



SIMULATION STUDY OF MICROWAVE TOMOGRAPHY FOR AGARWOOD EVALUATION

by

**THOMAS TAN WAN KIAT
(1430611538)**

A thesis submitted in fulfillment of the requirements for the degree of
Master of Science in Mechatronic Engineering

**School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS**

2018

ACKNOWLEDGMENT

I praise God, the almighty for giving me this opportunity and allowing me the competency to proceed successfully.

First and foremost, I am truly indebted to my main supervisor and mentor, Assoc. Prof. Ir. Dr. Mohd Hafiz Bin Fazalul Rahiman for his continuous support, patience, motivation, enthusiasm and immense knowledge in my M.Sc. study and research. His guidance helped me in all time of research and writing of this thesis. The questions pointed out by him had proved vital in solving the problem statement in relation to this research title.

Next, I would also like to extend my warmest gratitude to my co-supervisor, Assoc. Prof. Dr. Soh Ping Jack for sharing his scientific knowledge and the fruitful discussions to solve encountered research problem.

My acknowledgement goes to Kementerian Pengajian Tinggi Malaysia (KPT) for their financial support through the scholarship program; MyBrain15 during my M.Sc. study.

, thousands of thanks to my colleagues and seniors for whom I have great experience with during my M.Sc. study and for lending their helping hands directly or indirectly.

Last but not least, this thesis is dedicated to my family members for their understanding and support. I am also grateful to my parents, who shaped me as I am and always give me encouragement.

TABLE OF CONTENTS

	PAGE
DECLARATION OF THESIS	i
ACKNOWLEDGMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF ABBREVIATIONS	x
LIST OF SYMBOLS	xi
ABSTRAK	xii
ABSTRACT	xiii
CHAPTER 1 :INTRODUCTION	1
1.1 Research Background	1
1.2 Motivation	3
1.3 Problem Statement	4
1.4 Objectives	5
1.5 Scope of Research	7
1.6 Significant Research Contribution	7
1.7 Thesis Organization	7
CHAPTER 2 :LITERATURE REVIEW	9
2.1 Introduction	9
2.2 Agarwood	10
2.3 Tomographic Techniques for Detection of Agarwood in <i>Aquilaria</i> Tree	15
2.3.1 Non-Invasive and Non-Destructive Detection Technique	19
2.4 Model of Microwave Tomography System	28

2.4.1	Fundamental of Microwaves	30
2.4.2	Dielectric Properties	32
2.4.2.1	Factors Influencing the Dielectric Properties	33
2.5	Image Reconstruction Algorithm	34
2.5.1	Linear Back Projection	34
2.5.2	Filtered Back Projection	35
2.5.3	Newton's One-Step Error Reconstruction (NOSER)	37
2.5.4	Tikhonov Regularization	38
2.6	Image Quality Assessment	39
2.7	Summary	42
CHAPTER 3 :RESEARCH METHODOLOGY		43
3.1	Introduction	43
3.2	Simulation-based System Design	44
3.3	Finite Element Modelling	45
3.3.1	Configuration for the MWT Setup	46
3.3.2	Modelling and Simulation Criteria: Electrodes	47
3.3.3	Modelling and Simulation Criteria: Wood	48
3.3.4	Modelling and Simulation Criteria: Agarwood	50
3.3.5	Modelling the Electromagnetic Behaviour	51
3.4	Solving the Forward Model	54
3.4.1	Measuring Strategies	57
3.4.2	S-parameters	59
3.5	Solving Inverse Problem	60
3.5.1	Sensitivity Map	61
3.5.2	Image Reconstruction Algorithm	66
3.5.3	Image Quality Assessment	71

3.6	Summary	71
CHAPTER 4 :RESULTS AND DISCUSSION		73
4.1	Introduction	73
4.2	Simulation Studies	73
4.3	Simulation Results	74
4.3.1	8 Electrodes: Image Reconstruction	75
4.3.2	8 Electrodes: MSSIM Analysis	77
4.3.3	16 Electrodes: Image Reconstruction	79
4.3.4	16 Electrodes: MSSIM Analysis	81
4.4	Summary	83
CHAPTER 5 :CONCLUSION AND RECOMMENDATION		84
5.1	Conclusion	84
5.2	Significant Contributions towards the Research	84
5.3	Future Work	85
REFERENCES		87
LIST OF PUBLICATION		101

LIST OF TABLES

NO.		PAGE
Table 2.1:	<i>Aquilaria</i> species distributed in Malaysia	11
Table 2.2:	Agarwood's physical feature correlate with its different grade	12
Table2.3:	Disadvantages of the X-ray and ultrasonic tomography and thermography.	28
Table 2.4:	CCIR band designations	31
Table 2.5:	IEEE industry standards bands (microwave)	32
Table 3.1:	List of parameters for MWT simulation model	71
Table 4.1:	MSSIM Indexes computed on reconstructed images for 8 electrodes MWT.	77
Table 4.2:	MSSIM Indexes computed on reconstructed images for 16 electrodes MWT	81

LIST OF FIGURES

NO.		PAGE
Figure 2.1:	<i>Aquilaria malaccensis</i> , one of the species found in Terengganu.	11
Figure 2.2:	Grading agarwood by different color.	13
Figure 2.3:	Techniques to induce agarwood production. Technique (a) An intact <i>Aquilaria</i> tree which required years to produce significant amount of resin synthesis; (b) The stems, roots and large branches are drilled. The drilled pores were maintained exposed so that natural agents can access easily into the pores and attract insects and facilitates infection by adding sugary syrup or inocula to the pores; (c) Metal or PVC tubes were fitted with the tree's pores to avoid the pores to health and establish prolonged infection; (d) Inoculation and induction can be done continuously through syringes which contain inocula and inducers; (e) The bark of the tree is peeled off in order to encourage core tissues' infection and harvest the chips of woods on a rotation of 2 to 3 months from a living tree; (f) A hole has been dug in certain area of the tree to ease hatching of ants and snails for agarwood formation.	14
Figure 2.4:	(a) Double needle electrodes in tree. (b) Shigometer with digital display with its accessories.	16
Figure 2.5:	Resistograph system.	17
Figure 2.6:	A conceptual view of the X-ray tomography system	20
Figure 2.7:	A conceptual view of the passive thermography system.	21
Figure 2.8:	A conceptual view of the active thermography system.	21
Figure 2.9:	Diagram of thermography classification.	22
Figure 2.10:	A conceptual view of the ultrasonic tomography setup.	23

Figure 2.11:	A conceptual view of the MWT setup (e6 as transmitter and e15 as receiver)	29
Figure 2.12:	Block diagram of available MWT's inverse problem.	30
Figure 2.13:	Frequency spectrum.	31
Figure 3.1:	Flow chart of the overall simulation study.	44
Figure 3.2:	Block diagram of the finite element modelling.	45
Figure 3.3:	Configuration for MWT system: (a) 8 electrodes and (b) 16 electrodes.	46
Figure 3.4:	The transmission of electromagnetic wave into dielectric material.	55
Figure 3.5:	Geometry of the system: (a) 8 electrodes and (b) 16 electrodes.	55
Figure 3.6:	Mesh scheme of the system: (a) 8 electrodes and (b) 16 electrodes.	55
Figure 3.7:	Normalized electric field when one of the electrodes is radiating at 1 GHz : (a) 8 electrodes and (b) 16 electrodes.	56
Figure 3.8:	S-parameters	59
Figure 3.9:	Block diagram for doing image reconstruction	61
Figure 3.10:	Normalized sensitivity maps of an excitation at electrode $j = 1$ with corresponding measurements at electrodes $i = 2, \dots, 8$ in 8 electrodes setup.	63
Figure 3.11:	Normalized sensitivity maps of an excitation at electrode $j = 1$ with corresponding measurements at electrodes $i = 2, \dots, 16$ in 16 electrodes setup.	65
Figure 3.12:	Variations of regularization parameter in image reconstruction for 8 electrodes setup.	68

Figure 3.13:	Variations of regularization parameter in image reconstruction for 16 electrodes setup.	70
Figure 4.1:	Simulation Phantoms	74
Figure 4.2:	Image reconstruction simulation results in 2D view when no phantom for 8 electrodes MWT system.	75
Figure 4.3:	Image reconstruction simulation results in 2D view for 8 electrodes MWT system	76
Figure 4.4:	MSSIM Indexes calculated on reconstructed for 8 electrodes MWT system.	77
Figure 4.5:	Image reconstruction simulation results in 2D view when no phantom for 16 electrodes MWT system.	79
Figure 4.6:	Image reconstruction simulation results in 2D view for 16 electrodes MWT system	80
Figure 4.7:	MSSIM Indexes calculated on reconstructed for 16 electrodes MWT system	81

LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
FBP	Filtered Back Projection
LBP	Linear Back Projection
MSSIM	Mean Structural Similarity Index
MWT	Microwave Tomography
NOSER	Newton's One-step's Error Reconstruction
OUT	Object Under Test
TR	Tikhonov Regularization

@This item is protected by original copyright

LIST OF SYMBOLS

ϵ_0	Permittivity of Free Space
μ_0	Permeability of Free Space
ϵ_r	Relative Permittivity
μ_r	Relative Permeability
B	Magnetic Flux Density
D	Electric Flux Density
E	Electric Field Intensity
H	Magnetic Field Intensity
J	Electric Current Density
ρ	Charge density
σ	Conductivity
ω	Radial Frequency

@This item is protected by original copyright

Kajian Simulasi Tomografi Gelombang Mikro Untuk Penilaian Gaharu

ABSTRAK

Gaharu atau nama saintifiknya *Aquilaria* merupakan hasil hutan bukan kayu yang mahal dan amat berharga. Masalah yang dihadapi oleh industri gaharu ialah penebangan pokok gaharu yang dijalankan secara berleluasa tanpa kawalan yang rapi serta proses pengenalpastian dan pemeriksaan pokok *Aquilaria* yang tidak efektif telah dilaksanakan oleh prospektor dan penyelidik gaharu. Oleh itu, tomografi gelombang mikro dicadangkan untuk menilai kayu gaharu bagi menyelesaikan permasalahan ini. Teknik ini beroperasi dengan cara yang selamat, tidak invasif dan tidak sensitif kepada pengaruh alam sekitar. Satu kajian berdasarkan simulasi telah dijalankan di mana sistem tomografi gelombang mikro berdasarkan 8 dan 16 elektrod telah dimodelkan dengan menggunakan program COMSOL Multiphysics. Dalam kajian ini, enam profil telah diuji dan disimulasi pada 1 GHz. Medan elektrik disimulasi berdasarkan mod elektrik melintang yang akan dipancarkan ke dalam kayu yang telah dimodel dengan adanya gaharu dan tanpa gaharu. Selain itu, medan elektrik pada elektrod penerima telah disimulasi apabila medan insiden yang disimulasi dipancarkan ke dalam kayu yang dimodel dengan gaharu dan tanpa gaharu. Bacaan medan elektrik untuk kedua-dua elektrod insiden dan penerima dicatat untuk mencari perbezaan medan elektrik yang akan digunakan untuk pembinaan semula imej. Imej untuk enam profil telah dibina semula berdasarkan sensitiviti matriks, nilai medan elektrik yang diukur dan algoritma rekonstruksi imej. Algoritma-algoritma yang telah digunakan dalam kajian ini ialah unjuran belakang linear (LBP), unjuran belakang yang disaring (FBP), Newton satu langkah ralat pembinaan semula (NOSER) dan pengatur Tikhonov (TR). Imej-imej yang telah dibina semula kemudiannya dianalisis menggunakan indeks keserupaan struktural min (MSSIM). Perbandingan telah dilakukan antara algoritma rekonstruksi imej berdasarkan indeks MSSIM. Keputusan yang diperoleh menunjukkan bahawa NOSER lebih sesuai digunakan oleh sistem tomografi gelombang mikro berdasarkan 8 dan 16 elektrod untuk menilai gaharu secara efektif. Antara 8 dan 16 elektrod sistem MWT, 16 elektrod sistem MWT lebih diingini kerana sistem ini dapat mengelakkan profil data yang tertinggal dan mengurangkan artifak dalam imej yang dibina semula.

Simulation Study of Microwave Tomography for Agarwood Evaluation

ABSTRACT

Agarwood or its scientific name, *Aquilaria* is an expensive and precious non-timber forest product. The problems faced by the agarwood industry are the indiscriminate harvesting of agarwood and ineffective identification and inspection process of *Aquilaria* tree by the agarwood prospectors and researchers. Hence, microwave tomography is proposed to evaluate agarwood in order to encounter the problems. This technique operates in a safe, non-invasive and insensitive to environmental impacts. A study based on simulation had been performed where 8 and 16 electrodes microwave tomography system were modelled by using COMSOL Multiphysics software. In this study, six profiles were being tested and simulated at 1 GHz. An electric field was simulated based on transverse electric mode to be emitted into the modelled wood with and without agarwood. Besides, the electric field at the receiving electrodes was simulated when the simulated incident field emitted into the modelled wood in the presence and absence of agarwood. The readings of the electric field for both incident and receiving electrodes were recorded to find the difference of the electric field which will be used for image reconstruction. The images for the six profiles were reconstructed based on the sensitivity matrix, the value of measured electric field and image reconstruction algorithms. Algorithms that had been used in this study are linear back projection (LBP), filtered back projection (FBP), Newton's One-step's Error Reconstruction (NOSER) and Tikhonov Regularization (TR). The reconstructed images were then analyzed by using mean structural similarity (MSSIM) index. A comparison had been done between image reconstruction algorithms based on the MSSIM indexes. From the obtained results, it shows that NOSER is more suitable to be utilized by MWT system based on 8 and 16 electrodes for effectively evaluating agarwood. Among 8 and 16 electrodes MWT system, 16 electrodes MWT system is more desirable as it can prevent missing of data profile and decrease artefacts in reconstructed images.

CHAPTER 1 : INTRODUCTION

1.1 Research Background

Agarwood is the fragrant resin-infused wood obtained from the wounded trees of *Aquilaria* species (Liu et al., 2013). It is an essential non-timber forest product used for medical and cosmetic purposes, perfumery and as incense in religious ceremonies (Barden et al., 2000; Liu et al., 2013; Ismail et al., 2015; Liu et al., 2017). Direct harvesting natural forests and cultivated trees by depending on of agarwood prospectors' visual assessment and experience is a common approach for collecting agarwood. It is collected in the form of wood and then traded as wood chips, wood dust or powder and Agar-oil (Abdin, 2014).

Agarwood can be obtained in the *Aquilaria* tree trunk and other parts of the tree such as branches (Karlinsari et al., 2015). Non-destructive testing (NDT) and non-intrusive inspection (NII) are techniques which can helps to inspect the internal condition of the *Aquilaria* tree without destructing it. Specific instruments and apparatuses have been designed according to precise knowledge of object's physical properties to replace visual inspection. These approaches must be an accurate, robust, fast and inexpensive measuring technique. In particular, tomography is a reliable option to inspect defected and resin-containing trees.

Tomography is a technique which has been used to produce a cross-sectional representation of internal structure of object under test (OUT) through the penetration of light, electromagnetic field or waves (Bucur, 2003b; Ma, 2014). The reconstruction of an

image of an object is achievable through an entire projections of appropriate physical variables. The image has been obtained by mapping of singular evaluated parameters or has been achieved by a tomographic technique through algorithms and improved computational procedures for collecting data and reconstructing image.

Tomography can be divided into two categories (Dickin et al., 1992), the hard and soft field tomography. In hard field tomography, the transmitting signal travels in a straight line and its strength is affected by the object along that path without considering the position of the object (Wei & Soleimani, 2013; Ma, 2014). While in soft field tomography, the transmitting signal is influenced by the object's position in the region of measurement and object's dielectric properties distributed both inside and outside the region of measurement (Wei & Soleimani, 2013; Ma, 2014). Each tomographic method has its particular characteristics, restrictions and functions. Wei and Soleimani (2013) stated that soft field tomography is low cost and fast at the same time compare with hard field tomography.

Pastorino et al. (2015) reviewed microwaves have been used for in diagnosing wood. Different parts of the internal structure of the tree affect the propagation and the attenuation of the wave in different ways (Pastorino et al., 2015). The illumination from this technique is in the form of electromagnetic field which has the capability to propagate through most dielectric obstacles and preserving the separation between target and background (Abdullah et al., 2007). Hence, microwave tomography (MWT) which is a satisfactory NDT tool and soft field tomography has been considered as a promising system for the inspection of *Aquilaria* tree.

1.2 Motivation

Agarwood is one of the most valued non-timber forest product of the world. Currently, the international trade in agarwood entails at least 18 countries and comprises hundreds of tonnes worth millions of US dollars annually (Lim & Noorainie, 2010). Its demand has certainly increased significantly over for the past 30 years due to the growth in the population and affluence of its consuming markets (Lim & Noorainie, 2010). However, the rise in demand seems to have led to reducing supplies, leads to rising agarwood prices and affects the upcoming supplies of the commodity (Lim & Noorainie, 2010). Moreover, there are anxieties that the agarwood trade may impel some agarwood producing species to extinction.

Malaysia is one of the major agarwood producing countries of the world (Abdin, 2014). The Malaysia government has noticed the significant potential of this product which can become a major foreign currency earning sectors. Therefore, an instrument such as MWT can assists better harvesting of this product is highly needed. The key idea is that the inhomogeneity of the wood due to its complex anatomical structure produces voltage variations (Pastorino et al., 2015).

Detection of agarwood in *Aquilaria* tree can be challenging, but detection is essential to improve the efficiency to monitor the quantity of agarwood in the tree. There are challenges that require to overcome in order to implement MWT as the inspection system. First of all, it is still an unknown whether the voltage variations are slight or significant in the region with resin. Furthermore, MWT's reliability and feasibility in this field is still considered questionable as it is tough to acquire the available database and

conducted detailed research for agarwood due to non-uniform commodity. Consequently, the purpose of this study is to investigate the feasibility of MWT as a tool in agarwood inspection with the intention of establishing a new approach for a fast, reliable, inexpensive, harmless and non-invasive detection of agarwood.

In this research, a MWT is developed in a simulation platform for identifying agarwood in the wood through a systematic study. It is performed from analysis phase to the verification and validation phase. It comprises the generation of 2D models of wood with electrodes configuration of the MWT system, reconstruction of images is achieved from the simulation results using appropriate image reconstruction algorithm and verification of the system by applying appropriate image quality assessment method. This pioneering provides proof of concept for inspecting agarwood based on the electromagnetic field that differentiate *Aquilaria* tree with and without agarwood by employing MWT. Besides, this study is conducive to investigations of novel devices for agarwood inspection in non-timber forest product industry.

1.3 Problem Statement

The harvesting time for agarwood is solely depending on the agarwood prospectors based on their experience with *Aquilaria* tree in the agarwood industry. The decision and judgement of the harvesting are totally based on human perspective which is subjective and time-consuming. However, the main problem lies on the reliability of the expertise and accuracy of the agarwood prospectors in deciding with the harvesting of *Aquilaria* tree.

The most frequent way of harvesting agarwood in an *Aquilaria* tree for sales is fatal harvest (Barden et al., 2000; Lim & Noorainie, 2010). This harvesting method requires to chop down the whole tree without the certainty of agarwood content. The indiscriminate harvesting causes the extinction to the *Aquilaria* species due to one-in-ten trees naturally contain agarwood. Researchers try to increase the production of agarwood by using wounding and inducing methods. However, it is extremely difficult or even impossible to evaluate the amount of resin from the surface of the tree. So, cutting the tree is the only solution to obtain and analyze agarwood.

Therefore, the background study on this research area implied that there is a need to investigate the possibility of working on MWT to inspect agarwood in the *Aquilaria* tree. The investigation is done through simulation platform for solution and reliable image reconstruction algorithm.

1.4 Objectives

The intention of this research work is to simulate MWT system for agarwood detection. The detailed objectives of this research study are addressed as below:

- i. To develop simulation model of MWT system for agarwood imaging.

The model are based on two configurations which are 8 and 16 electrodes MWT system. They are generated through COMSOL Multiphysics software. It is a finite element method (FEM) tool. The input factors for simulation models are carefully considered and studied in term of the electrode size, arrangement of the electrodes,

operating frequency, transmission power, electrical properties of wood and agarwood, electromagnetic behaviour and measuring strategy.

- ii. To study the image reconstruction algorithms to reconstruct tomogram of agarwood from MWT simulation results.

The FEM simulations are optimized with real environment wood and agarwood's dielectric properties for both 8 and 16 electrodes MWT models. A wave propagation at a constant microwave frequency is simulated by resolving the direct electromagnetic problem based on the selected parameters. Remodelling and analysis are conducted from the simulated data to ensure the best MWT configuration to be applied in practical for identifying and localizing the agarwood. The simulations results are then exploited to reconstruct images using established qualitative linear inversion. The images are reconstructed to represent the internal part of the *Aquilaria* tree.

- iii. To evaluate the performance of the selected image reconstruction algorithms in different models.

An image quality assessment technique is used to test and validate the performance of the selected image reconstruction algorithms. The result of the assessment is crucial for the MWT system to evaluate agarwood in the *Aquilaria* tree. Therefore, the best image reconstruction algorithm is chosen so that the prediction of the agarwood in the *Aquilaria* tree can be made. Besides, it can be used as a reference for further improvement.

1.5 Scope of Research

The research scopes are presented as follows:

- i. 2D model simulation data is applied as a proof of concept for agarwood imaging using MWT.
- ii. The microwave mode of operation is based on transmission mode.
- iii. 1GHz is used in 8 and 16 electrodes MWT system based on the attenuation of microwave on *Aquilaria* tree.
- iv. Reconstruction image is based on computed data for wood with and without agarwood with constant moisture content using qualitative linear approach.
- v. Mean structural similarity index (MSSIM) is employed to evaluate the reconstructed images.

1.6 Significant Research Contribution

The outcomes that contribute to the research area are the application of MWT system in detecting the presence of agarwood through simulation and qualitative linear inversion approaches to determine the quality of the reconstructed image in MWT.

1.7 Thesis Organization

This dissertation discusses the topic of MWT based on simulation to evaluate agarwood. This thesis consists of six chapters to present the research work.

Chapter 1 introduces the idea to apply MWT for inspecting agarwood in an *Aquilaria* tree. This chapter briefly states the research study's background, motivation, problem statement, objectives, scope of research and significant research contribution. A simple overview of tomography, MWT and agarwood are covered. The following chapters consist a more detailed information regarding to this research project.

Chapter 2 would encompass the overview of agarwood and review about some available tomography technique relevant to this research work.

Chapter 3 covers the generation of 2D model for 8 and 16 electrodes MWT system. It discusses the configuration of the setup, material's parameter, source and measuring strategy used for the research work

Chapter 4 starts with the introduction of sensitivity map for 8 and 16 electrodes MWT system which is an important element in this research work. Next, it defines image reconstruction algorithms and image quality assessment are being discussed.

Chapter 5 presents the results and discussion of this thesis. The performance of 8 and 16 MWT system are being compared and discussed based on reconstructed images and image quality assessment's result. The method with the best performance is being justified.

Finally, Chapter 6 summarizes the findings of the research study with respect to the research objectives. Subsequently, current work's contributions as well as suggestions on future improvements for MWT to be implemented for agarwood inspection.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

Aquilaria is one of the genera of tropical tree that produces an incense-resinous wood called agarwood. Agarwood is more valuable compared with other forest products (Putri et al., 2017). Thus, it is sought intensively. All *Aquilaria* are required to be cut by agarwood prospectors in order to find a tree with the resinous wood inside. Unfortunately, indiscriminate harvesting has left most forest landscapes in country such as India and other countries in Indomalaya without *Aquilaria* growing in the wild (Blanchette, Jurgens, & Heuveling van Beek, 2015). It has been of great concern for the disappearance of the tree from the landscape. Several *Aquilaria* species have been listed as endangered tree species by the International Union for Conservation of Nature (IUCN) in 2010 (Lee, S. Y., 2016) and the Convention on International Trade (CITES) since 2009 (Lee, S. Y., 2016; Putri et al., 2017).

Collection of agarwood from *Aquilaria* tree has traditionally depended on visual identification. The process can be considered as trial and error by identifying spots or black marks on the wood when the bark is removed (Putri et al., 2017). It is challenging and beyond the ability of most enforcement personnel (Barden et al., 2000). The trees are often chopped without the certainty that they contain agarwood. Besides, it also opposes the sustainable principles for forest management (Indahsuary et al., 2014). Therefore, a technological innovation which is safe, non-destructive, non-invasive and insensitive to environmental influences is needed to identify the presence of agarwood within trees. The technological development must be able to minimize and prevent random harvesting.

This chapter discusses the overview of agarwood. Furthermore, the following section focuses the insights of four non-destructive and non-intrusive techniques. Finally, four image reconstruction algorithms and image quality assessment are discussed. This chapter discusses the background of breast cancer in regard to the physiology of breast, and current breast cancer detection modalities. This chapter provides essential and important background information for the following chapters. Furthermore, the final section focuses on the introduction of microwave imaging for breast cancer detection.

2.2 Agarwood

Agarwood is a scented resin impregnated in the heartwood of an *Aquilaria* tree. It was formed only when the tree experiences attack such as struck by lightning, grazed by animal, attacked by insect or invaded by microbial round wounded or rotted trunk in nature (Blanchette & Heuveling van Beek, 2002; Pojanagaroon & Kaewrak, 2005; Li, 2014; Kalita et al., 2015; Peng et al., 2015; Mohamed, 2016). There are a total 19 *Aquilaria* species that can be found in China, India, Burma, Laos, Vietnam, Cambodia, Malaysia, Sumatra, Borneo, Philippines, Bangladesh, and Papua-New Guinea (Liu et al., 2017). *Aquilaria* species acclimatized with various natural environments including rock-strewn, sandy or calcareous, and land near bogs and habitually cultivates between altitudes of 0 m to 850 m, in locations with daily temperatures of 20°C to 22°C (Ismail et al., 2015). *Aquilaria malaccensis* as a main genus found in Malaysia which is greatly distributed except Kedah and Perlis states (Ismail et al., 2015). Figure 2.1 shows *Aquilaria malaccensis* found in Terengganu. Table 2.1 indicates the available *Aquilaria* species in Malaysia (Ismail et al., 2015).



Figure 2.1: *Aquilaria malaccensis*, one of the species found in Terengganu. From “FRIM develops DNA markers for karas species identification,” by Forest Research Institute Malaysia, 2013 (<https://www.frim.gov.my/en/frim-develops-dna-markers-for-aquilaria-species-identification/>). In the public domain.

Table 2.1 : *Aquilaria* species distributed in Malaysia

Scientific Name	Distribution	Physical features
<i>Aquilaria malaccensis</i>	Throughout Peninsular of Malaysia, Sabah and Sarawak (except Kedah & Perlis)	Leaf surface glossy/waxy, oval shape
<i>Aquilaria hirta</i>	Terengganu, Pahang and Johor	Tiny tree (15m high), the leaf surface furry, ovate oblong shaped leaves
<i>Aquilaria rostrata</i> <i>Aquilaria beccariana</i>	Pahang (Gunung Tahan) South of Peninsular (Johor)	Second leaf veins not clearly visible. Medium-sized tree (diameter ~20cm), the second leaf veins more visible, gray leaves and non-shiny
<i>Aquilaria microcarpa</i>	Johor and the tobacco region	Large tree (~36cm), having heart-shaped tiny fruit.

Note. Adapted from “A review on agarwood and its quality determination,” by N. Ismail, M. H. F. Rahiman, M. N. Taib, M. Ibrahim, S. Zareen, and S. N. Tajuddin, August 2015, *In Control and System Graduate Research Colloquium (ICSGRC), 2015 IEEE*, 6, pp. 103-108. Reprinted [or adapted] with permission.

The demand for agarwood is very high due to its usage as medicine, perfume and incense. However, the supply of quality agarwood always insufficient to cope the demand due to agarwood is only discovered in a small percentage of *Aquilaria* trees (Barden et al., 2000; Kanazawa, 2017). This factor causes the agarwood to be so expensive. According to Naef (2011), the price of agarwood in the market ranges from USD 100 per kilogram for low quality to USD 100,000 per kilogram for high quality agarwood. The quality of agarwood is identified based on its constituents, specific gravity, odour shape, size, color and weight (Naef, 2011; Abdullah et al., 2012; Liu et al., 2017). Sinkage agarwood with darker color is designated to have better scent, higher resin content and higher density and therefore with the higher grade. Table 2.2 shows the agarwood's physical feature correlate with its different grade and Figure 2.2 illustrates the image of agarwood for each grade. Agarwood with Grade A has the best quality, followed by B, C and D.

Table 2.2 : Agarwood's physical feature correlate with its different grade

Physical feature	Grade			
	A	B	C	D
Color	Black	Black and brown striped	Brown and white striped	Yellowish white
Density of resin	Very dense and compact, sink in water when soaked	Dense and less compact, floating slightly above the water surface	Moderately dense and hollow, floating on the water surface	Light and not dense, floating on the water
Aroma	Very strong odor	Strong odor	Less potent odor	Less potent odor
Weight	Very heavy and not hollowed	Heavy and slightly hollow	Light and hollow	Very light and hollow

Note. Adapted from "A review on agarwood and its quality determination," by N. Ismail, M. H. F. Rahiman, M. N. Taib, M. Ibrahim, S. Zareen, and S. N. Tajuddin, August 2015, *In Control and System Graduate Research Colloquium (ICSGRC), 2015 IEEE*, 6, pp. 103-108. Reprinted [or adapted] with permission.



Figure 2.2: Grading agarwood by different color. From “A Review of Quality Assessment and Grading for Agarwood,” by Y. Y. Liu, J. H. Wei, Z. H. Gao, Z. Zhang, and J. C. Lyu, 2017, *Chinese Herbal Medicines*, 9(1), pp. 22-30.

Lim and Noorainie (2010) reported that there are two methods used in Malaysia to harvest agarwood which are fatal harvest and sub-lethal harvest. Fatal harvest is the most commonly used method. In this technique, the whole tree is required to be chopped down in order to identify and obtain agarwood. Malays in Johor and Selangor are the one who start to practice this method (Lim & Noorainie, 2010). Harvesting *Aquilaria* trees by using this method is said to be dangerous and yet only around one-in-ten trees naturally contain agarwood. This method can cause the extinction of the species if there are no measures to protect the habitat of the species.

Next, Lim and Noorainie (2010) stated that sub-lethal harvest mostly practiced by the indigenous peoples in Malaysia for every 2 to 3 months. The non-destructive harvest method is not commonly used. This method required to cut or chip the infected part of the *Aquilaria* trees. The robust trees can survive for more than 10 years when sub-lethal harvest is applied.

Inoculation method is introduced in order to overcome the low yield by wounding methods in *Aquilaria* tree. Some research had been done to induce agarwood production and increase the quality of agarwood by injecting certain chemical composition into the

trunk to wound the tree artificially (Liu et al., 2013; Yang et al., 2014; Huang et al., 2017). Akter et al. (2013) had presented some induction practices which are usually adopted by the aboriginal peoples and researchers. Figure 2.3 illustrates a diagrammatic representation of induction practices which are generally applied by the native and researchers.

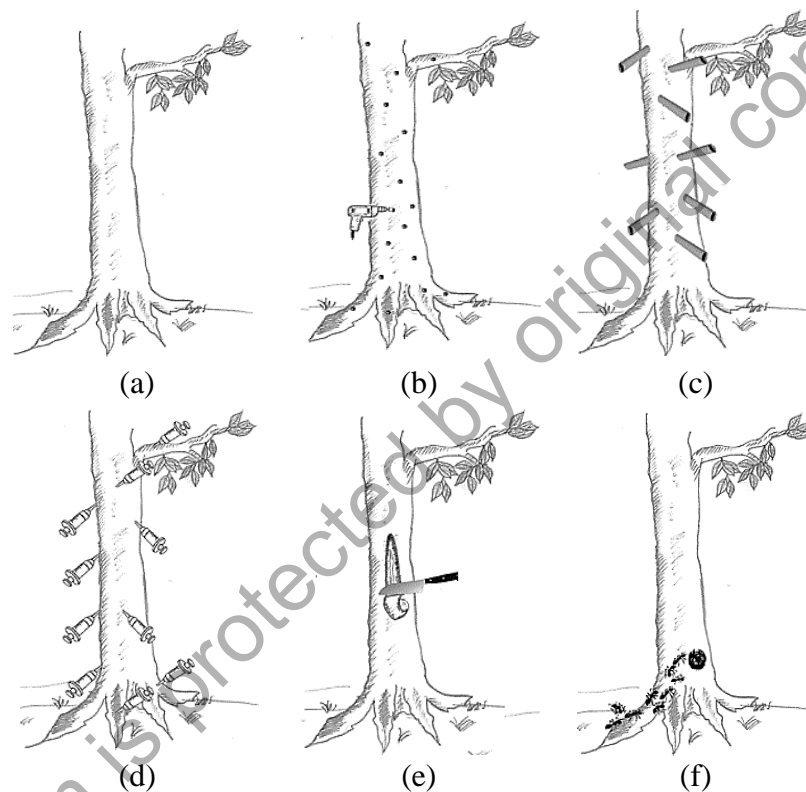


Figure 2.3: Techniques to induce agarwood production. Technique (a) An intact *Aquilaria* tree which required years to produce significant amount of resin synthesis; (b) The stems, roots and large brunches are drilled. The drilled pores were maintained exposed so that natural agents can access easily into the pores and attract insects and facilitates infection by adding sugary syrup or inocula to the pores; (c) Metal or PVC tubes were fitted with the tree's pores to avoid the pores to health and establish prolonged infection; (d) Inoculation and induction can be done continuously through syringes which contain inocula and inducers; (e) The bark of the tree is peeled off in order to encourage core tissues' infection and harvest the chips of woods on a rotation of 2 to 3 months from a living tree; (f) A hole has been dug in certain area of the tree to ease hatching of ants and snails for agarwood formation. From "Agarwood production-a multidisciplinary field to be explored in Bangladesh," by S. Akter, M. T. Islam, M. Zulkefeli, and S. I. Khan, 2013, *International Journal of Pharmaceutical and Life Sciences*, 2(1), pp. 22-32.

2.3 Tomographic Techniques for Detection of Agarwood in *Aquilaria* Tree

The deterioration of wood refers to the changes in the physiological and chemical compounds of the wood (Putri et al., 2017). These changes are induced by natural or artificial fungal attack, injury or other non-pathological processes (Putri et al., 2017). It is tough to determine interior deterioration of wood because there may be no visible signs of its presence (Fu, 2005). Agarwood is the heartwood of *Aquilaria* species produced through pathological or wounding processes and fungal infection (Persoon, 2007). The deteriorated areas of the tree contains incense agarwood (Putri et al., 2017). Various methods and tools have been employed to inspect the interior deterioration of wood. Nevertheless, the selection of the most suitable methods and tools which are appropriate for agarwood need to be done.

One of the conventional method to determine internal defect of wood is by using a Shigometer. It is an electrical conductivity meter for diagnosing decay in trees (Johnstone et al., 2010). It measures the electrical resistance by placing electrical twisted wire probe into a small and pre-drilled hole into the xylem which is approximately 3mm in diameter (Johnstone et al., 2010; Nurnadiah et al, 2014; Goh et al., 2018). Figure 2.4 (a) illustrates A pulsed direct current is then injected into it through the probe (Shigo & Shortle, 1985; Fu, 2005; Goh et al., 2018). It records the electrical resistance which is normally in thousands of ohms ($k\Omega$) as it passes through wood or bark (Shigo & Shortle, 1985; Johnstone et al., 2010). Before wood starts to decay, it has higher moisture content and contains more ions (Shigo & Shortle, 1985). It directly influences the electrical resistance of wood. In wood free from decay, the device acquires relatively high resistance readings whereas in discolored or decayed wood, electrical resistance

progressively decreases (Shigo & Shortle, 1985; Goh et al. 2018). Figure 2.4 (a) illustrates the appropriate position for the double needle electrodes in tree. The vertical fissures in the tree bark is injected with the needles. The procedure of injecting the needles into the bark is considered complete when they contact with the wood. Figure 2.4 (b) shows the Shigometer with digital display and its accessories include drill and electrodes.

The disadvantage of Shigometer is that it produces very inconsistent result (Zabel & Morrell, 1992; Johnstone et al., 2010; Martinez-Trinidad et al., 2010). Its results are depending on the electrode's tightness of fit and wood's relative moisture and resin content (Johnstone et al., 2010). Besides, it is functioning in resin soaked, frozen or dead wood (Zabel & Morrell, 1992; Johnstone et al., 2010). Last but not least, it requires experience in cautiously controlling the amount of needle electrodes contact with the wood (Johnstone et al., 2010).

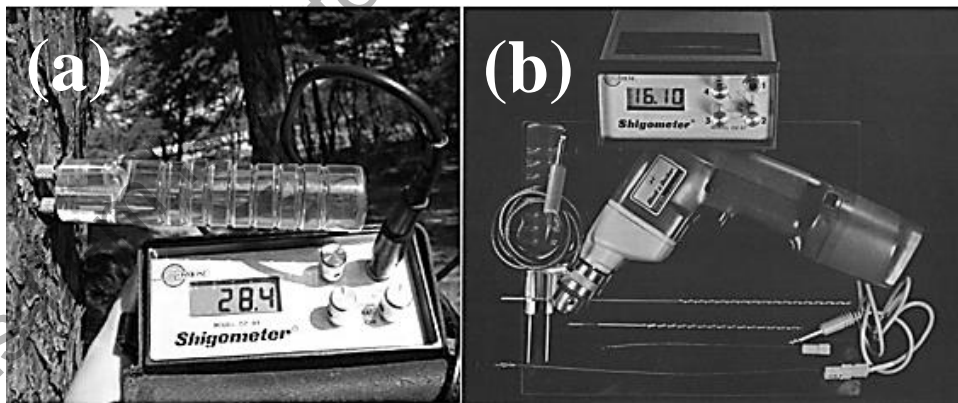


Figure 2.4: (a) Double needle electrodes in tree. (b) Shigometer with digital display with its accessories. Adapted from *Spruce Budworms Handbook: Shigometry – A Reference Guide. Agric. Handb. 646* (p. 30), by A. Shigo & W. Shortle, 1985, Washington, DC: U.S. Dept. of Agriculture, Forest Service, Cooperative State Research Service. Adapted with permission. and (b) Shigometer with digital display. From “수목보호관리-비배관리 (4) - 나무 힐링캠프,” by J. Byung-hun, 2015 (<http://www.hapt.co.kr/news/articleView.html?idxno=30938>). Copyright 2002 ~ 2018 by (주)한국아파트신문. All rights reserved.

Furthermore, Resistograph also known as resistance micro-drilling tool is a conventional non-destructive testing system (Jaskowska-Lemańska & Wałach, 2016) that diagnose defects in wood by measuring electrical resistance (Nurnadiah et al, 2014). Its inspection goes in depth across the observed wood section (Ceraldi, Mormone, & Ermolli, 2001; Nowak, Jaskowska-Lemańska & Wałach, 2016; Jasieńko, & Hamrol-Bielecka, 2016). It is a mechanical drill device that measures the amount of resistance which also refers its drilling torque as a rotation thin drill bit is driven into the wood at a constant forward speed (Gao et al., 2012). It is equipped with a drill bit with 2 to 5 mm in diameter (Gao et al., 2012; Jaskowska-Lemańska & Wałach, 2016) and used to drill in order to objectively evaluate the distribution of fungal decay occurs in wood along the route the drill has taken (Zahner, Sikora, & Pasinelli, 2012). A chart is produced to indicate the relative resistance profile of wood for each drill path (Gao et al., 2012). Figure 2.5 illustrates a Resistograph system evaluates a wood.

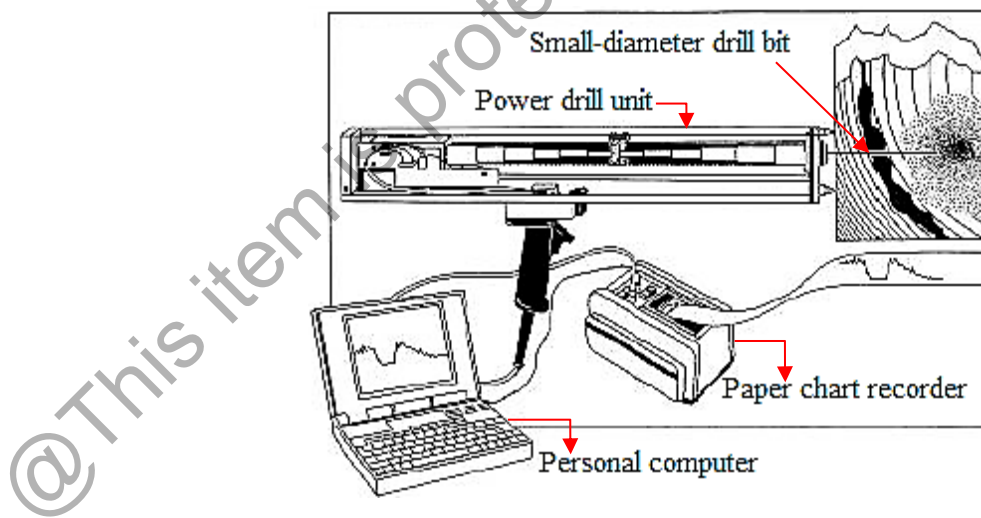


Figure 2.5: Resistograph system. From “Rapid assessment of wood density of standing tree with nondestructive methods—A review,” by S. Gao, X. Wang, B. K. Brashaw, R. J. Ross and L. Wang, 2012, *In Biobase Material Science and Engineering (BMSE), 2012 International Conference on* , pp. 262-267. Copyright 2012 by IEEE

The disadvantages of Resistograph is it requires experience to give a justification for drilling the number of hole and their positions either radially or tangentially to the growth rings in order to acquire precise results (Costello & Quarles, 1999; Nowak, Jaskowska-Lemańska & Wałach, 2016). Besides, the irregular decay pattern in the tree causes the reduction accuracy in using the drill (Gilbert & Smiley, 2004). The interpretation of results from the drilling resistance graphs can be very tough when drilling was not operated in an entirely radial direction (Kloiber et al., 2015) and its limitation to recognize particular types of natural growth variation in wood from defects (Seavey & Larson, 2002). Thus, expertise for wood and Resistograph is needed in order to interpret the data from the graphs (Kloiber et al., 2015; Seavey & Larson, 2002; Jaskowska-Lemańska & Wałach, 2016). Although the Shigometer and Resistograph can detect decay at an initial stage and a narrow hole is used to reduce the extent of injury of the tree, perhaps the most obvious issues with them is the fact that they are invasive method (Larsson, Bengtsson, & Gustafsson, 2004). According to Goh et al. (2018), the invasive method takes long time to make a measurement is also long and inspectors require a high level of specific knowledge and experience to use the tools or methods. Hence, a non-invasive method which is tomography is preferable for this study in order to prevent changing of the morphology and electrical properties of the tree and agarwood.

Tomography consents to a reconstruction of a cross section through the wood with the aid of measurements accomplished on the wood surface and measuring energy that penetrate into the wood (Nicolotti et al., 2003). Different types of energy can reveal information about different physical properties of the sensing zone (Nicolotti et al., 2003). Although there are numerous research had been achieved on numerous types of sensor for tomography in wood application, a non-destructive and non-invasive tomography is

such as x-ray, thermal, ultrasonic and microwave are discussed in the following subsections.

2.3.1 Non-Invasive and Non-Destructive Detection Technique

Visual inspection cannot identify decays of internal decay in *Aquilaria* tree in cases where a wound has created a cavity that has opened up into the heartwood zone (Goh et al., 2018). Computed tomography has been developed to produce imaging of internal structure of wood from a complete set of projections of relevant physical parameters of this material in the second half of the 20th century (Bucur, 2003a). The resolution of several methods involves from a very large spectrum ranging from 10^{-9} m for X-rays to 10^{-1} m for microwaves (Bucur, 2003a).

X-ray tomography is an ionizing radiation technique. X-rays are electromagnetic waves. They have a wavelengths in the range of 10^{-12} m to 10^{-9} m, corresponding to frequencies ranging from 3×10^{16} Hz to 3×10^{19} Hz (Bucur, 2003b). Besides, they have energies in the range 1×10^2 eV to 1×10^5 eV. The idea of X-ray tomography is to translate and rotate the x-ray source and detectors around the wood in order to obtain a tomographic images of wood as shown in Figure 2.6. This system depends on the X-rays' attenuation coefficient, which is relying on both the wood's chemical composition and the ionizing radiation's energy (Bucur, 2003b). The attenuation coefficient of X-ray can help to detect and localize internal structure of the wood (Gu, Yu & Wang, 2010). Some researches have been done to detect and localize the decay, knots, tree rings and pith in the wood (Mckenna, 1995; Pietikäinen, 1996; Borianne, Pernaumat & Subsol, 2011; Krähenbühl, 2012; Hervé, 2014; Hansson, Enescu & Brandt, 2015). X-ray tomography

is still being used and studied by some researchers because it has high penetrating power, efficiency and resolution and large volume inspection (Funck et al., 2003; Bhandarkar et al., 2005; Han, Yu & Qi, 2007; Maire & Withers, 2014; Fu, Liu & Wang, 2016; du Plessis, 2016). However, it cannot discover features that have similar density and cannot obviously discriminate between wood and defective wood. Subsequently, it is expensive, high risk to expose to dangerous radiation and time-consuming to inspect large object (Jalil, 2005; Fu, Liu & Wang, 2016).

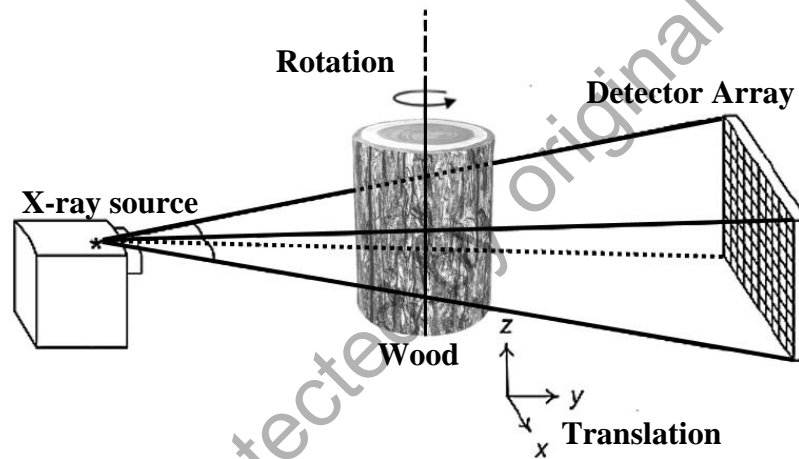


Figure 2.6: A conceptual view of the X-ray tomography system

Next, thermography principle involves distribution of heat in an object in order to visualize the temperature at the surface of the object in plane on a map view. The resolution of this technique covers a spectrum ranging from 3×10^{12} Hz to 3×10^{13} Hz (Bucur, 2003b). Bucur (2003a) claimed that this technique tends to observe the structural features of wood such as decay, knots, fiber direction, moisture content, effect of acid rains, rupture phenomena and subsurface integrity of composites. It utilizes an infrared camera system for inspection. It has two approaches which are active and passive heating procedure (Bucur, 2003b; Ibarra-Castanedo, Tarpani & Maldague, 2013). The active and passive approaches are illustrated in Figure 2.7 and Figure 2.8 respectively. Both of the

approaches look similar with the difference that an active thermography requires an external energy to induce a thermal contrast in the object repeatedly in order to obtain the image whereas passive thermography maps the object's temperature with respect to the environment.

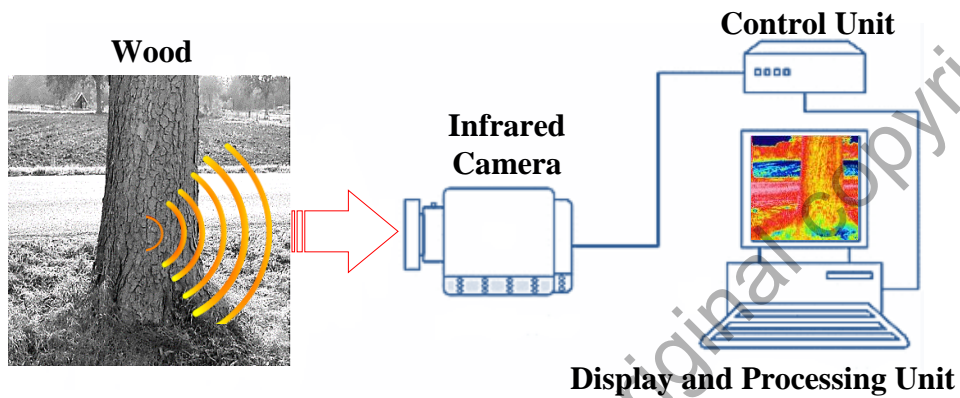


Figure 2.7: A conceptual view of the passive thermography system.

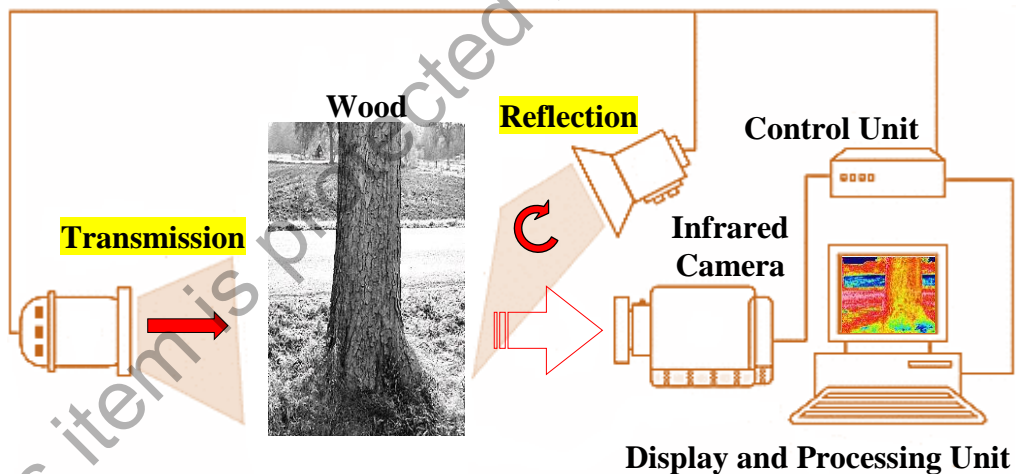


Figure 2.8: A conceptual view of the active thermography system.

Figure 2.9 exemplifies the several combinations of configurations, excitation modes, scanning, energy sources and waveforms for active and passive thermography. The active and passive thermography allow qualitative and quantitative assessment respectively. Thermography is a comparatively new research field in wood science. López, Basterra & Acuña (2013) applied thermography to estimate the density of wood.

It had been reported that the temperature in the wood decreases when the wood's density increases (López, Basterra & Acuña, 2013). Next, another researcher had concluded that the penetration depth of the thermal source in wood is 2 cm but a suggestion had been given is to soak the wood in liquid contains hydrogen such as glycol to improve the penetration limit (Osterloh, 2011). The system is still applicable since it is non-invasiveness, can work at far distance around 25 m and perform rapidly in real time. Nevertheless, unsatisfactory outcome from the system is produced if the surface of the wood is obscured by something like moss or vegetation or if it is wet or has been heated by direct exposure to sunlight which might changes the color, texture, grain and even tone of the wood (Catena & Catena, 2008; López et al., 2013).

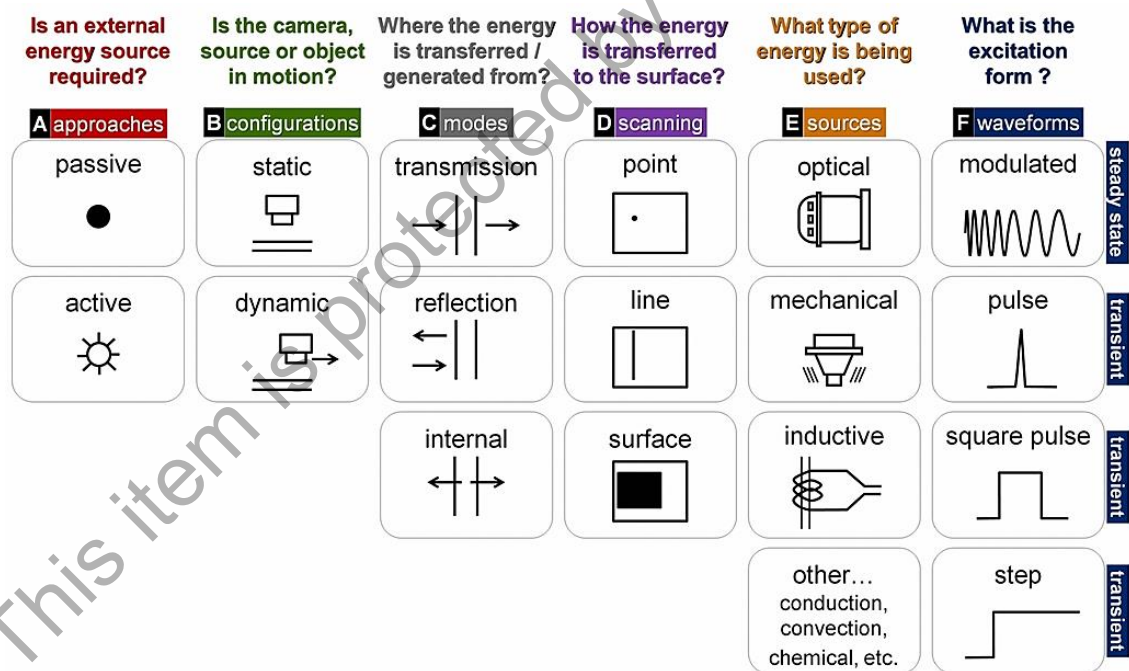


Figure 2.9: Diagram of thermography classification. From “Nondestructive testing with thermography,” by C. Ibarra-Castanedo, J. R. Tarpani & X. P. Maldague, 2013, In *European Journal of Physics*, 34(6), S91. Copyright 2018 by IOP Publishing.

Furthermore, ultrasonic tomography involves beams of sound waves with the frequency ranging from 5 Hz and 1 MHz (Bucur, 2003b; Arciniegas, Prieto, Brancheriau & Lasaygues, 2014). Figure 2.10 shows the setup for ultrasonic tomography in wood. It is non-invasive and safe to be used at low power. Furthermore, it has two operation modes. They are transmission and reflection mode. Next, the parameters used in ultrasonic tomography to reconstruct the images are the velocity of the sound wave, time of flight and amplitude. Subsequently, the distribution and flow of energy are crucial parameters for ultrasonic tomography in the image contrast enhancement.

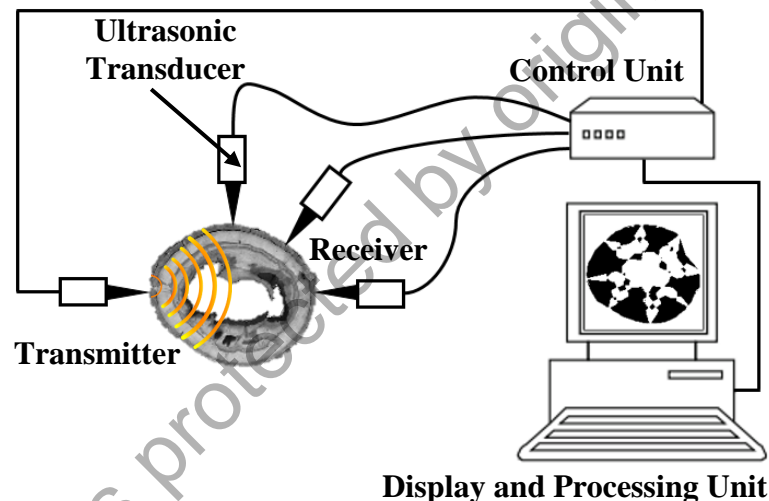


Figure 2.10: A conceptual view of the ultrasonic tomography setup.

Ultrasound tomography is widely used for decay and fungal attack diagnosis on a standing tree (Ouis, 2003; Socco et al., 2004; Wang, Wiedenbeck & Liang, 2009; Ahmad, Almuin & Mohammad, 2012; Gilbert et al., 2016; Putri et al., 2017). In addition, it is also commonly used in imaging of wood to reveal the compression of wood (Brancheriau, 2012), knot (Trinca, Gonçalves & Linhares, 2013), pith (Trinca et al., 2013) and crack (dos Reis, 2017). There are several problems with imaging wood using ultrasound. This method is sensitive to vibration, has poor resolution and lie in the need

for coupling transducer to the surface of the wood (Wei & Gu, 1993; Shull, 2002; Jalil, 2005). These factors are the obstacles which need to overcome in order to implement the system.

In 1950s, the development of microwave sensors had been initiated. There was an activity to produce better methods for measuring the permittivity and to research the interaction between the permittivity and the physical properties of materials and mixtures was done by R. Von Hippel (Nyfors, 2000). Initially, microwave sensors were for a long-term utilization for only a limited range of application due to their restricted obtainability, oversized components, high cost and the deficiency of signal processing power (Nyfors, 2000). After the intensifying supply of solid state components during the 1970s and the establishment of the microprocessors embedded into the measuring devices in the early 1980s, the situations have change completely (Nyfors, 2000). In Hornbuckle and Ancona's work, they had come out with a microprocessor which can handle both analysis and synthesis simultaneously five times faster and without hardware modifications, cost effective and able to perform real-time digital signal processing in a small computer (Hornbuckle & Ancona, 1970).

There are many kinds of microwave sensors, such as, free space transmission sensor, special transmission sensor, guided wave transmission sensor, reflection, time domain reflectometry (TDR) and radar sensor, tomographic sensor, resonator sensors and radiometers. MWT uses tomographic sensors. It is based on electromagnetic imaging as a diagnosis tool based on its unique features (Jacobi, Larsen, & Hast, 1979). There are two fundamental techniques for microwave imaging. They are the transmission and the reflection method. MWT uses transmission mode.