FINITE ELEMENT ANALYSIS APPROACH TO OPEN AREA CONCEALED WEAPON DETECTION SYSTEM

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ABSTRACT

Individuals carrying threat objects inside secured areas possess significant risk to security of establishments and safety of public. Traditional weapon inspection equipment is limited in portability and requires trained operators in confined security checkpoints. Although various methods to screen people for threat objects have been employed at secured establishments, screening equipment and procedures have not been designed to work in open spaces like airport check-in areas, hospitals, schools and university entrances. Coupled to this, relatively large numbers of false alarms from non-threat metal objects are identified as a threat by the current Concealed Weapon Detection (CWD) screening equipment, is a major cause of concern and is associated with higher operational costs. Hence, the design and development of a concealed weapon detection system, with reduced false alarms and increased detection along with classification capability that can operate in a large open area is essential.

A comprehensive numerical model of a CWD system, using the Finite Element Analysis (FEA) method, to detect and classify metal objects with accuracy within a single zone of a multi zone Open Area CWD (OACWD) system, was developed. A mathematical model was developed and applied to the time-domain transient electromagnetic field, which are modelled and simulated using FEA methods. The methods were then applied to a single zone of a multi zone OACWD system to create an object signature database utilising the decay time constant; a unique property of metal objects in time-domain transient electromagnetic fields. The objects were detected by the unique signature property in OACWD system, Since early and intermediate stages was found contain object signatures, receiver current for these stages are digitised and stored in a weapon database, which is then used to match target for identification within the OACWD system. The thesis analyses the following characteristics of a single zone OACWD system; target material variation, target shape (both geometric and common weapon shape) variation, size, rotational variation, proximity variation of targets, the successful estimation and comparison of these parameters lead to classification of metal objects in OACWD system. This work also explores the characteristic properties and components of OACWD models such as

public safety and the privacy of individuals using the system. The system, when integrated with other screening devices, e.g. Close Circuit Television (CCTV) monitoring system, is able to find individuals with threat objects in real-time detection space.

Summarizing, In this thesis work, single zone detection system was designed by developing have developed an electromagnetic circuit to design, which can successfully detect threat metal objects irrespective of their orientation based on time constant decay. This system is a significant advance over the existing portal based detection system, as it would reduce the incidence of false alarms and traffic congestion at the security establishment.

CHAPTER 1 : INTRODUCTION

The detection and classification of hidden threat objects is the key to achieve safety at security checkpoints [1]. People carrying guns or knives into aeroplanes, shopping malls and secured buildings are a potential risk to security. While there are detection systems for concealed threat objects employed in secured establishments, none are specifically designed to work in large or open area and crowded spaces like airports entrances, hospitals, schools, sports stadia etc.

Current screening systems are not able to screen large numbers of people in a crowded environment. Also high rates of false alarms (difficulty of determining between threat and non-threat metallic objects) in screening equipment are a liability to operational efficiency and day-to-day operational needs of secured establishments. Human operator intervention is often required to resolve alarms in the system, which causes delays and inconvenience to large numbers of people, where security personal often use physical search techniques to resolve the alarm [2].

The current screening systems can be divided into the following categories

- Imaging based

- Locating based
- Monitoring and Surveillance based
- Tracking type

1.1 IMAGING SYSTEMS

The imaging based system captures an image of a detection space and determines the threat objects by the use of image recognition software. The imaging systems are briefly described below.

1.1.1 X-RAY IMAGER

X-ray imagers used in CWD system are of low energy. An individual being scanned stand in front of the system for approximately 3 seconds. Each 3 seconds exposes a person to 3 microRem of radiation [3]. These imagers are capable of finding non-metallic, drugs, and chemicals weapons hidden in a person. However, the imaging system is unable to detect weapons concealed under flesh. In order to find hidden objects inside the person, each surface of a person needs to be scanned by the imager, which raises concerns about privacy for the individual. Consequently the images could be altered but altering image produces low quality image and small objects goes undetected by the system [4]. Additionally, a recent research done by STFC Rutherford lab (UK) has combined both radar techniques and X-ray imaging for concealed weapon detection. In this system, X-ray radar image is generated by combining short pulse radar with X-rays, in a horizontal scanning method. This enables to estimate the relative distance of the threat object located in CWD space. It also provides 3D information of the CWD space by simulating horizontal scanning of the area [5]. Further research in this area is channelled in improving the energy distribution of x-rays and scatter effects, which contributes to noise in the output.

1.1.2 MICROWAVE RADAR IMAGER

The microwave Radio Detection and Ranging (RADAR) imager is a small, lightweight device, typically remotely operated in the 20 GHz to 100 GHz range [4]. The spatial resolution of the imager is directly proportional to the microwave frequency [6]. Higher operating frequency of the imager results the RADAR energy being absorbed by intervening materials, such as walls etc. Therefore the spatial resolution required detecting weapons at a distance make it impossible to use the imager in surrounding intervening materials environments [4].

1.1.3 TERAHERTZ-WAVE IMAGER

Terahertz wave imager uses pulse of range 0.1 – 10 THz. The incident pulse on the object in detection space is reflected, which enables imaging of objects in the target space to be determined [7-9]. The quality of the image from the reflected signal depends on the transmit frequency, however, health and safety regulations restricts the upper band of transmitted frequency, limiting the amount of average energy that an individual can be exposed to at a given time. Hence, there is a bargain between safety and image quality in the operation of these types of imagers in a CWD space [10]. However, recent research carried out by the Rensselaer Polytechnic Institute, USA demonstrates better detection capability of Schottky diodes frequency multipliers in THz detectors [11].

1.1.4 MILIMETRE WAVE RADAR DETECTOR

The millimetre wave RADAR detector can be operated within 1m to 7m. The system uses frequency modulated continuous wave with emitter and detector. The detector consists of an emitter and sensors and uses the energy reflected from target objects to generate an image [12]. The object detection capability of the system is dependent on the operating wavelength and target object properties in detection space. The detection capability of the system in CWD space is also influenced by computational strength of image recognition algorithms.

1.1.5 INFRARED IMAGER

Infrared imager detects radiation from target in the infrared range of electromagnetic spectrum, typically 9000–14000 nanometres. These imagers are mostly used to detect vehicles and people during nocturnal period. Infrared radiation is transmitted causing the targeted object to heat the clothing and consequently emission of the radiation by the object is detected. For normal loose clothing, the radiation power is spread over the larger clothing area and correspondingly diminishing the chance to produce an output image of a hidden object. It is also difficult to identify the hidden object, when the weapon temperature matches to that of the body [4]. Skyward currently integrates this technology in combat aircraft search and track operations. The system can operate in automatic passive search and tracking functions to provide reliable performance in military environment. Both linear and non-linear data processing techniques are utilized to locate target in the detection space [13]. An integrated system is used for real-time data processing and integration during the flight mission.

1.1.6 MILIMETRE WAVE IMAGER

The millimetre wave imager operates by differentiating the temperature between target and its surroundings. The operating range frequencies of these imagers are just below the sub-millimetre terahertz range. The system imaging capability is not hampered by weather conditions [4]. However, these systems lack the temperature sensitivity, when compared with infrared imaging systems. Thus the effect of weapon to body temperature is also an issue with this system, it is difficult to identify weapon when the weapon temperature approaches body temperature. The system also requires that the person being scanned must remain stationary whilst the system is in operation or the image is distorted. Recent research carried out in Inha University shows improved signal processing capabilities of 3D millimetre wave imager by introducing zero padding Fourier transform method, general processing unit (GPU), high speed analogue to digital converter. Zero padding Fourier transform technique helps better sampling of spectra, whilst GPU and algorithm increases the speed of Fourier transform [14].

1.1.7 HYBRID MILIMETRE WAVE INFRARED IMAGER

In this system both millimetre wave and infrared imaging techniques are employed to detect threat items. The acquired image is filtered to remove noises associated with the images and then both images are aligned to form a fused image. In most situations different types of clothing prevents attainment of any information on a hidden object. The system depends on the imaging capability of infrared imager, if the infrared imagers provide no useful information about the concealed object; the system will fail to produce a useful output [4].

1.1.8 MAGNETIC RESONANCE IMAGING BODY CAVITY IMAGER

Magnetic Resonance Imaging (MRI) imager utilises magnetic pulses and radio wave energy to construct picture of the target, when it passes through the imager. The magnetic field strength of a typical MRI imagers employed in CWD is less than that of used in medical examination. The system is designed to be user friendly, whilst image processing speed and quality uncompromised. However, the system suffers foremost problem when used in crowded CWD screening environment [15]. MRI systems require relatively large amounts of power and are large and expensive to maintain. There is high cost associated in operation of the imager, as highly trained operators are required to deduce images. The system interferes on people with medical device such as a pace maker, cardiac defibrillator etc. and hence not suitable for use in people with above medical conditions [16].

1.1.9 VISIBLE LIGHT 3D SCANNER

Visible light 3D scanner, developed by the University of North Dakota, USA, is primarily used in detecting threat objects in a prison setup. In this technique, laser white beam is projected from Xbox Kinect scanner units towards a person at various angles, and then the distorted pictures of the person is captured by the Raspberry pi cameras mounted at different angles. The scanner is made from PVC pipe in an octagonal shape, where vertical and horizontal frames are attached to support the system that is cylindrical in shape, with 50 cameras mounted on the structure. When a person enters the system, scanning is initiated by an operator using a software script that controls the scanning of the object. A 3D image of the object is generated after the scan is completed by the system. The output image is analysed for discrepancies and anomalies, if large mismatch is detected the person is sent for re-scan. The object is matched for an expected pattern to distinguish between threat and non-threat objects. Three-dimensional scanning of humans is significantly different when compared to objects, as shape and dimension of human changes over time, which poses a challenge when comparing with a known shape. Besides that the system is known to be erroneous with a pose error level of around 3%. This system is currently undergoing further modifications to implement automatic characterisation of objects and better classification between threat and non-threat objects [17].

1.1.10 ELECTROMAGNETIC IMAGING WITH ATOMIC MAGNETOMETERS

This system was developed by the researchers at the University College London, which system utilises a pulsed transmitter with varied transmit frequency to excite the target object. When the primary field is switched off, eddy current is induced on the surface of the object that is captured by an Atomic Magnetometer. This new technique eliminates capacitative coupling effects and sensitivities issues normally associated with electromagnetic induction based detection techniques. In contrast to other detection techniques, magnetic shielding and calibration is not required in this system as it is sensitive to phase [18].

In another recent study, researchers have built a magnetometer array and used real-time inversion algorithm to accurately locate threat objects. Their results suggest that inversion algorithm when used in real-time significantly improves detection of threat objects as compared to use of field inversion in post processing [19].

1.1.11 ULTRA WIDEBAND PULSE RADAR

Ultra wideband radar has found use in military, security and training establishments, as it is capable of analysing the structural and material characteristics within the detection area. UWB pulse systems are capable of achieving, high spatial resolution, data acquisition and high feasibility. This system comprises of a transmitter that transmits high frequency signals cyclically; two receiver units that receive signal from the receiving antennae and also function to convert the radio frequency signal spectrum to intermediate frequency signal spectrum that is processed after Analog-to-Digital conversion in PC. The acquired signal is synchronised with the UWB pulse transmitted from the transmitter unit. Hyperbolic summation (HS) algorithm, that calculates the total scatter received from the object, is used for image reconstruction of the object in detection space. It has limitation in detecting and distinguishing metallic objects buried in environment other than air. However, using an improved HS algorithm, researchers at Ho Chi Minh City University of technology, Vietnam were able to detect and determine the relative position of metal objects in sand that was not possible using the earlier HS algorithm. Therefore this technique can be further developed in detecting metallic objects (possible threat objects) hidden in spaces like sand or concrete [20].

1.1.12 IMAGING BASED SYSTEM SUMMARY

The imaging based CWD systems are widely used in security industry due to the ability to show pictorial information of weapon locations. But most of the imaging based CWD screening systems, described in the section; develop an anatomical figure of people being scanned, which raises privacy concerns. Furthermore, the systems are not able to determine if the threat item, e.g. knife is oriented in 3D space to look like a non-threat item in 2D space [4], [21]. These systems depend on the judgement of an operator to determine whether an item identified is a threat.

1.2 LOCATING BASED SYSTEM

The aim of a locating-based detection system is to determine the location of a concealed item within a detection space. The cost and complexity of these systems are lower compared to imaging based systems. Data acquisition speed is higher, as no image processing capabilities are required, hence the systems are generally simpler to operate, and lower in cost when compared to image based system [4]. The following detection systems are described in Chapter 2; walkthrough, handheld metal detectors, gradiometers, magnetic imaging portal, Acoustic based hard object detectors, Pulsed RADAR or swept frequency detector, electromagnetic pulse detector, and body orifice security scanner.

1.3 SURVEILLANCE BASED SYSTEMS

A surveillance system is used where remote detection of objects is required. The system consists of a remote interface and information storage capability of threat items for the CWD system; this enables complex and detailed operations on acquired information, thereby improving the monitoring and surveillance capability of the system. It is useful to employ this system where it is unsafe or not useful to deploy human operators to screen threat items. The system finds huge success in retail, where tagging technology is employed to restrict theft in the shop.

1.4 TRACKING TYPE SYSTEMS

Tracking type CWD system provides real time information about the location of the target to the operator using imaging or detection only methods to identify a target object. Examples of these systems include the use of Tagging to track objects, which utilizes the unique object signature of the target, and is embedded into the target during manufacturing process. The signature of the object can be identified using many different techniques such as, embedded barcodes, Biometrics, Codes (Temporal, Spatial, Amplitude, Hybrids). The system is lesser in complexity and cost than a surveillance CWD system [4]. It is used in detecting targets within a short range, but additional development is necessary to make its available to detect long-range target objects.

Location based detection technologies such as metal detectors, imaging portals, and monitoring and tracking systems have limitations in open detection space, when used solely for detection of concealed weapons. Traditional metal detectors have limitation for detection of non-metallic weapons and X ray imaging poses health risks and has limited ability to determine threat items concealed in body cavities, while tracking type system cannot be used to detect object at long range.

Consequently, no single effective system is currently available that can detect a wide variety of concealed objects and materials in open space. Hence, development of a new OACWD system is necessary for open space environment and reduces false alarms caused by different metallic objects has become a necessity for the security of various secured establishments [1].

1.5 OBJECTIVES

The objective of the research is to develop numerical models for CWD detection and classification of metal objects in open space. Accordingly, the following objectives are identified.

- Review current EM based detection technologies (e.g. Walk through and Hand held metal detectors, Gradiometers, Electromagnetic Pulse Detectors etc.) to identify suitable methods for the development of an OACWD system.
- Application of EM based detection methods to derive a mathematical equation (time constant / object signature) for object detection and classification from the basic EM field equations in OACWD space.

- Mathematical model development of time stepping algorithms for creation of time varying EM field in open space. Implementations of boundary conditions for the OACWD models and estimation of depth capabilities of the model for embedded targets.
- The design of multi zone array OACWD system in open space.
- Design of coils for transmitter and receiver circuits in the system and use of receiver coil data for the development of an object classification technique and creation of a weapon database.
- Integration of remote operator interface with a CCTV system for real time tracking and alarm creation in OACWD detection space.
- Design of a finite element model of a transmitter, receive, and target in a single OACWD zone. The numerical model of a transmitter is verified for the following parameters: numbers of coil turns transmit pulse duration, drive current, safety analysis of transmitter EM field in OACWD space.
- Design of a transient electromagnetic circuit to link transmitter and receiver and a metal target in the OACWD zone.
- Development of a single zone finite element model with transient EM circuit linked with the model. Analysis of target response with following changes in parameters to generate an object signature and creation of a weapon database; material, shape (geometric and weapon), size, rotations, proximity, and relative permeability.
- Discussion of results and analysis of numerical models compared with mathematical models and the detection of unknown targets. Finally conclusion and future works are presented for further research and development of the system.

1.6 THESIS STRUCTURE

The thesis is organised in the following way:

- Chapter 2, reviews current EM weapon detection technologies, which include walkthrough and hand held metal detectors, gradiometers, acoustic based hard object detectors, pulsed radar detectors, electromagnetic pulse detector, and body orifice security scanner. Each of these technologies is briefly discussed along with the advantages and disadvantages.

- Chapter 3, presents the theory of EM weapon detection. It consists of an overview of EM Pulse Induction (PI) technology, basic electromagnetic field equations. A mathematical model for decay time constant in OACWD system is derived in this section. Time stepping equation and boundary conditions are derived from the basic EM field equations, which are used for the creation of the transient EM field and the restriction of an EM field within a finite domain for numerical analysis of the OACWD model. Depth capability of an embedded target is also discussed.
- Chapter 4, presents the design of Multi-Zone array architecture for OACWD system in an open area environment. Coils for the transmitter and receiver are designed for the OACWD multi zone array system. Transmitter and receiver circuit are designed and the object classification technique is presented. Weapon database and remote operator interface is designed with real time alarm generation CCTV tracking incorporating, is presented in this chapter.
- Chapter 5, presents the design criteria for the transmitter and receiver coil modelled for numerical analysis. Target response is analysed for the following varying parameters in the OACWD zone; material, shape, size, rotation, proximity, and permeability.
- Chapter 6 presents the Discussion of Results and detection of unknown target in the OACWD zone. The numerical results obtained in Chapter 5 are compared with the mathematical model derived in Chapter 3 for validity of object signature and classification of metal objects in OACWD zone.
- Chapter 7 present the conclusions and future work for this research.

CHAPTER 2 : REVIEW OF ELECTROMAGNETIC WEAPON DETECTION TECHNOLOGIES

This chapter reviews the current Electro-Magnetic (EM) based weapon detection technologies, which are predominantly used in location detection CWD systems. The most common EM based weapon detectors are walkthrough metal detectors.

2.1 WALK THROUGH METAL DETECTORS

The first known metal detector was built to protect a Chinese emperor more than 2000 years ago constructed of magnetic minerals to attract iron weapons carries through the doorway. When a person attempted to carry iron weapons such as swords, armours, and other weapons through the doorway, these objects would be drawn against the doorway and held fast [22].

Walk through metal detectors are commonly used in a large number of varied secured establishments across the world, as these are generally the most cost effective method to detect threat objects, especially metal objects.

Walkthrough metal detectors operate on electromagnetic induction (EMI) properties of metals in a time varying EM field, as illustrated in **Error! Reference source not found.**The Transmitter (TX) and Receiver (RX) coils are arranged on opposite sides of the walkthrough metal detector portal. Upon the application of time varying pulse to the TX coil a time varying magnetic field is generated [23], which in turn generates a secondary current in the metal object, when it is passed through the portal. The RX coil on the other side of the portal senses the secondary current from metal object. The position of a specific RX coil in the portal gives the approximate location of the metal object.

Walkthrough metal detectors portal are effective in detecting conductive or magnetisable metals, however, these systems have limitations in detecting small non-metallic objects. Since the average human body is also conductive and large. The receiver signal from the human anatomy is often larger than that for small objects [24]. Consequently, small objects often go undetected through the portal.

2.2 HAND HELD METAL DETECTORS

Handheld devices are often used, by the security personal, to detect threat items in close proximity situations. The principles of operation are primarily the same as those for walkthrough metal detectors; however the coil acts as both the TX and RX. The performance of these instruments significantly depends on the sensitivity adjustment of the equipment [25], [26].

2.3 GRADIOMETERS METAL DETECTORS

Gradiometer metal detectors are walk through type passive systems designed to be permanently installed at secure entry systems such as courthouses. In this type of screening system, people walk into a controlled area and remove all metal objects until all the alarms are resolved. Additionally, CCTV monitor systems may also be used within the detection space [27]. This system can typically detect only ferromagnetic objects, consequently objects not containing ferromagnetic material go undetected [28]. Therefore, this is not a model system that should be employed permanently in most practical cases, as false-positives often occur. Large vehicle movement, nearby equipment, wind, etc., can cause vibrations and movements inducing errors. This is eliminated by application of triple axis accelerometer, which measures positional change of sensors and compensates the output signal. But the installation of accelerometer to the system increases complexity and cost [4]. Reduction of environmental magnetic noise associated with gradiometer is an important parameter in CWD detection. Recent research has developed magnetometer without magnetic shield. The system implements magneto-impedance (MI) sensor, which can detect most environment magnetic noise in CWD space. The impedance of amorphous wire changes when high frequency current is passed through it. The sensor can then detect and classify on the basis of voltage induced in the receiver coil of the gradiometer [29].

2.4 MAGNETIC IMAGING PORTAL

Magnetic imaging portal system acquires an image of an object when it moves through the portal. The system is under development and a prototype of the system has been produced with multiple receivers and a single transmitter [30]. The resolution of the portal is currently 50 mm. A video camera image is superimposed with location data to locate the object in a detection space. The transient EM field is generated by a transmitter; when an object is moved through the portal, the magnetic field interacts with the object and the reflected magnetic field from the object is sensed by the receiver. The signal from the object is obtained by sequentially switching off each transmitter in the portal and sensing the reflected signal from the object by receivers. The image is constructed by inverse solution algorithm from the acquired data [23].

Slow image processing capability of the prototype is currently investigated with application of automatic image refinement algorithm, but the algorithm reduces spatial resolution required to find small objects in the portal. The inverse solution employed for image construction frequently gives poor quality images and consequently reduces object detectability.

2.5 ACOUSTIC BASED HARD OBJECT DETECTORS

These are generally handheld, small, battery operated, low cost and lightweight units that can be used to find threat items, typically within 1 to 5 m. The unit consists of a light beam focussed and aligned with emitted acoustic beam, so that acoustic beam is targeted towards target location [31].

The block diagram of acoustic based hard object detector is shown **Error! Reference source not found.**. Acoustic waves of <20 kHz are generated by a speaker and controlled by a system controller. The interaction of acoustic waves with a target is recorded by a microphone and the data received from the microphone is processed by a data acquisition system [32]; success of the system depends on the acoustic reflection, physical features and orientation of the object [31]. Generally, hard surface objects generate a higher acoustic reflection compared to soft surface objects. Hence, this technology is suitable to find both metal and non-metal weapons. The important detection parameters are target size, diameter of microphone, wavelength of acoustic time pulse, and emitted power.

Since the acoustic-based detector is sensitive to hard surface objects, therefore, it is unable to distinguish between weapons and non-threat hard objects. The acoustic nature of the device makes it impossible to find when an object is embedded within another object [33].

2.6 PULSED RADAR/SWEPT FREQUENCY DETECTOR

Swept frequency illumination techniques are used to obtain information about the object and uses radar incorporating a Doppler effect sensing circuit to calculate the range of the object (Fig. 2.3). The object is classified from the analysis of reflected signal from the object at an approximate range [34], however, it does not provide an image of the detected object. The electromagnetic signature of the object is compared with known threat object signatures in the database; consequently there is a delay while the computer executes database matching. The database also needs frequent updating to identify new threat items [35].

2.7 ELECTROMAGNETIC PULSE DETECTOR

This system identifies objects on the basis of electromagnetic properties; A TX coil is pulsed, illuminating the detection space, thus when an object is in the detection space; a secondary magnetic field is reflected from the object after the TX pulse is switched off. The reflected signal from the object is sensed by the RX and compared with the signature database to classify the object [36].

This method of determining whether a person carrying lethal objects in a detection space requires matching of the object signature in the stored signature database. Therefore, it is time consuming to maintain a large database and also it takes significant processor resources to determine whether an object is a threat item. More importantly, the measured object signature is dependent on the target object rotation in the detection space, which means the database also needs to contain the unique rotation signatures for each object. The system is dependent on the mixture of size, shape, and mass distribution of humans, it is difficult to obtain those values to create an average human signature [37].

In another new development, researchers at the University College London have shown that concealed metal objects can be detected by measuring their resonance values. This system utilizes LCR (Inductance, Capacitance, Resistance) circuit, incorporating a ferrite core coil with resistor and capacitor. The eddy current is induced on the surface of metal object, when it is introduced in the magnetic field of the coil, as a result LCR circuit parameters—dependent on resonant frequency—are modified. The change of LCR values in the magnetic field is found to be dependant on conductivity values of the metal object. Hence metal objects can be successfully identified by this system [38].

2.8 BODY ORIFICE SECURITY SCANNER

This system designed by the Ranger Security Company USA is quoted as fast reliable, simple to use and is designed to detect metal objects in abdominal cavity, rectal vaginal cavity and shin area [39]. It is designed in the shape of a chair, in which several EM zones are designed. The suspected person is allowed to sit on this chair for detection of hidden metal object within the body. It provides real time, highly sensitive detection, of most ferrous and non-ferrous metals and alloys. This system is generally used in prisons and detection centres, customs and border patrol facilities, precious metal mines, etc. The system cannot be used in an open area space due to design or procedural consideration and is impractical for situations with large numbers of individuals [39].

2.9 RADAR WEAPON DETECTION AND ELIMINATION SYSTEM

The system was designed by Jackson Walker LLP of USA. It employs a RADAR system to illuminate target space by varying frequency and vector orientation. This in turn, generates electrical effect in the weapon; the RADAR system then receives the electrical signals reflected from the weapon. The reflected signals are analysed to determine the weapon’s location, shape and size. This information is fed back to the RADAR system to energize ammunitions to detonate the target. In case the initial attempts to detonate the weapon fails, this system tracks and adjusts itself to the frequency and vector orientation of the target weapon to detonate it, however, the system fails to energize when the weapon is obscured by a visual barrier, as the energy field of the system neutralizes the threat produced by a nearby person. So, the system detects weapons, when a person is not within its energized zone. As this system relies on reflection of signals from the weapon and size of this signal is dependant on dimensions of the weapon, a small weapon carried by a person may go unnoticed [40].

2.10 WIDE BAND HIRF DETECTOR AND ANALYSIS SYSTEM

This type of system is currently developed by Euro copter Deutschland, where an electromagnetic threat to aircraft is calculated by analysing the electromagnetic field surrounding the aircraft [41]. The system relies on a wideband antenna (frequency 9 KHz to 40 GHz), that measures the electromagnetic field and the signal information is then processes by signal processing system, which analyses the detected signal for EM field intensity. A warning is issued when the calculated value is lower than the predefined value of the system as the aircraft flies into a threat electromagnetic field area. If multiple antennas are used, the detected parameter increases, which produces direction parameters of the EM field. The operator of the aircraft does not need to rely on external transmitter for the electromagnetic field associated with the aircraft, rather an on board warning system automatically detects any unknown threat by measuring the electromagnetic field intensity of the area [41].

2.11 MAGNETIC INDUCTION TOMOGRAPHY

Magnetic induction tomography (MIT) creates eddy currents on the surface of conductive objects, and the field generated by the decay of the current is measured to detect threat objects. Previously, MIT has been used in biomedical science applications however; researchers at University College of London utilized automated MIT technique to detect threat metal objects [42]. The system uses Helmholtz coil arrangement to create potential difference between driver and sensor coil, which is subsequently measured by the system. The planar and orthogonal arrangements of sensor arrays generate 3D image of the target object. The imaging process is automated by creating array of 20 x 20 switches for input and output of the sensor coil. Sensor reads data after activation of the coil and the output data is fed to MATLAB software to create 3D image of the target object. The system can detect images up to 80mm of depth, provided the resolution limit is lower than the size of the object.

2.12 W BAND MEMS DETECTION ARRAYS

This system utilized microstrip antennas arrays constructed from 256 to 1024 elements where,, the centre frequency of the array was 100 GHz or 220 GHz [43]. This system relies on property of material to emit different intensity of radiation, when exposed to millimetre wave technology. The radiation intensity detects threat items hidden underneath a person clothes. The system has an advantage of lower manufacturing cost, small, and lightweight. Traditionally, W band microstrip antennas network suffers from conduction and radiation losses however; these losses are avoided by introducing a patch antenna along the detection arrays. This system uses patch antenna used ranging from 300 x 300 micrometres that are 50 to 100 micrometres thick and in order to dissipate maximum power these patches are used in conjunction with a load resistor.

The reflected radiation travels from an isolated resistor to a Ti resistor and the electrical resistance of the resistor changes due to reflected radiation. The operating frequency range of this system is between 92 GHz and 100 GHz; this is chosen to present an optimum contrast rate of output images produced by the system. The system utilizes a detection sensor output to construct images by electronic and mechanical scanning, where the resolution of system depends on radiating element of the array.

2.13 HYPERSPECTRAL IMAGING TECHNIQUES FOR TARGET DETECTION

Hyper spectral imaging (HSI) technique is utilized to capture larger spectrum of light as compared to human eye. Human eye can detect ranges from 400nm to infra or near infra red (IR), while HIS can detect ranges from 400nm to 1500nm.The wavelength of HSI system is dependent on the sensors, data cubes are used to store the HSI sensor data and the interpretation of data yields the detection of target. Spatial data is derived from two-dimensional information, whereas spectral data is derived from three-dimensional information. There are three modules that describe this type of system: scene descriptions represented by scene module, sensor settings represented by sensor module and user inputs (processing settings) represented by processing module. The scene module calculates the spectral statistics that is fed to sensor module. The sensor imaging effects along with covariance noise cancelling matrix are added before processing module and the processor module calculates the signal mean and variance of the signal for HSI output [44].

2.14 HIDDEN OBJECT DETECTION USING EM PULSE MICROWAVE SIGNALS

University of Lithuania developed this system; where, a horn antenna is used as a transmitter antenna with an electromagnetic pulse of 200ps rise time and 15V. Wide band antenna is used as a receiver antenna within the frequency ranges from 0 to 18 GHz. Multiple receiver antennas of different frequency ranges are used in this system for detection of metal objects in the target space. In this experimental analysis, the materials are modelled as hollow cylinder and the cylinders are placed at the centre of the antennas, first the amplitude of reflected signal is measured and then frequency is measure and compared against database of undisturbed signal to detect the objects and its electrical properties. This, system can detect smaller metal items such as wrist straps but in the high frequency GHz range the experimental set up lacks analysing equipment to detect metal objects [45].

2.15 HIGH DYNAMIC RANGE, WIDE BAND ELECTROMAGNETIC FIELD THREAT DETECTOR

The system was developed by James Madison University USA, along with Beehive electronics, and Emprimus LLC USA. In this system, a high power electromagnetic field detection system was developed, where the data is processed by a central controller for the detection of objects as a result of electromagnetic interference and high peak electromagnetic pulse using Wide bandwidth antenna of frequency ranges from 100MHz to 10 GHz. Characteristics of the system includes: field strength ranging from 100V/m to 100kV/m, minimum pulse width of 10 ns, rise time of less than 10 ns with measurements being taken every 1 ms. The system generates high electric field, but this is shielded from the measurement, resulting in the elimination of system noises, arcing, and attenuation problems associated with high voltage output measurements. The data is transmitted through a single fibre cable, thereby eliminating the noise and interference associated with signal. The system is designed to create alarm if the level of electromagnetic field increases from a predefined value and the system can be implemented through a range of detection antenna arrays [46].

2.16 HAND HELD RADAR DETECTOR SYSTEM

Haeger et al invented a short range object detection system requiring human operator, that can detect concealed objects behind or within a volume of other materials like concrete or packed soil etc. It is a cost effective radar system where the hand held device transmits a pulse and the return echo is analysed for its strength. This system also calculates the duration of time between the transmission of the pulse and sensing of its return echo. On moving the radar unit over any surface, its display uniquely associates with a particular position on the surface being scanned. The operator has control over the surface of the object being scanned (X-and Y-co-ordinates) when the radar unit scans the volume of the object (Z- axis) at that point. So any variation in the amplitude can be precisely linked to a corresponding point on the surface of the object. The amplitude of the echo also provides information relating to the size and material of the concealed object beneath the surface. It was advanced compared to the older system, which gave errors in the measurement of depth at which the object was concealed as the depth increased. As this unit is easily movable over the surface of any object, it precisely determines the location of any hidden item below the surface [47].

2.17 INFRARED CWD WITH CLOSED-LOOP CONTROL OF ILLUMINATION BY MMW ENERGY

Brown *et al.* have recently developed an active infrared apparatus that consists of an imaging infrared sensor, a generator beam and an image processor that can store multiple infrared images of the scene in its memory for comparison. The initial temperature distribution, prior to exposure with the millimeter wave, within the subject is recorded as the first infrared image by the processor. Further, an altered temperature distribution is obtained to create a second infrared image of the scene, by subjecting the subject to millimeter wave generated by the beam generator. The processor identifies the changes in the temperature distribution and controls the beam generator such that it illuminates the subject till the highest temperature distribution either equals or exceeds the predetermined limit of temperature change stored in the database. Subsequently, once the generator has stopped illuminating the subject, a third infrared image is stored after a pre-set time interval. The processor analyses the changes in the temperature distribution between the first and the second infrared images and also between the first and the third infrared images to determine if the subject has a concealed threat object underneath the clothing. Though the system does not reveal the exact shape of the object but does illuminate the size and area of its location [48].

Previously, Demma et al. have utilized millimeter wave, but have been unable to detect non-metal threat objects. In addition, to not being able to penetrate layers of clothing, the unit could not detect a concealed weapon in warmer climates as the threat object carried on body will take the same temperature as that of the subject rendering the infrared technology ineffective for the purpose. Also, the system had a drawback of being effective only at a short range of 2 meters.

2.18 SUMMARY

Each detection technology, discussed above, has advantages and disadvantages for any specific purpose. The OACWD characteristics to be considered in order to be effective in detecting threat items; are the operational environment and the needs of the user (size, weight, etc.), acquisition and operation cost [49]. Other factors include; unobtrusive, minimal impact on operations, flexibility to scan both small and large areas with high/sufficient spatial resolution. Also, the processing speed (capable of video frame rate (3D) imaging of moving humans), safety in terms of danger to humans/animals, and individual right to privacy are important in the design of the system.

Following research challenges were identified for the OACWD system development.

From the literature review, it was concluded that no single detection technique was effective in screening of weapons in all possible secured establishments. Therefore, the success of a new OACWD detection system lies in the integration of existing techniques.

The increased system reliability by reducing false alarms is one of the significant factors for OACWD screening in public places. Intervention by human operator is normally required to resolve false alarms generated by current CWD devices. There are numbers of suspect weapons at security checkpoints everyday around the world, if the detection devices generate false alarms for the non threat items, additional security screening is required [2]. These devices require inspection of images or hand search by human operators to resolve alarms [50]. Hence, increase in false alarms is directly linked to the human intervention, which causes delays at the entry point of the secured establishment [2]. Therefore, the false alarm rates needs to be reduced by the implementation of an improved metallic weapon identification technique. This is to be achieved using the time constants (current decay time technique) to differentiate between different metal objects. This will enable threat and non-threat items to be defined and consequently build a database of threat items.

Electromagnetic fields in open space generally create zones of maximum sensitivity termed (hotspots) and zone of zero sensitivity termed (dead spots). A reduction in ‘hotspots’ and ‘dead spots’ in the detection space can be achieved by dividing OACWD space into multiple zones. Design of zones in open space also enables the location information of the object to be classified.

The success of the design of OACWD system depends on the successful design of transmitter and receiver, for the system, to achieve uniform illumination and uniform detection of metal objects in a detection space. The details about this method are discussed in chapter 4.

In the time domain transient analysis of metal objects, in open space, it is often found that the primary field (transmitter field) is embedded within the receiver signal after cessation of the transmitter field. Therefore, in order to detect metal objects, successfully in a detection space, it is necessary to detach the transmit signal from the receiver signal. The transmitter needs to be completely switched off before the receiver is activated in order to gather the signal from a metal object. A faster, switch off of the transmit pulse is required for the detection of objects in open space. This is achieved by a fast switch and a current sensor, which senses current from the transmit coil and allows current to pass to the transmit coil from the power source.

The design of OACWD system in open space is expensive in terms of time and cost. Hence, it is necessary to analyse the behaviour of all components of the OACWD system before the physical development of the system. Therefore, the modelling and simulation of transmitters, receivers, and metal objects in transient pulse magnetic environment is required. Details about the modelling and simulation of metal objects are described in chapter 5.

In this thesis, the time constant is used to detect and classify metal objects in OACWD space, as it is dependent of object shape, size, and material conductivity values. If these parameters were taken into account to create and weapon database, there would be duplicate values for the same object in the database. Hence, it is required to model and simulate each parameters of the time constant to analyse the behaviour of metal objects in OACWD space. This analysis classifies threat metal object depending on the variable parameters of the time constant.

Finally, the creation of a weapon database is considered, to store the signatures of threat metal objects to be compared against the time constant obtained from OACWD space in order to generate alarm for threat metal object in OACWD space.

CHAPTER 3 : THEORY OF ELECTROMAGNETIC WEAPON DETECTION

The Electro Magnetic Induction (EMI) based systems are primarily used in weapon and mines detection [51], since majority of the contents in weapon are metal. The systems in time domain mode of operation used for target discrimination, which eliminates physically search of each individual at security checkpoints. The time domain analysis used in EMI weapon detection system is investigated in this chapter. EMI techniques can be broadly divided into two groups; Frequency and Time domain; in the frequency method an AC current is applied to a transmit coil with frequency and amplitude parameters remaining constant, which generates eddy currents in metallic object and upon termination of primary EM field, the object produces a secondary EM field, which is acquired by a RX sensor. The frequency of the pulse is varied to detect different metals [52]. Whereas, in the time domain methods, a pulsed current is applied to the transmitter to generate a magnetic field; after the transmitter pulse is switched off a secondary field appears from any nearby metal objects and this field is then sensed by a RX sensor [53]. The advantages and disadvantages on use of time domain over frequency domain electromagnetic field are illustrated in **Error! Reference source not found.** and **Error! Reference source not found.** [54].

The OACWD system, based on the EMI pulse weapon detection method, is described below.

3.1 ELECTROMAGNETIC PULSE INDUCTION

When a metal object is entered in a transient EM field, it interferes with the field, due to the self-induction property of the object. After the EM pulse is propagated within certain duration and the object is passed near the TX, then the following effect emerges: after the primary transmit EM pulse is switched off, a fading current pulse appears on the object [55]. As the current collapses, a secondary fading magnetic field is radiated from the object. The radiated field contains information about the metal object and is the basis on which a metal weapon can be detected. Hence, the main task for the pulse weapon detection is to detect this fading pulse from a metal object and process it [56]. The basic of EMI pulse detection methodology is illustrated in

The EMI systems generally operate at frequency less than 1 MHz and primarily receptive to changes in conductivity and permeability values [57]. However, the induced current in a metal target in the time domain EMI field is dependent on several factors, which are described in section 3.2.

3.2 BASIC ELECTROMAGNETIC FIELD EQUATIONS

Low frequency electromagnetic fields used in this analysis are described by the quasi-static limit of Maxwell's equations, which exclude displacement currents, and given by the following equations 3.1 to 3.4 [58]

$$\nabla \times H = J \qquad \text{Eq. 3.1}$$

Where ∇ is vector differential operator, H is the strength of the magnetic field, and J is the current density.

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad \text{Eq. 3.2}$$

$$J = \sigma(E + u \times B) \qquad \text{Eq. 3.3}$$

Where E: electric field, B: magnetic flux density, t: time, J: current density, s : conductivity of the material, u: media velocity with respect to the field

From Eq. 3.3 it follows that the flux density B can be derived from a vector potential in Equation 3.4 [59], [60].

$$B = \nabla \times A \qquad \text{Eq. 3.4}$$

In the analysis, a combination of the total and reduced vector potentials is used to model time varying electromagnetic fields. The magnetic field produced by a known distribution of current in free space (for example, the field from a coil wound with fine wire carrying specified current) can be calculated by the integration of Biot-Savart's equation [58]. The vector potential describing the magnetic field excluding the fields from these source conductors, is called a reduced vector potential (A_R) and is defined by;

$$B = \mu_0 H_S + \nabla \times A_R \qquad \text{Eq. 3.5}$$

In regions where the field is only derived from a (total) vector potential, combining Eq. 3.3 and Eq. 3.5 gives the following equations for A:

$$\nabla \times \frac{1}{\mu} \nabla \times A = -\sigma \frac{\partial A}{\partial t} - \sigma \nabla V \qquad \text{Eq. 3.6}$$

The electric scalar potential (V) emerges because of the non-uniqueness of the potential, which arises during integration of Eq. 3.4. In free space the electric scalar potential can be set to zero without any loss of generality, however in conducting regions a secondary equation (derived from $\nabla . J = 0$) is introduced

$$\nabla . \sigma \nabla V + \nabla . \sigma \frac{\partial A}{\partial t} = 0 \qquad \text{Eq. 3.7}$$

so that both the electric scalar potential and the vector potential can be determined.

In free space regions containing source currents where the reduced vector potential is used, combing Eq. 3.5 and Eq. 3.7 gives the following equation for A_R:

$$\nabla \times \frac{1}{\mu_0} \nabla \times A_R = 0 \qquad \text{Eq. 3.8}$$

Where μ_0 : permeability in free space.

The total and reduced vector potential descriptions of the field are directly combined in the formulation used in the OACWD model. The normal flux and tangential field intensity interface conditions, determines the relationship between the two types of vector potential.

The time domain EMI field is created by time stepping equations in a time dependant EM field; the resulting equations are solved in the section 3.2.1.

3.2.1 TIME STEPPING EQUATIONS FOR ELECTROMAGNETIC FIELD

The transient EM problems are time dependent; therefore the resulting equations are solved using a time stepping algorithm [61].

Applying the Galerkin procedure to Eq. 3.8 produces a matrix equation of the form

$$R.A + S\frac{\partial A}{\partial t} + b = 0 \qquad \text{Eq. 3.9}$$

where A: represents unknown potentials vector and b: vector of driving terms. Discretising A and b as first order functions in time gives equation 3.10 and 3.11 [62]:

$$A(t) = (1-\tau)a_n + \tau a_{n+1} \qquad \text{Eq. 3.10}$$

$$B(t) = (1-\tau)b_n + \tau b_{n+1} \qquad \text{Eq. 3.11}$$

Where

$$\tau = \frac{t - t_n}{t_{n+1} - t_n} \qquad \text{Eq. 3.12}$$

where a_n and b_n are values of A and B at time t_n. τ is utilized as a weight in in Galerkin weighted residual solution. Eq. 3.12 shows a relation of a_{n+1} and a_n given by Eq. 3.13:

$$(R(1-\theta) - \frac{S}{\Delta t})a_n + (R\theta + \frac{S}{\Delta t})a_{n+1} + b_n(1-\theta) + b_{n+1}\theta = 0 \qquad \text{Eq. 3.13}$$

Where the time step $\Delta t = t_{n+1} - t_n$. The value of θ is dependent on each analysis type.

The time varying drive is provided by current sources in external circuitry. In each case, the value of the drive at any time is found by multiplying by a time function. In the OACWD model a DC (Uniform in all time) drive function TABLE (switch on) function in OPERA 3D software is used to control external circuitry in the model. The table consists of a file containing dual numbers per line format. Time and its function value are written in table file, the time in which TX is switched on starts at zero and increases through the file.

The EM fields derived by Eq. 3.3 to Eq. 3.13 are frequently not contained within a finite volume. Thus, in order to evaluate EM fields, boundary conditions is applied to limit the fields within a finite volume [63].

3.2.2 BOUNDARY CONDITIONS

Boundary conditions in the numerical calculation of EM fields are used in the following ways. Firstly, a boundary condition when applied to a model in a numerical method of solving EM fields reduces finite element representation of symmetrical models. The details about finite element methods are described in Appendix E.

Secondly, it is used to approximate EM field at large distances from the model (far field boundaries).

Boundary conditions are calculated from the integral forms of Maxwell's equations as shown in the Table 3.3 [64]. The detailed derivation of equations is beyond the scope of this chapter.

Magnetic Fields	**Field Symmetry**	**Scalar Potential**
Tangential Magnetic	$H.n = 0$	$\frac{\partial \phi}{\partial n} = 0$
Normal Magnetic	$H \times n = 0$	$\phi =$ Constant

Table 3.1 Scalar Potential Boundary Conditions [54]

Where n is the unit vector of the object being considered, and ϕ refers to either the reduced or total scalar potential.

Boundary conditions on the reduced scalar potential only affect the reduced field intensity. The boundary conditions in Table 3.3 are applied to the exterior portion of the model except in electrostatic fields and current flow electrode flow surfaces.

In time varying EM fields model, the symmetry is implied by the potential boundary conditions applied; the simplest types of boundary conditions are given in the Table 3.4:

Magnetic Fields	**Field Symmetry**	**Vector Potential**
Tangential Magnetic, Normal Electric	$H.n = 0$ $E \times n = 0$	$A \times n = 0$ $V = 0$
Normal Magnetic or Tangential Electric	$H \times n = 0$ $E.n = 0$	$(\nabla \times A) \times n = 0$ $\nabla V.n = 0$

Table 3.2 Vector Potential Boundary Conditions

A non-zero value for the electric scalar potential V on an external surface can be used to drive time varying current into the EM model.

The $H.n$ condition with a vector potential solution is imposed in time varying EM field analysis because the potentials are prescribed to the values specified. However, the field solution may not be exactly as expected; if the normal direction of the surface is discontinuous (e.g. the normal direction is ambiguous at an edge) this will produce a solution, which implies at least two possible values for the field at the edge.

The field computed by taking derivatives of the finite elements shape functions is discontinuous, but in each element, the potential boundary conditions are specified exactly. However, when the nodal averaging method (field smoothing process in EM simulation software) is applied to the problem, the true boundary condition is forced at the surface of the object to ensure accuracy is maintained as far as possible. It is to be noted that in surface potential formation, in the numerical analysis software, the magnitudes of both scalar and vector potentials are automatically gauged [65].

3.3 MATHEMATICAL MODEL FOR DECAY TIME CONSTANT IN WEAPON DETECTION

The detection and classification of threat objects described in this chapter, in low frequency transient EM fields. The system uses the solution of Maxwell's equation for detection and classification of targets in OACWD system.

Starting with estimation to the problem, assuming that a sphere shaped weapon with radius a, magnetic permeability μ and conductivity σ is illuminated with a transient EM pulse, which causes a step change in the amplitude of the EM field vector. The primary EM field is assumed planar (strength zero) near the weapon; denoted as 'H_0'

Using [66] a quasistatic solution of Maxwell's equations, it was found that the primary EM field around the sphere was increased due to induced currents flow within the sphere given by Eq. 3.14 – Eq.3.19. [66]

$$E_{\phi}^{e} = \frac{3KB_0 a^3 \sin\theta}{R^2} \sum_{s=1}^{\infty} \frac{q_s e^{-q_s t}}{[k_s^2 a^2 + (K-1)(K+2)]} \qquad \text{Eq. 3.14}$$

$$B_{R}^{e} = \frac{6KB_0 a^3 \cos\theta}{R^3} \sum_{s=1}^{\infty} \frac{e^{-q_s t}}{[k_s^2 a^2 + (K-1)(K+2)]} \qquad \text{Eq. 3.15}$$

$$B_{\theta}^{a} = \frac{3KB_0 a^3 \sin\theta}{R^3} \sum_{s=1}^{\infty} \frac{e^{-q_s t}}{[k_s^2 a^2 + (K-1)(K+2)]} \qquad \text{Eq. 3.16}$$

Where E_{θ}^{e}, B_{R}^{e}, B_{θ}^{a} are the azimuthal, radial, polar components, respectively of the anomalous fields caused by induced currents in the weapon.

The spherical coordinate system centred on the sphere is used to describe these components, where R being in the direction of incident field. R, θ and ϕ are spherical coordinates of the sphere with sphere's centre as its origin. The rest of the parameters in the equations are defined as below:

$$K = \frac{\mu}{\mu_0} \qquad \text{Eq. 3.17}$$

$$q_s = k_s^2 / \sigma\mu \qquad \text{Eq. 3.18}$$

$$k_s = \pi s / a \ (s=1.\ 2, 3, \ldots, \infty) \qquad \text{Eq. 3.19}$$

Where *K*: relative magnetic permeability of the weapon, q_s : point in space at which the field is observed, k_s : separation constant, s : constant, a :radius, and 't' : time after initial time step.

Each EM field component is the sum of exponentially decaying EM transients. During the early part of the EM field, expressions for the anomalous magnetic field components are given by.

$$B_R^e(t) = B_0 \left(\frac{a}{R}\right)^3 \cos\theta \left[1 - \frac{6}{\sqrt{\pi}}\sqrt{\alpha t}\right] \qquad \text{Eq. 3.20}$$

$$B_\theta^e(t) = B_0 \frac{1}{2} \left(\frac{a}{R}\right)^3 \sin\theta \left[1 - \frac{6}{\sqrt{\pi}}\sqrt{\alpha t}\right] \qquad \text{Eq. 3.21}$$

The early stage behaviour will persist over a longer time and is dependent of conductivity values and radius of the sphere. In particular, in the case of a perfectly conducting sphere, eddy currents are present only on the exterior parts of the sphere at all times, and do not decay. For this reason, the magnetic field of these currents is constant ($\alpha = 0$) with a value equal to that for t = 0. The important characteristic of the magnetic field during early stage is a due to the containment of eddy currents on the exterior portion of the conductor. Therefore, the magnetic field is only weakly related to conductivity and depends on the radius of the sphere and the location. However, the electric field generated by a change in the magnetic field, with time, therefore with the diffusion currents into the conductor, is directly proportional to the quantity $\alpha^{1/2}$.

A comparison of the early time approximations with the exact solution in Eq. 3.5 show the asymptotic formulas in Eq. 3.20 and Eq. 3.21 can be used with an error less than 10% when $\alpha t < 0.03$.

During the late part of the transient decay, the EM field is calculated by the exponential terms given in equations 3.22 – 3.24:

$$B_R^e = \frac{6B_0}{\pi^2}(\frac{a}{R})^3 \cos\theta e^{-t/\tau_0} \qquad \text{Eq. 3.22}$$

$$B_\theta^e = \frac{3B_0}{\pi^2}(\frac{a}{R})^3 \sin\theta e^{-t/\tau_0} \qquad \text{Eq. 3.23}$$

$$E_\phi^e = \frac{3B_0}{\tau_0\pi^2}(\frac{a}{R})^3 \sin\theta e^{-t/\tau_0} \qquad \text{Eq. 3.24}$$

Where, $\tau_0 = \sigma\mu a^2 \pi^2 a$ is a time constant.

The EM field components described in Eq. 3.22-24 is a product of two terms, the first one constitutes geometry and magnitude of the primary EM field near the weapon, and the second one is a time constant independent of primary EM field and weapon geometry. The time constant is utilised for detection of weapon, as it is independent of primary EM field strength and false alarms [66].

The time constant is also represented in the Eq. 3.25:

$$\tau_0 = -\frac{B_R^e}{\partial B_R^e / \partial t} = -\frac{B_\theta^e}{\partial B_\theta^e / \partial t} \qquad \text{Eq. 3.25}$$

The time constant is a product of the conductivity, permeability and cross sectional area of the weapon. Thus, it is signifies the “electromagnetic scattering cross section” of the weapon [67].

The above analyses were applied to axial symmetry of complex weapon geometry and eq. 3.26 gives the equation of time constant of complex weapon geometry

$$\tau_0 = \sigma\mu b^2 / q_1 \qquad \text{Eq. 3.26}$$

Where q_1 dependent of the shape of the weapon, b is an arbitrary geometric parameter. Time constant τ_0 is the product of the conductivity and a function that depends on the geometry [66].

$$\tau_0 = \sigma\mu F \qquad \text{Eq. 3.27}$$

Where $F = b^2 / q_1$

The time constant gives information about the time at which late-stage behaviour is demonstrated. From the physical point of view, increase in the conductivity values or the dimensions of the conductive body, it is evident that the induced currents decay more slowly and therefore the late-stage behaviour begins at a later time. The time constant τ_0 independent of the primary field, the position of the conductive body, or the position of the observation site, however, it depends on the property of the conductive body, which is vital, since it contains the conductivity value of weapon.

Thus from the analysis, it can be summarized that weapons of same shape, size within the transient EM field environment can be successfully differentiated as time constant decay is in independent of strength of primary EM field, proximity from TX and RX array. The time constant is determined by illuminating the weapon with EM pulse and calculating the time constant from the decaying EM field. Eq. 3.27 can be modified to find the precise value for time constant, e.g. assuming the $\mu.\sigma$ product in Eq. 3.27 as 1 $s.H/m^2$, the radius 0.01 m, and form factor q is 10, the time constant of sphere is calculated to be 0.1 ms. Human body is conductive and is usually carries a weapon. But the $\mu.\sigma$ product for human body is much less than that of a typical weapon, hence there is less chances that secondary EM field from human body hide the field from the weapon [66].

3.3.1 TIME DECAY RESPONSE

The time decay response is divided into three stages, early, intermediate, late, and is illustrated in Fig. 3.2, the early time stage occurs after the TX is pulsed off and from Faraday's law of induction, currents are induced on the exterior part of the target [67]. The field outside the target experiences a step change upon termination of TX pulse current; however, the field inside the conductor remains unchanged. From Lenz's law, it can be proved that, currents are induced on exterior part of the target to maintain the magnetic field interior of the target prior to the termination of TX pulse current [68]. Hence, a large interior magnetic field gives rise to increased eddy currents induced in the exterior part of the target.

The subsequent behaviour of the currents obeys diffusion equations after the currents are induced on the target surface as represented by Eq. 3.28.

$$\frac{\partial j\ (r,t)}{\partial t} = \nabla.[D(j\ ,r)\nabla j\ (r,t)] \qquad \text{Eq. 3.28}$$

Current
in Amp.

Where $j(r,t)$: density of the diffusing material. *r:* location, *t:* time $D(j,r)$: diffusion coefficient *and* ∇: vector differential operator.

It is known from the diffusion equation in Eq.3.28 that quantities satisfying the diffusion equation diffuse from areas of high to low concentration. Hence, the induced surface current diffuses from target edge (areas of high concentration) towards the centre of the target surface (areas of low concentration). This stage is characterized as intermediate time stage. This process continues until a steady stage is reached by the spatial distribution of currents. In this late stage, equilibrium distribution of currents simultaneously decays exponentially.

3.4 SUMMARY

In this chapter, time-domain EMI method within a tangential boundary and time stepping algorithm was applied to create a transient EM field. The EM field equations were derived from the solution of the Maxwell's equations in the transient time domain EM fields. Using time domain EM field, a mathematical model for current decay time constant of metal objects was presented. This current decay time constant is an inherent property of metal objects, which varies with values of electric conductivity, shape, and size of the metal objects. Hence, using this signature, the metal objects can be classified in the transient time domain EM field. The object signature graph of metal objects were analysed for early time and late time behaviour of current decay in metal objects. Thus using this analysis, a weapon database can be created successfully to detect and classify metal objects. The mathematical model for the object signature and characteristic properties were applied to create an OACWD system in Chapter 4.

CHAPTER 4 : OPEN AREA CONCEALED WEAPON DETECTION SYSTEM

A new OACWD model is introduced to enable the discrimination between concealed weapon and non-threat objects in large open space areas. The system is designed for high rate of detection of concealed weapons and lower rate of false alarms. The privacy of a user is not invaded by this system, as the user under surveillance, is not aware of the surveillance method used and no person specific image is produced [1].

4.1 MULTI ZONE ARRAY ARCHITECTURE

The 3D model of the OACWD system is shown in **Error! Reference source not found.**. the system uses time domain pulse EMI technology for the detection of threat objects. The advantages of this method were explained in Chapter 3.

The architecture of OACWD system is shown in **Error! Reference source not found.**.

The transient pulsed EM field TX and RX array are hidden under OACWD surface. Hidden sensors in wall are also installed in the detection space to locate concealed weapons vertically. The sensor array detects when a metal is entered through the OACWD zone; the object signatures of the object is calculated and is compared against the known threat objects in weapon database. If the time constant or the object signature matches with the existing weapon type in the database within a specified range, an alarm is activated. The alarm in an OACWD zone is coupled to a CCTV system to monitor the location and movement of threat metal objects, and the individual carrying it, in real time [1].

A picture of the specific suspected threat item is superimposed onto the CCTV image to enable the operator to evaluate the potential threat imposed by an individual. The zone OACWD system provides a zoomed view of the detection area for monitoring and tracking of individuals. The OACWD system is designed not to restrict the movement of individuals in open area, thus reduces blockages in security screening of large numbers of people in an open space [1].

The transmitter and receiver, in a single zone, are placed between one and two metres apart, while the target was placed at equal distance from both TX and RX. This configuration provides isolation between the TX and RX circuits and allows more flexibility in the RX coil design (e.g. different number of turns, size or differential configuration) and amplifier circuit design. A model of the single zone was designed and analysed using the OPERA 3D electromagnetic modelling software and the results are evaluated in Chapter 5 in order to determine the most appropriate parameters for the OACWD system.

4.2 COIL DESIGN

The TX produces alternate pulsed magnetic fields through a controlled power circuit, which induces eddy current in metal objects. The magnetic fields generated by these eddy currents, in turn, are detected, inductively by the RX. The area and uniformity of sensitivity of the TX and RX are determined by the geometry and orientation of the respective coils. The coil design ensures that the sensitivity to metal objects within a zone is uniform so that there are no areas of low sensitivity (dead spots) or areas of high sensitivity (hot spots) within a zone [69].

Several factors have been considered in the design of the OACWD system coils; one of the factors is ‘hotspot’ reduction. Hotspots arises because the field strength induced by a current in a wire bundle falls due to 1/radius [70]. In a zone of the OACWD system, when the wires making up the coil are brought together into a tight bundle, the resulting field becomes large at a small distance from the bundle and hotspots occur.

Tight bundling of the coil wires causes a detrimental increase in both inter-winding capacitance and coil inductance, both of which significantly increase response time and reduce the sensitivity to small objects [71]. Hence, standard aluminium sheet is placed under the receive array coils to standardize the environment and confine rapid magnetic flux changes in the volume above the floor. The flux lines divergence are confined to directions in a horizontal plane; and thus transmit and receive fields intersect at oblique angles, permitting detection of isotropic objects. This arrangement reduces attenuation of interference signals originating from the floor.

Inductance and DC resistance are important parameters in the design of multi layer coils for the OACWD system and are calculated using Wheelers Equation 4.1. The formula is valid for a circular air cored coil with less than 1% error [70].

$$L = \frac{7.87N^2M^2}{3M + 9B + 10C} \qquad \text{Eq. 4.1}$$

where

L is inductance of coil in nH, N is number of turns, M is mean diameter of coil, B is width or length, C is radial thickness

The DC resistance of the coil can be expressed in terms of the diameter and length of the copper wire, which is expressed in the number of turns and mean diameter of the coil given by Equation 4.2 [70]

$$R = \frac{NM}{14250W^2} \qquad \text{Eq. 4.2}$$

where, R is the DC resistance, and W is the diameter of the copper wire

Depth of the TX signal in a zone is an important parameter in the detection capability of a RX coil, and is directly related to the size of the TX coil. The depth of coil is expressed as the inverse square cubic law with the transmitting signal, which on re-transmission by the metallic object also, follows an inverse cubic law. This means that the signal sampled by a RX coil will decrease by an exponential factor of six [72]. By using a larger TX coil, the field remains uniform in depth thereby the received signal will only decrease by an exponential factor of three. Hence, it doubles the depth of detection of metallic objects compared to a normal size coil. The TX coil used in this model eliminates dynamic range problem which is generally associated with depth of transmit signals in Pulse Induction (PI) technology.

In PI technology method it is important to eliminate the TX signal when the pulse is switched off, otherwise coupling effects appear in the model and interfere with the target signal. Hence, coupling effects between coils are eliminated by the introduction of small diameter coils for RX and separation between the coils within a zone.

The design parameters for the TX and RX coil are shown in Table 4.1. The resistance and inductance of the coils are calculated from the Wheeler formula, whilst the all other parameters were assumed to be constant.

4.2.1 TRANSMITTER CIRCUIT

The TX circuit consists of an electronic switch, which connects for 5 µs to the low resistance TX coil, allowing the drive current to flow in the coil. The transmit drive current is pulsed for typically 5 µs as shown in **Error! Reference source not found.**. This method prevents the TX coil from overheating and reduces power usage, as longer pulse in transmitter tends to generate heating effect in the coil as evident by the Equation 4.3 [73].

$$H = i^2 R t \qquad \text{Eq. 4.3}$$

Where H is the heating effect, i is current , R is resistance , and t is the pulse duration of the coil.

The transmit circuit also consists of a current sensor to measure the current level of the transmit coil before the next pulse is transmitted. This assists signal detection for small metal targets as illustrated in **Error! Reference source not found.**.

4.2.2 RECEIVER CIRCUIT

The RX coil is isolated and thus protected from the high rate of TX coil current change, so that the output of the RX coil is relatively low. In an open area environment the RX signal is often corrupted by environment noise; EMI noises. Thus the RX circuit incorporates a filter to eliminate noise from the signal, and after amplification, the signal is passed through a high-speed 12-bit Analogue to Digital Converter (ADC) converter. The resultant digital signal is then transmitted to a control computer to classify the object.

The output from RX coil is pre-amplified with a low-noise, wide band differential transducer amplifier (Maxim MAX-4146) [74]. An ADC of 10 MSamples/sec is utilised to convert the analogue data to digital. The system controller block diagram is shown in **Error! Reference source not found.**.

4.3 OBJECT CLASSIFICATION AND WEAPON DATABASE

The accurate classification of threat metal objects from the RX sensor data remains a major problem in reducing false alarms in the OACWD system, due to the lack of an object classification procedure to handle data from multiple objects in OACWD detection space. The object classification algorithm can be broadly divided into two categories, model and data based. Data based algorithms are pattern recognition procedures that compare a library of signature data from various objects with, that of the detected object signature. Model based algorithms use forward modelling algorithms to determine a set of model parameters needed to replicate the object signatures, and subsequently relating the model parameters to physical parameters [75]. Further research has been proposed to determine time constants from the RX signature data, or equivalently, the poles of the frequency domain signal, to identify the threat metal objects. An hybrid method that represents a combination of model-based and data based algorithm has been proposed by Blackhawk Geometrics [76]. In this approach, a spheroid modeller, working jointly with a model-based inversion algorithm, generates a database of model parameters, which can then be operated upon by a neural network classifier for comparison with parameters derived from the RX signal.

In this thesis, a model-based transient electromagnetic model data interpretation algorithm that estimates the basic shape and magnetic characteristic of threat objects is presented in Fig. 4.6. The magnetic field strength of a target metal object decays with time, and the parameters that govern the time decay behaviour are related to the conductivity, permeability, shape and size of the objects within the detection space.

In a simple situation, items are classified on the basis of a single parameter such as object size. However, many object classifications cannot be handled successfully based on a single parameter [77], because the parameter estimation process is imperfect. Classification parameters for example, such as size and shape of threat objects can overlap with the size of non-threat objects; hence it is uncommon to get perfect separation based on one parameter. For this type of complex problem, sophisticated statistical classifier can combine the information from multiple parameters to estimate the likelihood signal match.

4.3.1 DATA ACQUISATION SYSTEM

The development of a rapid data acquisition system is the essence of effective development of the OACWD system, which enables real-time tracking of threat objects in a detection space. The data acquisition system is based on IEEE-P996 and is employed to perform data acquisition as illustrated in Fig. 4.6 and Fig. 4.7 [78]. The system controls the TX pulse frequency; drive current, statistical calculations and result display.

The sensed RX coil data is digitised by 12 bit 10 Msamples/sec ADC at a sample rate of 10 Msamples/sec. Hence data can be collected within micro seconds range. If the scan is greater than one, the controller collects additional data one-dimensional data array. The mean data for voltage values is plotted against time for further analysis. The above procedure (Fig. 4.7) amplifies the voltage drift and residual decaying current from TX coil and coupled into the RX coil. The time decay curve remains unchanged for larger objects as the background noise is minimum, but as the background noise is maximum compared to secondary EM field, as subtraction procedure is employed to improve the data quality. The signal is dependent on target size, metal conductivity, and target shape [77].

4.3.2 WEAPON DATABASE

As the number of unknown objects grows in the OACWD system, numbers of stored object signatures would exceed the storage capability of the weapon database used for database matching [79]. The time constants of common weapons are compiled within a catalogue-based database. The database is divided into number of cell; the address of each cell corresponds to time constant of a weapon. The time constant is determined by calculating logarithmic transformation of current decay time curve of weapon, this method transforms the exponential decay time curve in to straight line and slope of the curve being the time constant. Thus, in this approach, the searching time of extremely large database is reduced to few milli seconds.

4.4 REMOTE OPERATOR INTERFACE AND ALARM GENERATION

The remote operator interface consists of multiple CCTV cameras displayed in the monitor of remote operator. The multiple video cameras help the remote operator to monitor OACWD zones remotely. The monitoring system has the capability to zoom and pan tilt feature to pin point concealed weapon-carrying individuals in the OACWD detection space.

The CCTV remote operator interface system gathers all data from OACWD zones. The unknown threat and non-threat objects are both analysed by the control operator. The image representation of the weapon and approximate location are super-imposed on the display of the operator control monitor to enable the operator to classify threat objects. The alarm systems in the remote monitor automatically direct the operator to pin point threat object in the OACWD zone.

4.4.1 TRAFFIC FLOW CONTROL

Remote of monitoring of a person and alarm interface is illustrated in Fig. 4.8. The left hand side of the Fig. 4.8 shows that the person is walking in the OACWD space. The right hand side of the figure shows a remote operator interface displaying the OACWD zones. The video camera control system captures the information from OACWD zones and directs the camera to pinpoint the zone where the metal target was detected. The OACWD control system then monitors the individual possessing the weapon in real time. The tracking process is automated by integrating the OACWD sensor and CCTV image processing system.

In some cases it is possible that there may be large numbers of people in the detection space, however this system allows the person carrying threat object to be identified. The controlled flow of crowds and the placement of sensors and video cameras in a large detection space are illustrated in Fig 4.8. The flow of individuals is channelled over the OACWD space by series of control barriers. The usual barriers are flowerbeds, planters, which are actively submerged to the background or surroundings of the OACWD system [77].

4.5 SUMMARY

The basic architecture of a multi zone OACWD system is designed for use in open space consisting of several transmitter and receiver arrays arranged in zones. A single zone of the system consisting transmitter and receiver was modelled in this chapter. The design parameters both electrical and mechanical were calculated from Wheeler’s equation and validated as in Chapter 5. The transmitter circuit is designed to drive transmitter coils within certain time intervals in the OACWD zone and is controlled by a switch. The receiver circuit was designed to amplify and convert the signals from a receiver coil for identification of the signal. The TX and RX controllers are connected to the weapon database and a CCTV control system to create an alarm for threat objects and to track it in real time. A data acquisition method was defined for efficient data collection from the receiver by eliminating background noises. The collected data is matched with weapon database to create an alarm in remote operator interface terminal. The weapon database consists of object signatures of threat items based on model and data object classification techniques. An alarm is created after the data are classified as threats and consequently CCTV monitoring is activated to track threat objects in real time within a detection space. An efficient traffic flow model of an OACWD system allows the sensors and transmitters merged with environment and improve traffic flow at security checkpoints. A single zone of the model is simulated and analysed to verify effectiveness in Chapter 5.

CHAPTER 5 : RESULTS

The electromagnetic field computation of complex threat objects e.g. guns, knives, axes etc. is often derived from field equations by using integration or differentiation methods. The field quantities are calculated to achieve an accurate solution of the models. However, existing mathematical models are not generally sufficient to determine the exact solution, since weapons have different shapes, sizes, thus multiple parameters are required to classify and identify. Hence, in the absence of any other convenient method to find an exact or approximate solution of a problem, the Finite Element Method (FEM) is preferred [80].

It is necessary for the FEM models to be consistent within the physical model, thus the following code of practice is established in this analysis:

1. A simplified model of the system is initially solved; procedures 2, 3, and 4 are then applied with this solution used as an initial check of the full 3D solution.
2. Once the model has been defined, the simplest possible model is solved for accuracy i.e. using linear materials either with unity or large relative permeability or permittivity.
3. Expected symmetry of the solution is checked. For example, examination of the field boundaries of the model is performed to check against expected.
4. The solution is checked to agree with simple line integral predictions or images, if infinite permeability approximations are applicable.

The errors produced by FEM approximations are considered after the degree of confidence has been established within the model and are considered more straightforward to evaluate than the accuracy of the model [81].

A single zone of the OACWD system, described previously in Fig. 4.2, consists of a transmitter, receiver, and a target, which was detected and classified in the zone, is modelled in the FEM software. . The various components of the model are described as follows.

5.1 TRANSMITTER MODEL

Transmitter (TX) was modelled as a part of the coupling between an external circuit and the FEM; it had a physical representation within the FE mesh, which was achieved using volume mesh. Details of volume meshing of the TX can be found in Appendix B and Appendix E.4.

The characteristics of the TX coil are tabulated in Tables 5.1 and 5.2.

There are two types of representations of conductors in FE analysis; meshed and filament. Meshed representation of TX provides coupling of the inductive behaviour of the TX than a filament representation of the coil. This is because; the geometry of the TX is duplicated within the TX coil to match the circuit element name in the external circuit-driving TX within the FEA software. The mesh size of the cell of the TX model is controlled by the MESHSIZE and MESHFACTOR commands in the OPERA 3D FEA software [82], [83] .

Meshed model of the TX is shown in **Error! Reference source not found.**.

The Fig. 5.1 shows that the TX coil surface is divided into smaller parts to calculate magnetic field, surface current on the surface of the coil, while Fig. 5.2 shows the immediate regions outside the TX coil were modelled as air regions to measure the coil flux density.

A solenoid shaped TX coil illuminated in the OACWD space and the EM field distribution from the coil during the TX ‘ON’ period is shown Fig. 5.3, where the magnetic flux density vector diverges vertically with increase in distance from the coil and illuminated the zone effectively.

5.1.1 DRIVE CURRENT ANALYSIS

The aim of the simulation was to evaluate the optimum value of the TX drive current in the OACWD zone, whilst the other parameters for this simulation remained constant as in **Error! Reference source not found.** and **Error! Reference source not found.**, the drive current variation is shown in Fig. 5.4.

It can be observed in Fig. 5.5, that the flux density of the TX for all drive currents remains the same during the TX ‘ON’ period. TX coil was then switched off after 5 μs then the RX coil was turned on and the response from the target measured. It was concluded from **Error! Reference source not found.**, that the RX current was directly proportional to the TX drive current, i.e. RX current increased as TX drives current increased. This can be represented by the following mathematical equation:

$$R_i \, \alpha \, T_i \qquad \text{Eq. 5.1}$$

Where R_i is the receiver current and T_i is the transmitter current.

However, increasing the drive current to a maximum carries associated health risk to users.

In the last 20 years; efforts have been made by the World Health Organisation's (WHO) EMF-Project and International Commission of Non-Ionising Radiation Protection (ICNIRP) to investigate the harmful effects of exposure to EM fields on public health [84]. The restriction in the ICNIRP guidelines, based on the research evidence regarding acute effects EM field exposure, protects public from harmful low frequency EMF exposure [85] It was therefore important in the design of TX coil, that the drive current must be below the maximum safety level of ICNIRP and WHO guidelines [85]. It was calculated that the maximum allowed flux density is 10 μ Tesla. It was observed from the **Error! Reference source not found.** that as the drive current was increased the flux density of the TX coil also increased simultaneously, thus when the TX current was increased beyond 0.5 A the flux density crosses the safety level. Therefore, a 0.5A maximum current drive current was chosen for the TX coil.

5.1.2 TRANSMIT PULSE DURATION ANALYSIS

The success of an OACWD system lies in the detection and classification of all target shapes and sizes within the detection space. It is known from the mathematical modelling in Chapter 3 that the time constant varies with the shape and size of the target. In the time domain EMI system, longer transmit pulse durations often block the signal response from small objects. Therefore, the objective of the following simulations was to define the pulse duration for TX coil within the safety limits.

The following TX pulse duration which were analysed

Pulse duration were

- 2, 5, 7, 10 ns

It was observed from **Error! Reference source not found.**, that when the TX pulse duration varied between 2 μs and 10 μs, the response of the RX coil was longer than the of the signatures for other TX pulse durations, i.e. in case of 10 μs TX pulse the RX current lasted another 0.3 ms. However, when a typical small target was introduced in the OACWD zone, the object signature was smaller than that of a 10 μs pulse; hence the object remained hidden in the OACWD zone. When the transmit pulse duration was reduced to 2 μs, the RX missed the early time response from the target object signature which lead to non-identification of the target, shown in **Error! Reference source not found.**. Hence in the absence of an absolute value for transmit pulse duration and in consideration to detect a wide range of target shapes and size; a TX pulse of 5 μs was used in the rest of the models.

5.1.3 TRANSMITTER COIL NUMBER OF TURNS

In the OACWD system, it is necessary to illuminate the detection space to enable the identification and classification of metal targets. The detection depth of a TX coil is directly related to the number of turns of copper wire used to make the coil. In the pulsed EMI detection method if radius *r* is the distance of separation between transmitter and target, then the EM energy reduces as a function of $1/r^2$ [86]. Hence multiple turns of copper wires were used to increase depth of detection of the coil. The aim of the simulation was to determine the optimum number of TX coil turns.

It was observed from Fig. 5.10 that, doubling the number of turns in the TX coil doubled the flux density of the coil. Although, this achieved higher detection depth and a lower power loss, an increase in the number of TX coil turns increased intra-winding capacitance. This capacitance slows down the TX switch 'off' time, which affects the visibility of smaller objects within a zone. In the absence of an absolute value for the numbers of TX coil turns, and to achieve a balance between higher TX detection depth and low power loss of the coil, 20 turns of TX coil were chosen for the rest of the simulations.

5.2 RECEIVER MODEL

The aim of the RX design was to accurately detect signals from targets within the detection space. The RX was linked through secondary flux densities from the target within an OACWD zone with the changes of flux densities from the targets being directly responsible for the detection sensitivity of the RX coil.

The design of the RX coil was similar to that of the TX and was integrated within the modeller of the ELEKTRA Opera 3D simulation software [61].

Eddy current decay time of a metal object depends on the physical dimensions and electrical parameters of the object, with smaller objects having shorter decay times [1]. Therefore, a RX coil with a smaller diameter of 250 mm and a greater number of turns than the TX would be able to detect relatively small objects. **Error! Reference source not found.** shows the RX air model of the RX coil and Table 5.3 shows the parameter values.

5.2.1 RECEIVER COIL NUMBERS OF TURN

RX Coil

There were several factors; heating effects, inte itance, and wire resistance, which were neglected in the design of t pared to TX coil. Heating effect was negligible as only relatively small currents approx. 1 mA was sensed through the RX coil. Inter-winding capacitance and resistance in the RX coil can also be neglected as thinner copper wires (0.4 mm) were used in the RX coil. Both the internal and outer diameters of the RX coil were 50% smaller than that of TX, which enables the RX coil to detect smaller metal targets within a OACWD zone in the model [69]. The characteristics of both the TX and RX coil were described in Chapter 4.

Effect of Flux Densities on Doubling the Number of Turns in RX Coil

showed the effect of flux densities on the numbers of RX coil turns. In contrary to general belief, the flux density of the RX does not increase with increased coil turns, as evident from.

5.2.2 TRANSIENT ELECTROMAGENTIC CIRCUIT

The conductors defined in the model in **Error! Reference source not found.** were included as an external circuit to the model and incorporated into the FEM, represented by a volume-meshed conductor. **Error! Reference source not found.**

showed that the circuit was current driven and contained passive elements such as inductance and resistance, which were calculated from the specified TX and RX coils.

The initial current was assumed to be zero in both coils; in order to save computing time, only a quarter of model was solved to reciprocate the results for the rest of the model. Tangential model symmetry was used with both windings (TX and RX) modelled according to the symmetry. In order to achieve the accurate simulation results of the transient model, it was necessary to define the inductance and resistance of the coil, whilst the coil capacitance was neglected, as it was minimum for the model. The methods used to calculate electrical properties of the coil are outside the scope of this chapter, and are described in chapter 4. The electrical and mechanical properties of the coils remained fixed throughout the simulation, whilst the value of the TX drive current and switching circuit changed at different time intervals in the analysis. Both variable drive and switch currents were controlled by two separate drive functions.

The drive function switch was activated after 5 µs with a 0.5 A current from 1 to 5 µs into the TX circuit to stop drive current into the TX circuit. The details of script file control codes for the circuit are given in Appendix E.6.

In order to analyse the time constant and electrical parameters for a typical weapon in the OACWD model, it was necessary to analyse a multi metallic weapon in the single zone of the OACWD system. Section 5.3 illustrates the electrical behaviour of a multi metallic gun in a single zone of the OACWD system.

5.3 TARGET RESPONSE ANALYSIS

A multi-metallic and non-metallic gun was designed to analyse the EMI response in the model; details of the design is listed in Appendix A. The gun was placed at an equal distance from the TX and RX within the single zone model of the OACWD architecture. The electrical response of the individual parts of a gun is shown in **Error! Reference source not found.**.

It was noted from the **Error! Reference source not found.**, that the induced current within the 50 mm dia. bullet had a smaller decay current time constant than other metal parts of the gun. It was also observed from subsequent analysis that the decay time of circular or spherical objects was smaller than the square and rectangular object, because in spherical or circular object, the current path was shorter. Since the wooden handle of the gun was modelled with zero electrical conductivity, the surface current on this part remained zero, which can be seen in the bottom graph (c) in **Error! Reference source not found.**. From the above analysis, it can be concluded that in a complex shaped object like a gun, the induced current decays rapidly in round curvature surface of the object and decays rate reduces when the object was embedded within another object.

It was also observed that low amounts of flux linked through the wooden part of the gun and was influenced by the flux from the metal surface, which appeared above the wooden surface. Hence flux rate of decay of metal parts of the gun is approx. 50% less than that of a bullet.

Fig. 5.1 Total RX Current Obtained after TX was Switched Off

Fig. 5.1 depicts the object signature of a multi metallic target within the OACWD zone. The object signature curve can be categorised into three different time curves, the top curve (5.15 a) represents the early time, middle curve (5.15 b) represents the intermediate time, and bottom curve (c) represents the late time curve of the object signature. Since the late time (c) contains minimal information about the target and is often contaminated with environment noise, early and intermediate time of the object signatures were used to classify targets within the OACWD zone.

5.3.1 CHANGE OF MATERIAL ANALYSIS

The object signature of a metal object within a transient EM space depends on multiple variable parameters, e.g. shape, size, permeability material of objects. In order to detect and classify objects in OACWD space, it was necessary to analyse a single parameter change of an object. In the following simulation, the conductivity values were varied according to Appendix D.7, whilst the remaining parameters as given in table 5.1 were kept constant.

In Fig. 5.16 the early time of a signature curve was analysed for classification of metals and early time data of metals is shown in **Error! Reference source not found.**17. The conductivity values of gold, copper and silver are in close range; hence the decay curves of these materials are closely spaced within the RX current decay graph. The conductivity values of targets can be found in Table 7.4 in Appendix D7.

From the above analysis in Fig. 5.17, it was concluded that objects with higher electrical conductivity value have larger decay currents than objects with smaller conductivity values. Therefore, higher conductive metallic objects are easier to detect than non-metallic objects. Utilising high speed signal processing, the decay current from metallic object with lower conductivity values compared high conducting objects can also be classified.

5.3.2 CHANGE OF SHAPE ANALYSIS

In the next variation of parameters in OACWD space, the object shapes (same volume) was varied whilst all other parameters remained constant, as in Table 5.1 and Table 5.2. The models can be found in Appendix D2.

The total surface area and volume of each target is shown in **Error! Reference source not found.**. The total volumes of geometric shaped target remained constant, whilst surface areas of targets were varied within the model.

From Fig.5.18, it was observed that geometrically varied targets could be classified during the early stage of the current decay time curve. It was observed that, although geometric models have the same volume and varied surface area; the surface current of the target after the TX is switched off depended on the surface area of the target. For example, in a smaller surface area, the surface current decay time was observed to be 50% less than the surface area in a tube, this evident from fig. 5.19. Furthermore, lower levels of flux was linked through a small surface target, which in effect induced lower surface current of less than 15 mA and less flux density in the object compared to large surface target. This secondary field of the target influenced the RX decay current. Thus, a larger target generates larger current in the RX coil and vice-versa.

This is explained graphically in Fig. 5.19.

It can be confirmed that the volume of the target has no effect on the RX current and the decay rate is thus affected by the surface area of targets.

In the Fig. 5.20, when the target material was replaced with bronze (conductivity value 8.474e+6 S/m) for the same geometric shape, although the RX current for a bronze target was 10% higher than a steel target but this value only differs by 1 µA, Hence within a range in the weapon database, these non-threat items can be excluded from the weapon database.

5.3.3 ANALYSIS OF COMMON WEAPONS

The common weapons found at security checkpoints were used in this analysis to analyse the behaviour and to determine the detection capability in the OACWD zone. The physical weapon parameters of weapons varied in the model are shown in **Error! Reference source not found.**, with all other parameters remained constant in Tables 5.1 and 5.2.

The early time of the object signatures for common weapons are shown in Fig. 5.21, from which it is evident that signatures of sharp edged weapons e.g. knife, axe, and sword, vary significantly compared to rounded edged weapons (guns). Fig. 5.22 showed that the surface current of sharp edged objects e.g. knife is approx. 100% higher than those of the rounded objects. The rate of decay of surface current within sharp edged objects generates higher secondary flux density, which can be sensed by the receiver in the zone. This enables the early time signature classification of sharp edged weapons in OACWD zone to be achieved.

In the next analysis, when materials of common weapons were changed to bronze, higher receiver current decay curves were obtained from the receiver coil, which is shown in Fig. 5.23. Bronze based metals have higher conductive than steels, hence the result showed 15% increase of receiver currents when the material of weapons was changed from steel to bronze.

It can be concluded from the analysis of both the geometry and weapon shape models that the value of the RX current remains at higher levels for highly conductive and sharp edged objects. Therefore weapons can be potentially identified in the early time of the object signature curve.

5.3.4 CHANGE OF SIZE ANALYSIS

In the next decay current variable parameter analysis, the diameter of a plate was varied in the single zone of the OACWD space. The models are shown in Appendix D4, where the diameter of a plate was varied from 1cm to 50 cm, whilst all other model parameters remained constant, as in Tables 5.1 and 5.2. The aim of this simulation was to evaluate the detection capability of varied target object sizes within the OACWD zone.

From Fig.24 it is observed that the RX current is inversely proportional to the size of the diameter of the plate and as the diameter of the steel plate was increased in 10 cm in steps, the RX current was decreased to 10% accordingly.

It can be seen from the Fig. 5.25, that the slope of decay curve of surface current density of the 10 cm plate was lower than the 1 cm plate. It is known from Faraday laws of induction that the larger the rate of decays of surface current in the target, the larger the magnetic field. Furthermore, it was observed from Fig. 5.25 that as the slope of surface current on 1 cm plate decayed at higher rate than 10 cm plate, the secondary flux density of the 1 cm plate was higher than the 10 cm plate. Hence the receiver current from 1 cm plate was higher than that of the 10 cm plate. The secondary flux densities from the targets were presented in Appendix D4.

It can be concluded that as the size of the diameter of the plate increased to 10cm, RX current for the concerned plate decreases. Hence the RX coil current was observed to be inversely related to the diameter of the plate.

5.3.5 ROTATION OF TARGETS ANALYSIS

From the time constant variable analysis database creation, it was observed that for each weapon/threat object, leads to the creation of multiple signatures for the same threat object. Therefore the aim of this simulation was to verify the signature characteristics for a model when rotated at different angles, whilst all other parameters remained constant. The target objects were rotated with following angle from TX and RX coil; 180^0, 90^0, 45^0, 30^0.

It was observed from the Fig. 5.26, that the induced surface current on the metal surface varied, when the plate was rotated at different angles. The amount of flux linked at the metal surface increased when it was faced towards the TX coil as it was rotated in the EM field. The secondary flux linked through the metal plate is shown is Fig. 5.27.

Although the values of the surface current vary when the plate is rotated at different angles, Fig.5.28 shows that the RX current remained constant for all angles of rotations. Hence, it can be confirmed that rotation of the target has no effect on the overall detection and classification in an OACWD zone, which eliminates multiple signature databases for the same threat metal object. This is a significant finding in the EMI CWD detection, the finding are incorporated in the design of OACWD system.

5.3.6 PROXIMITY OF TARGETS ANALYSIS

In order to develop the model for outdoor and indoor environments, it was necessary to measure the optimum separation distance between the TX and RX coils. The separation between the two coils is shown in the Fig. 7.15 in appendix D.6, while all other parameters kept constant, as shown earlier in **Error! Reference source not found.** and **Error! Reference source not found.**. The distance of the plate from the TX and RX was changed from 20 cm to 80 cm from midpoint vertically both towards TX and RX. The typical separation between TX and RX in OACWD zone was assumed to be 2 m.

It is noted from Fig. 5.29 that when the target was moved vertically from mid point towards the RX the rate of decay of the current curve of the RX coil decreased and the RX current became weaker than when the target object was near to the RX coil and far from the TX. The target was then moved towards TX vertically from the midpoint of the OACWD zone. The behaviour of the target when separated vertically in receiver coil direction can be represented in below equations 5.1 and 5.2.

$i = i_n$ n = 20 (x+1), where x = 0, 1, 2, 3 Eq. 5.1

$i = 0.5\, i_n$ n = 20 (x+1), where x > 3 Eq. 5.2

where i is the receiver current, n is the distance of separation between receiver and target.

The receiver current of target is given in Fig. 5.30 and shows that when the target object is moved farther away from the RX in a vertical direction towards the TX, the rate of decay of RX coils current decreases. The behaviour of the target when separated vertically in transmitter coil direction can be represented in below equation 5.3.

$i = i_n$ n = 20 (x+1), where x = 0, 1, 2, 3.... Eq. 5.3

where i is the receiver current, n is the distance of separation between transmitter and target.

It can be noted from Eq. 5.3 that receiver current remains constant when the target was moved vertically towards transmitter coil. The maximum receiver current is obtained at the same time for all target displacement. Therefore, the object signature of a target is independent of target displacement in vertical direction towards transmitter.

The variation of signature of curve can be attributed to change in surface current on the surface of target, when the target is moved 80 cm from the mid point towards the TX coil, the total amount of surface current on the surface of the target plate is greater than when the plate is 20 cm toward the TX coil. When the TX is switched off, the larger surface current takes a greater time to decay from the target surface, hence this established a lower rate of decay of the secondary field, and this secondary field of the target sensed through the RX coil. The surface currents of targets are shown in Fig. 5.31.

It can be summarised from this analysis that the shape of the object signature did not vary, when the target was displaced vertically within the OACWD zone. But the amplitude of object signature curve varied significantly when the target was moved too close to RX. Hence within a 2m separation of coil within an OACWD zone, a target was successfully identified when it was displaced vertically towards both the TX and RX.

5.3.7 CHANGE OF RELATIVE PERMEABILITY

In relative permeability analysis, the value of target object was changed to a multiple of 160 and in other target it was remained at 1, All other parameters remained constant as in Tables 5.1 and 5.2. The aim of the simulation was to determine the effect of relative permeability value change of the object in the detection and classification of a metal target object in the OACWD system. The object signatures from both targets are shown in Fig. 5.32, where it can be observed that with a relative permeability 160, the receiver current decayed sharply during the early time, and then increase in the intermediate time and finally decreased in later time of signature curve. This behaviour was observed due to the flux density of target being 160 times higher when compared with free space permeability value. This increased in flux density caused the receiver current to drop sharply in the early time curve and then increased during intermediate times and finally decreased during the late time of object signature curve. This behaviour of the target can be explained that in high permeable target the flux linkage to target surface was high during early time, hence the higher receiver current, this flux decreases as they aligned together to create surface current in intermediate time and finally as the field strength decreases the late time stage of target signature appears. However in the target with a relative permeability value of 1, the signature curve increases during the early, intermediate and late time stage of signature curve. Hence the two targets were identified during the early time of object signature curve.

The relative permeability of metal is not constant in comparison to permeability and in target, it decreases when temperature is increased in the medium. However, in this analysis temperature was assumed to be at room temperature and was constant during the analysis.

5.4 DETECTION OF AN UNIDENTIFIED TARGET

In the single zone of the OACWD system, when a threat target is detected the measured signature is stored in a database, this database is compared against signature of an unknown targets to create an alarm and real time tracking by the OACWD system. In the following example a clear distinction was made in the object signature curve of two unidentified targets: Target 1 and 2.

Fig. 5.33, shows the object signature curve of Target 1 and Target 2. The object signature curves indicated the targets classification in early time region. The amplitude difference in early time of the curves confirmed the presence of two targets in the OACWD zone. When target 1 was compared with weapon database it was matched with object signature of knife (Fig. 5.23) and the target 2 signatures matched with steel plate . Hence target 1 was classified as threat item (knife) and target 2 (steel plate) was classified as non-threat object in detection space and subsequently knife is tracked with the aid of CCTV. Analysis of multiple targets in the OACWD zones is out of scope of this thesis.

It is confirmed from the analysis that objects signature is an inherent property of metal objects in transient EM field. It depends on the shape, sizes, permeability, and material conductivity of the object. This analysis re-confirms the mathematical model for object signature in Chapter 3. Hence using the amplitude and early time decay response of object signature curve, the metal objects can be classified in the OACWD system. The flow diagram of an unidentified target in OACWD space is shown in Fig. 5.34.

5.5 ANALYSIS

The components of an OACWD system e.g. Transmitter, Receiver and the Target were designed using the Finite Element Method (FEM) and modelled according to the specification in Chapter 4. A transient electromagnetic circuit was designed using FEM and the circuit was externally linked with the transmitter, receiver and the target. Both the transmitter and receiver models were meshed to calculate the flux density and current inside the coils. The important parameters for transmitter and receivers e.g. transmitter drive current was modelled and analysed to limit the maximum flux density of 10 μ Tesla as specified in WHO, ICNIRP guidelines. The numbers of turns of wire needed for transmitter and receiver was modelled to analyse in FEM. A typical response for a multiple material targets was analysed for both metallic and non-metallic parts in a transient electromagnetic field. A target was analysed for change of material, permeability, shapes, sizes, rotations, and proximity of the target within the OACWD zone, in this chapter. The variable parameters e.g. material conductivity, permeability, shapes and sizes of target object was analysed and the results of these analysis is presented below.

5.5.1 MATERIAL VARIATION

In the case of target material change (conductivity values) analysis, in the single zone of the OACWD, whilst the rest of the parameters remained constant, it was evident that the amplitude of the receiver decay current curve varied directly with the conductivity values of the target, i.e. amplitude of the receiver current was higher for higher conductive object due to the object excitation after the transient magnetic field was switched off; generated higher magnetic flux and the receiver coil sensed this field. The targets are classifiable within the early time in Fig. 5.16 and 5.17. Therefore, for uniform detection of different materials, the early time detection of objects is recommended in the OACWD system.

5.5.2 SHAPE VARIATION

In the decay time constant analysis, the geometric shapes of the object were varied, whilst the volume of the objects and all other parameters remained constant. The geometric shape of a target was found to be classifiable within the early stages of the decay time constant (object signature) curve. Cone, cube, cylinder, sphere, torus, and tube geometric shapes were analysed with the object signature remaining constant with amplitudes variation for different objects in early time stage. All the targets in the analysis were therefore classified during the early time object signature; this was due to small surface area of objects, which caused the current to decay at a higher rate than large surface targets. It was observed that the cone, cylinder, torus, and tube had a similar object signature curve and only differed by signature amplitude when compared to the cube or the sphere. This was due to the surface area of the cone; cylinder, torus and tube being similar to that of the cube and sphere. The objects are classifiable when shapes varied and for closely similar shapes objects e.g. cylinder, tube, early time response was observed along with amplitude of the object signature for classification of targets. But when the material was changed to bronze from steel, both the amplitude and shapes of object signature varied accordingly, this is due to higher conductivity values of bronze than steel. In the case for varying geometric shapes with different material, e.g. steel or bronze, the rate of change of early time response was used for classification of the target. In homogenous objects, where the mass was uniformly distributed over the object surface, the objects were cluttered together than non-homogenous objects, where the masses were non-uniformly distributed, e.g. cone. But in both types of objects were analysed during the early time of object signature curve. The common weapons (gun, spear, knife, axe, and sword) were analysed; it was observed that the weapons with sharp edges have similar object signatures than the other objects. The weapons were classified during the early time of object signature; this is illustrated in Fig. 5.21 and 5.22. When the materials of weapons were changed to bronze, the object signature curve varied with amplitude and shape of the curve remained constant, this is illustrated in Fig. 5.23. Therefore, weapons of same shapes with different material can be classified during early time of object signature curve by the amplitudes.

5.5.3 SIZE VARIATION

In the next analysis of target parameters in OACWD zone, the diameter of a steel plate was varied while rest of the parameters remained constant. The shape of the object signature curve remained constant while amplitude of the curve decreased on increase of diameter of the plate. It was because, on a larger surface area, the rate of change of surface current on the plate was small compared to small objects; hence the receiver current for large objects decreases. This is evident from Fig. 5.25; the surface current of a 10 cm plate is 10 times larger than 1 cm plate. All the objects in the analysis were classified on amplitude of object signature curve in early time decay of the curve.

5.5.4 TARGET ORIENTATION INSENSITIVITY

In the next analysis a target was rotated with following angles in the OACWD zone: 30^0, 45^0, 90^0, and180^0 while rest of the parameters remained constant as in Table 5.1 and Table 5.2. The receiver signal was observed to be unaffected by the rotation of the plate in the OACWD zone. This was because the equal amount of flux was linked through the surface of the plate, when it was rotated within OACWD zone; hence the receiver current was observed to be constant for all rotations of the plate. Therefore, it was observed that in the OACWD EMI system, target rotation has no impact on the target detection and classification in the detection space.

5.5.5 PROXIMITY VARIATION

Proximity of the target in the OACWD zone is an important factor in target classification in the OAWCD system. In this analysis, the target was placed in the middle of the OACWD zone at 1m from both TX and RX. The target was moved at 20 cm, 40 cm, 60 cm, and 80 cm towards both transmitter and receiver vertically within the zone, while rest of the parameters were remained constant. It was observed that the target was classifiable when it moved up to 80 cm towards TX and 60 cm towards RX. The shape of object signature curve was observed to be similar while, amplitude of the curve was different. But when target was moved very close (80 cm) towards receiver, the amplitude of object signature curve was found to be small but shape of the curve remains same as compared when moved toward transmitter, this was believed due to less amount of flux linked through the target by transmitter.

Hence it is recommended using additional transmitter in the OACWD zone for uniform detection of targets within the zone.

5.6 SUMMARY

In this chapter, targets were analysed for variable parameters in the OACWD zone. The successful estimation and comparison of these parameters lead to classification of metal objects in OACWD system. The signature curve of targets in these analysis were plotted against time, from the behaviour of the curve, it was divided into three different stages namely; early time, intermediate time, and late time stages. From the analysis, early time stage was used to classify these targets. The digitized values of the signature curve in early time stage are attached in the appendix of this thesis, which is utilised to classify targets. The object signatures obtained in this analysis can be used to build a weapon database, which can be integrated with OACWD control system for creation of alarm and activation of CCTV system for real time tracking of threat objects in detection space. Weapon database is created by the digitised data obtained during the early time of the signature curve. The database upgrades itself as the new threat objects detected in detection space. The next chapter discusses the results obtained in this chapter.

CHAPTER 6 : DISCUSSION

Most commonly used detection methods are portal based techniques, involving EMI and imaging methods. But these systems cannot be efficiently used in areas with a large crowd, most commonly encountered near the security checkpoints as these systems raise a large number of false alarms involving non-threat items such as pens, key rings. Therefore, it is important to design and develop a system that can reduce false alarms and screen a large number of people efficiently at security establishment. The OACWD system described in this thesis can be implemented as a pre-screening method to detect threat objects at security checkpoints.

Different types of weapons found at the security establishments vary in: shape, size, rotation, material, permeability etc. Thus, in order to detect and classify weapons in OACWD system, it is essential to analyse the parameter variables, which contribute to the classification of each weapon. A multi zone OACWD array was designed with transmitters and receivers array. A command control algorithm is developed to integrate different parts of the system for detection and classification of a metal target. Data collection method as shown in Fig. 4.7 improves the data acquisition for the OACWD system. Unique design of zone alarm system shown in Fig. 4.8 pinpoints target location and improves traffic flow in open area environment. The zone architecture of the OACWD design, assist tracking of individual carrying threat objects in detection space.

A single zone model of the OACWD system was modelled in electromagnetic simulation software, the model consists of a transmitter and receiver coil. The physical and electrical parameter of transmitter coil is listed in table 5.1 and 5.2. The FEM model of transmitter coil is shown in Fig. 5.1 and 5.2. Upward divergence of magnetic flux (shown in Fig. 5.3) from solenoid transmitter coil illuminates the OACWD detection space. The MESHSIZE and MESHFACTOR embedded commands were created within TX model to measure surface current and field accurately on the surface of the FEA TX coil. The transmitter coil is switched on for 5μs, induced surface current appears on the surface of metal target in detection space upon the termination of transmitter drive current, the induced current then generates secondary magnetic field, and is captured by receiver coil in the OACWD zone. The effect of longer transmitter pulse is analysed in Fig. 5.9, from the analysis it was evident that pulses longer or shorter than 5µs often block or miss target response in detection space. Therefore pulses of 5 µs were recommended for transmitter coil.

Transmitter drive current is modelled according to WHO and ICNIRP guidelines, which limits the maximum allowable EM radiation in open area environment to 10 µT. A mathematical relation between transmitter drive and receiver current is obtained in eq.5.1; this relation states that receiver current is directly proportional to transmitter drive current. The safety analysis of transmitter drives current in shown in the Fig. 5.7, and it is evident from the analysis, that 0.5A was recommended for the OACWD transmitter to operate within ICNIRP & WHO safety limits.

It was evident from the analysis of transmitter coil turns in section 5.1.3 that EM energy of transmitter reduces as a function $1/r^2$, where r is distance between TX and target within the OACWD zone. It was evident from Fig. 5.10 that increases of TX coil turns increases TX flux density, which achieves greater detection of depth of target. However increase in TX coil turns increases inter-winding capacitance of the coil, which slows down TX switch off time. It is known that OACWD space is divided into smaller zones with TX and RX array, hence in order to achieve optimum target detection depth within a zone 20 turns of TX is recommended.

Similar to transmitter model, a FEA model of receiver coil was modelled with small diameter compared to transmitter. The unique sensor design within a single zone of the OACWD model detects small targets within the zone. Both the internal and outer diameter of the RX coil were 50% smaller than that of TX, this enables the RX coil to detect smaller metal targets with the OACWD model. The receiver model and parameters are shown in Fig. 5.11 and table 5.3 respectively. It was found from the analysis in section 5.2.1, that smaller RX coil size with higher turn achieves target sensing within a OACWD zone.

Both TX and RX coil parameters were linked together to create a transient electromagnetic circuit in the FEM software, shown in Fig. 5.13. The circuit consists of coil inductance; resistance, windings, and transmitter drive current. The circuit parameters are calculated from eq. 4.1 and 4.2. The transmitter drive current is executed by an algorithm written into software to create a transient electromagnetic field within the single zone of the OACWD model. The details of the script file control codes for the circuit are given in Appendix E.6. Initially a single parameter was varied across the zone and the resultant output obtained from the receiver, known as object signature, was compared with the weapon database for classification of complex metal weapons. Object signature curve obtained in the zone explains the behaviour of metal weapons in transient electromagnetic field environment.

The object signature of a metal target is unique and depends on multiple variable parameters such as shape, size, and permeability of material objects; therefore, it is essential to analyse single parameter change of the metal target. In a real world scenario, the threat objects often have both metal and non-metal parts, which makes it important to test the viability of the system in detecting threat objects that consist of both metal and non-metal parts. A gun made of multi metal and non-metal components was successfully analysed in Fig. 5.14. After analysis, it was observed that the late stage of object signature is often contaminated with noise, so the gun can be detected only during early time stage of object signature.

In the first of metal target parameter analysis, the following metal targets were analysed; gold, copper, silver, bronze, tin, aluminium alloy, and steel. The conductivity values for these metal targets are listed in appendix D7. It is evident from the object signature curve that targets are classifiable during the early time of the object signature curve shown in Fig. 5.16. It is concluded from the analysis that higher conductive metal targets have larger the decay current and the materials demonstrate different current decay curve during the early time of object signature curve.

In the next analysis, the object shapes (same volume) were varied whilst all the other parameters remained constant, as in table 5.1 and 5.2. It was observed from the analysis that metal object with circular surface area; the surface current decay time was 50% less than the surface area of a tube, shown in Fig. 5.19. Furthermore, low amount of flux was linked through a smaller surface target, which in effect induced low surface current of less than 15mA and less flux density in the object compared to large surface. The secondary field of the target influenced the RX decay current. Thus, a larger sized target generates larger current in the RX coil and vice-versa. It can also be confirmed from Fig. 5.19 that volume of the target has no effect on RX current and the decay rates thus affected by the surface area of targets. When the material is changed to bronze from steel, RX current was observed 10% higher in amplitude than steel, since the early decay time has not changed and the material change only affected the amplitude of the curve, hence multiple similar targets could be excluded from weapon database.

It is observed from analysis of common weapons such as knife, axe, and sword, that surface currents around edges of weapon are higher, which result in higher secondary flux density, which can be sensed by the receiver in the OACWD zone. This enables the signature classification of sharp edged weapons in the OACWD zone.

In the next analysis, when the diameter size of circular target was increased from 1cm to 50 cm, it was observed that RX current is inversely proportional to size of diameter of plate, as the diameter of the steel plate was increased in 10 cm in steps; the RX current is decreased to 10% accordingly. Hence, in the OACWD zone early time of smaller diameter circular targets happens sooner than in larger diameter circular targets.

When the targets were rotated at different angles (180^0, 90^0, 45^0, 30^0), although variation in surface current was observed at each angle of rotation, but most importantly RX current remained same for all angles of rotation. These findings confirm that rotation of metal targets has no effect on detection and classification of metal targets in OACWD zone. This is significantly different from other portal-based 2D-imaging system, where detection of a threat object is dependent on target orientation. In portal based systems a skilled operator is required to classify threat and non-threat objects as sometimes rotating the object can make threat object appear as non-threat object on a 2D-screen. Since in OACWD system, detection is not sensitive to target orientation, it eliminates the need for a skilled operator.

In the proximity analysis of targets, the target is moved in both towards and away from RX coil. When the target is moved vertically from mid point towards the RX, the rate of decay of current curve of RX coil is decreased and the RX current is weaker than when the target object is near to RX coil. The finding is represented in eq. 5.1 and 5.2. Similarly, when the target is moved farther away from the RX in a vertical direction towards the TX, the rate of decay of RX coil current decreases. The behaviour of the target when separated vertically in TX coil direction is represented in eq.5.3. The object signature of a target is independent of target displacement in vertical direction towards transmitter. The variation of signature curve is attributed to change in surface current in the target, which is shown in Fig. 5.31. It can be summarised from the proximity analysis that the shape of the object signature did not vary, when the target was displaced vertically within the OACWD zone. But the amplitude of object signature curve varied significantly when the target is moved close to RX. Hence within a 2 m separation of coil within an OACWD zone, a target was successfully identified when it was displaced vertically towards both the TX and RX.

In the relative permeability analysis, when the relative permeability value is changed from 1 to 160, the receiver current decayed sharply during the early time, and then increases in the intermediate time and finally decreased in later time of signature curve. The behaviour of the target can be explained that in high permeable target the flux linkage to target surface was high during early time, hence the higher receiver current, this flux decreases as they aligned together to create surface current in intermediate time and finally as the field strength decreases the late time stage of target signature appears. However in the target with a relative permeability value of 1, the signature curve increases during the early, intermediate and late time stage of signature curve. Hence the two targets were identified during the intermediate time of object signature curve.

In the analysis, object signature curve was used for target detection and classification. The object signature curve is categorised into three different time stages namely, early, intermediate, and late time. The digitized data from all the stages are analysed for weapon detection; early time digitized data were found to be most suitable for detection and classification of metal targets. The digitized data from targets were analysed and target rotation was found not to affect signal detection and classification, whilst digitized early time data of rest of variable parameters of targets were stored in the weapon database to classify metal targets. The catalogue based weapon database saves data retrieval time of large weapon database, while remote operator interface makes the optimum utilization of space at security check points in open area environment.

6.1 WTMD PORTAL VS OACWD SYSTEM ANALYSIS

The most widely used CWD system available at security checkpoints is portal based Walk-Through Metal Detectors (WTMD). Tampere University Technology has demonstrated that in the WTMD system, when a person walks through the portal, magnetic field from the person's body affects the detection capability of the threat objects carried by the person [87]. The working principles of the EMI based continuous wave WTMD system as follows;

WTMD target classification system is shown in Fig.6.1. In this classification system, the sensor feeds the data to the receiver coil, the signal is then characterised, sampled and feature is extracted. Then the signal is classified and post processed to send output to WTMD for classifying the objects as threat or non-threat. Both OACWD and WTMD systems are based on EMI, where change in magnetic field is observed on introducing an object in the system. Both systems have transmitter and receiver coils to generate magnetic field and receive response from the target in detection space respectively. There are two different types of systems namely: Continuous Wave (CW), and pulsed EMI method. While WTMD system is based on CW method, OACWD system works on Pulsed EMI.

The CW system works by inputting varied frequency pulses to the transmitter, whilst pulsed system works by inputting low frequency pulse to the transmitter. The source is switched after certain interval in pulsed system to activate receiver coils and detect the target. As the frequency is changed in CW system the system suffers from skin effect, which can hinder the detection of threat object as the surface current penetrates below the surface of the target making it difficult to detect the target. Since CW system works on varied frequency ranges, it has higher signal to noise ratio compared to pulsed EMI system.

Since majority of portal based EMI systems work on CW technique, the WTMD system under analysis here is modelled in a CW-based dipole model system. This system works by modelling the primary field into a small source known as dipole. When a target is introduced into the system, eddy current is induced on the metal target, and correspondingly a voltage is induced in the receiver coil. The WTMD under analysis has 16 coils in total, eight transmitter coils are located on one side of the portal and the other eight receiver coils are located on the other side of the portal.

The coils are designed such that they are not aligned with each other, to reduce signal to noise ratio. Transmitter coil operates within the frequency range of 8 kHz to 14 kHz, this differentiates between the transmitter coils. The WTMD model along with coil geometry is depicted in Fig. 6.2. In this system, different target objects such as coins, knives, keys, guns etc. are modelled and their tensor values are calculated through inverse residual algorithm. These values are then stored in a library for target object detection and classification [88].

WTMD system relies on eigen values of the metal objects introduced into the detection space whereas the OACWD system relies on the object signature of the metal targets. Fig. 6.3 and Fig. 6.4 display the detection of various threat and non-threat target objects in WTMD portal and OACWD system respectively. In OACWD system the commonly used threat metal items are successfully identified in early time of the object signature curve, whereas in the WTMD system the threat objects are identified based on phase angle and magnitude of eigen values. Since only early time data of object signature is considered in OACWD system as opposed to the total receiver data in WTMD system, the target classification in OACWD system is quicker and requires a smaller weapon database.

One of the limitations in the WTMD system is that, when multiple targets are introduced in the detection space, eigen values and inversion algorithm, used for target object detection and classification becomes sensitive to target location detection. Also, Detection capability of this system is poor when the target is placed close to the floor or ceiling as the concentration of the coils at the very top and bottom of the detector is lesser compared to the concentration of coils present on the side of the portal. Unlike WTMD system, in OACWD system, target detection is uniform across each OACWD zone, such that all targets are effectively detected within each zone of the system. Since transmitter in each zone is sequentially switched ON, transmitting signal in one zone does not affect the signal in the other zone [88]. Also, The WTMD detection algorithm depends extensively on its database and the signal classification is hampered if there are lesser number of entries in the database, whereas OACWD system database updates itself continuously to incorporate new threat objects.

WTMD system also suffers from body effect, a phenomena where eddy current flows on the body of the person entering the WTMD portal, this creates a secondary magnetic field, which interferes with the primary WTMD magnetic field. This effect masks the detection of small threat objects in the detection space. However, OACWD system does not suffer from body effect phenomena, making it suitable for threat object detection in open area.

Future research for improving the sensitivity of WTMD system aims to implement curve fitting algorithm as used in OACWD system (as described in this thesis) instead of single point algorithm [88]. This suggests that OACWD detection, using curve fitting algorithm is more efficient in threat object detection.

CHAPTER 7 : CONCLUSION AND FUTURE WORK

The following challenges were identified in this research: ability to detect and classify threat and non-threat items in an open area environment at security establishment, reduction of false alarms in the current weapon detection technique, finding a reliable method to detect and classify metal objects, methods to improve reduce threat objects database, finding suitable method for EMI weapon detection, developing an algorithm for weapon detection and classification, implementing uniform magnetic field across all zones of the detection space and locating receiver and transmitter coils for optimum working of the system, and designing a safe system which improves customer queues at security check points.

In this thesis, current electromagnetic (EM) based detection technologies were reviewed. Following the literature review, time domain transient pulse detection method was identified as a suitable method for the design and development of OACWD system. The method was applied to derive a mathematical equation (time constant / object signature) for object detection and classification using fundamental EM field equations within an OACWD space. This mathematical derivation was further utilised for the development of a time stepping algorithm for the creation of a transient EM field in the detection space. A multi zone OACWD architecture was designed with multiple TX and RX sensors. A 3D finite element model of a single zone was designed in the FEA electromagnetic simulation software. Finite element model of TX and RX coil and transient electromagnetic circuit was developed. Time stepping algorithm was developed and applied to an OACWD zone. Various 3D finite element models of target weapons were developed. The target in the EM field was analysed in a zone of OACWD space, after the field was switched off. The targeted weapons were analysed for the following characteristics in transient FEA model; material, shape, size, rotation, proximity from TX and RX, relative permeability. The secondary field from target-induced current in receiver coil, known as object signature of the target, is unique for each target. This object signature was used for classification of targets in the OACWD system. The object signature was analysed with early, intermediate, and late time stages for target detection and since the early and intermediate stages were found to contain object signatures, the receiver current for these stages was digitised and stored in a weapon database; used to match target for identification within the OACWD system. The weapon database can be upgraded to store object signature of new metal targets. The results of finite element models, simulation, and analysis were discussed in chapter 5 and 6.

The new OACWD model is designed to be used primarily for pre-detection of threat objects at secured establishments. The system can be deployed at the security establishments without the need for trained operators and security personnel. The new OACWD system focuses on detection of common threat objects with minimum inconvenience to people at security establishments or checkpoints.

This new system will help to identify potential threat items by analysing the decay time constant of different metal objects. The multi-zone sensor array in detection space provides location information of threat metal objects, which can be tracked with the assistance of CCTV in real time. Selective use of object signatures for detection of target would enable the restriction of weapon database size, which in turn would be beneficial for data reading and writing to database, hence reducing the time of target detection and classification in the OACWD system.

The public safety at secured establishment is a major challenge these days. The new OACWD system classifies threat metal weapons, and this will improve the security of establishments and safety of public in public spaces. In addition to this, the system finds its usefulness where chances of security undermine by the presence of security equipment or agents.

This system can be successfully developed for pre-screening of individuals carrying threat items at security checkpoints. This system is easy to use as operator intervention is not required. Further, the system consists of a threat item database, which can self-update by including new threat items. This database would be capable of sharing its resources with other CWD detection system in a security establishment. As this system is designed for pre-screening of individuals, it can be further integrated with law enforcement agencies to catch suspected individuals carrying threat items at secured checkpoints. The unique design of this system helps to save space, reduce queues and remove bottlenecks at security checkpoints. Use of early time object signature improves the speed of threat object detection, as less data from object signature data is required to make a comparison. Also, as no image is processed and stored, the system improves data processing and storage requirement for the weapon database. The system can be further integrated with CCTV technologies to track individuals carrying threat objects in real-time.

The system may also be used in detecting:

- Geographical boundary crossing and entrance to secured establishments (airports, train stations, military and government offices)
- Prisoners in a prison environment
- People carrying metal weapons to schools, colleges, and universities

The research could be further implemented in development of future OACWD system, which is described in next section.

7.1 FUTURE WORK

The research in to the development of an OACWD system has indicated a promising future in detection and classification of metal objects on the basis of the secondary decay time constant in a transient electromagnetic field environment. The following future work has been recommended.

7.1.1 PHYSICAL MODEL OF THE OACWD SYSTEM

The following works have been identified as future work in this research

(a) Development of transmitter and receiver coil

The transmitter and receiver coil need to be developed according to the design specification in chapter 4 and analysed.

(b) Development of transmitter and receiver sensor for the OACWD zone

The sensor needs to be developed from the OACWD model, multi-zone array architecture described in chapter 4.

(c) Development of weapon database by the use of Oracle or SAP database software.

A weapon database containing all known target signature needs to be developed using Oracle or SAP database architecture. This database would be updated when an unknown target is detected in a real-time basis.

(d) Development of Data acquisition system for multiple sensors in the OACWD system.

A high speed data acquisition system needs to be developed to perform data acquisition and collect background reading and subtract background reading to gather information of the target decay response for data analysis

(e) Development of target matching algorithm for database matching

A target matching algorithm needs to be developed using the simulation model described in chapter 5, where the algorithm could be successfully implements for target object signature classification.

(f) Implementation of fuzzy logic and pattern matching algorithm to detect unclassified target object in weapon database.

In addition to target matching algorithm, fuzzy logic and pattern matching algorithm could be implemented for successive prediction of unknown targets in OACWD detection space.

(g) Implementation of CCTV monitoring system in the OACWD system.

CCTV monitoring system needs to be implemented with an automatic tracking algorithm to track threat targets in the OACWD detection space in real time, The video from a CCTV system would be superimposed on the top of a OACWD multi-zone array in a PC and would be tracked by a remote operator and subsequently, when a threat object is detected in the system, an alarm would be generated to track the individual carrying the threat object as shown in Fig. 4.8 in chapter 4.

7.2 AUTOMATIC TARGET DETECTION AND CLASSIFICATION

Automatic target identification is a key technology for future people screening at security checkpoints. The sensor data obtained from the OACWD system is integrated into a neural network analysis technique to detect new target and classify automatically. The adaptive neural networks are trained to classify targets in the CWD space [89]. An error back propagation supervised learning technique can be used to train the network. Common threat object signature data is inputted to network and compared till final output is calculated. Thereafter a decision making process can be enabled to evaluate the successful implementation of learning algorithm and if necessary further iteration can be made to achieve classification of threat object signatures [89].

7.3 WIRELESS LOCATION SENSING TECHNOLOGY

The next generation of OACWD system can be integrated with wireless location sensing devices. Wireless sensor networks within the OACWD system would combine sensor data with location data to provide real time location information of threat objects in a detection space. The system consists of a low power 802.15.4 standards based mesh technology with multi-channel time of flight measurement to enable a new real-time location technology known as Time Synchronized Position Time of Flight (TPST). The TPST location system is based on IEEE 802.15.4E protocol. In this system, no communication wires are required, as installations are non-disruptive and are suitable for use in both indoor and outdoor environments. No site surveying is required as self-healing slotted channel hopping mesh automatically adapts to a changing RF environment [90]. The system transfers location data along with sensor data securely to a remote server for classification of targets in detection space.

7.4 INTEGRATED SYSTEM

The OACWD system developed in this research can be integrated with other screening devices such as Biometrics Scanners, Imaging Scanners etc. for successful implementation of robust public safety system at security checkpoints. For example in an integrated system, biometric scanners along with trusted traveller scheme can be implemented to verify the identity of the individuals before entry into the secured areas [90]. The OACWD system employed along the corridor of the secured areas coupled with behavioural tracking equipment assists preliminary screening of individuals in the detection space. After the preliminary screening, the suspected individuals could be taken for further screening for explosives and image screening for objects hidden within the person’s body. This integrated system eliminates potential threats and streamline people flow at the secured checkpoints.