RAY-TRACING METHODOLOGY FOR THE DETECTION OF MATERIAL STRAPPED TO HUMAN TORSO USING MICROWAVES

Y.H. Teo¹, W.K. Chiu¹, X.M. Wang²

¹ Department of Mechanical and Aerospace Engineering, Monash University, Victoria 3800, Australia
² CSIRO Sustainable Ecosystems, Highett Victoria 3190, Australia

ABSTRACT

The aim of the project is to investigate the development of a rapid detection method which could be used to obtain the shape and dielectric contrast of a foreign object strapped to human torso in two-dimensional space. Microwaves and geometrical-optical method are proposed to reconstruct geometry and reflection coefficients of human torso as well as the foreign object. The results obtained show that distinctive reflection coefficients can be observed when foreign object is strapped to human torso, thus providing possibility for this foreign object to be detected. Reconstructed features of an elliptical model under testing using computational data are in good agreement with the analytical features of model, except at patch edges. Accuracy of reconstructed results can be enhanced through appropriate modifications to the measuring system and reconstruction algorithm.

1 INTRODUCTION

Human body has always been a popular smuggling medium within the group of highly-priced and low-in-quantity contrabands such as narcotics and explosives. One of the most common conventional countermeasures is narcotics- and explosives-sensitive sniffer dogs (Anon 2007a). The problem with this method is that reliability is very much dependent on the individual performance of attention level of each canine.

In order to maintain consistency and reliability of contraband scanning, various portals utilising different technologies have been marketed and are being tested at security checkpoints (Anon., 2007c), airports (Anon., 2005b, 2007d), and ferry docks (Anon., 2007b). Currently, portable systems in the market utilise four different technologies, (a) micro-wave (represented by People Portal II by EMIT Technologies (Yinon, 2007)), (b) millimetre-wave (represented by ProVision system produced by L3-Communications (Anon., 2008b)), (c) terahertz-wave (represented by model T4000 produced by Thruvision (Anon., 2008c)), and (d) x-ray backscatter technology (represented by the SmartCheck system by AS&E (Anon., 2008a)).

However, these systems can only detect differences in geometry or spatial-distribution of dielectric-properties of the object-under-testing (OUT). There is no rapid detection method available which allows for the detection of geometry and dielectric contrasts of an OUT at the same time.

The aim of the project is to investigate a rapid detection method to obtain the shape as well as the dielectric contrast of a foreign object with respect to human torso. A background search for viable technology and reconstruction technique has been carried out. Between the groups of micro- and macro-scale methods, macro-scale methods were preferred in comparison to the micro-scale methods, due to the low reliability in measuring vapour pressures of illicit materials and the inability to pinpoint the location of illicit material strapped on human torso. Within the group of macro-scale method, microwave was then chosen as the desired technique within the macro-scale methods, after costs, health concerns and quality of the reconstructed images were considered.

At the same time, geometrical optical method was adopted to reconstruct geometry and the surface dielectric properties of OUT, based on the small ratio of wavelength to OUT size, and hence insignificant diffraction effects. The sum of electromagnetical phenomena as a result can be deduced through the determination of electromagnetic ray paths and the associated intensity and polarization (Born & Wolf 2002). The study replaces human torso with an elliptical cylinder (Takuma et al 2006) for consistencies in temperature, surface geometry and surface material distribution. In addition, black powder (Watters et al 1995) had been selected to represent illicit patch and is replaced with silicone rubber (Johansson & Robertsson 2007) for availability and safety reasons.

2 BACKGROUND

2.1 Microwave

The analytical set of equations which describe microwave phenomena, i.e. the Maxwell's equations (Ramo et al 1994), is presented below:

\[
\begin{align*}
\nabla \cdot D &= \rho, \quad D = \varepsilon E \\
\nabla \cdot B &= 0, \quad B = \mu H \\
\n\nabla \times E &= -\frac{\partial B}{\partial t} - M \\
\n\nabla \times H &= -\frac{\partial D}{\partial t} + J
\end{align*}
\]

368
where $D$ and $E$ are the electric flux density and electric field, respectively. $\varepsilon$ represents permittivity of material while current density is defined as $J$. $\rho$ is the electric charge density. $B$ and $H$ are the corresponding magnetic flux density and magnetic field. Permeability of material is represented by $\mu$, and $M$ denotes a fictitious magnetic current. The first two equations are continuity equations that serve as boundary conditions. The latter two equations are Faraday’s law in electric and magnetic fields, which denote that electric and magnetic fields interchange between each other as waves propagate. Magnitudes and phases of electrical scattered field are used to characterize an OUT with unidentified dielectric properties.

### 2.2 Geometrical optical method

The geometrical optical method has been employed to compute acoustic (Agarwal et al. 2007), ultrasonic (Baskaran et al. 2005), and electromagnetic (Grubisic et al. 2006; Tan et al. 2008) scattered fields. Particularly, Khoh et al. (2004) have reported good agreement between the exact and reconstructed models using the geometrical optical method.

![Figure 1 General procedure of reconstruction](image1)

The general procedure for inversely determining the geometry and reflection coefficients is coded in MATLAB Version 7.1, and flow chart is shown in Figure 1. The process (see Stage 1 in Figure 1) starts with creating a pencil of rays and the reflected ray paths as well as the time delays due to the guessed geometry are calculated using the Law of reflection and Snell's Law. At the same time, Fourier Synthesis is used to transform frequency-domain reflection signals obtained from computational and experimental environments to time series. The guessed geometry is then corrected based on time delay differences found between calculated and transformed time series. Once the geometry corrections have been minimised, electrical wave magnitudes at material interface(s) are backward projected to determine the local reflection coefficients.

The backward projection method (see Stage 2 of Figure 1) for wave magnitudes is highly dependent on the surface curvature of OUT. A generalized form of the thin-lens equation is introduced to include normal and oblique wave-incidence cases (Lee et al. 1982): the divergence factor (DF) is defined to determine the reflected ($M_3$) and refracted ($M_2$) fields through

$$M_2 = M_1 (DF_2) T e^{-jk_2 b}$$

$$M_3 = M_1 (DF_3) T e^{-jk_3 c}$$

where $M_i$ is the incident wave at OUT surface, $DF_2$ and $DF_3$ are the refracted and reflected divergence factors, respectively. $T$ denotes reflection coefficient, while the transmission coefficient is represented by $T$. $k$ is the wavenumber of a particular material. The distance between measuring position and the wave-impinging surface of OUT is defined as $b$ while $c$ refers to the distance between measuring position and the wave-impinging surface of OUT, see Figure 2.

![Figure 2 Schematic of ray impinging on a curved surface](image2)

In two-dimensional space, definitions of $DF_2$ and $DF_3$ are

$$DF_2 = \frac{H_{1f}[k_2(R_2 + b)]}{H_{1f}[k_2(R_2)]}$$

$$DF_3 = \frac{H_{1f}[k_1(R_3 + c)]}{H_{1f}[k_1(R_3)]}$$

where $H_{1f}[]$ is the Hankel function of the first order, zeroth kind. $R_2$ and $R_3$ are the principal radii for curvature of refracted and reflected wavefront, respectively. These principal radii are dependent on the principal radius for curvature of incident wavefront, as well as the surface curvature of OUT and wave incident.
angle. Definitions of these principal radiuses have been reported in (Kouyoumjian 1965; Deschamps 1972; Rudge 1983).

2.3 Numerical simulation method

To reconstruct the geometry and dielectric contrast of OUT, a forward method is required to generate scattered field around the OUT. COMSOL is used as the finite element package to model microwave propagation in free space (see Figure 3). For each set of measurements, one antenna acts as the wave transmitter, while all antennas (including the transmitting antenna) collect magnitudes and phases of electrical scattered field.

In order to reconstruct a time pulse with minimum pulse width, frequency sweep with the maximum available frequency bandwidth is used, i.e. [7.1GHz to 13GHz]. Sizes of frequency steps and mesh are the two principal variables that control the stability and accuracy of simulated results. Nominal frequency step size was chosen to avoid errors in the phase unwrapping process, which in turn leads to inaccurate reconstructed time delays. Mesh size is important to avoid aliasing in the numerical analysis. Through trial and error, the nominal mesh size was set at one-sixth the wavelength at 10GHz.

2.4 Experimental method

Due to hardware limitations, a pair of horn antennas (instead of thirteen shown in Figure 3) with aperture size 75.2mm x 75.2mm (3in. x 3in.) was used for transmitting and receiving waves. Therefore, errors caused by misalignment of antennas would be increased significantly due to the regular shifting of antennas during measurements. The scanning method was hence modified and 85% reduction in total number of alignments was achieved. In the new scanning method, the transmitting antenna (Tx) was fixed while both the receiving antenna (Rx) and OUT were free to rotate. Rotation of OUT was guided and controlled through a rotating base (see Figure 4).

An Anritsu 37247D vector network analyser (VNA) was used to measure the magnitudes and phases of received signals. A controlling computer was employed to control this send-receive-savedata process through a GPIB interface as well as a GUI created using Labview version 6.1. Human torso was represented by a water-filled acrylic tank for similar dielectric properties between water and human body (Semenov et al 1999).

3 RESULTS AND DISCUSSION

In Section 3.1, a uniform-thickness layer of silicone rubber was wrapped around the human torso cylinder. Computational and experimental results were investigated and compared to the analytical values to ensure that good agreement can be achieved. Section 3.2 then studies the reconstructions of OUT geometry and reflection coefficients based on COMSOL and analytical results. The representations of human torso in these two sections are different: human torso in Section 3.1 has an elongated-circular cross section (see Figure 5) while the human torso in Section 3.2 has elliptical cross section. The elongated-circular cross section was created due to experimental hardware limitation: an acrylic water tank was fabricated to have elongated circular cross section, rather than having an elliptical cross section.

The approximation of human torso in elongated circular shape will not pose a problem for comparison of results between Sections 3.1 and 3.2. This is because the purposes for conducting work presented in Section 3.1 are to ensure good agreement among computational, experimental and analytical results and to confirm that contrast in reflection coefficients can be used as indicators for determining the existence of foreign object.

3.1 Uniform double-interface model

As shown in Figure 5, wall thickness of acrylic tank was 8mm and a silicone layer of 30mm was wrapped externally around the water tank. However, rigidity of silicone layer prevents the layer to maintain the cross-sectional shape of tank (see Figure 6, air gaps were shaded). To remove unwanted air gaps, the model was wrapped and vacuum sealed with a thin sheet of nylon. The undesired scattered waves generated by acrylic and nylon layers were eliminated by measuring and comparing the wave scattered fields around the model before and after the acrylic tank was filled up with...
water. The corresponding COMSOL model was modified to include only silicone and water.

![Figure 5 Schematic of uniform double-interface model used in laboratory](image)

**Figure 5** Schematic of uniform double-interface model used in laboratory

| Geometries reconstructed based on experimental and COMSOL results as well as analytical geometry are plotted in Figure 7. The geometrical values for both outer and inner interfaces are presented in Table 1. For outer interface, the maximum error for COMSOL results is 0.5mm, while the geometry reconstructed from experimental results has maximum error of 6mm. These maximum errors were mainly resulted from the surface at approximately $x = \pm 0.1m$. The reasons are explained below.

### Table 1 Dimensions of geometry for double-interface model

<table>
<thead>
<tr>
<th></th>
<th>Analytical Results</th>
<th>Reconstructed results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius of circle [mm]</td>
<td>130.0</td>
<td>130.0</td>
</tr>
<tr>
<td>Distance btwm. centers of half-circles [mm]</td>
<td>200.0</td>
<td>201.0</td>
</tr>
<tr>
<td>Maximum error [mm]</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Inner interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius of circle [mm]</td>
<td>92.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Distance btwm. centers of half-circles [mm]</td>
<td>200.0</td>
<td>195.0</td>
</tr>
<tr>
<td>Maximum error [mm]</td>
<td>-</td>
<td>4.5</td>
</tr>
</tbody>
</table>

#### a. Reconstructed geometry

Geometries reconstructed based on experimental and COMSOL results as well as analytical geometry are plotted in Figure 7. The geometrical values for both outer and inner interfaces are presented in Table 1. For outer interface, the maximum error for COMSOL results is 0.5mm, while the geometry reconstructed from experimental results has maximum error of 6mm. These maximum errors were mainly resulted from the surface at approximately $x = \pm 0.1m$. The reasons are explained below.

#### i. Equal-distance assumption

It was assumed that the distance between antenna $Tx$ and OUT surface ($d_{Tx}$) and distance between OUT surface and antenna $Rx$ ($d_{Rx}$) were directly proportional to the reconstructed time delay, or

$$d_{Tx} + d_{Rx} = \text{time delay} \times \text{speed of light}$$

and

$$d_{Rx} = d_{Tx}$$

However, $d_{Tx}$ and $d_{Rx}$ might not necessarily be equal.

#### ii. Unknown relationship between rays and horn antenna signals

This source of errors results from the geometrical optical assumptions of microwave propagation: microwaves propagate in ray form. It was assumed that when a pencil of scattered rays of a particular frequency is met by an antenna $Rx$, one magnitude and time-delay value are extracted by the $Rx$. However, as the relationship between rays and antenna signals is unknown, the extraction process was carried out through averaging the various magnitudes and time-delays of rays.

Based on this averaging method, less error in geometry was generated when the received rays had similar magnitudes and time delays. This situation can be better reflected by combining Figure 7 and Figure 8. In Figure 8, the illuminated regions (defined in dotted lines) of antenna ports 2 and 6 are of relatively uniform shape, while the region illuminated by antenna port 4 consists of curvy and flat surfaces (the region where maximum geometrical errors are observed in Figure 7). Due to this mixture of curved and flat surfaces, greater geometrical errors were generated when averaging was carried out across scattered rays.

To solve this problem, antenna $Rx$ of smaller aperture size can be employed. The signals received by an antenna with smaller aperture size correspond to a smaller area on the illuminated region on OUT surface. Therefore, magnitudes and phase angles of received reflected rays will be more uniform across the aperture as compared to those received by an antenna with greater aperture size.
iii. Experimental errors
The higher percentage of geometrical errors found in experimental results were caused by the presence of acrylic and nylon layers. The comparison of pre- and post-water-filled tank could only eliminate certain magnitude of errors in scattered field generated by extra layers. In addition, experimental errors were dependent on the spatial errors originated from misalignment of antennas and OUT.

For the inner interface, the maximum errors of geometrical reconstruction from COMSOL and experiments were 4.5mm and 8.5mm, separately. Apart from the errors discussed above, the accuracy of geometries for inner interface is also dependent on the reconstructed dielectric properties of the outer interface (see discussion in Section 3.1b).

b. Reconstructed reflection coefficients
In Figure 9, the reconstructed reflection coefficients from COMSOL and experimental data are plotted (in red, with DL legends) with respect to the transmitting port locations. The reconstructed reflection coefficients for a model (see Figure 5) without the silicone rubber layer are plotted in black (SL legends). Due to symmetry of the model mentioned in Figure 7 along the x-space, only results from Ports 1 to 7 are demonstrated. The reconstructed SL and DL reflection coefficients are compared to demonstrate the clear distinction between reflections from water and silicone surfaces.

For DL series, the maximum error found in Figure9a is 0.115 at Port 5, while maximum error found in experimental reflection coefficient is 0.078, at Port 5. As for SL series, the maximum COMSOL error is 0.084 at Port 3, and the maximum experimental error is 0.137 at Port 1. Reflection coefficients were highly sensitive to geometrical errors discussed in Section 3.1a. Generally, even though there are variations in reconstructed reflection coefficients, distinctive differences were observed throughout SL and DL series in Figure 9. This comparison provides encouragement for the possibility of detecting foreign object strapped to human torso with dielectric properties similar to that of silicone rubber, which includes TNT, C4, cocaine HCl and china white heroin (Watters et al 1995).

3.2 Models with patch at three locations
The aim of this study is to investigate the reliability of reconstructed geometries and reflection coefficients using the proposed reconstruction methodology based on a model with three different patch locations. As an initial feasibility study, this section examines the results reconstructed from COMSOL responses to the analytical parameters alone and does not include any experimental studies.

For all models considered in this chapter, the ellipse that represents human torso had major and minor axes of 0.2m and 0.1m, respectively. External patch of thickness 30mm was attached to the surface of ellipse. Three cases are considered in this section: when the center of patch was located at 90°, 60° and 30°, with respect to the major axis of ellipse (see Figure 11a-11b).

a. Reconstructed geometries
The method of geometry reconstruction can be divided into two processes, i.e. reconstruction of elliptical body, and reconstruction of external patch. First of all, the overall OUT is assumed to be a huge ellipse, and the major and minor axes are calculated based on the time delays measured at Port 1 and Port 7, i.e. ports located along the major and minor axes. Secondly, time series at different ports which receive secondary reflections are identified, and the corresponding illuminated regions in space are extracted. Secondary reflection is defined as
reflection originated from second material interface of a double-interface OUT (see Figure 10a). These illuminated regions are combined with the secondary reflection time delays to obtain geometry reconstruction for the patch.

Figure 10 Illustration for definition of reflections (a) Secondary reflection (b) Second-order reflection

Summary of maximum errors are reported in Table 2. Geometry reconstruction for both 90° and 30° cases were in good agreement with respect to the analytical geometries. Maximum errors of these two cases were 4mm for patch surface and 2.4mm for torso surface. As for the 60° case, Figure 11b shows that errors within the region of \( x = [-0.10m, 0.01m] \) increased gradually until a maximum of 6mm was reached at the right-hand-end edge of patch.

Generally, maximum errors were identified to be located close to patch edges and were found to be originated from the geometrical reconstruction algorithm. Apart from the geometrical-error-causing reasons presented in Section 3.1a, two other reasons within the geometrical reconstruction algorithm were identified:

i. Sharp edges of patch

The geometrical reconstruction process dealt with only the major features of a certain shape and minor details including the smoothness of geometry at patch edges were ignored. However, the presence of sharp edges could lead to significant changes in scattered field. Sharper edge (higher curvature) tends to scatter more rays than a rounder edge (lower curvature). This phenomenon is shown in Figures 11a-11c. The relative sharp edges for 30° case (10mm chamfering radius) were not reconstructed as well as the patch edges found in the 90° case, which had chamfering radius of 20mm.

Figure 11 Comparisons of reconstructed geometries to analytical geometries (a) 90° case (b) 60° case (c) 30° case
Table 2 Comparison of errors for patch models

<table>
<thead>
<tr>
<th>Location of patch</th>
<th>Patch geometry Maximum error [mm]</th>
<th>Elliptical geometry Maximum error [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch at 90° with major axis</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Patch at 60° with major axis</td>
<td>0.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Patch at 30° with major axis</td>
<td>4.0</td>
<td>2.4</td>
</tr>
</tbody>
</table>

**ii. Higher order reflections**

The geometrical reconstruction algorithm assumed that all reconstructed time series with two significant peaks were resultant of double-interface illuminated region on OUT (Figure 10a). However, reflections of higher order may be induced at patch edges. A ray is met with human torso- and patch- surfaces before travelling back to a receiving antenna (see Figure 10b). Errors were hence induced due to differences in ray paths.

When the patch was moved away from the minor axis towards the major axis of ellipse, the accuracy of reconstructed elliptical geometry was reduced. In overall, maximum error of 6mm was considered low when compared to the overall size of OUT. However, this inaccuracy in reconstructed geometry was expected to cause rather significant effects towards reconstructions of reflection coefficients (see Section 3.2b).

**b. Reconstructed reflection coefficients**

Reconstructed reflection coefficients for all three cases are plotted in Figure 12. Each subplot contains three different sets of results, i.e. the reconstructed geometry as well as the reconstructed and analytical reflection coefficients. Two sets of y-axes are used. The reconstructed geometry is represented by a black solid line together with the y-axis on the right hand side while values of reflection coefficients are shown by y-axis on the left hand side. As it is impossible to have values of reflection coefficients at every single location on the surface of OUT, interpolation method of type shape preserving spline was applied to the reconstructed reflection-coefficient values to approximate the spatial distribution of reflection coefficients.

From Figure 12a, the differences between reconstructed and analytical reflection coefficients were generally within 0.15 except at regions closed to the patch edges, where x=[±0.10m ±0.05m]. Similar to Figure 12a, errors of reflection coefficients in Figure 12b were found at near patch edges. Disregarding the effects of patch edges, it was noted in Figure 12b that geometry-dependent errors within the region of x=[-0.10 0.00]m increased gradually as x→0. Figure 12c shows clear distinction in reflection coefficients between silicone rubber and water surfaces. However, unlike the previous two cases, the number of reconstruction points in the region of x = [-0.20m - 0.10m] was much lower as compared to the reconstruction points in (-0.1m 0.2m).

A different scanning method was hence considered to demonstrate that distinctive dielectric-properties contrast could be obtained by increasing the illumination frequency of a particular region. The set of antennas was rotated by 90°-counterclockwise with respect to the center of ellipse, so that Port 7 was located along the major axis instead of minor axis. Reconstructions of geometry and reflection coefficients are shown in Figure 13a and 13b.

![Figure 12 Comparisons of reconstructed and analytical reflection coefficients (a) 90° case (b) 60° case (c) 30° case](image-url)
reconstruction was only limited to $|x| \leq 0.10m$. Errors at $|x| >0.10m$ were ignored. Figure 13a shows that the maximum error in geometry reconstruction was approximately 10mm, located at $x \approx 0.03m$. This error was originated from the geometrical reconstruction algorithm discussed in Section 3.2a. In addition, the reconstruction of reflection coefficients (shown in Figure 13b) had demonstrated a more distinctive difference between water and silicone surfaces, as compared to Figure 12c.

CONCLUSION

The simplicity of geometrical optical method and distinctive contrast in reflection coefficients of human torso and silicone rubber offer the possibility of rapidly detecting hidden objects strapped to human torso. However, this study is only limited to reconstructions using synthetic data with idealised beam shape. It is noted that the reconstructed geometry and reflection coefficients of OUT in two-dimensional space were in good agreement with analytical values except at patch edges. Geometrical errors were found to contribute significantly to the errors in estimation of reflection coefficients. Modifications to the geometrical optical method and increase in illumination frequency are hence required to enhance accuracy of reconstructed results. In conclusion, this preliminary research has demonstrated the possibility of using microwaves in conjunction with geometrical optical method to rapidly detect illicit materials strapped to human torso.

REFERENCES


