2006

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Anthony Scott Mercer
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Autonomous Unmanned Ground Vehicle for Non-Destructive Testing of Fiber Reinforced Polymer Bridge Decks

**By
Anthony Scott Mercer**

**THESIS
Submitted to the
College of Engineering and Mineral Resources
West Virginia University**

**In partial fulfillment of the requirements for the degree of
Master of Science in Electrical Engineering**

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Morgantown, West Virginia

2006

**Keywords: FRP, Defects, Debonds, Delaminations, Infrared Thermography, Ground
Penetrating Radar, Unmanned Ground Vehicle**

Abstract

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Anthony Scott Mercer

The objective of this research is to develop an Unmanned Ground Vehicle (UGV) that can autonomously gather data for analysis of FRP bridge decks. Both ground penetrating radar (GPR) and infrared thermography (IRT) have shown promise in the field of non-destructive detection of defects in FRP decks. Even though both technologies can be effective, they each have certain limitations. For example, GPR is sensitive to water-filled defects while IRT is more sensitive to air-filled defects. This thesis investigates the effectiveness of combining and automating the data acquisition for each technique. Since both IRT and GPR analysis are subjective in nature, automating the data collection, including the heating preparation required with IRT analysis, involved with surveying an FRP deck may allow for a more objective analysis of the FRP deck. The reliability of the autonomous data acquisition of the UGV was assessed, as well as the effectiveness of combining IRT and GPR. Experimentation with various heat sources showed that passive heating should not be used for autonomous data acquisition. Testing showed that active heating with a strong heat source produced good quality IR images a reasonable amount of time. Analysis of these IR images with various image processing techniques, such as fuzzy c-means clustering, automatic defect detection schemes with approximately 87.5% detection rates could be implemented. An Unmanned Ground Vehicle (UGV) was created that combined an active heating system, an IR camera, and GPR analysis. A pipelining process was implemented that allows the UGV to perform the autonomous data acquisition as efficiently as possible. The UGV was then used to evaluate the effectiveness of combining IRT and GPR. Due to laboratory limitations, no actual testing was done that incorporates both analysis methods simultaneously. However, results show that the data collected can be used to determine both air and water filled defects and will provide valuable data when combined.

Acknowledgements

While I would like everyone to think that I made it through college without help from anyone, we all know that is not true. Hard work and determination are important, but they can only get you so far in life. Blood, sweat, and tears need to be balanced with family, friends, and fun in order to be a well adjusted successful person. Without the support of my professors, my friends, my brothers, and my family I would never have made it through all the trials and tribulations.

My advisor, Dr. Klinkhachorn deserves a good deal of credit for finally getting me to think like a professional, instead of student. I have always been a good student. Teachers would give me an assignment and I would get it done and get my “A.” This way of working is fine for school, but in the real world you are not always given exactly what needs to be done. An engineer needs to be able to determine what needs to be done and decide on a course of action even when he is only given small pieces of an enormous puzzle. While I still have a ways to go, Dr. Klinkhachorn has helped me a lot with this aspect of my character.

As far as my research goes, Caleb Hing deserves a lot of thanks because he helped me collect all the preliminary data and taught me how to use the GPR module. The guys in the NDT lab also deserve thanks for allowing my stuff to clutter up their work space for so long.

Aside from my research, I have a few other people that deserve my thanks in shaping my life and my education. I would like to thank my family at home for always believing in me. I would also like to thank my fraternity brothers. They were my family when I was away from home and were always there for me, day or night. My cousin Josh deserves some thanks as well for reminding me that sometimes you just have to blow off some steam by doing something other than work. Also, I would also like to thank my wife Jenny. Throughout college she was always there with an ear to listen to my problems and a slap in the face whenever I would freak out.

Lastly, I would like to thank the Constructed Facilities Center at West Virginia University for funding this research as a part of a research grant from U. S. Department of Transportation - Federal Highway Administration (USDOT-FHWA) grant number DTFH61-05-C-00004.

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List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
IR	Infrared
IRT	Infrared Thermography
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
GPR	Ground Penetrating Radar
SDK	Software Development Kit
UGV	Unmanned Ground Vehicle
FHWA	Federal Highway Administration
GUI	Graphical User Interface
FCM	Fuzzy C Means

Chapter 1

Introduction

1.1 Background

Roadway infrastructure deterioration within the United States is a serious concern of civil engineers in this country. According to the Federal Highway Administration (FHWA) approximately 27% of the 594,220 bridges in the United States are either structurally deficient or functionally obsolete [1]. Even with billions of dollars devoted to the repair or replacement of these structures, the current design practices and technologies used by America's civil engineers may not be enough to overcome the deterioration of our infrastructure. The answer to this problem may lie in the research of new technologies. To this end, scientists and engineers have begun to experiment with new materials for civil infrastructure construction and repair.

Fiber Reinforced Polymer (FRP) composite is one such material that is gaining prominence in civil engineering infrastructure systems. FRP composites, as the name indicates are composites of different materials. Glass or carbon fibers are used for stiffness and tensile capacity. Resin is added to solidify the fibers into a strong matrix for high compressive strength. Various other additives are added to improve the polymer's mechanical and physical properties. Detailed information about the manufacture of FRP and its useful properties has been previously studied and published [2]. Because of its properties, such as high strength, a high stiffness to

weight ratio, resistance to fatigue, exceptional durability, and high resistance to environmental conditions, FRP bridge decks are being considered for replacing old concrete bridge decks.

With the introduction of new technology comes the need for ways of assessing and analyzing those technologies. Effective condition monitoring techniques for FRP materials need to be developed in order to detect subsurface cracks, determine the onset of structural failure, estimate any structural degradation, and locate any structural damages. Such techniques are necessary to evaluate the quality and integrity of a structure in the field. FRP bridge decks are susceptible to debonds, a subsurface defect that is present at the interface between the wearing surface layer and the underlying FRP deck, and delaminations, a defect present within the top or bottom flange of the FRP deck. These defects can lower the load carrying capacity and decrease structural integrity. Hence it is necessary to develop techniques that can effectively monitor the FRP deck for defective areas.

1.2 Research Objective

This research aims at building a UGV to autonomously analyze an FRP deck. To accomplish this objective, the following steps have been taken:

- Conduct a literature review on the advantages and disadvantages of IRT and GPR in regards to analysis of FRP bridge decks.
- Combine IRT and GPR analysis to create a robust subsurface defect detection system.
- Design and build a UGV to provide autonomous data acquisition for FRP decks analysis.
- Provide recommendations for future research to improve the autonomous data collection and defect analysis.

1.3 Scope

The aim of this research was to investigate the effectiveness of combining IRT and GPR in the hopes of creating a robust subsurface defect detection system for use with FRP decks. IRT data analysis through automated image processing algorithms designed to improve defect

detection is also explored. An active heating element to be used in conjunction with the IRT analysis performed by the UGV was also researched. The scope of this research also includes methods for shortening the data acquisition time for the IRT analysis.

1.4 Organization

This thesis is organized into six chapters. The first chapter gives a brief introduction to the objective and scope of this research. The second chapter contains a literature survey on the effectiveness of infrared thermography and ground penetrating radar when used as separate defect detection methods. In the third chapter, the design of the active heating element used by the UGV is described. In the fourth chapter, the data acquisition method of the UGV, the control algorithms, and the physical implementation are explained. The experimental setup for testing the UGV and the results are described in the fifth chapter. Next, the sixth chapter expresses the conclusions drawn from the research and presents some suggestions for future work. Lastly, the appendices provide a user's manual describing how to set up the data acquisition of the UGV, how to operate the UGV, and how to get the data from the UGV after testing.

Chapter 2

Literature Review

2.1 Introduction of Infrared Thermography

Infrared thermography (IRT) is a non-destructive testing technique that uses thermal images to detect voids, cracks, and delaminations in decks and pavements [8]. The thermal images, which are commonly called thermograms, use shading, intensity, or color to represent different surface temperature levels. Figure 2-1 shows a thermogram of an FRP deck that has been heated and allowed to cool.

Figure 2-1 Thermogram of an FRP deck

The principle behind IRT is that subsurface defects will affect the rate of heat flow through a deck, which will result in temperature differences on the surface of the deck. The bright yellow spots in the image are artificial air filled defects. The air acts as an insulator allowing less heat to pass through the material. This causes the material above the defective area to heat to a higher temperature than the surrounding area, thus allowing a tester to identify a defect in the deck.

Some of the advantages of IRT in regards to civil engineering applications are:

1. IRT is a non-contact evaluation method so no damage to existing civil engineering structures will result from analysis.
2. Since the data generated by IRT analysis is a thermal image it is easier to interpret when compared to other methods like GPR or ultrasound.
3. An infrared image can cover large area so the time required for testing a structure can be reduced.

4. IRT only measures thermal radiation emitted from a surface. As a result no radiation is generated by the test equipment that could be harmful to the person conducting the analysis.
5. IRT is able to detect air filled defects very well.
6. The entire process of capturing and analyzing the thermal images can be automated.

While there are quite a few advantages, IRT also has some downsides. Some of the disadvantages of IRT are:

1. The cost of thermal imaging equipment can be fairly high. While there are more affordable IR cameras around in today's market, someone wanting to perform IRT could expect to pay \$15,000 to \$75,000 or more for a reliable IR camera.
2. Since IRT only measures surface temperature, the accuracy of defect detection will decrease if the depth of the defect increases.
3. Abrupt changes in temperature, such as high winds, could affect the surface temperature therefore affecting the quality of defect detection.
4. Smaller defects cannot be detected as readily as larger defects. The reason for this is smaller defects does not affect the thermal conductivity of the area as much as larger defects because of their decreased surface area.
5. Water filled defects are hard to detect. This can present problems because some defects are caused by water getting trapped in or between materials.
6. This testing requires some type of heat source. Passive heating, such as heating from the sun, may be used, but may not be reliable due to factors such as differences in heating throughout the day. This creates a disadvantage because for reliable results the weather must accommodate the surveyor or the surveyor must provide some type of active heating with a heater.

Even though IRT analysis has many useful characteristics for civil engineering application, it is limited by its dependence on a heat source. Most IRT applications rely on solar heating to prepare a surface for IR imaging. The data collection therefore is dependent on location, weather, and season, among other factors. Active heating, which is heating with

heaters, has been proposed as an alternative to of solar radiation by Infrasense Inc [25]. This research used vehicles with mounted pavement heaters to prepare a bridge deck surface for IR imaging. Results obtained from this research show that short durations of intense constant heating provide infrared analysis that is comparable to longer durations of solar heating.

Research conducted by the Constructed Facilities Center (CFC) at West Virginia University (WVU) has shown that IRT can be used to defects in FRP decks [12]. THE CFC researchers used both active and passive heating to evaluate the quality of IRT analysis on FRP decks. The results from this research show that IRT can be used to accurately detect subsurface defects in FRP decks.

Infrared Thermography has also been used in other FRP health monitoring research. The CFC subjected FRP deck specimens with plan dimensions of 24” x 12” to accelerated aging and used IRT to monitor the decks [11]. Simulated defects were embedded in the decks during construction. The specimens were placed in pH3 solutions (acidic) and then subjected to freeze-thaw cycles in an environmental chamber. Infrared Thermography was used to observe the growth of the existing defects and the formation of new defects. The CFC also used IRT to observe the effects of fatigue loading on FRP decks with embedded defects [10].

Like all digital images, the infrared images that are generated from IRT analysis can be subjected to automated image processing algorithms. There has been some success in automating defect detection in IR images. A study by Gajanan Lonkar at West Virginia University involved creating a MATLAB based defect detection system for IR images [21].

2.2 Introduction to Ground Penetrating Radar

Ground penetrating radar (GPR) was first used by the U. S. Army for detecting mines during the Vietnam War [14]. GPR is a non-contact technique that uses an antenna to transmit electromagnetic energy into a surface [8]. The energy that is transmitted is reflected back by interfaces between materials with different dielectric properties. This reflected energy is then

collected by the antenna, converted to voltage levels, and combined to form a waveform. Figure 2-2 shows a GPR waveform.

Figure 2-2 GPR waveform

The different dielectric properties of the materials are the reason that GPR works. For example, the circled area on the left of the image represents aluminum tape placed on top of an FRP deck. Since aluminum reflects virtually all electromagnetic radiation, the interface between the air and the aluminum tape, which have very different dielectric properties, shows up as a bright spot near the top of the waveform. The other circled areas represent water filled debonds between a wearing surface layer and an FRP deck. They are lower in waveform because they are underneath another layer of material. The dielectric properties of FRP and water are different enough to allow some electromagnetic waves to reflect off the interface of the two materials. In this way, GPR is able to detect subsurface defects and other object such as steel drums, rebars, etc.

Some of the advantages of GPR in regards to civil engineering applications are:

1. Very fast data acquisition.
2. The GPR unit is completely self-contained. This means that the system is fully mobile and can be deployed with minimal preparation.
3. GPR analysis requires no pre-test preparation, such as heating. This decreases the overall analysis time.
4. GPR is able to detect water filled defects very well.
5. GPR testing can be performed in any type of weather.
6. Defect depth can be determined with GPR.

While there are quite a few advantages, GPR also has some downsides. Some of the disadvantages of GPR are:

1. The cost of thermal imaging equipment can be fairly high.
2. Air filled defects are hard to detect. This is because that the dielectric properties of air are similar to FRP.
3. The data is harder to interpret than other methods.

GPR is used in a variety of applications. Defect detection in civil structures is not the only application of this technology. The FBI uses GPR in forensic applications to detect subsurface objects, such as buried bodies [19].

Even though the applications of GPR are varied, the data processing techniques remain the same. Since the GPR survey equipment produces a visual representation of the reflected radar waves, most of the actual analysis is done visually. This creates a very subjective data analysis. It is possible to eliminate this subjectivity of the analysis by introducing some signal processing algorithms. Signal processing algorithms have been applied to GPR data to improve the GPR capabilities in terms of damage localization, identification and diagnosis of the causes [17].

2.3 Combining IRT and GPR

While IRT and GPR are generally employed separately, based on the experience of the person performing the tests, it may be beneficial to use both methods during testing. The advantages of one method can be used to leverage the disadvantages of the other technology. For example, since one of the major disadvantages of IRT is the fact that it requires a temperature difference to detect structural defects, a heat source of some kind must be used. For situations where passive heating can be used, like on a hot sunny day, this is not a major issue. However, such sunny days are not always available. On the other hand, GPR is not limited by temperature and can be used even on cold days. Also, since GPR has been found to be sensitive to water-filled defects and IRT is more sensitive to air-filled defects, a combined system would be able to detect both types of defects. Finally, since IRT can only be used to detect defective areas near the surface of a deck or structure, the GPR can compensate for this weakness because it has the ability to penetrate deeper into the material.

Research has been conducted on the feasibility of combining IRT and GPR. Donald Jackson, Federal Lands Division of the Federal Highway Administration (FHWA), evaluated the results of both techniques with regard to FRP wrapped concrete columns [17]. It was found that GPR was a useful tool for monitoring progressive deterioration of the concrete inside the FRP wrap. It was also observed that IRT is very effective in detecting blisters and shallow defects, as well as entrapped moisture between the FRP and the concrete. These results show that the IRT and GPR results compliment each other.

Kenneth Maser at Infrasence Inc. took this research one step further by setting up a Case study involving the evaluation of the bridge decks of the two Grand Island Bridges, which are over the Niagara River [24]. This study used infrared cameras in conjunction with standard color video cameras to discriminate between infrared anomalies caused by defects and surface conditions. This study also used GPR data collected from a 1 GHz air launch horn antenna attached to a test vehicle traveling 20-30 mph. The results from each method were then combined. The results were then tested by taking core samples from the defective areas of the

bridge deck. The core samples were taken from locations that the IRT and GPR analysis determined were defects. From all of this data it was concluded that 5 of 8 core samples were from defective areas. It was also observed that both IRT and GPR methods may overestimate or underestimate the degree of delamination. Lastly, the combination of IRT and GPR was found to provide a reasonable estimate of the total quantity of concrete which is either damaged or in questionable condition.

2.4 Automating IRT Analysis with Fuzzy C Means clustering

Since IRT analysis is performed by analyzing IR images, image analysis techniques can be employed to automate the detection of subsurface defects. Many different algorithms, such as thresholding, contouring, and morphology, have been used to identify defects in IR images. One of the more powerful methods is Fuzzy C Means clustering.

Fuzzy C Means clustering (FCM) is an unsupervised data clustering technique wherein each data point belongs to a cluster to some degree that is specified by a membership grade [21]. This technique was introduced as an enhancement to hard clustering methods in which a data point either belongs to a cluster or it does not. It can group multidimensional data into a finite number of data clusters. Image segmentation is a common use of FCM and a procedure using fuzzy clustering has been exploited by researchers such as Horvath [15]. Modified versions of the fuzzy clustering algorithm have also been used in the field of medical imaging [16]. For the algorithm to work an initial guess of the cluster centers must be made. For example, in image analysis a cluster would be a 3 dimensional $\langle x, y, z \rangle$ vector where the first and second dimensions correspond to the image coordinates and the third dimension corresponds to the pixel value. Most of the time, this initial guess is incorrect, but it provides a reference for future calculations. Every data point is also assigned a membership grade for each cluster. This value is a number between 0 and 1 that represents how well the data point fits in a certain cluster. A higher membership grade means that it is likely that the data point belongs in that cluster and not the others.

After the initial guess of the cluster centers, the membership grades are updated. This process calculates the Euclidean distance between the actual data and the cluster centers. The results are then used to update the membership grades. The cluster centers are then updated with the new membership grades and the process is repeated. The end result is that the cluster centers move toward the centers of data clusters in the original data.

2.5 Summary

Based on previous research in this area, a system combines IRT and GPR would be advantageous to the field of non-destructive testing. The system should incorporate active heating, as well as automated data analysis, to reduce the survey time and increase the reliability of the results.

Chapter 3

Design of Active Heating System

3.1 Need

The increased use of FRP composites in many civil engineering applications has made it highly important that engineers know how to detect subsurface defects in FRP decks. Naturally an engineer would want to gather data quickly with as little work involved as possible. Both GPR and IRT have shown promise in the field of non-destructive detection of defects. Even though both technologies can be effective, they each have certain limitations, which can mean that some defects may be missed due to the inability of the technique to recognize it. A logical decision then would be to combine both technologies to see how they can be used together given their combined strengths and weaknesses. For example, since one of the major disadvantages of Infrared Thermography is the fact that it requires a temperature difference to detect structural defects, a heat source of some kind must be used. For situations where passive heating can be used, like on a nice sunny day, this is not a major issue. However, such sunny days are not always available. This means that IRT testing cannot be used on-demand, but can only be used whenever the weather is convenient. On the other hand, GPR is not limited by temperature and can be used even on cold days. There are other ways that one technology complements the other. GPR has been found to be sensitive to water-filled defects; infrared thermography; however, is more sensitive to air-filled defects. By combining GPR and IRT a more complete analysis of subsurface defects can be achieved.

Also, it would not be very cost effective for someone to conduct an IRT analysis of a deck and then a GPR analysis of the same deck. Saving time and money, as well as not having to stop traffic for an extended amount of time, are some reasons it would be prudent to develop some sort of automated way that an engineer can perform both tests simultaneously.

3.2 Active Heating System

Before any actual design work can be done on any project, a design criteria must be determined. A design for a system that will house both IRT and GPR must take into account that, while both techniques can be used to detect defects in an FRP deck, they are inherently different technologies. IRT uses thermal radiation to measure differences in temperature over defective and non-defective areas to analyze an FRP deck. This means that a heating source of some kind is required so that data can be collected. This makes heating the FRP deck a crucial part of the design of the UGV. This chapter will discuss research into an active heating system to be mounted onto the UGV that will be used to prepare the FRP deck surface for analysis.

3.2.1 Simulated Defect Samples

Simulated defect samples were used for both the research into the active heating system as well as the testing of the defect detection of the UGV. The first type of simulated defect was an air filled void built directly into a Glass Fiber Reinforced Polymer (GFRP) bridge deck specimen. These specimens, which were constructed to be similar to the ones used in GFRP bridges, were bridge deck modules that were 2' x 1' (0.6m x 0.3m) in size. The GFRP decks were composed of E-glass fibers and polyester resin combination. The specimen also had a wearing surface layer 3/8" (9.5 mm). The specimen contained simulated 3" x 3" and 2" x 2" debonds that were located between the 3/8" wearing surface and the underlying FRP deck. Figure 3-1 shows a sample GFRP deck specimen.

Figure 3-1 Bridge deck specimen with embedded defects [32].

The second type of simulated defect involved wearing surface slabs with notches cut out on the underside of wearing surface that were then placed on FRP decks. This was done to simulate debonds between the wearing surface and the top of the FRP deck. These notches were either left empty to simulate an air filled debond or filled with a water pouch to simulate a water filled debond, and could be changed during testing to create different defect scenarios. These simulated defects were created by Vasudevan [32] and Cheng Hing [14] to facilitate their research. These simulated defects were used during both the GPR and IRT testing. Figure 3-2 shows the bottom side of a wearing surface slab with one 2 inch x 2 inch simulated air filled debond and two simulated water filled debonds, which had plan sizes of 3 inches x 3 inches and 4 inches x 4 inches.

Figure 3-2 Bottom side of the wearing surface slab showing 2 water filled debonds (left and right sides) and 1 air filled debond (center) [14].

3.2.2 Experimental Setup for Determining the Best Heating Source

Passive heating from the sun was considered along with active heating provided by various electric and propane heaters. Regardless of the heat source used for the testing, analysis for each case was conducted using the same method. The GFRP bridge deck specimen with embedded defects was used. The specimen was heated for a specific amount of time. If the test involved cooling, the specimen was then cooled with liquid CO₂, for a specific time. IR images were then recorded using a FLIR ThermaCAM S60 IR camera. A set duration of recording time was not specified but for analysis only the first 50 seconds of each trial was used. It was experimentally determined that after 50 seconds nothing new would appear on the images and if something else did appear that it was well outside of a reasonable analysis time.

3.2.3 Issues with Passive Heating

Using passive heating, such as the sun, would be the most cost efficient heating alternative. To assess sunlight as a viable option, a solar heating test was conducted. The specimen was left outside for 1 hour on sunny days where the ambient temperature was 60°F (day 1), 70°F (day 2), and 80°F (day 3). During all tests, the specimen was left outside at 1:00pm and the temperature readings were taken at 2:00pm. Previous research indicated that this time of day would produce good results [32]. Figure 3-3 shows the difference in surface temperature between the two defect areas (3 inches x 3 inches and 2 inches x 2 inches) and the surrounding defect free areas for day 1. Figure 3-4 shows the resulting IR image from the same day. Figures 3-5 and 3-6 show the data acquired from the testing on day 2. Figures 3-7 and 3-8 show the data acquired from the testing on day 3.

The results of this test show that when using solar heating as a heat source, large defects can be seen easily with IR imaging. This is not ideal because smaller defects would evade detection. Active heating, as shown in the next section, allows for smaller defects to be seen. Another reason using solar heating is not feasible for automated image acquisition is that various objects, such as clouds, trees, and guard rails, can block sunlight from getting to some areas of the deck. This would lead to differences in the heating of the deck and unreliable data collection.

Figure 3-2 Temperature Differences from day 1.

Figure 3-3 IR image of specimen from day 1.

Figure 3-4 Temperature Differences from day 2.

Figure 3-5 IR Image of specimen from day 2.

Figure 3-6 Temperature Differences from day 3.

Figure 3-7 IR image of specimen from day 3.

3.2.4 Testing of Active Heating Methods

Since passive heating has been shown to be unreliable for autonomous data collection, testing was done to determine the best active heating method. Three different heaters were analyzed. The first heater was a 5000 BTU quartz heater, model number 7260, designed by W.B. Marvin Mfg. Company. The second was a 9000 BTU propane convection heater, model number MH9B, designed by Mr. Heater. The last was a 35000 BTU forced air propane heater, model number SPC35, designed by All Pro Portable Heaters. Figures 3-9, 3-10, and 3-11 show the 5000 BTU, the 9000 BTU [37], and the 35000 BTU heaters [38], respectively.

The first test was conducted indoors using the 5000 BTU electric heater. Trials were conducted with heating times of 10 seconds, 20 seconds, and 30 seconds. In addition, the effectiveness of cooling via liquid CO₂ was also tested. In one trial, the deck specimen was heated for 10 seconds and then cooled for 2 seconds. In other trials, the same procedure was used with 20 and 30 second heating times. Figures 3-12 through 3-23 show the temperature differences and resultant IR images for all the trials.

Figure 3-8 5000 BTU Electric Heater.

Figure 3-9 9000 BTU Propane Heater.

Figure 3-10 35000 BTU Forced Air Propane Heater.

Figure 3-11 Temperature Differences after heating for 10 seconds with 5000 BTU quartz heater.

Figure 3-12 IR image after heating for 10 seconds with 5000 BTU quartz heater.

Figure 3-13 Temperature Differences after heating for 20 seconds with 5000 BTU quartz heater.

Figure 3-14 IR image after heating for 20 seconds with 5000 BTU quartz heater.

Figure 3-15 Temperature Differences after heating for 30 seconds with 5000 BTU quartz heater.

Figure 3-16 IR image heating for 30 seconds with 5000 BTU quartz heater.

Figure 3-17 Temperature Differences after heating for 10 seconds with 5000 BTU quartz heater and CO₂ cooling.

Figure 3-18 IR image after heating for 10 seconds with 5000 BTU quartz heater and CO₂ cooling.

Figure 3-19 Temperature Differences after heating for 20 seconds with 5000 BTU quartz heater and CO₂ cooling.

Figure 3-20 IR image after heating for 20 seconds with 5000 BTU quartz heater and CO₂ cooling.

Figure 3-21 Temperature Differences after heating for 30 seconds with 5000 BTU quartz heater and CO₂ cooling.

Figure 3-22 IR image after heating for 30 seconds with 5000 BTU quartz heater and CO₂ cooling.

The result of these tests was the demonstration of improved defect detection using a small heater. The images in Figures 3-13, 3-15, and 3-17 clearly show the larger defect on the left. The smaller defect is not visible in the 10 second trial, somewhat visible in the 20 second trial, and fully visible in the 30 second trial. Also, it can be seen that the addition of a cooling step after heating can produce slightly better visual results; however, there is a slight decrease in the temperature difference between the defect and defect-free areas. This difference is less noticeable as the heating times increase because higher heating times force more heat below the surface and as a result takes more effort to remove. Also, care has to be taken that the cooling does not negate the effects of the heating. An example of this can be seen in Figure 3-23. The larger defect is less defined after the cooling than it was in the corresponding trial without cooling.

Despite the promising results from this test, this heating method was not implemented in the UGV design. This heater runs at 1500 Watts. This would place a significant drain on the UGV batteries. For this reason other heating methods were explored.

The next test involved testing with a 9000 BTU propane convection heater. The heater used a small 1 lb. propane tank. The logic behind this test was that a stronger heater would require less heating time to produce the same results. Trials 1, 2, and 3 were conducted with heating times of 10 seconds, 20 seconds, and 30 seconds, respectively. In addition, cooling via liquid CO₂ was implemented. In trial 4, the deck specimen was heated for 10 seconds and then cooled for 2 seconds. Figures 3-24 through 3-31 show the temperature differences and resultant IR images for all the trials.

Figure 3-23 Temperature Differences after heating for 10 seconds with 9000 BTU propane heater.

Figure 3-24 IR image after heating for 10 seconds with 9000 BTU propane heater.

Figure 3-25 Temperature Differences after heating for 15 seconds with 9000 BTU propane heater.

Figure 3-26 IR image after heating for 15 seconds with 9000 BTU propane heater.

Figure 3-27 Temperature Differences after heating for 20 seconds with 9000 BTU propane heater.

Figure 3-28 IR image after heating for 20 seconds with 9000 BTU propane heater.

Figure 3-29 Temperature Differences after heating for 15 seconds with 9000 BTU propane heater and CO₂ cooling.

Figure 3-30 IR image after heating for 15 seconds with 9000 BTU propane heater and CO₂ cooling.

The results of this test were less promising than previously expected. The reason for this is the method of heat conduction. The 9000 BTU heater is designed to operate standing vertically. It cannot be turned so that heat is directed downward because then it would run the risk of catching fire and eventually exploding. This meant that during the test the specimen also had to be standing vertically. This limited the affected area on the specimen. This could possibly have been avoided if the specimen were moved back and forth like the 5000 BTU heater was during its testing. The size and weight of the deck specimen; however, prevented this from being done easily. Since the UGV was designed to survey FRP bridge decks, and bridge decks are generally horizontal not vertical, this heating method could not be used. Even though it may have produced viable data, it would be highly unsafe.

Still holding with the idea that a stronger heating method would produce more efficient results, a 35000 BTU forced air propane heater was tested. Trials 1, 2, and 3 were conducted with heating times of 10 seconds, 20 seconds, and 30 seconds, respectively. Figure 3-32 through 3-37 show the temperature differences and resultant IR images for all the trials.

Figure 3-31 Temperature Differences after heating for 5 seconds with 35000 BTU forced air propane heater.

Figure 3-32 IR image after heating for 5 seconds with 35000 BTU forced air propane heater.

Figure 3-33 Temperature Differences after heating for 10 seconds with 35000 BTU forced air propane heater.

Figure 3-34 IR image after heating for 10 seconds with 35000 BTU forced air propane heater.

Figure 3-35 Temperature Differences after heating for 15 seconds with 35000 BTU forced air propane heater.

Figure 3-36 IR image after heating for 15 seconds with 35000 BTU forced air propane heater.

The results of this test showed that even after only 5 seconds of heating a temperature differences of 2 degrees can be observed around the 3” by 3” defect. Both the large defect and the smaller defect were clearly visible, though the temperature difference of the small defect was not as large as expected. One of the main highpoints for the forced air heating is that it provides a uniform heating, which is preferable in IR analysis. This was the heating method chosen for implementation on the UGV because it provided uniform heating and only minor modifications are needed to be able to mount it on the UGV.

3.2.5 Design of Active Heating System

After performing the preliminary IR analysis with a number of heaters, the 35000 BTU forced air heater was chosen because of its fast consistent heating and reliable defect detection. Since this heater forces air forward to heat a surface, it provides very direct, even heating. The only downside is that the heater is oriented so that it directs heat forward and not down. Since it would not be safe to operate the heater in an orientation other than the designed direction, an aluminum heat shroud was designed to conduct the heat produced by the heater down to the FRP deck. This shroud is 6 inches x 6 inches at the top and expands to 13 inches x 13 inches at the bottom. The heater was then mounted to an aluminum box to allow for air circulation and cooling of the deck before IR imaging is done. The heater was then inserted into the cone through a hole cut in one side. The fan that originally came with the heater was replaced with a PWM controlled motor [39] so the strength of heating could be controlled. Two adjustable cooling fans were also added to the heating system to provide optional cooling steps. From the research conducted in the previous sections, it can be determined that better results are observed if there is sufficient time between heating and temperature measurement. This design, with its two cooling sections, provides this time delay. Figure 3-38 shows a block diagram of the final design for the active heating element.

Figure 3-37 Block Diagram of the Active Heating Element.

3.2.6 Testing of Active Heating System

Before mounting the active heating element onto the UGV it had to be tested. These tests were conducted to look for accurate results and structural durability. For these tests, wheels were mounted onto the sides of the heating element with strips of FRP angle bar so that it could be moved easily. The heater was then placed on an FRP deck with embedded defects and turned on. It heated the deck surface for 15 seconds and then was moved forward so that the next area could be heated. Figure 3-38 shows the temperature differences resulting from this test. Figure 3-39 shows the resulting IR image

Figure 3-38 Temperature Differences after heating for 15 seconds.

Figure 3-39 IR image after heating for 15 seconds.

The results of this test showed that this design produced even heating and could be used very reliably in the UGV design. The 3 inch x 3 inch defect in on the left of the image is clearly visible. The 4 inch x 4 inch defect in on the right of the image is visible, but not completely clear. It is clear that something is there but we cannot determine its exact shape. The discontinuities in the middle of the image come from human error when moving the heating element across the deck. These minor errors are virtually eliminated; however, when the heating element is mounted on the UGV. The reason for this is the movement of the heating element is more precisely controlled by the motors and encoders on the UGV as compared to simply using human judgement to move the heating element the correct distance.

3.3 Summary of Passive and Active Heating

Passive heating is not a feasible heating method to be used in conjunction with the UGV due to various problems, such as dependency on weather and possible uneven heating. By using active heating, the UGV will avoid the problems that can occur with passive heating. It can be observed from the data presented in this chapter that a stronger active heating source allows for faster defect detection in the IR images. The active heating system that was designed is able to produce good quality IR images after heating a FRP deck for only 15 seconds. This heating time of 15 seconds produces a combined preparation time of 45 seconds (15 seconds of heating and 2 stages of cooling at 15 seconds each).

Chapter 4

Design of UGV

4.1 Design Goals

The overall goal of this research is to produce a UGV capable of surveying an entire FRP bridge deck with both IRT and GPR analysis. The UGV will be expected to perform this task quickly and efficiently. The UGV is also expected to perform its task autonomously, with little or no human intervention. To accomplish this task, an approach called pipelining was incorporated into the UGV design.

4.2 Pipelining the Analysis Process

The pipelining process basically divides the overall task of analyzing an FRP deck into smaller tasks, such as GPR analysis, heating, cooling and IRT analysis, and performing these subtasks in a sequential order. The active heating system, described in the previous chapter, was designed with this idea in mind. Its task, which is to prepare the deck surface for IRT analysis, is divided into smaller tasks, heating and cooling. Afterwards, a section of the active heating system was designated to perform each subtask. This subdivision of labor allows the active

heating system to prepare the FRP deck in stages. Figure 4-1 shows the pipelining that the active heating system performs.

Figure 4-1 Pipelining of Active Heating System.

The diagram shows how the pipelining process can streamline the preparation of the FRP deck. When the process begins, at time T0, nothing is happening because this represents the start of analysis. The heating of the first section is done at time T1. At time T2, heating is performed on the second section of deck while the first section is going through a cooling stage. Time T3 marks the beginning of heating for the third section of deck while sections 1 and 2 are undergoing cooling stages. This process continues until each section undergoes 1 heating stage and 2 cooling stages. Based on this method, a design for the actual implementation of the UGV was developed. Figure 4-2 shows a block diagram for the layout of the UGV.

Figure 4-2 Block Diagram of UGV Layout.

This incremental model allows the pipelining process to be extended to include the entire UGV. Figure 4-3 shows the pipelining process for the UGV.

Figure 4-3 Pipelining Performed by the UGV.

This pipelining method attempts to minimize the amount of time it takes to survey an FRP deck. GPR analysis is conducted first. This is because one of the strengths of GPR is the detection of water filled defects, and the heat generated by the active heating system may decrease the amount of water present in any such defects. After GPR analysis is conducted, the deck surface can then be prepared for IRT analysis by the heating and cooling stages. At the end of time period T5 an IR image of the FRP deck surface is obtained. After this point, IRT analysis will be conducted at every interval because the next section of deck has already been prepared.

Now that the method of movement for the UGV has been determined, the next step in the design process is to decide on the movement and time intervals that will be implemented in the pipelining process.

The movement intervals are determined by the size of defects that can be detected with IRT and GPR. The smallest defect that can be detected reliably by IRT and GPR is approximately 2 inches by 2 inches [14, 32]. Another factor that was considered was the area that each GPR antenna could survey. Each GPR antenna has a 6 inch wide footprint. Two antennas can be used simultaneously to provide the UGV with the ability to survey a 12 inch wide strip. Since the maximum width of the GPR analysis is 12 inches, the IR images that were collected from the IR camera were cropped from 320 pixels by 240 pixels to 240 pixels by 240 pixels by eliminating area on the sides of the image. This means that the IR images will now have a 12 inch by 12 inch area of interest. Because of this, every 20 pixels in the image correspond to 1 inch of the deck, which correlates into a minimum defect size of 40 pixels by 40 pixels. This was experimentally determined to provide sufficient data to analyze the IR images.

The timing intervals are determined by the heating and cooling times required to produce good IRT analysis. It was experimentally determined during the active heating system design that generally no new defect information will be collected from an IR image after 50 seconds. It was also determined that longer heating times produce clearer defect images. For these reasons, a timing interval of 15 seconds was implemented by the UGV. This gives a heating time of 15

seconds and a cooling time of 30 seconds. This ensures a long heating duration to produce clear IR images and more than enough cooling time to allow any defects to be seen on the IR image.

The last element of the design is to determine how to apply this pipelining process to an FRP deck. Most FRP decks are rectangular. This simple geometry lends itself very nicely to the pipelining scheme. The deck can be divided into strips. The UGV can analyze one strip of the deck and then turn around and analyze the next strip. Figure 4-4 shows a graphical representation of this analysis scheme.

Figure 4-4 Method of Analysis for FRP Deck.

The UGV can start at one end of the deck. It will then move in 12 inch increments to collect both GPR and IRT data using the pipelining method. When it gets to the end of the deck, the UGV can then turn around. After turning, it will analyze the next strip of deck. It can then continue in this fashion until the entire deck is surveyed. Using this method with the pipelining is very efficient. Using intervals of 15 seconds with 1 foot increments means that surveying an FRP deck that is 50 feet long by 20 feet wide would take approximately 4.6 hours.

While this method provides an efficient way to survey an FRP bridge deck, it does not completely survey the deck. The reason for this is that the GPR antennas can only distinguish data in the direction of motion. Basically since the antennas have a 6 inch footprint, any defects detected in that 6 inch area will show up as a defect in the resulting waveform. This means that to completely acquire GPR data on an FRP deck data must be collected in one direction and then data must then be collected in the perpendicular direction. Figure 4-5 shows a diagram of the data acquisition described here.

Figure 4-5 Complete GPR survey of an FRP deck

This method of data acquisition was not implemented on the UGV for a couple of reasons. First this method of data acquisition only benefits the GPR data collection. This is because that the IR images that are taken by the UGV are 2-D images that have both a length and a width. Performing this type of data acquisition would essentially mean that each area of the FRP deck would be surveyed twice with IRT for every one time with GPR. The other main reason that this method was not implemented would be that it would increase the overall survey time considerably. If one was to consider the same 50 feet long by 20 feet wide FRP deck discussed earlier, this method would add another 5.2 hours to the overall analysis time. This would more than double the aforementioned time of 4.6 hours.

4.3 Physical Implementation of UGV

Figure 4-6 shows the final implementation of the UGV. Figure 4-7 shows a block diagram of how the various components of the UGV are connected.

Figure 4-6 Final Physical Implementation of UGV.

Figure 4-7 Hardware block diagram of the UGV.

The UGV was designed to accommodate the pipelining technique discussed earlier. This means that the UGV has 3 basic sections: the GPR analysis section, the active heating system, and the IRT analysis section.

The front section of the UGV contains the GPR antennas used for analysis. The 1.5 GHz antennas [7] that were mounted on the UGV have an analysis footprint of approximately 6 inches. Since the UGV would be surveying 1 foot wide strips of an FRP deck at a time 2 of them were mounted. The antennas themselves are housed in a plastic tray. This tray rides along the ground and protects the antenna from wear and tear by providing a buffer between the ground and the antennas. The plastic tray allows the radiation emitted by the antennas to pass directly through it and into the deck surface for analysis. The antennas are connected to a SIR-20 GPR data acquisition system [30] designed by Geophysical Survey Systems, Inc, which is located on the upper deck of the UGV.

The active heating system is located in the middle of the UGV. This positioning allows the active heating system to prepare the FRP deck for IRT analysis. IRT analysis is done by a FLIR ThermaCAM A20M infrared camera [5]. This 320x240 resolution camera takes infrared images of the deck and sends them via a firewire connection to a laptop computer located on the upper deck of the UGV. Figure 4-8 shows a picture of the ThermaCAM A20M camera.

Figure 4-8 FLIR ThermaCAM A20M infrared camera. Picture taken from FLIR website [5].

The UGV frame itself is made out of 1.5 inch x 1.5 inch fiberglass T-slotted bar. These bars are very sturdy, corrosion resistant, and are non-conductive to lessen electromagnetic interference on the GPR system.

To allow the UGV to move, a 12V DC motor from NPC Robotics [27] was mounted on each side of the UGV. A VICTOR 883 motor controller from IFI Robotics [16] was used to control each motor. Figure 4-9 shows a picture of the VICTOR 883.

Figure 4-9 VICTOR 883 Motor Controller. Picture taken from IFI website [16].

On each motor, a modified VEX optical shaft encoder [33] was installed to monitor the velocity of the UGV by counting the revolutions of the motor. Figure 4-10 shows the 12V DC motor with the modified VEX encoder mounted.

Figure 4-10 12V DC motor with modified VEX encoder.

To provide enhanced mobility, omni-wheel casters [2] were used as front and rear wheels. These wheels have rollers on their sides to decrease the amount of friction when the wheel is sliding. By using these wheels, the UGV minimizes its skid and steer friction. Figure 4-11 shows a picture of the omni-wheels.

Figure 4-11 Omni-wheel used for front and rear wheels.

The UGV is powered by two 17 Ah Gel Cell lead acid 12V batteries. One battery is used to power a 300W AIMS Power pure sine wave inverter [1] which is mounted on the underside of the upper-deck. The power inverter provides AC power to the GPR data acquisition system, the controlling laptop, and the IR camera. Figure 4-12 shows a picture of the AIMS power inverter.

Figure 4-12 AIMS power inverter.

The second battery is used to power the motors, the motor controllers, and the heating and cooling motors [39]. The UGV uses two batteries because this isolates each circuit. This means that a stall in a motor, for example, would not cause a drop in power for another component.

At the heart of UGV is a VEX robot controller [34]. This controller is mounted on the underside of the upper-deck. The VEX robot controller is responsible for generating the PWM signals that will control the motors. It also reads the optical encoders and uses a PID control algorithm to autonomously control each motor's velocity.

4.4 Autonomous Control of UGV

The autonomous movement and data acquisition of the UGV will be controlled by a laptop computer located on the upper deck of the UGV. Figure 4-13 shows what the GUI on the laptop looks like.

Figure 4-13 GUI Application on the Controlling Laptop.

This program controls the data acquisition and motion of the UGV. For information pertaining to the use of this program consult Appendix C found at the end of this thesis. Autonomous data acquisition begins when the operator clicks the “Enable Auto Acquisition” button. Figure 4-14 shows a flow chart of the basic control algorithm.

Figure 4-14 Flow Chart for Autonomous Movement and Data Acquisition.

4.5 Automatic Defect Detection in IR images

Since the goal of this research is to develop a fully functional defect analysis system for FRP decks, automated image analysis algorithms have been implemented to provide defect detection. The goal was to create a detection algorithm that was robust, but at the same time

could perform the analysis quickly enough to be implemented on the UGV for real time defect detection. Image processing algorithms have already been implemented for analyzing IR images for defects [13]. While these algorithms have shown good capabilities in identifying defects, their processing times and their implementation do not allow for their use in real time applications. To this end, 3 different algorithms were developed to detect defects from the images that the UGV generates. The first is a very simple, but highly effective, method consisting of grayscale thresholding. The second algorithm is a similar algorithm but it does its thresholding on the actual temperature values of the IR images instead of the grayscale pixel values. The last algorithm uses a fuzzy C-means clustering algorithm on the temperature data to cluster like values together.

4.5.1 Analyzing IR images with grayscale thresholding

The grayscale thresholding algorithm that was first implemented uses the grayscale image captured from the camera for its data. The grayscale pixels are subjected to a simple algorithm involving 2 basics steps: gray level quantization, and thresholding. The first step, gray level quantization, is done to make different gray levels easier to distinguish. By reducing the image from 256 gray levels to around 12 gray levels, makes the edges of each region in the image much more defined. To reduce the number of gray levels, a cumulative histogram is obtained. This histogram is divided into 2 regions at the median of the histogram. Each new region is divided again at its new median. The process continues until there are 12 regions. The gray values that fall in these regions are then remapped to the average pixel value of that particular region. Figure 4-15 shows the histogram of an image on the left and the histogram of the same image after quantization.

Figure 4-15 Histogram of an Image before and after grayscale quantization.

The second step is thresholding. Since the image has been quantized into fewer grayscale values, the threshold is simply the highest pixel value of the image. Any pixel that is less than the threshold is changed to black and any pixel that is equal to the threshold is changed to white. The image is then inverted and combined with the original IR image. The end result of this step is that it removes everything in the image except the pixels that are the same intensity as the whitest spots, which usually correspond to defect areas. Figure 4-16 shows an image of an FRP deck specimen with two embedded defects, a 2 inch x 2 inch air filled defect in the upper section and a 3 inch x 3 inch air filled defect in the lower section.

Figure 4-16 Defect Analysis of FRP Specimen with Built-in Defects using Grayscale Thresholding.

In this test this basic algorithm performed well. Both defects in the specimen were detected. It is a simplistic algorithm so the data processing time is small, typically less than 0.5 seconds. This fact coupled with the success of defect detection in the test images led to the conclusion that this algorithm could be implemented on the UGV for real time analysis of defects. After being implemented, images were collected from the UGV and analyzed with this method. The images captured the UGV are not as clear as the test images shown in Figure 4-15. There is noise present and the defects are not as easily seen. As a result, the algorithm does not

perform quite as well at analyzing the images obtained by the UGV as it does with the test images. While it does detect the defects that are present in the images, the algorithm tends to generate a lot of false positives, which are cases where the algorithm finds a defect where none exist. Figures 4-17, 4-18, and 4-19 show images obtained by the UGV and the resulting defect images.

Figure 4-17 IR image of 2" x 2" air filled defect and results of analysis by grayscale thresholding.

Figure 4-18 IR image of 3" x 3" air filled defect and 2" x 2" air filled defect and results of analysis by grayscale thresholding.

Figure 4-19 IR image of 2" x 2" air filled defect and 3" x 3" air filled defect and results of analysis by grayscale clustering.

In Figure 4-16 the defect is clearly visible in the original image, and is highlighted in the defect image. There is much more highlighted in the defect image than just the defect. This is caused by those pixels being grouped together with the defect pixels during quantization. The images in Figure 4-17 show very good defect detection. The defects are clearly discernible in the defect image. The results from Figure 4-18 also show good defect detection. The problem with this set of images is that the 2" x 2" defect in the top part of the image is not recognized. This is because the defect is faint and almost blends in with the surrounding pixels. This algorithm tends to work well on images where the defects are visibly discernible. Since the whole point of automated detection algorithms is to detect defects that are not visible to the naked eye, this algorithm also had to be tested with images that were not as clear. Figure 4-20 shows an image obtained by the UGV where the defect is not clearly discernible and the results when analyzed with this algorithm. The circles of the left image denote where the simulated defects are embedded.

Figure 4-20 Fuzzy IR image of 2" x 2" air filled defect and 3" x 3" air filled defect and results of analysis by grayscale clustering.

While the highlighted areas are centered on the actual defect location, some noise can be observed in the defect image. Overall, the grayscale thresholding algorithm does produce very fast, moderately accurate results with fairly simple unsophisticated techniques.

4.5.2 Analyzing IR images with temperature thresholding

Since the basic idea behind computer aided image analysis is to detect objects in images that a human observer would not be able to see, a more accurate analysis method had to be implemented. While grayscale images are easier to visually inspect, the temperature data may actually provide more precise analysis. The temperature thresholding algorithm uses the temperature data captured by the camera to perform its analysis. The entire image is thresholded with a set temperature value. If the temperature value at any point in the image is greater than the threshold then the corresponding pixel in a grayscale image is highlighted. This is done so the defects can be seen visually when the analysis is done. The threshold is then increased and the process is repeated again. The levels are chosen so that each temperature level represents, at the most, a range of 0.025°C. This means that since the most of the images have approximately 10°C difference between the lowest and highest temperature values, there will end up being 400 temperature levels. The end result is a series of images that represent temperature levels in the

data. Figure 4-21 shows how the progression of the temperature levels throughout the execution of the algorithm.

Original Image	Threshold Level 50	Threshold Level 60

Threshold Level 70	Threshold Level 75	Defect Image

Figure 4-21 Progression of temperature levels during the temperature mapping method.

One of the advantages of this method of analysis is that it has the ability to find defects in very fuzzy IR images. The precision of the temperature data allows it to be analyzed much more accurately than the grayscale pixels in the grayscale clustering method. For increased accuracy, the number of temperature levels that are found could be increased. This would add very little processing time since the actual processing is very small. This was also the fastest method that was implemented for image analysis on the UGV. Despite all the positives about this particular method, there is one blaring negative that cannot be avoided, which is where to stop the temperature level mapping. For the image shown above the best possible result was at temperature level 76. Each IR image will have a different temperature level that corresponds to the defects in the image. With no intelligent way of determining the cut-off for each image, this

method can not be reliably used for automatic defect detection. That does not mean that this method is worthless. The temperature mapping algorithm could be very beneficial as a manual analysis method. If an NDT engineer was surveying an FRP deck and he could look at the temperature levels of each image, he or she could very easily scroll through the levels and pick out the defective areas in the deck. Since the goal of the UGV is to produce autonomous results, another analysis algorithm had to be implemented.

4.5.3 Analyzing IR images with Fuzzy Clustering

Fuzzy clustering of IR image pixels has been performed by other researchers. Accurate defect detection is possible with fuzzy clustering. To increase the accuracy of defect detection, temperature values were clustered instead of clustering the grayscale image pixels, which was done by Lonkar [13]. Since the temperature mapping algorithm showed that increased accuracy could be obtained from the temperature data, this seemed like a logical step. Figures 4-22 and 4-23 show the results of analyzing images obtained by the UGV with the FCM algorithm.

Figure 4-22 IR image of 2" x 2" air filled defect and results of analysis by fuzzy clustering algorithm.

Figure 4-23 IR image of 2" x 2" air filled defect and 3" x 3" air filled defect and results of analysis by fuzzy clustering algorithm.

The FCM algorithm assigns each temperature value in the image to a cluster. The clusters with the highest temperature values are then chosen to represent the subsurface defects in the image.

Judging from these images it could be said that the fuzzy clustering on the temperature values provides an accurate method for defect detection. These images only represent temperature data from clearly discernible defects. For images that have less obvious defects, the fuzzy clustering algorithm must be improved, such as adding more clusters to the algorithm, to provide reliable results. The number of clusters has a large effect on the fuzzy clustering algorithm. By adding more clusters, it is possible to detect defects in images that cannot be seen by the naked eye. Figure 4-24 shows an IR image being analyzed with the fuzzy clustering algorithm. The middle picture is the result when clustering with 6 clusters. The image on the right is the result of clustering with 12 clusters.

Figure 4-24 IR image of 4" x 4" air filled defect and results of analysis by fuzzy clustering algorithm with 6 clusters and 12 clusters.

The defect generated at the interface between the slabs is detected in both cases because this is the hottest spot in the image. The 4 inch x 4 inch defect is not found with 6 clusters but is detected with 12 clusters. The temperature difference between the defective area and the surrounding defect-free area is approximately 0.8°C. This means that less heating is required for defects to be detected. The downside to using 12 clusters is that the algorithm takes much longer to compute, roughly 25 seconds, on a PC, than it does with 6 clusters. The algorithm takes roughly 5 seconds on a PC to process the data with 6 clusters. Experimenting with different numbers of clusters: 7, 8, 9, etc. could produce an optimum solution to the trade-off between accuracy and the execution time. On the plus side the FCM algorithm may be able to provide real time defect detection during testing with the UGV. It may be possible to employ multi-threaded code to allow the image analysis to be done in one thread while another controls the movement of the UGV. That way accuracy would not have to be sacrificed for speed. Neither the implementation of different numbers of clusters nor multi-threading was implemented on the UGV however due to time constraints and inexperience.

4.5.4 Comparison of Image Analysis Techniques

To quantify the results of the 3 different image analysis algorithms, defect analysis was conducted on a number of images obtained by the UGV during testing. Twenty four IR images with a total of 48 defects were subjected to each algorithm. The grayscale thresholding algorithm performed the worst out of the 3 algorithms. Out of 48 defects 40 or 83% were correctly identified, while 21% of the images reported false positives. The temperature thresholding algorithm performed a little better, correctly identifying 85% of the defects with only 16% of the analyzed images producing false positives. The Fuzzy C Means algorithm performed the best, though. It correctly identified 42 out of 48, or 87.5% defects while only generating false positives in 8% of the analyzed images.

Chapter 5

Experimental Setup and Results

5.1 Experimental Limitations

All tests that were conducted during this research were laboratory tests. As a result, no testing was done on a full FRP deck. Individual tests were conducted on smaller FRP deck samples as well as a concrete floor. Individual tests were either conducted with IRT analysis or GPR analysis.

5.2 Testing of Autonomous Control Algorithm

Since the majority of actions performed by the UGV are autonomous, the algorithm that will move and control the UGV had to be tested to insure accurate data acquisition. To test the quality of the autonomous control, a GPR survey would be conducted on a surface using the autonomous movement of the UGV. The objective of the test was to produce a 3D map of the surveyed concrete floor showing the metal plates as well as any subsurface features, such as rebars.

5.2.1 Experimental Setup

A 10 foot x 5 foot area on a machine shop's concrete floor was sectioned off with aluminum tape. The aluminum tape was used to mark the beginning of a measurement. This means that since virtually all of the electromagnetic radiation is reflected by the aluminum tape, the tester knows where to begin looking for defects. The UGV was supposed to survey the area as it would an FRP deck. The area chosen had rectangular metal plates spaced evenly at every 3 feet as well as rebar embedded in the floor. Once the UGV was running and the GPR acquisition was begun, the size of the “deck” was fed into the GUI running on the controlling laptop. Figure 5-1 shows what the setup for this test looked like.

Figure 5-1 Setup for Testing the Autonomous Motion of the UGV.

5.2.2 Experimental Results

Three different trials were conducted to see if the control algorithm performed consistently and reliably. The GPR data that was gathered was then segmented into smaller files each representing a strip of the deck. The 3D mapping software then stitches these files together to create a model of the entire decks. Figures 5-2, 5-3 and 5-4 show 3D map that were generated with the data collected during this testing. It is important to note that the rebars shown are only in the x direction, even though a rebar mat is typically both in the x and y directions. For an explanation of why this occurs consult section 4-2.

Figure 5-2 3D maps obtained during Autonomous Motion Testing.

Figure 5-3 3D maps obtained during Autonomous Motion Testing.

Figure 5-4 3D maps obtained during Autonomous Motion Testing.

5.2.3 Conclusions from Experiment

The rebars underneath the concrete floor are clearly visible and straight; however, they do not line up precisely. This has more to do with the way the data collected was analyzed than the actual data collection. When analyzing the GPR data, the beginning and ending points for the data are user defined and can introduce some error. The rectangular metal plates appear in the 3D map as bright white rectangular areas, which are evenly spaced and easily discernible. The results from this test show that the data being collected during the autonomous motion is very consistent. The metal plates appear in the same places in all the images. The same can be said for the rebars. This means that the results from this test are repeatable. From this test it is safe to assume that if the UGV is given the length and width of an FRP deck, the UGV will be able to autonomously survey the FRP deck.

5.3 Testing of GPR Defect Analysis

Since the GPR system will be used to test for water filled defects, testing was done to determine the accuracy of the analysis. The main purpose for this testing was to figure out how to efficiently employ a two GPR antenna system, as opposed to the common one antenna system.

5.3.1 Experimental Setup

For this test the simulated defects described in the previous section were used. The notches were filled with water pouches. Defects of plan sizes 2" x 2", 3" x 3", and 4" x 4" were used. The wearing surface with the simulated defect samples were placed on an FRP deck. The GPR data acquisition was then started and the UGV moved the antennas over the wearing surfaces slabs. Figure 5-5 shows the setup for this experiment. Aluminum tape was used to mark the beginning of a measurement. This lets the tester know where to begin looking for defects, because virtually all of the electromagnetic radiation is reflected by the aluminum tape.

Figure 5-5 Wearing surface slab with simulated defects on top of an FRP deck during testing.

5.3.2 Experimental Results

GPR data was collected for defects of various sizes. The water filled debonds were detected very efficiently using the GPR data. Bigger defects were more discernible than smaller defects, but defects as small as 2 inches x 2 inches were visible. Figure 5-6 shows a GPR scan of a 2 inch x 2 inch defect. Figure 5-7 shows a GPR scan of a 4 inch x 4 inch defect and 3 inch x 3 inch defect.

Figure 5-6 2" x 2" water filled defect observed in the data acquired using the UGV.

Figure 5-7 4" x 4" and 3" x 3" water filled defects observed in the data acquired using the UGV.

These images show the waveforms collected during testing. Since the waveforms that were collected were identical for each antenna, only the image that looked the clearest was displayed. The clearer image generally came from the antenna that was closer to the defects. Despite their appearance these images are not 2 dimensional scans. These images are 1 dimensional scans taken in the direction of travel. To get the width of the defects, the test would have to be conducted again so that the scans were perpendicular to the previous scans.

5.3.3 Conclusions from Experiment

From this experiment it can be observed that the 2 antenna setup can provide adequate defect detection. Defect sizes as small as 2 inch by 2 inch can be detected with this setup. It is important to point out that when employing a two antenna system, one of the antennas will generally produce a clearer waveform. This is generally due to the position of the defect with respect to the antennas.

It was also observed that using 2 antennas can decrease the overall resolution of the GPR scanning. This is because the SIR-20 GPR acquisition system has a maximum number of samples per scan of 1024. Since the UGV uses two antennas, the number of samples for each antenna must be cut in half. This means that each antenna is only taking 512 samples per scan instead of 1024. While this did not affect the quality of the GPR data in this particular test, it may allow for very small defects to go undetected while performing analyses in the field.

5.4 IRT Defect Analysis

The IRT analysis conducted by the UGV was primarily used to detect air filled defects between a wearing surface and an FRP deck.

5.4.1 Experimental Setup

The setup for the IRT testing was very similar to the setup for testing the GPR defect analysis. This test used the simulated defects described in section 3.2.1. Instead of water

pouches, the notches were left empty to simulate air filled debonds. Defects of plan sizes 2 inches x 2 inches, 3 inches x 3 inches, and 4 inches x 4 inches were used. The wearing surface with the simulated defect samples were placed on an FRP deck for testing.

5.4.2 Experimental Results

During the IRT testing, images were obtained and examined to determine the quality of the IRT analysis. Images acquired using the optional cooling fans were not as definitive as some of the images that were acquired without the optional cooling. Images could be acquired with heating times as little as 10 seconds; however. Figures 5-8, 5-9, and 5-10 show a few sample images of the FRP deck that were obtained with 15 seconds of heating and both cooling fans active. This means that there is 30 seconds of total cooling (15 seconds for each cooling fan).

Figure 5-8 3" x 3" air filled defect observed after heating and cooling.

Figure 5-9 4" x 4" air filled defect observed after heating and cooling.

Figure 5-10 4" x 4" (top, center) and 2" inch by 2" (bottom, center) air filled defects observed after heating and cooling.

While the defects in the images are visible, it is very hard to say with certainty that a defect actually exists in each image. It would take an experienced eye to find the defects in images such as these during testing in the field on actual FRP decks. In these cases the temperature differences observed between the defective area and the surrounding defect-free areas are below what is considered acceptable in the field. The highest temperature difference, which is observed in Figure 5-10, is roughly 0.95 degrees Celsius. This is much lower than the typical 3-4°C that is typically needed to confirm a defect in actual field testing.

The images that were acquired without the optional cooling provided much better results. Because there were no cooling fans speeding up the process, a longer waiting time between heating and analysis was needed. Heating times of 15, 20 seconds were explored, with waiting times between heating and analysis of 30 and 40 seconds, respectively. Figure 5-11 shows some sample images obtained with 20 seconds of heating with 40 seconds of waiting. In the image on the left, a 4" x 4" air filled defect is clearly visible. An average temperature difference of 2.9°C between the defective area and the defect-free area is observed. In the image on the right, a 3" x 3" air filled defect can be seen but the boundary is less defined. An average temperature difference of 3°C between the defective area and the defect-free area is observed. Also visible in both images is the gap between the wearing surface slabs. In essence when the wearing surface slabs are placed on the FRP deck they create an air filled defect at the meeting of the slabs. Since this is also an artificial air filled defect it shows up as a hotspot in the images.

Figure 5-11 IR images taken by UGV 20 second intervals of heating and no cooling.

The images generated without cooling are much easier to interpret and the observed temperature differences are much higher. Another positive aspect of acquiring the images without the cooling is that a problem with the heating was found and could be addressed. The problem is visible in the images displayed in Figure 4-12 but is easier to see in Figure 4-13.

Figure 5-12 IR image of 4" x 4" air filled defect with heating anomaly present.

The defect in the image is clearly visible. The circled area in the image; however, is not a defect. The hot spot on the left hand side of the image could be interpreted as a defect, but this would be incorrect. This anomaly shows up in every IR image that the UGV takes. This is an artificial hotspot that is generated by the heating system. After trying to correct the problem, the intensity of the anomaly has been lessened. Since we are cropping the image to a 240x240 image to give an analysis window of 1 foot by 1 foot, this anomaly does not show up as a defect in any of the analyzed images.

5.4.3 Conclusions from Experiment

Even though the preliminary IR research showed that a cooling step could increase the quality of the IR images at the cost of lower temperature differences, the optional cooling fans actually made the data much harder to read. High quality images were obtained without the cooling and defects could be observed by both human analysts and automated software routines.

5.5 Combination of IRT and GPR

At this point in time, no tests have been conducted with both IRT and GPR analysis. From the result of the previous tests, however, it is possible to speculate what a combined system would be able to accomplish. The system would be able to detect both water and air filled defects. By providing these capabilities, the UGV would be able to provide a much more thorough picture of the subsurface condition of an FRP deck.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The UGV described in this research is a major step in the automation of non-destructive evaluation of FRP decks. Incorporating both IRT and GPR allow the UGV to gather valuable data that can be used to determine both air and water filled defects.

Through experimentation with various heating sources, it was determined that passive heating is not a feasible heating method to be used in conjunction with autonomous acquisition of IRT data due to various problems, such as dependency on weather and possible uneven heating. By using active heating, the UGV can avoid the problems that can occur with passive heating. The active heating system that was designed allows the UGV to collect high quality infrared images regardless of weather conditions. This alleviates one of the major disadvantages of IRT. The autonomous motion of the UGV also alleviates the operator error that can be introduced during testing, such as uneven heating of areas.

Also, even though the preliminary IR research showed that a cooling step could increase the quality of the IR images at the cost of lower temperature differences, the optional cooling fans on the UGV actually made the data much harder to interpret. High quality images were

obtained without the cooling and defects could be observed by both human analysts and automated software routines.

Automated defect detection using software algorithms for analyzing the IRT data was also explored. Three different algorithms were implemented and tested. The grayscale thresholding algorithm performed the worst, correctly identifying 83% of the simulated defects but producing false positives in 21% of the images. The temperature thresholding algorithm performed a little better, correctly identifying 85% of the defects with only 16% of the analyzed images producing false positives. The Fuzzy C Means algorithm performed the best, though. It correctly identified 42 out of 48, or 87.5% defects while only generating false positives in 8% of the analyzed images. Real-time defect detection with any of aforementioned algorithms can be performed. To achieve real-time detection with fuzzy clustering, however, some multi-threading techniques may have to be employed.

The UGV that was built was able to successfully gather both IRT and GPR data. Through the use of pipelining, the acquisition process is highly efficient. At this point in time, no tests have been conducted with both IRT and GPR analysis. From the result of the previous tests, however, it is possible to speculate what a combined system would be able to accomplish. The system would be able to detect both water and air filled defects. By providing these capabilities, the UGV would be able to provide a much more thorough picture of the subsurface condition of an FRP deck.

It is important to realize that the UGV concept presented in this research is only a preliminary design, not a final product. The UGV is a platform that combines IRT and GPR, but at this point it is not a fully functional analysis system. While some data analysis is done on the IRT data, no GPR automation has been done except collecting the data. Despite the lack of automated analysis software for the GPR data, this UGV is a good first step in combining the strengths of IRT and GPR for comprehensive testing of FRP bridge decks.

6.2 Future Work

It is recommended that future research into the automation of subsurface defect analysis be focused on automating the GPR analysis. Signal processing techniques can be employed to analyze the GPR signals. Macros could also be written to automate the generation of 3D maps from the GPR data. Also at the current time the IRT analysis can be controlled easily from a laptop through the use of a Software Development Kit (SDK). This software library allows the functionality of the IR camera to be controlled automatically through software. GSSI does not provide any SDK for the GPR module. Since no SDK is provided by GSSI, a software library to interface with the GPR module needs to be written to allow for complete automation of GPR acquisition and analysis.

Research into improving the design of the active heating system should also be considered. While the heating system provided reliable results, a better heating system could be implemented to provide even better analysis.

Lastly, until the detection algorithms used with IRT data produce 100% accuracy, they need to be improved further or new algorithms will have to be developed. Not detecting defects in an FRP deck could be disastrous. If a structure is defective and the defect was not recognized it could collapse and injure people. False positives, which are detecting defects where none exist, are not as serious a problem but could cost money fixing areas that do not need to be fixed. For these reasons, 100% accuracy is desired and the algorithms should be improved until that accuracy is attained.

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Appendix

Since the UGV will operate autonomously during testing, most of the operator interaction will involve the setup of the UGV and the retrieval of data from the UGV. This manual will describe the basics of powering the UGV, setting up the GPR data acquisition, testing with the UGV, and getting data from the UGV for post-processing.

Appendix A. Powering the UGV

1. Enable the motors and fans by turning on the switch located on the right side.
2. Turn on the power inverter, which is located on the underside of the upper deck. A red LED will light up to show that the inverter is ready for use. This supplies the FLIR A20M IR camera and the GSSI SIR-20 GPR unit with power.
3. Turn on the VEX robot controller. This is located beside the power inverter and is also on the underside of the upper deck.
4. Power up the GPR laptop.
5. Power up the control laptop. Make sure that the serial cable from the VEX robot controller and the firewire cable from the IR camera are connected to the laptop.
6. Lastly, turn on the VEX transmitter so that the robot can be moved. The transmitter is used to move the UGV manually, but unless the transmitter is enabled, all functions of the VEX robot controller are disabled. This means that even though the operator does not plan on driving the UGV manually, the transmitter must remain on.

Appendix B. Setting up the GPR data acquisition

First of all, make sure UGV is in starting position for test. Once the GPR data acquisition is enabled, the data will be gathered anytime the UGV is moved. To get the UGV in the right place, manually drive the UGV into position. The first turn that the UGV will make is a left hand turn so be sure that the UGV is positioned on the far right edge of the deck to be surveyed before operation.

To begin, start the program SIR-20 on the GPR laptop. Next set up the working directories so the software knows where to put the data. Go to View->Customize. A window like the one in Figure B-1 is displayed.

Figure B-0-1 Customizing Directories Window.

Now set the source and output directories. Once everything is to your liking then click OK. Now to start a new project, go to File->New. This will open a window where you can name a project. Enter a name and hit OK. The Project Information screen will appear next. Make sure information on this page is correct and hit OK. This brings up the Data Collection Model window. Select the survey wheel option and click the calibrate button. The calibration distance should be 10 feet and the number of ticks per unit should be 625. Click Save.

The data collection parameters window, like the one shown in Figure B-2, should now be displayed.

Figure B-0-2 Data Collection Parameters Window.

Since we are using two antennas, select “Multi-chan” in the “Config Name” dropdown box. In the samp/scan drop down box select 512. This value is the most we can use with 2 antenna channels. In the scans/sec text box enter 78, which again is limited by using 2 antennas. Enter the dielectric constant for the FRP deck (for this research a value of 5 was used). Scans/in should be 10 and in/mark should be 1. Once all this data is entered click apply.

Now you have to load a macro for the antennas so that the system can initialize them. The macro file can be found at Desktop\Shortcut to Fixed SIR-20 Setups\1.5 GHz. You should hear a series of beeps during which time the antennas will be initialized by the SIR-20 module.

The data being displayed may not be very good. To fix this Go to Process->Correct Position. A window like the one in Figure B-3 will appear.

Figure B-0-3 Position/Range Setup.

Uncheck the “auto position servo” check box. Now change the “Range (nS)” text box from 12 to 4. Click apply and wait for the antenna to be reinitialized, during which time there will be a series of beeps. Click the “Chan 2” tab at the top and do the same thing for channel 2. The data in the graph will adjust itself each time you hit apply. When you are finished with this step, the graph should look like the one in Figure B-4.

Figure B-0-4 Position/Range Setup After Correction.

The next step is to set the gain on the antennas. To do this, go to Process->Range Gain. The Range Gain Window, like the one in Figure B-5, should appear. Check the "Use Common Channel Parameters" check box. The wave form for each channel should take up about 1/3 of the graph at the difference between peak amplitudes. To change the amplitude of the waves, drag the endpoints of the lower red line up or down and click apply to update the waveform. Make sure that if you make any changes here that you click the apply button. Otherwise your changes will be lost.

Figure B-0-5 Range Gain Window.

The GPR system is now set up to acquire data. Click the "Run" button (the little green arrow at top of screen) to begin gathering data. Once the "Run" button is clicked, the GPR data will be collected whenever the UGV moves.

Appendix C. Operating the UGV during testing

1. On the control laptop, start up the IR_Auto_Acquisition GUI. Make sure that all other programs, especially ThermoCAM Researcher or FLIR QuickView, are closed before beginning the test.
2. Choose whether the UGV should operate in "Normal" mode or "GPR Only" mode. In Normal mode, the UGV will collect IR images as well as GPR data. The wait time between movements will be 30 seconds. This is done so that the heater can prepare the

deck for IR imaging. In GPR mode, the UGV will simply move forward in 1 foot increments. The wait time between movements will be significantly less (approximately 1 second).

3. Enter the deck dimensions. The dimensions will determine when the UGV will turn and when the IR images will be taken. Make sure that you set these before the test begins, otherwise the UGV will not perform correctly.
4. If operating in the normal mode, which means that IR and GPR data will be gathered, now is the time to turn on the heating system. First, turn on the heating fan with the additional remote control. If cooling is desired also use the remote to enable the cooling fans. Now connect the propane tank to the hose. Hold the propane switch and use the ignite switch to light the heater.
5. Lastly click the “Enable Auto Acquisition” button on the GUI. This will turn over control of all functionality of the UGV to the GUI. It will move and gather data on its own.
6. When the test is complete, a deckmap showing all the defects can be created by clicking the “Generate Deckmap” button.

Appendix D. Getting IR data from the UGV after testing

Images captured from the IR camera during testing can be found in the CapturedImages directory. The directory is located on the controlling laptop at “C:\Documents and Settings\Robot\Desktop\IR_Auto_Acquisition\CapturedImages.” The filenames for the images are numbered to make finding an image of a certain section easier. The images are named as follows: Image_Row_X_Col_Y.jpg where X is the row number of the image and Y is the column number. Figure D-1 shows an example of the layout of the images for a deck 10 feet long and 5 feet wide.

10					
9					
8					
7					
6					
5					
4					
3					
2					
1					
	5	4	3	2	1

Figure D-1 Numbering format for Images captured by the UGV.

These images are grayscale images. Also in this directory are full color radiometric JPEG files and temperature data files. There is one radiometric JPEG and one temperature file for each grayscale IR image.

Images that were captured during testing were also processed. The analyzed images can be found in the ProcessedImages directory. The directory is located on the controlling laptop at “C:\Documents and Settings\Robot\Desktop\IR_Auto_Acquisition\ProcessedImages.” The filenames for the images are numbered to make finding an image of a certain section easier. The images are named as follows: OutputImage_Row_X_Col_Y.jpg where X is the row number of the image and Y is the column number. Each grayscale output image corresponds to one grayscale captured image. If a deckmap was generated during testing then the output file will also appear in this directory named “Deckmap.jpg.”

The GUI program does not check for pre-existing files before generating new ones during testing. As a result if the files are not moved they will be overwritten and previous test data will be lost. To avoid lose of data, after finding all the IR data files, the operator must move them to a new directory before any further testing. It is suggested that a new folder be created in the

“CapturedImages” and “ProcessedImages” directories. The files can then be copied into these new directories.

Appendix E. Getting GPR data from the UGV after testing

To begin creation of a 3D map of the FPR data start the program RADAN5.0 on the GPR laptop. Open the project by going to File->Open and selecting the project that was created during testing. This will appear in whatever directory was designated as output when you set up the GPR data acquisition. The first step that needs to be done is to correct the position on the GPR data. This is done so that all measurements start at the same depth. To do this, go to Process->Correct Position. A window like the one in Figure E-1 will be shown.

Figure E-1 Position Correction Window.

Use the “Delta Pos(nS)” to reposition the data. You should change the position such that the first rise on the waveform begins at far left side of the graph. Next, click on the channel 2 tab at the top of the page and do the same thing. Click “Apply.” After clicking “Apply,” the data will be shifted so that the starting depth corresponds with the new depth. Since we changed the starting depth we now have to change the label for the starting depth. To change these settings, go to Edit->File Header. This will bring up the Edit File Header window, which is shown in Figure E-2.

Figure E-2 Edit File Header Window.

Change the value in the “Position (nS)” text box to 0. Use the "Channel" button to switch to the second channel. Change the value in the “Position (nS)” text box to 0. Click save. The file settings are now updated.

The next step is to split the GPR data into 2 separate files, one for each antenna. Go to “File->Save As” and in the lower left check the split channels check box. This will save the data into two separate files. The base filename remains unchanged but two files will be generated in

the same directory that will end in an "A" (meaning data from the antenna in channel one) or a B (meaning data from the antenna in channel two).

Now we have to segment each antenna file into strips. Close the current file and open the file ending in "A." At the beginning of the data you will see an area where all the energy is reflected. This is the aluminum tape that was placed to denote the beginning of data. From this point to the next section aluminum tape is the data from the first strip of deck that was surveyed. To extract this data, we need to select a data block. First, right click on the scale on the left side of the data. In the pop-up menu, change the horizontal scale to scans. Now go to Edit->Select. This will bring up the Edit Block window shown in Figure E-3.

Figure E-3 Edit Block Window.

Change the starting point to the scan number of the first section of aluminum tape. Find the next piece of aluminum tape and use that scan value for the End Scan value. Click OK. Go to Edit->Save. This will open a save dialog box to save the block of data as a new file. Save the newly segmented data file as something meaningful because you will be using it when you form the 3D file. The next section of data should not be used. This is because that between the second and third sections of aluminum tape is data taken while the UGV is turning. This data is not considered part of the deck that is being surveyed. The section of data after the turning data is the data collected from the second strip of deck and should be saved just as the first section was. The 4th section should then be discarded because this is again turning data. Continue segmenting the data in this way until you have pulled out each strip of the deck. Once this is done, the same process must be completed for the data from the other second antenna, which is stored in the file ending with a "B."

After all the data is segmented, close all the individual files. Go to File->New to begin the 3D project. Make sure that the RADBridge Project option in the lower right is checked. Click save. Check the information in the project information window and click OK.

The next window that pops up, which is shown in Figure E-4 allows you to add files to the project.

Figure E-4 Adding Files to the Project.

The files that will be added are the segmented files that were just created. Each represents one strip of the deck. The files must be added in the order of the scan (from right to left). This means that since we are using two antennas we would have to add the first scan from the antenna on the right first, then the first scan from the left antenna. Next would be the second file from the left antenna, since we are turning the UGV which reorients the antennas. After all the files have been added in the correct order click done.

Next you have to attach a macro to each file that was added in the previous step. Since the macro is not used for anything just create a file called "dummy.cmf" and attach it to each file. When this is finished, click Done.

After assigning the macros, a window will pop up so the output parameters for the 3D file can be set. Figure E-5 shows the 3D file parameters window.

Figure E-5 3D File Parameters window.

Make sure to specify a filename for the 3D output file, and then enter the dimensions of the deck that was surveyed. The last settings are to specify the starting points in each file. To do this click on the Files 1-8 tab, which displays a list of files in the project. Figure E-6 shows this window.

Figure E-6 File listing for the 3D File.

The button labelled "Click" shows the data file so you can click the starting position. Remember that since the UGV collects data in one strip then turns around to get the next strip, every other 2 files, meaning the 3rd and 4th files as well as the 7th and 8th, must be reversed by checking the "rev" checkboxes. The starting point can then be chosen in the same way but the user must select it from the end of the file, not the beginning. When all the files have been assigned a starting point, click OK. The files will then be stitched together. Use the 3D Mode button to look at the 3D model that was generated. Use the X, Y, or Z-Slice to look through the model.