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Segmentation of Thermal Images for Non-Destructive Applications

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SEGMENTATION OF THERMAL IMAGES FOR NON-DESTRUCTIVE APPLICATIONS

by

Solange Yohali

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science in Engineering (Electrical)
Department of Electrical and Computer Engineering

Western Michigan University
Kalamazoo, Michigan
June 2005
ACKNOWLEDGMENTS

First and foremost I would like to express my gratitude to Dr. Abdel-Qader for allowing me to work with her on this project and for her advice and guidance throughout my research. Thank you for taking time to review the manuscript of my Thesis and for your constructive and helpful comments.

Second I would like to thank other members of my Thesis committee; Dr. Abudayyeh and Dr. Yehia for allowing me to use the concrete specimens that are the testing objects of this study and for their ideas along my work, Dr. Pernalete for her support and encouragements.

Last but not least I would like to thank my Father for always encouraging me to have confidence in my abilities and for his prayers on my behalf.

Partial support of this work was provided by the National Science Foundation grant MRI- 0215356. I would like also to acknowledge Western Michigan University for its support and contributions to the Information Technology and Image Analysis (ITIA) Center. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the University of Western Michigan University

Solange Yohali
Infrared Thermography (IR) is used in this project to detect subsurface conditions in concrete specimen for nondestructive testing and evaluations. This thesis goal is to bridge the gap between Infrared Testing and image analysis by developing an algorithm based on the region growing approach to segment the images and identify the voids without human interference or prior knowledge of the conditions. The segmentation algorithm starts with seed points as the hottest pixels in the image, and then regions are grown based on a neighborhood comparison criterion. The algorithm was tested on images collected from concrete specimen containing various man-made defects and also on defect-free model. The experimental work successfully identified defects from the surrounding bulk material and all the results indicate that Thermography can detect hidden defects up to 3 inches below surface.
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1. INTRODUCTION

1.1 Thesis Organization

The thesis is divided into the following chapters:

**Introduction:** This part presents the study overview, introduces Non-Destructive Testing (NDT) and the motivation for which this work was carried out.

**Background:** The chapter presents a theory on thermal imaging, reviews image segmentation techniques with emphasis on region growing methods and also presents a review of related work on both segmentation and Thermography as a NDT tool in construction.

**Methodology:** This chapter describes how the image acquisition and preprocessing were done and finally a detailed explanation of the segmentation algorithm is presented.

**Experimental Results and Analysis:** This chapter discusses thermal results from the different concrete slabs and also presents results obtained by implementation of the new region growing algorithm. Finally it discusses how several parameters may have affected results.
Conclusions: The chapter summarizes the work done and its importance to NDT. Also it discusses major problems encountered.

Future Work: The last chapter suggests possible future work and improvements.

1.2 Motivation

Traditionally Nondestructive Testing (NDT) for condition assessment of highway bridges was limited to visual examination of the structure followed by strength testing techniques. In the last few decades other more sophisticated NDT methods such as Ground Penetrating Radar (GPR) and Infrared Thermography (IR) have been developed.

Nondestructive Testing (NDT) refers to all the methods that are used to detect hidden defect in material without disturbing its usefulness. In this study, transportation infrastructures in particular bridge decks are objects of interest. There exist many NDT techniques used in testing highway bridges such as the rebound hammer method, Ground Penetrating Radar (GPR), ultrasonic, acoustic emission, half-cell corrosion potential method, Infrared Thermography and many more [1]. Each one of the techniques has its own limitations and advantages. These different monitoring techniques are being widely used and preferred over invasive method due to their preventive nature reducing breakdowns and emergency maintenance costs. Most of the work done in
infrared imaging is limited to a visual analysis of collected thermographs, very little or no effort is available to automate the inspection.

The main contribution of this work is to enhance defect visualization to further ease interpretation of thermographic images. Ultimately an algorithm is proposed and implemented that could be used to automate the analysis of captured infrared images for defects identification.
2. BACKGROUND

Imaging using Infared Thermography (IR) is one of the NDT approach used to detect shallow delaminations in concrete decks. Thermographs could be hard to interpret with the naked eye. In order to increase the visibility of the voids on thermal image; segmentation could be used to separate defects from the surrounding areas.

2.1 Thermal Imaging

All materials above absolute zero (-273 °C) radiate infrared energy in the infrared spectrum [2]. The infrared system will then convert the infrared heat emissions into a picture, different shades of gray or different colors correspond to different temperatures.

Infrared wavelength of the electromagnetic spectrum are between the visible and microwave wavelength of about $10^{-6}$ and $10^{-3}$ m, see figure 2.1

![Figure 2.1: Electromagnetic Spectrum](image-url)
Infrared light is not visible because its wavelength is too long to be detected by a human eye. By definition IR is a technique by which the user can observe abnormalities by observing radiant heat pattern emitted from the material of investigation [2]. These points of defects represent the areas where the heat emission is either higher (hot spot) or lower (cold spot) than the predicted amount [3].

The infrared radiation of a matter depends on both the temperature of the component and of course on the nature of surface subject to inspection; as the temperature decreases the radiation intensity is lower and this produces longer wavelengths.

2.1.1 Theory and Terminology

Infrared cameras do not directly measure temperature; all they measure is the radiation which is then converted to temperature depending on the emissivity value of the specimen. IR imaging theory involves following terminologies:

- **Blackbody**: The term refers to an object that absorbs all lights that falls onto it, obviously no light passes through it nor reflected.

- **Emissivity**: Is defined as the ratio of a body at a given temperature to that of a black body at the same temperature [4]. Emissivity values are in the range of 0 to 1, the highest emissivity is associated with a perfect blackbody and zero value corresponds to a perfect mirror that reflects all the received energy. Appendix A
contains emissivity tables for a wide range of materials. The values in the available tables are approximation and do not take into consideration the fact that emissivity may vary with wavelength and especially varies with the material conditions; for example the real emissivity will change between two specimen with same material but different finish.

-Planck’s Law: One of the several approaches used to define emission of radiation of a blackbody. According to Planck the intensity of infrared radiation from an object is function of its temperature.

\[ E = h\nu \]

\( E \): Quantum Energy (joule)
\( h \): Planck Constant= 6.626068 \times 10^{-34} \text{ m}^2\text{ kg} / \text{s}
\( \nu \): Frequency of Electromagnetic radiation (hertz)

From this equation, amount of energy emitted depends on the frequency. The shorter the wavelength is, the higher the energy.

2.1.2 Advantages and Limitations of IR

Due to many advantages it offers, Thermography is one of predictive maintenance tools being used commonly in commerce and industry.

- Fast inspections: With IR camera large areas can be scanned in a short time such as taking an image of a large building façade checking for insulations or scanning a highway bridge with a camera mounted on vehicle moving about 15 km / h [5]
• Safety: Thermographic devices do not emit any radiation; the only radiation is emitted from the material of investigation. This safety is what prompted medical applications to use IR on humans and animals.

• Easy interpretation of results

• In some applications, infrared is the unique tool such as when detecting corrosion around rivets [4], due to its portability and non-contact features.

On the other hand, infrared imaging presents several challenges:

• In general Infrared is known to detect shallow defects only.

• Thermographic results are very dependent on the atmospheric conditions especially in passive outdoors applications.

• In case of Active Thermography the challenge is getting uniform heating across the surface to be inspected, otherwise the image will contain false alarms.

• Determining the exact emissivity involves complex computation, in most of applications well-established emissivity tables, containing approximate values are used (appendix A).

• Infrared cameras are expensive
2.1.3 Thermography for NDT in Civil Engineering

Often in construction structures such as bridge deck, airport pavements and large building, problems and their causes are not discovered until costly damages have already been done.

The most common IR applications in construction and civil engineering are; insulation checking, air leakage location, moisture intrusion or condensation, detecting failure in water pipes and monitoring highway bridges.

Nowadays IR Thermography has many techniques but they can be divided into two major groups; active and passive Thermography. The choice of which one to use depends on several considerations such as the temperature, the component matter or the environment.

The main difference between these two techniques is the manner in which the heat energy is transferred into the object under investigation.

*Passive Thermography:* The testing is done without any of external heating or cooling. Often the object is inspected during or after a natural operational cycle. This approach is mostly used while testing large structures such as bridge and building and also in medicine to diagnose some illnesses.

For the scope of this study the focus is put on Thermography as used in concrete bridge decks but it could be applicable to any other type of civil structure.

Traditionally highway bridges were subject of a regular visual inspection to monitor their conditions. The new generation methods used on these complex
structures include Infrared Thermography among other NDT techniques. Since highway bridges repair and or replacement is expensive, a condition assessment is needed to determine existing conditions, nature and causes of problems before making a decision [6].

The study of common types of bridge defects and their causes is beyond the scope of this thesis, but more details can be found in literature such as [5, 6].


In all three cases the thermographic system was mounted on a vehicle along with a video camera to capture real images of the scanned area for latter mapping. In [5] the author included a Ground Positioning System (GPS) to ease defect localization on the map.

The above investigations are done in a passive way and consequently they are heavily affected by the environmental conditions such as solar radiation intensity, wind, and possible shadows like building, trees or cloud cover.

The greatest challenge with IR is emissivity measurement. According to the ASTM Standard D4788-88 defects are identified as areas presenting a difference of 0.5 °Celsius with respect to their surroundings. Infrared camera reads and record surface radiation and not temperatures [2]. Then the radiation
is then related to temperature depending on the emissivity value, which is input by the user. That is the reason using the correct emissivity is crucial to the IR imaging.

*Active Thermography:* This method involves intentionally heating or cooling of a surface to be tested to induce temperature differences. A typical set-up in active Thermography approach contains an infrared camera with good lenses, a thermal stimulating device and a digital recording system. The applicability of active Thermography has been well studied in [7, 8, 9] and [10], where a numerical or physical model is subject to infrared imaging to detect well known subsurface defects.

The heating/cooling devices vary per applications; in [4] hot water bags in one case and hot concrete bricks were used to induce thermal difference in concrete testing.

The idea behind active Thermography is that after the energy from a thermal source is absorbed by the object, the surface temperature changes and by the diffusion property it propagates underneath surface. When this energy encounters zones having different thermal properties than the surrounding area the diffusion rate changes and temperature differences on surface is observed by an infrared camera [11].

Most of the research in active Thermography is applied on metallic materials [8, 9, 10, 12], and since metals are good conductors, the heating period is short and
defects are easily detected. Boras and Svaic [10] used a combination of a mathematical model and thermographic measurements to determine subsurface characteristics.

Weritz et al.[7] conducted a Pulsed Phase Thermographic investigation on a concrete specimen similar to the one used in this thesis. The analysis of the captured images was done in frequency domain. Authors were not able to determine the actual depths of defects; however analysis of phase images defects were classified according to their size. Also they were able to detect voids up to approximately 4 inch below surface.

In this Thesis the active approach was selected to test the concrete specimens.

2.2 Image Segmentation

Segmentation is done by dividing image into its constituent parts or objects [13]. Image segmentation is often a prior step for image analysis since it usually allows performing clustering, pattern recognition or object classification. The literature includes a variety of methods, however image segmentation algorithms tend to be application dependent and each method has its own advantages and limitations. Most segmentation algorithms are based on similarity or discontinuity features such as points, edge and line between different pixels in the image.
One category of segmentation algorithms is based on intensity of pixels which contain four major classes, all described below.

2.2.1 Threshold Based Techniques

Methods by which usually threshold values are selected from the image histogram. If two pixels may have similar intensity, color, or match in statistical parameters chances are they belong to the same region.

Thresholding based algorithms can be subdivided in four fundamental categories:

General Thresholding approach a single or more value is chosen from the histogram and used to segment the whole image whereas in Adaptive of Local Thresholding the image is divided into blocks and for each block a threshold value is calculated.

Unlike General Thresholding, Local Thresholding is known for coping well when the illumination in the image is varying.

The third class is that of Optimal thresholding methods, the optimization is done by modeling the histogram as a weighted sum of normal Gaussian distribution, then the threshold is chosen as the minimum probability distribution [14] i.e. the lowest point between the two peaks. The two most popular algorithms in this class are Otsu's technique and Entropy based approaches [15]. Often the process of choosing the threshold is automated
instead of choosing values manually and the conditions that control the automation are well defined.

Finally the last class of Threshold based techniques is Multi-Stage Thresholding. Unlike traditional thresholding, these processes reduce the search space of threshold candidate values stage by stage, each stage using different threshold. When the final stage is reached the threshold value is chosen [16]. At each stage 3 sub-images are produced: foreground, background and a set of non-categorized pixels as seen in figure 2.2. This iterative process will end when all the pixels had been assigned to either background or foreground class. One example is the Quadratic Integral Ratio (QIR) [17].

![QIR Histogram Analysis](image)

Figure 2.2: QIR Histogram Analysis

2.2.2 Edge Based Techniques

In this case the object of interest is the rapid transition between two regions of different intensities. By computing the pixel gradient it can
determined if it lies on the boundary or not. The most commonly used edge
detectors are the Hough Transform and the Laplacian Masking, but currently
researchers are focusing on using wavelets to identify image object contours. If
the gradient magnitude is high there is large possibility that the pixel is on
boundary between two regions [13].

2.2.3 Mixed or Hybrid Techniques

In this case region and boundary detection methods are combined. The
most commonly used hybrid algorithm is the watershed method. The main
drawback of these techniques is the heavy computations. Fan et al.[18] an
algorithm is proposed by first determining the color edges in an image by an
isotropic edge detector and a fast entropic threshold techniques then use the
centroids between adjacent edge regions as initial seeds for further region
growing.

2.2.4 Region Based Techniques

The aim of region based techniques is to group together pixels that satisfy
a defined homogeneity criterion. The Split/Merge technique and the Seeded
Region Growing (SRG) are the mostly used approaches in this category.

SRG algorithm start by selecting few pixels called seeds that are
representative of regions of interest depending to the type of image and
application type. Then the regions are grown around the seeds by adding
neighboring pixels that meet the homogeneity criteria. Two questions arise:
• How to select the initial seeds

• How to define the Homogeneity Criteria

The seed selection is delicate step since the growing process depends heavily on representative pixels [19]. Lu et al. [20] considered each pixel as seed in Magnetic Resonance Images (MRI) segmentation whereas Huang and Ma [21] approach allows the user to pick a seed by interactively slicing through the volume data. Some advanced techniques such as the one developed by Fan et al. [18] have made the selection of the seeds fully automatic which makes the segmentation almost immune to noise.

Homogeneity criteria selection has always been the challenging step in order to effectively extract regions. Possible criteria include texture, region homogeneity and contrast with background, characteristics of a region boundary or size [21].

For robust algorithms a pixel and its neighbors are compared to the seeds, some approaches go further by taking into consideration pixel region statistics such as the mean and variance. The neighborhood size varies depending on the region of interest and image type. The algorithm developed by Fan et al.[18] consider the neighborhood size 9 pixels, while the algorithm developed in by Huang and Ma [21] for 3-D MRI images uses large neighborhood of 26 pixels. The idea in comparing with regions instead of single pixels to produced regions that are identical under varying noise conditions.
This algorithm developed in this Thesis is a SRG based and also it takes into consideration a neighborhood of nine pixels centered at the pixel of interest.
3. METHODOLOGY

3.1 Overall Methodology

This thesis work involves two major components. First using Infrared Images using Active Thermographic method to detect subsurface defects then process the images using a new SRG based segmentation algorithms to divide images into defects and sound areas. Block Diagram in Figure 3.1 summarizes the methodology applied in this study to detect subsurface in concrete blocks and the segmentation applied.

![Methodology Block Diagram](image)

Figure 3.1: Methodology Block Diagram
3.2 Image Acquisition and Pre-processing

3.2.1 Image Acquisition

For the purpose of this research a thermal camera EZ-Therm™ manufactured by Electrophysics™ was used. The device has a double usage; it could be used with or without a Personal Digital Assistant (PDA). It is powered with an uncooled imaging sensor one of latest and affordable technology on the market. The sensor uses 320 x 240 resolutions [22]. Uncooled sensors are manufactured to withstand high temperature; the EZ Therm™ detector can accurately measure from -20 °C to 500 °C.

Unlike photon detectors which need to be cooled down in order to be sensitive enough and able to detect radiation with wavelength longer than 1μm, uncooled detector sense radiation in the range of 8-20 microns spectral region.

The camera used is also equipped with a PCMCIA card for image storage. It allows the user to choose from a large number of settings for better quality of the image. Once images are transferred to a computer, the file is ready to be used with any external software compatible with .JPG files.

The heating source was a set of six halogen flood-lights with a total of 3200Watts.
Figure 3.2: Testing Set-up

Figure 3.2 displays the testing set-up scenario that took place in the Information Theory and Image Analysis Laboratory (ITIA). Three flood lights were placed on each of the three sides of the concrete block and the camera was mounted on a tripod on the forth side. Since concrete is a poor heat conductor, each specimen was heated for several minutes; 45 for the small blocks and 85 minutes for the 8-inch slab. Then the heating source was removed and the camera used to capture infrared camera was used to observe and record the cooling down process. After a certain period defects started to appear on PDA screen.

3.2.2 Concrete Specimen Description

Testing specimens used (Figure 3.3) are 45 x 45 inch concrete slabs with varying thickness built by students in the Civil and Construction Engineering laboratory at Western Michigan University. The slabs were modeled after
bridges with steel bars on the bottom and filled with concrete. The concrete blocks have well defined induced defects. The defects were of three types; air-filled defects, polyvinyl chloride (PVC) pipes inserted in the concrete (figure 3.3) and plexiglas debris inserted into the surface to simulate surface cracks.

![Concrete Slab Schematic](image)

**Figure 3.3: Concrete Slab Schematic**

A detailed description of the specimens and their defects are available in Appendix B. A set of three blocks were used; one 4-inch thick had no known defect whereas the other two 4-inch and 8-inch thick respectively had different known defects at various depths.
3.2.3 IR Data Pre-processing

Once the infrared images captured and transferred to a computer, Matlab was used for image analysis and segmentation.

The first step was to remove the noise and adjust the image contrast thus preparing the images for further analysis. According to Maldague [4] infrared images are often corrupted with a stationary Gaussian type noise. The noise present in thermal images is mostly due to a poor focus of infrared camera lens since focusing is much harder than in visible light cameras. Also the concrete specimen used had a rough surface which contributed to the noise present in the captured images.

In most cases before processing images they were blurred using a 3x3 Gaussian filter, this was needed to smooth out isolated bright pixels. In Figure 3.4 the smoothing was illustrated by plotting a 3-D model of one of the captured images. Figure 3.4(a) and 3.4(b) show a sample of IR data before and after the smoothing process respectively.
Figure 3.4: Gaussian Smoothing Results

One major drawback of active Thermography is to attain a uniform heating across the object of investigation’s surface.

Another preprocessing step that was implemented is histogram stretching. The process was essential to enhance the contrast of the IR images. In general IR images are of low contrast and the Gaussian filtering increased the blur. Figure 3.5(a) and 3.5(b) show a sample of the IR image and histogram respectively, it is clear that the histogram is of a low contrast image.
Figure 3.5: Original Image and Histogram

The processed IR image and its corresponding histogram are shown in Figure 3.6(a) and 3.6(b) respectively. The resulting image exhibit better contrast, the new histogram is more balanced and the bright areas were enhanced.

Figure 3.6: Pre-processed Image and Histogram
The last preprocessing step consists of padding the image with zeros since the Matlab computations involve using a pixel and its neighbors.

3.3 Automatic Seeded Region Growing Algorithm

As in any other SRG algorithm, the program has three main components; first the determination of seeds pixels, second the choice and definition of the homogeneity criteria and finally the iterative steps through which segmentation is completed. The block diagram in figure 3.7 illustrates the algorithm.

3.3.1 Identifying the Seeds

Any region growing algorithm start from a few isolated or group of pixels called seeds or seed regions respectively. Seeds pixel depend on the image feature's of interest and image type. The selection of the seeds pixels is crucial to the segmentation results since the decision for a candidate pixel to join a particular group is based on the comparison with between itself and seeds, thus any error in seeds will only worsen segmentation results.

In this algorithm the seed region is selected as follow:

- For an M x N size image $A(i, j)$ where $i=1,2,...M$ and $j=1,2,...N$

- First the value of the hottest pixel in the image is found:

$$\text{hot} = \max[A(i, j)]$$
Figure 3.7: Proposed Region Growing Algorithm
• All the pixels \( p \) in the image that correspond to the maximum value are found and called candidate seeds:

\[
S_k = A(i, j) = \text{hot} \quad \text{where} \quad k = 1, 2, 3 \ldots p
\]

• For each seed \( S_k \), the seed region is made of 9 connected pixels centered at \( S_k \) as in figure 3.8 configuration:

\[
R_k = \sum_{i=1, j=1}^{m,n} A(i, j)
\]

<table>
<thead>
<tr>
<th>A(i-1,j-1)</th>
<th>A (i-1,j)</th>
<th>A (i-1,j+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (i,j-1)</td>
<td>A (i,j)</td>
<td>A(i,j+1)</td>
</tr>
<tr>
<td>A (i+1,j-1)</td>
<td>A (i+1,j)</td>
<td>A (i+1,j+1)</td>
</tr>
</tbody>
</table>

Figure 3.8: Region Neighborhood Configuration

• For each labeled candidate seed region \( S_k \) the mean is calculated as follow:

\[
\mu_k = \frac{1}{mn} \left[ \sum_{i=1}^{m} \sum_{j=1}^{n} A(i, j) \right] \quad \text{where} \quad m = 3, n = 3 \quad \text{and} \quad k = 1, 2 \ldots p
\]

• From the candidate seed regions the one with the highest mean is selected to be the image seed region reference and the rest of seed candidate pixels and their regions are added to the background class.

\[
\mu_s = \max( \mu_k )
\]
• Once the representative seed region is selected we calculate the standard deviation between the seed and each of the other 8 pixels in the neighborhood:

\[ \text{Diff}_k = |S_k - R(i, j)_k| \text{ where } k=1,2 \ldots 8 \]

• The minimal deviation distance between the seed and its region is chosen:

\[ \text{Dev} = \min(\text{Diff}_i) \]

• Finally the minimal standard deviation value is squared and referred to as Minimal Deviation Distance MDD

\[ \text{MDD} = (\text{Dev}^2) \]

MDD value is then saved and will be later used in deciding if a particular pixels belongs to the object class or not.

Figure 3.9: Seed Image
Figures 3.9(a) and 3.9(b) illustrate an image and its corresponding candidate seeds respectively. The solid line on the contour is from the zero padding step that was performed during the pre-processing step.

### 3.3.2 Homogeneity Criterion

Once the representative seeds located, the algorithm proceeds by comparing pixels or regions to the seeds according to a pre-defined criterion. In this thesis the growing criterion was based on both region homogeneity and statistical information of each pixel.

- For each pixel in the background the considered region includes all the 8 neighboring pixels and the pixel itself as illustrated in figure 3.8. Then for that nine pixels sub-image the intensity mean is calculated:

\[
\mu_s = \frac{1}{mn} \left[ \sum_{i=1}^{m} \sum_{j=1}^{n} B(i, j) \right]
\]

- Starting in the upper left corner of the image each pixel mean is compared to the representative seed mean describe in section 3.3.1 by calculating the absolute distance between the two means:

\[
\delta = | \mu_B - \mu_s |
\]

### 3.3.3 Region Growing Test

The thermal images used in this study have only two main classes a large background class which characterizes the sound area of the material and small
bright areas regarded as defects. After the seed is selected the rest of the candidate seeds are first assumed to belong to the background.

A pixel that does not meet the criterion remains in the background otherwise it is a defect pixel.

Whether a pixel is admitted or rejected is based on the following criterion:

- If \( \delta \leq MDD \) then \( B(i, j) = 1 \)
- If \( \delta > MDD \) then \( B(i, j) = 0 \)

This step is done iteratively until all pixels are classified either as defects or background, resulting in a binary image where 1 represents defects and 0 the sound area.

3.4 Post-processing

Generally segmentation is followed by post-processing to enhance the results. Typically segmented images may have holes in large objects or isolated pixels that do not have connected neighbors to make their own regions. In this work the first problem does not exit because of the pre-processing. As to the second it can be resolved by morphological operations [13].

Fundamentally two techniques are mostly used in morphological operations of binary images: dilation which thickens an object as it fills holes and erosion which shrinks the object and removes undesirable pixels on the surface of the object. In both cases the extent of shrinking or thickening is controlled by a
structuring element. The two methods are very successful in trend removing after segmentation though they are known to change the size of the object.

Often dilation and erosion are used in various combinations. In this thesis in order to preserve the size of the defects is very crucial. To preserve the size of defects, most segmented images were subject to a Close-Open operation which is an erosion followed by a dilation using the same structuring element. In case dilation was applied to fill the holes in the segmented image. Figure 3.10 shows segmentation of an image containing the pvc pipe and in which dilation was applied for post-processing purpose.

![Image after Segmentation](image1.png) ![Image after Morphological Operations](image2.png)

(a) (b)

Figure 3.10: Morphological Operations Results
4. EXPERIMENTAL RESULTS AND ANALYSIS

In this chapter experimental results are presented both from Thermographic testing and form the implementation of the new region growing algorithm on the captured IR images.

4.1 Thermal Results

Three concrete blocks were subject of the testing in this work; two of the blocks with equal surface size 8 inch thick and 4 inch thick respectively were built with similar defects at the same spatial locations but at variable depths (see Appendix B). The third block was 4 inch also 45x 45 inches square and had no known defect. Both the two 4 inch blocks were heated for a period of 45 minutes and left to cool down while being observed with a thermal camera. Approximately 20 minutes later defects were best distinguishable in the images.

Figure 4.1: Thermal Results (4 inch)
Figure 4.1 is of the 4-inch thick specimen. Most defects are visible; D3 is on top, D2 in the far right, D1 in the lower right and D5 & D6 on the lower right side very close to each other that they almost appear as one defect, but if observed closely one can see a thin line between them. The air-filled defects appear as hot spots because air has low thermal conductivity and thus has poor transfer of heat.

In some cases by moving the camera closer to the objects detailed information was obtained such as in figure 4.8 where the PVC pipe V3 was detected by zooming in into a small region.

The larger specimen took longer to heat evenly; 85 minutes, and the cooling down process was slower. Figure 4.2 shows the 8-inch block’s thermal results.

Only three air-filled defects were detected in the image; D1, D5 and D6.

Figure 4.2: Thermal Results (8 inch)
The last image tested is of a four inch block with no known defects, the results are shown in Figure 4.3 and as expected there is no visible defect.

![Figure 4.3: Non-defective Specimen Thermal Results](image)

Table 4.1 summarizes results from applying active Thermography. The table features the defect size and their depths below the surface for both the two defective specimen tested. For the 4 inch block all the air-filled defects were detected except D4 which is the smallest in size compared to others and is at the maximum depth of 1.25 inch. On the larger block only 3 defects were detected and the maximum depth detected was 3 inch. Only one pvc pipe; V3 was detected in the 4-inch block by moving the camera closer to the specimen.
<table>
<thead>
<tr>
<th>Defect</th>
<th>Size (inch)^2</th>
<th>4-inch</th>
<th>8-inch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth (inch)</td>
<td>Results</td>
<td>Depth (inch)</td>
</tr>
<tr>
<td>D1</td>
<td>6</td>
<td>1</td>
<td>D</td>
</tr>
<tr>
<td>D2</td>
<td>3</td>
<td>0.75</td>
<td>D</td>
</tr>
<tr>
<td>D3</td>
<td>16</td>
<td>0.75</td>
<td>D</td>
</tr>
<tr>
<td>D4</td>
<td>2.25</td>
<td>1.25</td>
<td>ND</td>
</tr>
<tr>
<td>D5</td>
<td>12</td>
<td>1.25</td>
<td>D</td>
</tr>
<tr>
<td>D6</td>
<td>9</td>
<td>1.5</td>
<td>D</td>
</tr>
<tr>
<td>V1</td>
<td>0.5</td>
<td>1</td>
<td>ND</td>
</tr>
<tr>
<td>V2</td>
<td>0.25</td>
<td>0.5</td>
<td>ND</td>
</tr>
<tr>
<td>V3</td>
<td>1</td>
<td>1.25</td>
<td>D</td>
</tr>
</tbody>
</table>

D: detected, ND: Not Detected

Table 4.1: Overall Thermal Results

4.2 Transient Analysis

Figure 4.4 displays two temperature profiles of the four inch slab after heating it for 45 minutes. The data collection was done in two areas; one above air-filled defect D6 and the other above a sound area, near the defect. The
cooling down process was recorded for a period of 65 minutes with a 5 minutes time interval. The temperature sampling was done manually.

![Temperature Cooling Down Behavior](image)

**Figure 4.4: Temperature Decay Curves**

From the two curves in Figure 4.4 a thermal contrast was computed to illustrate the evolution of temperature differences between the area above the void and the area above a no-defect area with respect to time.

The following formulas were used:

\[ \Delta t = T_d(t) - T_{nd}(t) \]

\[ C(t) = \frac{\Delta t}{T_{nd}(t)} \]

Where \( T_d(t) \) is the temperature above a void and \( T_{nd}(t) \) is the temperature above a sound area. Then the graph in figure 4.5 was constructed. At first the two values are close indicating that the heating was even across the object surface, then as time progress the thermal contrast shows a sharp increase.
between 12-25 minutes and seems to peak around 25 minutes, after that the contrast signal weakens. The decreasing in contrast signal amplitude is due to the diffusion property, which will tend to make uniform the temperature distribution as the specimen cools down [4], until the whole block reaches a uniform temperature and is referred to as cold object. The contrast curve is often used in Thermographic analysis since it contains important information of the defects such as its thermal resistance and depths [4].

![Thermal Contrast Graph](image)

**Figure 4.5: Thermal Contrast**

### 4.3 Segmentation Results

The new automatic region growing algorithm was implemented on a total of five images; three of which are from the 4-inch block, one from the 8-inch and finally in order to validate the algorithm it was implemented on a non-defective
model image. In each case the original, the seed image, segmented image and image after post-processing are shown in figure 4.6(a), 4.6(b), 4.6(c) and 4.6(d) respectively.

The first image is of the 4-inch block and features defects D3 on top, D1 on the lower right side and D5 &D6 are appearing touching on the lower left corner of figure 4.6.

Figure 4.6: Segmentation Results (D1, D3, D5 &D6)
The second image shows one of the PVC pipes inserted into the 4-inch block. In this case the use of morphological operations was well needed in order to fill the holes in the segmented image. The results are shown in figure 4.7.

Figure 4.7: Segmentation Results (PVC pipe)
The third image that was tested is shown Figure 4.8. It contains defects D2 and D1 present in the 4 inch block. In this case the selected seed was a group of very few pixels located on defect D2.

Figure 4.8: Segmentation Results (D2, D1)
This next image in Figure 4.9 was captured from the 8-inch block only three defects are visible. In this case the algorithm tends to over-segment the image around defects D5 and D6 on top whereas defect D1 is on lower left side.

![Original Image](image1)

![Segmented Image](image2)

![Image after Segmentation](image3)

![Image after Morphological Operations](image4)

**Figure 4.9: 8-Inch Block Segmentation Results**

The segmented image shows defect D5 and D6 as one large defect, this can be attributed to the captured image size; the image shows only about a quarter
of the whole slab about a quarter of the whole slab that is why most of the image appear as warm since it only contains areas close to defects.

Finally the algorithm was implemented on a non-defected image (Figure 4.10). As expected since there is no defect the temperature all across the surface is uniform which should result in a single color segmented image.

Figure 4.10: Segmentation of a Non-defective Image

One point is barely distinguishable on the seeded image, if the algorithm was not taking into consideration pixel's spatial information, then segmentation
of such image would definitely result in false alarms. The only difference that is visible between the segmented image and its post-processed version is the solid black contour that is a result of the padding which was then removed by the open-close operation.
5. CONCLUSIONS

In this thesis work Active Thermography was applied to concrete in order to detect subsurface voids and structure failures. A new region growing based algorithm was developed and implemented to automate the inspection by segmenting the images into defected and good regions. From the experimental results the following conclusions were deducted:

- From Thermographic results the maximum depth detected was 3 inch
- The heating time of specimens was proportional to their size; 45 minutes for the 4-inch block and 85 minutes for the larger block
- In general air-filled defects were best detected than PVC pipes. Experimentally 83% of air-filled defects and 33% of the PVC inserted in the specimen were detected.
- No surface crack was detected. Since they are made of plexiglas which is a highly reflective material the emissivity is very low.
- Due to the amount of noise in the image, pre-processing was necessary and proven to be effective.
- The size of masking window during the smoothing operation greatly affects the segmentation outcome. In this case the masking window was limited to a size 3 x 3.
- The new segmentation algorithm is fully automatic; no prior knowledge of the object of investigation is required.

This study encountered two major problems:

1. Getting a homogenous heating pattern across a material in Thermography is a complex task, and this study was no exception. One suggestion made elsewhere in the literature [4] is to black-paint the surface to increase surface emissivity. The process has proven to be successful in aerospace industry where the airplane exterior is painted with a washable dark paint before thermal investigation, but since concrete is a very porous material the question rises; if black-painting won't change the material properties thus resulting in erroneous results.

2. The greatest challenge in this experiment was positioning the camera relative to the specimen. Due to the large size of the experimental concrete block and their horizontal position, though the camera was mounted on a tripod it was impossible to have a perpendicular view between camera and center of the block. Due to that inconvenience most of the captured images were distorted narrow on top and larger on the bottom.

   The fact that the PVC # 3 was detected, and not others, was attributed to the size of the tube. Though V3 was deeper beneath surface than V2 and V1 located at 1 and 0.5 inch below the surface respectively, these two were much smaller in size (see appendix B).
Overall the developed algorithm proven to be successful in segmenting the captured IR images into voids and sound areas, most of its success could be attributed to the fact that the segmentation takes into consideration the spatial and statistical information of the pixel.
6. FUTURE WORK

In order to verify consistency in the proposed algorithm we intend to implement it on many more images in the future for validation purpose.

Also now that the defects were located the next step will be to proceed to a more complete transient analysis and try to find the characteristics of the defects such as depth and size. We intend to use a video recorder to capture the IR data then transfer a series of images on a computer using a frame grabber.

Finally it would be interesting to extend this work to actual real bridges applying the passive Thermography approach, since bridge decks are covered with asphalt which has a higher emissivity 0.96 compared to concrete 0.92 defects visualization may be easier, and IR images less noisy.
REFERENCES


[21] R Huang K Ma. RGVis: Region growing based techniques for volume visualization.

Appendix A: Emissivity Tables
<table>
<thead>
<tr>
<th>Material</th>
<th>Temp °C/°F</th>
<th>E</th>
</tr>
</thead>
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<tr>
<td>Aluminum foil</td>
<td>27/81</td>
<td>0.04</td>
</tr>
<tr>
<td>Aluminum disc</td>
<td>27/81</td>
<td>0.18</td>
</tr>
<tr>
<td>Aluminum household (flat)</td>
<td>23/73</td>
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<tr>
<td>Aluminum (polished plate 98.3% pure)</td>
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<td>0.04</td>
</tr>
<tr>
<td></td>
<td>577/1070</td>
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</tr>
<tr>
<td>Aluminum (rough plate)</td>
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<td>0.06</td>
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<td>Aluminum (oxidized @ 599°C)</td>
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<td></td>
<td>599/1110</td>
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<tr>
<td>Aluminum surfaced roofing</td>
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<td>0.22</td>
</tr>
<tr>
<td>Aluminum colorized surfaces @ 599°C</td>
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<td></td>
</tr>
<tr>
<td>Copper</td>
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<td>0.18</td>
</tr>
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<td></td>
<td>599/1110</td>
<td>0.19</td>
</tr>
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<tr>
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<td>0.93</td>
</tr>
<tr>
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<td></td>
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<td>0.03</td>
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<tr>
<td>Brass (hard rolled - polished w/lines)</td>
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</tr>
<tr>
<td>(some what attacked)</td>
<td>23/73</td>
<td>0.04</td>
</tr>
<tr>
<td>Brick (red - rough)</td>
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<td>0.93</td>
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<td>Brick (silica - unglazed rough)</td>
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<td>Copper (plate heavily oxidized)</td>
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</tr>
<tr>
<td>Material</td>
<td>Density (kg/m³)</td>
<td>Reflection Coefficient</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-----------------</td>
<td>------------------------</td>
</tr>
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<td>Enamel (white fused on iron)</td>
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<td>Formica</td>
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<tr>
<td>Frozen soil</td>
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<tr>
<td>Glass (smooth)</td>
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<tr>
<td>Gold (pure highly polished)</td>
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<tr>
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<td>0.69</td>
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<td>Rolled sheet steel</td>
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<td>Lead (pure 99.9% - unoxidized)</td>
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<td>0.06</td>
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</tr>
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<tr>
<td>Paper (white)</td>
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<tr>
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<td>0.23</td>
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</table>
Appendix B: Concrete Specimen Information Tables
### 4 inch concrete block, defect specifications

<table>
<thead>
<tr>
<th>Flaw Type/Name</th>
<th>Length (Inch)</th>
<th>Width (Inch)</th>
<th>Thickness (inch)</th>
<th>X-Displacement (Inch)</th>
<th>Y-Displacement (Inch)</th>
<th>Depth from surface (inch)</th>
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<tbody>
<tr>
<td>D1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>33.5</td>
<td>26</td>
<td>1</td>
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<tr>
<td>D2</td>
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<td>26</td>
<td>30.5</td>
<td>0.75</td>
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<td>D3</td>
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<td>4</td>
<td>.5</td>
<td>13</td>
<td>24.5</td>
<td>0.75</td>
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<td>1.5</td>
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<td>23</td>
<td>18</td>
<td>1.25</td>
</tr>
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<td>4</td>
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<td>2</td>
<td>34.5</td>
<td>10</td>
<td>1.25</td>
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<td>3</td>
<td>1.5</td>
<td>31.2</td>
<td>10.2</td>
<td>1.5</td>
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<td>D7</td>
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<td>.5</td>
<td>24.5</td>
<td>39</td>
<td>1.5</td>
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<table>
<thead>
<tr>
<th>Flaw Type/Name</th>
<th>Diameter (Inch)</th>
<th>Length (Inch)</th>
<th>Y-Displacement (Inch)</th>
<th>Depth from surface (inch)</th>
</tr>
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<tbody>
<tr>
<td>V1</td>
<td>0.5</td>
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<tr>
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<td>7.5</td>
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<td>1.25</td>
</tr>
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<td>Thickness</td>
<td>Length (Inch)</td>
<td>Depth in Concrete</td>
<td>X-displacement inch</td>
</tr>
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<td>----------------------</td>
<td>-----------</td>
<td>---------------</td>
<td>-------------------</td>
<td>--------------------</td>
</tr>
<tr>
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<td>1 inch</td>
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<tr>
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<td>.5 inches</td>
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### 8 inch concrete block, defect specifications

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<th>X-Displacement (Inch)</th>
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<td>30.5</td>
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<td>N/A</td>
<td>N/A</td>
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<table>
<thead>
<tr>
<th>Flaw Type/Name</th>
<th>Diameter (Inch)</th>
<th>Length (Inch)</th>
<th>Y-Displacement (Inch)</th>
<th>Depth from surface (inch)</th>
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<tbody>
<tr>
<td>V1</td>
<td>0.5</td>
<td>12</td>
<td>37.5</td>
<td>3</td>
</tr>
<tr>
<td>V2</td>
<td>0.25</td>
<td>16</td>
<td>7</td>
<td>3.5</td>
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<tr>
<td>V3</td>
<td>1.0</td>
<td>12</td>
<td>16.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Crack</td>
<td>Thickness</td>
<td>Length (Inch)</td>
<td>Depth in Concrete</td>
<td>X-displacement inch</td>
</tr>
<tr>
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<td>30.5</td>
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<tr>
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<td>2 mm</td>
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<td>2 inches</td>
<td>3.5</td>
</tr>
<tr>
<td>C2</td>
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<td>2 inches</td>
<td>10.2</td>
</tr>
<tr>
<td>Crack three</td>
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<td>.5 inches</td>
<td>20.8</td>
</tr>
<tr>
<td>Crack four</td>
<td>3 mm</td>
<td>2</td>
<td>1 inch from surface</td>
<td>1.1</td>
</tr>
<tr>
<td>Crack five</td>
<td>1 mm</td>
<td>2.5</td>
<td>2 inches from surface</td>
<td>32.2</td>
</tr>
<tr>
<td>@ 315 angle C5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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