NORTHLAND ADVANCED TRANSPORTATION SYSTEMS RESEARCH LABORATORIES

Final Report

Research Project Title:

Survey and Evaluation of Ice/Snow Detection Technologies

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NATSRL

Index

Figure Index

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Survey and Evaluation of Ice/Snow Detection Technologies

Summary

Weather is a principal factor that contributes to traffic accidents. Thus Road and Weather Information Systems (RWIS) has been deployed by MNDOT to proactively detect adverse weather and road conditions so as to provide motorists with advanced warning of hazardous conditions. Ice on the roadway is one of the leading contributors to winter weather accidents. There are many ice detection technologies, however it is not clear whether these sensors are accurate for detection of ice on the roadway surface. The development of a reliable ice detection sensor would provide MNDOT engineers and maintenance personnel the tools they need to warn drivers of potentially hazardous road conditions due to ice formation on the road surface and mobilize MNDOT's maintenance fleet with anti-icing treatments to the road surface.

The usefulness of any weather sensor is determined by the accuracy of the parameter(s) it sensed. An accurate ice detection sensor could provide the tools necessary for engineers to make informed decisions on proper use and sensor specifications. Weather sensors accuracy is affected by temperature, light availability, visibility, pavement's conditions and wind. Often, many vendors do not provide detailed information regarding sensor specifications and proper application. In this research, a thorough evaluation of the Infrared Road Ice Detection System *IRID* is being conducted. IRID, which is an active IR remote ice sensor, offers distinct advantages over embedded road sensors. It has lower installation costs, lower cost of ownership, improved safety, and gives better results.

The objective of this research has been to investigate the IRID sensor in terms of accuracy and sensitivity to distance and different deicing materials. Different measurements have been collected in different weather conditions, and on concrete and asphalt pavements. Data analysis indicates that this sensor is sensitive to weather conditions and the presence of two contaminants salt brine (NaCl) and Magic (Magnesium Chloride). Thus the ultimate goal after a successful evaluation is to mount this sensor on a bridge on a busy highway and use it to monitor the weather conditions remotely. In addition to the infrared ice sensor, the IRID comes with a camera that can be used to show pictures of different locations near the pavement using pan/tilt capability.

Benefits

Automating pavement condition sensing in locations that experience severe winter weather conditions is important for both the public and highway maintenance personnel. This research could significantly improve highway safety by providing a better understanding of IRID sensing capabilities. The development of an accurate ice detection sensor could provide the tools necessary for engineers to make informed decisions on sensor specifications and proper application.

Fig. 1. - IRID Original Location in Downtown Duluth

Introduction

Remote measurement of amount and type of precipitation that can be accessed remotely is very important in many transportation applications. This information is crucial for the maintenance manager in deploying available resources most effectively [1]. There are many ice detection technologies, however it is not clear whether these sensors are accurate for detection of ice on the roadway surface [2]. An active IR remote ice sensor offers distinct advantages over embedded road sensors [3, 4]. It has lower installation costs, lower cost of ownership, improved safety, and gives better results. Additionally, IRID sensors can be mounted on roads or bridges. Information regarding the pavement surface condition at the sensor location can be accessed through a server based Internet Web page.

This project will help to improve the understanding on the use of a non-intrusive sensor to detect the presence of ice, snow, water, etc, on the road's surface and to evaluate its accuracy. Based on these parameters we will evaluate its ability to detect development of pavement icing and the present of chemical agents on the roadway, and as a final result to improve the level of confidence on both the road's maintenance crews and the traveling public.

Currently there is no comprehensive spectral guide for deicing salts and freezing point depressants [5,6] that can be used in remote sensing applications. In this research we used the IRID sensor (Figure 1), to test if is possible to use, identify, and differentiate among these chemicals.

The Innovative Dynamics Inc.'s (IDI) Active Infrared Ice Detection Sensor (IRID) was relocated from downtown Duluth, to the University of Minnesota Duluth's Advanced Sensor Research Laboratory (ASRL), which is located outside Duluth on I-35 (Figure 2). During the spring, 2003 the infrared sensor was re-installed after the manufacturer fixed some hardware problems. The IRID sensor was designed originally to detect the presence of water, snow and ice on the roadway [7]. We are presently investigating the performance and applications of IRID.

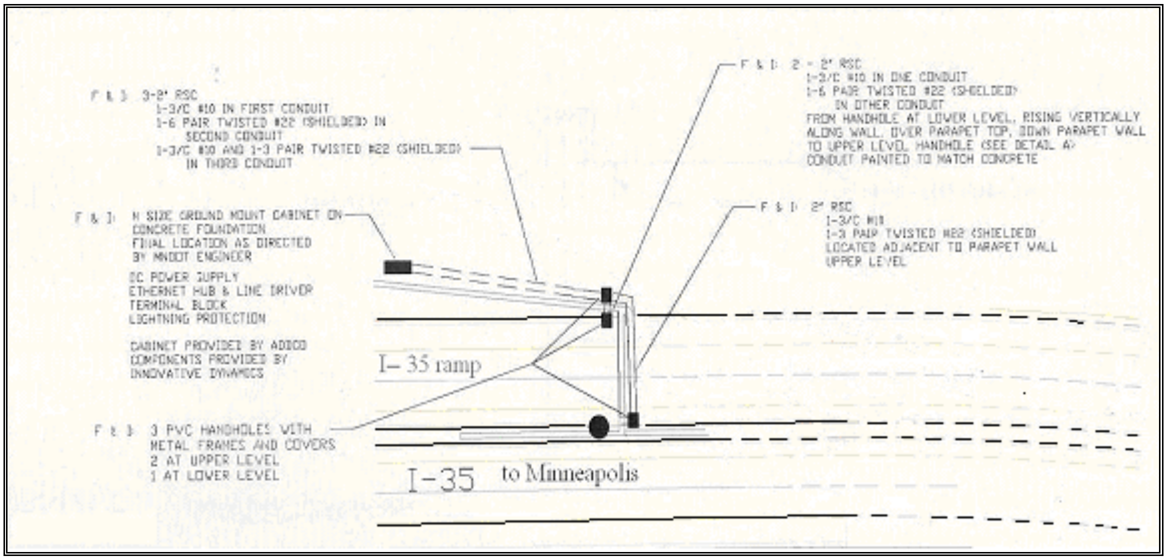

Fig. 2. - IRID new Location in an off ramp near Cloquet, MN

Research Goals

The main goals of this research are:

1) To examine the performance of the refurbished IRID Active Infrared sensor in terms of detection and accuracy.
2) To measure the sensitivity of this sensor to different surface conditions of the pavement and to investigate whether it can be used to measure the thickness of ice, water, or snow layers
3) To evaluate IRID to determine whether the presence and concentration of freezing point depressant chemicals can be detected and measured on the roadway surface.

IRID Sensor's Hardware and Software

In May 2002, the IRID sensor was removed from its original location in downtown Duluth, and relocated on top of a bridge, on a side road along Interstate 35, nearly 20 miles south from UMD (Figure 3).

Fig. 3 .- IRID sensor new location

The IRID sensor is designed to detect the presence of water, snow and ice on the roadway. It is a non-contact and non-intrusive technology that does not require embedded or contact sensors. Although this kind of sensor provides information only at a limited area of the road, its pan/tilt capability could provide reliable information about the pavement surface in multiple points.

The sensor uses a three-program software package to control its operation. These programs are *Main, Dispatcher and Toolset*. The Main program is used to provide the number of testing points and to specify their location on the road and the order in which they will be tested. This set of points is called the *Road Map Canvas*.

The *Main* program is used to provide the number of testing points and to specify their location on the road and the order in which they will be tested. This program main use is to create the road map canvas.

The *Toolset* is the principal program used to control the infrared sensor. This program can be used to set or modify the sensor parameters such as gain, position, base line, etc. In addition, this program is used to receive the raw information measured by the sensor for the points specified in the road map canvas.

The *Dispatcher* program, as its name implies, is used by the main operator of the system to display the weather conditions retrieved from the sensor, using a user friendly display window that specifies the present status (dry, wet, snow, ice, etc) for each point in the road map canvas.

Tasks Description

During the period of this project, we achieved the following tasks:

1) Testing and performance evaluation of the IRID system.
2) To investigate the effectiveness of this system in detecting dry, wet, water, snow and ice covered road surface conditions
3) Evaluation of ranging and accuracy of detection of water, snow and ice layers.
4) To analyze the performance using different situations as to detect ice through a thin layer of snow, or to detect ice or snow in the presence of deicing chemicals, etc.
5) Characterize road contaminants and environmental factors
6) Explore the detection of deicing chemicals such as Sodium Chloride and MAGIC.
7) Define if the overall IRID system can be used as a non-invasive, remote pavement ice detector to be used as an Intelligent Road Weather System.

Initial System Characterization

Water and ice have been characterized as having different reflectance spectra in the near and middle infrared region [7, 8]. Because of this, we wanted to evaluate the response of the IRID sensor to different weather conditions on the road. In order to accomplish this we identified a set of testing points on the pavement to be used later through the sensor pan/tilt operation. This process is described next.

Pan and Tilt Angle Measurements and Conversions

As mentioned before, the sensor is now located on top of a metallic bridge (18 feet above the road level), pointing downwards to the road, as shown in Figures 3 & 4.

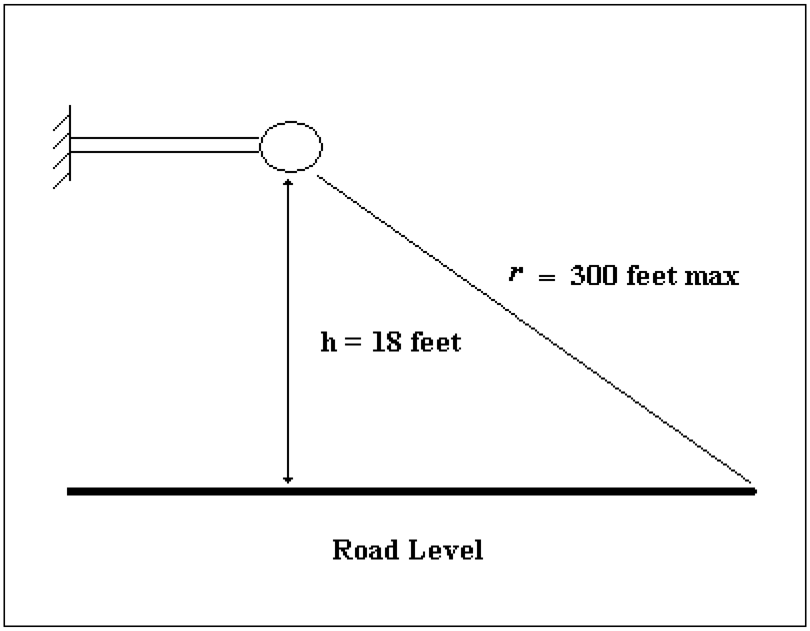

Fig. 4. - IRID height and beam maximum range

From its original location the sensor can be rotated horizontally in a 360-degree angle (*pan* angle), and rotated vertically in a 90-degree angle (*tilt* angle), as shown in Figure 5. With this, the sensor can be positioned to point to any location dawn the road in a half sphere, with a maximum radius of about 300 feet (as shown in Figure 4).

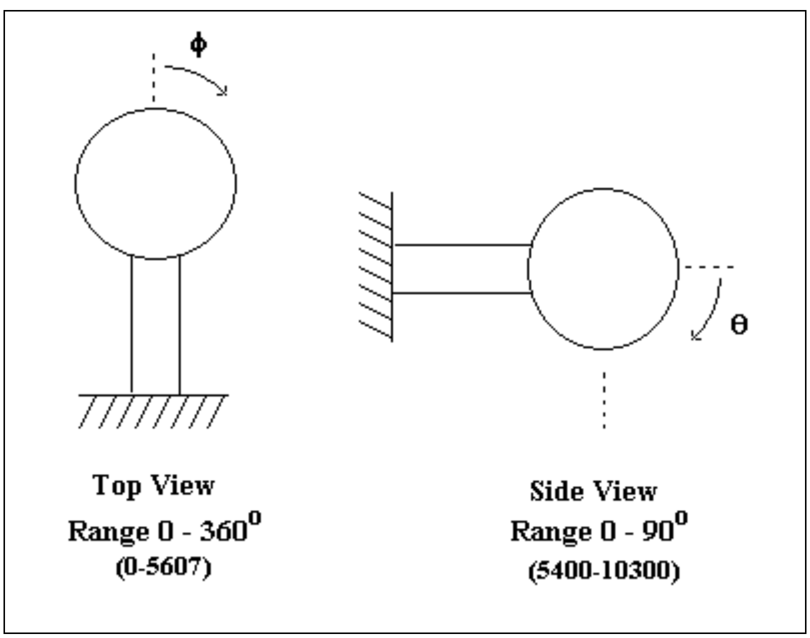

Fig. 5. - Sensor's Pan and Tilt angles reference

Consequently, one of the first activities that had been performed was to develop a practical procedure to determine the spherical coordinates (tilt and pan angles) that correspond to any point on the road, i.e., we needed to determine the relationship between the spherical coordinates and the latitude and longitude angles or (*tilt/pan*). This relationship can be derived as follows. Assuming that the sensor is the origin of a spherical system in which the z-axis is the line passing through the sensor and perpendicular to the road. Using the diagram shown in Figure 6, the following equations are obtained:

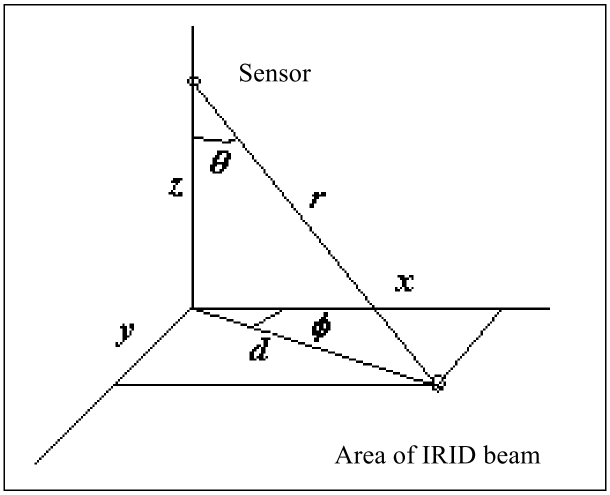

Fig. 6. - Relationship Between Tilt and Pan Angles and Testing Point Coordinates

$$x = r\sin\theta\ \cos\phi \qquad (1)$$

$$y = r\sin\theta\ \sin\phi \qquad (2)$$

$$z = r\cos\theta \qquad (3)$$

$$r^2 = d^2 + z^2, \quad d^2 = x^2 + y^2 \qquad (4)$$

Clearly,

$$r^2 = x^2 + y^2 + z^2 \qquad (5)$$

Hence:

$$r = \sqrt{x^2 + y^2 + z^2} \qquad (6)$$

$$\phi = \tan^{-1} y/x \qquad (7)$$

$$\theta = \tan^{-1} \frac{\sqrt{x^2 + y^2}}{z} \qquad (8)$$

From these equations, it follows:

$$y/z = \tan\phi \qquad (9)$$

$$d = \sqrt{x^2 + y^2} = r\sin\theta \qquad (10)$$

$$z = r\cos\theta \qquad (11)$$

$$\theta = \tan^{-1} \frac{\sqrt{x^2 + y^2}}{z} = \tan^{-1} d/z \qquad (12)$$

Thus, with the measured height h = z = 18 feet, we compute the latitude and longitude angles using the above equations. In the control programs (*Main, Toolset and Dispatcher*) the *pan* and *tilt* angles are given using angular displacements of the mechanisms, and they have a range of 0-5607 and 5400-10300 respectively. Given these ranges, we needed to find a relationship between these units and the respective angles. We verified through measurements that each unit of the pan angle corresponds to approximately 6 degrees. So that we can write the following equations:

$$pan = 6.28 * \phi \quad \text{(deg)} \qquad (13)$$

Moreover, the relationship between θ and *tilt* angle is given by:

$$tilt = 5400 + \frac{2450}{45}\theta \quad \text{(deg)} \qquad (14)$$

Using Equations 1 through 14, the correct pan and tilt angles are entered as inputs to the *Toolset* program (see Figure 7). This triggers IRID to illuminate the location of the testing point with infrared energy. A red laser pointer also indicates this location visually.

Thus using a measuring tape, the Cartesian coordinates are converted to spherical as tilt and pan angles for any point on the road. This task would not have been necessary if IRID software is fully operational.

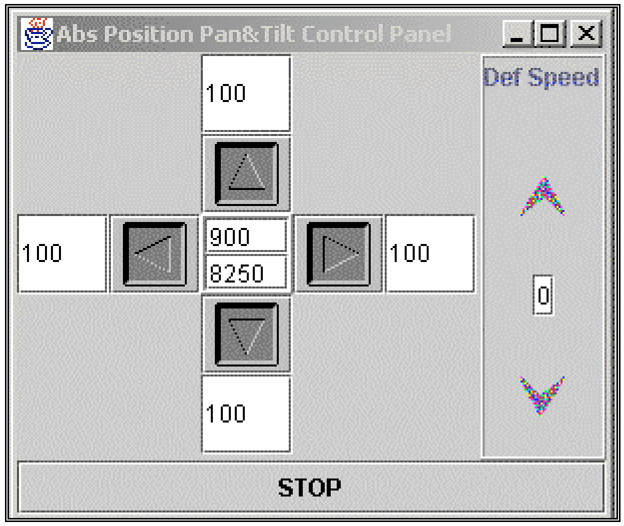

Fig. 7.- IRID Positioning Window

Next, we proceeded to identify test points on the road. We selected two types of surface for testing: cement and asphalt to verify if the sensor detects any possible differences between these surfaces. At this time, there are no indications of any differences for the tested points under dry conditions.

Testing Points Identification

During the summer 2003, the infrared sensor was re-installed after the manufacturer fixed some hardware problems. Several measurements for the road under different weather conditions were taken using the only functioning software *Toolset*. The main window for this program is shown in Figure 8.

Using the *toolset* program the user can specify different parameters to initialize and control the operation of the infrared sensor. Some of the parameters that can be specified by the user are Gains, Thresholds, Baselines values, etc. Also on the bottom of this window the user can observe the sensor's actual measurements (circled values), notice that these four values represent the response of the sensor to the road conditions as measured using the two wavelengths (*1550 and 1430 nm*), and two polarizations (*S* and *P*). These values are the ones that we used in our measurement and characterization process for the road's surface weather conditions.

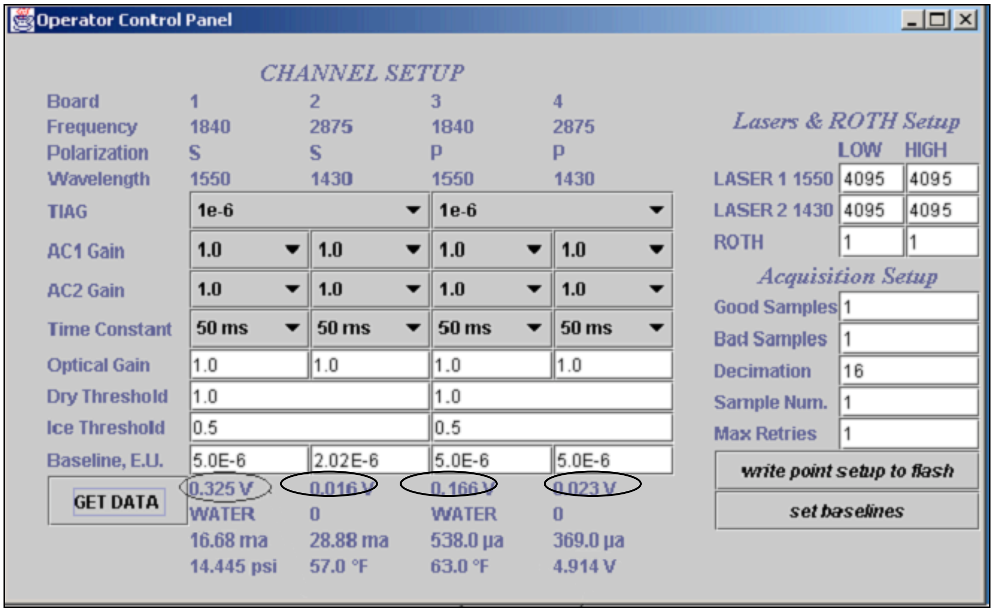

Fig. 8. - Toolset program main Window

The next task that we accomplished was to define an appropriate set of testing points to be used in our measurements (Figure 9). The locations for the testing points were selected so that we could test the sensitivity of the sensor to both location and road type (asphalt and cement). For this research, we identified a total of six testing points. Four of the testing points are on the asphalt side, two are located far from the sensor; two more are located closer to the sensor. The other two points are located on the concrete side of the road, one far and the other nearer to the sensor. The points were marked so that they could be easily identified. The coordinates of the testing points are given in Table 1.

The coordinates of these points were found by measuring the perpendicular distance *d* and height z (see Figure 6). Then, by using Equations 1-14 we devised a mathematical method to find the pan and tilt angle for the sensor in terms of the actual coordinates of the testing points.

Fig. 9. - Testing Points Identification

The Pan and Tilt angles found by applying the set of equations given above are shown in Table 1.

Point	Pan Angle	Tilt Angle	Road Type
1	0	8920	Asphalt
2	200	8060	Asphalt
3	1160	6910	Asphalt
4	2340	8110	Asphalt
5	5407	8060	Cement
6	5407	7032	Cement

Table 1. - Testing Point Coordinates

Testing Methodology

During the summer 2003, we proceeded to test the sensor by simulating wet and winter weather conditions on the road's surface. Thus we devised a method to artificially create wet, icy and frosty conditions on the road surface in the region of interest. Water detection tests were performed by spraying water on the area of interest to create damp and wet situations. To get thicker layers of water, we simply poured water on the testing spot to simulate heavy rain weather conditions. To create ice, we used blocks of dry ice (CO_2) to cool the pavement. It takes about 30 minutes for the pavement to cool bellow the freezing point of water. After the blocks of dry ice are removed or evaporated, we used a mist sprayer to create uniform layers of ice and frost. Using the dry ice, we were able to create uniform layers of frost and ice of different thickness.

To measure the water and ice thickness, we used a feeler gauge and a micrometer to estimate their value. It should be noticed that by using this method, we couldn't get a precise thickness measurement, because of the natural imperfections on the road's surface which generates pooling of the water and hence the ice layers. In the measuring of the ice thickness we scratched the ice surface down to the pavement. Although the thickness measurement is not precise, we still could get a good estimation of the water and ice layers thickness. In addition, we tested the sensor to check if it was able to detect the presence of freezing point depressant chemicals and their concentration.

Snow measurements for naturally produced icy and snowy conditions have been collected starting November 2003. These include measurements involving thin and thick ice layers, and unpacked and packed snow layers on the road surface. Additionally, we sprayed freezing point depressant chemicals, to observe whether there is a distinguishable pattern or signature that can be detected. The results that we obtained will be shown later. Several other data sets using real weather conditions were collected in December 2003, and during January and February 2004. We also tested the system for different concentration of freezing point depressant chemicals, namely salt brine and MAGIC, to observe whether there is a distinguishable pattern or signature that can be detected. Preliminary data analysis was conducted to compare the new results with those of the data collected using dry ice during the summer 2003.

Baseline Identification.

In order to recognize the road's weather condition, the identification process requires an infrared (IR) baseline measurement be obtained to set the detector gain parameters based on the user's range and incidence angle requirements.

The baseline is also used, as a dry reference threshold needed by the general decision algorithm in obtaining ice, water, and snow calibration. The sensor discriminates ice from water based on laser energy absorption ratios, substantial change of the baseline condition will decrease the identifying algorithms overall reliability.

Baseline stability measurements were taken during the testing. It was discovered that for surface measurements taken at lower incidence angles, the baseline was less stable than for those obtained at higher incidence angles, where the laser is more normal to the surface. Also, seasonal changes in the IR reflectivity/absorption of the road surface have been shown to causing a shift in the baseline, due to variation in surface roughness and road contaminates. Though the amount of seasonal change should not affect the ice detection capability, it can affect sensitivity. It is therefore recommended that the user periodically update the system baseline readings, being most desirable to calibrate just prior to each experiment. The unit can update the baseline either manually or automatically. In the automatic mode, the program uses a feature that ensures dry surface conditions exist when the new baseline measurement is taken.

Testing Results

Initial Testing

We start with initial measurements performed with the IRID sensor during the summer 2003. For every road condition, a set 12 of measurements were taken. These measurements are plotted in Figure 10. This graph particularly shows the data collected by the sensor for wet and icy conditions at the test point 2 (see Table 1). In this figure, each of the four colors represents the response of the sensor for the combination of the two frequencies and two S and P polarizations. The blue dots represent the response to the road's conditions for the 1840 nm frequency with *S* polarization, the Magenta dots represent the 2875 nm frequency with *S* polarization, the Yellow dots indicate the response to the 1840 nm frequency with *P* polarization, and the Teal dots is the response to the 2875 nm frequency with *P* polarization, respectively.

In all graphs that follow, the vertical axis represents the signal level reflected by the road (in Volts), while the horizontal axis represents time. On top of this graph, we specify the actual road's surface conditions. Notice that the sensor's response changes drastically depending on the particular situation. It is interesting to note that, as expected, the signal level of the sensor for dry road is practically constant, indicated by the flat response in this part of the graph. On the other hand, the response for the wet and icy road conditions was not constant, perhaps due to evaporation and to ice melting.
The positive slope of the graph corresponding to the wet condition was perhaps due to the natural evaporation of the water on the road. Thus the road becomes drier due to high temperature, while the negative slope in the icy road response is due to the deicing process of the road, i.e., ice is converting to water creating a wet road's surface.

While gathering these initial measurements, the IRID laser pointer (see Fig 15) was turned on and it seems it affected the sensor's response when it was left on during the testing. Thus all data obtained afterwards are taken while the laser pointer is turned off.

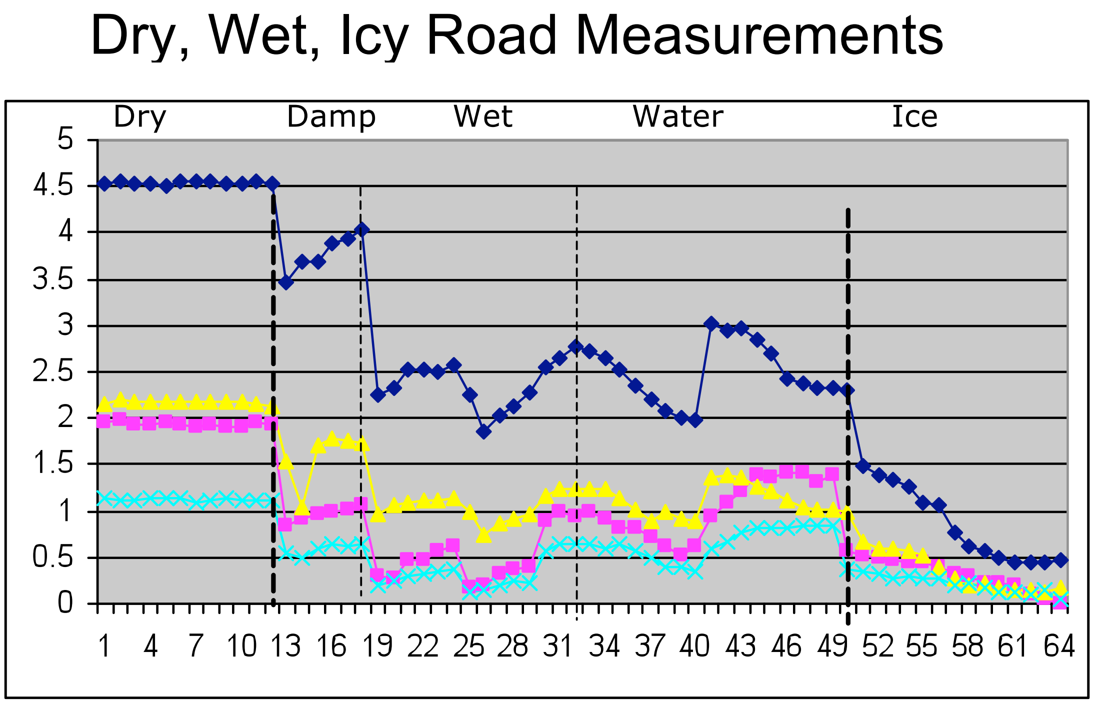

Fig. 10 .- Summer Initial Measurements

The response of the IRID sensor to different ice thickness is shown in Figure 11. Again, this graph shows the rapid deicing effect due the hot environmental conditions during the summer. In addition, the sensor's 1840 frequency, in both polarizations S & P (blue and Yellow points) is more sensitive to the ice layers than the 2875 frequency (Magenta and Teal points).

From these initial observations, we can say that the sensitivity of the sensor to changes on the road surface is very good. However, this high sensitivity is affected by many factors. For example, on windy days the movements generated on the bridge structure by the wind currents affected the sensor's measurements.

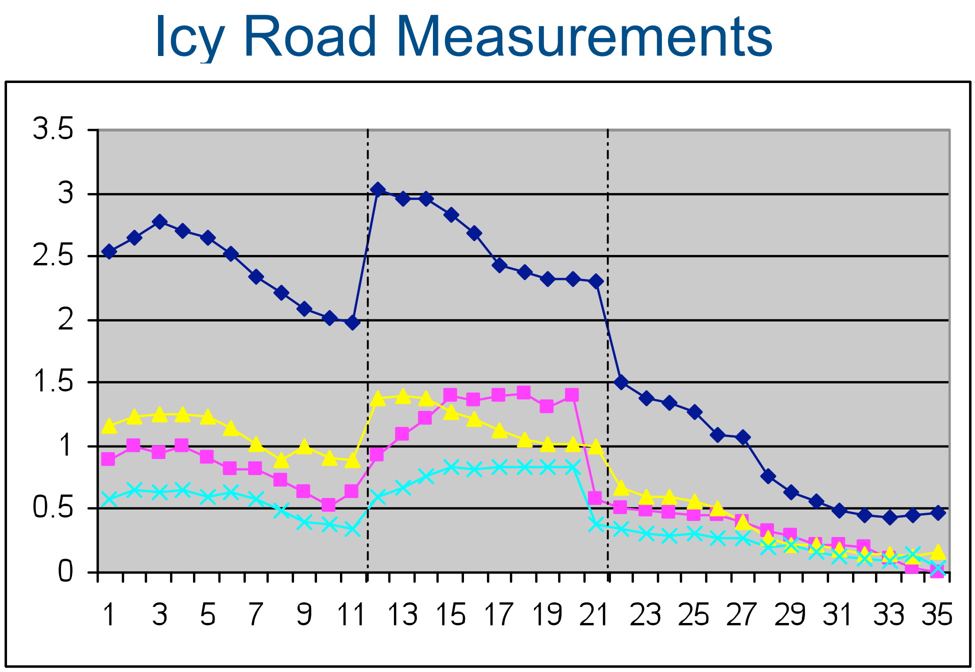

Fig. 11 .- Ice on Road Measurement Detail

In Figure 12, the response of the sensor is displayed for a case where we created two layers of different thickness (approximately of 2 and 4 mm respectively) of Water, and the two freezing point depressants Salt Brine, and MAGIC. As can be seen from the graph, the sensor is able to differentiate between simple water on the road, and the two different depressant types. Moreover it is able to detect different thickness of the ice layers.

The above graphs displayed the behavior of IRID responses at a testing point on asphalt. In Figure 13, we show a graph of the measurements we performed with the IRID sensor for the cement road surface during the summer. In particular, this graph shows the data collected by the sensor when for wet and icy conditions around test point 5 (see Table 1). The data measurements shown in Fig. 13 corresponds to the response of the sensor to test point 5, which is on the cement side of the road. Notice that the basic response of the sensor does not changes for this kind of surface. These measurements were collected during the fall, when the ambient temperature was not as hot as during the summer. Because of this, the slopes in these curves are not as steep as the ones showed on Figures 10 & 11.

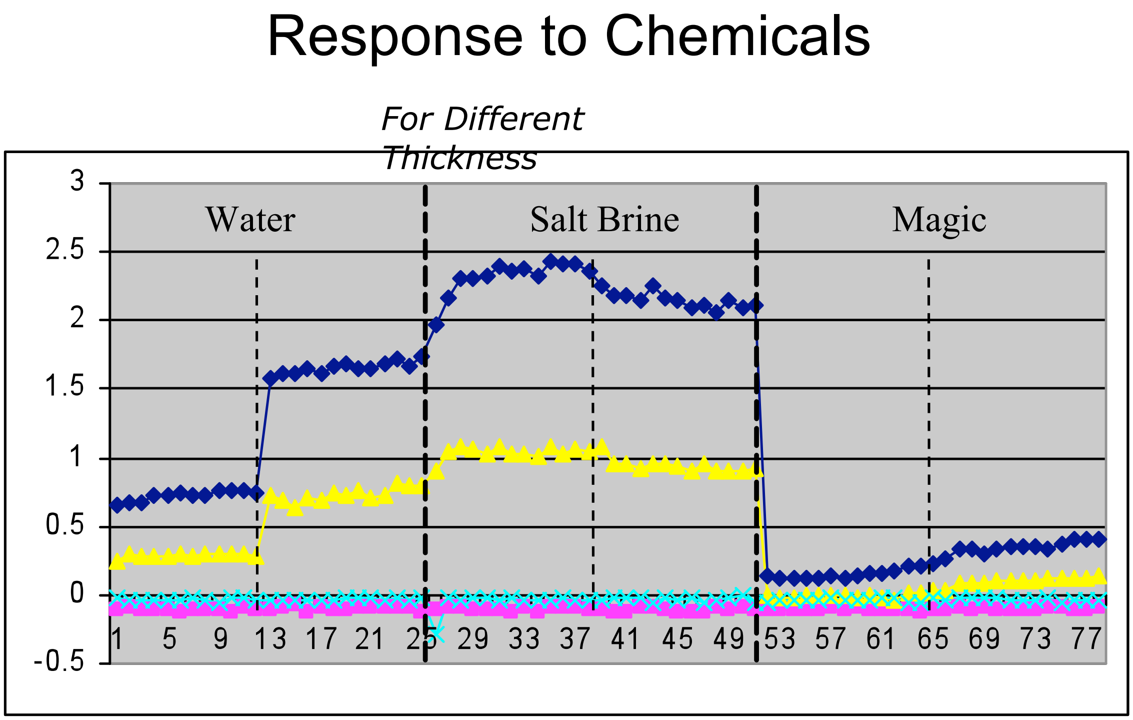

Fig. 12 .- Sensor's Response to Deicing Chemicals

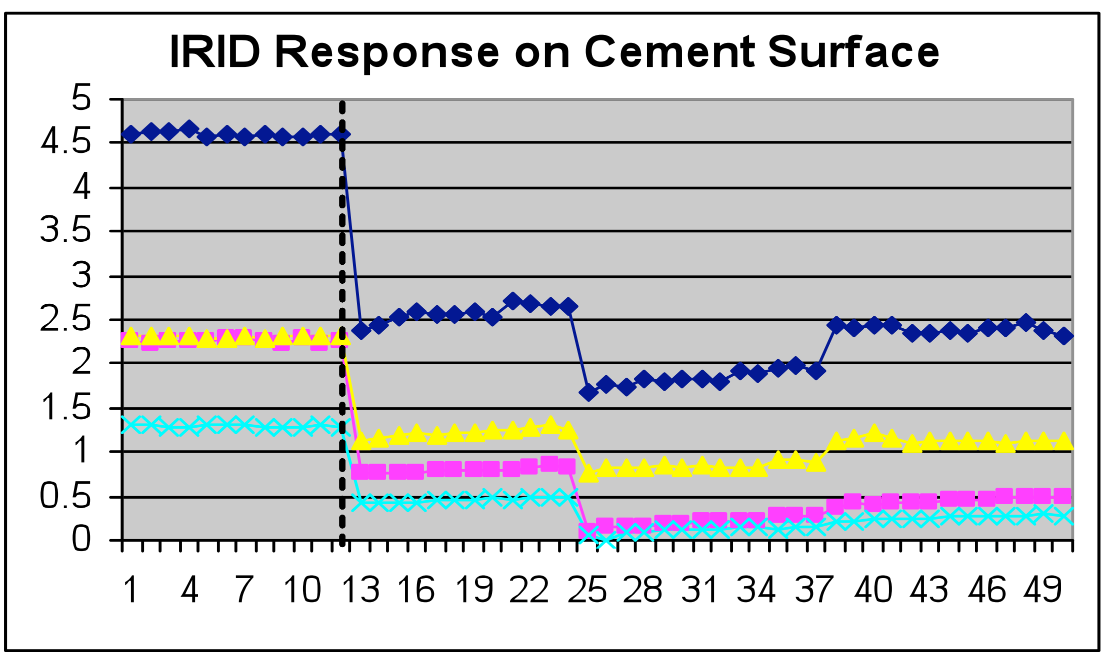

Fig. 13 .- Sensor's Response for Cement Surface

The effect of deicing chemicals on the IRID response is also examined. In Figure 14, we show the response of the sensor for naturally formed layers of snow and ice that were collected on the month of November. Notice that the ambient temperature was not a factor in this case, as it was during the fall and summer experiments; therefore we obtain flat responses for snow and ice regions.

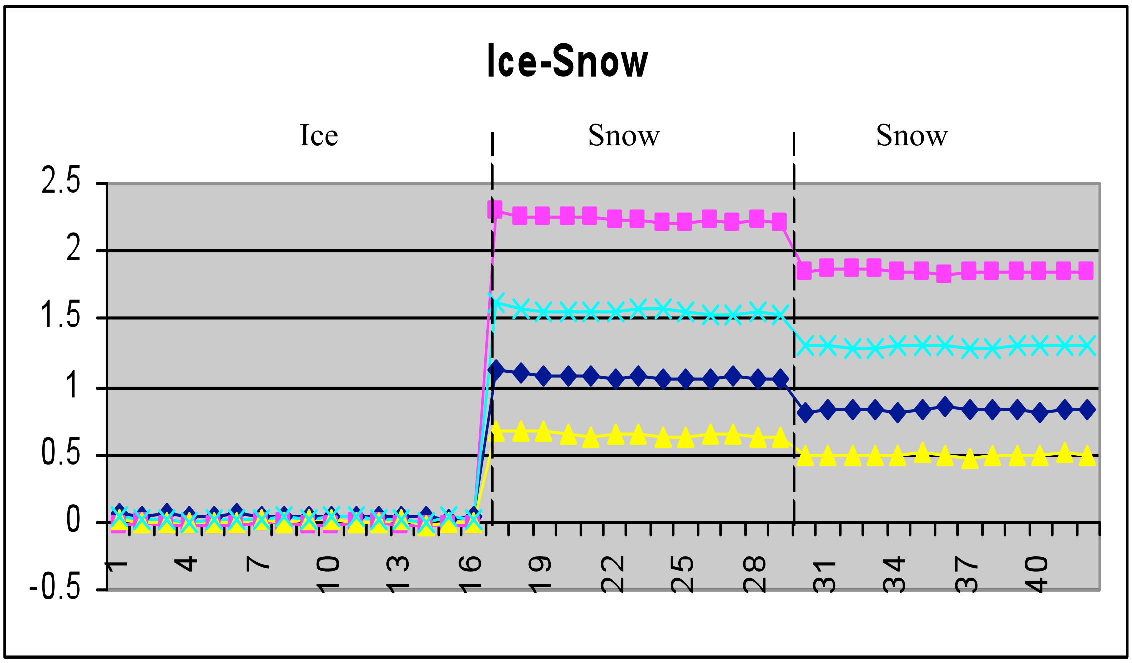

Fig. 14 .- IRID Ice/Snow Characterization

Problems Encountered

We encountered many hardware and software problems in this research effort. Soon after the initial testing process, the whole IRID unit stopped functioning due to some electronic component failure perhaps caused by lighting or an over-voltage from the power supply. After contacting the manufacturer (IDI Company), they presented two options, repairing the board/unit at the IDI location, or we could exchange the original ice detector with a smaller unit that they recently developed, which does not require any software, using an RS232 link. They also suggested providing a wireless link on the unit to send the serial data directly to their computer provided the user is within 500 feet or so. They also suggested signing a $5000 per year Maintenance agreement, in order for them to perform the necessary changes and upgrades to the system, which at the present time has not been signed. We decided to take the first option of repairing the unit, so it was shipped to IDI for its repair. Repairing the IRID lasted the whole winter and Spring Semesters, and consequently we did not have the full opportunity to work on this project until it was repaired and installed again in May 2003. According to IDI, most of the electronics was damaged, the computer board (where a burnt communication chip was found) had to be replaced. The board was re-programmed and tested to check that it was fully functional.

However, testing the unit after we received it from IDI revealed that it still has software problems. It turned out that among the three programs, only the *Toolset* is operational. We tried unsuccessfully to contact IDI many times to fix these problems. Thus we have been using IRID with much less than its full potential. Without full functionality, it took more work to calibrate and locate the points on the pavement. Nonetheless, the results obtained so far are promising.

Conclusions

Extracting pavement conditions is a difficult task due to many contaminants that exist on the road. It is shown in this research that the IRID sensor is capable of distinguishing various cases of rainy, snowy or icy road conditions. We also evaluated IRID sensitivity for the presence and concentration of freezing point depressant chemicals on the roadway surface. Most of the evaluations are accomplished using controlled conditions, while some others used real weather conditions. Although IRID has shown to be effective under controlled conditions, more testing of IRID is needed in real world environment. It is our hope that this research will eventually result in significant improvement in providing meaningful pavement condition information to motorists and transportation professionals [9].

Future Work

We have evaluated IRID sensitivity for the presence and concentration of freezing point depressant chemicals on the roadway surface. However, many other questions about IRID remained unresolved. These include:

1. Sensitivity of IRID to distance, i.e., how far can IRID detect pavement conditions reliably?

2. As most of the tasks in Phase I are accomplished using very controlled conditions, it would be natural in Phase II to expand and test its effectiveness in real world conditions.

3. The IRID is equipped with a camera (Fig 15), with pan/tilt capabilities that can be used to show pictures of the environmental conditions of the different locations near the pavement. We would like to use image-processing algorithms to enhance the overall IRID data so that reliable information about weather conditions can be obtained.

4. The remote access of IRID data is crucial for real time weather information, thus automatic remote access of IRID is needed.

Fig. 15 .- Weather Conditions displayed by the IRID's Camera

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