Chapter 1 – Introduction

1.1 Scope

There are currently 367,950 bridges (Bettigole, 1997) in service in the United States that incorporate concrete bridge decks into their design. The deterioration of these concrete decks is more rapid than any other bridge component and therefore most bridge decks currently require a complete replacement before the bridge superstructure needs to be replaced (Bettigole, 1997). Deterioration results from a variety of mechanisms, but the primary one is corrosion-induced concrete cracking (Weyers, 1993), which frequently results in delaminations. Tools for detecting distress that results from this deterioration have had undesirable limitations in the past and these same limitations extend to the detection of construction flaws. Meanwhile, the life cycle cost of maintaining concrete bridge decks increases when distress is not detected before it becomes too severe for effective bridge deck repair or rehabilitation (Weyers, 1993). This situation has prompted the Federal Highway Administration (FHWA) to contract Lawrence Livermore National Laboratory (LLNL) to develop two new prototype ground penetrating radar (GPR) systems for bridge deck analysis. These two systems offer unprecedented capabilities to generate three-dimensional data, which provide a representation of features that lie below the bridge deck surface. Due to the large amounts of data that both of these systems produce for an individual bridge deck, it is highly desirable to automate the characterization of bridge deck distress represented in the data. This study will focus on (a) collecting data from a variety of sample bridge decks using one of these prototype systems and (b) presenting the development and implementation of appropriate methods for automating data processing. This automated data processing will be accomplished using image processing and pattern recognition algorithms, introduced in Section 1.1.5 and described in detail in Chapter 3.
1.1.1 **Bridge deck distress**

The deterioration of bridge decks in the United States can be described by a variety of physical and environmental damage modes. For concrete bridge decks, the dominant mechanism is the chloride-ion-induced corrosion of reinforcing steel, which accounts for approximately 40% of the current backlog of highway bridge repair and rehabilitation costs (Weyers, 1993). A variety of other problems make up the remainder of bridge deck deterioration modes including structural cracking and chemical degradation of concrete. These two less common deterioration modes can frequently be detected using visual inspection techniques and chemical analysis because their effects are observed at concrete surfaces. However, flaws in bridge decks produced during construction such as subsurface voids (Figure 1.1) are usually difficult or impossible to detect using a visual inspection technique. Corrosion of reinforcing steel is also difficult or impossible to detect visually because the corrosion takes place beneath a cover layer of concrete. Corroding reinforcing steel produces a significant type of damage in concrete called a corrosion induced delamination (Figure 1), which is of particular importance for bridge inspection.

*Figure 1.1 Diagram of a concrete bridge deck cross section with delamination distress and void flaws.*
Corrosion induced delaminations are cracks in concrete bridge decks that form when reinforcing steel in the deck corrodes. This corrosion is generally caused by the presence of chloride ions, (from deicing salts) that have diffused through the cover layer of concrete and arrived in a moist location at the reinforcing steel surface. The corrosion process causes the volume that the reinforcing steel occupies in the concrete to increase by as much as 600 percent (Mehta, 1993). The reinforcing steel volume expansion applies pressure to the surrounding concrete, which eventually leads to cracking.

Delamination cracking generally propagates in the plane of the top reinforcing steel layer, which is typically 5 cm to 15 cm (2 in to 6 in) below the bridge deck surface. Eventually the delamination will propagate to the surface, causing the cover concrete to spall and form a pothole in the bridge deck. Spalls can cover large areas and compromise both the driveability and the integrity of the bridge deck surface. If a delamination can be located in the early stages of propagation, while it is beneath the surface, a small area of the bridge deck can be repaired or rehabilitated to remedy the problem. However, if the delamination progresses until it spalls, the problem can cover an extensive area and cost significantly more to repair or rehabilitate.

1.1.2 Infrastructure problems and current technological solutions

The ongoing deterioration problem with concrete bridge decks and other bridge components has been recognized for decades. Because a large proportion of highway bridges were built during the 1950’s, more bridges than ever before have recently reached the end of their forty to fifty year design life. Inspection programs have been instituted and standardized to evaluate bridge decks, but they have largely been limited to visual inspection methods, (Hartle, 97) which are frequently inaccurate. For concrete bridge decks with asphalt overlays, problems with visual inspection are compounded because visual evidence of significant distress is often hidden beneath the asphalt that covers deteriorated concrete. Technologies for evaluating deteriorating bridge decks have been developed, but they have significant drawbacks.

The chain drag test (ASTM D 4580-86, 1992) involves dragging a heavy chain over small areas of a bare concrete bridge deck, while a technician listens to the acoustic
response of the deck. Areas where significant delaminations have occurred often have an audible acoustic response that contains different frequencies than areas where sound concrete is located. These areas can be noted and marked as possible areas of delamination. This process is subjective, but it can be effective for bare concrete bridge decks where delaminated areas are large, (the accuracy and precision of this method varies with bridge deck geometry). Chain drag testing does not work on concrete bridge decks with asphalt overlays.

Another test that detects delaminated areas using acoustic responses is the impact-echo test (Sensalone, 1997). Impact-echo testing involves striking a concrete deck surface with a hammer or implement and subsequently measuring the acoustic response of the deck using an acoustic transducer, in contact with the deck surface, connected to an oscilloscope. High and low frequency responses are often observed in signals from delaminated areas relative to frequencies obtained from sound concrete areas. Precise measurements are difficult to make because impact energy varies with each strike. This makes impact echo data subject to erroneous interpretation.

Another test uses a half-cell potentiometer (ASTM C 876 91) to quantify the probability of corrosion in reinforcing steel beneath a concrete bridge deck surface. This is accomplished by measuring the electrical potential of the galvanic cell that is causing corrosion. The measurement requires direct access to the reinforcing steel and involves a significant amount of time to set up. Locations are chosen to make the measurements that provide a representative sample of the probability of corrosion that is occurring in the bridge deck reinforcing steel. This measurement is one of the few means of ascertaining a bridge deck’s overall potential for deterioration, but the measurement varies with the seasons and does not detect delaminated areas that have resulted from the corrosion process.

Corrosion rate measurements are another means of evaluating the deterioration of bridge deck reinforcing steel in-situ. Methods for measuring corrosion rate include the linear polarization technique and the AC impedance technique (Liu, 1996). The linear polarization technique uses a counter electrode to apply a cathodic current to the steel reinforcement, called the working electrode. Another electrode, the reference electrode, monitors the corresponding change in potential at the steel/concrete interface.
Measurements made at these electrodes and the Stern-Geary relationship allow the corrosion current to be computed (Liu 1996). If the area of the steel that is polarized is known, a corrosion current density can be calculated. Two commercial devices that use the linear polarization method are, K. C.Clear’s 3LP and Geocisa’s Gecor. The second technique, AC impedance, maintains the corrosion potential of the working electrode by applying a small amplitude sinusoidal voltage over an extensive frequency range. The response at each frequency is a sinusoidal signal with a different amplitude and phase shift relative to the input signal. The impedance can be decomposed into a resistive term in phase with the input signal and a capacitive term with a phase shift of 90 degrees. Through the Stern-Geary formula, the corrosion intensity may be calculated using these resistive and capacitive terms (Liu, 1996). Both linear polarization and AC impedance provide a measurement of the corrosion rate, but they do not measure distress damage in the concrete caused by the corrosion.

Evaluation technologies and techniques for concrete bridge deck inspection such as chain drag and impact-echo tests, the half-cell potentiometer, corrosion rate measurements, and a variety of other methods have demonstrated potential for improving bridge inspection efforts. However, these technologies each have significant limitations that prevent their regular use. These limitations include requirements for prolonged bridge closures, significant measurement uncertainty, and problems with using methods on decks with asphalt overlays. These uncertainties and problems are reflected in inaccurate assessments of bridge deck condition that occur on a regular basis. For many bridge decks, (particularly those that have asphalt overlays), currently available technologies are inadequate for accurately characterizing flaws or distresses that may be present.

Ground penetrating radar (GPR) is a nondestructive evaluation technology that has significant potential for improving bridge deck inspections, but it has many drawbacks in currently available configurations. In these typical configurations, GPR does not have fine enough resolution to detect many distress areas in concrete bridge decks. Concrete can be effectively evaluated by GPR systems that operate at very high frequencies and sample waveforms at closely spaced cross-range intervals, but these types of radar have only recently been developed. Because high frequencies reduce
penetration depth capabilities for radar, most GPR systems operate at low frequencies to provide deep penetration into the ground. Deep penetration is not crucial for bridge deck applications, where typical flaws and distresses are located in the top 15 cm (6 in) of concrete as measured through the thickness. This means that high frequencies can be used for bridge deck applications of GPR to improve resolution, as long as the signal has enough power.

Typical GPR configurations move a single radar antenna along a linear path to collect data, creating a two dimensional real aperture. This real aperture radar (RAR) data can be viewed as an image of reflected intensities by plotting collected waveform responses as a function of time along one axis and the waveform collection location on a second axis. An example of raw two-dimensional data from a GPR system is presented in Figure 1.2. In this example, strong reflections from a metal plate are observed as high |

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**Figure 1.2** Raw two-dimensional GPR data.
magnitude responses at approximately 2.0 nanoseconds and between 30 cm and 70 cm across the width. Expert interpretation is generally required to recognize features in the data, since radar responses are dependent on the scattering of the radar pulses at dielectric material interfaces. The resulting radar reflections are frequently complicated. Two-dimensional reconstructions that use backpropagation calculations on the RAR data to produce synthetic aperture radar (SAR) data can calculate the locations that radar reflections emanate from, (within physical limits). This reconstruction frequently makes radar images easier to interpret. However, the resulting two dimensional images still lack significant information that three dimensional data could provide.

Unlike typical systems, the two prototype GPR systems built by Lawrence Livermore National Laboratory (LLNL) collect data in three dimensions at high frequencies that range between 500 MHz and 5 GHz. The raw three-dimensional RAR data can be reconstructed using backpropagation algorithms to produce three-dimensional representations of target features beneath the bridge deck surface. The high resolution, three-dimensional data provides unprecedented opportunities for automating the detection and analysis of bridge deck distresses that will be discussed in detail in this study.

1.1.3 Principles of GPR systems

GPR systems provide information about subsurface features by taking advantage of the physical characteristics of microwave radiation propagation. Typical GPR systems use a transmitting and receiving antenna pair controlled by appropriate electronics to generate and detect radar pulses. A wide range of parameters can be examined to design a radar system, (Daniels, 1996) but the primary characteristics used to describe a typical system are its range, depth resolution, plan resolution and the clutter in the received signal. These characteristics are dependent on the radar system design and the materials that the radar pulse will be traveling through. These four characteristics will be described in further detail in this section after a brief description of electromagnetic wave propagation in dielectric materials.

Electromagnetic-wave propagation in one dimension can be represented by a one-dimensional wave equation, Equation 1.1 (Daniels, 1996). The propagation of the
electromagnetic wave is along the z-axis, with perpendicular electric (E) and magnetic (H) fields.

\[ \frac{\partial^2 E}{\partial z^2} = \mu \epsilon \frac{\partial^2 E}{\partial t^2} \]  

(1.1)

where the velocity of propagation is given by (Daniels, 1996)

\[ v = \frac{1}{\sqrt{\mu \epsilon}} \text{ meters/sec} \]  

(1.2)

and the velocity of light in free space is (Daniels, 1996)

\[ c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3 \times 10^8 \text{ m/s} \]  

(1.3)

where:

absolute magnetic permeability of free space, \( \mu_0 = 1.26 \times 10^{-6} \text{ H/m} \)

absolute electric permittivity of free space, \( \epsilon_0 = 8.84 \times 10^{-12} \text{ F/m} \)

absolute magnetic permeability of medium, \( \mu = \mu_0 \mu_r \)

absolute electric permittivity of medium, \( \epsilon = \epsilon_0 \epsilon_r \)

The relative permittivity \( \epsilon_r \) of a material changes the propagation velocity relative to propagation in a vacuum according to the following relationship (Daniels, 1996).

\[ v_r = \frac{c}{\sqrt{\epsilon_r}} \text{ m/s} \]  

(1.4)

At an interface between materials with different relative permittivities, a reflection is produced where the reflected field strength can be described by the reflection coefficient
The reflection coefficient has a positive value when $\varepsilon_{r2} > \varepsilon_{r1}$, for example where an air filled delamination crack exists in a concrete bridge deck. Equations 1.1 through 1.5 describe the propagation of electromagnetic-waves in dielectric media for ideal conditions. The brief discussion of radar system design in the following paragraphs provides some background for understanding the propagation of electromagnetic-waves through real materials that differ from theoretically ideal materials.

Range, resolution, clutter and noise must all be accounted for in the design of a radar system. In order to calculate an estimated range, the total path loss or attenuation the radar pulse experiences as it travels from the transmitting antenna to the target and reflects back to the receiving antenna must be considered. Three categories of loss contribute the most to the total. These categories are the material loss, spreading loss and target scattering loss (Daniels, 1996). Material loss occurs at material interfaces, (such as the air to concrete interface of a bridge deck surface), where a portion of the radar pulse is reflected and the remainder is scattered or transmitted. For radar pulses with normal incidence the reflection coefficient, Equation 1.5, can be used to compute the loss at each interface. Spreading loss is generally related to the inverse fourth power of target range for a point reflector, but will vary with the geometry of the target (Daniels, 1996). Targets such as line reflectors and planar reflectors will have a smaller spreading loss. Target scattering loss is caused by scattering from the target, away from the receiving antenna, and also varies with the geometry of the target.

Depth resolution determines the size of the target that can be resolved through the depth of the material under examination. The receiver bandwidth $B$, obtained by calculating the power spectrum of the received signal, can be used to determine depth resolution using the following equation (Mast, 1994).
\[
\Delta R_z = \frac{\nu}{2B}
\]  
(1.6)

Based on this estimate of depth resolution, the velocity of propagation through the medium, \(\nu\), and the bandwidth determine the depth resolution. The relationship shows that a broad bandwidth is desirable for high range resolution.

Plan resolution, (also called cross-range resolution), is important for detecting localized targets or for distinguishing more than one target at the same depth beneath the radar antenna. This type of resolution is measured in the two orthogonal directions relative to the range resolution. The plan resolution limit for a synthetic aperture radar can be estimated by (Mast, 1994)

\[
\Delta R_x = \max\left(\frac{\lambda_{\min}}{2}, \frac{\lambda_{\min}}{2\tan\left(\frac{\theta_a}{2}\right)}\right)
\]  
(1.7)

where \(\lambda_{\min}\) is the minimum propagating wavelength and \(\theta_a\) is the antenna beamwidth. Small wavelengths and large beamwidths are both advantageous for achieving fine plan resolution.

The following excerpt from Daniels describes clutter in GPR applications:

Clutter can be defined as response signals that are unrelated to the target scattering characteristics but occur in the same sample-time window and have similar spectral characteristics to the target…Clutter can be caused by breakthrough between the transmit and receive antennas as well as multiple reflections between the antenna and [material interfaces]…[Breakthrough can be reduced by careful design, but this can make the antenna] susceptible to “bridging” by dielectric anomalies on the near surface, which can degrade the breakthrough in a random manner as the antenna is moved over the ground surface. Local variations in the characteristic impedance of the ground can also cause clutter, as can inclusions of groups of small reflection sources within the material… In general, clutter is more significant at short range times and reduces at longer times, (Daniels, 1996, pp. 24).
Based on this description, clutter can affect the received GPR signal under a variety of circumstances. The amount of clutter in the signal is primarily determined by the antenna design, but it can also be affected by the geometry of the specimen being studied. Specimen boundaries and the relative location of features in the specimen can both contribute to signal clutter.

Dielectric properties of the materials scanned by a GPR system, (along with the specimen geometry and texture), determine the scattering that occurs at material interfaces. The reflection coefficient, Equation 1.5, was reviewed earlier in this section to illustrate how dielectric properties affect electromagnetic-wave propagation. For concrete bridge decks, the dielectric properties of concrete, asphalt, air, and water are of interest, along with the knowledge that reinforcing steel is a conductor. The typical ranges of the relative permittivities of the dielectric materials are (Daniels, 1996):

\[\varepsilon_r\text{ concrete (dry)} = 4-10\]
\[\varepsilon_r\text{ asphalt (dry)} = 2-4\]
\[\varepsilon_r\text{ air} = 1\]
\[\varepsilon_r\text{ fresh water} = 81\]
\[\varepsilon_r\text{ sea water} = 81\]

The reflection coefficient allows the magnitude of reflections at interfaces between these materials to be determined. At interfaces where reinforcing steel is present, an essentially undiminished reflection occurs with a phase shift of 180 degrees (Shadowitz, 1975).

Essential principles of GPR and electromagnetic-wave propagation have been presented in this section. The material presented here provides the necessary background for understanding further discussion of GPR concepts in Chapters 1 and 2 and the automated processing algorithms and results presented in Chapters 3 and 4 respectively.

1.1.4 The state of the art in ground penetrating radar for bridge deck applications

Ground penetrating radar (GPR) technology has been used for the nondestructive evaluation (NDE) of bridge decks since the 1970’s (Saarenketo et al., 1994). Cantor et
al. (1978) conducted initial tests using GPR on field bridge decks, which were followed in the 1980’s by their continued tests (1982) and more testing conducted by Clemena (1983), Kunz et al. (1985) and Manning et al. (1986). The results of this testing showed significant promise for GPR in determining asphalt pavement cover depths, reinforcing steel cover depths and for locating voiding and delamination distress beneath concrete bridge deck surfaces. Despite the technology’s promise for bridge deck applications, government transportation organizations and private industry did not promote its development much further until the 1990’s.

More rigorous tests, evaluating a variety of GPR systems in the lab and in the field, have been conducted from the early 1990’s up until the present. Important work was done by Alongi et al. (1992) that demonstrated delamination detection in field bridge decks and proposed a method for locating distressed areas. Problems with ground truth data for this study prevented definitive conclusions from being drawn, but significant progress was made. Maser (1995) showed that GPR systems can be developed that operate at highway speeds, and the attractive concept of evaluating a bridge deck without interrupting traffic flow brought the technology increased exposure. Mast (1993) developed algorithms that used synthetic aperture radar data to produce three-dimensional reconstructions of features, such as reinforcing steel in synthetic bridge deck specimens. Chung et al. (1994) and others measured responses to reinforcing steel and simulated distress in synthetic laboratory specimens for a wide range of configurations. The work carried out by Mast and Chung showed that responses to important internal features of concrete bridge decks, such as reinforcing steel and simulated subsurface cracking, could be detected with GPR under controlled conditions.

In order to perform the calculations for GPR reconstructions, determine an accurate range to a detected feature or generally interpret GPR data, accurate dielectric constants for the materials under evaluation are required. Al-Quadi et al. (1996) presented techniques for measuring the dielectric properties of concrete over the wide range of frequencies that GPR can operate in. This was important because concrete has a range of dielectric properties depending on its mix design, environmental exposure and the frequency content of the incident GPR pulse. This work addressed the variations in the dielectric properties of concrete over the frequency range of most GPR systems.
As responses to bridge deck materials and features became better understood and the amounts of data collected in testing increased, automated methods for processing data became desirable. Alongi et al. (1992) obtained interesting results by developing an automated thresholding algorithm based on reflected waveform characteristics from reinforcing steel. Again ground truth data from this study were not reliable. Udaya et al. (1995) developed a waveform synthesis model capable of back-calculating material properties such as water content and salt content based on GPR data from synthetic specimens. This study presented an interesting concept for GPR data processing under specific laboratory conditions. Shoukry et al. (1996) subsequently suggested the potential utility of pattern recognition techniques for evaluating radar waveforms in their research. They used a neural network classifier to evaluate a small sample of laboratory waveforms. The results were inconclusive, but this was attributed to the small sample of waveforms used in the analysis. More recently, Daxin et al. (1998) presented a paper that used a neural network method to identify the GPR response to a subsurface building over a two-dimensional synthetic aperture. This paper described an approach that was specifically tailored to a single experiment on raw two-dimensional data, but the concept of automated GPR data processing was illustrated.

Davidson et al. (1998) described a new generation of radar technology for highway applications embodied in two prototype systems built for the Federal Highway Administration (FHWA) by Lawrence Livermore National Laboratory (LLNL). Both of these field deployable systems were more amenable to new data processing techniques than their predecessors because the data they produced could be reconstructed in three dimensions, (as Mast had been doing in the laboratory in 1993). One of these systems was used extensively for this study. As a whole, this body of work chronicles the development of better systems, new capabilities for data collection, new ways of measuring material properties, GPR response modeling, and initial attempts to automate data processing.

The development of automated data processing has lagged behind other areas in these research efforts. Saarenko et al. (1994) pointed out that the greatest problem facing GPR surveys of bridge decks is the time-consuming, expensive manual interpretation of
the collected data. Since this statement was made, an effective method for automating the interpretation of GPR data from bridge decks has not been published.

1.1.5 Pattern recognition and its application to GPR data collected from bridge decks

“Pattern recognition” has been defined by Nadler and Smith as, “The process of identifying objects in images or data.” Pattern recognition engineering is concerned with developing the means to perform identification tasks with limited or no direct human intervention. The automatic recognition of characters on a printed page is an example problem that pattern recognition engineering has been applied to with significant success (Nadler, 1993). Due to the development of the digital computer, research in the area of pattern recognition increased tremendously in the 1960’s and has progressed significantly since then (Duda, 1972). The faster speed of computers and their increasing availability recently have prompted research into new applications for the technology, (Nadler, 1993) but the basic principles these applications rely on are grounded in previous work.

Ground penetrating radar data collected from bridge decks is one application where this technology has real potential for application development.

The pattern recognition field has two primary areas in which it has developed. These two areas are statistical pattern recognition and syntactic pattern recognition (Nadler, 1993). Statistical pattern recognition provides methods for classifying and identifying features in data based on statistical measurements of the data or features in the data. An example of this would be classifying apples and pears based on their height to weight ratio. Hypothetically, this ratio could be used to differentiate a particular variety of apples from pears, with an error rate that could be statistically measured. Syntactic pattern recognition uses sets of specific data sub-features, (which are known to be in data), that can be combined to classify a complete feature. An example of syntactic pattern recognition is the recognition of a word based on a combination of letters.

Statistical and syntactic pattern recognition methods each have their advantages, but the statistical approach is generally favored (Nadler, 1993). Devising even a single syntactic approach is very difficult and may be intractable for complicated data, while a variety of
reasonable statistical approaches can often be tested to solve a pattern recognition problem.

For any pattern recognition approach, the success of the method is reliant upon features of interest in the data that possess consistent measurements. The distribution of the feature measurements is a major factor in determining the error rate of a pattern recognition classifier and eventually determines whether a useful classifier can be designed (Fukunaga, 1972). In statistical pattern recognition, this error rate determination can be illustrated by examining distributions of feature measurements from two different classes, as shown in Figure 1.3. The distribution of measurement values for each class are normal and the class means are 60 measurement values apart. The optimum statistical pattern recognition classifier, (discriminant classifier), for this measurement uses Bayes decision theory (Box, 1972). This decision theory selects the distribution with the maximum likelihood to make correct classification decisions. For

![Figure 1.3 Distributions of measurement values for two feature classes.](image)
the illustration above, this means that class 1 would be selected as the appropriate
classification if a measurement value was lower than 68, (where the two distributions
intersect at a “decision boundary”) and conversely that class 2 would be selected as the
appropriate classification if a measurement value was higher than 68. The hash marked
area in the illustration represents classification errors that the Bayes method would
produce. For normally distributed data, a Bayesian classifier produces the minimum
error rate (Box, 1972).

Most classification problems require more than one measurement variable to meet
performance objectives and an n-dimensional measurement space is used to represent the
data. In these cases, class measurements can be plotted in up to three dimensions.
Beyond three dimensions, class measurements cannot be plotted and must be examined
by mathematical means or representative projections. Therefore, it is desirable to keep
the number of measurement variables small if possible. This results in a simpler
classifier based on data that can be plotted and examined graphically. However,
classifiers will often use data from many measurements to improve accuracy. For these
classifiers, and simpler ones, the locations of decision boundaries between classes are
optimized using systematic methods. The methods parameterize decision boundaries by
training a pattern recognition classifier. This training is based on the distribution of data
in measurement space and appropriate assumptions.

A variety of methods exist for training pattern recognition classifiers. Basic
methods, (such as linear discriminant analysis and quadratic discriminant analysis),
parameterize decision boundaries based on intersections of normally distributed data
(Duda, 1973). If data from each class is normally distributed in measurement space,
these analysis methods are frequently very effective. If the distributions of data in
measurement space are complicated and do not approximate a normal distribution, a
variety of methods including neural-networks can be used to parameterize decision
boundaries. Regardless of the choice of pattern recognition classifier, training data with
known classifications is used to train the classifier if it is available. If this training data is
not available, unsupervised learning methods can be used, but these are far less desirable
than supervised learning methods that use known training data.
Until recently, GPR data from bridge decks has been difficult to categorize based on a pattern recognition approach. It is still a very complicated problem, but the recent development of an effective method for generating three-dimensional tomographic images of interior bridge deck features has made real progress in this area possible. This method, (developed by Mast, 1993), uses wavefield backpropagation calculations, which will be described in Section 1.3.3. The images resulting from the calculations depict an estimate of the locations where radar reflections originate, (interfaces between materials with different dielectric constants such as concrete and air). Although these images contain some distortions, due to the physical limitations of radar, the features in these images are representative of the locations and shapes of the material interfaces in the concrete. Consistent imaging and the capability to define characteristics of interior bridge deck features, such as reinforcing steel and interior cracking, allow a pattern recognition approach to be used.

1.2 Bridge deck inspections

Concrete bridge deck inspections currently involve a visual examination of the top and bottom surfaces, (when visible), of the deck to locate distress that results from corrosion induced delamination, structural damage, and other physical and chemical problems with the concrete material. These assessments are effective for locating material degradation after it has manifested itself as a surface flaw, but detection at this late stage of deterioration is undesirable. Large damage and distress areas that have resulted from long term deterioration are very costly and difficult to repair or rehabilitate. If damage and distress goes undetected for too long, the deck may even have to be replaced. Life cycle costs of operating a bridge may be reduced significantly by detecting damage and distress early on, allowing repair and rehabilitation efforts to be focused on small areas. Tools that provide a means for detecting bridge deck distress in its early stages may make it possible to reduce life cycle costs and anticipate future costs with greater confidence.

Technologies such as the half-cell potentiometer, corrosion rate devices, the chain drag test, cover depth meters, chloride content measurements and impact-echo have been
developed to improve inspection capabilities for bridge decks, but they are not currently used in the majority of concrete bridge deck inspections. Each of these techniques provide significant information to bridge inspectors, but they require bridge closures and often provide insufficient or erroneous information (Bettigole, 1997 Appendix A).

 Appropriately configured GPR systems, (such as the prototype systems that will be described in later sections), have the potential to provide information about the location and extent of distress in concrete bridge decks that is currently difficult or impossible to obtain through other methods. These GPR systems can also be designed to detect distress in concrete decks that have asphalt overlays without removing the overlay or portions of the overlay, (although capabilities of GPR for this situation are still being evaluated). This capability is currently unavailable through any other means, which makes it a potentially major advance in distress detection technology. Useful GPR systems have been developed in the past, Section 1.1.4, but none have the combination of high range/cross-range resolution and capabilities to produce data amenable to three-dimensional backpropagation calculations that the prototypes described in later sections have.

1.2.1 Economic problems with current bridge inspections and potential improvements

Current practices for inspecting and maintaining bridges in the United States have identified large problems that categorized 136,000 bridges, from a total of 578,000 estimated to be in service, as structurally deficient and 130,000 as functionally obsolete in 1992 (Jones, 1992). Problems with these bridges have produced a backlog of repair, rehabilitation and replacement work that is believed to be even larger today than it was in that year. It is important that current inspection procedures have identified these problem bridges, clarifying the urgent need for bridge deck maintenance in particular. Bridge deck problems accounted for two-thirds of the obsolete or structurally deficient bridges in the United States, using current inspection practices, while bridge decks lasted approximately half of the average bridge service life (Wolchuk 1988). Current inspections cannot detect delamination cracking and other problems in bridge decks in the early stages, indicating that bridge deficiencies are likely to be worse than current
estimates. These current bridge inspection procedures do frequently identify material and structural problems that lead to bridge deficiency and obsolescence in their late stages, when damage and distress affects large areas. Significantly lower costs for repair or rehabilitation activities, along with more predictable life cycle costs may be achieved by detecting damage and distress early on.

The current bridge inspection program therefore meets one basic need of bridge management programs, identifying bridge damage and distress when it becomes critical to the integrity or safety of the bridge. However, meeting this basic need does not allow bridges to be managed economically or effectively. Managing bridges economically requires accurate data that reflects their current condition and the progress of distress damage in them. Bridge management that keeps bridges open and usable can only be accomplished when the integrity of the bridge structure and materials is understood over the service life, (particularly in the present), of the bridge and can be predicted with a degree of certainty in the future.

Improving on current bridge inspection practices requires the development of new tools, which will provide better information on bridge condition than current inspection practices. The high cost of current bridge maintenance and rehabilitation practices may be reduced with this improved information, but the cost reduction may only be realized by paying for improved inspection tools up front. Using the new tools on a large number of bridges will create the economies of scale necessary to keep these increased inspection costs at a minimum. The maintenance savings that may be achieved with the new tools should be much larger than the costs of using them if the new data is accurate. Current United States bridge maintenance costs are $400 million annually (Chase, 1998). Accurate data, in terms of distress detection in bridge decks, may reduce repair, rehabilitation and replacement costs to decrease this significant outlay.

1.2.2 Prototype ground penetrating radar (GPR) systems

Two new prototype GPR systems have been developed by Lawrence Livermore National Laboratory (LLNL) for the Federal Highway Administration’s (FHWA) Nondestructive Evaluation (NDE) Validation Center (Phares, 1999). These two systems were developed specifically for evaluating bridge decks. The first prototype is the
Precision Electromagnetic Roadway Evaluation System (PERES) (Davidson, 1998) and the second is the High-speed Electromagnetic Roadway Measurement and Evaluation System (HERMES). Each of these systems provides the capability to generate three-dimensional representations of interior bridge deck features, such as delaminations, voids, and reinforcing steel. These representations, which can be displayed as images, are generated by reconstructing collected synthetic aperture radar (SAR) data using wavefield backward propagation techniques (Mast, 1993).

PERES data is collected using a single antenna pair (Figure 1.4) that is mounted on a robotic cart (Figure 1.5). PERES creates a synthetic aperture by rastering the antenna over the area of the bridge deck that is under examination. The system has the capability to collect data with a 1 cm cross-range sampling density and operates in the frequency range between 500 MHz and 5 GHz. PERES uses integration of radar pulse returns to reduce the signal to noise, (here thermal noise is reduced), ratio. An individual

Figure 1.4 PERES transmitting and receiving antenna pair.
Figure 1.5  PERES robotic cart shown with transmitting and receiving antenna pair in the foreground.

Figure 1.6  Reflected waveform from a metal plate collected using PERES.
Figure 1.7 Power spectral density of the waveform in Figure 1.6.

Figure 1.8 HERMES trailer being towed across a bridge by a van.
reflected radar pulse from a metal plate, collected using a PERES antenna, is presented in Figure 1.6 and the power spectrum of this pulse is presented in Figure 1.7.

HERMES collects data using an array of sixty-four antennas that are mounted in a trailer (Figure 1.8). This trailer can be towed at highway speeds and the system is capable of acquiring data while driving at these speeds. The antenna array, located in the rear of the trailer, is coupled to a distance encoder wheel that determines the trailer’s position over the bridge deck. HERMES has a 3 cm cross-range sampling density for its synthetic aperture, which is lower than PERES. HERMES has essentially the same frequency bandwidth as PERES.

When PERES and HERMES are used to evaluate bridge decks in the field, it is anticipated that they will generally be used together. HERMES will acquire data from a bridge deck initially, providing a scan of the entire deck in a relatively short time. Where HERMES data indicates there are potentially flawed or distressed areas, PERES will be used to more accurately define the locations of these problems by taking advantage of its high resolution capabilities.

1.3 Bridge deck distress detection using PERES and HERMES

Both PERES and HERMES are currently being tested to determine their performance capabilities. Thus far, there have been more opportunities to test PERES, since this prototype was delivered to the NDE Validation Center first and is much simpler to operate than HERMES. The following discussion summarizes the basic principles which allow PERES to detect bridge deck features and subsequently provides initial descriptions of PERES data and a wavefield backpropagation algorithm that is used on the data.

1.3.1 Subsurface bridge deck feature detection using PERES

PERES detects subsurface bridge deck features using a radar that is specifically designed for this application. However, the system still operates using the same basic principles that typical radar systems are based on. A radar pulse is sent from a transmitting antenna and is received a short time later by a receiving antenna when
materials in the path of the radar pulse cause it to be reflected. The time delay between the transmission and reception of the pulse is related to the range to the reflector. The radar pulse is reflected when materials in the path of the pulse have different dielectric constants. Strong reflections are generated at interfaces between materials with extreme differences in dielectric constants, while weaker reflections result at interfaces between similar dielectric materials (Daniels, 1996). A phase change also occurs when a radar pulse passes through or reflects at an interface between two different dielectric media. When a radar impulse travels from a fast medium into a slow medium, (relative to air) the phase of the reflected wave changes from negative to positive, while the opposite phase change occurs when the pulse travels from a slow medium into fast one (Mast, 1993). At an interface between a dielectric material, such as concrete, and a conductor, such as reinforcing steel, a reflection with a nearly undiminished amplitude and a 180 degree phase shift results (Shadowitz, 1975).

The behavior of radar pulses in dielectric media can be exploited for applications in detecting anomalous areas in materials that are found in concrete bridge decks. Specifically the differences between the dielectric constants of concrete and air, (properties given in Section 1.1.3), allow corrosion-induced delaminations to be detected due to the concrete/air interface they introduce below the concrete surface. Similarly, conductive reinforcing steel can be detected in the dielectric concrete due to the strong radar reflections that result at the steel/concrete interfaces. Details on how these features are imaged using PERES will be provided in the following two sections.

1.3.2 Data interpretation

The first tests of PERES used a concrete bridge deck (R13) fabricated by FHWA (Figure 1.9) containing simulated distresses as well as reinforcing steel. The layout of the four simulated distresses in bridge deck R13 is presented in Figure 1.10, (a scale drawing of the plans for bridge deck R13 is presented in Figure C1, Appendix C). Each of the simulated distresses is a synthetic insert (materials are indicated in Figure 1.10).
Figure 1.9 A fabricated concrete bridge deck (in the picture foreground) at FHWA. The deck has dimensions of 1.83m X 3.66m (6 ft X 12 ft) and is designated by the label R 13.
Figure 1.10 Locations of simulated delaminations (synthetic inserts) in bridge deck R13.
Figure 1.11 Image of reconstructed magnitude data from depth=2.0 cm through depth=12.0 cm for bridge deck R13.
Figure 1.12  Image of reconstructed magnitude data at depth=4.0 cm from bridge deck R13.
embedded in the concrete deck. These inserts, which have varying thickness, were designed to provide information about the detection capabilities of PERES for a variety of target features. Data taken over bridge deck R13 will also have a wide variety of uses that will become apparent in future sections and chapters. Figures 1.11 and 1.12 show magnitude response images of reconstructed PERES data from bridge deck R13 in two different formats. Figure 1.11 is a plan view of the three-dimensional data visualized as a semi-transparent solid. In this format, the image data can be thought of as a stack of one hundred images that form the rectangular solid. The viewer looks through the data volume from top (depth=2 cm) to bottom (depth=12 cm). This is possible because all layers in the image are partially transparent, allowing the viewer to see data features throughout the volume. In this image, the 2.54 cm thick foam insert is clearly visible as a large magnitude response on the left hand side of the image that is predominantly yellow and has a rectangular shape. Visual cues from the 0.635 cm thick insulation material insert can also be observed in this image as areas of blue and light pink. However, this response is not particularly distinct in this image. Responses from the other two features in the bridge deck are not observed in the image. The grid pattern, indicated by predominantly blue areas, is indicative of the reinforcing steel mesh in the deck.

Figure 1.12 is a two dimensional plot extracted from the same PERES data presented in Figure 1.11. The Figure 1.12 plot presents response magnitudes from the deck at a selected depth. This can be thought of as taking a two dimensional slice (1 mm thick) out of the complete three dimensional data volume. The 2.54 cm thick insert is clearly visible as a high magnitude response represented in white, while the 0.635 cm thick insulation material is clearly discernable as a light colored area. Both of these areas are more clearly defined in this image than in Figure 1.11 because features are viewed without obstruction from intermediate layers. Again, the other two features in the deck are not discernable. This is primarily due to the extremely thin profile of the thin polyethylene sheeting, and lower dielectric contrast between concrete and polyethylene than the foam and insulation, \( \varepsilon_{\text{polyethylene}} \sim 3, \varepsilon_{\text{foam and insulation}} \sim 2 \) (Chen, 1994).

These sample data from PERES show that materials and features inside a concrete bridge deck that have different dielectric constants than concrete can be successfully
imaged. It also indicates that features with extremely thin profiles made from synthetic materials are difficult to detect and image. Based on these results the size and properties of materials that can be detected with PERES have been broadly characterized, but further tests of the system over a variety of bridge decks in this study (Chapters 2 and 3) will provide the best test of the system.

1.3.3 Backpropagation algorithm

Raw data from the PERES system does not represent target features in the familiar, visually appealing way that is presented in Figures 1.11 and 1.12. Instead, raw PERES data displays reflected energy from a broad beamwidth pulsed radar. The beamwidth of the radar is defined by a solid angle that subtends the area the antenna beam covers. This concept of beamwidth is presented in Figure 1.13.

![Figure 1.13 Conceptual drawing of PERES radar transmitting antenna beamwidth.](image)

Because PERES has a broad beamwidth (approximately 160 degrees), reflected energy returns to the receiving antenna from an individual target when the antenna is in several different locations (Figure 11).
Figure 1.14 Reflected pulses are captured for a single target feature when the antenna pair is in different locations.

When a target feature is centered below an antenna pair, (as illustrated by location 1 in Figure 1.14) the travel time for the reflected energy to reach the antenna is short. This travel time is increased when the antenna is translated to location 2 in Figure 1.14. Sampling reflected radar pulses at a regular time interval, after a single pulse has been transmitted, produces a return waveform. Capturing waveforms at evenly spaced intervals, (for example at several positions between location 1 and location 2), produces a real aperture. If the real aperture is produced along a linear path, a two dimensional real aperture is created. An image can be constructed from this two dimensional data (where space is on one axis and time is on the other), which allows the reflected magnitudes in time and space to be visualized. This visualization of raw data reveals that reflected energy from individual targets becomes spread out in time and space for raw real aperture radar (RAR) data, which produces images of target features that do not closely resemble
the original features. This same type of target feature distortion also occurs if RAR data is collected in three dimensions, as PERES data is.

To overcome some of the distortions inherent in raw RAR data, a wavefield backpropagation algorithm developed by Jeff Mast (Mast, 1993) can be used to convert raw three dimensional RAR data collected using PERES to reconstructed synthetic aperture radar (SAR) data that focuses energy back to its reflection sources. The details of this algorithm are not provided here, but the general principles the algorithm operates on can be defined succinctly. In basic terms, the wavefield backpropagation method reconstructs a source distribution by inverting the effects of the forward propagation of the wavefield from the source distribution to the receiving aperture (Mast, 1993). Some assumptions must be made to perform this operation. These assumptions include plane-to-plane wave propagation, scattering objects act independently, the medium is homogeneous between the scatterer and the synthetic aperture and sources in the distribution are invariant with respect to the location of the receiver (Mast, 1993). After this wavefield backpropagation has been performed, many of the difficulties inherent in visualizing radar data can be reduced or eliminated. The advantages and drawbacks of this method will become apparent in future chapters.

1.4 Data collection

Developing an effective pattern recognition algorithm for identifying distress and construction details in PERES GPR data from concrete bridge decks required significant data from a variety of sources. This type of varied data allows the algorithm to function properly for a range of expected inputs. The primary source of data was 12 concrete bridge deck sections cut to dimensions of approximately 1.8 X 3.7 m, (6 X 12 ft), and made available by the NDE Validation Center. Five of these deck sections had asphalt overlays, while seven were bare concrete decks with no asphalt overlay. Photographs of these 12 decks are provided in Appendix A. Many of the deck sections contained indications of distress, such as corrosion induced delaminations, that were visible at the cut edges, (Figure A12, Appendix A). PERES GPR data was collected from each of these twelve deck sections.
Another data source that contributed to the development of the pattern recognition algorithm was taken in the field from the Van Buren Street Bridge, (in Virginia approximately 1 mile South of I-95, Exit 52). Data was obtained from a location where delamination distress had been detected using a standard chain drag technique leading to its selection for scanning with PERES. Field data collection was limited to this particular location due to technical difficulties with PERES. Details about this data will be provided in Chapters 2 and 4.

A third category of data was obtained by scanning two experimental concrete slabs that contained known features. For one of the concrete slabs, these scans were repeated while overlays of different thickness were placed on it. This testing was performed in response to difficulties in testing and analysis that were encountered for the five asphalt overlayed concrete deck sections. Data from both concrete slabs contributed to a better understanding of PERES performance on asphalt overlayed decks.

In the future (after this dissertation has been completed) data will be collected from bridge decks using HERMES that will be in a compatible format with current PERES data. If the potential inconsistencies in the HERMES data (due to data collection with an array of 64 different antennas) are small, the pattern recognition algorithm developed for this dissertation will also have applications to this data. Analysis of HERMES data using the pattern recognition algorithm may be extremely useful for reducing the time and effort required for data interpretation in the future.
1.5 Dissertation objective

The objective of this study is to develop, test and evaluate pattern recognition algorithms that locate indications of distress and construction details in PERES ground penetrating radar (GPR) data from bridge decks. In addition, the performance of PERES will be tested and evaluated under a variety of conditions. PERES performance will be described in detail, particularly when it relates to pattern recognition algorithm performance and suggested hardware improvements.