RFID Tags for Detecting Concrete Degradation in Bridge Decks

Final Report
December 2013

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Center for Nondestructive Evaluation

IOWA STATE UNIVERSITY
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16. Abstract

Steel reinforcing bar (rebar) corrosion due to chlorine ingress is the primary degradation mechanism for bridge decks. In areas where rock salt is used as a de-icing agent, salt water seeps into the concrete through cracks, causing corrosion of the rebar and potentially leading to catastrophic failure if not repaired. This project explores the use of radio frequency identification (RFID) tags as low-cost corrosion sensors.

RFID tags, when embedded in concrete, will fail due to corrosion in the same manner as rebar after prolonged exposure to salt water. In addition, the presence of salt water interferes with the ability to detect the tags, providing a secondary mechanism by which this method can work.

During this project, a fieldable RFID equipment setup was constructed and tested. In addition to a number of laboratory experiments to validate the underlying principles, RFID tags were embedded and tested in several actual bridge decks.

Two major challenges were addressed in this project: issues associated with tags not functioning due to being in close proximity to rebar and issues associated with portland concrete coming in direct contact with the tags causing a detuning effect and preventing the tags from operating properly. Both issues were investigated thoroughly.

The first issue was determined to be a problem only if the tags are placed in close proximity to rebar. The second issue was resolved by encapsulating the tag. Two materials, polyurethane spray foam and extruded polystyrene, were identified as providing good performance after testing, both in the lab and in the field.

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Principal Investigator
Stephen D. Holland, Associate Professor
Center for Nondestructive Evaluation, Iowa State University

Co-Principal Investigator
Terry J. Wipf, Professor and Chair
Civil, Construction, and Environmental Engineering, Iowa State University

Research Assistants
Tyler Lesthaeghe and Samuel Frishman

Authors
Tyler Lesthaeghe, Samuel Frishman, and Stephen D. Holland

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A report from
Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 Fax: 515-294-0467
www.intrans.iastate.edu

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Problem Statement

Steel reinforcing bar (rebar) corrosion due to chlorine ingress is a primary degradation mechanism for bridge decks. In areas where rock salt is used as a de-icing agent, salt water seeps into the concrete through cracks, causing corrosion of the reinforcing steel and potentially leading to catastrophic failure if the bridge is not repaired or replaced.

Project Description and Background

This project explores the use of radio frequency identification (RFID) tags as low-cost corrosion sensors. RFID tags, when embedded in concrete, will fail due to corrosion in the same manner as reinforcing steel after prolonged exposure to salt water. In addition, the presence of salt water in the concrete interferes with the ability of an RFID scanner to detect the tags. The degradation of the concrete is monitored by scanning for these tags and, when tags start to disappear, it is an indication that the concrete is beginning to degrade.

Research Methodology

During this project, a fieldable RFID scanner was constructed and tested. In addition to a number of laboratory experiments performed to validate the underlying principles, RFID tags were embedded and tested in several actual bridge decks.

Two major challenges were addressed in this project: tags not functioning due to being in close proximity to reinforcing steel and a detuning effect associated with portland cement coming in direct contact with the tags, preventing them from operating properly. Both issues were investigated thoroughly.

Interference from reinforcing steel is unavoidable except by placing the tags at least a few inches away from it. The detuning effect is caused by the dielectric constant of the concrete and can be resolved by encapsulating the tag in a foam that more closely approximates the dielectric constant of air.

Key Findings

Two materials, polyurethane spray foam and extruded polystyrene, were identified as providing good performance after testing, both in the lab and in the field. The encapsulated RFID tags were tested successfully in an actual bridge deck and, while only a portion survive the pour and are readable, the fraction is sufficiently high to make this a practical approach.

Implementation Readiness and Benefits

One of the biggest challenges in inspection is actually locating the tag. Because our reader is limited to a small area at a time, scanning a bridge can be time consuming (many hours for a typical highway bridge). However, this issue could be resolved by consistent tag placement—by placing tags near easy reference points such as near control joints for example. In addition, a much larger antenna could be utilized.

Overall, we have determined that, while there are a few minor issues that need to be considered, this technique is very promising as a simple, easy-to-implement, and low-cost supplement to current inspection techniques seeking to identify chlorine ingress and resulting reinforcing steel corrosion in bridge decks.

Some issues remain to be addressed. The most significant one is to determine exactly when in the degradation cycle of a modern bridge these tags begin to fail. Unfortunately, a small-scale test is unlikely to provide a meaningful answer.

The most practical answer would probably come from field experience, although an accelerated lifing test would be possible (albeit expensive). In addition, incremental improvements to the RFID reader and antenna to support higher speed, larger area, and higher sensitivity would reduce cost and improve performance. Another option is that the practicality of tags with genuine on-board sensors increases as RFID tag technology matures, and these sensors could give a more direct readout of internal conditions within the concrete.

INTRODUCTION

Steel reinforcing bar (rebar) corrosion due to chlorine ingress is the primary degradation mechanism for bridge decks. In areas where salt is used as a deicing agent, salt water seeps into the concrete through cracks, causing corrosion of the rebar and potentially leading to catastrophic failure if not repaired. Because of these concerns, it is critical that appropriate methods are deployed to monitor for such damage. However, difficulties arise in identifying methods that are cost effective and provide useful data over long periods of time, since this kind of damage tends to occur slowly.

The current method of monitoring and preventing such damage involves regular visual inspection for the existence of cracks in the deck surface and making small repairs quickly to prevent salt water from ever entering the concrete. In some applications, sensors are used to monitor the level of salt present beneath the surface of concrete. These sensors, however, tend to have a high cost associated with them, and typically require dealing with issues of power supply, data collection, etc.

This work explores the idea of using commercial off-the-shelf radio frequency identification (RFID) tags as low-cost (5 to 50 cents apiece) corrosion sensors. These tags are passive radio transponders that are commonly used in electronic article surveillance, access control, and inventory management.

The principle behind this method is that such a tag, if embedded in a concrete bridge deck, will fail when exposed to salt water percolating through the structure. Therefore, the next time the structure is scanned with an RFID reader, the tag will be seen as absent. While a single tag that has failed might be an anomaly, a cluster of failures indicates a developing problem with the structure.

There are two major challenges associated with this method that need to be addressed for this method to be viable: the cement creating a detuning effect on the RFID antenna and the ferromagnetic properties of rebar interfering with radio signals. These issues are further explained in detail and we identify a mechanism to overcome these issues.

This project consisted of several tasks: 1) a literature review, 2) building a fieldable global positioning system (GPS)/RFID reader, 3) adding RFID tags to concrete being poured both in the lab and in the field, 4) evaluating performance and determining which techniques are effective and which techniques are not effective, and 5) reporting.

THEORY

Recently, RFID has become a popular tool in numerous applications, including asset management, electronic article surveillance, and access control. A vast array of varying tag designs with a variety of features are now available and are generally very inexpensive, depending on design and application.

Overview of RFID Technology

RFID tags can be split into two separate categories: active and passive. Active RFID tags utilize some external or built-in power source and generally have a limited life. In addition to having a limited life, these tags typically have a higher cost and are generally physically larger, making them impractical in many applications (*1*).

Passive RFID tags do not require a power source. They are generally powered via a reader, using one of two fundamentally different approaches: magnetic induction (near-field) or electromagnetic (EM) wave capture (far-field) (*1*). A near-field system takes advantage of inductive coupling between the tag and energy being produced by a reader antenna; whereas, a far-field system captures EM plane waves propagating through free space being produced by a dipole antenna (*1*, *2*).

Both methods have distinct advantages and disadvantages. For the purposes of this project, far-field RFID technologies present some difficulties, despite having the major advantage of a significantly longer read distance and relatively lower cost. These tags are typically either embedded in integrated circuits or are designed in a way that can make them slightly more sensitive to the stresses they would be exposed to when being embedded in concrete. In addition, there are concerns about the effects of moisture on EM plane waves (*3*). Finally, obtaining such tags is also a difficulty, as they are only distributed typically in quantities of thousands or more.

As a result of some of these difficulties, this project utilized a near-field RFID system, specifically operating in the 13.56 MHz range. This frequency range provides a balance between read distance and data transmission speed, and also meets the other needs required for this project (4).

It is worth noting that this frequency is not chosen arbitrarily. RFID technologies are assigned specific frequencies by the Federal Communications Commission (FCC). Therefore, regulatory issues are also a factor here.

RFID in Embedded Concrete Applications

The idea of embedding RFID tags in concrete is not a new one (*5-9)*. Several projects in the past have produced sensors that utilize RFID technology to passively report the level of chloride ingress in bridge decks (*5*). Some projects have also done in-depth studies using RFID technology in a wide variety of sensor applications (6). However, these methods typically have a much higher level of cost associated with them than the method being explored in this project.

There are some difficulties associated with embedding RFID tags in concrete. As previously mentioned, this project utilized tags using near-field communication. This is based on the principle of mutual inductance, whereby some of the magnetic field lines induced by a loop of current in the reader antenna also pass through the tag antenna and create a loop of current in the tag. This is illustrated in Figure 1.

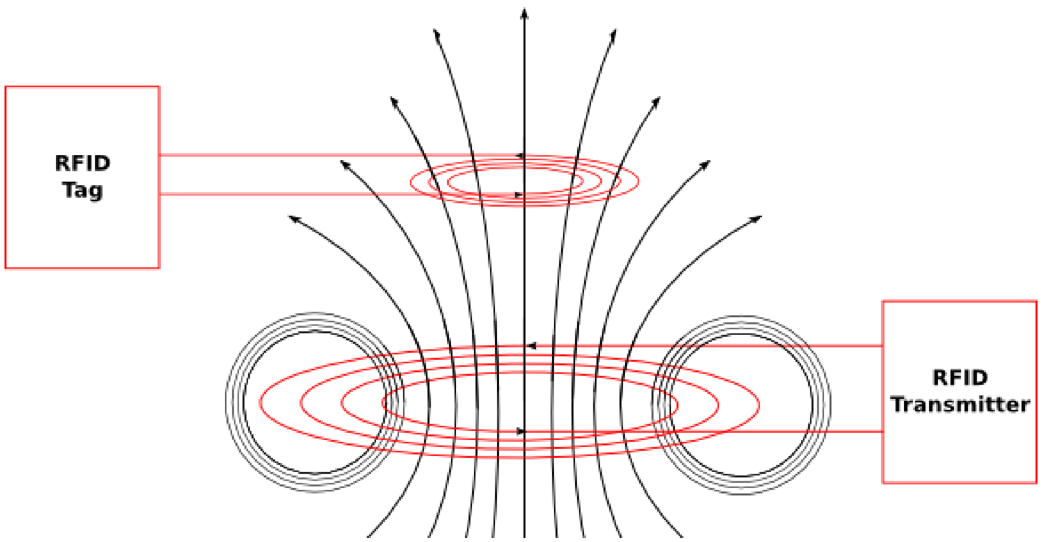

Figure 1. Mutual inductance in RFID near field communication

Communication with the tag is governed by the laws of electromagnetics, as they apply to the tag and the concrete above the tag, and by the resonant circuits that are the tag antenna and the reader antenna. Specifically, the key material properties of the concrete are its electrical permittivity ε and its conductivity σ. These are compared to the permittivity of the surrounding air, the physics constant $\varepsilon_0 = 8.854 \times 10^{-12}$ Farads/meter, and the zero conductivity of the surrounding air. The remaining key electromagnetic property, magnetic permeability μ, is roughly the same for concrete as for empty space (*10*).

The permittivity ε affects electrical capacitance. The tag antenna is a tuned resonant circuit where energy oscillates between being stored in the electric field of the antenna capacitance, *C* and the magnetic field of the antenna inductance, L (*10*). The resonant frequency is as follows:

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad \textbf{(1)}$$

The increased permittivity of concrete compared to air slightly increases the antenna capacitance *C*, causing *f* to be reduced slightly from the nominal resonance of 13.56 MHz. By FCC regulation, the reader must operate at 13.560 MHz +/- 0.007 MHz, so even a very slight shift will prevent communication.

Only the material in very close direct contact to the antenna matters so, in this project, we mitigated the frequency shift successfully by gluing lower permittivity material (foam) to the surface of the antenna.

The conductivity σ of the concrete also affects the ability to communicate with RFID tags (σ is driven by the presence of water and chloride ion and can be a useful diagnostic of its own). Basically, if the concrete is conductive, then the magnetic field generated by the reader antenna will create little circular eddy currents in the concrete between the reader and tag. These eddy currents oppose the magnetic field of the reader and prevent it from penetrating. The characteristic penetration depth is known as the skin depth:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \qquad \textbf{(2)}$$

If the tag is deeper than the skin depth, it will likely be unreadable (*10*).

Another potential issue is the influence of the rebar itself in affecting the ability to read the tags. Rebar is ferromagnetic, so it attracts the magnetic field lines away from the RFID tag, reducing the distance at which the tag can be read. Previous work has shown that rebar can greatly reduce the read distance; however, these effects can be reduced by proper tag placement (*3*).

EQUIPMENT DEVELOPMENT

Prior to beginning any studies, a fieldable RFID reader was required. A setup was needed that could be transported easily and used in a safe and efficient manner, on both construction sites and active roadways, in addition to being used in a laboratory setting. We sought to create a functional and versatile setup. Power was also a major design consideration.

Hardware

As shown in Figure 2, a modified infant stroller was chosen as an apparatus to make the equipment mobile and easily usable in the field.

Figure 2. RFID equipment cart

A wooden frame was built around the stroller to mount all of the equipment. An electrical pull box was used to house a battery, charging circuit, and the RFID reader. A 14.4 V NiMH battery was chosen, along with an appropriate smart charger for the battery. A simple relay circuit was built, as detailed in Appendix A with complete specifications for the apparatus, to allow the equipment to function on an external power supply while charging.

An appropriate 13.56 MHz RFID reader allowing an external antenna was chosen, again with specifications provided in Appendix A. An appropriate external antenna for the reader was also chosen and mounted to place it parallel to and as close to the ground as possible.

In addition, we desired to track the physical locations of these tags, not only to aid in locating embedded tags, but also to give us an easily understandable visual representation of the tags and their locations. This was accomplished by integrating a universal serial bus (USB)-based GPS reader into the cart.

Data collection was accomplished by way of a relatively inexpensive ChromeOS-based netbook with Red Hat Linux installed on it. The choice of using a netbook like this enabled us to avoid worrying about supplying power to a computer or other such device to collect data.

Software

Data collection was powered by a data collection package called Dataguzzler. Dataguzzler is an open-source high-speed data collection platform created at Iowa State originally for acquisition of data in flash and vibrothermography; however, it has been used in a wide variety of projects. This software package provided a reliable and well-tested mechanism for data collection, enabling rapid deployment and a high level of reliability.

In addition to Dataguzzler, Google Earth was utilized to allow real-time visual mapping of tag location, both of tags previously located and of tags being located in real-time. Dataguzzler also outputs the necessary information to display the cart's real-time GPS coordinates. This can be seen in Figure 3, which shows the cart and software in action being used on a bridge to detect RFID tags.

Figure 3. RFID equipment in use on a bridge

RFID Tags

Several different models of RFID tags were used throughout the course of the project. All of these tags, as previously mentioned, operate at 13.56 MHz. The difference between each of these different models of RFID tags are the shape and size of their antennas.

Early work in the project tested several different types, shown in Figure 4; however, we eventually decided on using a Texas Instrument RI-I16-114A-01 24.2 mm circular RFID tag. This model tag was chosen due to its small form factor and the desire to minimize the inclusion in the concrete.

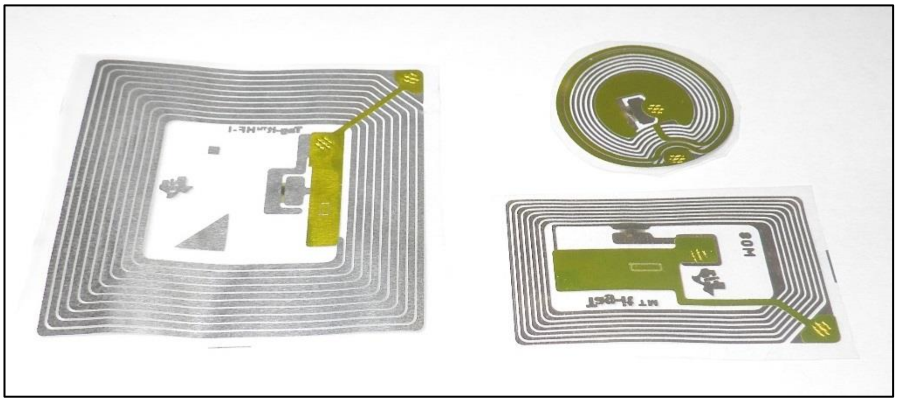

Figure 4. Several RFID tag styles tested

EQUIPMENT AND RESULTS

A series of experiments were performed to test the performance of RFID tags, both in the laboratory and in situ on several bridges poured throughout central Iowa during the project. These results are presented below.

Experiments on RFID Tags near Metal and Other Conductors

A series of experiments were conducted to determine the responsiveness of tags when placed in the proximity of metal and other conductors. These experiments involved placing tags in or around conductors in various configurations and simply checking for a response using the equipment previously described. These experiments simply sought to obtain a qualitative understanding of how conductors can interfere with reading a tag.

Table 1 shows a summary of these experiments and their results.

Table 1. Summary of tag performance near metal and other conductors

Scenario	Performance
Tag set on rebar	Tag Responds
Tag curled around rebar	No Response
Rebar duct taped and tag curled around taped bar	Tag Responds
Tag placed in distilled water	Tag Responds
Tag placed in salt water	No Response

A series of tests involving placing aluminum foil around and on the tag confirmed that, when a tag is mostly blocked from the field being generated by the antenna, the tag will not respond; however, tags that are only partially covered, about one third or less, will still respond. Tags placed extremely close to and on a piece of rebar will have a reduced response distance, but still typically respond. However, a tag configured in a scenario where a conductor is directly blocking the path to the tag typically results in the tag failing to respond. These observations agree with previous literature results on the topic.

Furthermore, we confirmed that tags placed in a salt water solution will not respond, but tags placed in a distilled water solution will respond. We also confirmed that tags will eventually stop responding permanently after being placed in salt water for an extended period of time. This result was also confirmed on tags that were protected with various materials.

Experiments on RFID Tags Embedded in Small Concrete Slabs

Several concrete slabs were poured to test the response of tags protected by a variety of materials and embedded in a concrete slab. Tags of various shapes and sizes were used in these experiments as well. Materials used to protect the tag included several epoxies, plastic, paper, cardboard, wax paper, and several different types of foam.

A summary of results is displayed in Table 2.

Table 2. Summary of tag performance after encasement in various materials

Tag Protectant	Performance
Normal Epoxy	Non Functional
Five Minute Epoxy	Poor Performance
Plastic	Good Performance
Paper	Non Functional
Card Board	Okay Performance
Latex Foam	Bad Performance
Polyurethane Foam	Good Performance
Extruded Polystyrene	Good Performance

In general, tags protected with a hard and relatively thick material functioned properly after being embedded in concrete. We found that materials that were particularly absorbent would not function after exposure to the hydrated cement mixture or salt water, in spite of the fact that the tag inside was still functional, as determined by later cutting the tag out of the material. The best results came from tags protected with certain kinds of foam, such as polyurethane spray foam and extruded polystyrene. It is also worth noting that these materials have low relative permittivity values, also making them ideal.

Figure 5 shows these tags after being encased in their respective protectant materials.

Figure 5. Tags encased using extruded polystyrene (center) and polyurethane spray foam (right)

An observation from this series of experiments indicated that many of the tested tags were not responsive immediately after the pouring process. However, as time progressed after pouring, tags would often begin responding, typically within one to two weeks. This result agrees with results from the literature as well.

Several experiments were also performed that involved submerging these slabs into salt water solution for various periods of time. After submersion in salt water for approximately 15 minutes, all tags were non-responsive until the concrete was fully rinsed and dried. Tags protected with materials that we identified as having poor performance, mostly due to the low likelihood that they will survive pouring, would eventually permanently stop working as well after long-term exposure to salt water. Tags protected with polyurethane spray or extruded polystyrene continued to function after several weeks of continuous exposure after the concrete was rinsed and dried.

Experiments on RFID Tags Embedded in Bridge Decks

RFID tags were placed in several bridge decks during the pouring process. Three locations in central Iowa were utilized: 1) Interstate 35 (I-35) just south of Grand Avenue in West Des Moines, 2) I-35 northbound over Northeast 36th Street in Ankeny, and 3) 34th Avenue Southwest over I-80 in Altoona. Different tags and placement methods were utilized at each site.

I-35 over Railroad just South of Grand Avenue in West Des Moines, Iowa

Several different shapes and sizes of RFID tags were zip-tied down to the rebar. These tags were protected by a fast-curing epoxy (thought to be a good starting strategy given that rebar in Iowa is also protected by epoxy). This site was intended as an opportunity for our team to become familiar with the bridge pouring process and get a better feel for optimal tag placement. Fourteen tags were placed in this bridge during pouring in September 2011; however, none of them survived the pour. Follow-up visits to the site were conducted several days, several weeks, and one year after the pour to find the same results.

I-35 Northbound over Northeast 36th Street in Ankeny, Iowa

Two different sets of RFID tags were placed in this bridge during pouring in October 2011: 1) varying shapes and sizes of tags protected with fast-curing epoxy, and 2) small circular plastic-encased tags.

The plastic-encased tags are designed for extreme applications, such as those involving exposure to chemicals, heat, stress, and so forth. It was known that these tags would never fail in the way primarily intended for them to fail; however, as noted previously, there is a secondary mechanism available in that the tags become unresponsive when submerged in salt water. Thus, the tag could still serve its purpose in a scenario where the surface of the bridge has dried after exposure to salt water, but there is still salt water inside the deck of the bridge. This, however, potentially limits the time and conditions for which inspections could occur.

Some tags were zip-tied to the rebar, some were taped down with electrical tape, and some were pushed into the concrete while it was being poured. In general, very few of the epoxied tags survived the pour; however, as expected, the plastic-encased tags worked well.

Follow-up inspections occurred after several days, several weeks, and one year. After one year, most of the tags that survived the pouring process are still responsive. In fact, we were able to find additional plastic-encased tags that we were not able to locate in the days after the pour. It is worth noting that there is a bit of a challenge in actually finding the tags. GPS coordinates can help the inspector get within a couple meters of the tag, depending on the conditions in which the coordinates were originally recorded, but there can be some difficulty from there. It is important that tags are placed in a consistent manner relative to the roadway to make inspection easier, and there may be other ways that this can be simplified or made easier as well.

34th Avenue Southwest over I-80 in Altoona, Iowa

After poor results with epoxy-coated tags, two other coating methods that had good success in the lab were placed in in this bridge. Thirty-nine tags were placed in this deck during pouring in August 2013, split between tags protected by polyurethane spray foam and extruded polystyrene. These tags were all pushed into the concrete during the pouring process, to a variety of depths. All work prior to this had mainly kept the depth of embedded tags to around the first layer of rebar near the surface of the deck.

A follow-up shortly after the pour identified 13 tags. We expect that further follow-ups after the concrete has fully cured will identify more tags. Given that some of these tags were placed deeper into the surface, they will be more difficult to find.

CONCLUSIONS

The data from our experiments confirm that RFID tags (other than those fully encapsulated in plastic) will fail and stop responding, as expected, after sufficient exposure to salt water. As a secondary mechanism, RFID tags will generally not respond if there is a high enough concentration of salt water between the tag and the reader due to absorption of the electromagnetic energy by electric conduction in the salt water.

Tags also may not respond if placed too closely to rebar; however, difficulty reading tags has only been observed when the tag is in immediate proximity (almost direct contact) with the rebar. Hydrated portland cement also typically causes tags not to respond; however, they will respond after curing is mostly completed as long as the tag is sufficiently protected.

We can confirm that tags can be embedded in concrete and generally require some sort of protection to prevent detuning of the antenna resonance. Extruded polystyrene and polyurethane spray foam were tested as possible protective materials. Both of these materials were tested as readable in both the lab and in actual bridges. Because these materials were developed late in the project, we did not have time to verify that the protected tags do eventually fail when exposed to salt water. Nevertheless, we have little doubt that they will based on how they are constructed and the limited nature of the protection provided.

One of the biggest challenges in inspection is actually locating the tag. Because our reader is limited to a small area at a time, scanning a bridge can be time consuming (many hours for a typical highway bridge). However, this issue could be resolved by consistent tag placement—by placing tags near easy reference points such as near control joints for example. In addition, a much larger antenna could be utilized.

Overall, we have determined that, while there are a few minor issues that need to be considered, this technique is very promising as a simple, easy-to-implement, and low-cost supplement to current inspection techniques seeking to identify chlorine ingress and resulting reinforcing steel corrosion in bridge decks.

Some issues remain to be addressed. The most significant one is to determine exactly when in the degradation cycle of a modern bridge these tags begin to fail. Unfortunately, a small-scale test is unlikely to provide a meaningful answer.

The most practical answer would probably come from field experience, although an accelerated lifing test would be possible (albeit expensive). In addition, incremental improvements to the RFID reader and antenna to support higher speed, larger area, and higher sensitivity would reduce cost and improve performance. Another option is that the practicality of tags with genuine on-board sensors increases as RFID tag technology matures, and these sensors could give a more direct readout of internal conditions within the concrete.

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APPENDIX A. EQUIPMENT SPECIFICATIONS

The components listed in Table A.1 were purchased to assemble the equipment used for scanning RFID tags in this project.

Table A.1. Parts list for RFID cart

Cart Frame	
Cart	Swivel Wheel Jogging Stroller – Target Part # 2097
Wood	1x3x8/1x2x8
Screws	8x1-1/2/6x2
Bolts/Wing Nuts	Lowe's Part # 63334
Electric Box	
NEMA Enclosure	Hoffman ASE10x10x4 Pull Box
RFID Reader	DigiKey ID.MR101
Battery	NiMH Battery Pack – 14.4V 4500 mAh - BatterySpace Part #2627
Battery Charger	Universal Smart Charger – BatterySpace Part #2350
GPS	USGlobalSat BU-353 USB GPS Receiver
RFID Antenna	DigiKey Part # ISC.AMT340/240-A

An infant stroller was modified to serve as the frame for the cart, and a wooden frame was assembled around it. Electrical components were installed into a National Electrical Manufacturers Association (NEMA) enclosure using the wiring diagram found in Figure A.1.

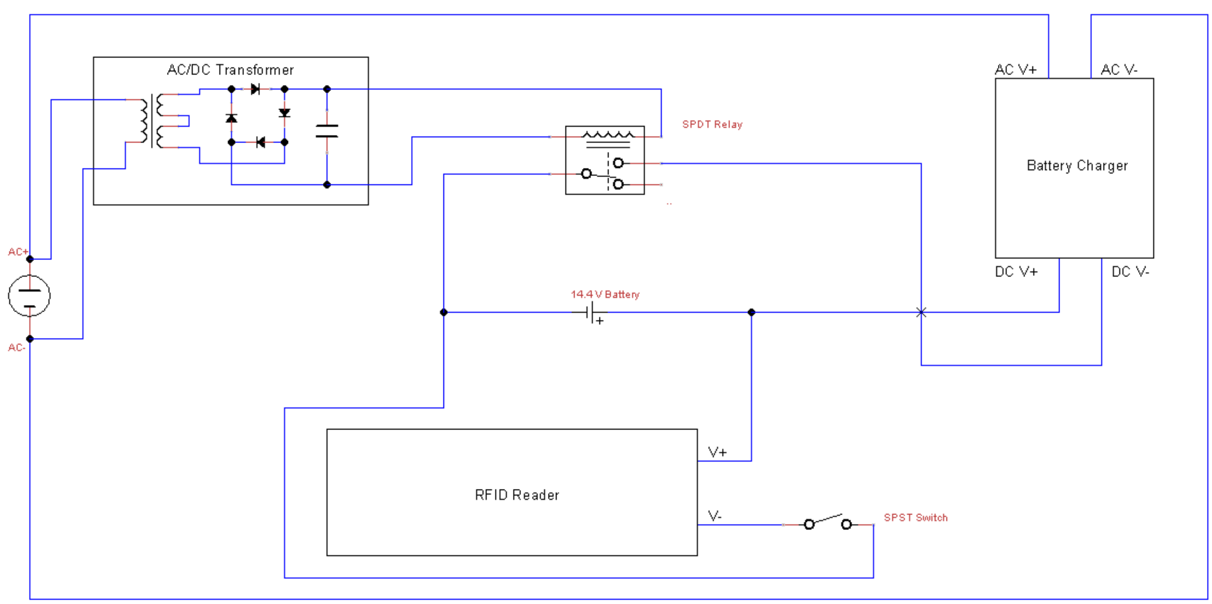

Figure A.1. Wiring diagram for RFID cart