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Wireless sensing in road structures using passive RFID tags

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Abstract. In northern countries several freeze-thaw cycles may occur per day making it especially significant to monitor temperature and water content in road structures. This information is a valuable feedback in performance measurement systems to avoid unsustainable road technologies and as an input by choosing the suitable road design. The way to acquire this data in different layers of the road structure is costly, difficult and time consuming. In this article an idea is presented and preliminary laboratory tests are carried out to use radio frequency identification (RFID) tags with sensors in road structures to measure real-time data about significant parameters throughout the designed lifespan. RFID technology is a relatively new technology in road construction field that has widely spread in intelligent transportation systems (ITS). Because of its benefits, construction and transportation industries are researching and implementing RFID technology to improve data acquiring and storage applications. The results of these tests have proved that RFID tags can be read through different layers and depths of road construction materials. The use of gathered data in road performance measurement systems is proposed.

Key words: road structures, data acquisition, sensor networks, radio frequency identification.

1. INTRODUCTION

In all Northern countries similar special problems with road deterioration due to cold climate occur with variations in temperature, geology and other conditions as traffic configuration, road design practices etc. The deterioration of roads can have serious consequences for the safety and comfort for road users and reconstructions cause extra need for financial assets.

The focus of this research is to verify feasibility of RFID technology in road structures to gather continuously and with relatively low cost significant information about processes in road structures. RFID technology is becoming increasingly viable as a commercial and technological solution to wireless identification [1].

In developed countries, investments in transportation infrastructure form a significant part of all investments. Adequate data from performance measurement systems is required for making investment decisions and in monitoring executed projects. RFID technology is a relatively new technology in road construction field but has widely spread in intelligent transportation systems. Because of its benefits, construction and transportation industries are researching and implementing RFID technology to improve data storage applications and also to develop “smart RFID tags” that are able to sense, monitor, and adapt to their changing environment. RFID has been identified as one of the cornerstones of the upcoming Internet of Things and the focus is moving from conventional RFID towards next generation networked and inter-connected systems [2].

In soil, RFID applications are currently used in farming to regulate irrigation. Vuran developed the world’s first underground radio frequency (RF) sensor network [3]. Embedded wireless sensors monitor soil condition underground, transmit the data from one sensor node to another, and finally either to a hand-held computer, a fixed base station or an irrigation system. The use in agriculture and positive test results gave confidence to the authors that RFID technology can be used in moist soil conditions.

Off-the-shelf passive RFID tags as a telemetry link in a wireless sensor for real-time monitoring of soil properties such as temperature, but also how the same RFID system could be used for various types of sensors was investigated in [1]. The concept of using radio telemetry for wireless monitoring of soil properties is not new. NASA researchers have developed a wireless mesh of radio sensors for monitoring heat, humidity, and soil moisture. In 1984 a wireless soil moisture telemetry system was developed that had multiple individually addressable moisture sensors in the field [1]. The base station would query all the sensors in turn using RF transmission, and the appropriate sensor would transmit data in reply, also over RF.

In road construction, several RFID applications have been tested, but their focus has been on the increase of the supply chain efficiency. Researchers at the University of Alaska evaluated how RF identification can be used to track the amount of time that passes between the moment a truck is first loaded with asphalt and the instant the hot mixture is dumped [4]. They have reported that RFID was effective to gather information and to issue alerts regarding the movement of those vehicles.

2. MOTIVATION OF THE RESEARCH

Currently pavement and road structure monitoring needs significant personnel time or the use of costly equipment. This data is an important input by the design of new roads [5]. In this article we suggest to use passive and battery assisted passive (BAP) RFIDs with sensors in road structures to measure continuous data about significant parameters throughout the lifecycle of the road. Previous research [6] has indicated readability problems with the use of RFIDs; therefore the authors conducted preliminary tests to verify the suitability of RFID.

The estimated lifetime and durability of suggested technologies are more close to the lifetime of the road than other low-power wireless technologies such as wireless sensor networks and active RFID sensor tags. Therefore they do not require intrusion to road structures for data acquisition and maintenance reasons.

The climate of Estonia, comprising several freeze-thaw cycles even per day in winter, makes it particularly important to have information about temperature changes and about the amount of water moving through pavement in different layers of the embankment. Cracking of pavements related to low-temperature frost and freeze-thaw cycles is a well-recognized problem in most northern countries. Premature deterioration of road pavements is related to high frequency of freeze-thaw cycles, primarily where subgrades are composed of fine-grained, saturated material [5,7].

Once in a pavement or embankment, water plays a primary role in shorterning the service life of the pavement and increasing the need of rehabilitation measures. In order to have a sustainable road it is necessary to consolidate well the earthworks, have good sub-base drainage, keep the water-table low, prevent increasing of the moisture content of the sub grade, avoid failures due to binder stripping and not to allow water to remain on top of the surface, weakening the surface due to hydraulic pressure. If improperly canalized, water can also cause soil erosion and a breakdown of pavement edges.

By freezing temperatures, the deteriorating effect of water is even greater. Cold temperatures in winter are a significant concern for transportation agencies because due to frost the phenomena called *frost heave* occurs, a road will actually "heave up", being the major deterioration of roads, especially in case of insufficient drainage.

Therefore it is essential to monitor the above mentioned causes of deterioration in order to avoid design failures and to give support to the road agencies to establish the best requirements for designing and constructing sustainable roads. Authors suggest to measure water content and temperature simultaneously in road structures using passive and BAP RFIDs with sensors (see Fig. 1).

3. RFID TECHNOLOGY

RFID technology as we know it today dates back to 1970's [8]. Cardullo's and Walton's devices were patented in 1973, succeeded by the marketing of first usable products in 1979. The RFID technology is a means for uniquely identifying an object with a wireless radio link, allowing data to be stored on an RFID tag and retrieved in remote application at a later point of time.

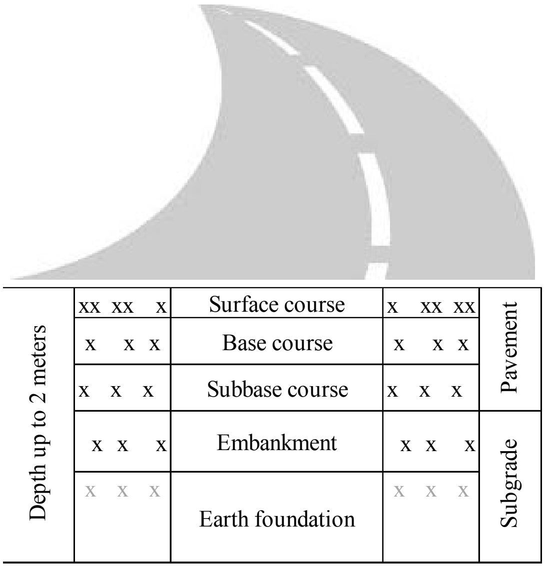

Fig. 1. Road cross-section (x marks the planned locations of tags).

Wireless sensors, incorporated in RFID systems, are important in several industrial, consumer and logistics applications. By extending RFID tags to sensing applications, the products become smarter and RFID sensor network applications are emerging and moving towards commercialization [9].

RFID tags can be classified into two categories: passive and active. The active RFID tags have their own internal power source that is used to power the integrated circuits and broadcast the response signal to the reader [10].

Two passive RFID technologies are available: surface acoustic wave (SAW) and integrated circuit (IC) based. Passive RFID sensor tags may be categorized as SAW, IC Passive and IC BAP (Fig. 2).

These technologies have been successfully used in various applications, amongst others also in the construction industry. Due to the progress in integrated circuit technology, it is expected that RFID will play an important role in the global circulation infrastructure. It is expected that more RFID tags will be used in the future as sensory functions come more commonplace [11].

A typical RFID system includes three components: an antenna or coil, a transceiver (with decoder), and a transponder (RFID tag), electronically programmed with unique information, as shown in Fig. 3 [12].

There is an emission of radio signals by the antenna in order to activate the tag and to read the data written to it. Antennas establish the communication between the tag and the transceiver. The transceiver is responsible for the data acquisition. The antenna can be packaged with the transceiver and decoder in order to form a reader. An RFID reader contains power supply and software to enable it to communicate with both RFID tags and an upstream computer system.

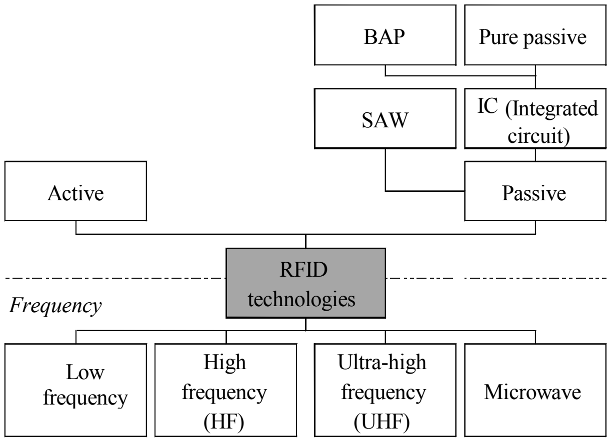

Fig. 2. Typology of RFID technologies.

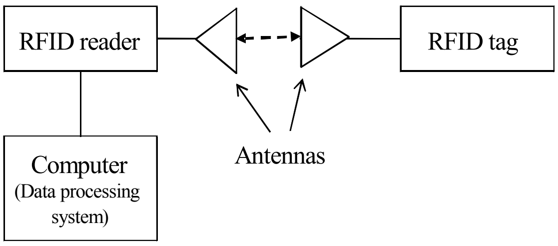

Fig. 3. RFID system generic structure.

In case an RFID tag is found in the electromagnetic field that is produced by the antenna, it detects the activation signal of the reader. The reader decodes the data that are encoded in the integrated circuit of the tag and the data can then be transferred to any computer system for processing.

RFID tags can be designed to transmit at one of several frequencies. Generally, the higher frequency tags transfer data more quickly but are less able to penetrate water, grease, and other obstructions.

4. SYSTEM DESIGN

4.1. System architecture

Authors have studied RFID tags with sensor functions because it is assumed that the RFID tag can detect the conditions of structures and transfer its information through the external reader [10]. With this in mind, a system was developed (Fig. 4) to monitor the condition of the road structure and establish the impact of water content and temperature change to road deterioration.

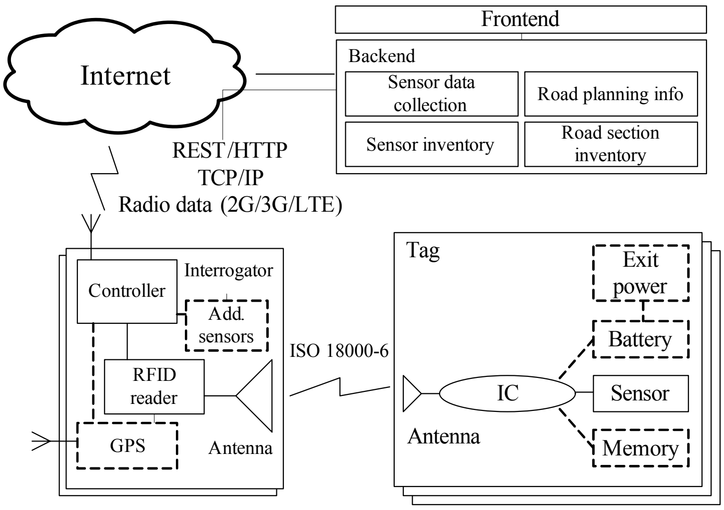

Fig. 4. System architecture.

The interrogator may be located in the moving vehicle or placed stationary on the road side. The RFID reading on motion adds certain requirements on the tag and reader antenna orientation, but at the same time reduces costs. Having many metering points with stationary readers costs more than a few, but often the by-passing vehicles have the interrogator on board [12,13].

Interrogator processes and enriches the raw sensor tag data. It consists of a RFID reader together with an antenna and data processing system. It may contain the GPS module to add the location coordinates to the sensor reading, to allow reporting on deviations of stored data and field information. The backend system will do the matching of the received information based on tag identifier and reporter trustworthiness. If the coordinate deviation threshold is calculated based on the speed of the vehicle, a signal to sensor inventory maintenance personnel is created to check the coordinates. Interrogator contains additionally sensors for reading the air temperature, relative humidity and speed of the interrogator when in motion.

The data from interrogator towards the backend server is transmitted over REST style HTTP(S) interface on top of the TCP/IP network to avoid possible data communication network operator restrictions. For moving units, radio network is a necessity. Stationary units may be connected to the fixed communication line, if available.

Backend server keeps the inventory of installed sensors (location, installation date, depth, layer material) and collects the sensor data (interrogator identifier, sensor identifier, reading location, temperature and water content in road structures, signal strength, temperature and relative humidity in air) sent by interrogators. Road section inventory (section name and identifier, owner, maintaining organization, condition, and history) is kept in the same database to allow reporting, based on the road sections.

Backend server keeps also road planning information (e.g price of the road section) to be able to report on the deviations between the plans and current situation and to do the cost calculations to assist modelling of upcoming road construction projects. The reports and online sensor data is displayed and rendered to the graphical format in frontend graphical user interface to be used by the stakeholders. Sensor data is made available to third parties through public application programming interface using open data principles. Correction functions for sensor readings are applied in the backend during the data collection process.

4.2. Sensor applications

For IC tags, normally a sensor tag comprises four major blocks – an analogue sensor, analogue-to-digital converter (ADC), digital controller circuit and RF part with antenna. The BAP tag may contain optionally non-volatile memory (e.g. FeRAM) for data storage, ultra long-life energy storage (e.g. lithium-polymer, thin film super-capacitor) and renewable power source (e.g. piezoelectric or photovoltaic generator).

It is known that low-cost capacitive soil water content sensors are sensitive to soil density, temperature, salinity, and supply voltage (RF signal strength) variations [[14,15]]. The calibration method to correct the readings, based on geostatistics, sensor clustering and information sharing has been proposed in [[16]].

The proportional-to-absolute temperature (PTAT) current generator, directly representing the temperature, delivers the PTAT current and a reference current, keeping the latter's value constant over the temperature range of interest. In the RFID tag the ADC then processes both currents into the digital data stream and passes it to the controller, which encodes the result into the response [[17,18]]. Also a design without ADC has been proposed in [[19]] to even more reduce the power requirements to the sensor.

The capacitance and time domain reflectometry methods are two widely used electromagnetic (EM) techniques for soil water content estimation. Both methods make use of the strong dependence of EM signal properties on volumetric water content that stems from the high permittivity of water compared to mineral soil solids, and air. The basic principle of the capacitance method is to incorporate a dielectric medium (e.g. soil) as part of the dielectric of the sensor capacitor [[14]].

Temperature and water content measurement using SAW tags has been considered in [[20]]. The SAW RFID tag consists of an inter-digital transducer (IDT) and a series of acoustic reflector traps, etched into a piezoelectric substrate. The tag reader emits a radio wave pulse to IDT that is converted piezoelectrically into a nanoscale acoustic wave. The wave travels past the reflectors to produce a unique pattern of reflected pulses. These travel back to IDT, where they are piezoelectrically converted into an encoded radio wave reply signal to the reader. The SAW chip operates in a purely passive mode and does not require supplementary direct current [[21]].

5. PRELIMINARY TESTS

Authors conducted a preliminary empirical test in laboratory conditions to check whether the ultra-high frequency (UHF) IC passive tag transmittance in dry soil and in road construction materials is similar to the expected.

For that we connected ThingMagic Vega UHF RFID reader to RHCP (Right Hand Circular Polarized), 7.5 dBiC antenna and to a PC with software needed for reading. In another end, the authors used Confidex Ironside metallic, ALN-9629 "Square" Inlay and Avery Dennison AD-824 RFID tags. Authors were aware of the fact that the metallic tag performance is suboptimal when placed on a non-metallic surface, but it was decided to test a tag with average performance in the air, which is approximately at a four meter distance from our reader. All the tests were executed in laboratory environment at room temperature.

Second set of tests was conducted at a road construction site to get a proof that the signal could be read through different materials used in road construction from the depths up to two metres. During the experiment we inserted the tag at various depths into the soil, going up to two metres, and took readings leaving the variable air gap between the soil and antenna so that the distance between the antenna and the tag was never bigger than three metres. The success rate of the reading was as expected and we were able to get readings using all three types of RFID tags.

The results provided a solid ground for continuing the testing with different materials to simulate actual conditions. In the preliminary field trials authors tested the Confidex Ironside metallic RFID tag in soils (sand, gravel) with various moisture. We placed the tags in depths up to two metres, leaving the gap between the antenna and the tag so that the distance between the antenna and tag was also never bigger than three metres. Authors were able to get readings through all tested materials and are confident to move to the next stage to start preparing a field test at a road construction site.

6. CONCLUSIONS

In all Northern countries cold climate is a cause for road deterioration. Long term monitoring of the parameters of the pavement and traffic helps to reduce maintenance costs, improves longevity, enhances safety and research in pavement design.

The use of sensor equipped RFID technology in agriculture as part of automatic irrigation systems gave the idea to use passive and BAP RFID tags with various sensors in road structures to measure temperature and water content. Authors conducted a series of tests in laboratory and field conditions and confirmed the RFID tag applicability in different depths up to two metres in soil and road construction materials. Literature review and preliminary tests prove that the technical solution presented in this article is perspective.

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Juhtmevabade RFID-tehnoloogial põhinevate sensorite kasutamine teekonstruktsioonis

Kati Kõrbe Kaare, Ott Koppel ja Kristjan Kuhi

Infrastruktuur, eriti kvaliteetne teedevõrk, on iga riigi jaoks strateegiliselt oluline. Sellest sõltuvad nii elanikkonna rahulolu, paljude elutähtsate valdkondade toimimine kui ka majanduse areng tervikuna. Seega on möödapääsmatu, et teedeehituses kasutatakse konkreetse paikkonna klimaatilistele tingimustele ja liikluskoormusele vastavaid tehnoloogilisi lahendusi ning materjale. Normdokumentide koostamiseks, millest tulenevad ka vastava piirkonna jaoks soovitatavad tehnoloogiad, on muude parameetrite kõrval vaja ka väga täpseid andmeid temperatuuri ja niiskussisalduse kohta teekonstruktsiooni erinevates kihtides.

Käesolevas artiklis on autorid kirjeldanud võimalust kasutada teekonstruktsioonides passiivseid või poolpassiivseid RFID-kiipe, paigutades need tee erinevatesse kihtidesse. Juhtmevabad kiibid on varustatud sensoritega, mis mõõdavad temperatuuri ja niiskussisaldust pinnase erinevates kihtides. Toiteallika ja juhtmega lahenduste kasutamist ei pidanud autorid otstarbekaks katsetada, sest külmakergete ning nihkepingete tagajärjel on juhtmeühendused varasemates uuringutes ebakindlateks osutunud.

Autorid viisid laboritingimustes läbi esialgse katsetuste seeria, mille käigus testiti RFID-kiipidest lugemite saamist pinnasest ja erinevatest teedeehituses kasutatavatest materjalidest eri sügavustel. Kiipidest kasutati Confidex Ironside Metallic'u, ALN-9629 "Square" Inlay ja Avery Dennison AD-824 RFID-d. Sellise valiku tegid autorid, arvestades mitmeid varasemaid uuringuid, mis kaardistasid erinevate transponderite tagasilevi signaali tugevust lugeja konstantse väljundsignaali korral.

Antud kiibid osutusid oma klassis omadustelt Eesti kliimatingimustele kõige sobivamateks. Pinnasest oli võimalik saada andmeid kuni kahe meetri sügavuselt. Sellel sügavusel lõpetati katsed, arvestades külmumispiiri. Teise katsete seeria viisid autorid läbi tee-ehitusel, paigaldades kiibid pinnasesse, kontrollimaks, kas on võimalik lugemeid saada. Katsetatavateks materjalideks olid pinnas, liiv ja killustik, sügavuseks samuti kuni kaks meetrit.

Peamise järeldusena leidsid autorid, et on põhjendatud detailsema uuringu läbiviimine RFID-tehnoloogia kasutamise võimaluste kohta erinevatest materjalidest koosneva teekonstruktsiooni sees temperatuuri ja niiskussisalduse mõõtmiseks.