3D BREAST CANCER VISUALIZATION USING FUSION TECHNIQUE AND AUGMENTED REALITY

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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

6 February 2018

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P72356

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ABSTRACT

The increasing rate of breast cancer is alarming with a very high count in most countries and in Malaysia 1 out of 19 women is at risk of getting breast cancer. A very high false positive rate that occurs while the routine examination takes place makes the diagnosis worst. This is partly caused by the lack of tumor visualization. Medical AR makes it possible to visualize the virtual model on its precise position and in its proper size, respective to the real model. Exact localization of the tumors and a high degree of accuracy is a still a concern in medical augmented reality visualization process. An Augmented Reality visualization guidance has become the method of choice for researchers, yet this AR tumor visualization has limitation to the extent of just superimposing the 3D Imaging Data but it still has problems of occlusion and depth perception. Therefore, this study is aimed at developing the visualization techniques using breast cancer 3D data to test the accuracy of the techniques in regard to occlusion and depth perception. Fusion technology of XRay and Focus+Context visualization technique are introduced to accurately visualize 3D multiple tumor (AR-XFC) inside the phantom for augmented reality breast cancer 3D visualization. The virtual 3D breast cancers model has been enhanced by giving measurement values which are the cancer position and the layers. The AR-XFC Visualization technique is to not only see through the skin of the phantom but also to solve the problem of occlusion and depth perception. This mobile AR visualization technique will initially acquire the 2D image from MRI and process the medical images into 3D slices. Then it will purify these 3D grayscale slices into 3D breast cancer model using 3D modeling reconstruction technique. The 3D data set is implemented in XRay visualization technique but the depth perception problem has not been solved. The Focus+Context visualization technique was also tested with the 3D data set and has solved the depth perception but still cannot solve the occlusion problem. To evaluate the proposed technique, breast phantom US-9 has been used which has 12 tumors in different sizes and categorized in 3 different levels. AR-XFC technique was implemented on a mobile AR visualization application where the final composition of the breast cancer is displayed on handheld device with top angle and side angle view. 32 participants have been selected to test the application based on Augmented Reality and MRI or biopsy knowledge. These participants have successfully locate multiple tumor through the skin of the phantom and also identified the depth of the multiple cancers and no occlusion were found. The technique has an accuracy of 87.85% compared to the other visualization techniques in showing the 3D tumor visualization with depth perception and no occlusion. The technique is perceived as an improved visualization because the AR-XFC visualization allowed direct understanding of the breast cancer beyond the visible surface and direct measurement guidance towards accurate cancer visualization and can be used in medical application such as the biopsy procedures.

ABSTRAK

Peningkatan kadar pengidap barah payudara dengan jumlah yang sangat tinggi di kebanyakan negara adalah membimbangkan dan di Malaysia, 1 daripada 19 wanita berisiko mendapat kanser payudara. Penggunaan MRI menyebabkan kadar positif palsu yang tinggi berlaku semasa peperiksaan rutin membuatkan diagnosis menjadi buruk. Kejadian ini sebahagiannya disebabkan oleh kekurangan pada visualisasi tumor dalam imej MRI. Perubatan AR membolehkan pemvisualan model maya tumor pada kedudukan yang tepat dan dalam saiz yang sesuai, masing-masing kepada model sebenar. Pengenalpastian lokasi tumor yang tepat dan tahap kejituan yang tinggi masih menjadi perhatian dalam proses pemvisualan realiti tambahan perubatan. Panduan pemvisualan realiti tambahan telah menjadi kaedah pilihan untuk penyelidik, namun visualisasi tumor AR ini mempunyai batasan iaitu ia hanya ditindihkan dengan Data Imej 3D tetapi masih mempunyai masalah oklusi dan persepsi kedalaman. Oleh itu, kajian ini bertujuan untuk membangunkan teknik pemvisualan menggunakan data 3D kanser payudara untuk menguji ketepatan teknik berkaitan dengan oklusi dan persepsi kedalaman. Teknologi gabungan teknik visualisasi XRay dan Fokus + Konteks telah diperkenalkan bagi menggambarkan dengan tepat 3D kanser berbilang yang berada jauh di dalam payudara untuk visualisasi Augmentasi Realiti barah payudara dalam 3D. Model kanser payudara 3D maya telah dipertingkatkan dengan menyediakan nilai pengukuran lokasi yang merupakan kedudukan kanser dan jumlah lapisan. Teknik Visualisasi AR-XFC bukan sahaja hanya untuk melihat melalui kulit fantom tetapi juga untuk menyelesaikan masalah oklusi dan persepsi kedalaman. Teknik pemvisualan AR mudah alih pada awalnya akan memperoleh imej 2D dari MRI dan memproses imej medikal ke dalam kepingan 3D. Kemudian ia akan membersihkan kepingan kelabu 3D ini ke dalam model kanser payudara 3D menggunakan teknik pembinaan semula pemodelan 3D. Set data 3D telah dilaksanakan dalam teknik visualisasi XRay tetapi masalah persepsi kedalaman masih belum diselesaikan. Teknik visualisasi Fokus + Konteks juga diuji dengan set data 3D dan telah menyelesaikan persepsi kedalaman tetapi masih tidak dapat menyelesaikan masalah oklusi. Untuk menilai teknik yang dicadangkan, fantom payudara US-9 telah digunakan yang mempunyai 12 tumor dalam saiz yang berbeza dan dikategorikan dalam 3 tahap yang berbeza. Teknik AR-XFC dilaksanakan pada aplikasi visualisasi AR mudah alih di mana komposisi terakhir kanser payudara dipaparkan pada peranti mudahalih dengan sudut atas dan sudut pandangan sisi. 32 peserta telah dipilih untuk menguji aplikasi berdasarkan pengetahuan mereka di dalam Augmentasi Realiti, MRI atau biopsi. Peserta berjaya mengenalpasti lokasi beberapa tumor melalui kulit fantom dan juga dapat mengenal pasti kedalaman beberapa kanser dan tidak ada oklusi yang ditemui. Teknik ini mempunyai ketepatan 87.85% berbanding dengan teknik visualisasi lain dalam memaparkan tumor 3D dengan persepsi kedalaman dan tiada oklusi. Teknik ini meningkatkan visualisasi kerana AR-XFC membenarkan pemahaman langsung tentang kanser payudara lebih jauh ke dalam payudara berbanding pemerhatian di permukaan kulit sahaja. Tambahan lagi, teknik ini menyediakan panduan pengukuran langsung ke arah visualisasi kanser yang tepat dan boleh digunakan dalam aplikasi perubatan seperti prosedur biopsi.

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LIST OF ABBREVIATIONS

UKM	Universiti Kebangsaan Malaysia
AR	Augmented Reality
VR	Virtual Reality
HMD	Head-mounted Display
3D	Three-dimension
RFA	Radiofrequency Ablation
F+C	Focus-plus-Context
PDA	Personal Digital Assistant
XFC	XRay and Focus-plus-Context
OR	Operation Room
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
TOF	Time-of-flight
ICP	Iterative Closest Point
PCA	Principal Component Analysis
GPS	Global Positioning System
CAS	Computer Assisted Surgery
IOD	verlay projection device
CV	Computer Vision
PTAM	Parallel Tracking and Mapping
CAOS	Computer-Assisted Orthopedic Surgery
GPU	Graphics Processing Unit
DCE	Dynamic Contrast-Enhanced
DCE-MRI	Dynamic Contrast-Enhanced Magnetic Resonance Imaging
ROI	Regions of Interest
TIC	Time-intensity Curves
3TP	Three Points In Time

CA	Contrast Agents
CVP	Closest Vessel Projection
LSM	Linear Sampling Method
DBIM	Distorted Born Iterative Method
CC	Craniocraudal
DOI	Degree-Of-Interest
POI	Point of Interest
IBIS	Intent-Based Illustration System
FNAB	Fine Needle Aspiration Biopsy
CNB	Core Needle Biopsy
RTP	Radiotherapy Treatment Planning
OAR	Organ at Risk
DMVR	Dense Multi-View 3D Reconstruction
SFM	Structure-From-Motion
DICOM	Digital Imaging and Communications in Medicine
CAD	Computer-Aided Design
NPR	Non-Photorealistic Renderin
ANOVA	Analysis of Variance
MDCT	Multidetector Computed Tomography
PACS	Picture Archiving And Communication System
MPR	Multiplanar Reconstruction
MIP	Maximum Intensity Projection

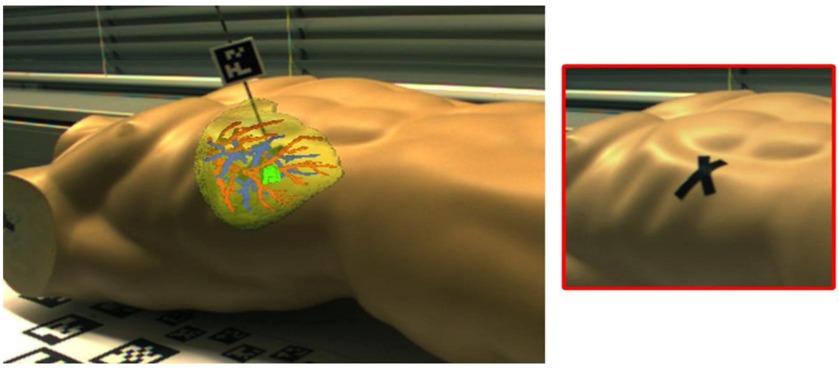
CHAPTER I

INTRODUCTION

The Augmented reality (AR) is a field of research that concerns the fusion of virtual and real worlds. Virtually generated objects are thereby embedded into an image of the real scene. These objects are intended to provide additional information to the viewer and are integrated in a preferably smooth and intuitive way. Besides the use of AR for industrial applications (e.g. in the automobile industry), this technology can also be utilized for medical purposes. Medical augmented reality is still in the stadium of research and is not practically applied yet. The main research objectives of medical AR are the use of AR technology for pre-operative diagnoses (surgical planning), intra-operative guidance and navigation and for post-operative control. Medical AR is a technique that is intended to be applied for augmenting the medical data in real view. Visualization is one of the major components in medical AR where medical data can be obtained from multimodal scans taken from computer tomography (CT) or magnetic resonance imaging (MRI). One of the major cased related to CT or MRI are cancer related data e.g Breast Cancer. The increasing rate of breast cancer is alarming with a very high count in most countries (Pisani et al. 2002). Although there are many types of cancers, breast cancer is the most commonly affected with over one million people each year (Stuckey 2011). However, a very high false positive rate that occurs while the routine examination takes place makes the matter worst. This is partly caused by the lack of tumor visualization (Nelson et al. 2009). Medical AR makes it possible to visualize the virtual model on its precise position and in its proper size, respective the real model. Exact localization of the tumors and a high degree of accuracy is a still a concern in medical augmented reality visualization process. Therefore, this study is aimed at investigating the visualization techniques using breast cancer 3D data to test the accuracy of the techniques in regards to occlusion and depth perception. This introductory chapter presents the research background, problem statement, research objectives, research scope, research methodology, and organization of the thesis.

1.1 RESEARCH BACKGROUND AND RELATED STUDIES

Augmented Reality displays extend viewer perception via the addition of computer generated information. The AR system generates the final image by overriding parts of the real-world image using renderings of virtual objects. Since 2003, the arrival of mobile technology has also influence AR system and currently known as Mobile Augmented Reality (Wagner & Schmalstieg 2003). Mobile augmented reality is AR that you can take with you wherever you go. Most specifically, this means that the hardware required to implement an AR application is something that you take with you wherever you go. Another important component of Augmented Reality is visualization and a basic Augmented Reality visualization is a process to visualization the superimposed virtual information on top of the reality model. However, careless replacement of parts of the real-world imagery can easily cause a number of problems. For example, if XRay visualizations render hidden structures on top of occluding objects, the augmentation may obscure important real-world information. This problem is illustrated in the simulated surgery depicted in Figure 1.1.



a) b)

Figure 1.1 (a) Augmentation of the liver with its portal & hepatic vessel trees (red & blue) and a tumor (green), (b) Original photo before augmentation, the black cross indicates the insertion point for the RFA-needle

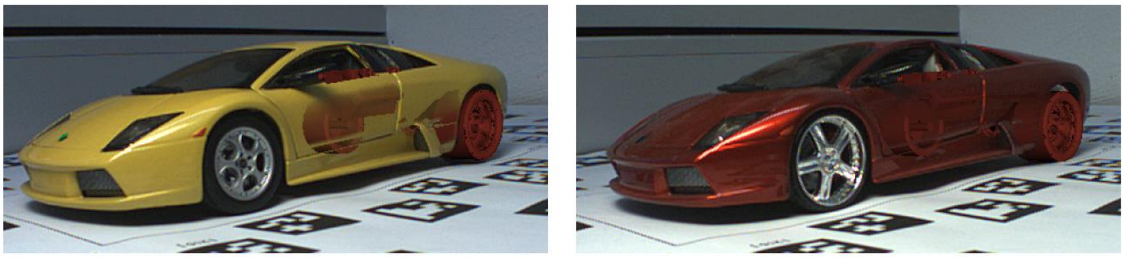
Source: Kalkofen et al. (2011)

The computer-generated rendering of some of the inner anatomy obstructs the view of highly relevant landmarks which are present in the real-world imagery. In this example, the objective is to insert a needle into a patient's abdomen using a pre-defined entry point (black crossing). By overlaying virtual organs on top of the real-world imagery, the user is left unable to see the entry points which are marked on the skin of the patient. This effect happens due to the lack of occlusion cues. If no partial occlusion exists, judgment concerning the order of objects becomes difficult. Other existing depth cues (such as object size or object detail) are not strong enough to communicate the order of objects in an XRay visualization (Zhai et al. 1996).

To successfully communicate the spatial relationships between 3D objects, more than just their occlusions must be communicated. The shapes of the objects themselves must be visible to allow the viewer to understand the objects in the scene before their relationship can be perceived. If only an application's landmarks are preserved (such as the entry port in Figure 1.1), the final visualization may still suffer from a lack of shape cues. Even though depth cues can communicate the order of structures, if the preserved features do not line up to a single shape the obscured object may not be perceived properly and consequently no relationships between it and other objects can be communicated.

In addition to the problems caused by overriding (and thus removing) real world imagery, careless generation of XRay visualization in AR environments may lead to misleading interactions of colors and shades representing the real and the virtual objects. If the rendering of virtual objects does not take the prospective real-world surroundings into account, the composition of both may fail to transport the intention of the visualization. Consequently, to be able to generate understandable XRay visualizations in AR environments, the appearance of the added 3D computer graphics should fit into the real-world environment. Following this line of thought, both the coloring and the shading of the virtual and the real-world objects must be analyzed and adapted to correspond to each other.

Accessible XRay visualizations consist of the uncovered hidden structure, preserved shape features and sometimes preserved landmarks. As these are the most important elements in communicating the spatial relationships in an XRay visualization, they have to be easily distinguishable from their surroundings. For example, Figure 1.2(a) shows an XRay visualization with a similar appearance of both the hidden and occluding structures. Even though shape and depth cues are preserved, it is difficult to make out the elements of the XRay visualization and as a result the spatial relationships are difficult to perceive.



(a) (b)

Figure 1.2 Visual interaction between real and virtual renderings in XRay visualization. Both visualizations use the same parameter, however, (a) The red overlay is hardly visible over the red car, (b) The visualization parameter are more affective on the yellow car

Source: Kalkofen et al. (2011)

Conventionally, F+C visualizations consider a single level of discrimination into focus and context. However, if the presentation's environment is very complex, single level F+C classifications may result in a presentation of visually isolated elements (Kalkofen et al. 2007). The relationship between focus and context data can either be spatially or knowledge driven. Spatially driven techniques retain or enhance information in close proximity to the focus object. While some applications select the focus' proximity directly in its presentation space (Kosara et al. 2001), others first transform the data into a new space to allow for easier identification of the desired contextual information (Tweedie et al. 1994).

Focus and Context visualizations demand the visual discrimination of objects depending on whether they are marked as focus or context. In addition, F+C visualizations have to encode different degrees of importance in order to communicate the prominence of the focus element relative to its contextual information. This is usually implemented by visually directing the user's attention to the object of interest while presenting its contextual information in a less salient style. Psychological research has identified a number of features which can influence the mental process of visual search (Ware 2012). Figure 1.3 and Figure 1.4 demonstrate the different effects of F+C visualizations in purely virtual compared to complex AR environments. All visualizations use a single level of F+C discrimination (meaning that visual elements either belong to the focus or the context group). The goal of all visualizations is to direct the user's attention to the central part of the robot. It can be seen that the visualizations in Figure 1.3 effectively communicate their message, while the renderings in the real-world environment are more difficult to read.

(a) (b) (c)

Figure 1.3 (a) Rendering of a Lego robot in a VR environment (b) F+C visualization in VR using de-saturation to suppress visual attention of context structure (c) F+C visualization in VR using blur to communicate the F+C roles

Sources: Kalkofen et al. (2011)

For example, even though the focus clearly stands out (Figure 1.4(d)), its remainder cannot be discriminated from the information in the background. In contrast, the same visual discrimination is effective in purely virtual environment (Figure 1.3 (c)). Figure 1.4(a) shows the lego robot presented in a real-world environment without any stylization and Figure 1.4(b) shows the F+C visualization is using de-saturation to suppress visual attention of context elements. Figure 1.4(c) is the F+C visualization by applying a blur on contextual fragments and Figure 1.4(d) is the F+C visualization using de-saturation. In contrast to the visualization shown in image b, the F+C roles are identified in object space resulting in a de-saturation of only those structures which are in direct contact with the focus object F+C visualization using the same classification as image d, but applying a blur to visually communicate the roles (Figure 1.4(d)). A combination of F+C communicators in Figure 1.4(f). The context information is visually suppressed using blur and de-saturation, while saturation is increased at focus elements.

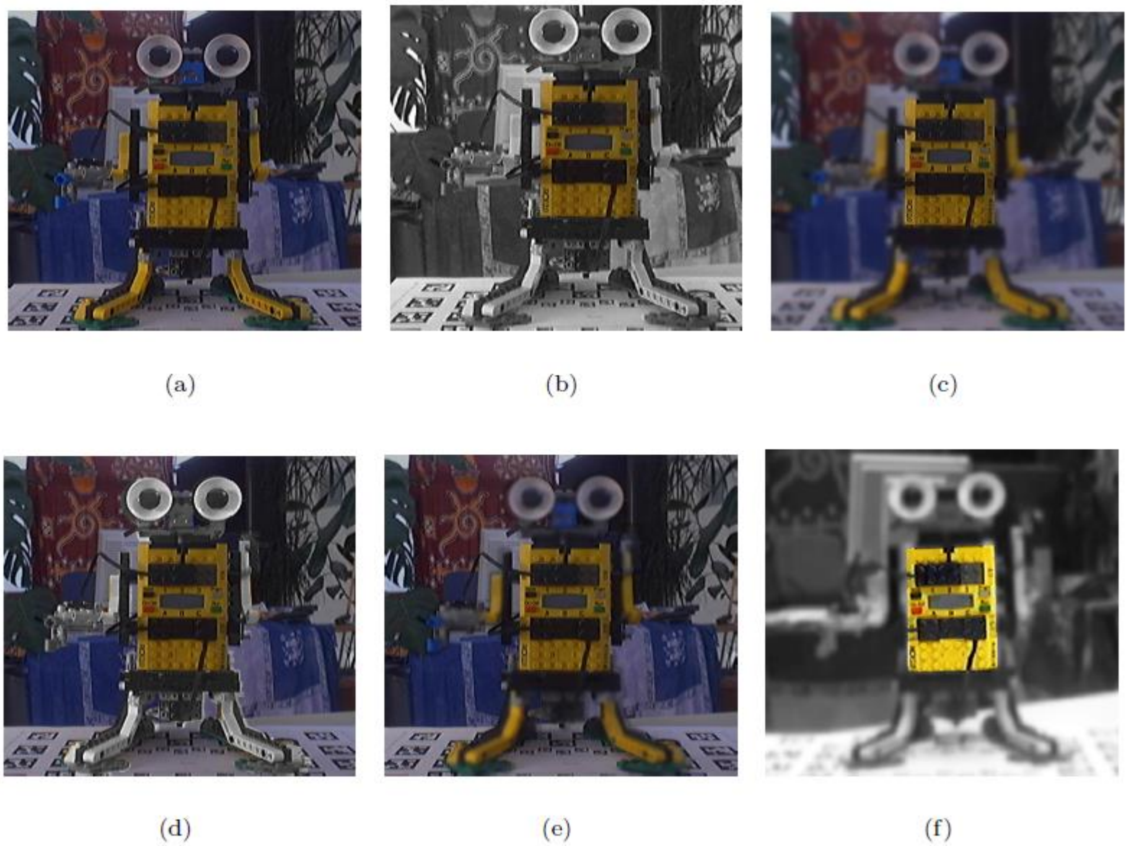


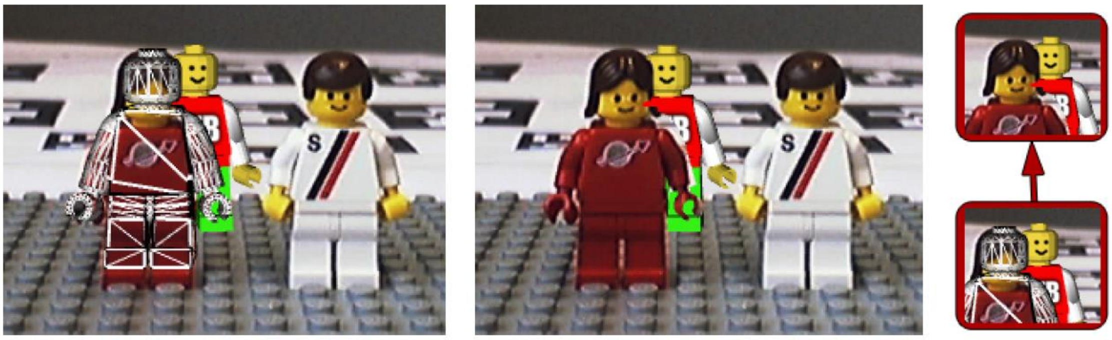
Figure 1.4 (a) The Lego robot presented in a real-world environment without any stylization, (b) The F+C visualization is using de-saturation to suppress visual attention of context elements, (c) F+C visualization by applying a blur on contextual fragments, (d) F+C visualization using de-saturation, (e) F+C visualization using the same classification as image d, but applying a blur to visually communicate the roles, (f) A combination of F+C communicators

Sources: Kalkofen et al. (2011)

The following subsections discuss all the possible problems in detail, beginning with those originating from carelessly adding virtual information to real world environments followed by those caused by imperfect data and concluding with a discussion of the possible problems inherent in XRay visualizations itself.

Imperfect Data

To handle the problems originating from carelessly overriding real world information or those which come from independent shading of the data, the virtual information has to be integrated with the real-world environment instead of being independently rendered and simply overlaid. This means that to be able to comprehensively visualize hidden structures or to preserve the shape cues of real world objects, the AR system has to correctly identify real world structures first and then analyze the relationships between virtual and real data and subsequently adapt the output to rendering parameters. This strategy allows the presentation of virtual information relative to the identified real-world information, enabling proper visual interplay between all types of data in the AR environment.



(a) (b) (c)

Figure 1.5 Occlusion Handling and Sources of Error (a) rendering of a virtual Lego figure which is behind a real one (b) fragments of the virtual figure which are behind the real one has been suppressed (c) the process of transformation

Source: Kalkofen et al. (2011)

To identify real world structure, a virtual counterpart of the real object is commonly registered in real-world space. If this registration perfectly maps the virtual object to its real-world counterpart, subsequent analysis can be completed using only the virtual counterpart. For example, to identify occlusions between virtual and real structures, the depth values of both types of objects per pixel needs to be compared in the screen space of the AR display. By using a registered virtual counterpart of a real 3D object, depth values can be compared in a common virtual space. For example, Figure 1.5 shows a rendering of a virtual Lego figure which is behind a real one. By using a virtual model of the real figure in front, the fragments of the virtual figure which are behind the real one has been suppressed and only those which are not occluded have been overlaid on top of the AR system's video feed.

However, to perfectly map a virtual object to its real-world counterpart, the virtual model has to exactly reflect the real object's shape, and its 3D registration has to transform the virtual model perfectly to fit to its real location. While both steps are prone to errors, both also influence the quality of the resulting visualization in AR. Figure 1.5 shows the effect of a virtual counterpart which does not perfectly reflect the real-world object. The classification falsely identifies parts of the background as being in front of the virtual figure while parts of the face of the real figure have been classified as background information causing the rendering of the virtual figure to falsely override them.

Even though a virtual model perfectly mirrors its real-world counterpart, in order to precisely match it, the virtual model has to be placed exactly where the real object is located. The location and orientation of the real-world object can be computed using either direct vision-based tracking of structures that are visible in the video image or indirectly by using another type of tracking system (such as a tracking by an analysis of an induced magnetic field at the location of the real object). In case of direct visual tracking, often simple and easily detectable objects are added to the scene to reduce the computational complexity of the algorithm. In addition, an offset between the tracked object and its more easily detectable tracking target has to be specified to allow the transformation of the virtual object based on the information from the additional tracking target. While this strategy reduces the complexity of the tracking algorithm, it introduces another source of errors.

If the tracking data is not derived from the same image which is used for augmentation, a problem of synchronization between tracking, rendering and real - world data may occur. Since all of the mentioned factors have to be estimated precisely to classify real world information, a visualization in AR environments will most likely never be free from errors. Consequently, the visualization techniques have to consider the existence of erroneous data and support error-friendly visualizations which are robust enough to communicate the spatial relationships even if they are based on erroneous or missing data.

Multiple Occlusions

If multiple objects occlude the object of interest, preservation of landmarks or shape cues may result in an overflow of information. In the worst case, all preserved shape cues and landmarks of all objects which lie in between the viewer and the object of interest add up to a complete obscuration of the object of interest. If multiple occlusions must be addressed, a choice must be made concerning which object's shape to preserve in order to communicate the visualization's intention best.

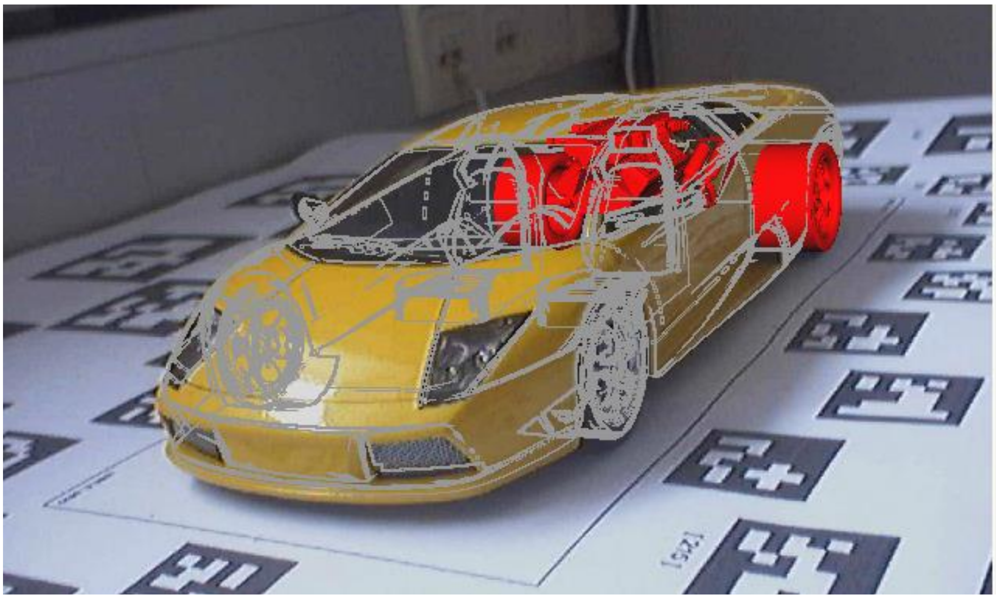


Figure 1.6 Multiple Occlusions

Source: Kalkofen et al. (2011)

Figure 1.6 shows an example in which too many objects occlude the object of interest. The resulting display is cluttered and the object of interest (the engine and the back wheels) is hardly visible. Notice, that the previous sections address problems which are specific to XRay visualizations in AR environments, this problem is independent from the presentation space of the XRay visualizations and also occurs in virtual reality environments.

1.2 PROBLEM STATEMENT

In order to implement and develop any visualization technique in medical augmented reality, Medical 3D dataset is required. However, in our research of study, this was not possible because there is no such Breast Phantom 3D Dataset available. That is because not many MRI dataset are available for Breast cancer, even those available data are full MRI breast cancer patient data on two breasts. For augmented reality tracking it only requires single breast data. Furthermore, the available MRI breast cancer data is only in 2D DICOM format (Pisani et al. 2002) whereas in medical AR visualization process, a basic requirement is to have a 3D virtual dataset to achieve the visualization. Thus, Breast Phantom US-9 has been selected, which is the best suitable Breast Phantom available with multi-tumors.

Further, in order to implement the 3D dataset in Augmented Reality, an appropriate visualization technique have to be analyzed. Based on the literature review, two suitable visualization techniques have been identified, which are XRay Visualization and Focus+Context visualization. XRay is normally used in medical application where it gives the visibility of virtual data, where Virtual data can be occluded by physical objects or be directly visible. On the other hand F+C visualization is computed from different information sources that contains contextual information about the physical and virtual world. However, XRay visualization is still suffering in depth perception (Choi et al. 2016; Livingston et al. 2011), partially occluded (Breen et al. 1996; Gheorghe et al. 2015; Tian et al. 2015) and visibility (Lisa et al. 2015; Marques et al. 2015; Pierdicca et al. 2015), where as in Focus+Context visualization depth perception between physical and virtual claim to be resolved (Kalkofen et al. 2009; Kalkofen et al. 2013). Table 1.1 summarizes the problem in XRay and Focus+Context visualizations in Augmented Reality environments.

Table 1.1 Main problems of XRay and Focus+Context visualizations in Augmented Reality environments

XRay Visualization	Focus + Context Visualization
Landmarks and shape cues may get lost upon overlaying of virtual on real information	False classification due to erroneous data
Depth perception may become ambiguous upon visualizing overlay information	Incomplete classification due to incomplete data
Overlaying of virtual on real information, the contrast and attention deficiencies may occur	Misplaced overlay upon data visualization
Multiple occlusions hide the objects of interest due to an increased depth complexity	

Therefore, an improved visualization technique need to be designed and implemented to visualize the tumor accurately from different angles to visualize multiple 3D tumors. Thus, fusion technique of XFC (XRay and Focus+Context) visualization is proposed to increase the accuracy of 3D tumor visualization on a mobile device display like Apple Pro Tablet for better 3D tracking and processing.

1.3 OBJECTIVES OF RESEARCH

The main objective of this research is to develop an XFC visualization technique that combines the XRay and F+C visualization technique using the 3D Dataset of MRI breast phantom to achieve the visualization accuracy breast cancer. An accurate visualization technique is also designed for successful implementation of the proposed XFC visualization technique. The specific objectives of this research are:

1. To propose a 3D dataset for 3D virtual breast phantom and 3D tumor through 3D segmentation of MRI breast phantom.

2. To increase the tumor accuracy in occlusion and depth perception using XRay and Focus+Context visualization techniques.

3. To introduce the fusion technology of XRay and Focus+Context visualization technique for augmented reality breast cancer 3D visualization.

1.4 SCOPE OF RESEARCH

The scope of this research involves the development of an accurate Augmented Reality visualization technique to visualize breast cancer accurately using 3D data from MRI breast phantom. The techniques proposed for this research are specifically for cancer visualization on tablet device. A proof of concept medical augmented reality application on an IOS Table is developed specifically to resolve depth perception and occlusion.

1.5 RESEARCH METHODOLOGY

Research methodology is an essential part to employ the research methods in any study to understand its research issues. The main goal of this research is to develop an Xray and Focus-plus-Context (XFC) Visualization technique for breast cancer to overcome existing problems of occlusion and depth cures in Medical AR Visualization. Although there are many existing visualization techniques available in medical augmented reality however those techniques still persists depth perception and occlusion especially when implemented for tumor visualization. The research methodology is developed into four main phases: theoretical study, defining the evaluation criteria, analysis and designing the visualization technique, development of XFC AR visualization technique and at the end implementing and evaluating the visualization technique. In addition, statistical analysis of the results is carried out. The main phases of the research methodology are shown in Figure 1.7.

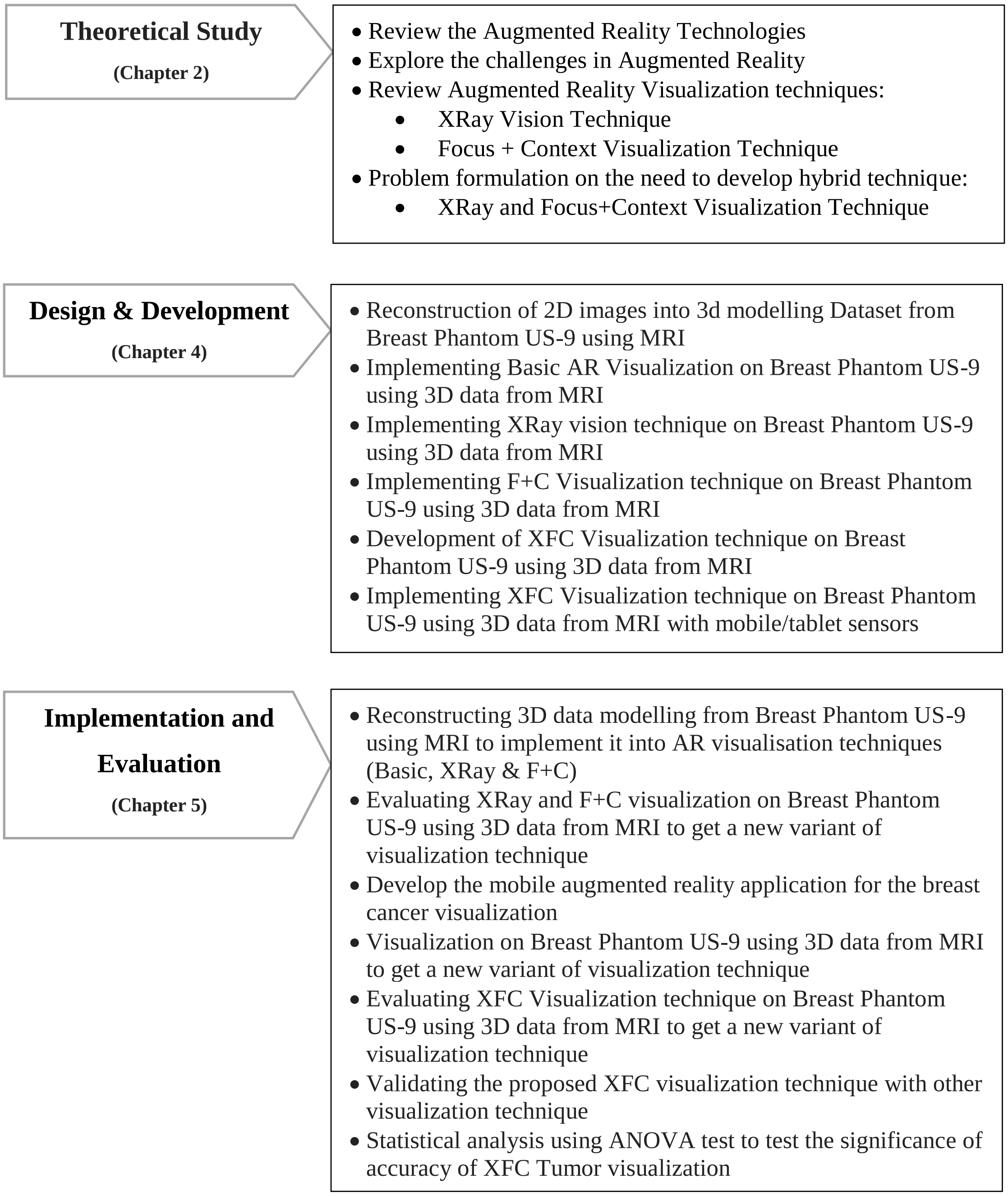


Figure 1.7 Main phases of Research Methodology

1.6 ORGANIZATION OF THESIS

The current research consists of 6 chapters; 1. Introduction; 2. Literature Review; 3. Research Methodology; 4. XFC technique development; 5. Implementation and Evaluation; and 6. Discussion and Conclusion. The study is structured to represent the original development of the research to help visualize the stepping-stones on which the study was built in order to achieve the overall study objective. This section will briefly present the purpose and content of each of the six chapters.

Chapter One: This chapter gives a brief explanation of the research background, problem statement, research objective, research scope and the significance of this study.

Chapter Two: This chapter will shed light upon the details of the topics focused upon during the course of this research. It will be the main source of reaching to the research problems and objectives of this research as it will critically analyze the current and previous researches and understand the core concepts of the research. This chapter will start with the overview of Augmented Reality (AR) technology and its components. The challenges in AR visualization will be discussed which include the types of visualization and the applications in medical area specifically the breast cancer visualization. A special focus is on XRay and Focus+Context visualization techniques related to occlusion and depth cues problems.

Chapter Three: This chapter will present the methodology applied in this research which are explained in four main phases. First, the theoretical phase provides a review of the problems and challenges related to Augmented Reality 3D Visualization for breast cancer, from the literature. The second phase, Design and Development, discusses the designing and development of the visualization techniques in order to evaluate and investigate the accuracy of the proposed XFC visualization technique into breast cancer using MRI 3D dataset. In the final phase, Implementation and Evaluation, describes the implementation of techniques into the mobile application process flow and evaluation criteria employed to evaluate the proposed visualization technique on breast phantom US-9 using 3D date from MRI and its comparisons with statistical analysis of accuracy measurement the all four techniques.

Chapter Four: In this chapter, it will present the proposed Augmented Reality XRay and Focus+Context (XFC) visualization technique is a hybrid technique that integrates the XRay visualization technique and Focus+Context visualization technique to solve the occlusion and depth perceptions problems to accurately visualize the breast tumors position in Augmented Reality environment. It utilizes the basic Augmented Reality visualization technique where almost all of the visualization process is implemented in the rendering task. Since it will be implemented in medical application that is for breast cancer visualization, it can be called Medical AR visualization technique. Initially the 3D data set is being created from the MRI using multiple processes and then the 3D dataset is applied into the XRay and Focus+Context visualization techniques. However, the occlusion and depth perception problems were not solved thus an XFC visualization technique are designed and developed and the 3D dataset were applied to evaluate its accuracy in breast cancer visualization.

Chapter Five: This chapter will explain about the Implementation and evaluation about the research. The implementation of all the four techniques and creation of 3D Dataset from MRI breast phantom has to be done under the Mobile Augmented Reality process flow to have the application ready for the users to perform the experiments. Then in the evaluation, a basic AR technique is compared with XRay and F+C visualizing technique using MRI 3D dataset. This testing will further done to compare XRay and F+C visualization. This research will then evaluate the XFC visualization technique by comparing with XRay and F+C visualization technique. The testing using dataset from experiment by studying the accuracy of tumor detection by participant. The result of this experiment will be validated and analyzed using ANOVA statistical testing to show the accuracy of visualization between basic AR, XRay, F+C and XFC visualization techniques.

Chapter Six: Finally, chapter 6 concludes the research by reviewing the research aims and discussing how each aim has been achieved throughout the study. In addition, the contributions of the research for academia and medical practitioners are presented. Furthermore, limitations of the thesis are discussed reflecting on the process of the overall study. Lastly, recommendations are provided with regards to future research, as well as recommendations for the validating the application at the clinical side related to biopsy.

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CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will shed light upon the details of the topics focused upon during the course of this research. It will be the main source of reaching to the research problems and objectives of this research as it will critically analyze the current and previous researches and understand the core concepts of the research. This chapter will start with the overview of Augmented Reality (AR) technology and its components. The challenges in AR visualization will be discussed which include the types of visualization and the applications in medical area specifically the breast cancer visualization. A special focus is on XRay and Focus+Context visualization techniques related to occlusion and depth cues problems.

2.2 AUGMENTED REALITY

Augmented Reality (AR) was described regarding to the display technologies like head-mounted displays. This is due to the importance of display devices that played a crucial part in the early AR system. Azuma (1997) has described AR as any system that consist of three properties; registration of three-dimensional, interaction with the environment in real time, and combination of both real and virtual object. The said interpretation weight on the importance of integration between real and virtual world with its interaction of human. Wu et al. (2013) argued that defining AR as a concept rather than a type of technology is more constructive for researchers, designer, and educators. Therefore, AR can be said as a developed form of experience where users are provided with a composite view of the scene of real-world and computer generated virtuality, with the experience of real environment. The virtual and real world are overlapped to provide user with a synthetic environment that they can interact.

2.2.1 Augmented Reality Taxonomy

"Augmented Reality" is a terminology that is well classified in the taxonomy model of virtuality continuum, which "connects completely real environment to completely virtual ones" (Milgram et al. 1994). A general schematic view is depicted in Figure 2.1.

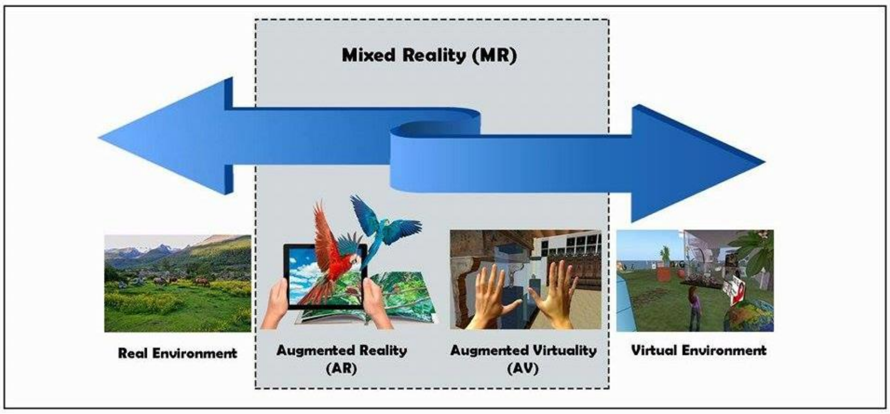


Figure 2.1 Simplified representation of a "Virtuality continuum"

Source: Milgram et al. (1994)

In this taxonomy, it shows the AR is in the Mixed Reality field that associates the emergence of real and virtual environments. The real environment is all the things around us that can be felt physically using our senses. In Virtual Reality (VR) environment, users are wrapped inside a synthetic world but are not able to view their surrounding real world. The typical AR techniques supplement the real environment with virtual objects that coexist in the same space as the real world. Nevertheless, the Augmented Virtuality is closer to the virtual extremity off the Mixed Reality spectrum. Artificial environment integrated with real world experience produces a unique experience to the user.

2.2.2 Major Components of Augmented Reality

An AR system has the following components: Tracking, Calibration, Registration, Display, and Visualization.

Tracking is the process of measuring the positions and orientations (the poses) of objects with respect to a reference coordinate system. Tracking systems have the task of localizing (moving) objects in space in real-time. Generally, under a wide range of environmental differences, AR trackers need to give low latency, high accuracy, and robust operations. A top-down classification of tracking technologies are presented by Rolland et al. (2001). There are three kinds of tracking techniques that usually are utilized in AR system that are sensor-based tracking, hybrid tracking techniques and video-based tracking.

Calibration is the process of instantiating parameter values for "models" which map the physical environment to internal representations, so that the computer's internal model matches the physical world. For an AR system to be successful it is crucial that this calibration process be both complete and accurate. Otherwise, the scene rendered by the computer using the internal model of the world will look unrealistic (Tuceryan et al. 1995).

Registration is the process of aligning images so that corresponding features from different image data can easily be related (Hill et al. 2001). Image registration is an instance of an inverse problem where the transformation parameters are derived by the images (Fluck et al. 2011). Registration must be made with pixel accuracy at interactive frame rates to preserve the illusion of real and virtual coexisting in the same domain (Henrysson 2007). When a user remains in static position and receives pixel-perfect alignment of the real world and virtual images, a system can be said to offer good static registration. However, if users move around with AR system, they might face jitter problem between real and virtual world. AR systems should further exhibit good dynamic registration (Kong et al. 2017). Augmented Reality superimposes the virtual elements upon the real world and both are integrated into a seamless synthetic environment. Hence the display technologies, which allow users to perceive the real and virtual contents at the same time, play a vital role in AR system.

Visualization is essential to verify registration results and to display the fused image data. Both visualization tasks are challenging, since the underlying data is more complex compared to image segmentation. In general, it is difficult to understand and verify the registration process. Checkerboard visualizations are frequently used to evaluate the registration accuracy in different portions of the data (Stokking et al. 2003). Koenig & Peitgen (2005) discussed visualization techniques to convey the locally different amount and direction of transformation in a non-rigid local registration. This local examination is often essential because a correct transformation in certain parts of an image is more important than in others.

2.2.3 Challenges in Augmented Reality

Researchers were first able to find the potential of mobile and handheld devices for AR as early as 2003. Even though today mobile devices ecosystem provides all ingredients to deploy AR as a software-only solution to a mass audience but one should not overlook that despite all technical and logistic improvements, there are still major obstacles for a large-scale deployment of AR applications. Although many works have been carried out in the area of Augmented Reality but there still exist several challenges. Figure 2.2 shows the overview challenges in AR.

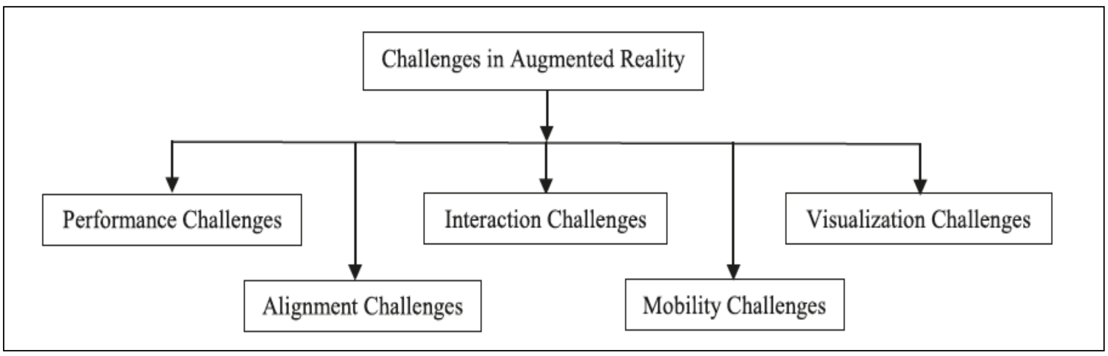


Figure 2.2 Challenges in Augmented Reality

Source: Rabbi & Ullah (2013)

a. Performance

Challenges faced by Augmented Reality concerning real-time processing, responding and evolving with the change of real world environment are generally categorized under performance challenges.

Real-time processing is capable of slowing down the overall performance and quality of augmented reality applications. Performance issues are a major concern of mobile AR (J. Yang & Maurer 2010). Even for simple markers, visual recognition is computationally very expensive. Therefore, the implementation of markerless tracking techniques which can detect natural features is of major concern in terms of the performance of AR (Daniel Wagner & Schmalstieg 2009a). Other major processes such as rendering, also affects the real-time performance of AR, especially in smartphones. Hence, the 3D models used for mobile AR implementation should be of reduced complexity to achieve an acceptable memory footprint (Daniel Wagner & Schmalstieg 2009b).

b. Tracking

One of the most significant technical challenges in mobile AR is the detection of the objects and then measuring the camera's position and orientation (pose estimation) between the virtual object and real object. These two combines together and completes process which is known as 'tracking' or 'localization' (Gervautz & Schmalstieg 2012). Tracking challenges have a direct impact on the performance of AR. Continuous localization in AR applications is essential for registering and augmenting the digital content on top of the real world. Accurate registration depends on correct pose information (Kruijff et al. 2010). Tracking is often difficult for outdoor AR than indoor AR. Indoor AR depends on marker based tracking, natural feature tracking or installing a sensor system and outdoor AR rely on sensor tracking such as GPS and inertial sensor tracking.

Computer vision (CV) based tracking could be the best alternative for tracking. It promises highly accurate tracking and allows tracking in unknown environment. Although it may be a good alternative of tracking, but it is often related with costly computations which hinders the performance of AR. These computations include the implementation of essential key elements required for markerless tracking such as keypoint detection, keypoint description, keypoint matching and pose estimation (Yang & Lu 2015). Tracking also includes alignment which is relates to proper placement of a virtual objects with respect to the real-world objects. Problems such as incorrect rendering of information to the real world are generally caused due to incorrect alignment. This misalignment can cause some severe problems in medical applications. Challenges related to alignment also include registration problems, which are one of the most basic problems of AR (Hoff et al. 1996).

Modern day smartphones are equipped with GPS, compasses, accelerometers and gyroscope sensors. With the help of these sensors, smartphones can calculate position and orientation of the device and the user. However, these sensors provide low quality pose estimation, especially in large environments. GPS does not work well in indoor environments. Even in outdoor environments GPS readings are not always accurate and are affected by surrounding environment. Similarly compass readings are affected by magnetic fields of the surrounding environment (Maloney 2008). Several approaches are taken to give accurate pose information in indoor and outdoor AR environment, such as the work of Gerstweiler et al. (2015) and PTAM by Klein & Murray (2009). However, most of these works were proposed for small workplaces. To work in a large environment, AR system need more robust and accurate tracking system. Similarly, to work on mobile platforms AR systems needs more efficient and robust tracking system.

c. Interaction

Over the past few years handheld device become widely popular for augmented reality application. Current handheld devices have all the necessary hardware for AR application. However, user interaction is very challenging in handheld AR environment. There has been lots of research in handheld AR for tracking, registration but less in user interaction (Chun & Höllerer 2013). In order to realize full potential of handheld AR, users must able to interact precisely with virtual object in handheld AR environment.

Touch screen interface is the common and popular in handheld AR applications. While touch screen interface is popular and easy to use it can be less affective. One of the problems is ‘fat finger’ when user use their finger for interaction it covers the content in display. Another problem is user need to hold their device with one hand and interact with other hand which needs accurate coordination between both hands. In handheld environment it is difficult because hands can shake and it could lead to unexpected error. Users often need to move their devices which make the problem worse (Kurkovsky et al. 2012; Lee & Billinghurst 2012). Handheld AR can provide software only solution on device that billions of users own. Current handheld devices hardware is insufficient for high quality applications because of small display, power consumptions, camera quality, and network problem. These limitations make it hard to develop real-time AR system in handheld device. However, developers are aware of this limitation and assume in near future hardware would be more advance for high quality handheld AR application.

d. Mobility

According to Azuma (1997), the best augmented reality system will be portable outside a controlled environment. In 2000, Schmalstieg et al. (2000) developed a wearable system which needs to carry a whole set of heavy equipment for a long time. Therefore, the portability of augmented reality system is the most concerned challenge. It ought to be small and light so it could be easy to bring around and utilized in anywhere.

e. Visualization

In AR, a visualization technique allows users to perceive computer generated information in the real world. Challenges related to visualization generally include display issues, contrast, brightness, resolution, and field of view. Both the virtual objects and real world objects are required be of the same illumination (Drettakis et al.

1997). Occlusion, is another major challenge related to visualization. It is a process which determines which surface or its parts are not visible from a certain view-point (Fuhrmann et al. 1999; X. Wang & Dunston 2007). In an AR application users must be able to simultaneously see the real environment and the augmented information and it should be indistinguishable (D. Kalkofen et al. 2009). However mixing the computer generated object with the real world is one of the problems in AR visualization due to occlusion handling, especially in outdoor environment (Arth & Schmalstieg 2011; Kruijff et al. 2010). To make the AR visualization more realistic, photorealistic rendering technique and interaction between real and virtual world are required. The problem in occlusion is to distinguish between foreground and background, such that some objects can be rendered behind a particular object instead appearing in front of it (Kruijff et al. 2010). This can cause incorrect depth ordering and may look like that the objects does not belong to the scene. With advent of AR, researchers have tried to solve occlusion problem using XRay vision. XRay visualization allows users to see virtual object through real object. However XRay vision techniques suffer from depth ordering problem (Kytö et al. 2013).

Next section will discuss in detail on visualization with focus on XRay and Focus+Context visualization.

2.3 VISUALIZATION

Visualization is any technique for creating images, diagrams, or animations to communicate a message. Visualization through visual imagery has been an effective way to communicate both abstract and concrete ideas since the dawn of man. Examples from history include “cave paintings” (Fryer et al. 2005), “Egyptian hieroglyphs” (MacDonald et al. 2014), “Greek geometry” (Korakakis et al. 2009), and “Leonardo da Vinci's” (Johnson 2004), revolutionary methods of technical drawing for engineering and scientific purposes.

2.3.1 Types of Visualization

Computer graphic visualization is the use of interactive, sensory representations, typically visual, of abstract data to reinforce cognition, statistical graphics, and spatial data or perceptual data. Visualizing data has been used in maps, scientific drawing and data plots for over a thousand years and is further subcategorized into many visualization domains. Below are the main types of visualization.

a. Scientific visualization

Scientific visualization is the transformation, selection, or representation of data from simulations or experiments, with an implicit or explicit geometric structure, to allow the exploration, analysis, and understanding of the data. Scientific visualization focuses and emphasizes the representation of higher order data using primarily graphics and animation techniques (Griffith 2003).

b. Educational visualization

Educational visualization is using a simulation not usually normally created on a computer to create an image of something so it can be taught about. This is very useful when teaching about a topic that is difficult to otherwise see, for example, atomic structure because atoms are far too small to be studied easily without expensive and difficult to use scientific equipment (Lu & Olson 2008).

c. Information visualization

Information visualization concentrates on the use of computer-supported tools to explore large amount of abstract data. The term "information visualization" was originally coined by the User Interface Research Group at Xerox PARC (Card et al. 1999). Practical application of information visualization in computer programs involves selecting, transforming, and representing abstract data in a form that facilitates human interaction for exploration and understanding. Important aspects of information visualization are dynamics of visual representation and the interactivity. Strong techniques enable the user to modify the visualization in real-time, thus affording unparalleled perception of patterns and structural relations in the abstract data in question.

d. Visual analytics

Visual analytics focuses on human interaction with visualization systems as part of a larger process of data analysis. Visual analytics has been defined as "the science of analytical reasoning supported by the interactive visual interface" (Thomas & Cook 2005). Its focus is on human information discourse (interaction) within massive, dynamically changing information spaces. Visual analytics research concentrates on support for perceptual and cognitive operations that enable users to detect the expected and discover the unexpected in complex information spaces (Fisher 2010).

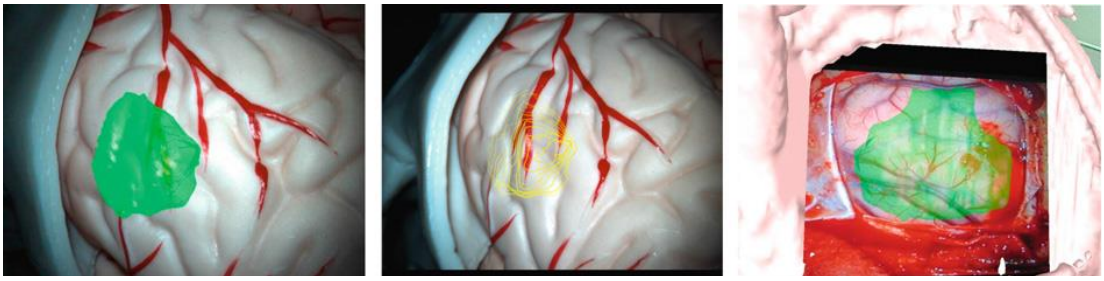
e. Medical Augmented Reality visualization

Medical Augmented Reality visualization covers visual analytic and scientific visualization where the visual overlay of real and virtual information requires not only an appropriate display device but also appropriate visualization techniques (Baudisch et al. 2001). Thus based on the research conducted by Brodlie et al. (1992), Tobias Isenberg (2015) and Ivan Viola & Gröller (2005), derives the following: Basic Augmented Reality Visualization, XRay Visualization, and Focus+Context Visualization.

2.3.2 Basic Augmented Reality Visualization

The overlay of intraoperative images with preoperative image data is a very similar visualization task like overlaying original image data with segmentation information. Consequently, basic solutions are also similar, the region of a crucial anatomical structure may be drawn semi-transparently or the boundary may be indicated by contours.

In contrast to the overlay of segmentation information that is usually performed in slice views, there is a more complex 3D situation here. Thus, instead of presenting one contour, a stack of contours is essential and the contour corresponding to the focus layer of the microscope should be emphasized. These basic techniques are widely used. In the work of Salah et al. (2010), the tumor were fine-tuned for brain tumor surgery and discussed with neurosurgeons. Figure 2.3 shows the preoperatively acquired segmentation information of a brain tumor should be overlaid with the brain surface. The tumor region is transparently overlaid on a phantom in Figure 2.3(a). The contours of the tumor are shown on top of a phantom in Figure 2.3(b) and colored overlay on images of a real surgical microscope in Figure 2.3(c). The transparency level was carefully adjusted to enable a sufficiently clear view on the operating area.

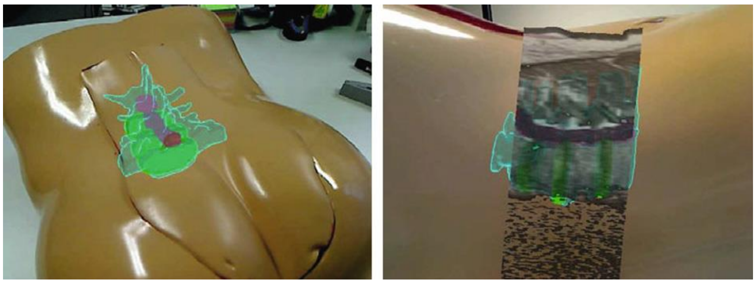


a) b) c)

Figure 2.3 The preoperatively acquired segmentation information of a brain tumor should be overlaid with the brain surface. (a) The tumor region is transparently overlaid on a phantom (b) The contours of the tumor are shown on top of a phantom. (c) Colored overlay on images of a real surgical microscope

Source: Salah et al. (2010)

As a second example, it shows the overlay of relevant information for minimally-invasive spine surgery. Here, the exact position of the vertebrae is essential to guide the needle insertion process. The phantom shown in Figure 2.4 is realistic, since in surgery also only the skin is visible. In addition to the segmentation information, it may be useful to display also original data, at least optionally. In Figure 2.4 the relevant information for minimally-invasive spine surgery is overlaid with data from the operation room (here simulated with a phantom). In Figure 2.4(a), only segmentation information related to vertebra (cyan), discs (green), and spinal canal (pink) is shown while in Figure 2.4(b), a portion of the underlying MRI data is presented.



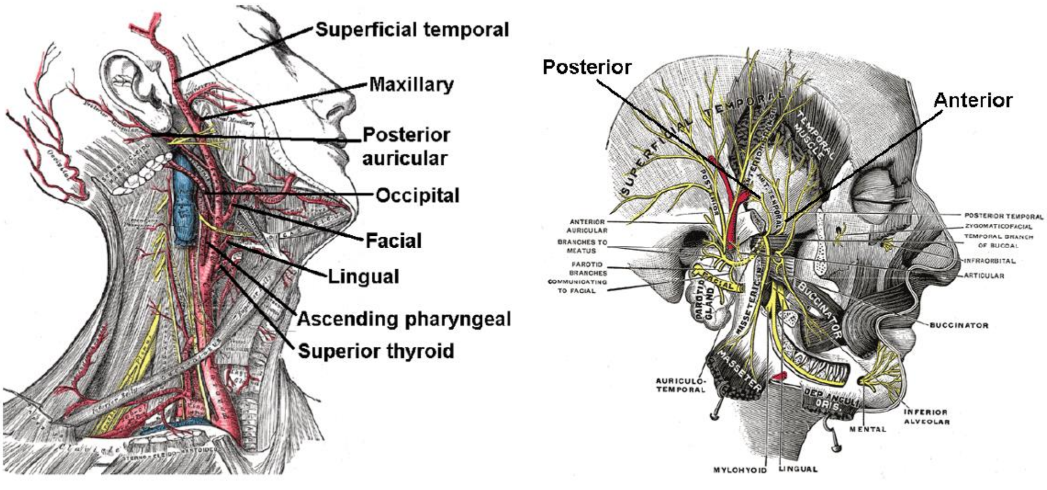
a) b)

Figure 2.4 Relevant information for minimally-invasive spine surgery is overlaid with data. (a) shows only segmentation information, (b) with underlying MRI data

Source: Salah et al. (2011)

2.3.3 XRay Visualization

XRay visualization can represent an occluded region in-situ with the user's current view, improving cognition by representing both as a single, unified visual event instead of disparate events. This is recognized as requiring greater cognitive effort. Naively rendering AR XRay, such as rendering the occluded region on top of the occluder can be problematic. For example, a photographer tries to share a moment with the viewer of a photo while a pie chart is usually intended to present some kind of distribution. Of the various motivations, illustrations aim to communicate a specific meaning, and they do this very well. Since meaning is often better conveyed using an abstraction or distortion of reality, illustrations often do not even try to perfectly mimic real-world conditions. Instead, they trade reality for comprehensibility. Consequently, illustrations include many kinds of Focus and Context techniques in the presentation of information wherein the goal is to emphasize aspects which are needed to communicate their message while at the same time reducing the visual impact of things which are less important. Sometimes distortion techniques are applied, multiple windows are used or in-place visual encodings use different styles on different structures (Gray & Goss 1973). Figure 2.5(a) shows the facial nerves while Figure 2.5(b) shows the facial nerves along with contextual information of the head. While the nerves and arteries are emphasized, the contextual information is presented in a less dominant way using only hatching and line rendering to preserve shape and shading.



(a) (b)

Figure 2.5 Illustrative Visualization of Human Anatomy Facial arteries

Source: Gray & Goss (1973)

To stylize their data, illustrations often include Non-Photorealistic Rendering (NPR) techniques. Notice that while research on NPR looks into many kinds of rendering techniques to mimic artistic drawings, illustrative renderings only exploit a subset of them. They apply the methods which can "convey meaning" and those which "clarify relationships between language and pictures" (Strothotte & Schlechtweg 2004), for example using algorithms to automatically place labels (Hartmann et al. 2004) or automatically generate page layouts (Ali et al. 2008; Grabler et al. 2009)

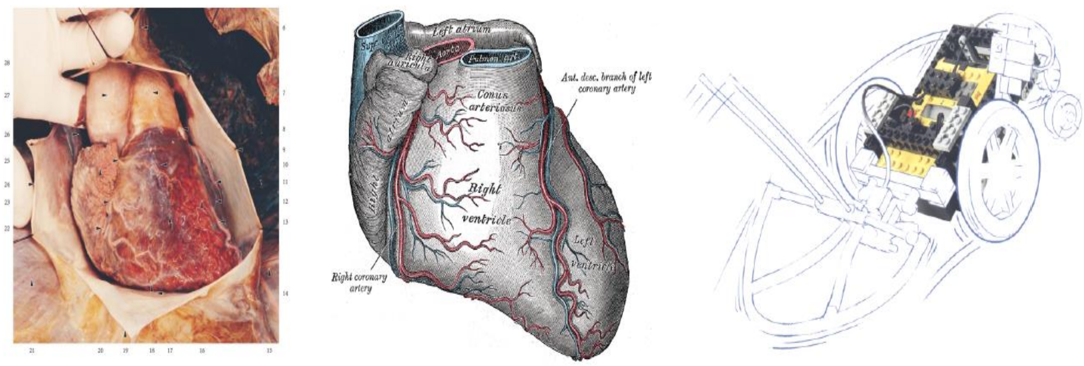
NPR offers a wide range of abstraction techniques. If high abstraction is required, illustrations often use line renderings to convey shape information only. In Figure 2.6(a), line drawings abstract shape presentation using a minimal set of graphical items while in Figure 2.6(b), hatchings and cross hatching abstract shading by varying its density (DeCarlo et al. 2004). Dark areas use dense pattern or cross hatchings while light regions apply sparse hatchings (Raab & Rüger, 1996). In Figure 2.6(c) Cartoon shading reduces the number of different shades (Lake et al. 2000). Line renderings are very effective as they use only very sparse graphics (Gooch et al. 2004; Santella & DeCarlo 2004). However, if more details is required, illustrations commonly apply hatching or stippling techniques (Hodges 2003) to abstract the shading of an object. Stippling, hatching and line renderings usually do not use colors. However, if an abstraction of shade information is desired the illustration may exploit a cartoon shader Figure 2.6(c) which reduces the amount of shades applied to simplify the rendering (Lake et al. 2000). In addition to these abstraction techniques, Gooch et al. (1998) noticed that colorized technical illustrations can apply some kind of tone shading to better communicate depth arrangements. The tone of an illustrated object is often altered depending on the intensity of its shading. Since cool colors are perceived of as being further away, technical illustrations often vary tone from cool to warm colors instead of shifting from light to dark.

(a) (b) (c)

Figure 2.6 Non-Photorealistic Rendering (NPR) techniques provide the tools to abstract information in illustrative visualizations

Sources: Raab & Rüger, (1996), DeCarlo et al. (2004), Lake et al. (2000)

In contrast to non-photorealistic renderings, real world objects present texture and shape in full detail as well as in correct perspective and scale. In Figure 2.7(a) and (b) the images offer a comparison of photo-realistic and illustrative presentation techniques. The images are both taken from anatomy texts by Thiel (2006) so it can be assumed that both have the same intention (they try to communicate anatomical structures of the human heart). The illustration in Figure 2.7(c) uses a photorealistic presentation of the focus element and a non-photorealistic rendering of contextual information (Kelly 2007). However, even though the illustrative rendering seems to be more effective in communicating the information, medical students usually have to dissect organs and muscles as part of their training. The amount of detail and the realistic nature of a photography makes the presentation more believable.



(a) (b) (c)

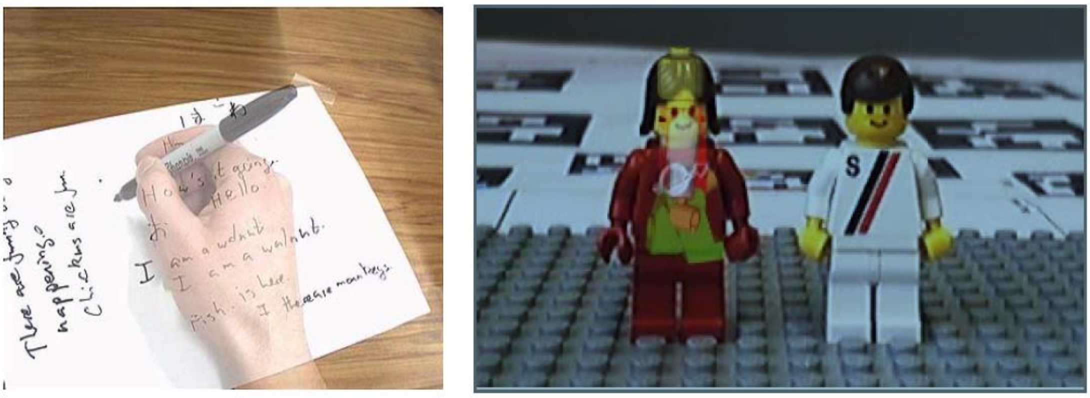
Figure 2.7 Photorealistic versus illustrative presentations a) anatomy of the human heart (b) photo-realistic and illustrative presentation techniques (c) photorealistic presentation of the focus element and a non-photorealistic rendering of contextual information

Sources: Kelly (2007)

a. Ghosting

The easiest approach to present both hidden and occluding structure is to make the occluding one transparent so that hidden structure is visible. However, a simple uniform modification of the transparency values of occluding structures will most often result in ambiguous presentations. Figure 2.8(b) demonstrates the presence of clutter after blending the occluding structure uniformly with hidden objects. Even though very uniformly colored occluders covering high contrastive structures, as shown in of Figure 2.8(a), may allow one to perceive both types of data, Buchmann et al. (2005) showed that spatial relationships are lost if transparency is uniformly altered. The user perceives the hidden text as an overlay on top of the hand if transparency is too high.

Since uniform modulations of transparency create a number of perceptual problems, illustrative XRay visualizations vary transparency values non-uniformly over the object (Figure 2.9). This results in a so-called ghost presentation of the occluder. In order to automatically generate ghost illustrations, a number of different approaches have been applied to control the means of modulation. Very early work from Crow (1978) proposes a function of the cosine of the angle between a normal surface point and the current viewing vector.



(a) (b)

Figure 2.8 Uniform Transparency Modulation (a) Uniformly colored occluders allow one to see through them (b) More complex color distribution result in an ambiguous presentation

Source: Maier (2016)

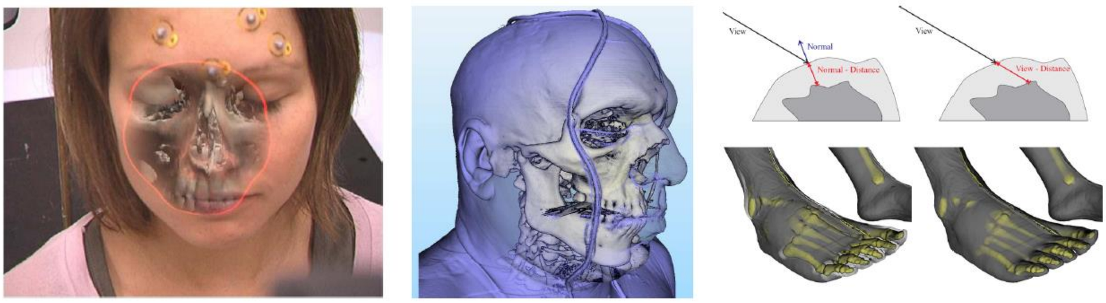
To simulate different transparent media, Crow additionally uses the cosine to a modifiable power which is can vary the drop-off function of his transparency modulation. Notice that the silhouette of a 3D object is defined at those points where the viewing vector hits a surface point within an angle of 90 degree to the normal vector of this point. Even though he didn't explicitly points it out, Crow's approach allows for transparency decrease close to the silhouette of the occluding structure.

(a) (b)

Figure 2.9 Two Types of Ghosting. (a) Ghosting of hidden objects shine through occluding Structures (b) Occluding structures use a ghost presentation to uncover the inner parts of the sports car

Source: Kalkofen et al. (2011)

A more direct approach to compute a ghost representation which depends on the silhouette of the object is presented by Diepstraten et al. (2002). First the silhouette is computed by comparing the orientation of adjacent faces (which is similar to Apple's algorithm (Appel et al. 1979)) followed by a computation of the distance in 2D between vertices and the detected silhouette. To encode different material, the transparency is encoded by weighting the distances.



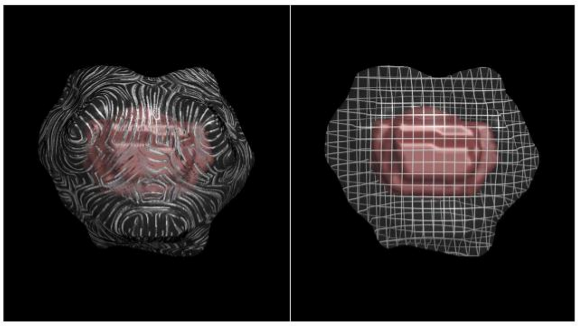
(a) (b) (c)

Figure 2.10 Different Strategies for Modulating Transparency (a) Curvature dependent transparency modulation using a user controlled 2D mask in AR. (b) Curvature driven values opacity modulation in volume rendering. (c) Distance dependent transparency modulations

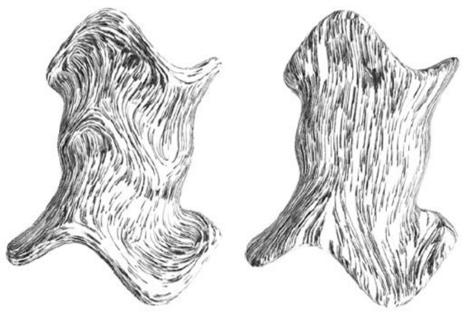
Source: Kr¨uger et al. (2006)

Non-uniformly modulated transparency presentations preserve certain parts of the object while other parts are completely removed. In Crow's approach the ghost presentation preserves the silhouette of the occluding structures. However, other line renderings are also able to convey shape information very effectively. For example, crease lines or suggestive contours (DeCarlo et al. 2003), have been proven to be good shape communicators (Tjan et al. 1995). It seems natural that illustrators and computer graphics researchers exploited these types of lines to generate ghost representations. For example, Interrante et al. (1995) demonstrated the effectiveness of preserving crease lines in transparent visualizations. In addition to a uniform transparency modulation of de-saturated occluding structure, she emphasizes valley and ridge lines by rendering them fully opaque using an increased saturation. Tietjen et al. (2005) uses silhouette lines to present context in an otherwise volume rendered image. Kr¨uger et al. (2006) and his colleagues use a curvature estimation in 2D to vary transparency values (Figure 2.10(a)). Moreover, instead of a discrete emphasis of crease lines, Krueger's technique enables one to smoothly vary transparency values. In addition, he used the relationship between occluding and hidden structure to control transparency modulations. For example, Figure 2.10(c) shows a transparency modulation using the distance between the occluding and hidden structure. Krueger also demonstrated the effect of interactively weighting the transparency values (computed from curvature or structure relations) using a 2D Magic Lens. Transparency values at the center of the Magic Lens are increased while those close to its boarder either remain unchanged or are increased (Figure 2.10(b)).

While Krueger combined creases (due to their curvature approximation) and a user controllable mask, Stefan Bruckner and his colleges combine shape and view dependent information. They evaluate shade information, which is previously computed using the Blinn-Phong mode, to subsequently modulate transparency. Since lighting can be easily altered, a shade based transparency modulation allows one to preserve silhouette and crease lines in an interactive manner. To also mimic the behavior of a clipping plane, the distance between the viewer and the model is encoded in Brucker's system. Interaction is accomplished by changing the distance between the camera and the object itself.



(a)



(b)

Figure 2.11 Ghost Presentations Using Texture to Communicate Shape (a) stroke direction follows a principal curvature, (b) texture orientation follows a constant up direction

Sources: Interrante et al. (1995) and Kim et al. (2004)

Bichlmeier et al. (2007) applied a similar system to the one presented by Krueger to an AR environment. It modulates the transparency of previously classified video information with respect to a mixture of curvature and a user controllable 2D Magic Lens. Their classification of video data is done using a three-dimensional registration of the virtual objects relative to its real-world counterpart, as in Figure 2.11(a), left: stroke direction follows a principal curvature and on right: "solid grid" generated by cross-section. In Figure 2.11(b) left: texture orientation follows the direction of a principal curvature. Right: texture orientation follows a constant up direction. (Interrante et al. 1995; Kim et al. 2004).

Even though a modulation of transparency values based on certain features is able to preserve the shape information of some objects, it has been noticed that not all shapes present characteristic shape features which are worth being preserved (Hodges 2003; Interrante et al. 1997a). Instead smooth shapes, for example a sphere or a cylinder, may not be correctly preserved if high transparency values cause very sparse ghost presentations. Therefore, instead of modulating transparency depending on a certain set of features, Interrante et al. (1995) and Kim et al. (2004) experimented with textures which introduce feature which are able to convey shape information. Inspired by hatchings which abstract shading (Figure 2.11(b)), they evaluated the perceptual applicability of directional stroke textures to convey both shape and depth information simultaneously. They could prove that strokes aligning with a principal direction are able to convey shape information better than strokes aligned in a constant direction.

Nonetheless, Interrante et al. (1997b) could not measure a statistically significant difference between a constant pattern and curvature directed strokes for the communication of depth values in XRay visualizations. However, since the difference seems to be very obvious, she attributes the rejection of her hypothesis to the design of the experiment.

While Interrante et al. (1997b) used hatching to present the occluder covering a smoothly shaded hidden object, Hamel et al. (1998) incorporated transparent surfaces using hatching on hidden and occluding structure. Inspired by an illustration made by Hodges & Guild of Natural Science Illustrators (U.S.) (2003), they darken the hidden object where it enters the transparent occluder while they lighten the hidden structure where the edges at the entry point of the occluder overlap. In addition, they alter the hatching of the occluder where hidden structure "shines through" by darkening the texture with increasing distance to the previously lightened edges. The occluder's hatching is darkened by either changing the thickness of its lines, by modifying their density or by a combination with a set of stipplings and as you can see in Figure 2.12(a), to allow hidden structure to shine through, hatching of occluding structure is modified by altering the thickness of hatch lines, the amount of hatch lines and the style (Hamel et al. 1998). Figure 2.12(b) Line halos communicate depth arrangement in line drawings. In addition, thickness and brightness of hidden lines decreases with increasing distance (Diepstraten et al. 2002). Figure 2.12(c) By convention, hidden lines are often dashed (T. Isenberg et al. 2006).

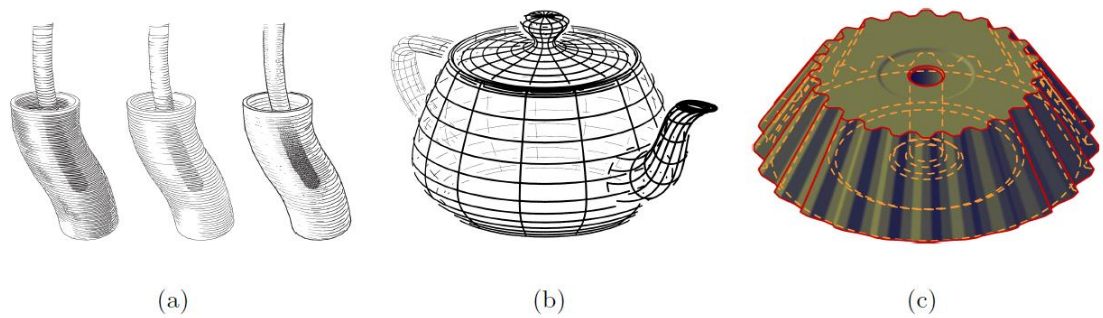


Figure 2.12 Communicating Depths via Line Stylizations

Sources: Maier (2016), Hamel et al. (1998), Diepstraten et al. (2002), Isenberg et al. (2006)

A similar technique is suggested by Hodges (2003) if the application requires one to present occluding structure as mostly visible. She proposes the generation of ghost presentations of hidden structure by lightening their features so that hidden structures "shine through". The appearance changes only where hidden and occluding structure overlap in 2D. Figure 2.12(a) shows an example application of this technique in a handmade illustration by.

Both hidden and occluding lines have also been shown to be useful for architectural visualizations using a blueprint rendering technique (Marc & J"urgen 2005). The blueprint is rendered by blending all possible edges into a single rendering and detects the edges from a set of 2D layers which are generated by using the depth peeling technique (Everitt & Williams 2001).

However, when line renderings are used on visible and otherwise invisible information, cluttering may result. To counteract cluttering in line renderings, a stylization of the lines often helps to communicate depth arrangements. For example, Figure 2.12(b) shows a line rendering using thick and dark lines close to the camera while thin lines represent structures further away. This rendering also demonstrates the effect of using line halos around line in front (Appel et al. 1979). By introducing discontinuations of otherwise hidden lines at those places where they intersect, the impression of occluding lines is caused. A similar technique for presenting both hidden and occluding line rendering is demonstrated in Figure 2.12(c). However, while occluding lines are still rendered continuously, hidden lines have been dashed to uniformly introduce discontinuations.

Livingston et al. (2003) evaluated additional visualization parameters to the style of line renderings in visualizations of multiple occluding structures in AR environments. He considered the object's relative intensity, the structure's opacity and whether they are drawn using the outline alone or in combination with a single colored virtual phantom object. Similar to the experiments of Interrante et al. (1997b), they asked users to determine the location of a hidden structure. Livingston et al. (2003) compared the error measurements in different combinations of the visual parameters with the error measured using a ground plane which introduces perspective distortions of a known pattern (this is known to be a good indicator for depth (Wolfe et al. 2014). His study showed that a configuration of an outline together with a single colored phantom rendering in combination with decreasing opacity and intensity at increasing distances was almost as powerful as the ground plane visualization in indicating the depth of hidden objects.

b. Cutaways

Instead of trying to preserve depth cues by preserving a certain amount of characteristic information, cutaway illustrations completely remove occluding structures. However, while the careless removal of occluding information will most likely result in ambiguous presentations, cutaway illustrations design the cut out in a way that depth cues are introduced and missing shape information can be mentally