--- *TECHNICAL REPORT* ---

[Microwave Scanning System Correlations]

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Abstract

The purpose of this research was to determine the capabilities of two different microwave scanning technologies. This research focuses on each system's ability to detect the presence of defects within materials consisting of Lexan or Nylon. The defects for this evaluation consist of four inline holes of known diameter and varying depth across a dielectric plate. Special consideration was given to the each systems ability to dimension the plate defects accurately with repeatability. It was found that the XY Table Scanner and Handheld Scanner are both capable of detecting the induced defects in the Lexan and Nylon plate. It was concluded that the XY Table Scanner is a better system for increased accuracy in dimensioning with a percent error range of 44.452% to 94.899% compared to a range of 191.713% to 338.693% for the Handheld Scanner. The XY Table was also shown to produces higher quality images and was easier to use than the Handheld Scanner. However, it was also found that neither scanning technology was capable of determining the depth of surface or sub-surface defects.

Introduction

This report summarizes the evaluation and comparison of the Evisive microwave XY table scanner and the Evisive Handheld Bluetooth Infrared-tracked millimeter-wave probe. The two system's ability to detect defects in dielectric materials was assessed. Accurate dimensioning and high resolution scan images formed the basis of the evaluation. Nylon and Lexan plates with diagonal drilled holes were the scan samples with artificial defects, the holes. Each plate was scanned several times and on both faces for surface and sub-surface defects.

The Evisive microwave XY table scanner was provided with software that allows for automated scanning of samples. The microwave probe is fixed to the XY scanning table which is controlled with the Evisive Velmex Table GUI. The probe moves over the sample scanning a predetermined width, height, and step size. The probe standoff distance can be set manually. Gain and null voltages are adjustable for both real probe channels A and B.

Evisive Handheld Bluetooth Infrared-tracked millimeter-wave probe is used to manually scan a sample for defects. The user moves the probe across the surface of the sample and an infrared camera tracks the probe. The provided software combines the location and signals to produce an image. As with the microwave scanner the gain and null voltages are adjustable for the real probe channels. The standoff distance is fixed due to the function of the system.

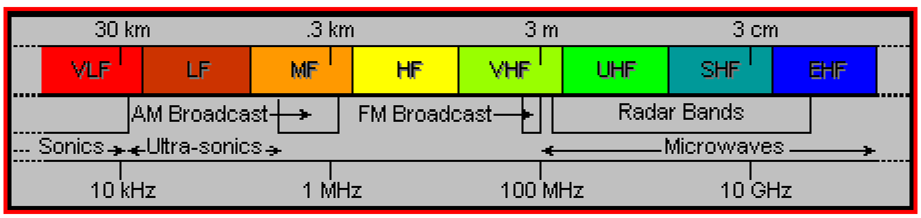
The difference in the scanning process and applications of the systems are the main reasons for comparison. The difference in signal frequency is also a factor that will affect performance. The portability of the handheld scanner leads it to be more useful in a field environment but automation and precision are sacrificed. Whereas the XY table scanner is a fixed bulky system that allows for precise scans. The handheld scanner is also able to scan a sample that is not flat but the XY table scanner is only practical for flat samples.

Background

Overview of RF Spectrum

The term radio frequency (RF) refers to the electromagnetic field that is generated when an alternating electrical current is input to an antenna. This field is also called an RF field or radio wave. Radio waves have the longest wavelengths in the electromagnetic spectrum. Radio waves range from 1000 km down to just 1 m or frequencies ranging from 3 Hz to 300 MHz [1]. Radio waves are commonly used to communicate in all different forms, they are use to carry FM and AM radio stations, cell phone calls, and television signals. Radio waves transfer information well through air and can penetrate non-conducting materials such as wood, bricks, and concrete. However they cannot pass through electrical conductors.

The microwave portion of the electromagnetic spectrum consists of wave lengths ranging from 1 m to 1 mm or a frequency band of 300 MHz to 300 GHz and includes the super high and extremely high frequencies. Microwaves are good for transmitting information from one place to another because microwave energy can easily penetrate nonconductive solid materials as well as haze, light rain and snow, clouds, and smoke. Higher frequency microwaves are used in remote sensing. These shorter period microwaves are used for RADAR. The wavelength and frequencies at which radar is used is depicted below by the radar band in Figure 1 [2].



Radio waves:
EHF = Extremely high frequency (Microwaves)
SHF = Super high frequency (Microwaves)
UHF = Ultrahigh frequency
VHF = Very high frequency
HF = High frequency
MF = Medium frequency
LF = Low frequency
VLF = Very low frequency
VF = Voice frequency
ELF = Extremely low frequency

Figure 1: Radio Frequency Spectrum [3]

Microwaves Interaction with Solids

When microwave energy strikes a solid, energy is transmitted through gaps and material variations for nonconductive materials. Along with being transmitted through the medium some energy is backscattered as the microwaves travel from one media to another media. Different media could consist of small deformities or defects in the material or a change from one material to another. As another media is encountered there is a change in the dielectric constant which scatters the microwaves at a different rate and phase from the surrounding medium [10].

Dielectric Constant

The dielectric constant, a property of a dielectric material, is a ratio that describes the material's tendency to oppose an applied electric field. While dielectric materials may be polarized in an electric field, they do not exhibit a flow of charge. The dielectric constant for several common materials can be found below in Table 1 along with dielectric constants for Nylon and Lexan.

Table 1: Common Dielectric Constants [4]

Material	Dielectric Constant
Pure Water	50
Glass	7.6-8
Rubber (pure)	2.1
Polyethylene	2.3
Nylon 6,6	3.6
Lexan	2.5

The dielectric constants for materials are determined based on the measurement of dielectric permittivity of a material. The constants are a function of the electric field frequency that the material is in. The permittivity consists of both a real and complex portion. The real portion describes the polarization of the material and the complex portion accounts for losses due to phase shifted movement of polar molecules [5].

RADAR

RADAR is an acronym for "radio detection and ranging". RADAR was developed to detect objects and determine their range by transmitting short bursts of microwaves. Those microwaves were then reflected back to a receiver and from the "echoes" the objects range and velocity are determined[6]. The range can be determined by either the time of flight of the wave or by frequency modulation. Frequency modulation allows the returning signal to create a beat frequency as a result of interference with the broadcasting signal and from that the range is calculated.

Early radars used very long wavelengths that were larger than the targets and received a vague signal, whereas most modern systems use shorter wavelengths that are most capable of tracking smaller objects.

Reflection

Electromagnetic wave reflection is caused by scattering of the wave. This occurs when the wave encounters changes in a dielectric or diamagnetic constant of the medium through which it is traveling. The larger the change in dielectric or diamagnetic constant the more the wave will be scattered; this accounts for RADAR's especial sensitivity to metallic objects. The reflected wave signal is a small fraction of the incident signal due to scattering, only part of the scattered wave is "reflected".

The amount of reflection is determined by the object material, size, wavelength, and shape. The object material determines its dielectric constant and consequently its ability to reflect electromagnetic waves upon change of medium. The wavelength must be sufficiently small in comparison to the objects size to produce a good reflection. Reflection amount is also dependent on the cross sectional area presented by the target; generally, the larger the cross sectional area presented the greater the amount of reflected signal.

Michelson Interferometer

The Michelson interferometer is an experimental device that demonstrates interference. The device uses a monochromatic wave source, splits the beam, and recombines the two waves into a single path [7]. The key to the interferometer function is after the beam is split the two waves travel different distances before being combined. This shift in phase allows for the interference by the superposition principle. The interferometer has a movable mirror that is adjusted to cause interference. By moving the mirror a distance and counting the observed fringes that pass a specific point, the wavelength of the source may be determined [7].

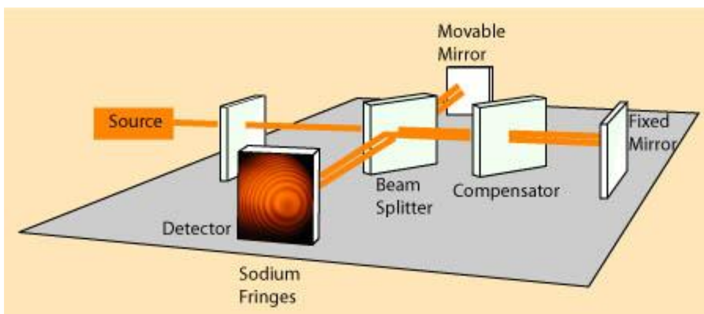


Figure 2: Michelson interferometer device setup [8]

Fabry-Perot Interferometer

The Fabry-Perot interferometer causes multiple reflections of a wave source to be out of phase by a constant increment [8]. Figure 2 shows the multiple reflections that occur between two parallel partially silvered glass plates or etalon. The rays escape through the partially silvered surface and fringes are observed. The phase shifts cause the fringing to occur.

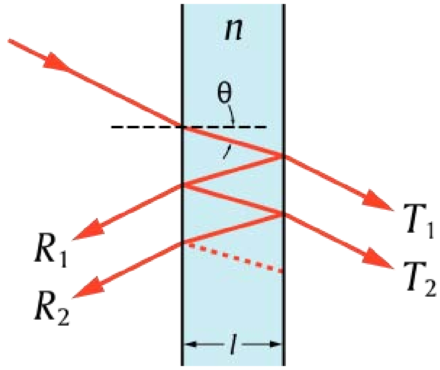


Figure 3: Reflections and transmissions of waves from parallel plates or etalon [9]

The interferometer principles relate to the microwave system by the incorporation of superimposed signals. The interference patterns caused by interferometers are analogous to the patterns that will be observed in the microwave system. In the microwave system the projected microwaves will reflect when any change in dielectric constant occurs. The projected microwaves and reflected waves combine and create an interference pattern which is observed by a sensor diode [10]. The differences in the interference pattern can then be used to indicate a change in the dielectric constant and consequently a change in the material quality.

The handheld millimeter-wave scanner functions like the microwave scanner. It emits a millimeter-wave signal that is backscattered by the scanned object. The backscattered waves then combine and interfere with the outgoing signal. The combined wave is read by a sensor and processed to produce an image. Backscattering amount depends on the change in the dielectric constant as the signal wave travels through the target material.

Both systems convert the interference signal received by the diode to a voltage that is recorded along with the position of the probe. With position coordinates and a voltage the image of the scan can be created. The position is determined by the XY scanner using the x and y coordinates of the probe. The handheld system uses an infrared tracking system. An infrared camera tracks an infrared LED that sits atop the probe and the software uses the LED’s position in the camera image to obtain position coordinates.

Apparatus

The follow equipment is needed for each of the individual scanning systems:

Handheld Scanner

Equipment list

1. Dell Netbook (with the proper software installed by Evisive)
2. Bluetooth USB port transmitter
3. Handheld Probe
4. USB to mini-USB Converter (links camera to netbook)

5. Optitrack IR camera
6. Charger

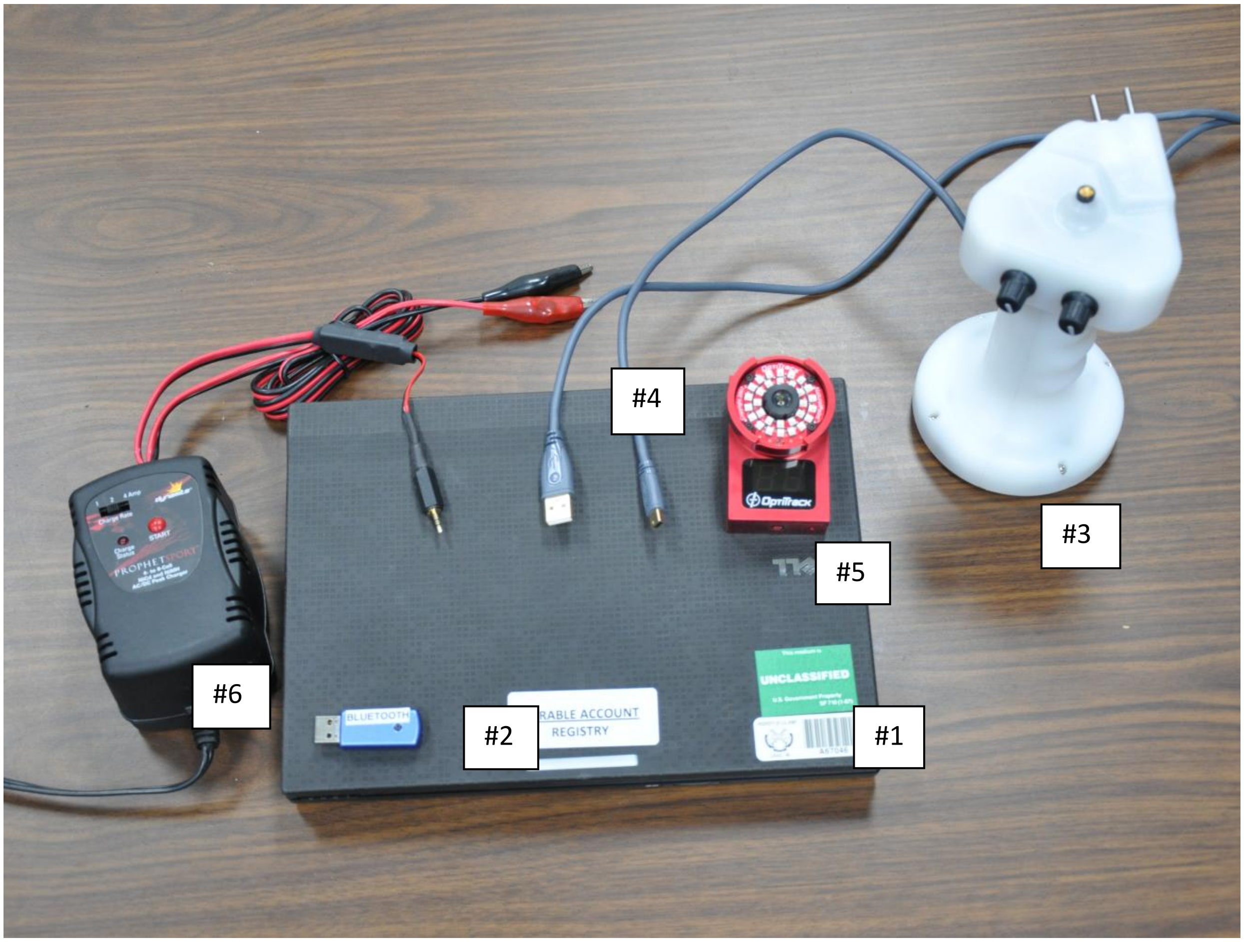


Figure 4: Required Equipment for Handheld Scanner

Setup

The photography platform with adjustable camera mount is an optimal location for scanning samples. The camera mounts to the height adjustable arm that extends from a post. A screw protrudes from the mounting face that will thread into the base of the Optitrack camera. This Apparatus is portrayed below in Figure 5.

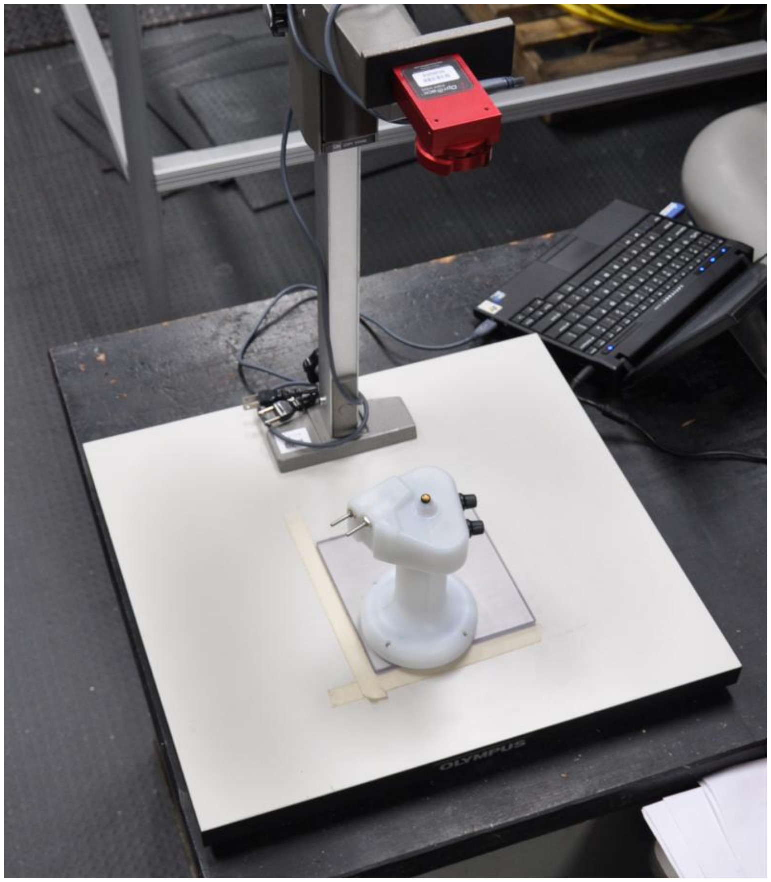


Figure 5: Apparatus for Handheld Scanner

Procedure

1. Conduct the preliminary setup as per Evisive Handheld Bluetooth Infrared installation and instructions document provided.
2. Install the camera on the photography platform as depicted in the above mentioned documentation.
3. Place the sample plate to be scanned on the table. The plate should be entirely visible in the video mode display in the data acquisition software. For consistency use masking tape to make a 90 degree angle so that the plate will be in the same location for every scan.
4. To null the probe click “Start” on the Evisive Scan Data Acquisition software. Place the probe on the plate in a location free of holes or defects. Use the null knobs to bring each channel’s voltage curve on the Evisive Scan Data Acquisition readout to zero volts. Click “Stop” to stop the scan, do not save.
5. Adjust the raster width to 3.
6. Click “Start” on the Evisive Scan Data Acquisition software and then depress the trigger. Slowly and evenly cover the sample, when finished depress the trigger to release. During the scan observe the probe voltage signal and make gain adjustments as necessary based on clipping, the scan must be restarted if the gain is changed.
7. When the raster is finished click “Stop” on the Evisive Scan Data Acquisition software.

8. Use this procedure to scan each plate with the holes up two times and with the holes down two times.
9. Evaluate the image in the Evisive Scan Imaging software.

XY Table Scanner

Equipment List

1. XY Table Setup
2. Laptop (with the proper Evisive software)
3. Evisive Inc. Control Module
4. Evisive Probe
5. Z Directional Control
6. Velmax VXM Stepping Motor Control
7. Differential Encoder Breakout (not pictured)
8. Micro scanning system lab manual (provided by Evisive and not pictured)
9. Proper Cables need for all connections (provided by Evisive and not pictured)

Setup

The setup of the XY table scanner includes the items listed above in the manor that is depicted below.

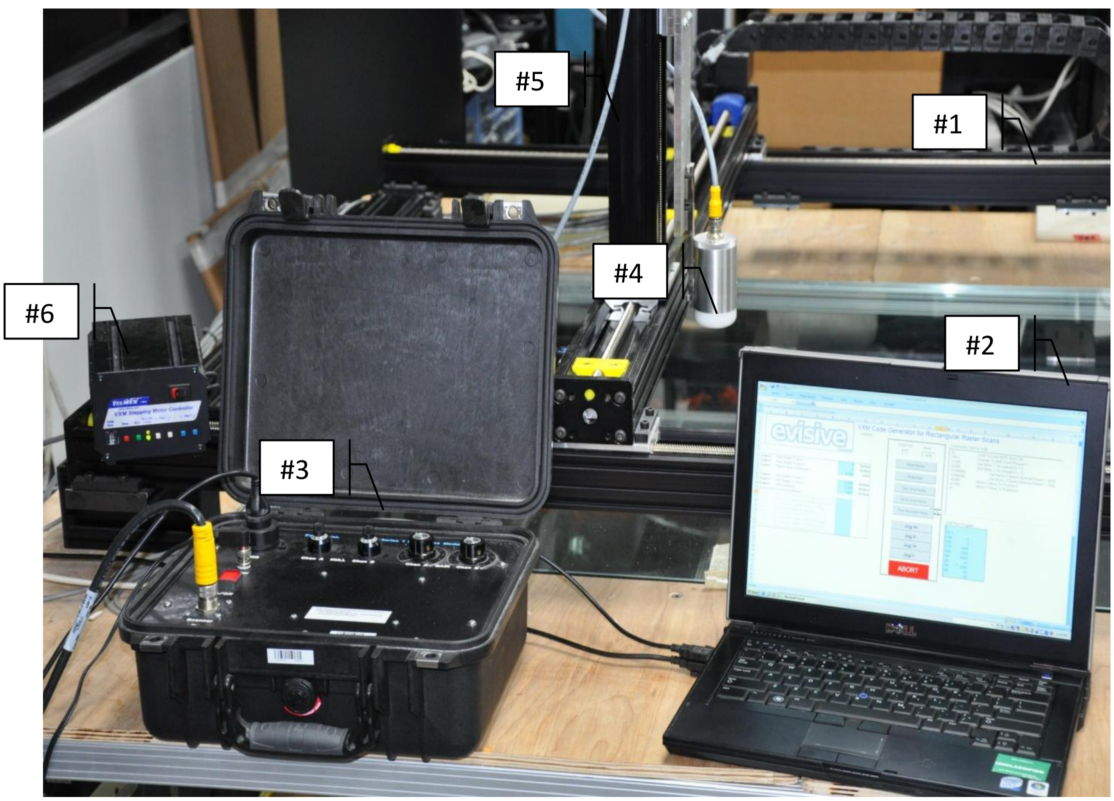


Figure 6: Apparatus for XY Table Scanner

Procedure

1. Conduct the preliminary setup as per Evisive instructions provided.
2. Place the sample plate to be scanned on the table. For consistency use masking tape to make a 90 degree angle so that the plate will be in the same location for every scan.
3. The axis of the scanner is as depicted. The sample plate should lie entirely in the first quadrant of the scanner axis with the plate's corner on the local home (origin). If the local home is not set already this may be done with the Evisive Velmex Table GUI.
4. Using Evisive Velmex Table GUI set the part width and height to 6 inches with a raster index distance of 0.05 inches.
5. Set the null width to 4 inches and null height to 2 inches.
6. Use the probe null button to send the probe to the null location.
7. Adjust the height of the probe using the crank. Move the probe close to the plate and use a sheet of white printer paper as a feeler gauge to give adequate stand-off.
8. Use the knobs on the control panel to set the gain for channel A and B to 3 volts.
9. To null the probe click "Start" on the Evisive Scan Data Acquisition software. Use the null knobs to bring each channel's voltage curve on the Evisive Scan Data Acquisition readout to zero volts. Click "Stop" to stop the scan, do not save.
10. Using the Evisive Velmex Table GUI return the probe to the local home.
11. Click "Start" on the Evisive Scan Data Acquisition software and then click "Start Raster" on the Evisive Velmex Table GUI. During the scan observe the probe voltage signal and make gain adjustments as necessary based on clipping, the scan must be restarted if the gain is changed.
12. When the raster is finished click "Stop" on the Evisive Scan Data Acquisition software.
13. Use this procedure to scan each plate with the holes up two times and with the holes down two times.
14. Evaluate the image in the Evisive Scan Imaging software.

Each plate was scanned twice with the holes facing upwards and holes facing down by both scanners, for a total of 48 scans. Twenty four scans were performed with each scanning system. The data retrieved from the probe system was collected by the Evisive software package to produce the images located below in Figure 7.

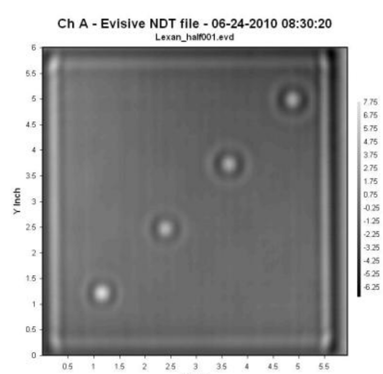
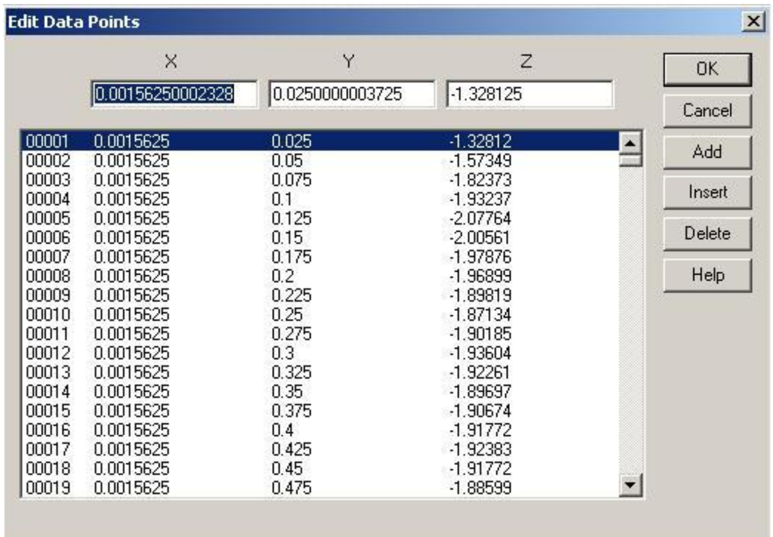


Figure 7: Raw Image of Evisive Data Software

In order to generate the figure above the Evisive software uses the data point represented below by Figure 8.



Edit Data Points

	X	Y	Z
	0.00156250002328	0.0250000003725	-1.328125
00001	0.0015625	0.025	-1.32812
00002	0.0015625	0.05	-1.57349
00003	0.0015625	0.075	-1.82373
00004	0.0015625	0.1	-1.93237
00005	0.0015625	0.125	-2.07764
00006	0.0015625	0.15	-2.00561
00007	0.0015625	0.175	-1.97876
00008	0.0015625	0.2	-1.96899
00009	0.0015625	0.225	-1.89819
00010	0.0015625	0.25	-1.87134
00011	0.0015625	0.275	-1.90185
00012	0.0015625	0.3	-1.93604
00013	0.0015625	0.325	-1.92261
00014	0.0015625	0.35	-1.89697
00015	0.0015625	0.375	-1.90674
00016	0.0015625	0.4	-1.91772
00017	0.0015625	0.425	-1.92383
00018	0.0015625	0.45	-1.91772
00019	0.0015625	0.475	-1.88599

OK Cancel Add Insert Delete Help

Figure 8: Raw Data from XY Table Scanner

Analysis and Discussion

Image Manipulation

Using software tools, all 48 images were cropped and colored to make analysis easier. A summary of software functions can be found in the Evisive Handheld *Bluetooth Infrared Installation and Operating Instructions* and Microwave Scanning System Software Manual documents. The image on the left is a representation of the images produced by the handheld scanner. The image on the right is an image produced by the XY table scanner. All of the images produced as well as the settings used during testing can be found in Appendix A.

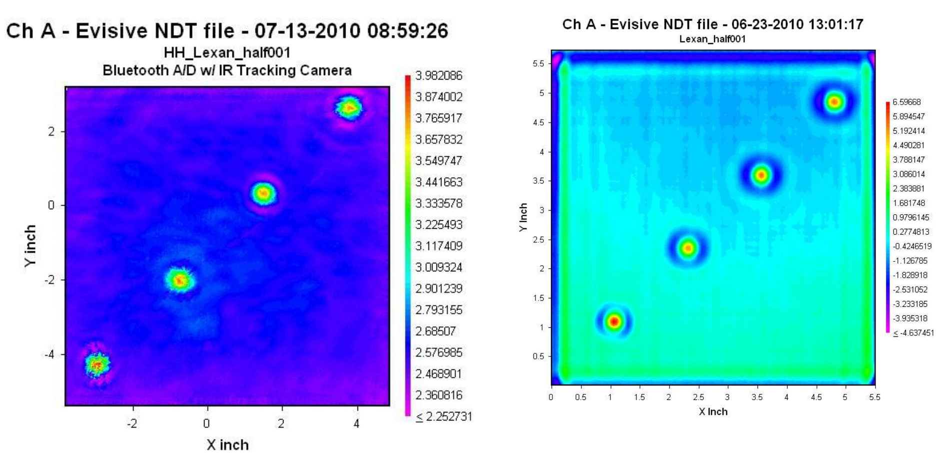


Figure 9: Sample of Cropped and Colored Images

Scan images can also be manipulated to form 3-D plots of the voltage signal surface, as shown below.

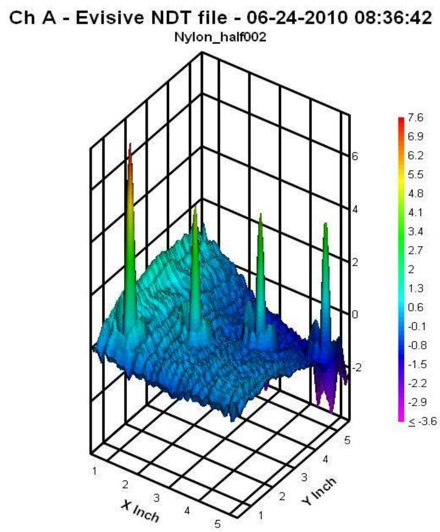


Figure 10: Sample 3D Image

Signal to Noise Validation

To determine if the image is valid the signal to noise ratio (SNR) was calculated to verify the results. This ensures acceptable system sensitivity. *EI-NDT-05 Rev. 0 General Procedure for the Nondestructive Testing of Dielectric Material via the Evisive Microwave Scanning System* section 5.9 describes the procedure used to calculate the SNR. For both channel A and B the SNR should be calculated. From the images produced by Evisive, the SNRs were computed for both channel A and B images. The formula used to calculate the SNR is as follows.

$$SNR = \frac{V_{Signal}}{V_{Noise}} = \frac{(V_{max} - V_{min})_{Signal}}{(V_{max} - V_{min})_{Noise}} \qquad \text{Eq.1}$$

Where the *Signal* refers to a point at which a defect is located and the *Noise* refers to an area of normal defect-free material. From SNR calculations it was found that all of the XY table scans had a SNR>3.0 indicating adequate defect detection sensitivity. However for the handheld scanner the SNR values were less than 3.0 identifying that the scans of HH_Lexan_quarter003 and 004, HH_Lexan_one003, HH_Nylon_quarter001 and 004, and HH_Nylon_one004 are inadequate in showing defect detection sensitivity. These scans were repeated, however a SNR greater than 3.0 was still not achieved. A sample of SNR values are shown below in Table 2 and the complete table can be found in Appendix B.

Table 2: Sample of Signal to Noise Data

Handheld Scanner Lexan 0.5” plate

Scan Number	Channel	SNR
001	A	11.7
001	B	5.4
002	A	6.4
002	B	3.7
003	A	2.48
003	B	5.1
004	A	2.7
004	B	4.04

Defect Diameter Dimensioning

To determine the diameter of the defects (holes) on the plate the Evisive Scan Imaging software was used. In order to determine the diameter the following procedure was used. First, find the average voltage of an approximately 1"x1" square near the defect. This can be done using the magnification tool and reading the average voltage displayed in the status bar on the bottom of the window. Then, measure across the center of the defect from two points that equal the average value, a software tool exists to find the distance between points.

The diameters of each hole in the plates were measured with calipers and through the use of the evasive imaging software. The percent error was calculated from the image measured diameter to the actual using Eq.2.

$$Percent\ Error = \frac{|Theoretical\ Diameter - Measured\ Diameter|}{Measured\ Diameter} \times 100\% \qquad \textbf{Eq.2}$$

Samples of the results are presented below in Table 3. A complete table can be found in Appendix C.

Table 3: Sample of Hole Diameter Measurements

Handheld Scanner				
File Name	**Hole Depth (inches)**	**Calculated Dia. (inches)**	**Known Dia. (inches)**	**Percent Error Calc.**
Lexan_quarter001	0.6550	0.47	0.2490	88.755
Lexan_quarter001	0.1263	0.36	0.2450	46.939
Lexan_quarter001	0.1900	0.25	0.2475	1.010
Lexan_quarter001	0.2305	0.27	0.2495	8.216

From the diameter data graphs were generated to aid in the comparison of the two different scanner technologies and their ability to dimension the diameter of the defects accurately.

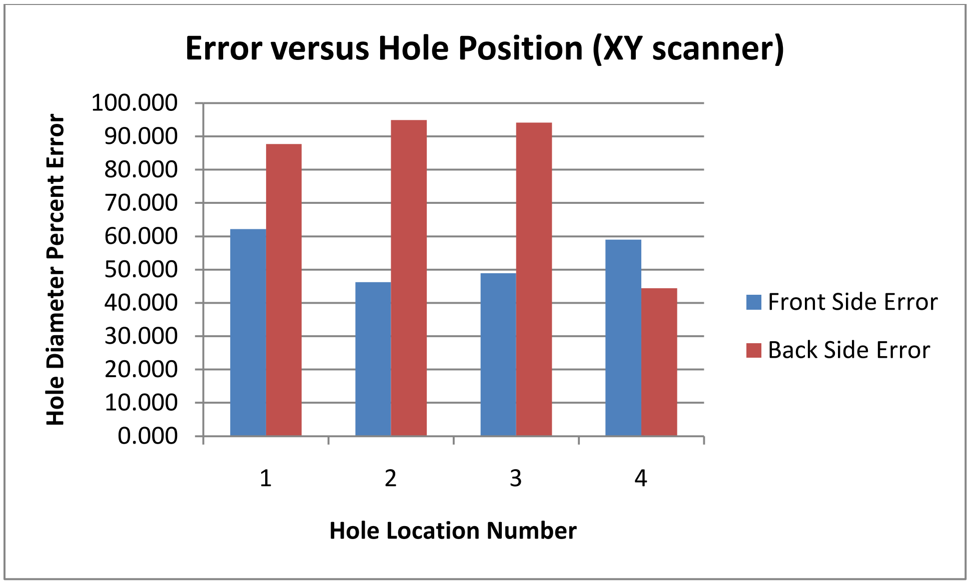


Figure 11: Percent Error by Defect Position for XY Scanner

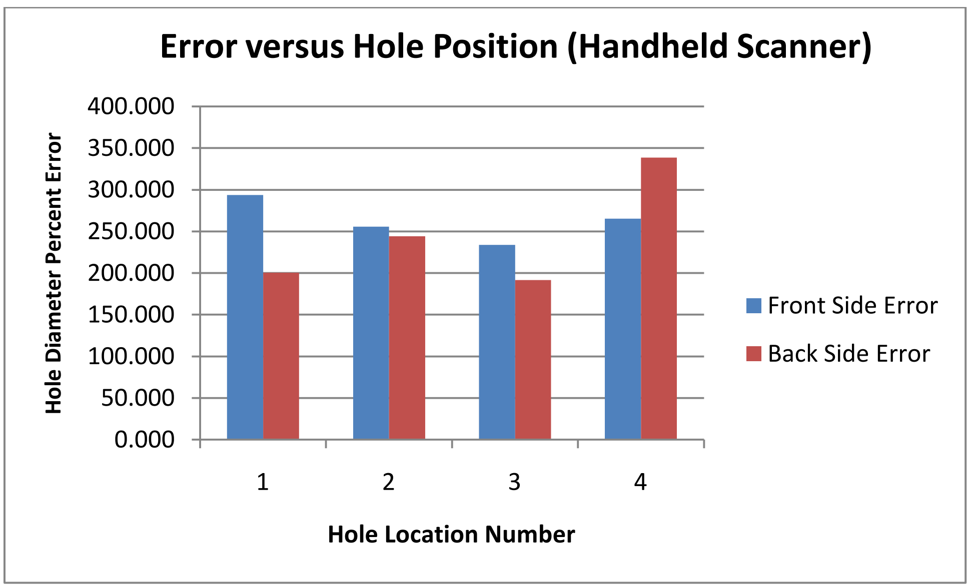


Figure 12: Percent Error by Defect Position for Handheld Scanner

From Figure 11 and Figure 12 it is clear to see that show that both systems proved unreliable in producing accurate dimension. This can be seen in the large range of the percent errors found from the comparison of the known diameter to the measured diameter. The error ranges from 44.452% to 94.899% for both materials, Lexan and Nylon, for the XY table Scanner. For the Handheld Scanner the error ranged from 191.713% to 338.693% again for both materials. From the analysis performed it is evident that the Evisive microwave XY table scanner is more accurate than the Evisive Handheld Bluetooth Infrared-tracked millimeter-wave probe.

Depth Dimensioning

In order to determine the depth of a defect in the plate several methods were used. However, neither method was found to be effective in consistency defining an accurate depth of a defect.

The first method was a visual cue that the halos located around the defects could lead to a way of defining depth. The halos mentioned above are shown below in Figure 13.

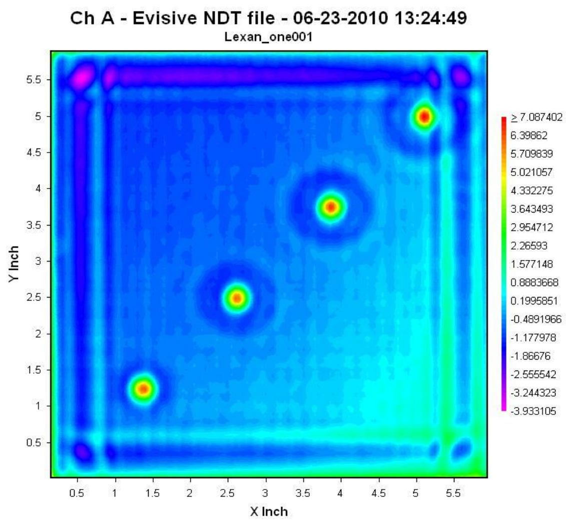


Figure 13: Halos on Lexan_one001 Scan

Through further research it was found that the wider halos corresponding to the deeper holes was just a coincidence and no correlation was relevant due to inconsistency from scan to scan.

The second Method consisted of changing the image via Dplot into a 3D image and attempt to derive a correlation between the voltage peaks and the actual depth of the holes. Again due to inconsistencies no correlation was found. An example of the inconsistencies is depicted below in Figure 14

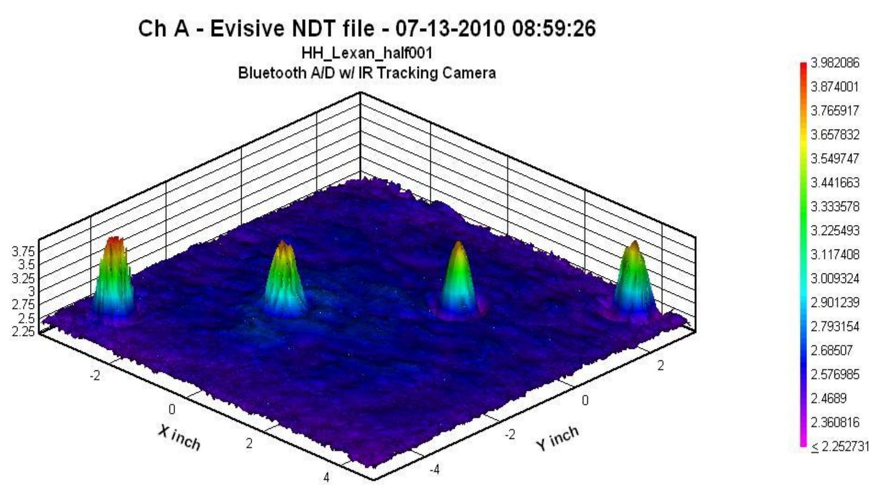


Figure 14: 3D Image (Depth Example)

In Figure 14 the actual defect depth increases from left to right, which is not depicted by the peak voltage across the defects. This is common with most of all **t**he plates that were scanned.

Image Quality and Resolution

While both methods showed defects, the XY table scanner gave more resolved images then the handheld scanner as show in below in Figure 15.

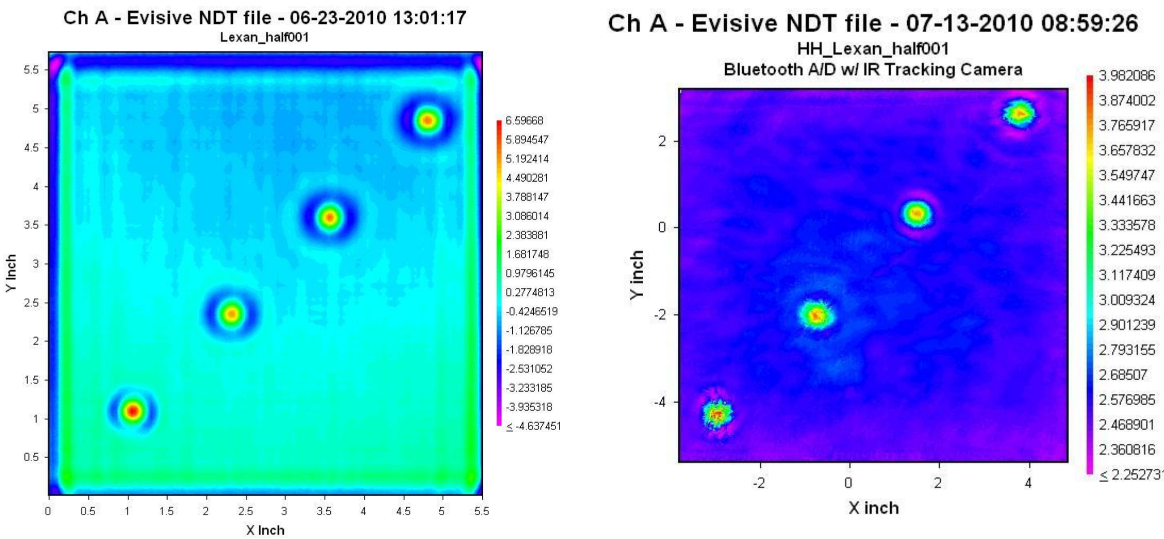


Figure 15: Image Comparison of Handheld and XY Table Scanners

The image representation of the defects is very circular on XY table scans whereas the handheld scans are roughly circular with lower certainty of the defect position. This shows that the handheld system was slightly less sensitive to plate defects.

Conclusion

In Conclusion, it was found that the XY Table Scanner and Handheld Scanner are capable of detecting simulated defects in the form of drilled holes in Lexan and Nylon plate. It was concluded that the XY Table Scanner is much better choice for more accuracy in dimensioning with a percent error range of 44.452% to 94.899% compared to a range of 191.713% to 338.693% for the Handheld Scanner. The XY Table also produces higher quality images and is easier to use then the Handheld Scanner. Furthermore, it was found that neither scanning technology was capable of determining the depth of surface or sub-surface defects.

Recommendations

In the experiment it was found that there may be a correlation between material and accuracy of the scan with respect to dimensioning. The data shows that with both systems the Lexan plates gave more accurate scans than the Nylon plates. It is our recommendation that other materials need to be scanned, such as ceramics, to verify this observation. This difference was shown by the percent error data and illustrated below in the graph.

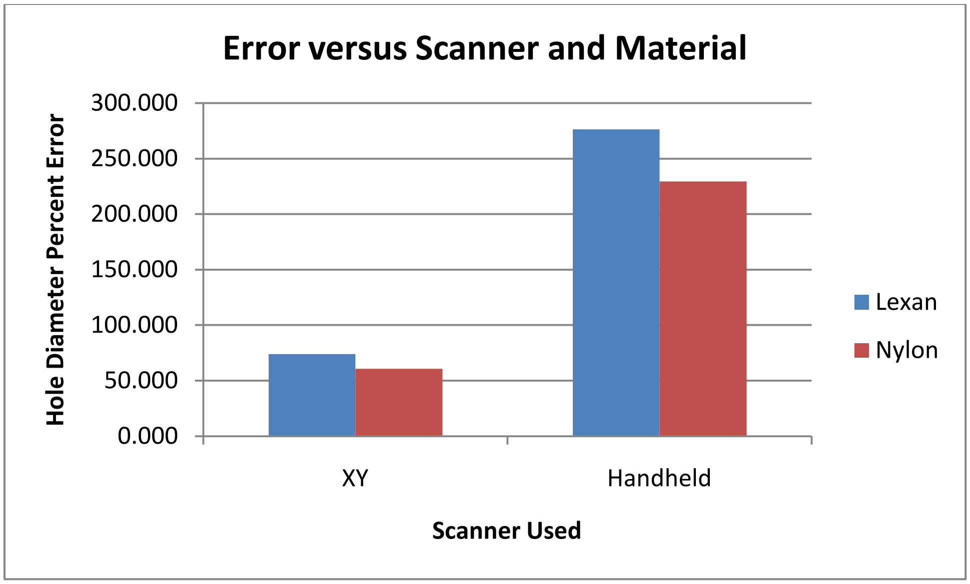


Figure 16: Percent Error Comparison in Different Materials

Furthermore, other research shows that using different frequencies and signal power for specific applications can be beneficial to scan quality. This would allow the scan systems to be tuned to each material and thickness. We recommend that more work be done with Evisive Inc. to determine if this is true.

Also further research is needed to determine the maximum depth that the systems can detect defects in specific materials should be investigated. This information is vital in ensuring the quality of scan results.

Additionally, the two systems should be compared in detecting unknown defects and defects likely to occur in the field. This would lead to an investigation into practical field uses such as detecting damage or defects in ceramic composite armors.

Further studies should include experiments tailored to diversifying the use of the scanning systems. Evisive has done work in *Large Tire Scanning in Mining Operations*[12], which could be applied to evaluating wear and damage to the expensive rubber components in tracked vehicles.

References

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Appendices

Appendix A: Scan Report Forms

Appendix B: Signal to Noise Data

Appendix C: Defect Diameter Data

Appendix D: Defect Diameter Graphs