An innovative water and ice detection system for monitoring road and runway surfaces

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***Abstract*—Detection of water and ice over road and runway surfaces is an important issue in improving traffic safety and reducing costs for the maintenance, especially during winter. A low cost capacitive sensor for the estimation of road and runway conditions is studied. An algorithm for the estimation of the state of road and runway surfaces (dry, wet, or icy) was developed based on experimental results, which indicated that the time derivative of the measured capacitance provided optimal information. Accuracy and reliability of the estimates provided by the sensor was assessed in laboratory conditions, placing more sensors in a climatic chamber in the same conditions and investigating the estimates of the state of the sensors and the timing of the identification of wet-icy or icy-wet transitions. Reliable estimates were obtained by all the sensors, with a dispersion of the transition times of the order of a few minutes.**

Keyword: sensor, ice and water detection, road and runway surfaces information

I. INTRODUCTION

Investigation of ice formation found important applications in different fields. For instance, an adequate assessment of the environmental conditions of road surfaces may significantly contribute to enhance traffic safety [1]. The investigation of ice formation on the runway of airports can improve safety during take off and landing of the aircrafts [2]. The accretion of ice is a common occurrence on the aircraft, due to the high velocity, and the high humidity and low temperature in upper air [3] [4]. The detection of the presence of ice allows its quick removal, which increase flight safety. Ice formation over the seas is investigated to control iceberg growing and to avoid possible accidents (e.g. crash with boats) [5]. Investigation of ice formation on walkways may prevent people falls.

The detection of water and ice is one of the main problems in the assessment of the environmental conditions on road and runway surfaces. The investigation of pavement conditions is attracting increasing attention, as it may significantly contribute to reduce costs of highway and airport snow and ice control [6]. This allows agencies to efficiently plan the maintenance of roads and runway during winter, to reduce wear on the vehicle fleet, to decrease chemical, sand and salt usage, and to provide a better level of service by applying anti-icing practices. Three types of weather information are important: atmospheric data (e.g. air temperature and humidity, visibility distance, wind speed and direction, precipitation type and rate, cloud cover, lightning, air quality), water level data (stream, river and lake levels near roads) and pavement data (temperature, freezing point, chemical concentration and pavement condition, e.g., dry, wet, icy). Pavement data are typically used to forecast surface conditions and choose proper anti-icing procedures [6].

There are already available some solutions which recognize the presence of ice. Some methods are indirect techniques that can detect icy conditions by image-processing techniques. These methods are commonly used to monitor the formation of ice on a wide area. Wide area measurements can be performed using different methods, for example time-domain reflectometry [7], polarimetry technique [8], weather satellite [9], microwave sensors [10], spectroradiometers [11], and ultrasonic guided waves [12]. In order to detect ice directly, putting a sensor in contact with the surface over which ice may develop, physical sensors are used. Different kinds of sensors were developed exploiting different physical principles, for example micro-fabricated diaphragms [13], fiber optic [14], and resonant piezoelectric [4]

An innovative ice sensor was introduced in [15]. The sensor detects water and ice on exposed surfaces, based on a capacitance measurement. This work is devoted to the investigation of the accuracy and reliability of the indication provided by this new ice detection system using experimental results.

II. METHODS

A. *Ice detection system*

The ice detection system consists in a capacitance measurement [1] [15]. In general, the value of capacitance of the electrode assembly depends on the geometrical configuration and dimensions of the surfaces of the electrodes, and on the permittivity and thickness of the material placed between the electrodes. The permittivity, in turn, depends on temperature and measurement frequency [16]. The relation between the relative permittivity of water or ice, and the temperature and measurement frequency, is shown in Fig. 1. The relative permittivity of ice at approximately –1°C is substantially constant within a range from DC to about 1kHz, and decreases in the range of approximately 2kHz to several hundred kHz. On the other hand, the relative permittivity of water at approximately 1°C is substantially constant up to

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approximately 10^9Hz and decreases within the range from 10^9Hz to 10^{10}Hz. The relative permittivity of air can be assumed as low and constant for each frequency.

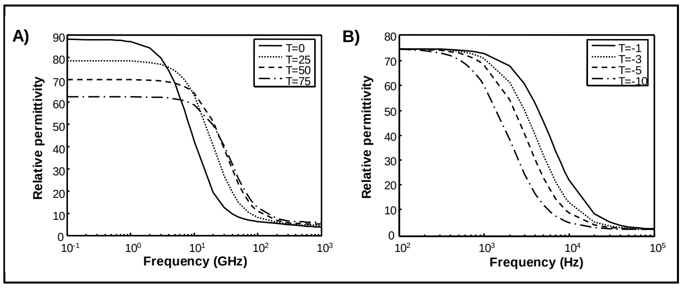

Figure 1. Relative permittivity of water as a function of temperature and measurement frequency. (A) Water at temperature higher then 1°C. (B) Ice at temperature lower then -1°C.

When measuring the capacitance, it is not possible to distinguish reliably between water and ice at low frequencies (lower than 1kHz), but only air can be identified; on the other hand, ice and air cannot be distinguished at high frequencies (between 100kHz and 1GHz), but it is possible to identify the presence of water. Thus, it is possible to distinguish between water, ice and air by two capacitive measurements, at low and high frequencies [15].

The currently available ice sensor is shown in Fig. 2A. This device performs measurements at two different frequencies, at 200Hz and 20MHz. The sensor system consists on a pair of concentric conductive electrodes (with geometry indicated in Fig. 2B), which are the sensing device, a frequency generator and a charge detector. The sensor electrodes of the ice detector are directly connected to the capacitance measurement circuit, shown in Fig. 2C. This circuitry is implemented on a printed circuit board using commercial available low power components. The frequency generator is obtained by a reference voltage source V_R and a controllable switch S_1 to provide different frequencies. The electrode assembly and the material placed over the sensor constitute the capacitor C_X. In the basic measurement circuit, the charge detector comprises only a reference capacitance C_S that is connected to the electrodes by closing the switch S_2. At the end of the measurement process, C_S is discharged by closing the switch S_3. In order to increase accuracy in measuring the very small value of capacitance C_X, the sensor was charged n times and its charge was transferred n times to the reference capacitor before taking a measurement of V_S. Therefore the value of the capacitance of the sensor is given by [15]:

$$C_X = \frac{C_S}{n} \frac{V_S}{V_R} \qquad (1)$$

An automatic calibration procedure is included in the ice sensor to prevent error in the data due to parasitic capacitances [15]. Also the capacitance of the dry electrode is subtracted by the calibration procedure. The device also comprises an internal temperature sensor.

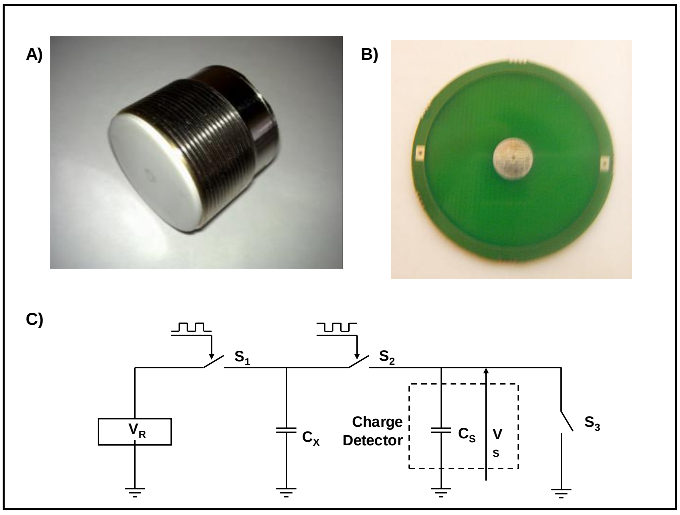

Figure 2. The ice sensor. (A) Picture of the ice sensor. (B) Picture of the concentric conductive electrodes. (C) Schematic layout of the capacitive measurement circuit.

A layer 3 mm thick of Arnite was mounted over the sensor electrode, for protection purposes. Arnite was chosen because its dielectric constant is nearly constant (equal to 3.5) within the range of temperature and measurement frequency in which the sensor is used. The ice detection system arrangement was included in a metallic box filled with resin, which protects the circuitry from infiltration of water or chemical agents. The only exposed parts are the Arnite covering the sensor (on the top) and the connector for the power supply of the circuitry and for the connection to a personal computer.

B. *Experiments*

The reliability of the estimates provided by the ice sensor was investigated during laboratory experiments. Laboratory tests were performed applying the same environmental conditions to more ice sensors and evaluating the dispersion of the time instants in which phase changes of water were detected. Nine ice sensors were placed at the same time in a climatic chamber (Angelantoni - Challenge 250; temperature range for climatic test from -40°C to +180°C). At the beginning of the experiment, sensors were placed in the climatic chamber at ambient conditions, with a temperature of 25°C and humidity of 50%, for approximately 10 minutes in order to adjust sensor’s parameters. Then, 1mm of tap water was placed over each sensor. Sensors were left in ambient conditions for 10 minutes. Then, the climatic chamber was arranged to reach -20°C with a temperature gradient of -1°C per minute. During this period, water placed over sensors froze. The climatic chamber kept the temperature of -20°C for approximately 10 minutes and then it was arranged to reach 25°C with a temperature gradient of 1°C per minute. During this period, the ice formed over the sensors melt. The climatic chamber kept the temperature of 25°C for approximately 10 minutes. Then each sensor was dried. Data were acquired for additional 10 minutes, with a temperature of 25°C and humidity of 50%. The experiment was repeated in 3 different days, in order to investigate the repeatability of the capacitance values and the reliability of the sensor.

C. Signal processing

In order to discriminate between different states of the sensor surface (dry, wet, or icy), the capacitance values obtained at the two measurement frequencies were digitally processed using an innovative algorithm. Data were digitally low-pass filtered, in order to reduce high frequency variations and instrumentation noise. Since jumps in the capacitance values were associated to a state variation of the sensor (dry-wet, wet-icy, icy-wet, and wet-dry), a first-order derivative was computed on the filtered data in order to emphasize these jumps. A jump was considered significant if the first-order derivative of the capacitance was higher then a threshold value. The algorithm identified the changes of the phase over the sensor based on the jumps on the first-order derivative of the capacitance values estimated at the low and high measurement frequency.

Capacitance values and time instants of state transitions obtained for each sensor during the experiments were then compared in order to study the repeatability of the measures

III. RESULTS

Capacitance values (raw data) obtained from a sensor during the first experiment at two measurement frequencies are shown in Fig. 3A. Variations of the values of capacitance in different states of the sensors are clearly visible. During the dry state, values of capacitance were close to zero, due to the calibration procedure. During the wet state, the values of capacitance at high and low frequency are close to 0.3pF, so that there is no distinction between different measurement frequencies. During the icy state, the values of capacitance at high frequency are close to 0.15pF while at low frequency are close to 0.3pF, so that the value of capacitance can be easily distinct for different measurement frequencies. Low pass filtered values of capacitance are shown in Fig. 3B. First-order derivative of the values of capacitance are shown in Fig. 3C (below). Peaks are clearly visible in correspondence of a variation of the state of the sensor. States of the sensor revealed by the algorithm are shown in Fig. 3C (above). The estimated states agreed with the observed state of the sensor (Fig. 3A).

Capacitance values (raw data) obtained for each sensor during the first experiment (high and low measurement frequencies) are shown in Fig. 4A. Internal temperature of the climatic chamber during the first experiment is shown in Fig. 4B as measured by the internal temperature sensor of the ice detection system. The state condition detected by such a sensor is also shown. The wet-icy transition is identified at about -7°C, whereas the icy-wet transition is identified when the internal temperature is about 0°C.

Time instants of state transitions estimated for each sensor during the 3 experiments are shown in Fig. 4C. The standard deviations of the time instant of the state transitions wet-icy and icy-wet estimated for each sensor are shown in Fig. 4D. In the 3 experiments, the standard deviation obtained for the state transition wet-icy is larger than that obtained for the state transition icy-wet.

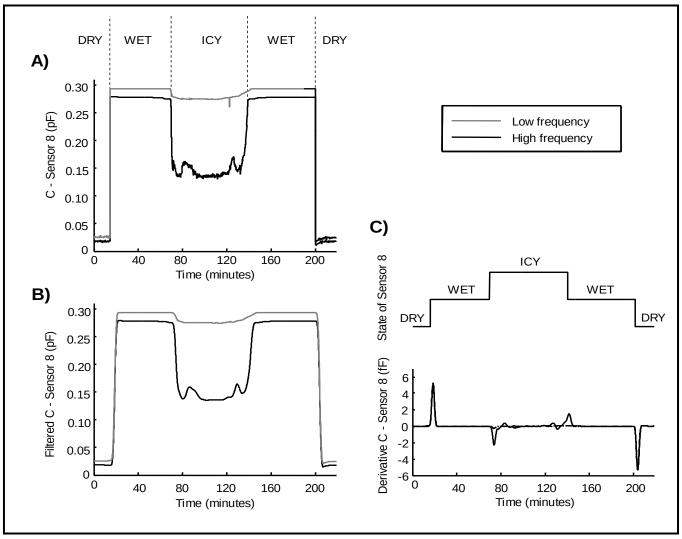

Figure 3. Signal processing algorithm applied to experimental data. (A) Capacitance's values (raw data) obtained for the sensor 8 during the experiment 1 at different measurement frequencies, during the entire experiment. (B) Low pass filtered values of capacitance obtained from the raw data. (C) States of the sensor revealed by the algorithm (above). First-order derivative of capacitance values obtained from the low pass filtered data (below).

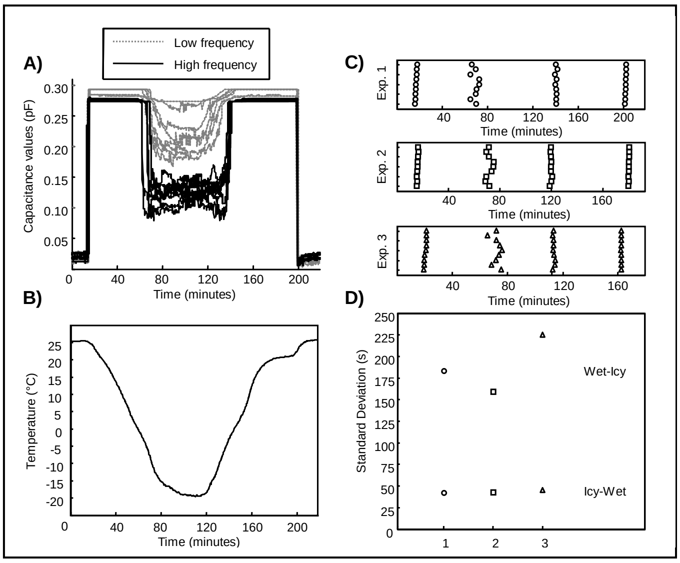

Figure 4. Statistical analysis of laboratory data. (A) Values of capacitance (raw data) obtained for each sensor during the first experiment. (B) Internal temperature of the climatic chamber during the first experiment. (C) Time instants of state transitions estimated for each sensor during 3 experiments. (D) Standard deviations of time instants of state transitions wet-icy and icy-wet estimated for each sensor during 3 different experiments.

IV. DISCUSSION AND CONCLUSIONS

This paper investigates the performance of a system which can be embedded in a road or runway pavement to monitor continuously the surface condition. The sensor is based on a capacitance measurement and houses a cheap and efficient technology [1] to identify the presence of water or ice on the road. The sensor was investigated with experiments in laboratory conditions.

More sensors were considered on the same laboratory conditions in order to investigate the dispersion of the times in which transitions between wet and icy state were identified. Differences of the estimated times of transition were of the order of a few minutes, which is related to the spatial heterogeneity of the icing and melting processes. A higher dispersion was found in the case of wet-icy transition with respect to the icy-wet one. Indeed, water started freezing from the surface proceeding downward, so that a small difference in the thickness of the layer of water could determine a spread of the delays of different sensors in the identification of the presence of ice. On the other hand, the melting process started at the sensor surface (probably due to low energy dispersions from the device). The wet-icy transition was detected at lower temperatures with respect to the icy-wet transition in the laboratory experiments. This is probably due to the freezing and melting processes described above, but also to the higher value of specific heat for water (about 4000 J kg-1 K-1) with respect to ice (about 2000 J kg-1 K-1), which determines a higher time to cool water than that needed to warm ice, keeping constant the magnitude of the temperature gradients imposed by the climatic chamber.

The measured value of capacitance also depends on possible contaminations (e.g. dirt, fuel or salt) present in the water covering the sensor. For this reason, a salinity sensor was included in the system proposed in [1]. Future work will be focused on the assessment of the effect of salt concentration of water on the indication of the considered sensor.

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