2016-2017 ACRP UNIVERSITY DESIGN COMPETITION

Airport Runway Ice and Snow Monitoring System with Remote Sensing Technology

(January 2017 – April 2017)

Design Challenge: Runway Safety/Runway Incursions/Runway Excursions

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1 Executive Summary

Undetected snow or ice on the runway or taxiway can be dangerous to aircraft during landing, takeoff and ground maneuvers. In fact, many runway or taxiway excursion incidents or accidents were caused or contributed by undetected snow or ice. Current practices of measuring the runway condition involve the applications of CFMDs (Continuous Friction Measuring Device) and decelerometers. While these devices can produce direct runway friction readings, they cannot monitor the ice and snow on the runway in real-time without runway closures.

To improve runway safety and to reduce the risk of runway excursions by providing real-time runway condition information without interrupting aircraft operations, the design team studied the principles and the applications of remote sensing technologies. Since remote sensing technologies have been commercially used for glacier and climate monitoring, ski resort snow monitoring and even parking lot snow monitoring, the design team suggested that such technologies can be applied to airport runway monitoring as well.

To study the potential implementation of remote sensing technologies, these four aspects were carefully considered for the proposed runway or taxiway snow or ice monitoring system:

1) regulations, laws and procedures regarding runway snow and ice monitoring,
2) possible designs and implementation setup of the proposed system,
3) safety/risk assessments of the proposed system, and
4) cost/benefit analysis of the proposed system.

An example scenario based on Purdue University Airport was developed to better demonstrate the system implementation. It shows that with an initial investment of $300,000 and an annual operation and maintenance cost of $25,000, the proposed system could potentially save about $500,000 over 10 years without even considering human injury or fatality.

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3 Background and Problem Statement

In this project, we focused on the design of an innovative runway or taxiway snow or ice monitoring system because there is a need for airports to be able to identify the hazards that present the greatest risk to air carrier operations within the runway environment (ACRP, 2016).

Snow is not uncommon in the United States. For example, over half of the land of the United States experienced a snow depth of over 5 inches in January 2016, according to National Centers for Environmental Information (National Weather Service, 2017). Approximately the same snowfall occurs every year, affecting many airports throughout the northern half of the country such as Chicago O'Hare, Denver, Boston Logan, Newark Liberty, New York LaGuardia and John F. Kennedy.

Snow, ice or other frozen precipitation covering airport runways and taxiways are potentially dangerous to aircraft operation, as they often greatly reduce pavement friction, resulting in runway excursions.

Figure 1. Delta 1086 on March 5, 2015 at New York LaGuardia Airport (Defrancisci, 2015).

Chicago News (2016) published that the National Transportation Safety Board (NTSB) had investigated the accident of United Airlines flight 441 traveling from Orlando to Chicago on

December 18, 2016. The report shows that precipitation on pavement was one of the contributing causes to aircraft sliding off taxiways. Other earlier incidents or accidents involved with precipitation include Delta Air Lines flight 1086 that veered off the runway at New York LaGuardia Airport on March 5, 2015 (NTSB, 2015) and Southwest Airlines flight 1248 that was unable to come to a complete stop before reaching the end of the runway at the Chicago Midway International Airport on December 8, 2005 (Wald, 2006).

To reduce the risk of landing or maneuvering aircraft on frozen precipitation contaminated runways or taxiways, the Federal Aviation Administration (FAA) has established a series of strategies and regulations within Takeoff and Landing Performance Assessment (TALPA) program (FAA, 2017). TALPA program provides various runway condition assessment matrixes and approaches and requirements for runway contaminants reporting. Similarly, International Civil Aviation Organization (ICAO) also initiated a draft of Runway Surface Condition Assessment, Measurement and Reporting (Cir 329 AN/191), intending to provide a better understanding of the surface friction characteristics contributing to aircraft control within the tire to ground contact area (ICAO, 2017). The European Aviation Safety Agency (EASA) and United Kingdom Civil Aviation Authority (UK CAA) each has their own regulations and documents about assessing frozen precipitation contaminated runways or taxiways.

However, current runway precipitation assessing, monitoring and reporting approaches have significant disadvantages. First, measuring runway friction with Continuous Friction Measuring Device / Equipment (CFMD / CFME) or decelerometer / brakemeter / dynometer, which are current standard equipment, requires the airport to close its runway (ICAO, 2017). Aircraft takeoffs and landings must be suspended to perform this task. At busy airports where takeoff and landing happen frequently, the time interval of runway friction measuring might be increased significantly due to significant cost of frequent runway closures, resulting in another disadvantage that runway condition is not reported in real-time. While the weather is changing continuously, the validity of runway condition report decreases greatly over time. As suggested by investigations of accidents or incidents, undetected precipitation was created within only an hour prior to the occurrence of tragedies. Some airports rely on feedback from pilots who have just performed takeoffs and landings or to determine the runway condition. These are called PIREPs or pilot reports. However, accidents or incidents can be prevented only when pilots are informed about runway conditions before attempting a takeoff or a landing.

To solve this problem, the major consideration is that the monitoring system should be able to measure the precipitation on runways or taxiways in real-time without interrupting aircraft takeoffs and landings. Inspired by the advancements in remote sensing and information technology, the design team sought an innovative runway precipitation monitoring approach. In this design project, the principle of remote sensing technologies, an example scenario, a safety-risk and cost-benefit assessment, and potential impacts of the proposed design are presented.

4 Summary of Literature Review

In the literature review, the classification of runway precipitation is reviewed according to Federal Aviation Administration (FAA) regulations. Selected studies of runway friction measuring approaches and applications of snow and ice remote sensing technologies are introduced as well. It is suggested that snow or ice on airport surfaces increase the risk of incidents or accidents. While current regulations and applied technologies may not provide airport operators, air traffic control and pilots with sufficient information, the advancement of remote sensing technologies may offer more options for better awareness of runway conditions.

4.1 Effect and Classification of Runway Precipitation

The type and amount of precipitation that is on a runway can drastically affect the braking action of aircraft (Nrotheim, Sinha, & Yager, 2001). This design project focuses on snow and ice, which can create slippery conditions. Both types of precipitation lower the amount of friction that the tire has on the runway and taxiway pavement. Snow or ice on runways require longer takeoff and landing distances. Snow or ice on taxiways reduce aircraft maneuverability while taxiing (Yager, 1999).

Assessment Criteria		Downgrade Assessment Criteria		
Runway Condition Description	**Code**	**Mu (μ)** [1]	**Vehicle Deceleration or Directional Control Observation**	**Pilot Reported Braking Action**
• Dry	6		---	---
• Frost • Wet (Includes Damp and 1/8 inch depth or less of water) ***1/8 inch (3mm) depth or less of:*** • Slush • Dry Snow • Wet Snow	5	40 or Higher	Braking deceleration is normal for the wheel braking effort applied AND directional control is normal.	Good
5º F (-15ºC) and Colder outside air temperature: • Compacted Snow	4	39 to 30	Braking deceleration OR directional control is between Good and Medium.	Good to Medium
• Slippery When Wet (wet runway) • Dry Snow or Wet Snow (Any depth) over Compacted Snow ***Greater than 1/8 inch (3mm) depth of:*** • Dry Snow • Wet Snow ***Warmer than 5º F (-15ºC) outside air temperature:*** • Compacted Snow	3	39 to 30	Braking deceleration is noticeably reduced for the wheel braking effort applied OR directional control is noticeably reduced.	Medium
Greater than 1/8 (3mm) inch depth of: • Water • Slush	2	29 to 21	Braking deceleration OR directional control is between Medium and Poor.	Medium to Poor
• Ice [2]	1	29 to 21	Braking deceleration is significantly reduced for the wheel braking effort applied OR directional control is significantly reduced.	Poor
• Wet Ice [2] • Slush over Ice • Water over Compacted Snow [2] • Dry Snow or Wet Snow over Ice [2]	0	20 or Lower	Braking deceleration is minimal to non-existent for the wheel braking effort applied OR directional control is uncertain.	Nil

Figure 2. Runway Condition Assessment Matrix (RCAM) (FAA, 2016)

Figure 2 shows the Runway Condition Assessment Matrix (RCAM) published by the FAA. It can be seen from the chart that thick ice and snow are the most dangerous runway precipitations as compared to just water or frost.

According to the FAA AC (Advisory Circular) 150/5200-30D, “for purposes of generating a runway condition code and airplane performance, a runway is considered contaminated when more than 25 percent of the overall runway length and width coverage or cleared width is covered by frost, ice, or any depth of snow, slush, or water” (FAA, 2016, p. 8). In other words, when less than 25% of the runway surface is contaminated, no associated runway condition code will be generated resulting in a potential unknown risk awaiting for the participating aircraft. In order to deal with this safety concern, the FAA has partnered with a few stakeholders (aircraft operators, aircraft manufacturers, airport operators, international civil aviation authorities and professional aviation organizations) to develop a more comprehensive and standardized method of assessing and reporting surface conditions.

According to the FAA AC (Advisory Circular) 23-32, runway contamination or the presence of a fluid contaminant (water, slush or loose snow) or a solid contaminant (compacted snow or ice) adversely affects braking performance (stopping force) by reducing the friction force between the tires and the runway surface. The reduction of friction force depends on the following factors: tire-tread condition (wear) and inflation pressure; type of runway surface; and anti-skid system performance creating a layer of fluid between the tires and the runway, thus reducing the contact area and creating a risk of hydroplaning (partial or total loss of contact and friction between the tires and the runway surface) (FAA, 2015). Among all these factors, the layer of fluid between tires and the runway is the direct result of remaining snow or ice. And it is an important factor that lacks real-time monitoring at airports.

4.2 Current Runway Friction Measurement

The 14 CFR (Code of Federal Regulations) §139.339 – Airport Condition Reporting states that "In a manner authorized by the Administrator, each certificate holder must (a) Provide for the collection and dissemination of airport condition information to air carriers. (b) Use the NOTAM system, as appropriate, and other systems and procedures authorized by the Administrator. (c) Provide Snow, ice, slush, or water information on the movement area or loading ramps and parking areas" (FAA, 2011, p. 537). It is clear that airport operators are highly responsible to inform related people about the airport runway or taxiway conditions.

Currently, runway friction measurement relies on the application of Continuous Friction Measuring Device / Equipment (CFMD / CFME), or sometimes called a mu-meter (ICAO, 2017). This technology presents some promising advantages such as direct replication of aircraft tire and pavement contact in the last century (Horne, Yager, Sleeper, & Merritt, 1977). However, it shows several disadvantages as it does not meet the need of busy airports where a faster and non-interrupting way with better coverage is needed.

Figure 3. Surface Friction Tester (NASA, 2007).

(Image by: NASA, in the public domain in the United States, public usage allowed by NASA copyright)

According to FAA AC (Advisory Circular) 150/5220-16D (FAA, 2011), current Automated Surface Observing System (ASOS), Automated Weather Sensor System (AWSS) and

Automated Weather Observing System (AWOS) also provide information about falling precipitation, runway conditions and the amount of accumulated snow or ice. However, only major commercial airports have installed high-level AWOS that reports precipitations and accumulated snow and ice information. Most low-level AWOS only include more general information such as temperature, air pressure, visibility and wind. Even with high-level AWOS, the sensors do not record or measure runway conditions directly, which may result in missing some critical information. FAA AC (Advisory Circular) 150/5220-16D allows non-certified sensors and custom configurations to be attached to AWOS providing advisory information in voice communications, which encourages the implementation of newer technologies (FAA, 2011).

4.3 Other Innovative Runway Snow/Ice Measurement

An innovative system for the monitoring of the state of the runway surface is used at Turin-Caselle Airport, in Italy (Troiano, Pasero, & Mesin, 2010). Implemented since 2011, it has fulfilled the need of an ice/water detection system to a certain level at Turin-Caselle Airport. The system consists of several ice/snow/rain sensors and wireless transmitters. The data is sent to a central server and is displayed to the users. Three sensors were buried in the center line of the touchdown area, the breaking area and the takeoff area of the runway to check the state of its surface. The sensor consists of a multi-frequency capacitance measurement system to measure the change of capacitance resulting from the relative permittivity and thickness of snow and ice between the electrodes (Troiano, Pasero, & Mesin, 2010).

The system used a set of wireless transmitters based on cell phone networks. The data from the sensor is transmitted wirelessly to the central server. The data is stored in a MySQL database. Several webpages were developed, to provide graphical indications and visualization of the conditions. This would provide a direct indication of runway conditions to the users (Mesin, Troiano, & Pasero, 2010). While this system can give a general information of ice and snow coverage on the runway, it does not provide a detailed coverage map for further evaluation of runway conditions.

Another innovative runway snow and ice measurement technology include in-pavement sensors developed by a company called Airport Surface Friction Tester and implanted at Denver International Airport (Wysocky, 2016). However, installing such sensors involves shutting down the runway for three months to rebuild the pavement, which greatly affects airport operations.

4.4 Advancement of Remote Sensing Technology

Generally speaking, remote sensing is the acquisition of information about an object or phenomenon at a distance without making physical contact (Schowengerdt, 2007). It is not a brand-new technology. In fact, taking pictures with a camera can be considered as a form of remote sensing.

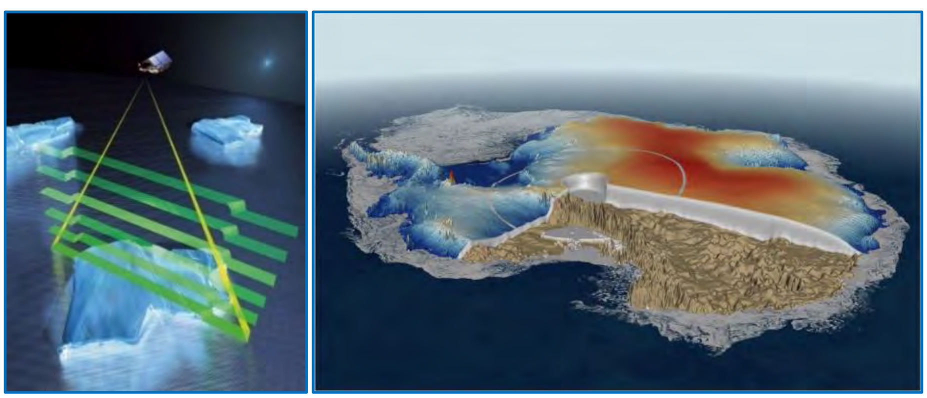

Figure 4. Antarctic Ice Sheet from Cryosat-2 (ESA, CPOM, UCL, & Planetary Visions, 2017).

(Image by: ESA, from ESA website, informative usage allowed by ESA copyright)

In 1992, a research review pointed out that obtaining information of ice and snow coverage by interpreting satellite data from visible-light, infrared and microwave channels was rapidly maturing, adding ice and snow into the long list of items that can be detected by remote sensing technology (Carsey, 1992). Due to the limitation of imaging resolution and high-speed computation in early years, remote sensing for ice and snow coverage was only applied to monitoring large landscapes from satellites (Solorza, 2012). Figure 4 shows the satellite based remote sensing images for ice and snow coverage of Antarctic.

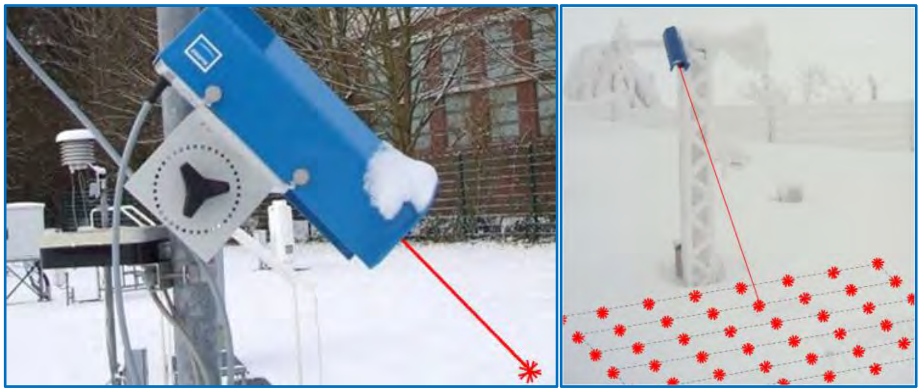

Figure 5. Laser Snow Depth Gauge (Lanzinger & Theel, 2016).

(Image by: Eckhard Lanzinger and Manfred Theel, through online public access of [SlidePlayer website])

Some further studies showed that snow and ice have unique optical properties that can be utilized for remoted sensing (Kaasalainen, et al., 2006). Together with the advancement of laser sensing technology and ground based light detection and ranging (LIDAR) technology, it is now possible to detect snow or ice depth from over 7,000 feet away at a precision level of no more than 3 inches (Deems, Painter, & Finnegan, 2013). In addition, the thickness of ice or snow required to be detected can go from 1/2 inch at a distance of 300 feet to 1/16 inch at 30 feet (Prokop, 2008). Figure 5 shows a complete device that measures the depth of snow directly by taking multiple measuring point within an area as an example. As remote sensing technology continues advancing, it is time to consider its potential application for airport runway ice and snow monitoring.

5 System Principle and Design

5.1 Technology Principle

In this design project, two major approaches of snow ice monitoring with remote sensing technology developed by scientists and engineers introduced above were applied. First, the approach is to take advantage of the unique optical properties of ice and snow and the capabilities of laser scanning technology so that direct monitoring of the depth of snow and ice on the runway can be achieved. Second, with LIDAR technology, the change of the depth of snow and ice on the runway can be monitored as well.

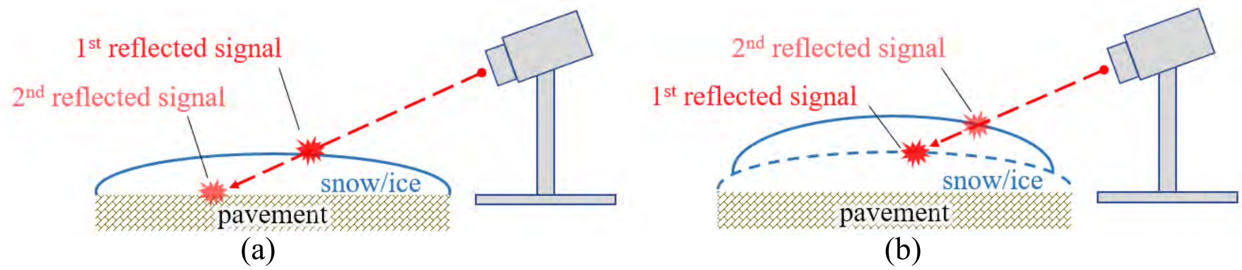

Figure 6. System Principles. (a) Direct measure of snow/ice depth with laser scanning and (b) measure of the change of snow/ice depth with laser ranging.

Figure 6 here demonstrates the principles of two major approaches of measuring snow or ice depth. For laser scanning technology, two reflected signals will be received for every single measurement. Computing the time interval between two signals will give the depth of snow and ice directly. For laser ranging technology, only one reflected signal will be received for every measurement. However, measuring the same spot at different times will give the change of the depth of snow and ice. Or in other words, it answers how much new snow or ice has been accumulating on the runway or how much snow or ice has melted.

Table 1 shows some details of laser scanning (Lanzinger & Theel, 2016) and laser ranging approaches (Deems, Painter, & Finnegan, 2013) according to the latest study. It can be seen that both approaches have their advantages and disadvantages. Laser scanning technology provides a more accurate and direct measurement of depth of snow and ice. However, it has a relatively short working distance. Meanwhile, laser ranging technology has a long working distance with a lower precision level. Both approaches apply short laser pulse (shorter than 1/1,000 s) to perform measurements. Then even with visible laser wavelength, the operation of the device will not affect pilots' vision or other light-sensitive elements. These properties suggest that a combination of two approaches may better serve the purpose of airport runway ice and snow monitoring.

Table 1

Comparison between Major Snow and Ice Remote Sensing Technologies

Approach	Working Distance (feet)	Precision Level (inch)	Frequency	Mode
laser scanning	10 – 100	1/16 – 1	visible	pulse
laser ranging	1000 – 7000	1 – 3	infrared	pulse

5.2 System Design

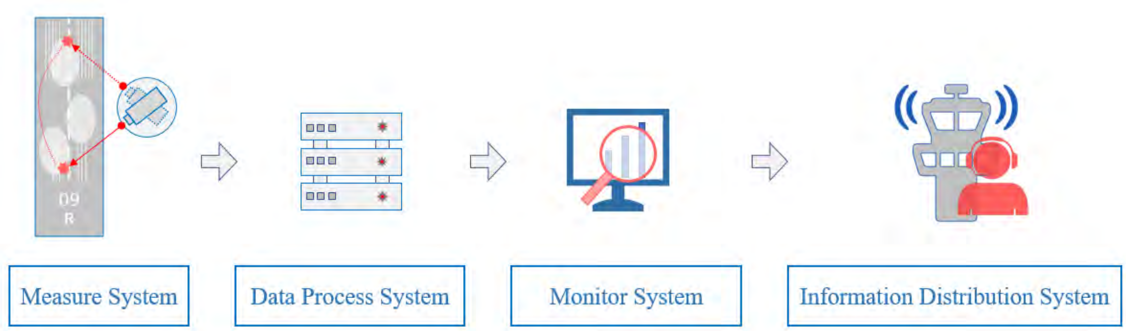

Figure 7. Sub-system Structure Demonstration.

The proposed airport runway and taxi way snow and ice monitoring system is designed to provide information of snow or ice coverage on airport runway to air traffic control (ATC), airport operators or managers and pilots. The system contains four major sub-systems:

a. Measure system (measure the depth and the change of depth of snow and ice);

b. Data process system (calculate and process acquired data for mapping);

c. Monitor system (monitor the results of the data processing and mapping);

d. Information distribution system (notify ATC, airport operators/managers and pilots).

Figure 7 and Figure 8 demonstrate the system structure and system process flow described above. For measure system, it applies laser scanning and laser ranging technologies to acquire data of the depth or the change of depth of snow and ice on the runway and taxiway. Then, the data process system will complete a serious of calculations, transforming the acquired data into runway and taxiway snow/ice coverage map. Now, the monitor system will monitor any dangerous situation allow information distribution system to send out warning messages to ATC, airport operators/managers and pilots.

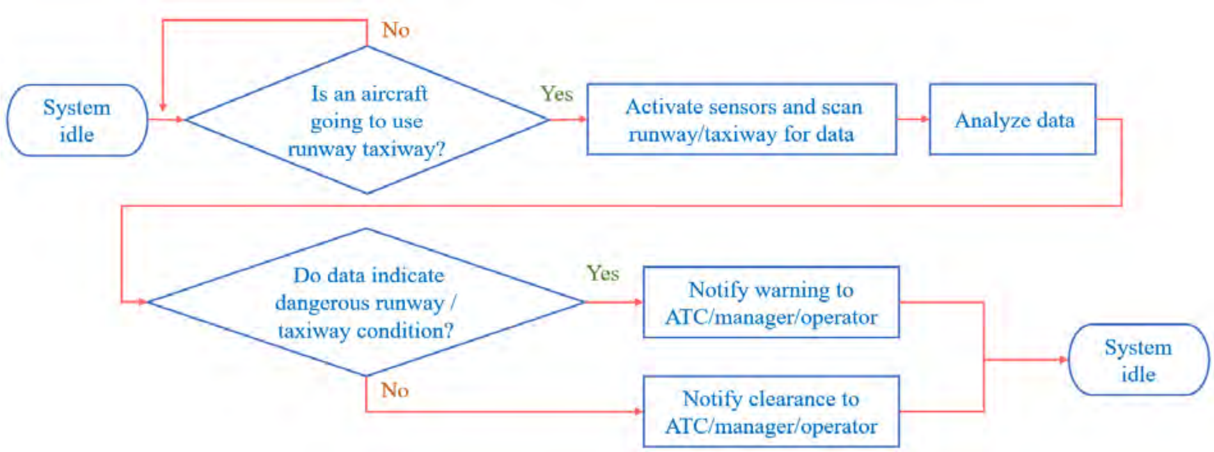

Figure 8. System Flow Chart.

Scanning runway or taxiway for data is one of the most important steps in this system. However, the deciding step is also critical. There are two major considerations when deciding if the data indicate a dangerous runway or taxiway condition. The first consideration is related to regulations and laws. For example, when over 25% of the runway is covered with snow or ice, the runway is no longer safe for takeoffs and landings (FAA, 2016). This is the situation when a warning must be sent to related personals. The second consideration is "customized threshold" meaning that although the runway condition is still safe according to the regulations, a warning will be sent when certain scenarios such as accumulated snow or ice covering landing area only is satisfied. How to set this customized threshold may need more study and operational experiences and may vary from airport to airport. However, it is believed to be a more practical and personalized solution than the universal regulations.

5.3 Regulation Consideration

First, the size of the device must be considered. As shown earlier in Table 1, two remote sensing technologies have different characteristics. Laser scanning for accurate readings of depth of snow and ice works at a close distance, it means that the device has to be installed close to the runway. In this case, it is pointed out by FAA AC (Advisory Circular) 150/5300-13 Airport Design that anything installed close to the runway or taxi way must be in compliance with regulations related to Object Free Area (OFA), Obstacle Clearance Surface (OCS) and Obstacle Free Zone (OFZ) (FAA, 2008). Current design can fit the laser scanning device into a 15 inch × 4 inch × 4 inch housing case with an extendible stand (pause state: 1 foot for minimum influence on runway; operation state 5 feet for better measurement precision). So, the device can be installed by the side of runway or taxiway without violating FAA regulations. Integrating laser scanning device together with runway taxiway signs could be a good solution to .

Second, FAA AC (Advisory Circular) 70-1 Outdoor Laser Operations lists detailed tables for single pulse maximum permissible exposure limits, pulse repetition frequency limit for visible and infrared wavelength (FAA, 2004), as partially shown in Figure 9 as an example. Actual operation of laser scanning and laser ranging technologies must be carefully calibrated according to these limitations.

Wavelength (nm)	Exposure Duration (sec)	MPE (J/cm^2)
Ultraviolet		
180 to 400	10^{-9} to 10	Reference American National Institute Standard (ANSI) Z136 series
Visible		
400 to 700	$<10^{-9}$ 10^{-9} to 18×10^{-6} 18×10^{-6} to 10 0.25	Reference ANSI Z136 series 0.5×10^{-6} $1.8\times t^{0.75}\times10^{-3}$ 0.64×10^{-3}
Infrared		
700 to 1050	$<10^{-9}$ 10^{-9} to 18×10^{-6}	Reference ANSI Z136 series $0.5\times C_A\times10^{-6}$

Figure 9. Partial Table of Outdoor Laser Operation Limits (FAA, 2004).

Third, FAA AC (Advisory Circular) 150/5220-16D allows non-certified sensors and custom configurations to be attached to Automated Weather Observing System (AWOS) providing advisory information in voice communications (FAA, 2011). This regulation ensures the possibility of integrating remote sensing technologies for ice and snow together with AWOS and the approach of warning distribution.

5.4 System Implementation

There are several different setups to implement remote sensing technologies for ice and snow on runway and taxiway. Different setups can match different runway or taxiway scales and operational budget, which is shown in Figure 10. Laser scanning sensors work at closer distance for more precise measuring so that they are installed along the runway and taxiway. Laser ranging sensors work at long distance so that they are installed on the roof of terminals or other airport buildings for a wide coverage. To reduce the cost of implementation, partial coverage is also possible. In this case, only critical areas such as runway touch down area and taxiway turning area are covered with laser scanning sensors. Furthermore, runway and taxiway can have different system setup to achieve a better balance between budget and sensor coverage.

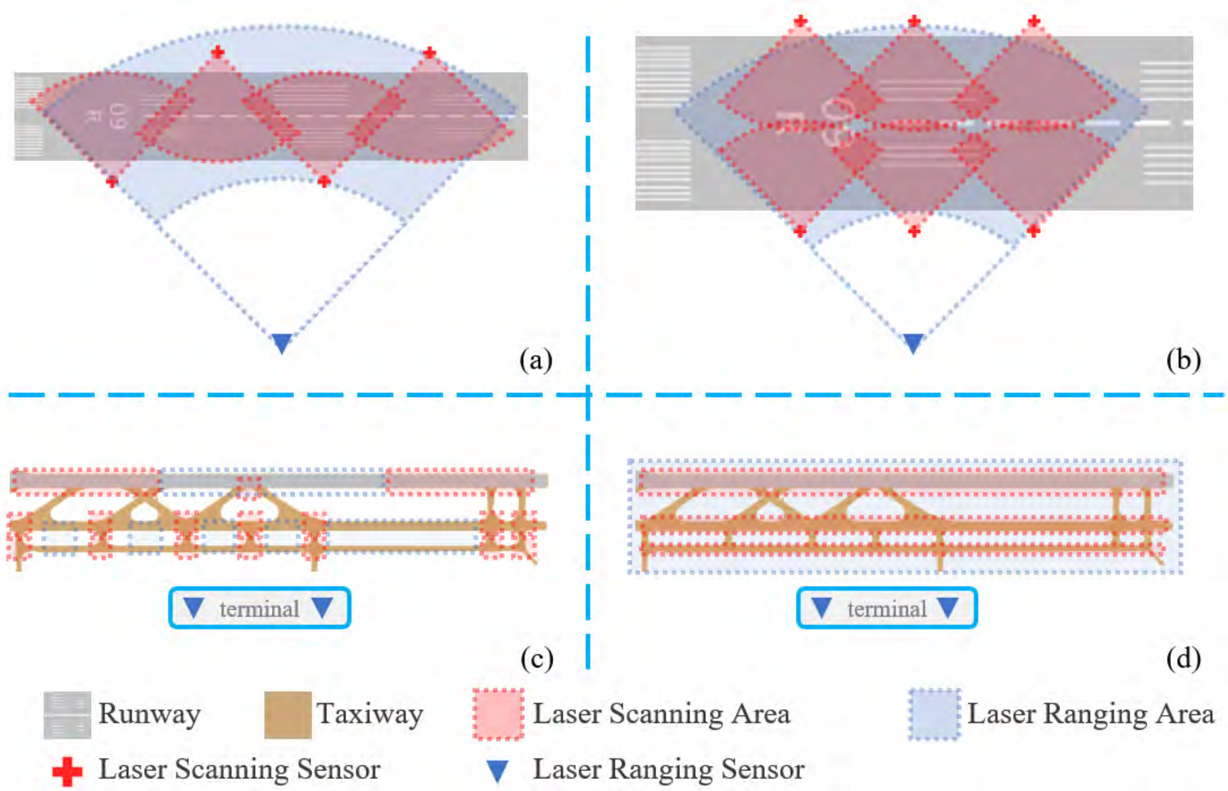

Figure 10. System Implementation.
(a) Unsymmetrical arrangement of laser scanning sensor for narrow runway/taxiway or low budget,
(b) Symmetrical arrangement of laser scanning sensor for wide runway/taxiway and better resolution,
(c) Partial sensor coverage for touch down and turning area, and
(d) Full sensor coverage for entire runway/taxiway.

Table 2

System Implementation Setup Decision Matrix

Decision Element		Aircraft Wingspan (feet)					
		<50	50-80	80-120	120-170	170-215	>215
Relative Budget	Extremely Low	UP	UP	UP	SP	SP	SP
	Low	UP	UP	SP	SP	SP	SF
	Moderate	UP	UF	SP	SP	SF	SF
	High	UF	UF	SP	SF	SF	SF
	Extremely High	UF	UF	SF	SF	SF	SF

Note. UP means unsymmetrical sensor arrangement with partial coverage.
SP means symmetrical sensor arrangement with partial coverage.
UF means unsymmetrical sensor arrangement with full coverage.
SF means symmetrical sensor arrangement with full coverage.
Aircraft Wingspan is the wingspan of the largest aircraft that operates at the airport. Wingspan classification is derived from ICAO Aerodrome Reference Code (Airbus, 2015).

To help make decisions about which setup should be selected for a particular airport, a decision matrix shown in Table 2 is designed. Two elements are needed for this matrix including wingspan of the largest aircraft that operates at this airport, and financial budget. Financial budget determines whether a full coverage setup can be selected. Wingspan of the largest aircraft that operates at the airport is directly related to the width of runway or taxiway, determining whether symmetrical or unsymmetrical arrangements can be selected. For example, if the Pilatus PC-12 (53-foot wingspan) is the largest airplane that can operate at an airport, and the airport had arranged high budget to improve its winter operation safety, then it should apply unsymmetrical sensor arrangement with full runway coverage.

6 Example Scenario

To fully explain the application of the proposed runway and taxiway snow and ice monitoring system, an example scenario with Purdue University Airport (KLAF) is presented. Purdue University Airport is located in West Lafayette, Indiana with about 264 aircraft operations per day including GA, charter and cooperate services (AirNav, 2017). It experiences heavy snowfalls every winter with an average of 18 inches (U.S. Climate Data, 2017).

In this potential application, the symmetrical sensor arrangement with partial coverage is recommended for this airport due to its limited budget and capability of operating larger aircrafts such as Boeing 737. As shown in Figure 11, corners and crossings of the taxiways and touchdown zones of the runways are more precisely monitored by laser scanning sensors, the rest area is covered by laser ranging sensors for lower cost. ATC, pilots, managers or other related people can access this interface online to see runway snow/ice coverage in real-time by selecting the desired monitoring area. In Figure 11, runway 10 touchdown zone is selected and a warning is presented due to dangerous snow/ice accumulation.

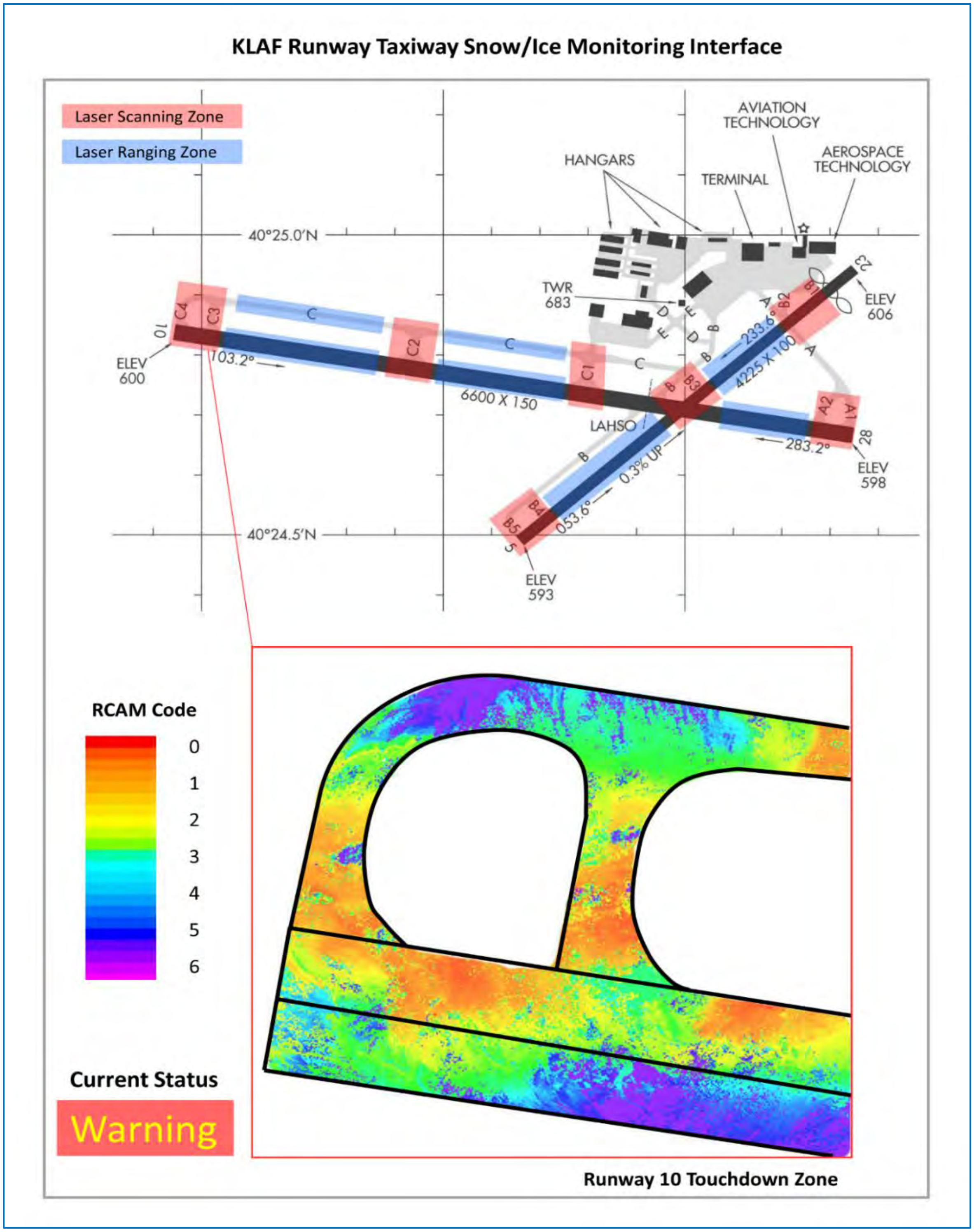

Figure 11. A Demonstration of Runway Snow/Ice Monitoring System Interface.

It shows a warning that some of the runway 10 touchdown zone and taxiway C4 and C3 have dangerous snow/ice accumulation according to the FAA Runway Condition Assessment Matrix. The airport diagram in the figure was acquired from FAA KLAF Airport Diagram.

The coverage map is converted from snow/ice depth to FAA RCAM (Runway Condition Assessment Matrix) code for easy interpreting and faster decision making. Figure 11 suggestes a situation when aircraft operations on runway 10 should be paused and snow removal or deicing procedures should be performed.

7 Safety Risk Assessment

FAA AC (Advisory Circular) 150/5200-37 (FAA, 2007) provides a matrix for safety risk assessment. The matrix is based on the assumption that $Risk = Likelihood \times Severity$.

Table 3

Risk Assessment Matrix

		Severity of Potential Damage/Injury				
0-5 Low Risk; 6-10 Moderate Risk; 11-15 High Risk; 16-25 Unacceptable Risk		Insignificant damage to property, equipment or minor injury **1**	Non-reportable injury, minor loss of process or slight damage to property **2**	Reportable injury, moderate loss of process or limited damage to property **3**	Major injury, single fatality, critical loss of process or damage to property **4**	Multiple fatalities, catastrophic loss of business **5**
Likelihood of Hazard	Extremely Unlikely **1**	**1**	**2**	**3**	**4**	**5**
	Remote Possibility **2**	**2**	**4**	**6**	**8**	**10**
	Possible Occur **3**	**3**	**6**	**9**	**12**	**15**
	Will Probably Occur **4**	**4**	**8**	**12**	**16**	**20**
	Almost Certain **5**	**5**	**10**	**15**	**20**	**25**

Note. This table is modified from FAA AC (Advisory Circular) 150/5200-37 (FAA, 2007) and Wolfuas website (Wolfuas, 2015).

Table 3 shows the risk assessment matrix with 4 risk levels. For any possible risk situation, the likelihood and the severity of the consequence will be evaluated separately. Then the risk score of the situation can be identified according to the risk assessment matrix. For different situations with different risk levels, methods including transferring the risk, eliminating the risk, accepting the risk or mitigating the risk can be applied accordingly (Timmons, 2016).

The proposed runway/taxiway snow/ice monitoring system is designed to mitigate or even eliminate the risk of aircraft runway excursions by providing accurate runway condition information in real-time. However, other potential risks still exist even with the proposed monitoring system. Table 4 shows some of the potential risk assessments including their likelihoods, severities of possible consequences, risk levels and possible solutions.

Table 4

List of Potential Risk Assessment

Situation		Likelihood	Severity	Risk	Possible Solution
1	Sensor damage from severe weather	1	1	1	Water/dust resistant design
2	Sensor damage from wildlife	2	1	2	Tamper resistant design
3	Sensor collision with aircrafts	1	3	3	Minimize sensor size
4	Sensor collision with ground vehicles	2	2	4	Clear labels or signs for sensors
5	Sensor calibration error	2	3	6	Regular sensor calibration
6	System malfunction or lost signal	3	3	9	Regular system diagnosis
7	Power outage	3	4	12	Backup power
8	Sensor blocked due to extreme weather	5	3	15	Multi-bands for enhanced laser visibility
9	Human errors including poor maintenance or incorrect operation	4	5	20	Regular employee training and scheduled maintenance

Note. Scores for likelihood, severity and risk level are evaluated according to Table 3.

The worst identified risk of the proposed system is giving out incorrect runway condition information, resulting in aircraft runway excursions. However, this system does not add new risks when comparing to airports without snow/ice monitoring sensors. Besides the potential risks caused by severe natural disasters, most risks can be mitigated or even eliminated by careful system design and detailed operation procedures. Generally speaking, the proposed runway/taxiway snow/ice monitoring system has little operational risk.

8 Cost Benefit Assessment

The cost benefit analysis of the proposed system is vital to the actual practicality and implementation of the system. The cost analysis of the system includes prototype design and test cost, initial field test cost, installation/implementation cost and operational/maintenance cost. For each stage, the cost analysis also includes labor (scientists and workers), material (equipment, device and parts) and resource (land, electricity and water) cost. Table 5 lists the detailed cost of the proposed system. The cost estimation is based on the symmetrical sensor arrangement and partial coverage of Purdue University Airport described in part 6 of this paper.

Table 5

Cost Analysis of the System for Purdue University Airport

Labor Cost		Material Cost		Operation Cost		Total
Type	Cost	Type	Cost	Type	Cost	
Prototype Design & Test Stage (6 month) (One-time cost, not for all airports)						
2 Scientists 2 Engineers	\$10,000/m×6 m = \$60,000 \$10,000/m×6 m = \$60,000	Tool Supply	\$15,000 \$10,000	Lab Operation	\$3,000/m×6 m = \$18,000	\$163,000
Initial Field Test Stage (3 month) (One-time cost, not for all airports)						
3 Researchers 2 Workers	\$15,000/m×3 m = \$45,000 \$8,000/m×3 m = \$24,000	Equipment Supply	\$3,000 \$5,000	Office Operation Shipping Cost	\$1,500/m×3 m = \$4,500 \$1,000/m×3 m = \$3,000	\$84,500
System Installation & Implementation Stage (2 month, no runway closure) (Initial Investment)						
4 Engineers 10 Workers	\$24,000/m×2 m = \$48,000 \$50,000/m×2 m = \$100,000	Sensor Server Wire/Cable Equipment Other	\$100,000 \$10,000 \$20,000 \$6,000 \$5,000	Construction Operation Equipment Transportation	\$3,000/m×2 m = \$3,000 \$1,000/m×2 m = \$2,000	\$294,000
System Operation & Maintenance Stage (For December, January and February) (Annual Cost)						
1 Technicians 1 Workers	\$10,000 \$7,000	Part Equipment Supply Other	\$1,000 \$500 \$500 \$500	Office Operation System Operation	\$4,500 \$1,000	\$25,000

Note. "m" means month. "y" means year.
Tool and Equipment means any hand tool or heavy equipment needed for a certain stage.
Supply means any consumable material needed for a certain stage.
Other means any other material needed for a certain stage.
Transportation is the cost of transporting people or material for a certain stage.
Office / Construction Operation cost is for office administration.
This table was inspired by ACRP Resource Video (Byers, 2016).

Due to the maturity of laser sensing technology, the prototype design and test and the initial field test will not cost a lot of money. Applying existing technologies and merging them together into airport operation are the major challenges. System installation will not need major financial investment because there is no interference between installation and normal airport operation. Due to the fact that this system may only be working in winter, the operational and maintenance cost is also limited. While the cost of implementation, installation and operation is low, the benefit of the system is high.

Table 6

Benefit Analysis of the System for Purdue University Airport

Potential Benefit	Occurrence /year	Unit Benefit	Benefit/year
Share Data for Academic Research	1	$0	$0
Prevent Runway Excursion	0.05	$370,000	$18,500
Improve Snow Removal Efficiency	4	$5,000	$20,000
Prevent Taxiway Excursion	0.1	$370,000	$37,000
Reduce Tarmac Deicing Chemical usage	5	$8,000	$40,000
Human Injury or Fatality	0.05	$9,000,000	$450,000
Total (without injury or fatality)			$115,500
Total			$565,500

Note. Excursion benefit is estimated according to SR-20 aircraft price. Deicing and snow removal benefit are estimated according to ACRP Fact Sheets (ACRP, 2009).

Table 6 listed potential benefits of the proposed system. The estimation is also based on the condition of Purdue University Airport. The data acquired can be used to study snow and ice on different concretes. Accurate snow/ice information on runway can help reduce preventive chemical overuses and snow removal operations. The benefit per year is greater than operational cost. Although the difference between cost and benefit is relatively low, the system is may benefit the airport in the long run without even considering the injury or fatality it could save.

Until now, the cost and benefit analysis is based on the condition of Purdue University

Airport, a busy GA airport with about three months of frequent snowfalls and about 250 daily aircraft movements. Table 7 shows the net benefit estimation for different airports with different snowfalls. It can be concluded that the proposed runway snow/ice monitoring system is not recommended for smaller airports with no more than two months of frequent snowfall. However, the system can be very beneficial for busy airports such as O'Hare International Airport with over 2,000 daily aircraft movements (ACI, 2017) and four months of frequent snowfall (NWS, 2017).

Table 7

Net Benefit Estimation of Different Airports in Ten Years

Not Recommend		Average Daily Aircraft Movement					
No Financial Benefit Recommend Must Have		< 50	51 – 150	151 – 500	501 – 1000	1001 – 1500	≥ 1501
Number of Month with Frequent Snowfall	≤ 1	- \$50k	- \$100k	- \$200k	/	/	/
	2	- \$60k	- \$150k	/	\$150k	\$1,000k	≥ \$4,000k
	3	- \$70k	/	\$100k	\$300k	\$3,000k	≥ \$6,000k
	4	- \$80k	\$60k	\$300k	\$450k	\$5,000k	≥ \$8,000k
	≥ 5	/	≥ \$120k	≥ \$500k	≥ \$600k	≥ \$7,000k	≥ \$10,000k

Note. Month with Frequent Snowfall means over six inches of snow in one month. Aircraft Movement includes takeoffs and landings. "k" means thousands of dollars. Human injury and fatality are not included due to its great variation in different accidents or incidents.

9 Industry Interaction

We have conducted interviews with the airport managers at four different airports in Indiana and Illinois, including:

1) White County Airport (KMCX) Assistant Manager: Brian Townsend,
2) Frankfort Airport (KFKR) Manager: Dan Montgomery,
3) Purdue University Airport (KLAF) Manager: Adam Baxmeyer,
4) Central Illinois Regional Airport (KBMI) Director of Airport Facility Operation: Javier Centeno.

We have paraphrased and summarized our understanding and information gathered during the interviews. We appreciate the help of these experts. If we have misunderstood them, then please attribute it to our learning stage.

We separated the airports in two different groups for the interviews: towered and non-towered. Two non-towered GA airports are KMCX and KFKR. The other two towered airports are KLAF and KBMI with GA, commercial, charter, and cooperate flight services. From the gathered information, runway ice/now contamination does not pose any significant impact on the airport operation at both KMCX and KFKR. Majority of the traffics at these two airports involve only small GA aircrafts. Unlike commercial/charter pilots, GA pilots are not always on pressured by the schedule and the company to fly when the weather or the runway condition is poor. Therefore, the operational impacts due to snow or ice at those two airports are relatively small. Unlike non-towered GA airports, the operational impacts on KLAF and KBMI from runway snow/ice contamination are a lot more significant. KLAF has very large volume of training flights and corporate flights while KBMI has frequent scheduled commercial and charter services. Snow/ice covered runway usually causes many delayed or cancelled flights, resulting in insufficient parking spaces and lost in revenue.

As far as the snow and ice monitoring, no special equipment is used at both the non-towered airports we have interviewed, and the ice/snow removal are mainly done by snow plows without any chemical deicing fluids. According to Brian Townsend and Dan Montgomery, non-towered airports currently may not feel it is worth the investment to purchase special snow/ice measuring equipment with only a few uses per year. At KLAF and KBMI, the decelerometer and Continuous Friction Measuring Equipment (CFME) are the two techniques being used to measure runway ice/snow conditions. The entire measurement process takes about five minutes to complete. The cost of the decelerometer is around $5,000 with additional $500 to $700 for annual recalibration. The cost of CFME is over $150,000 with additional maintenance and operation cost. Runway deicing fluids such as potassium acetate are sometimes applied to prevent snow/ice accumulation. However, it is hard to determine when to use deicing fluids because they can be washed away by water and they can potentially worsen the condition if ice is already on the runway. It costs several thousand dollars for each deicing fluids application and sometimes it could be unnecessary or a waste of money because of the lack of real-time runway information according to our interview with Adam Baxmeyer.

Runway condition reports at KMCX and KFKR are simple. Airport staffs drive trucks alone the runway to test the braking condition and eyeball the depth of the snow/ice accumulation, the observation results are inputted into the airport AWOS (Automatic Weather Observation System) in the form of voice recording. At KLAF and KBMI, Bowmonk® airfield friction meter and Halliday® friction testers are used to measure runway surface frictions. The testing results are sent to the air traffic controller by the airport manager. Pilots then obtain the runway braking condition from the air traffic controller. Some other possible ways to measure ice and snow accumulation on the runway in the future as described by the airport managers are: drones and laser technologies.

After conducting the interviews, our group has gained more knowledge in airport winter operations, runway snow/ice removal and friction measuring process. We have realized that being an airport manager is not a simple task. It requires a lot of professional knowledge and coordination with the airport ground staffs, air traffic controllers, airport administrations, and pilots. The amount of work and decision-making involved in the daily airport operation are substantial. We have definitely gained more understanding and respect for the airport managers after the interviews.

10 Potential Impact and Conclusion

The proposed airport runway/taxiway snow/ice monitoring system with remote sensing approach is designed to mitigate the risk of aircraft runway excursions caused by undetected ice or snow. While the main purpose of this design project is to improve safety, the proposed system may also have operational impacts, economic impacts, environmental impacts and social impacts on airports, communities and other related people or areas in terms of aviation sustainability.

10.1 Operational Impact

The detailed real-time runway/taxiway snow coverage map has many potential impacts on airport operations. With this information, the scheduling of snow/ice removal operation can be optimized. Airport managers will be capable of knowing exact when and where to send out de-icing blowers or sweepers, or to use de-icing chemicals. Pilots and air traffic controllers will also have a better knowledge of runway conditions, preventing runway or taxiway excursions, or runway closures for manual inspections. Continued monitoring of snow and ice on the runway may also provide clearer connections between weather forecasts and actual runway conditions. Airport managers may be able to conclude some working experience for better operational decisions. For example, one may conclude that 20 minutes of medium snowfall will result in dangerous snow accumulation on runway A but not on runway B; and runway A may be useable 30 minutes after the snow.

10.2 Economic Impact

With an optimized snow/ice removal schedule, the preventive overused of expensive de-icing chemicals may be reduced. The real-time runway condition information can also mitigate the need of hiring on-call field workers and operating ground vehicles for manual runway inspections in winter. Furthermore, runways and taxiways can remain open until dangerous snow/ice accumulation is discovered, reducing the lost in operational revenue. All these may result in a great saving in the cost of airports or carriers. Last but not least, the lowered possibility of runway excursions caused by undetected ice/snow results in a lower chance of severe property damage or even injury and fatality. Less property damage, injury or fatality may reduce the insurance cost of airports or air carriers as well.

10.3 Environmental Impact

As mentioned above, the usage of ground vehicles, de-icing equipment and chemicals can be reduced by applying the proposed system. This results in a decrease in energy consumption, carbon emissions and environmental pollutions. The constant monitoring of snow and ice at open areas such as airports, may also provide a great amount of data for scientific research in terms of global warming and regional precipitations. This kind of research may also end up in an advancement in weather forecast and climate science.

10.4 Social Impact

The proposed system may increase employment in product design, development and manufacturing. There could be more job openings at airports and air carriers to work with the new system. Reduced worker on-call rate and working intensity may help increase workers' happiness as well. Scientific findings based on the snow/ice data acquired by the system may benefit community or even human kind at a later date. Decreased risk of aircraft operations is also a great news to passengers, pilots, managers and other related people and their families.

10.5 Conclusion

In this design project, the airport runway/taxiway snow/ice monitoring system with remote sensing technologies is presented for ACRP "Runway Safety/Runway

Incursions/Runway Excursions" challenge. By introducing the remote sensing technology to aviation industry, it is hoped that risks of aircraft runway excursions caused by undetected ice and snow on runways can be reduced. Details of the principles of the system, the implementation approach, the safety risk assessment and the cost benefit assessment are all explained in this design project. The assessments show that both of aviation safety and aviation sustainability can benefit from the implementation of the proposed airport runway/taxiway snow/ice monitoring system with remote sensing technologies.

Table 8

Potential Impacts of Runway/Taxiway Snow/Ice Monitoring System

Category	Impacts	
Operation Impact	Real-time knowledge of runway/taxiway snow/ice coverage Improve deicing/snow removal operation schedule Improve runway condition forecast/prediction Eliminate runway shutdown for runway condition measuring Reduce change of runway/taxiway excursion incident/accident ……	
Economic Impact *estimates are based on KLAF*	Prevent runway/taxiway excursion Improve snow removal efficiency Prevent taxiway excursion Reduce tarmac deicing chemical usage Reduce human injury or fatality ……	\$18,500 \$20,000 \$37,000 \$40,000 \$450,000
Environmental Impact	Reduce usage of ground vehicle fuel Reduce usage of pollutive deicing chemicals More data source for climate/weather forecast research ……	
Social Impact	More employment in product design/development/manufacturing Reduce worker on-call rate; Improve worker happiness Benefit community/public by reducing chances of incident/accident ……	

Appendix A: List of Complete Contact Information

Faculty Advisor:

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Students:

This team comes from a multi-disciplinary background including Aviation Management, Physics in Laser Optics, and Professional Flight majors. Two students are also completing Master's Degrees in Aerospace and Aviation Management. Another two students also hold positions as FAA Certified Flight Instructors at Purdue University. Our rich background in all of these fields has collectively come together for the success of finding a solution to our problem.

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Appendix B: Description of the University

About the University:

Purdue University, the land, sea grant University in Indiana, is a vast laboratory for discovery. Purdue is a public university known not only for science, technology, engineering, and math programs, but also for our imagination, ingenuity, and innovation. It's a place where those who seek an education come to make their ideas real – especially when those transformative discoveries lead to scientific, technological, social, or humanitarian impact.

Founded in 1869 in West Lafayette, Indiana, the university proudly serves its state as well as the nation and the world. Academically, Purdue's role as a major research institution is supported by top-ranking disciplines in pharmacy, business, engineering, and agriculture. More than 39,000 students are enrolled here. All 50 states and 130 countries are represented. Add about 950 student organizations and Big Ten Boilermaker athletics, and you get a college atmosphere that's without rival.

School of Aviation and Transportation Technology Mission Statement:

The mission of the School of Aviation and Transportation Technology is to support the missions of the Purdue Polytechnic Institute and Purdue University in serving the citizens of the State of Indiana, the nation, and the world, through learning, scholarship (discovery), and engagement activities that extend aviation technology education, aviation technology discovery efforts and technology transfer, and implementation (application) of emerging technology for the global aviation industry. Student learning is advanced by discovery and engagement activities that enhance economic and social development.

Appendix C: Description of Non-University Partners Involved in the Project

Not Applicable.

Appendix E: Evaluation of the Educational Experience Provided by the Project

Students (Answers were discussed by all team members)

1. Did the Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airports Needs provide a meaningful learning experience for you? Why or why not?

→ It was a meaningful learning experience for our group because it required us to apply knowledge and skills that we have obtained in class to an industry-related project. The laser technology that has been widely used in many industries but not yet being applied in runway monitoring field, so this program truly gave us a chance to look into it.

2. What challenges did you and/or your team encounter in undertaking the competition? How did you overcome them?

→ Airport taxiway and runway are vital places under heavy regulations. Our biggest challenges were to make sure that our idea works and also complies with different FAA regulations at the same time. We overcame it by looking over associated FAA airport regulations, advisories and asking airport managers then adjusting our design accordingly.

3. Describe the process you or your team used for developing your hypothesis.

→ We reviewed the properties and advantages of remote sensors and found out that they could all be used for monitoring ice and snow on the surface, so we thought it could be a good idea to apply them in the airport to increase runway safety.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

→ We had several interviews with airport managers via phone call or in person. We learned what the current situation for runway monitoring looked like in the industry. It is very meaningful because then we were able to incorporate some common needs into our project such as applying partial coverage setup to better satisfy the budget limit of airport operations.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

→ We learned the importance of teamwork, and this project provided us a chance to develop our project management skill, research skill, and analytical skill. Those skills are important for future career and study. We are definitely more prepared right now compared to when we started.

Faculty (Mary E. Johnson, PhD)

1. Describe the value of the educational experience for your student(s) participating in this competition submission.

→ This competition is a valuable educational experience for the students in my graduate level aviation sustainability course because it provides a vehicle for the students to explore the applicability of sustainability to real-world airport design challenges. Two of the course objectives are applicable to the design competition:

A. The student will be able to evaluate sustainability projects affecting aviation and aerospace using multi-attribute analysis techniques such as triple bottom line analysis.

B. The student will be able to develop, communicate and defend an analysis of a sustainability initiative in the aviation or aerospace industry.

The structure of the design package deliverables is the first formal design requirements package that many of these students have seen. In the course, the students must prepare responsive deliverables, show how they have used the evaluation checklist, provide status updates to the class, and present their final reports. The amount of detail required by the ACRP closely correlates to my experience with proposal requirements in industry. ACRP emphasis on total cost of ownership, safety analysis and risk analysis are important elements of understanding the potential impact of their designs on aviation sustainability. The design challenges presented on the ACRP website are starting fodder for creativity and brainstorming. In my course, the design teams purposefully have students with different aviation backgrounds, sometime from different countries; and sometimes with team members new to aviation. The active learning of working in teams to accomplish a long-term goal (12 weeks) is one element of their preparation for entering the work force. I also use this project to instill the habit of lifelong learning. While many of the students are already familiar with locating research articles and perhaps three or four Federal Aviation Regulations, they may not be familiar with the entire breadth of 14 CFR regulations or with the wealth of information produced by other credible sources. By showing the students where they may find information to support their project work, the students now have first-hand experience in turning to the TRB, FAA, ICAO, and aviation trade groups such as ATAG, A4A, Airports Council International (ACI), and IATA for industry-specific information from around the globe. The value associated with the incentive of participating in a competition cannot be understated. The students embrace these projects with a zeal that can be best attributed to the fact that they know that their results will be reviewed by a team of aviation experts and are competing against other collegiate design teams. Thank you for allowing my students the opportunity to learn and compete.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

→ Yes. The ACRP design challenges and ideas for projects are used by the project teams to develop their ideas for the design competition. The course is a one-semester course. The project duration is 12 weeks. Because airport sustainability has been adopted by the FAA and more and more aviation organizations are including the EONS model, these students know that their project will be valued when they are interviewed by potential employers.

3. What challenges did the students face and overcome?

→ These four Purdue MS Aviation and Aerospace Management graduate students are from dissimilar backgrounds and cultures. One team member has an undergraduate background in physics, one in aviation management, and two in professional flight. One is from undergraduate program in China, currently doing his Master study at Purdue. Three are from the Purdue aviation program and two of them are active CFIs. Three team members have very limited knowledge of physical sciences, and the fourth team member had very little knowledge about how airports operate and how pilots operate in and around airports. They all had to learn more about regulations for airport runways. The primary challenge for this team was developing an understanding of their different backgrounds and then figuring out ways to become a productive team. Recognition of their individual strengths took a few weeks during the forming stage. While always civil and polite, the team experienced a little bit of storming while figuring out what the others' strengths and weaknesses were. Near the end, the team became a true team and started to norm and then perform. The team did overcome their lack of knowledge about runway icing, the physics of the ice depth detection methods, and about the nitty-gritty of teamwork. My view is that they overcame the teaming challenges by learning how to work with people who have different personalities, different knowledge and skills, and different work styles.

4. Would you use this competition as an educational vehicle in the future? Why or why not?

→ Yes, definitely. The competition instructions are clear and the challenges address real problems for US airports. The materials are understandable, but not easy to perform. The expectations for safety, risk and total cost analyses are directly applicable to my course. The videos on analyses were especially helpful to the teams. The teams chose their projects. Because the teams have so many ideas to choose from or to use to generate their own ideas, the competition appeals to the team members' intrinsic motivation as the project is something that they chose to learn more about.

5. Are there changes to the competition that you would suggest for future years?

→ A suggestion to consider is to encourage the use of the EONS sustainability model in the analyses presented in project reports.
http://www.aci-na.org/static/entransit/Sustainability%20White%20Paper.pdf,
https://www.faa.gov/airports/environmental/sustainability/ and ACRP reports on aviation sustainability are good starting points.

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