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Magnetic Tomography – Assessing Tie Bar and Dowel Bar Placement Accuracy

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Correct placement of reinforcing steel in the PCCP is critical for good performance and long life of highways. However, once immersed in the concrete paste, steel placement is difficult to measure with non-destructive methods. Sometimes the steel bars are inserted (placed) using automated equipment. If the insertion process isn't accurate, such that the steel bars are mislocated, costly remedial action can be required.

Timely detection of misplaced steel would provide feedback needed to correct the construction process. To address this need, KDOT developed a field instrument capable of non-destructively assessing the placement (depth and orientation) accuracy of reinforcing steel in PCC pavement using magnetic tomography technology with real time feedback. Several iterations of prototype carts were developed. The final prototype cart developed and constructed used two sensors to determine the steel location.

The long-term direction for this research project was to develop an instrument capable of efficiently assessing the real-time placement accuracy of reinforcing steel in slip-form PCCP paving operations. However, the project was discontinued when the sensor supplier's modified sensor boards weren't reliable, their customer service was less than desired, and no alternate sensor suppliers were available.

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Final Report

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Abstract

The Kansas Department of Transportation (KDOT) constructs portland cement concrete pavements (PCCP) for new highway expansions and/or for replacement of existing highway pavement using slip-form paving operations. Typical concrete pavement construction in Kansas requires reinforcing steel across the joints.

Correct placement of reinforcing steel in the PCCP is critical for good performance and long life of highways. However, once immersed in the concrete paste, steel placement is difficult to measure with non-destructive methods. Sometimes the steel bars are inserted (placed) using automated equipment. If the insertion process isn't accurate, such that the steel bars are mislocated, costly remedial action can be required.

Timely detection of misplaced steel would provide feedback needed to correct the construction process. To address this need, KDOT developed a field instrument capable of non-destructively assessing the placement (depth and orientation) accuracy of reinforcing steel in PCC pavement using magnetic tomography technology with real time feedback. Several iterations of prototype carts were developed. The final prototype cart developed and constructed used two sensors to determine the steel location.

The long-term direction for this research project was to develop an instrument capable of efficiently assessing the real-time placement accuracy of reinforcing steel in slip-form PCCP paving operations. However, the project was discontinued when the sensor supplier's modified sensor boards weren't reliable, their customer service was less than desired, and no alternate sensor suppliers were available.

Acknowledgments

The financial support for the final stage of study on this project was provided by the Kansas Department of Transportation (KDOT), Kansas State University (KSU), and the Advanced Manufacturing Institute (AMI) – affiliated with KSU.

The initial investigators in 2002 were Stan Young, now with the National Renewable Energy Laboratory (NREL) (formerly with KDOT's Bureau of Materials and Research), James DeVault of the KSU College of Electrical and Computer Engineering, and Ruth Douglas Miller, also of the KSU College of Electrical and Computer Engineering.

Bret Lanz and Matt Molz of AMI, who lead the effort to harden the design and commercialize the device.

And, a "Special Thank You" to all who served on the project Steering Committee over the years and to all of you who contributed in some way to this endeavor.

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Chapter 1: Introduction

1.1 Overview

The Kansas Department of Transportation (KDOT) constructs portland cement concrete pavements (PCCP) for new highway expansions and/or for replacement of existing highway pavement using slip-form paving operations. Typical concrete pavement construction in Kansas requires 31-inch-long, #5 rebar placed at mid-depth along the longitudinal joints on 24-inch centers (called “tie bars”) to keep the lanes and/or shoulders “tied” together. Epoxy-coated smooth steel dowel bars ranging in diameter from 1 to 2.5 inches and 18 inches long are placed mid-depth at 1-foot centers across transverse concrete joints to transfer load from one concrete panel to another and to allow for thermal expansion and contraction.

Correct placement of reinforcing steel in the PCCP is critical for good performance and long life of highways. However, once immersed in the concrete paste, steel placement is difficult to measure with nondestructive methods. Tie bars are frequently inserted (placed) using automated equipment. If the insertion process isn’t accurate, such that the steel bars are mislocated, but still under the surface of the pavement, the placement problem can persist indefinitely while going undetected. Steel bars can be misplaced for numerous reasons, including too much vibration during consolidation, obstructions along the insertion path, and mis-calibrated inserters. When placed improperly, costly remedial action consisting of angled drilling and steel insertion (referred to as “stitching”) can be required.

Timely detection of misplaced steel would provide feedback needed to correct the construction process, thus minimizing the need for costly remedial action. The inability to monitor dowel bar placement in real-time has prevented the adoption of automated dowel insertion equipment in Kansas, and its associated cost savings. When owners gain the ability to assess steel placement efficiently during construction, the cost savings from avoiding remedial action may provide the market incentive to integrate the technology into the production equipment.

The long-term direction for this long running research project was to develop an instrument capable of efficiently assessing the real-time placement accuracy of dowel and tie bars in slip-form PCCP paving operations.

1.2 Background

KDOT developed a prototype scanning device that would give real time feedback on the placement of steel bars in slip-formed concrete pavement. This scanning was achieved via a push-cart that houses magnetic scanners coupled to electronics, software and a laptop that gathers and records the data. The push-cart device provides direct feedback, while collecting data, by graphing the magnetic return in real-time on the computer screen. Although the push-cart device is intended for quality control and quality assurance practices of owners, the long-term goal was to provide the technology for immediate feedback behind the concrete paving machines so process control problems can be detected and resolved as quickly as possible to avoid misplaced steel bars. The device maps (locates) and reports the location of steel tie and dowel bars. The accuracy of the instrument is dependent on the steel depth.

A preliminary study funded by KDOT and completed by Kansas State University (KSU) from August 2002 to November 2003 assembled a working instrument capable of collecting the magnetic-pulse-induction sensor readings from steel tie and dowel bars in a manpower and time efficient manner and converted the scanned sensor readings into easily discernable graphics, as well as to estimate the position of the steel from the sensor readings (DeVault & Miller, 2005). The steel finder cart design from 2003 is shown in Figure 1.1.

Figure 1.1: Prototype Instrument Developed by DeVault and Miller in 2003

The prototype device developed by DeVault and Miller in 2003 went through several more development iterations during 2003 and 2004 by personnel at the KDOT Materials & Research Center (MRC) laboratory before a functional prototype was produced and successfully demonstrated in field tests during the 2004 summer construction season (Young & Holle, 2005). The steel finder cart design from 2004 is shown in Figure 1.2.

Figure 1.2: Prototype Built and Tested by MRC Personnel in 2004

A second study completed by KSU and funded by KDOT, Koss Construction, and others improved on the 2004 prototype and added a second sensor for a 3-D magnetic mapping system. The 2006 prototype mapping device extended the work previously done with versions that incorporated single sensors. Multi-sensor capability was added to enable determination of spatial orientation of the steel bars with a single data pass over a pavement joint. Additional features such as GPS location and in-field calibration techniques were used to streamline the data collection and report generation process (Holle, 2017). The steel finder cart design from 2006 is shown in Figure 1.3.

Figure 1.3: Prototype Built and Tested by KSU in 2006

The 2006 prototype PCCP steel bar scanning device had resolved many design problems encountered with previous prototypes and proved the functional real-time concept. The selected electronics integrated custom cover meters with a laptop computer using several off-the-shelf components to convert magnetic signals to show the steel location, log the position, and record the GPS location.

Chapter 2: Commercialization Effort

2.1 Problem Statement

The 2006 prototype steel finder cart required further development and hardening for commercialization as a production cart before prototyping the sensors and electronics directly behind a PCCP slip-form paver.

Though functional and field tested, the software's mechanical interface required additional refinement for user friendly operation and shelf appeal. The required mechanical work consisted of re-engineering the push-cart for user-friendly operation and hardening for a road construction environment. Upgrading the software to be more user friendly was also required.

After the refinements to the steel finder cart were completed, commercialization of the cart product would commence.

2.2 Objective

The Advanced Manufacturing Institute (AMI), an affiliate of Kansas State University (KSU), was chosen to perform the refinements and commercialization stage of development for the steel finder cart.

AMI and KDOT executed a contract in May 2006 for refinement of the existing prototype steel finder cart and production of two additional Steel Finder Carts. AMI proposed a development schedule to ensure the product entered the commercial market in a timely and effective manner.

2.3 Scope

Cart development consisted of design and modeling of all key components to determine the most user-friendly arrangement of the equipment on the cart. A third sensor was to be added to improve the accuracy of the bar location and orientation.

Software and operator interface refinement consisted of refining and necessary redesign of the user interface to make interaction with the system more efficient and user friendly and to incorporate the third sensor being added for location accuracy.

After development of a model cart which met all the requirements, AMI would fabricate two steel finder carts for KDOT and proceed to the commercialization effort.

Chapter 3: Cart and Software Refinement

3.1 Cart

A range of cart designs and configurations were developed to be analyzed for economics and functionality. The final design chosen was dependent on the fiberglass process chosen as discussed below.

Several fiberglass apparatus manufactures were approached for discussion on options available to produce the cart body. The processes available varied greatly as to the cost of production. A cost-efficient method of production was investigated and decided upon.

The steel finder cart design from late 2007 is shown in Figure 3.1.

3.2 Software

The addition of the third sensor required a different microcontroller platform than what the existing MPC555 microcontroller was capable of providing. A “Rabbit Semiconductor” microcontroller was selected and purchased as the replacement platform.

To simplify the electronics and eliminate several individual boards, a central processor board layout was developed to incorporate the individual boards into one with the “rabbit” microcontroller.

Software development was underway in late 2007 to incorporate three sensors rather than the two sensors, which the 2006 prototype cart utilized.

The modified covermeter boards and sensors utilized were manufactured and modified by Kolectric Research Limited (the Vendor) of the United Kingdom. The Vendor notified AMI they were discontinuing the MC 8010 covermeter in 2007; the MC 8010 is the covermeter the prototype cart was designed around. Discussion with the Vendor was opened to determine if they would continue to support AMI’s commercialization effort with the same modified sensor or if some other option would be required.

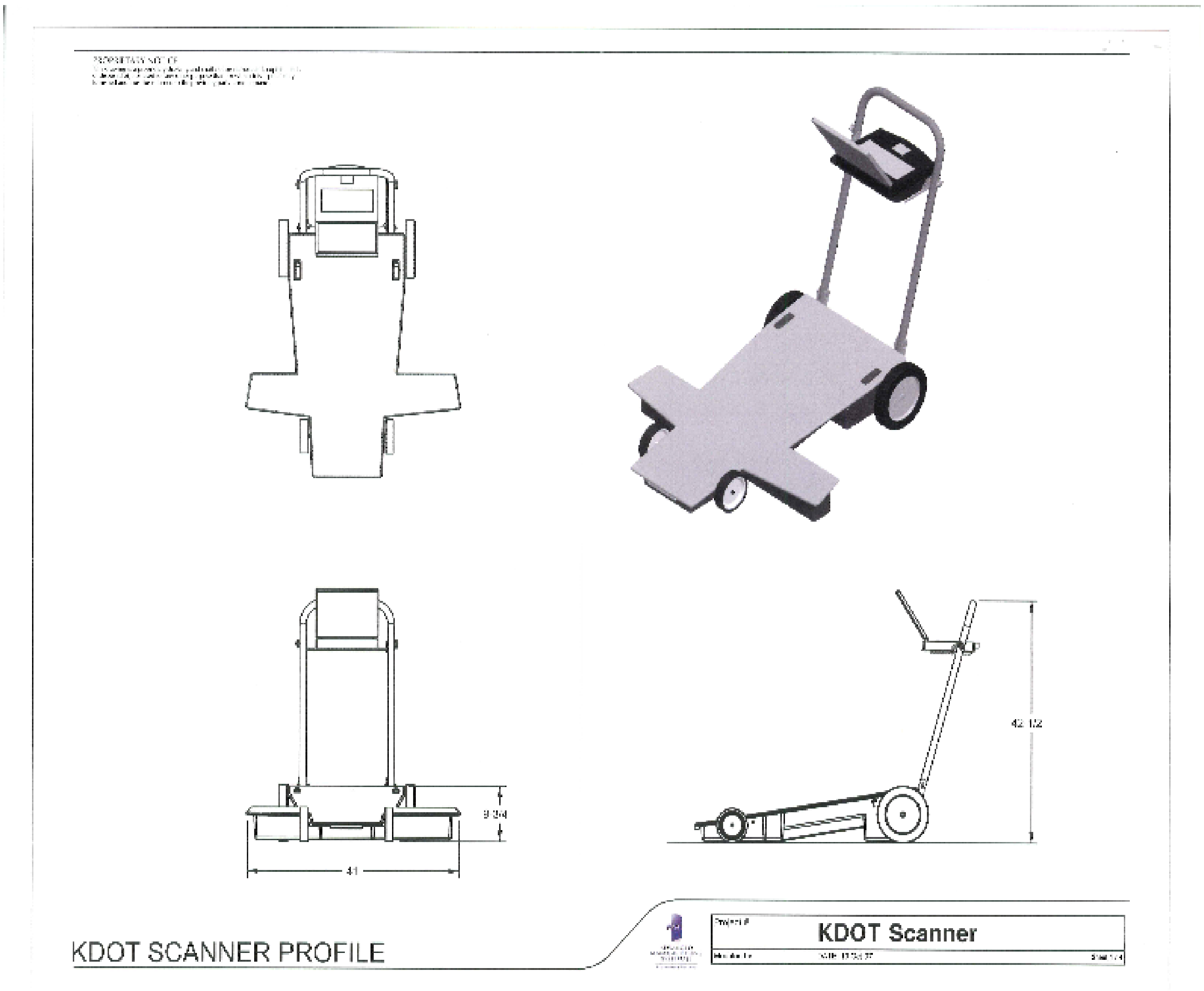

Figure 3.1: Steel Finder Cart Design – Late 2007

Also, in mid-2007, previously purchased modified sensor control boards were returned to the Vendor for diagnosis and repair when AMI discovered they didn't operate correctly. These boards had been powered up upon receipt at AMI to confirm they operated as intended and then placed on a storage shelf.

The Vendor indicated the returned sensors were not repairable during October 2007 and sent a price quote of $21,000 to supply new boards and sensors to support the three-synchronized-sensor setup. The Vendor didn't warranty any part of the previously purchased modified boards that had failed to operate as intended.

3.3 Concerns

Working with the Vendor was difficult at best; sometimes it took several weeks to receive responses to emails and/or telephone calls. Their willingness to partner with AMI/KDOT appeared to be lacking during the commercialization stage of the project.

The Vendor had modified the sensor boards for KSU/KDOT on a previous contract. When AMI went to use those boards, they didn’t operate correctly as noted above. The boards were returned to the Vendor for diagnosis and possible repair. The Vendor said the boards had been damaged and didn’t warranty those boards. The Vendor then proposed AMI/KDOT purchase new boards with a minimum order. The minimum order was for more boards than were initially required. The project didn’t have funds to purchase new boards, let alone more than were needed. AMI tried to negotiate an agreement for fewer boards.

The Vendor was also discontinuing the specific covermeter the cart was built around. AMI discussed the possibility of changing sensors if the Vendor wouldn’t continue to support the modified covermeter boards the cart required. The Vendor proposed to continue with the existing sensor and modified boards with an initial tooling fee, and then with the tooling, be able to produce the sensor and boards in the future.

Attempts to negotiate with the Vendor from October 2007 through June 2008 proved to be fruitless.

Chapter 4: Discussion

4.1 Development Concerns

Based on the customer service and product reliability experienced with the Vendor, AMI had serious reservations about launching a product based around their covermeter technology.

An investigation of other available sensor technologies was accomplished. Ground-penetrating radar (GPR) was investigated as others had developed systems to locate steel in concrete using the technology. GPR systems were determined to be costly and water continues to adversely affect the data output. The end goal of this research project was to incorporate the steel finder system with or directly behind paving machines and be sensing in “wet/non-cured” concrete.

In addition, changing technologies would require a major change to the project scope of work and require additional funding.

After the investigation, magnetic tomography was again the technology of choice based upon KDOT’s specifications for the scanner cart. However, a supplier capable of providing a sensor component meeting the specifications for the overall system didn’t exist.

4.2 Development Options

A steering committee meeting was held November 8, 2007, to discuss the status of the steel finder cart project and to determine a path forward. The consensus indicated there was a need for a steel tie/dowel bar locator unit as more and more distress in pavements is attributed to improper placement of and/or missing bars. The general feeling was that owners must first specify tie/dowel bars be located within specific tolerances and then follow-up with QC/QA checks before there would be a demand for an instrument such as the steel finder cart. Suggestions included getting a larger contractor/manufacturer involved at that time rather than after prototypes were proven, or partner with other DOTs to resolve additional funding issues.

The Director of Engineering at the Missouri/Kansas Chapter of the American Concrete Pavement Association (ACPA) took the steel finder cart concept and sensor board specifications to a large manufacturer in the Kansas City area to see if they would be interested in partnering with KDOT/AMI. Unfortunately, they were not interested in partnering at the time.

Data from questionnaire responses at the Technology Transfer Concrete Consortium in Baton Rouge, Louisiana, in April 2008, indicated several states felt there was a need for a method to locate steel tie/dowel bars in concrete pavement after paving. Most respondents didn't want to spend more than $50,000 for the equipment and indicated the state inspector would utilize the unit.

The AMI development options and their status in November 2008 included:

- Obtain two new boards from the Vendor
    - No additional funding was available and the Vendor had been unresponsive to efforts dealing with products and purchasing inquiries
- Repair old boards or use as a two-sensor setup
    - Repair of old boards was not possible as per the Vendor
- Use boards on original cart and incorporate the new micro-processor
    - Significant development costs remained to incorporate the new micro-processor

4.3 Commercialization Concerns

Based on the development concerns and options discussed above, AMI concluded a supplier capable of providing reliable magnetic tomography sensing equipment to meet the specifications didn't exist. Therefore, AMI didn't see a clear direction or cost effective solution to bring the project to completion with the stated objectives.

4.4 Commercialization Recommendation

Based on AMI's market assessment, the target customer (the contractor) indicated there was no demand for the product and the only reason they would utilize such a device was if there was a regulatory requirement. At that time, no such regulatory requirement had been written to require paving contractors to provide steel tie/dowel bar locations. The MIT Scan device for locating dowel bars had been on the market for a few years and KDOT and AMI weren't aware of any other Department of Transportation with a regulatory document in place requiring proof of the tie or dowel bar locations after paving.

AMI recommended the steel finder project be cancelled and the remaining funds be transferred to other projects.

4.5 Project Assessment

KDOT decided to cancel the steel finder project based on the lack of a reliable sensor supplier, lack of additional funding streams for the additional material required, and AMI's recommendation.

The 2006 prototype loaned to AMI at the start of the project was reassembled with the two-sensor setup and returned to KDOT in August 2008.

The steel finder cart project was closed out during the last quarter of 2008 and the remaining funds were transferred to another KDOT/AMI partnership project.

Chapter 5: Project Closeout Summary

This project proved it was possible to develop a field instrument capable of non-destructively assessing the placement (depth and orientation) accuracy of steel tie and dowel bars in PCC pavement using magnetic tomography technology installed on a push cart.

The original thoughts were to use commercially available equipment in the design and construction of the steel finder equipment. However, to obtain the accuracy required at a depth of 6–8 inches or more in concrete pavement, modified magnetic tomography covermeter sensing equipment was required. Also, the original intent was to develop equipment to be installed on or directly behind a PCCP slip-form paver to give the tie and/or dowel bar locations in real time. Adjustments could then be made as soon as placement went out of specifications rather than finding out after the fact when expensive remedial action would be required.

Several iterations of prototype carts were developed. The final operating cart developed and constructed used two sensors to determine the steel location. Further investigation determined a three-sensor cart was required to obtain the level of accuracy required to find the location and orientation of steel dowel bars for use as a quality control tool.

The three-sensor cart was under development when the project was discontinued due to the lack of reliability of the sensor manufacturer's modified sensor boards. The sensor board supplier wasn't willing to warranty modified boards during the cart development process and their customer service was less than desired, such that commercializing the steel finder equipment around their sensors didn't seem realistic. The sensor board supplier had also discontinued the specific sensor the steel finder cart was built around and wasn't making sensors to locate steel at an 8-inch depth in concrete at that time.

Alternate commercial sensor suppliers who could meet the required specifications weren't available at the time; therefore, switching suppliers wasn't an option. The commercial covermeters available at the time would only sense to approximately 6 inches deep in concrete.

The two-sensor prototype steel finder cart is still operational and has been used several times for QA testing of construction projects since this project was discontinued.

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