frac{1}{9} \times \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

The convolution process that take part in mean filtering can be written mathematically as:

$$O(i,j) = \sum_{k=1}^{M} \sum_{l=1}^{N} I(i+k-1, j+l-1) K(k,l) \tag{2.1}$$

where

- I: Image to be processed
- K: Kernel used in convolution
- O: Resultant image

- M and N: sizes of the kernel

Sample 5x5 kernel applied to Figure 2.18 to see effect of mean filtering on noise. Resultant image can be seen in Figure 2.19. Since mean filtering introduces blur to the image, it is not suitable if edge details are important.

Figure 2.19 Denoised image after applying a 5x5 mean filter to Figure 2.18

2.3.1.2 Median Filtering.

Median filter is a two dimensional edge-preserving denoising filter. It works like the mean filter except it computes the median value of the pixel neighbours instead of the mean value. NxN matrix is passed over source image data and at each step intensity values on the matrix are sorted in increasing order. Then, center value of the matrix replaced by the median value of the sorted array. While median filter preserves edges, it takes more time than mean filter to sort and replace values. Example of median filtering is shown in Figure 2.20.

Figure 2.20 Denoised image after applying a 5x5 median filter kernel to Figure 2.18

2.3.1.3 Gaussian Filtering. Gaussian filter works in the same way the mean filter does. But the kernel is designed in such a way that it represents two dimensional discrete approximation of a gaussian distribution. Example of a 5x5 kernel of a gaussian filter can be given as:

$$\frac{1}{273} \times \begin{pmatrix} 1 & 4 & 7 & 4 & 1 \\ 4 & 16 & 26 & 16 & 4 \\ 7 & 26 & 41 & 26 & 7 \\ 4 & 16 & 26 & 16 & 4 \\ 1 & 4 & 7 & 4 & 1 \end{pmatrix}$$

The result of denoising of the same noisy image with this gaussian kernel is shown in Figure 2.21.

Figure 2.21 Denoised image after applying a gaussian filter to Figure 2.18

2.3.2 Image Enhancement

2.3.2.1 Retinex. Retinex is an image enhancement method which is proposed in 1971 by Edwin H. Land. It is based on dynamic range compression, color independence from the spectral distribution of the scene illuminant, and color/lightness rendition. It models how human visual system perceives color in different lighting conditions. At first, it is proposed for satallite images and then extended and used in different areas for general purposes such as medical radiography, forensic investigations [19]. Several extensions of retinex have been defined. Single scale retinex (SSR) which is one of these extensions can be expressed as:

$$R_i(x, y) = \log I_i(x, y) - \log\left[F(x, y) * I_i(x, y)\right] \tag{2.2}$$

where

- $I_i(x, y)$: Image distribution in the i^{th} spectral band

- $R_i(x,y)$: Retinex output
- $F(x,y)$: Gaussian function which equals to $Ke^{-(x^2+y^2)/c^2}$
    - K is determined by $\int\int F(x,y)dxdy = 1$
    - c is the Gaussian surface surround constant

SSR extended to Multi Scale Retinex (MSR) in which different scaled SSR images are added with different weights. It is reported that MSR is better than SSR in dynamic compression and color rendition [20]. MSR is formulated as:

$$R_{MSRi}(x,y) = \sum_{n=1}^{N} \omega_n (\log I_i(x,y) - \log\left[F(x,y) * I_i(x,y)\right]) \tag{2.3}$$

where

- N: Number of scales
- ω_n: Weight associated with n^{th} scale

Example for SSR and MSR images are shown in Figure 2.22.

2.3.2.2 Histogram Equalization.

Image histograms are graphical representations which shows tonal distribution in a digital image. It is a discrete function and can be formulated as below:

$$h(x) = n \tag{2.4}$$

where

- x is the tonal value
- n is the total number of the x tonal values in the image

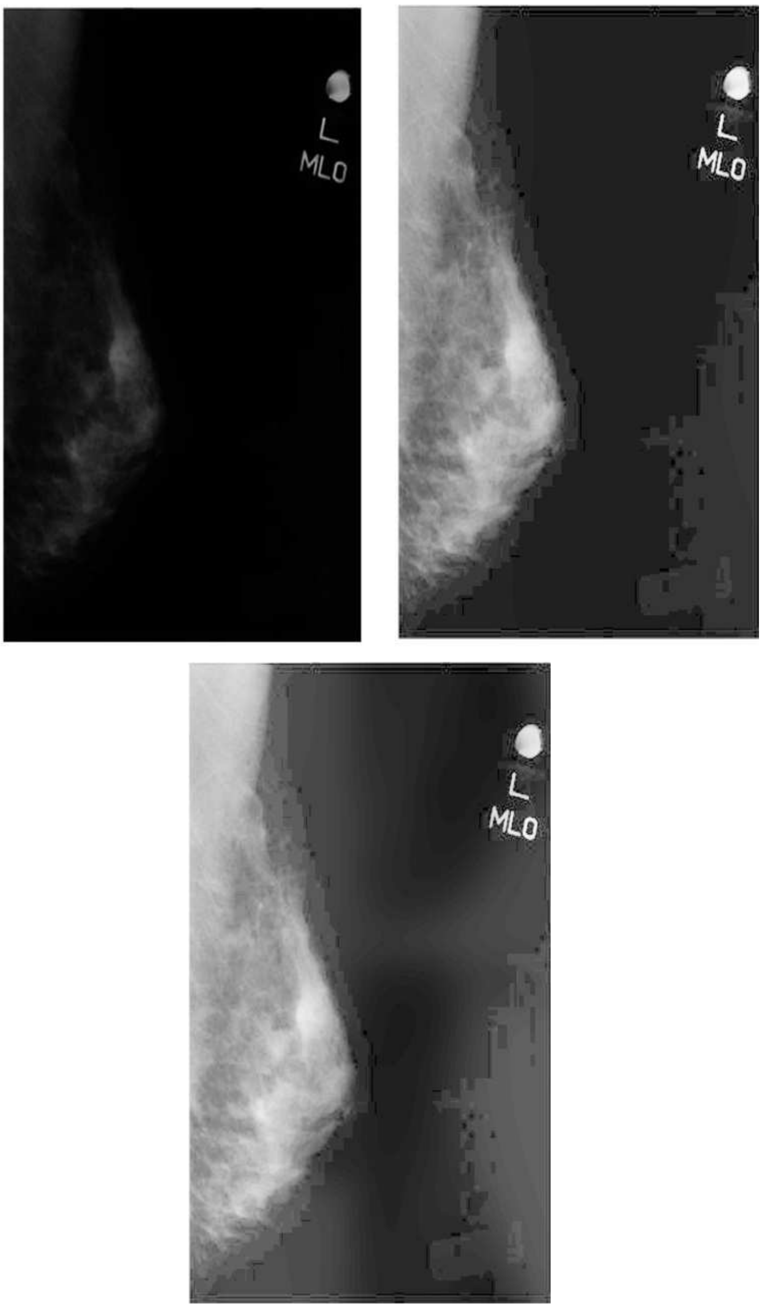


Figure 2.22 The image on the upper left is the original version of the mammogram image. The image on the upper right is the processed image with SSR where c value is 250. The image on the bottom is the processed image with MSR where c values are 250, 80, 15 [21].

As an example, histogram of the Lena image (Figure 2.17) is given in Figure 2.23. Image histograms can give information about intensity distribution.

Histogram equalization (HE) is a method where compressed tonal values are strecthed out such that new histogram looks more uniformly distributed (Figure 2.24). This technique increases global contrast of the image. Therefore, it is good for images

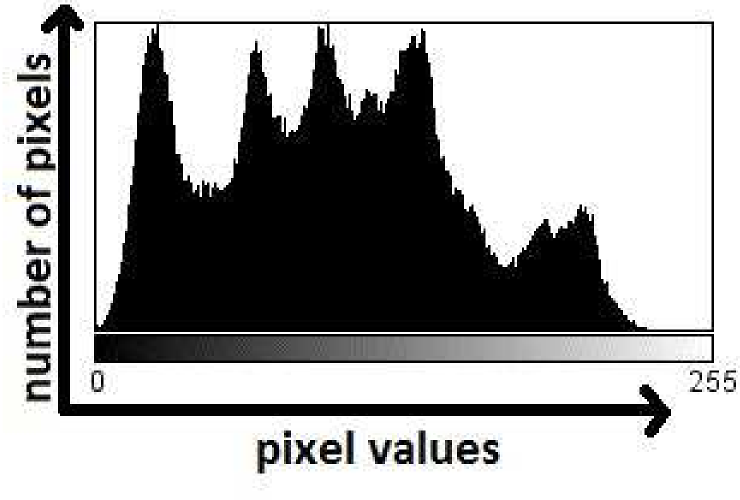


Figure 2.23 Histogram of the lena image in Figure 2.17

with foreground and background that are both dark or bright but not for images that have locally different dark or bright regions. Also, it is reported that HE introduces background noise to image and decreases brightness of the image as well [22].

Figure 2.24 Left image is the original image before applying HE. Left image is the resultant image after applying HE.

2.3.2.3 Contrast Limited Histogram Equalization. Contrast limited histogram equalization (CLAHE) is considered as an improved version of HE [23]. As it is stated above, HE is good for global contrast enhancement. If the image has locally dark and bright areas then HE fails to produce good enhancement and some sharp features in the image get lost. In order to overcome this problem CLAHE divides image into subregions and applies HE them seperately. After calculation of new local histograms, regions are stitched together by using interpolation. Effect of CLAHE can be seen in Figure 2.25.

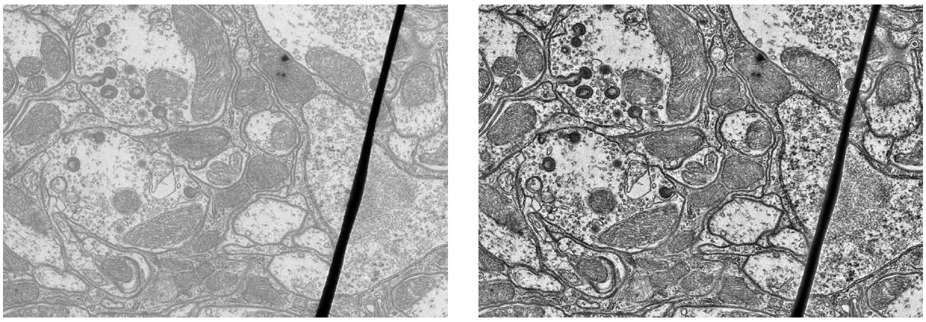


Figure 2.25 Image on the left is before applying CLAHE. Image on the right is after applying CLAHE.

3. Development of a Dental X-ray System

The aim of this thesis is to set up a simple digital intraoral X-ray system and more specifically to develop a preliminary software for acquiring and processing X-ray images using these system. There are mainly three components in such a system which are X-ray source, digital X-ray sensor and a computer. Since the current level is low and imaging duration is short, overheating does not occur. Therefore, there is no need to put a cooling system for the X-ray source which allows to use portable tube as an X-ray source. Digital sensor is directly connected to a computer via cable and continuously waits for the trigger that comes from the X-ray tube. Once the image is acquired, a dedicated software program is used to get, process and store it. Simple diagram of the system can be seen in Figure 3.1.

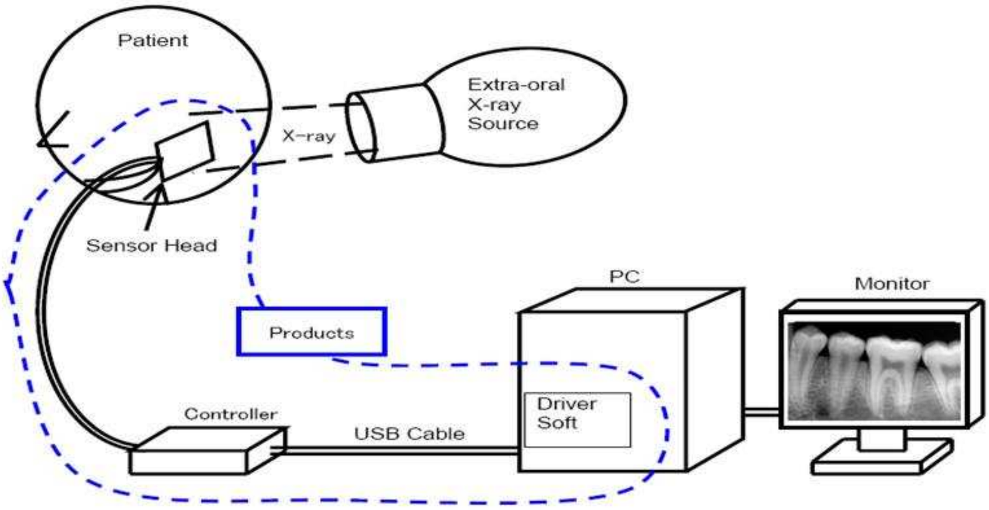


Figure 3.1 Schematic view of digital dental system

For the first experimental system, a portable X-ray tube which operates on 60 kVP and 1mA is selected. As the digital sensor, Toshiba dental CMOS type sensor is chosen. The size of this sensor is 20x30 mm and supports 1006x1500 pixel resolution. It has its own triggering mechanism which enables it to be triggered automatically when exposed to X-rays.

3.1 Standalone Application

In this section, standalone software which was developed for this thesis and its implementation details will be explained. The core driver of the dental sensor is a dynamic link library (dll) which is provided by Toshiba. Significant coding effort were necessary to make a standalone software starting from this dll. Application is implemented currently for windows operating system and its structure depends on windows shared libraries. There are two basic types of programs in windows operating system environment: a console program and a windows program. Console program is any executable that runs through command console without any user interface. The second type is window programs which includes a windows style user interfaces to allow user to communicate with an application.

Windows programs use message based event-driven paradigm. In this type of programming paradigm, main flow of the program determined by events e.g. mouse click, keyboard entry, object specific messages etc. Every message is sent to related window or object by the operating system (OS). When a window or object gets message from OS, it calls corresponding function which is defined in its message handler routine.

Win32 api is a low level programming library implemented by Microsoft for developing windows programs. Microsoft Foundation Classes (MFC) Library is an abstraction over win32 api in order to make it more usable and practical. It wraps portions of win32 api in C++ classes.

Imaging applications use image input, output and processing operations extensively. Most of these type of operations are standart for each medical imaging application. The rapid way of implementing error-free applications is the use common libraries. Open Computer Vision (OpenCV) real time computer vision library, which is released under BSD license and open for both academic and commercial use, was used for image related operations.

Digital imaging systems are capable of storing images for later evaluations. This application also uses database management system (DBMS) to keep image and patient records. Open Database Connectivity (ODBC) is used for database processes. ODBC provides general standard interface for DBMSs. Any DBMS which provides ODBC driver can be accessed via same methods. Once the connection is established with ODBC, rest of operations are same regardless of used DBMS. In this application, ODBC driver that is supplied by Microsoft Access DBMS is used to manage database related operations.

Last but not least issue when handling software projects is choosing and using appropriate framework. Framework is simply an application that is used to handle and manage source code and built options of the project. Microsoft Visual Studio C++ (MSVC) framework was chosen and used in this project.

To sum up, for our software, MFC and OpenCV libraries were used with MSVC framework. Sample diagram of digital dental X-ray software architecture is shown in Figure 3.2.

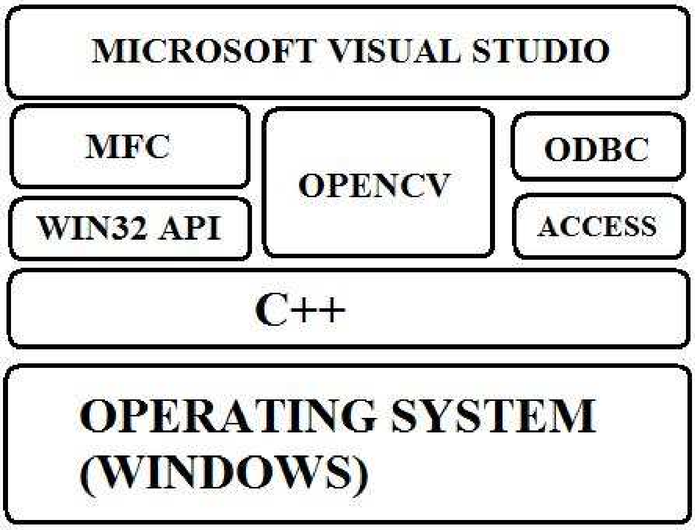


Figure 3.2 Diagram of the standalone application architecture

3.1.1 General Structure of Application

Dental X-ray application is designed to have user-friendly interface with lots of functionalities. Thus, main window contains a menu, image editing and processing toolbar and image explorer panel. Patient images are listed on this image explorer panel. Acquired or loaded images are displayed in a image viewer window. There may be multiple image viewers opened at the same time. But only one of them is active at a time and all image related operations are directed to this active image window. Detailed user manual can be found at appendix A.1.

3.1.2 Modules

Modularity of application is an important property in software engineering in order to manage a project with less effort. A module can be thought as a sub-application which has its own specific inputs and outputs and communicates and exchanges data with other modules. Dental X-ray application consists of four main modules which are acqusition module, image editing module, image processing module and database module. Their schematic view is shown in Figure 3.3. This section describes these modules one by one.

3.1.2.1 Acqusition. Acquisition module is responsible from communication with dental sensor before and after capturing an image. Once the user activates acquisition module, it checks for existense of sensor, pixel gain correction (PGC) file and pixed defect correction (PDC) files. If one of them is missing, module exits with error.

PGC and PDC are name of files that are used for sensor calibration. Since each sensor has different hardware characteristics, there is a seperate PDC and PGC file for each of them. PDC file keeps information of the defected pixels on the sensor, which can cause noise on the image. When the sensor acquires image, value of defected pixels are interpolated by using its neighbours' pixel values. The second calibration file PGC

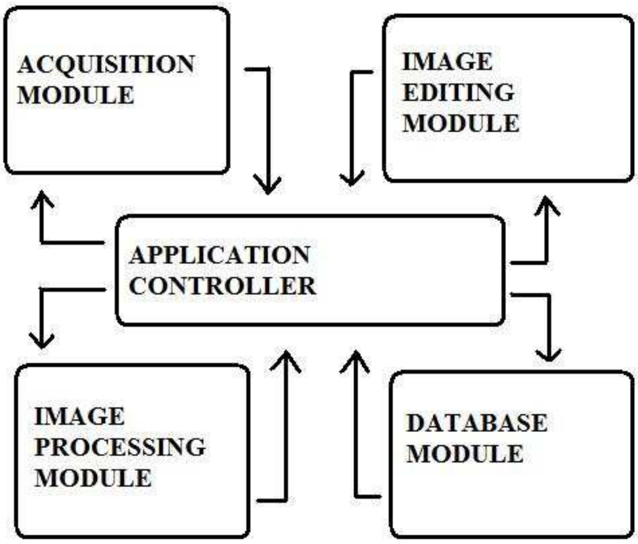


Figure 3.3 Schematic view of application modules

keeps track of gain value of each pixel. Gain value is the ratio between number of electrons that are captured by the camera and number of electrons that are converted to pixel value and it is specific to each camera pixel. They are measured by applying some electronic tests after manufacturing the camera and are kept in a PGC file. By using gain values in PGC file, real signal values can be calculated. If no PGC correction is done or gain values are measured wrong, then additional noise could appear in each captured image.

After sensor localization and calibration file check-steps are succeeded, digital sensor is powered, initialized and started to wait for X-ray trigger. The sensor is self-triggered and is sensitive to X-rays. If X-rays come and strike the surface of the sensor, then sensor driver sends the auto trigger message to the acqusition module. When the module gets this message, it creates new openCV image object and fills its data array with values coming from newly acquired image buffer. The sensor is capable of getting 12 bit images. In order to prevent any data losses, 16 bit short integer array openCV image object is used. Acquired image is sent to image viewer window in order to show it live on the screen.

If there is no X-ray triggering occured within a timeout duration, sensor driver sends a message which ends acquisition with a failure code and module is terminated.

3.1.2.2 Image Editing. Image editing is controlled via main toolbar. Images are showed with image viewer control. Basic operations that can be done in application are: open image, save image, zoom in/out, rotate image and flip image. These editing operations except image i/o are done on the memory copy. Thus, none of them modifies the original image.

Open: 16 bit Tagged Image File Format (TIFF) is only the type of image that is supported by the application. Image is stored without any compression. This is necessary for preventing data loss, on the other hand, size of images are larger. Approximately, a typical dental image occupies 2.88 megabytes.

Opening a new image is handled with openCV routines by loading image from harddisk to openCV image object. User can open and show any 16 bit TIFF image.

Close: Restrictions when opening an image are valid in saving operations. Files are saved and stored as 16 bit TIFFs with openCV image save function.

Zoom In/Out: One of the most necessary operation is zoom in and zoom out. They are used when user wants to see and examine a small region of interest on the image. This operation is controlled by MFC paint function. When a modification occurs on any window, onPaint message is sent to main application which forces it to redraw window by calling paint function. In image viewer class, paint function calls another drawing function which is used to copy image data to display buffer. This function also controls which portion of image will be displayed. Float variable named ZoomFactor which is used to keep how much image is zoomed in or out is defined in image viewer class. When user wants to apply zoom operation, this value is increased or decreased and onPaint message is sent. According to the value of ZoomFactor, paint function calculates boundaries of the image to be displayed and calls draw function with these new boundaries. The new center coordinates are calculated as well and are passed to drawing function to display zoomed region correctly.

When image is zoomed, the effective display resolution gets lower which could cause image to look bad. If halftone option is set to true before using drawing function, it automatically interpolates new points to make image look smoother. Still, after reaching some point it is meaningless to zoom in or out image. Thus, ZoomFactor is limited with lower and upper boundaries which means when it reaches these values, drawing function does not make image bigger or smaller anymore.

Zooming can be done either via toolbar or via middle button of mouse.

Rotate: Rotating an image is another necessary task, because, according to the position of sensor, dentist may need to rotate image. This operation is done on memory. Actually, drawing function function can deal with rotation as well but in order to keep track of how many rotations are done and to combine this operation with other operations like flip, it is simpler to make rotation on memory each time.

Rotate can be towards to left or right direction. When image viewer dispatches the rotate message, it creates a new openCV image and copy each image array element to its new position. After rotation is done, new image is set to be shown in image viewer and onPaint message is sent to make application redraw the window. Old image is released and deleted from memory.

Flip: Flip operation is similar with rotation. Only difference is calculation of new coordinates. Instead of rotation, flip function should flip pixels horizantally or vertically. Again old image is changed with new image and onPaint message is sent.

Grid: Grid may be useful when user compare distances over the image. It draws lines on the display area with 1 mm intervals by using MFC draw line method. This operation is done in drawing function. If grid option is set true, then application draws vertical and horizantal lines over display area. ZoomFactor of the image is considered while drawing lines such that intervals becomes bigger and smaller according to ZoomFactor. When user turns off grid option, previously displayed grids are removed.

3.1.2.3 Image. Displaying the image is something more than just sending image buffer to dispay buffer. Because acquired images are stored in 16 bits and a routine display card supports only 8 bits. It is very important to downsample image data correctly. Otherwise, resultant displayed image may be judged as having a poor quality. First thing that should be considered when working with medical images is that contrast level should be adjusted appropriately. In 12 a bit digital imaging system, pixel values vary between 0 and 4095. But only 256 different levels of gray shading could be displayed on screen. Therefore, there should be a transfer function which gets original image data as input and transfers it to desired range for the display. Graphical view of transfer function is shown in Figure 3.4. This operation is called windowing.

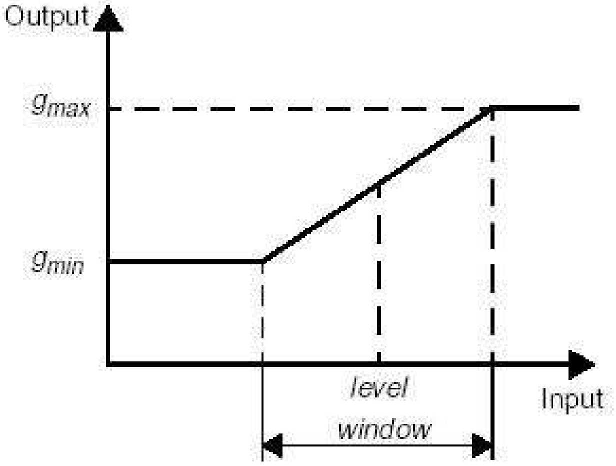


Figure 3.4 Windowing on 12 bit images. Input axis and output axis represent the initial pixel values before the windowing process and the resultant pixel values after the windowing process respectively. Window level controls the number of pixel levels that are going to be displayed in the output image. Pixel value which corresponds to the center point of window level is called window center and is used to specify the pixel values to be used in windowing.

Histogram of an image shows the intensity distribution of all of its pixel values. Before displaying image on screen, our application calculates its histogram. If the histogram of the displayed image is restricted on a specific region, a standart image contrast will be non ideal due to many zero valued bins. In order to prevent this, first the smallest and biggest histogram values are determined on the original 12 bit image.

All values between them are linearly transferred to corresponding value between 0 and 255. This is called automatic windowing or histogram clipping.

In some cases, linear contrast adjustment is not enough. Applying some image enhancement algorithms may result in better images. Three known enhancement algorithm are implemented in this application: Retinex, Contrast Limited Histogram Equalization and Histogram Equalization(HE). Background information on these algorithms were given on the previous chapter. Comparative test results of these algorithms are discussed at last chapter.

HE is already found in openCV library. When application needs to apply HE, it first converts openCV image to appropriate type and then applies HE. Resultant image is displayed in a new image viewer window.

An implementation of retinex as an opensource, is used in this application. Multi Scale Retinex is used with 15, 80, 200 sigma values with equal weights. The image and three filtered images with given sigma values are converted to the log domain and subtracted from the original with equal set of weights. Resultant image displayed in a new viewer window.

In Graphic Gems IV book, Karel Zuiderveld implemented C version of CLAHE. It is encapsulated so that it can run with openCV image objects and used in the application. This implementation needs number of regions, image data, histogram clip limit as an input parameters. If these parameters are provided, algorithm runs and returns a new image with enhanced contrast. At first, it calculates histograms of sub regions one by one. Then applies histogram equalization to each region. At the last step, interpolation is done between region borders in order to eliminate border artifacts. Resultant buffer is used to create new OpenCV object and displayed in image viewer.

3.1.2.4 Database. Database module uses ODBC with microsoft access database as a database language. There is not any heavy database processes expected in the current application. For database structure, two tables for patients and images are created. There is one to many relation between patients and images via patient's unique id. Schematic view of tables are shown in Figure 3.5.

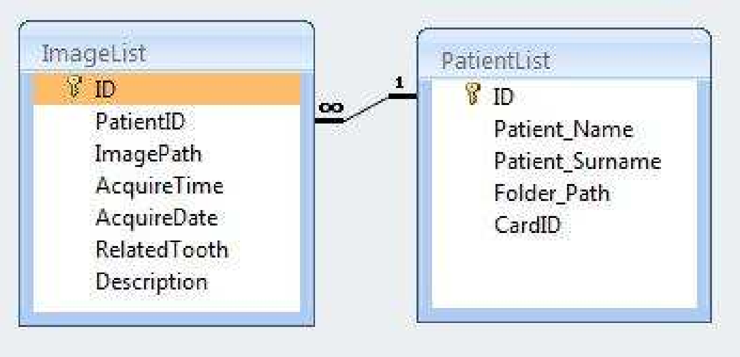


Figure 3.5 Database relation between patient and image tables

Every patient record consists of unique id, name, surname and folder path fields. Folder path is the directory name where images are saved. Application keeps active patient id. When new image is acquired, it is saved to patient's image folder path. Database module also responsible from creating new patient and loading old patient and retrieve its information. Application allows user to edit name or surname.

Image structure contains fields to store path of the file, name of related tooth, acqusition time and date and description about treatment. When patient is loaded, database retrieves image list related to loaded patient and sent it to application. Any image from the list can be loaded and displayed in a image viewer upon request.

3.2 PC MFC Plugin

This section describes developed MFC plugin which can be called from any standalone MFC application in order to capture digital dental image. Plugin is compiled as windows shared dll library with embedded MFC user interface. This plugin also uses in its core the Toshiba dental sensor driver to capture images. Once the dll is called, the dialog window pops up and waits for X-ray trigger. There is no timeout for dialog. Unless user cancels dialog box, it remains open in waiting state. If digital sensor exposed to X-rays, sensor driver sends trigger message to dialog window. Message handler dispatches the trigger message and reads image buffer in the driver.

Transferred image data should be prepared before showing on the screen. A typical flow will be as follows: image buffer is first sent to windowing function which determines width and level of image automatically. Then, median filter is applied to reduce noise originated from signal source. CLAHE is applied to denoised image in order to adjust local contrast. At last step, orientation of image is adjusted according to the sensor position in patient's mouth. Position information should be provided by dentist before shoting X-ray tube by choosing position of sensor from top-right corner of dialog window.

After all of the processing done succesfully, each image is downsampled to 8 bit to be displayed on the screen. At the center of dialog window there is a picture viewer object which shows the last acquired image. When a new image comes, old one is minimized to thumbnail sizes and is transferred to the first empty slot on left or right side of dialog. If the number of images reaches twelve which means there is no more slot left for old images, dialog box terminates and exits after saving acquired images.

There are also extra control buttons on the dialog box. First one is exit button. Whenever this button is pressed dialog window saves acquired images and terminates. Second one is the grid button which draws a grid with 1 mm intervals on the image.

These are main functionalities of MFC dll plugin. User guide of this plugin can be found in appendix A.2.

3.3 Ipad Client Application

With evolutions in touchscreen technology, tablet devices became more popular. One of the most succesful product on the market is Apple's Ipad. Its compact design and high-sensitive touchscreen makes it practicle for multimedia applications. It may also be practical for dentists to use these devices in their clinics. They can view acquired images and apply simple image editing procedures easily. Furthermore, they can show images to patients in order to give information about treatment. For these reasons, we developed Ipad client application for dentists to view dental images on tablet devices.

We need an Apache web server which responds to http requests on server side. Client side was implemented with php with javascript. It sends http requests with small time intervals continuously to ask for new image. If there is a new image on server, server notify client to load and show it.

There is a toolbar on top of the screen which enables user to edit image. User can invert, flip and restore original image with the help of toolbar buttons. Contrast of the image can be adjusted by using touchscreen. Sliding finger to the right or left on screen causes contrast to be increased or decreased. Zoom in and out operations can be performed with touchscreen as well. User manual of this Ipad client application is given at appendix A.3.

4. Initial Tests Performed Using X-ray Images

In this chapter, initial tests of the X-ray imaging system and their performance results are given. These tests are focused on two main topics; first one is the performance of digital sensor, and the second is the performance of the software. Both groups of tests are designed to understand if it is possible to have good quality images with reduced radiation dose.

Dosimeter is a device which measures exposure to a physical entity like radiation, sound etc. Ionization dosimeter is a type in which ionized radiation in the environment is measured. A radcal mark ionization dosimeter is used in tests of this thesis to measure radiation dose of X-ray tubes that are used in digital system and analog system. The dosimeter can be seen in Figure 4.1.

Figure 4.1 Ionization dosimeter that is used in measuring radiation. exposure of the X-ray tubes

The dosimeter works by counting the air particles that X-ray causes to get ionized while passing through. All the measurements are done from the front side of the tube cone. Their results are given in Table 4.1. The first X-ray tube is at 60 kVp and 1mA (used in digital imaging) whereas the second one is at 70 kVp and 8mA (used in standard analog imaging). In general, analog films are acquired in 0.3 seconds. It will be used as a reference value to compare with digital imaging.

Table 4.1
Dose measurement results of dental X-ray tubes

70KvP, 8mA, 20 cm bore		60KvP, 1mA, 10 cm bore	
Exposure Time	Front (mR)	Exposure Time	Front (mR)
0,05	30,21	0,05	5,4
0,08	43,62	0,1	9,18
0,1	49,21	0,15	16,01
0,12	54,11	0,2	21,18
0,15	69,53	0,25	27,39
0,2	87,63	0,3	32,54
0,5	208,9	0,5	50,85
0,6	258	0,75	73,82
0,7	305,1	1	82
2	842,8	1,2	117,5

When the measurements in Table 4.2 is examined, it is observed that there is a linear relation between exposure time and exposed dose. This shows each tube operates properly.

Peak signal-to-noise-ratio (PSNR) is used when comparing quality of the images after applying image filters. PSNR can be calculated by using mean square error (MSE) which is define as:

$$MSE = \frac{1}{m \times n} \sum_{i=1}^{m-1} \sum_{j=1}^{n-1} [I(i,j) - K(i,j)]^2 \tag{4.1}$$

where

- mxn: Dimensions of the image.
- I and K: Images where one of them is considered as a noisy approximation of the other.

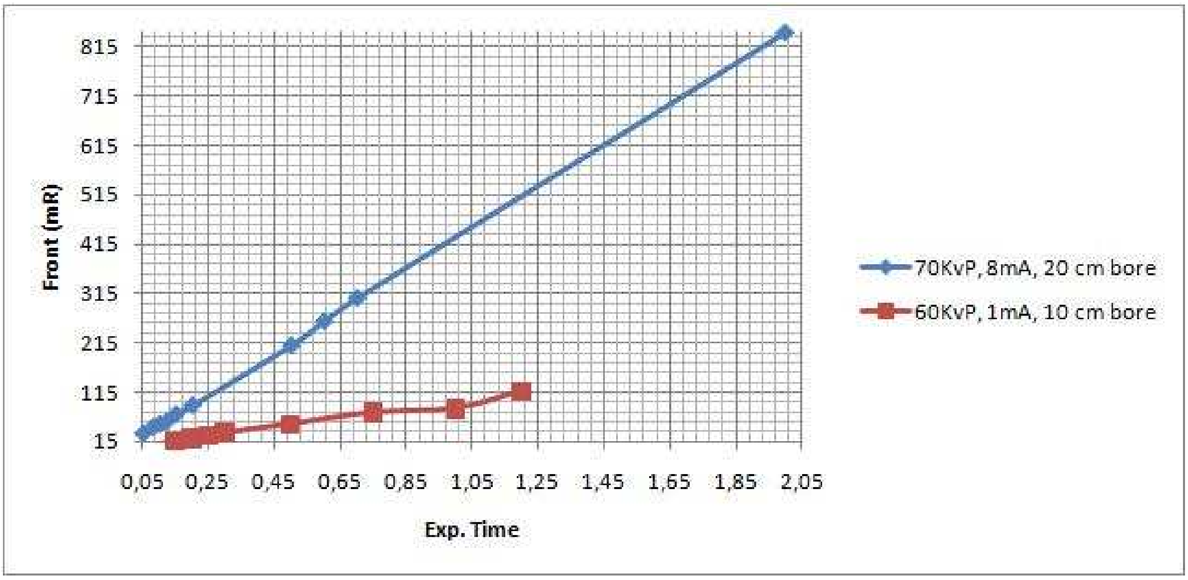


Figure 4.2 Plot of dental X-ray tubes exposure time vs. exposed dose

The PSNR is defined as:

$$PSNR = 20 \times log_{10}\left(\frac{MAX_I}{\sqrt{MSE}}\right) \tag{4.2}$$

where

- MAX_I: Maximum possible pixel value in the image I.

Higher PSNR value means lower MSE value which indicates less deterioration in the image after processing it. It is used in this thesis to see how much images are distorted after applying enhancement filters.

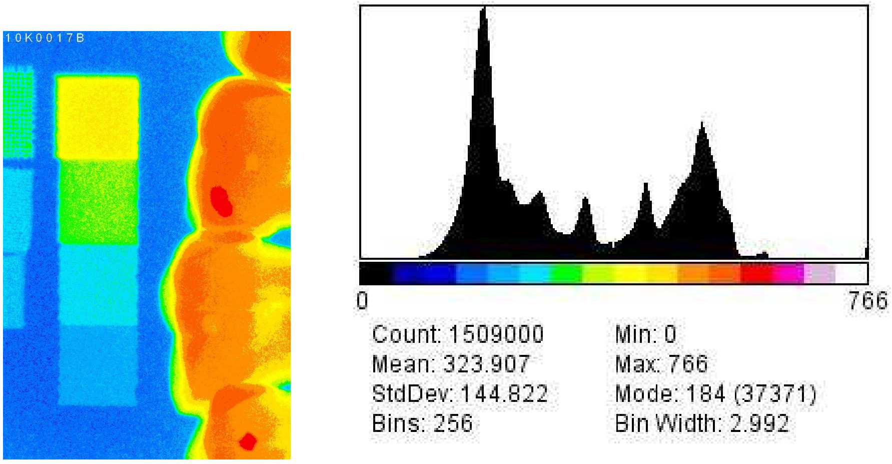
4.1 Field Testing Results of Application

4.1.1 Performance Criteria

Performance tests were performed to understand the effects of sensor integration time, kVp and mAs on acquired images. In all test cases, dental phantom which is seen in Figure 4.3 was used. There are sample teeth and line patterns inside this phantom. Line patterns are helpful to compare the resolution of images. Test results and effect of each parameter are examined in the following sections of this chapter.

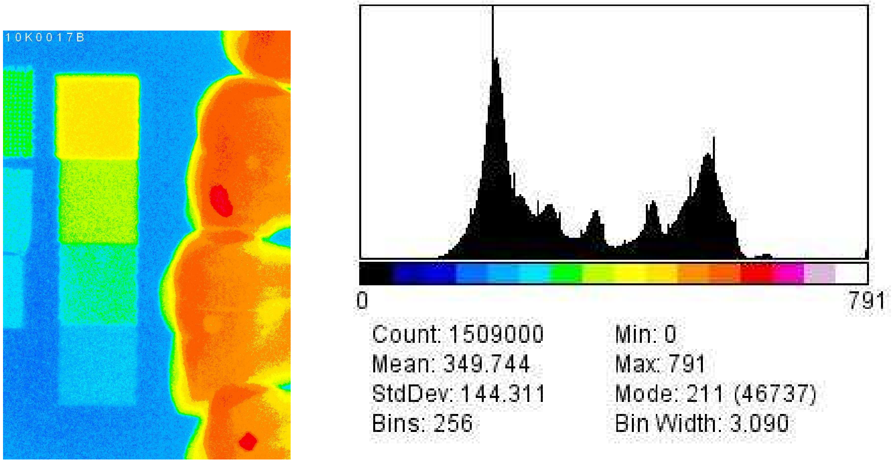
Figure 4.3 Dental phantom which is used in initial tests

4.1.1.1 Sensor Integration Time. Integration time is the time during which one pixel converts input light photons to charge. It can be thought as the read time of the sensor. In these tests, it is examined that whether integration time causes noise on images if it lasts longer than exposure time. Three images are acquired in 0.05 seconds exposure time with 100, 500 and 1200 miliseconds integration times. Resultant images and their histograms are colorized and showed in Figures 4.4, 4.5, 4.6 respectively. By looking at these histograms, it is observed that pixel distribution of images in three cases are identical. When their PSNR values are compared [Table 4.2], they are found to be very close to each other which concludes integration time does not have significant effect on noise.



Count: 1509000
Mean: 323.907
StdDev: 144.822
Bins: 256
Min: 0
Max: 766
Mode: 184 (37371)
Bin Width: 2.992

Figure 4.4 The image on the left is acquired with integration time=100 ms. The image on the right shows histogram of the acquired image.

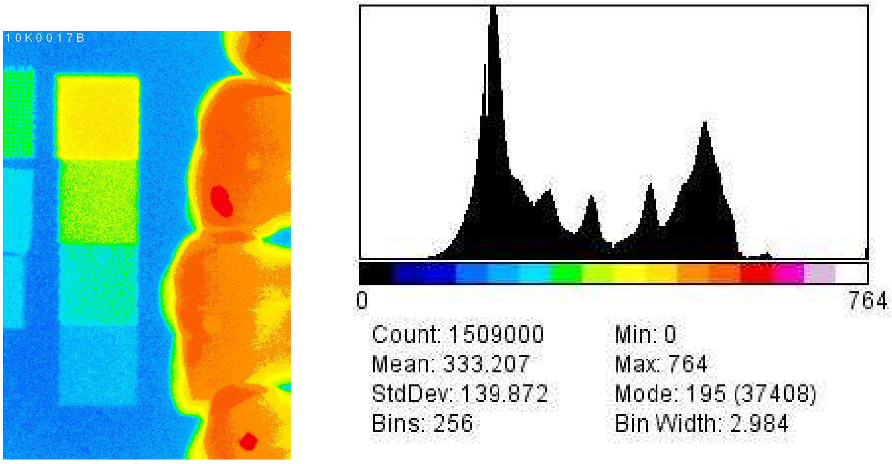


Count: 1509000
Mean: 349.744
StdDev: 144.311
Bins: 256
Min: 0
Max: 791
Mode: 211 (46737)
Bin Width: 3.090

Figure 4.5 The image on the left is acquired with integration time=500 ms. The image on the right shows histogram of the acquired image.

4.1.1.2 kVp. Originally these experiments were planned to test the sensor at different kVp. Since the X-ray tube used in digital system does not allow to operate on varying voltage values, it is taken out from our final test cases.

4.1.1.3 mAs. mAs refers the combination of time and current; it is calculated by multiplying both of them. In this test case, effect of mAs is examined using the same dental phantom, digital toshiba sensor and portable X-ray tube. Images of phantom



Count: 1509000
Mean: 333.207
StdDev: 139.872
Bins: 256
Min: 0
Max: 764
Mode: 195 (37408)
Bin Width: 2.984

Figure 4.6 The image on the left is acquired with integration time=1200 ms. The image on the right shows histogram of the acquired image.

Table 4.2
PSNR values of the images with different integration times

Integration Time (ms)	PSNR value
100	reference image
500	22.0223
1200	21.3504

are acquired with different mAs values at fixed kVp. Resultant images and their histograms are shown in Figures 4.7, 4.8, 4.9 respectively. When we tabulate the mean and standard deviation values of the image histograms [Table 4.3], contrast increment in high mAs value is observed by looking at the standard deviation values. It should be noted that contrast increases until some limit point. When limit point is reached, number of saturated pixels start to increase which causes contrast to decrease.

As it is stated in previous chapters, operation of digital sensor is based on counting number of photons that strike the sensor surface. The lower the number of photons are, the lower the created current is. This is the reason why there is more noise on image when the exposure time is low. We want to minimize the exposure, so we further examine image enhancement methods to check if we could obtain acceptable level images at lower exposure levels.

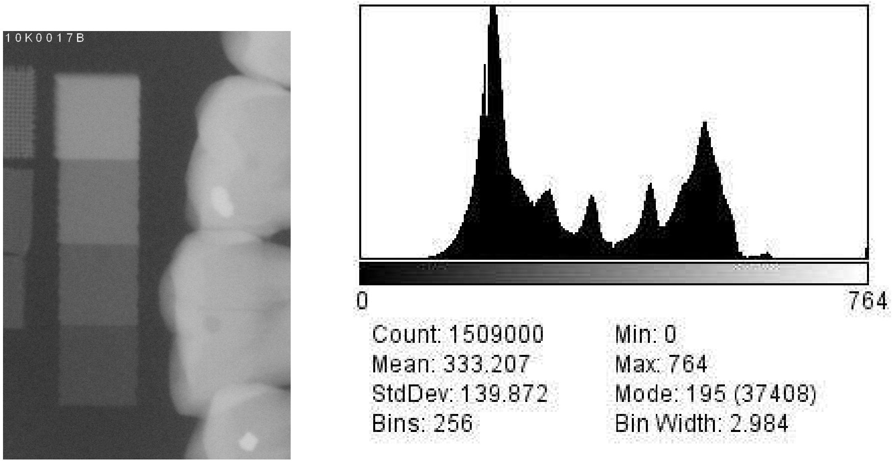


Figure 4.7 The image on the left is acquired with exposure time=0.05s. The image on the right shows histogram of the acquired image.

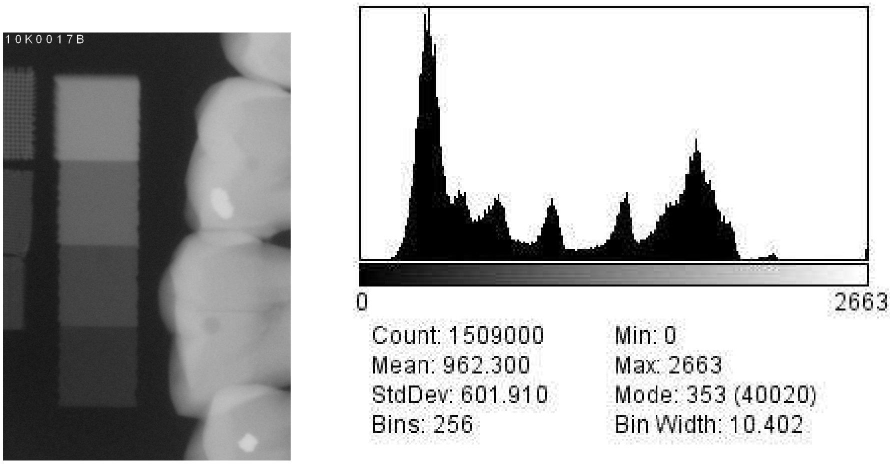
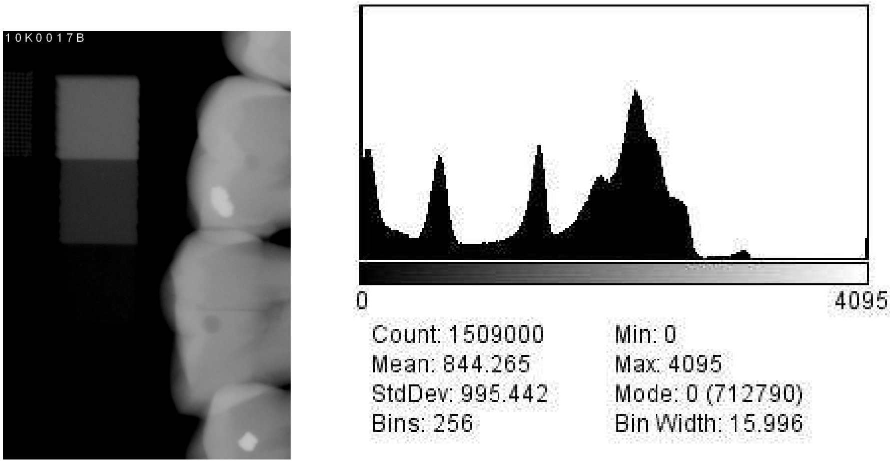


Figure 4.8 The image on the left is acquired with exposure time=0.15s. The image on the right shows histogram of the acquired image.

4.1.2 Image Enhancement

Image enhancement tests were performed on fresh cadaver. An incisor and a molar teeth are used for the tests. The incisor tooth was imaged with 60 kVp and 0.3 mAs, whereas the molar tooth was imaged with 60 kVp and 0.5 mAs. The reason why different mAs values are used is that the incisor and the molar teeth have different thicknesses. Acquired images are processed by HE, CLAHE and Retinex. The original and the resultant images are shown in Figures 4.10 and 4.11 respectively.

When the histograms of the original images are examined, it is seen that the



Count: 1509000
Mean: 844.265
StdDev: 995.442
Bins: 256
Min: 0
Max: 4095
Mode: 0 (712790)
Bin Width: 15.996

Figure 4.9 The image on the left is acquired with exposure time=0.3s. The image on the right shows histogram of the acquired image.

Table 4.3
Mean and standard deviation values of the histograms of the images in Figures 4.7, 4.8, 4.9.

MAS	Mean	Standard Deviation
0.05	333.207	139.872
0.15	962.300	601.910
0.3	844.265	995.442

digitized pixel values are restricted within a specific portion of the whole axis which makes the image contrast low. After applying post-processing filters it is seen that almost in all processed images, effective image contrast is raised up to higher levels. This can be observed by looking at the Table 4.4, where mean value and standard deviation of each image are given. Since the standard deviation is a measure of variation from the mean value, the higher standard deviation is, the higher the contrast is.

Histogram equalization filter could cause some image details to be lost to the observer. When the histograms of the original image and the HE image are examined (Figure 4.12) it is seen that the difference between local peak values get reduced by the filter which is caused by applying the filter globally. As a result of this decrement between the peak values some sharp regions get lost. Also, on the right bottom region there is a very bright region (Figure 4.13) which makes the image brighter than the

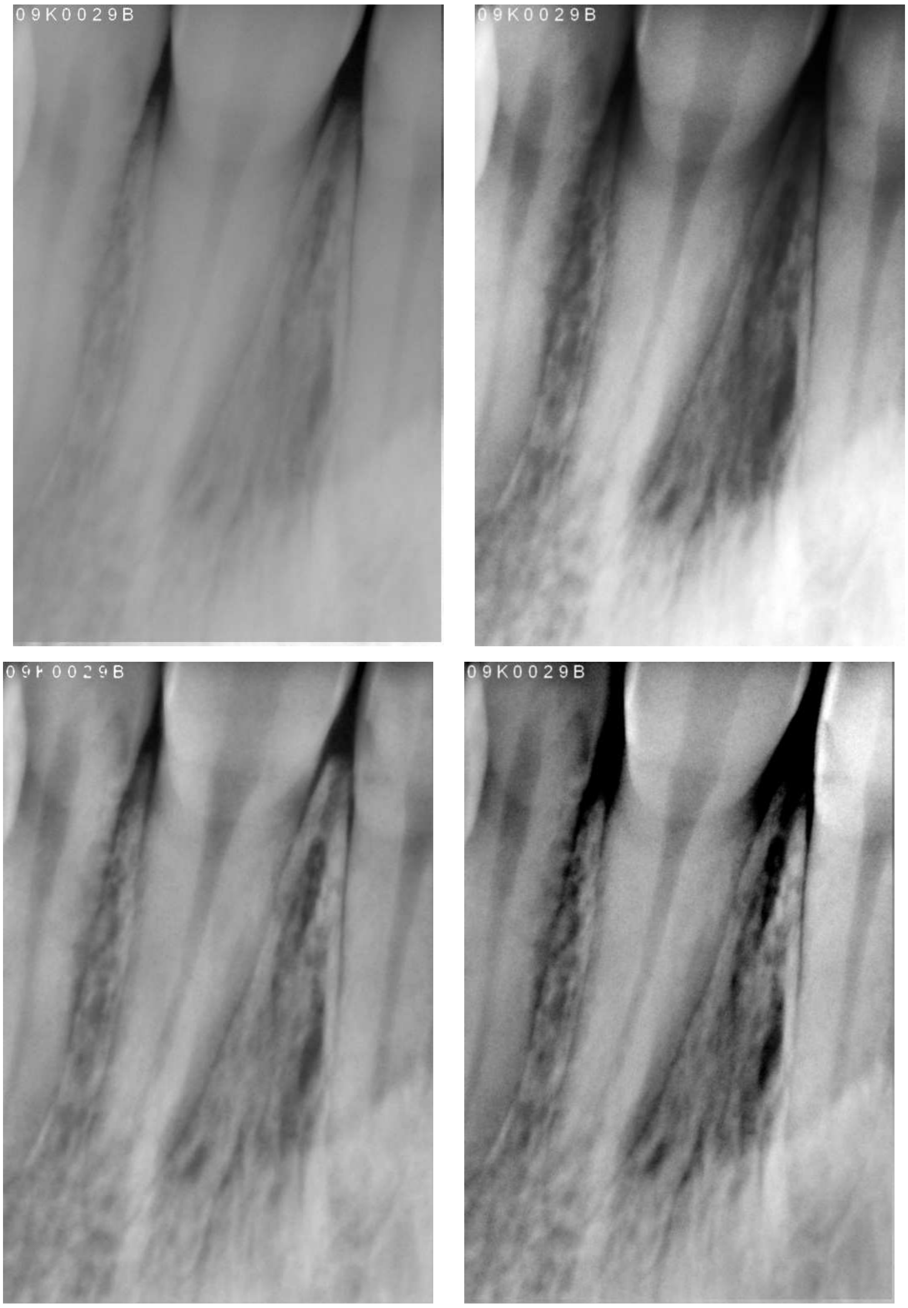


Figure 4.10 The image on the upper left is the original image of the incisor tooth acquired from fresh cadaver. The image on the upper right is resultant image after applying HE. The image on the bottom left is resultant image after applying CLAHE. The image on the bottom right is resultant image after applying Retinex.

others.

When it comes to CLAHE and Retinex, it is observed that they introduce some new features that cannot be realised on original images (Figure 4.14). These features may have diagnostic value or simply they may be artifacts due to post processing steps.

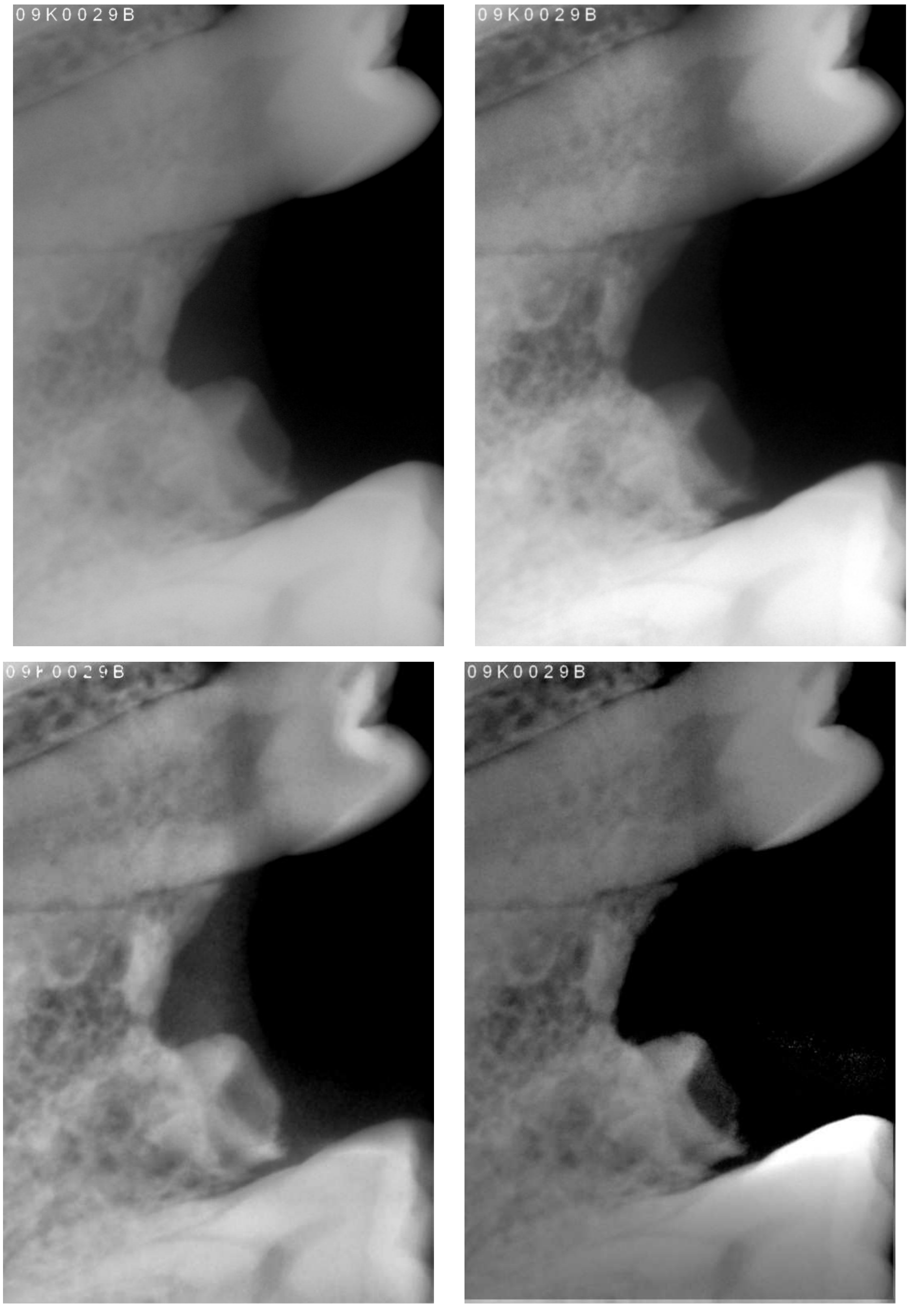


Figure 4.11 The image on the upper left is the original image of the molar tooth acquired from fresh cadaver. The image on the upper right is resultant image after applying HE. The image on the bottom left is resultant image after applying CLAHE. The image on the bottom right is resultant image after applying Retinex.

Further examinations should be done in order to understand whether they are artifacts or not.

Another point that should be mentioned is that CLAHE works better for soft tissue contrast than Retinex. It is seen that some parts of the soft tissue in the original

Table 4.4
Mean and standard deviation values belong to images in Figures 4.10, 4.11

	The incisor tooth		The molar tooth	
	Mean	Std. Dev.	Mean	Std Dev.
Original	141.764	27.381	104.756	64.172
HE	145.345	57.216	116.635	79.551
CLAHE	145.276	29.373	111.463	64.820
Retinex	139.488	46.884	84.096	58.133

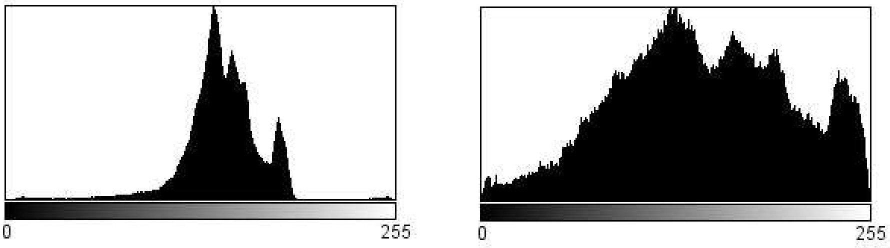


Figure 4.12 The histogram on the left is the histogram belongs to the original image in Figure 4.10. The histogram on the right is the histogram belongs to HE image in Figure 4.10. It is seen that HE reduces the difference between local peak points.

image became darker and lost its contrast after applying retinex filter where CLAHE makes this region more clear (Figure 4.15).

Last result with the processed images is that they all introduce noise. PSNR values of the images are tabulated in the Tables 4.5 and 4.6. It is seen that, especially, Retinex distorts the image more than the HE and the CLAHE images do.

4.2 PC MFC Plugin Test Results

MFC plugin is a dll so it should be tested with an application which also implemented in MFC. Initial test of plugin was performed with DentalineSuit application. DentalineSuit is a digital dental imaging application which is on the market and uses MFC. Initial release of this MFC plugin is tested in the field; some bugs are detected

Figure 4.13 Since HE enhances the image globally, it causes undesired shinings on some parts of the image as seen in red circle.

like unexpected crashes, memory leaks, etc. and these were fixed. The last version of this plugin is stable and works properly.

There are three steps: acquiring image, clipping its histogram and applying CLAHE in the plugin. Histogram clipping makes image look better. Three dentists are asked to use the plugin and give their feedbacks. According to them; new plugin displays the acquired images clearer without introducing any distortions. Two of the dentists prefered the images processed with CLAHE, one of them did not. The reason for not liking was that it introduces some additional noise to the image.

All the dentists are also reported that automatic orientation adjustment makes it easier for them to see the image properly. In addition, it may be confusing to rotate and flip image in order to make its orientation correct before getting use to it. Lastly,

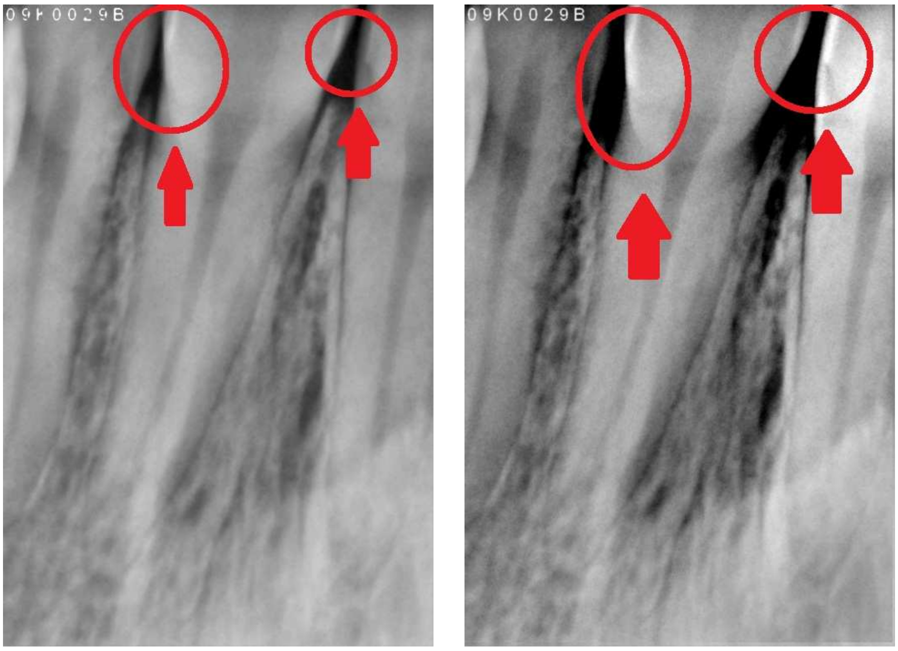


Figure 4.14 The image on the left is the CLAHE image in Figure 4.10. The image on the right is the Retinex image in Figure 4.10. Red circles show the new features detected after applying CLAHE and Retinex.

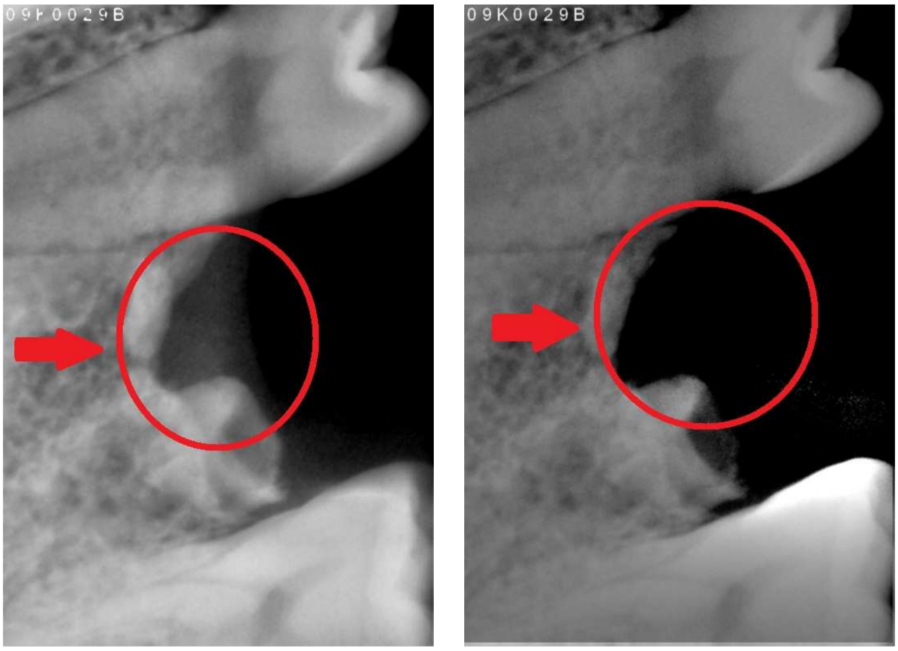


Figure 4.15 The image on the left is the CLAHE image in Figure 4.11. The image on the right is the Retinex image in Figure 4.11. Red circles show the soft tissue of the molar tooth. It is more clear in CLAHE than Retinex.

it is pointed out that the plugin increases imaging time about 2 or 3 seconds because of extra image processing step.

Table 4.5
PSNR values of the images in Figure 4.10

Image	PSNR value
Original	reference image
Retinex	17.1135
CLAHE	23.2169
HE	20.7977

Table 4.6
PSNR values of the images in Figure 4.11

Image	PSNR value
Original	reference image
Retinex	17.44
CLAHE	23.5027
HE	17.5526

4.3 Ipad Application Test Results

Ipad application works through the browser and supports image editing. Once image is transferred from server, all operations are done on client side with javascript. Javascript is scripting language. Therefore it is slower than native languages. As an example while adjusting contrast level on touch screen, there are some lags. It would be better if it is reimplemented preferably with objective C.

Except its efficiency problem, thanks to its cordless and portable design, using iPad is practicle for dentists to take a look at images and show them to patients in their clinics.

5. Discussion

A dental digital X-ray system is set up from off-the-shelf components and an image processing software is developed to communicate and acquire images from a digital sensor. In addition, a seperate MFC image acquiring plugin and an Ipad client are developed.

In order to compare radiation dose usages of digital imaging and analog imaging, X-ray tube radiation exposure measurements are done on a dental phantom. According to these results, X-ray exposure of the proposed portable X-ray tube and the digital sensor is significantly lower than traditional systems. Main factor of this decreased dose level is the digital sensor itself. Since it can acquire images at acceptable good quality with much lower radiation. They utilize lower radiation, because they are more sensitive to X-rays than traditional films. Another advantage of using digital sensor is that they can be stored and processed in computers. Moreover, there is no chemical processes take place while working with them. Digital sensors have disadvantages as well. Due to their wired and rigid structure, they make patients feel incomfortable. Also, they introduce noise that could originated from digital circuitry or post-processing. Especially, when operationg with low doses, noise of the image increses.

At second part of thesis, additional tests are performed to understand the effects of image enhancement algorithms on digital X-ray images. Three image enhancement algorithms are used which are retinex, CLAHE, histogram equalization. CLAHE is a more developed version of histogram equalization. When the results of these two algorithms are compared, CLAHE works better than histogram equalization. But it is also noted that CLAHE amplifies the perceived noise in the image significantly more than histogram equalization. Furhermore, if standart denoising filters are used to remove this noise, additional blurring occurs and small details are started to disappear on the image.

When it comes to retinex algorithm, it is good for increasing contrast around bony structures. It does not cause noise as much as CLAHE. Some images are enhanced better with retinex than CLAHE. According to these preliminary image enhancement results, it can be said that there is not any single algorithm that works for every dental application need. Therefore, it is better to determine and classify image enhancement algorithms for different types of dental images.

Lastly, implemented MFC plugin and Ipad client are developed and tested in the clinical use. MFC plugin acquires image and displays it properly without errors. It may be improved in future by adding image editing tools and more image controls. Ipad client is also working properly but it is slow because it is written with javascript. It needs to be reimplemented with a native language in order to work with better efficiency.

APPENDIX A. USER MANUALS

A.1 USER MANUAL OF STANDALON APPLICATION

Main concern of the user interface design is to keep it as much as simple. As it is showed in Figure A.1 main screen can be divided into three sub regions. Left region is the control panel inwhich user can see and change the patient information. This panel also shows thumbnails of images related to patient. Right side of the main screen is reserved for processing and editing toolbar. Middle portion of the main screen is the region where images are shown. Application supports multi-windowing. Therefore there can be several open image windows. Only one of them can be active at a time and processing commands are applied to this active window. Standalone application is basicly composed of four main modules which are acqusition module, editing module, processing module and database module. Each user interface item controls functionality of these modules. They are described in below sections.

A.1.1 CONTROL PANEL

Control panel is composed of buttons and list viewer control. When user wants to acquire new image, he/she clicks "Acquire" button. This pops up a dialog box which shows information about the acquisition process. User can cancel this action by pressing "Cancel" button on the dialog. Unless trigger is sent from digital sensor, acqusition dialog box waits on the screen during timeout period. When trigger comes, application saves image to active patient's folder, updates the image list on the control bar and closes the dialog box.

Second button on the control panel is "New Patient" button. When user clicks this button a dialog box (Figure A.2) pops up and asks user for new patient name and patient surname. After user fills up these fields, if he/she clicks "OK", then new patient

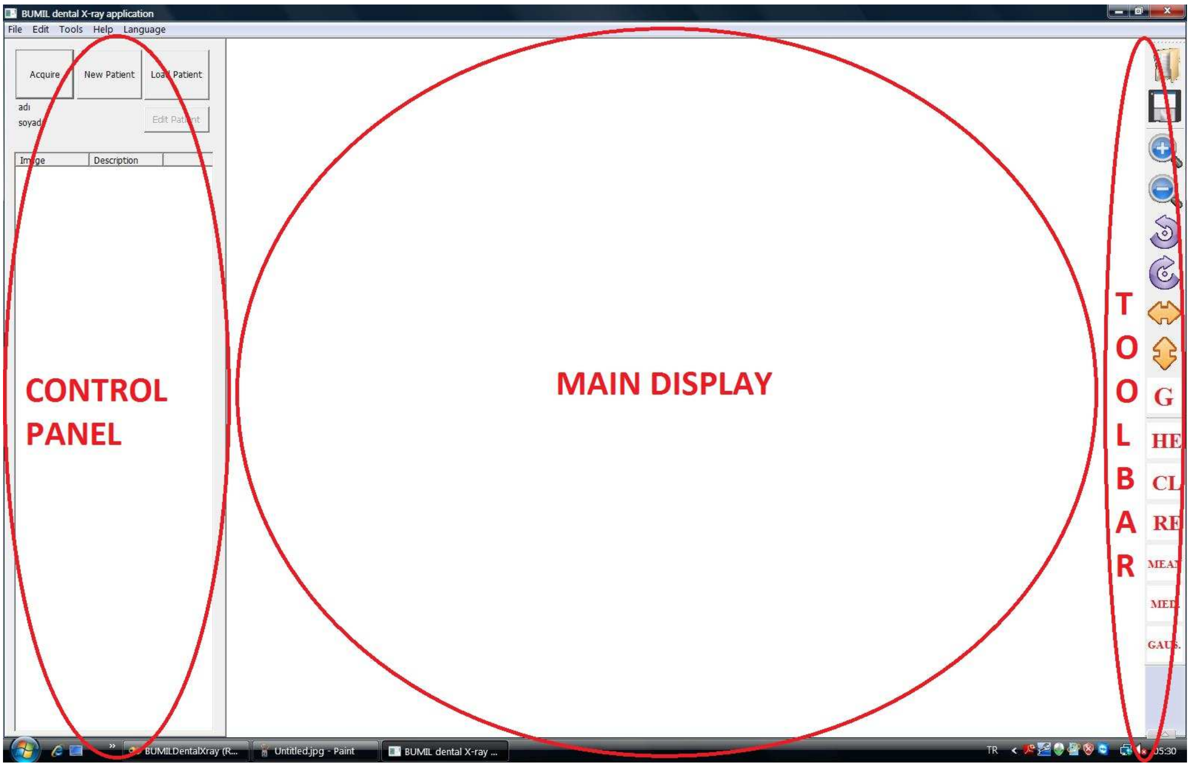


Figure A.1 Main screen of application. Left region is control panel, right region is toolbar and middle of the screen is used as main display area

is added to database and specific ID number is created for him/her. User can cancel new patient creation by pressing "Cancel" button. If new patient is added to database succesfully, its name and surname will be shown on the control panel.

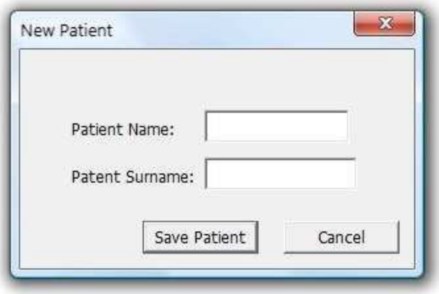
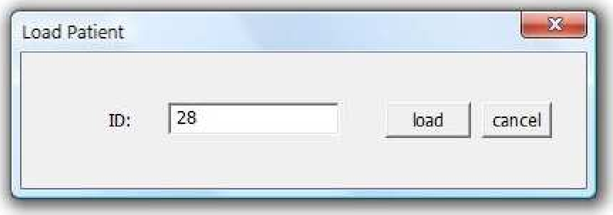


Figure A.2 New patient dialog box.

Another button on the control panel is "Load Patient". This button is used to load old patient data and related images to loaded patient. When user clicks this button, a dialog box (Figure A.3) pops up and asks user to provide a patient ID. Patient loading can be done only via ID number of the patient. If user enters corresponding ID number of the patient, then this patient and its images are loaded from database. Name and surname of the patient is shown on the control panel. Images of the patient is listed on the list control below the buttons.



28

Figure A.3 Load patient dialog box.

Last button on the control panel is "Edit Patient" button. User can use this button to edit patient information. Edit patient dialog (Figure A.4) pops up when user clicks this button. If user confirm changes, then new patient information will be updated in the database.

Large portion of the control panel reserved for image viewer (Figure A.5). Image viewer is the control which shows acquired image thumbnails to make navigation through images easier. If user double clicks on one of thumbnails in the list, then new image window holding requested image will be created and showed on the main display region. Since application support multi windowing, user can open and modify several images at the same time.

A.1.2 IMAGE EDITING AND PROCESSING TOOLBAR

All image processing commands except mouse commands are sent via the toolbar located at the rightmost side of application. Toolbar can be divide into three sub

ID: 28

Name: abdul

Surname: yazici

Folder: c:\Users\akadiryazici\Documents\Visual

Figure A.4 Edit patient dialog box.

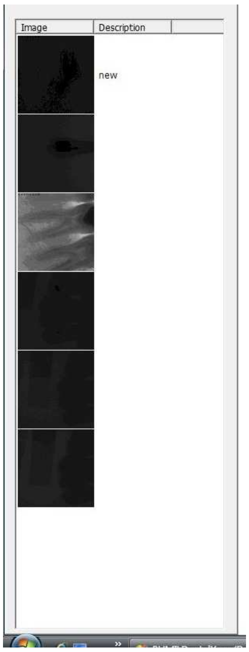


Figure A.5 User can navigate among images via image list control.

categories. These categories are Input/Output commands, image editing commands and image processing commands.

Input/Output commands are used to load and save images externally. There are two buttons at the top of toolbar: "Open" and "Save". Their icons can be seen in Figure A.6. Only TIFF image format supported by the application. Therefore, only TIFF images can be loaded from file system and only image type that can be saved is TIFF. These operations are done via open and save dialog boxes (Figure A.7) respectively.

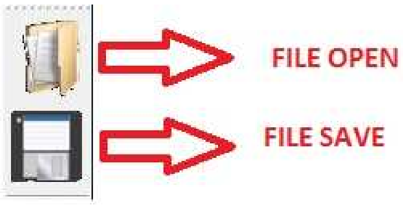
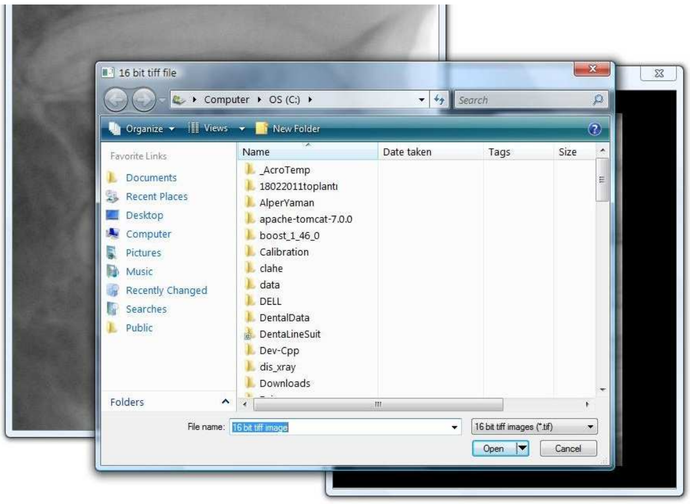


Figure A.6 Open and save buttons on toolbar



File name: 16 bit tiff image

16 bit tiff images (*.tif)

Figure A.7 Open file dialog for loading TIFF images from file system

Second part of toolbar is responsible for image editing. User can apply zoom, rotate, flip and grid view operations on active image. Their corresponding icons are shown in Figure A.8. When user clicks zoom in or out, image on the window gets bigger or smaller. Zoom operations can be done via mouse wheel when cursor is on the active image window. If the image on the window exceeds window limits then user can drag the image by holding left mouse button pressed. Rotate buttons are used when user wants to rotate image right or left. Two sided arrows show flip buttons and they are used to flip image on horizantal axis or vertical axis. Last button on image editing toolbar is grid view button. When this button is clicked, a grid is drawn on the image with 1 mm intervals. This can be used to calculate distances on the image.

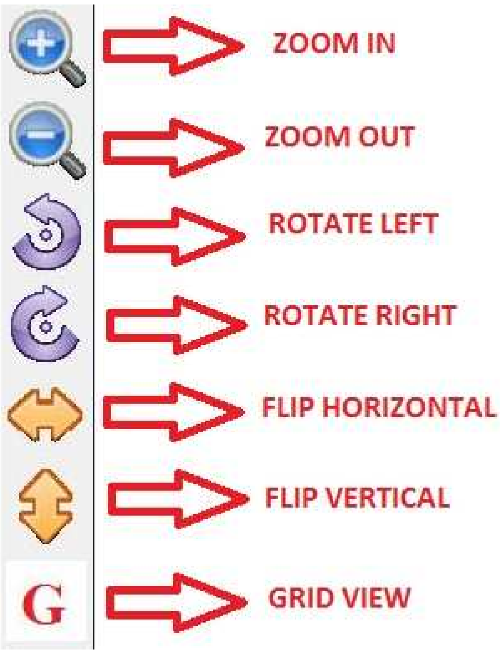


Figure A.8 Several image editing operations can be done via these buttons.

Last part of toolbar is processing toolbar. There are mainly six buttons. Three of them can be used to apply image enhancement filters. Other three buttons are used for image denoising filters. All these six buttons and their corresponding functionalities can be found on Figure A.9.

A.1.3 MAIN DISPLAY AREA

When user acquires an image or opens saved image from database or file system, an image viewer window holding the image is created and showed on the middle of application screen. There may be several image viewer windows opened at the same time. User can switch between them and apply any editing or processing operation to active image. All editing and denoising operations are done inplace whereas for image enhancement operations resultant image is viewed in a new viewer window. Typical image windows are shown in Figure A.10.

Figure A.9 User can apply both image enhancement and denoising filters from toolbar.

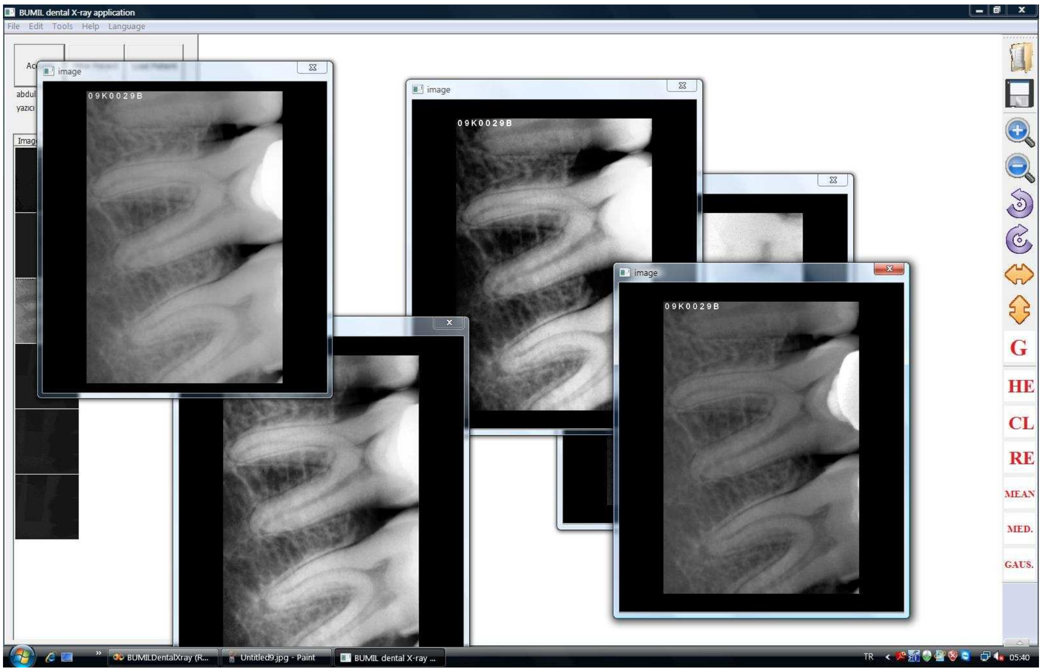
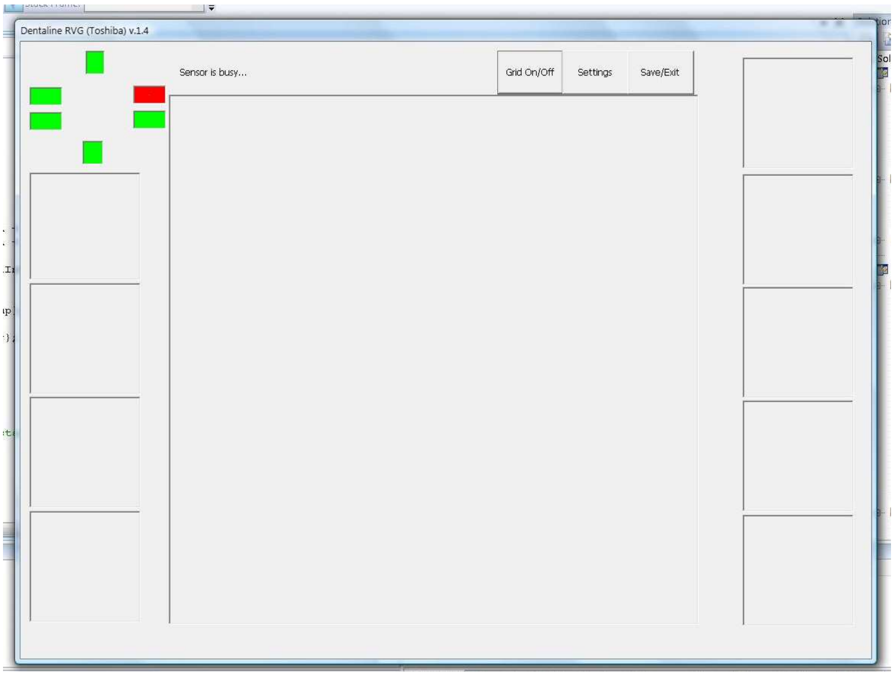


Figure A.10 Multiple images can be displayed on main display screen at the same time.

A.2 USER MANUAL OF MFC PLUGIN

General view of MFC plugin is shown in Figure A.11. All controls are placed on a dialog window. This window can be divided into three main categories. First one is buttons, second one is image orientation adjustment panel and last one is display area where captured images are displayed. Once user calls the plugin and it is loaded, it stays and waits until trigger comes or user cancels acqusition. Indeed, sensor driver works in the background as it works in standalone application. Plugin cancels and starts itself again automatically when sensor sends timeout message. By doing so, it prevents dialog window to exit when it receives timeout message.



Sensor is busy...

Figure A.11 Typical view of MFC plugin.

There are three buttons on the dialog window. Grid button is used to display grid on the recent captured image with 1 mm intervals. Another button on the dialog window is settings button. When user clicks this button, settings dialog window pops up and user can set some of parameters with the help of controls on this pop-up. Currently, there is only one parameter available (Figure A.12). Later, more control parameters can be added to this dialog. Last button is save button. It is used to end acqusition and copy acquired images to main application.

Second part on the dialog window is image orientation adjustment panel. As it is seen in Figure A.13, there are six rectangular boxes which represent sensor position in patient's mouth. Before acquiring the image user has to choose one of these boxes

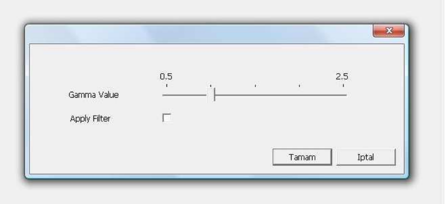


Figure A.12 User can change parameters through settings window.

to determine sensor position. According to this position, plugin adjusts the correct orientation of image without any further input.

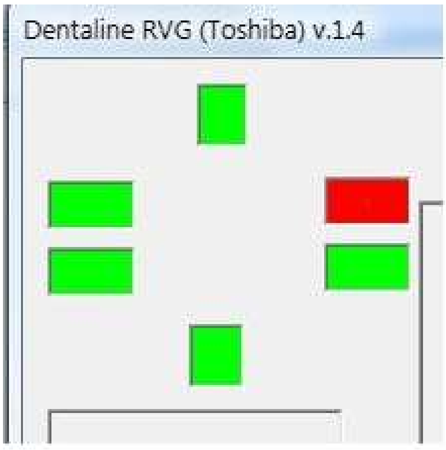


Figure A.13 User can set the orientation of the sensor by clicking on the boxes above. Each box symbolizes the sensor position as if they are located inside the patient's mouth.

Last region of dialog window is image display area. As it is seen in figure A.10, there is one main image rectangle in the middle of dialog and eleven small image rectangles around it. Recently captured image is always shown in big area and old images are shifted over small rectangles as new images comes.

A.3 USER MANUAL OF IPAD CLIENT APPLICATION

Ipad application is composed of two regions. First one is control buttons located at the top of page and second one is display are where images are showed. Typical screen view can be seen in Figure A.14. One important point when discussing Ipad application is that there is no image processing routines implemented in it yet. Therefore, control panel is responsible from simple editing operations only.

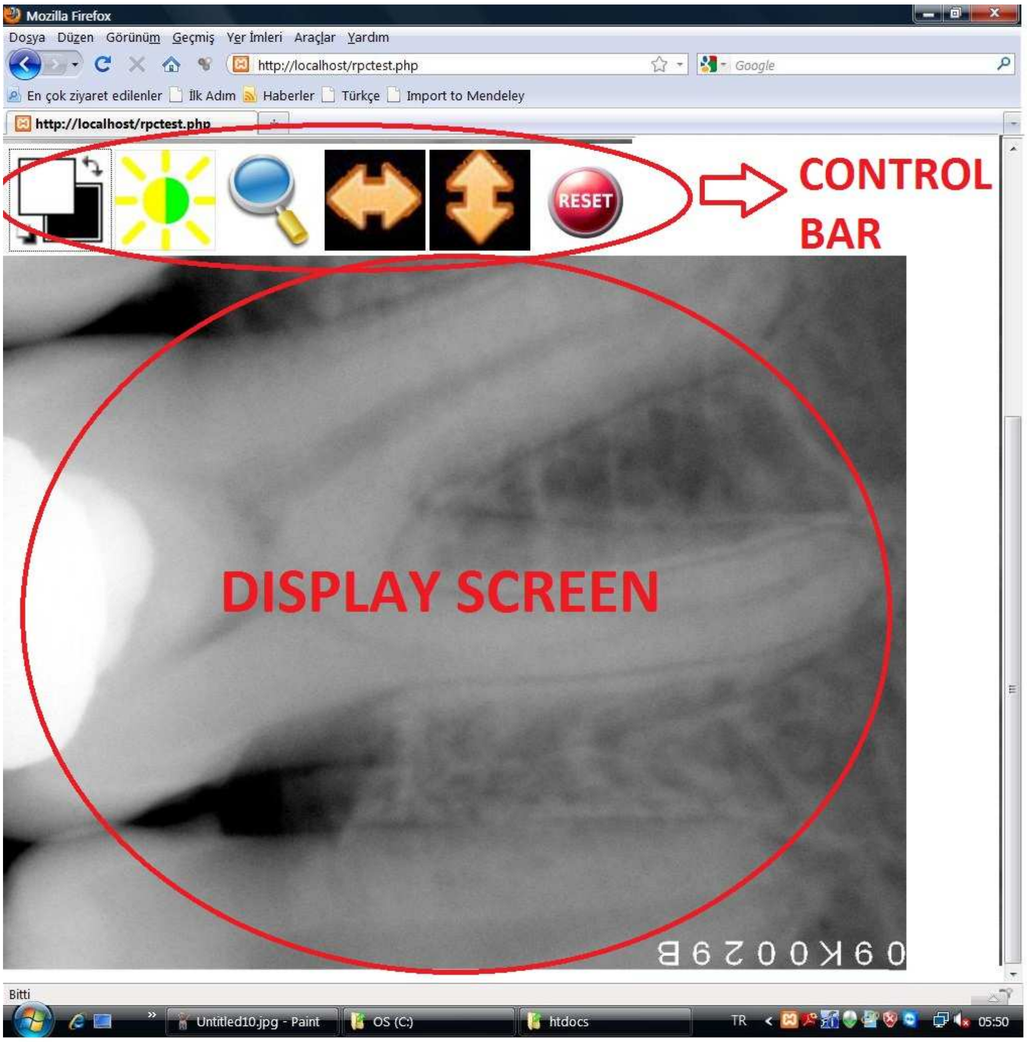


Figure A.14 There are two main regions on Ipad client. Control buttons and display area.

Buttons and their functionalities can be seen in Figure A.15. First button is invert button. It simply converts black colors to white and white colors to black. Second button is used for switching contrast adjustment mode. Since, Ipad has touch screen contrast adjustment is done by sliding over screen. When user slides his finger over the screen in this mode contrast value changes. Right side increases the slope of contrast curve whereas left side decreases it. Next button is used to switch zoom mode. If zoom mode is active then touch screen controls can be used to zoom in, zoom out and dragging operations. Flip buttons are used to flip image horizontally and vertically. Last button is reset button which is used to reset image and returns it to its original state. There is no button for rotation, because Ipad is portable device and rotating can be done by rotating Ipad more practically.

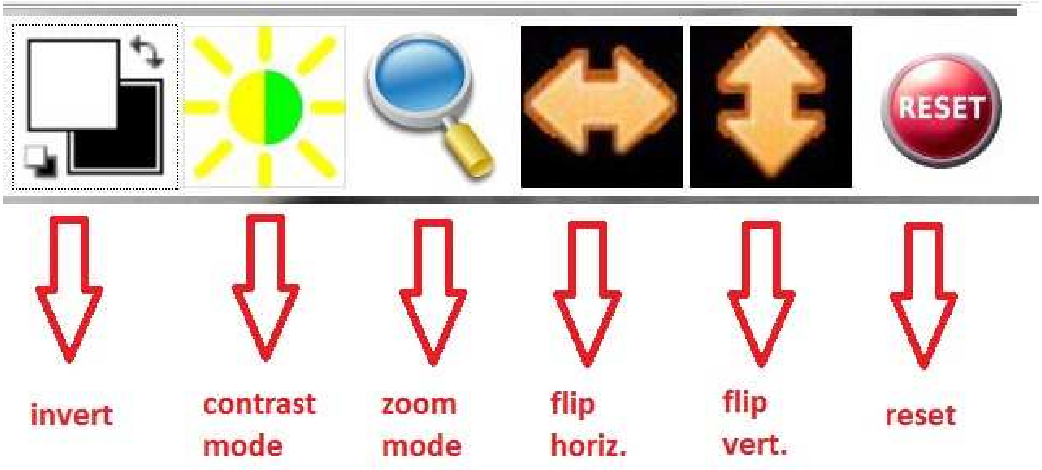


Figure A.15 Control bar and functionalities of buttons.

Display area simply shows last captured image on the server. If new image comes to server, it is automatically loaded to display area.

APPENDIX B. TOOTH GLOSSARY

Canine: A type of tooth with a single point (also called canine tooth) and a single root. Cuspid teeth are used to hold and tear food. Adults have 4 canine teeth (2 in the top jaw and 2 in the bottom jaw). Canine means, "of or like a dog."

Cementum: A layer of tough, yellowish, bone-like tissue that covers the root of a tooth. It helps hold the tooth in the socket. The cementum contains the periodontal membrane.

Crown: The visible part of a tooth.

Dentin: The hard but porous tissue located under both the enamel and cementum of the tooth. Dentin is harder than bone.

Enamel: The tough, shiny, white outer surface of the tooth.

Gums: The soft tissue that surrounds the base of the teeth.

Incisor: A type of tooth with a narrow edge (in humans, the front teeth). Incisors are used to cut food. An incisor has 1 root. Adult humans have 8 incisors (4 in the top jaw and 4 in the bottom jaw).

Molar: A wide, flat tooth found in the back of mammal's mouths. Molars grind food during chewing. Molars in the top jaw have 3 roots; molars in the lower jaw have 2 roots. Adults have 12 molars (6 in the top jaw and 6 in the bottom jaw).

Nerves: Nerves transmit signals (conveying messages like hot, cold, or pain) to and from the brain. periodontal membrane/ligament - the fleshy tissue between tooth and the tooth socket; it holds the tooth in place. The fibers of the periodontal membrane are embedded within the cementum.

Premolar: The type of tooth located between the canine and the molars in humans. A bicuspid tooth has 1 root. Bicuspids have two points (cusps) at the top. Adults have 8 premolars (4 in the top jaw and 4 in the bottom jaw).

Pulp: The soft center of the tooth. The pulp contains blood vessels and nerves; it nourishes the dentin.

Root: The anchor of a tooth that extends into the jawbone. The number of roots ranges from one to four.

REFERENCES

1. Parks, E.T., and G. F. Williamson., "Digital Radiography: An Overview," The Journal of Contemporary Dental Practice, Vol. 4, pp. 23-39, November 15, 2002.

2. United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionizing Radiation, UNSCEAR Report Volume 1, United Nations, New York (2000).

3. U.S. National Library of Medicine, "Dream Anatomy", September 18, 2002, available @ http://www.nlm.nih.gov/dreamanatomy/da_g_Z-1.html.

4. Frame P., "Coolidge X-ray Tubes", June 24, 2009 available @ http://www.orau.org/ptp/collection/xraytubescoolidge/coolidgeinformation.htm.

5. Disher B., L. Lenarduzzi, B. Lewis, J. Teeuwen, "The Physics of Computed Tomography", March 21, 2006, available @ http://web2.uwindsor.ca/courses/physics/high_schools/2006/Medical_Imaging/ctphysics.html.

6. Eggert F., "Basics of the X-ray Excitation by Electrons", August 30, 2009, available @ http://microanalyst.mikroanalytik.de/info1.phtml.

7. U.S. Food and Drug Administration, "FY 2001 Medical Imaging Evaluation", April 11, 2011, available @ http://www.fda.gov/AboutFDA/CentersOffices/OfficeofMedicalProductsandTobacco/CDRH/CDRHReports/ucm126797.htm

8. Gabriel, A., Y. Dupont, "A position sensitive proportional detector for x-ray crystallography", Review of Scientific Instruments, Vol. 43.11, pp. 1600-1602, 1972.

9. Ladislas W., "Microchannel plate detectors", Nuclear Instruments and Methods, Vol. 162.1-3, pp. 587-601, 1979.

10. Brenner, D., J. Eric, "Computed tomography: An increasing source of radiation exposure", The New England Journal of Medicine, Vol. 357.22, pp. 2277-84, 2007.

11. Banerjee, P., “Diagnostic X-Ray Shielding”, Glass Processing Days, Vol. 2003, pp. 345-347, 2003.
12. Burbridge B., “Saskatoon Medical Imaging/Saskatoon Women’s Imaging”, 2006, available @ http://smiswi.sasktelwebhosting.com/xray.htm.
13. Klinikums Mannheim, “Dual-Source CT Installation”, available @ http://www.umm.uni-heidelberg.de/inst/ikr/klinik_CT.html.
14. Perry Foot and Ankle Center, 2012, available @ http://www.no1footdoc.com/additional-services/c-arm/.
15. Vandenberghe, B., R. Jacob, H. Bosmans, “Modern dental imaging: a review of the current technology and clinical applications in dental practice.”, European Radiology, Vol. 20.11, pp. 2637-2655, 2010.
16. ARDET Dental and Medical Devices, available @ http://www.ardetsrl.com/ENG/pagine/prodotti/orix70.php.
17. Lazzerini, F. et al. “The measurement parameters in dental radiography: a comparison between traditional and digital technics.”, La Radiologia Medica, Vol. 91.4, pp. 364-369, 1996.
18. University of Mancheste, “Technical Description of CBCT,” 2009, available : http://www.sedentexct.eu/content/technical-description-cbct
19. Rahman Z., D. Jobson, and G. Woodell, “Retinex processing for automatic image enhancement,” Journal of Electronic Imaging, Vol. 13(1), pp. 100-110, Jan 2004.
20. Rahman, Z., D. Jobson, and G. Woodell., “Multi-scale retinex for color image enhancement,” Advances, Vol. 3, pp. 1003-1006, 1996.
21. Rahman, Z., G. A. Woodell, and D. J. Jobson, “Retinex Image Enhancement: Application to Medical Images,” presented at the NASA workshop on New Partnerships in Medical Diagnostic Imaging, Greenbelt , Maryland, July 2001
22. Yeong T. M., “Contrast enhancement using brightness preserving bi-histogram equalization”, IEEE Transactions on Consumer Electronics, Vol. 43, pp. 1-8, 1997.

23. Pizer, S., R. Johnston, J. Ericksen, B. Yankaskas, and K. Muller, “Contrast-limited adaptive histogram equalization: speed and effectiveness,” Proceedings of the First Conference on Visualization in Biomedical Computing, 1990.