Check for updates

Smart Surveillance of Runway Conditions

Gabriel Pestana[1](✉), Pedro Reis[2], and Tiago Rocha da Silva[1]

[1] INOV Inesc Inovação, Lisbon, Portugal
{gabriel.pestana, tiago.r.silva}@inov.pt
[2] Ana Aeroportos - Vinci, Lisbon, Portugal
pereis@ana.pt

Abstract. Runway safety-related accidents represent the most significant source of aviation accidents worldwide. Runway contaminants are typically associated with extreme weather conditions but can also include other safety-issues such as foreign object debris, cracks, and pavement deformation. Although airports are required to perform periodic runway inspections, it is clear that manual inspections alone are not sufficient to mitigate this type of threat. The paper outlines the need to implement automated procedures for runway inspections, seeking to improve runway safety.

The paper presents a project with an innovative approach for automated runway inspections using laser scanning equipment. The compliance with airport regulation, standards, and business logic has driven the architectural solution, co-designed with end-users to increase understandability, and to create a product that provides the best possible user experience, addressing relevant concerns and information needs. The project solution provides a set of data analysis services addressing the Analytics-as-a-Service (AaaS) paradigm, where the concepts of information visualization and context-awareness are essential in supporting the surveillance of the runway status, in particular, for events which may lead to aquaplaning phenomena. Monitoring such water-events enables the detection of drainage problems as well as the identification of areas that might compromise runway safety.

Keywords: Spectral analysis · Runway contamination · Context-awareness · Information visualization · Terrestrial Laser Scanning

1 Introduction to Airport Runway Safety

The international civil aviation network carries over 4 billion passengers around the world annually [1], corresponding to a significant number of runway movements (i.e., aircrafts' landing and take-off). Assessing and reporting runway surface conditions is, therefore, a critical task when analyzing the runway functional and operational conditions for improved safety.

Runway safety-related accidents represent the most significant source of aviation accidents worldwide and remain aviation number one safety risk category [2]. Over the past eight years, most of the aviation accidents reported to ICAO[1] was Runway safety-

[1] ICAO - International Civil Aviation Organization (www.icao.int).

A. L. Martins et al. (Eds.): INTSYS 2020, LNICST 364, pp. 252–270, 2021.
https://doi.org/10.1007/978-3-030-71454-3_16

related. Of those runway-related accidents, 35% were the result of a runway excursion, which occurs when an aircraft veers off or overruns the runway.

A runway excursion occurs when “An aircraft veers off or overruns the runway surface during either take-off or landing” [3]. One of the contributing factors involves adverse weather conditions that result in the runway surface being contaminated. Runway contaminants are typically associated with extreme weather conditions (e.g., snow, ice, mud, frost, and water) but can also include other safety-issues, namely extreme hot weather. Such weather conditions may cause the pavement to blow up and buckle. A deteriorating runway may also pose a foreign object debris (FOD) threat.

The runway is constantly suffering damage, such as potholes due to wear and tear of aircraft or other vehicles using the pavement. Sometimes debris or foreign objects may appear on the runway, which may be caused by jet explosions, aircraft take-offs, and landings, natural causes, etc. On active runways involving aircraft movement, the existence of FOD may cause air disasters and subsequent loss of life, causing significant losses to airlines. Therefore, different methods are used to conduct runway inspections and surveillance. By convention, inspectors will move around the runway for visual and manual inspections periodically (i.e., multiple times a day). However, such type of inspections is slow and labor-intensive. Furthermore, manual visual inspection is unreliable as it is subjected to human errors and conditions surrounding the runway. Accordingly, there is a need to implement automated procedures for runway inspections, seeking to improve Runway safety.

In this paper, we present a research project, named *Monitorização Persistente de Pista* – MPP, (ref. ANI 31/SI/2017 ID: 39876), that is funded by the Portugal 2020 program. The Portugal 2020 is a partnership agreement between Portugal and the European Commission. It applies to the principles of the European Strategy 2020[2] and focuses on the economic, social, environmental and territorial development policy aspects that may stimulate Portugal’s growth and job creation.

Within the Portugal 2020 program, the main goals of MPP are to strengthening research, promote technological development and innovation. As such, MPP addresses the following thematic objectives: transfer of knowledge from the scientific community to the market (airport sector), promoting sustainable transport, and eliminating bottlenecks in major infrastructures, as it is the case of an airport and, in particular, actions to improve the awareness of safety issues at the runway.

MPP will implement a non-intrusive solution, based in LIDAR technology (TLS - Terrestrial Laser Scanning) to perform inspections in an automated way and to report measurements on the conditions of the runway, including data related to the risk of runway contamination, deformations in the pavement and FOD, while simultaneously allowing the visualization of a high precision 3D representation of the runway status. In terms of innovation, the proposed process includes mechanisms for information awareness and visualization. The objective is to provide information semantically aligned with the stakeholder’s information needs, allowing quick navigation through the information structure for rapid identification of situations related to a safety risk, triggering notification regarding the severity level associated with each type of

[2] EUROPE 2020: A strategy for smart, sustainable and inclusive growth.

occurrence. MPP is a web-based platform designed to provides a set of data analysis services addressing the Analytics-as-a-Service (AaaS) paradigm.

The remainder of the paper is structured as follows. Section 2 presents an overview of the classification of runway events; in particular, events relate to FOD, deformation, and runway contamination. Section 3 provides a short introduction to the scope of the MPP project, with an overview of the Terrestrial Laser Scanning equipment. The section explains how the proposed solution uses spectral analysis to analyze the runway pavement based on the current environment/context conditions. Section 4 describes how the proposed technology is being tested at Lisbon airport, presenting a business scenario related to inspections and the report of measurements on the conditions of the runway, namely for identifying risks of Runway contamination. Finally, In Sect. 5, the paper presents the achievements accomplished up to now and future work for the MPP project.

2 Classification of Events Related to Runway Conditions

The aviation industry has recognized the need to develop appropriate procedures and guidelines for operations on contaminated runways. In response, ICAO is committed to formulating a unified global reporting format (GRF) for timely and more accurate assessment and reporting of runway surface conditions [4]. The GRF comprises a standardized runway condition matrix - Runway Condition Code (RWYCC), covering conditions found in all climates. The goal is to enable airport operators to quickly and correctly assess the state of the runway surface regardless of whether it is in wet runway conditions, snow, mud, ice or frost.

The results of the RWYCC assessment are forwarded to air traffic services and aviation information services for dissemination to pilots. This helps the pilot to correctly perform landing and take-off performance calculations for wet or contaminated runways. Another essential element of GRF is the process of enabling pilots to report their observations of runway conditions, thereby confirming RWYCC or alerting to changes in conditions [5]. GRF proposes a method that is easy to understand and implement on a global scale. This is an important means to reduce the risk of runway excursion risk and improve the safety of runway operations. According to [4], in November 2020, all airports will have to report runway conditions according to the GRF format.

2.1 Pavement Cracks and Deformations

The structure of the runway pavement can provide sufficient support for the loads applied by the aircraft, and produce a firm, stable, smooth, all-weather surface, free of debris or other particles that may be blown or picked up by propeller wash or jet blast. In order to meet these requirements, the pavement must have a certain quality and thickness so that it will not fail under the applied load. In addition, it must have sufficient inherent stability to withstand and not be affected by damaging traffic erosion, adverse weather conditions, and other deterioration influences [6].

However, runway pavement deteriorates during service due to traffic and climate effects; therefore, systematic monitoring is required to assess their structural and functional condition. It is vital to identify the different surface defects and link them to a cause. Gradual deformations are typically the result of drainage and geotechnical characteristics. The majority of runway inspections tries to identify the following situations: surface defects, surface deformation, cracks, and patches, which may represent safety hazards. Therefore, the key to a useful pavement evaluation is identifying different types of pavement distress and types of pavement distress and linking them to a cause [7]. Understanding the cause of the pavement condition along with the historic deterioration rate, assist in making appropriate maintenance and rehabilitation plans.

Some airports use radar-based automated systems to detect damage, debris, and other hazards in the runway and its adjacent areas. However, the use of any radar system for runway surveillance has its limitations. Although radar is an excellent method for detecting metallic objects, it is not as sensitive in detecting non-metallic objects such as rubber. Alternatively, some airports use infrared or thermal imaging systems to detect objects and cracks voids. However, systems that use infrared or thermal imaging systems can only sense infrared radiation (radiation emitted by objects), which is outside the thermal balance of the surrounding environment. Such infrared or thermal imaging systems can only detect objects (e.g., in a warm metal fragment on the runway) that have sufficient thermal contrast. Small objects with poor thermal contrast can pose significant challenges to infrared/thermal imaging systems. Besides, under adverse weather conditions (such as cold weather), the performance of these systems is unpredictable.

Other tools [8] provide information about runway deformation using heatmaps, which is an efficient way to show an overall picture of the situation. The outcome (e.g., deformation data) feeds directly into the maintenance planning in the form of increased runway pavement periods, premature infrastructure life cycle shortening, or as a response to geohazards from flooding and seismic activity. Such systems typically provide static dashboards (with pre-processed images) for airport officers to get access to the information relevant for their decision-making process.

2.2 Detection of Foreign Object Debris

Foreign body debris (FOD) materials may cause hazards to aircraft operations. Every year, more than 66% of airport emergencies are related to FOD, causing nearly 4 billion U.S. dollars in financial losses in the global aviation industry every year [9]. All aircraft occasionally lose small metal or carbon parts during take-off and landing. These parts remain on the runway and may damage the tires of other aircraft, hit the fuselage or windshield, or get sucked up into an engine. Other examples of FOD include tire parts, asphalt blocks, screws, inset lights, and anything that may appear on the runway but is not part of the runway. During take-off and landing operations, the presence of these objects may become extremely dangerous. FOD also brings operational difficulties to the airport. It takes approximately 30 min to collect debris, during which time the runway remains closed for aircraft operations.

Even if the airport is required to conduct manual inspections of the entire runway surface multiple times a day, it is clear that manual inspections alone are not enough to mitigate FOD threats [9]. It is foreseeable that an automated method for detecting FOD or damage on the runway can reduce the cost and human error, acting in a complementary way to manual inspections. Continuous inspections using an automated surveillance system facilitate FOD detection 24/7 in all weather conditions. The advantages of such a system over conventional vehicle inspections are:

- Continuous monitoring, including night and low visibility conditions.
- Detect FOD faster and more reliable.
- More efficient traffic flow (e.g., uninterrupted by inspection vehicles).
- Reduce the risk of inspection vehicles entering the runway (e.g., runway incursions due to a controller error).
- Reduced risk of birdstrikes (e.g., optical sensors to identify birds).

Current solutions use a combination of radar and photoelectric sensors. Other (more reliable for runway FOD) solutions include installing cameras to capture images of the runway under ambient light conditions during day and night without the need for auxiliary lightings such as infrared or laser illuminator. Although image processing systems can apply image enhancement methods to enhance images captured by cameras, such systems have some limitations in FOD detection. It depends on ambient lighting conditions and is not suitable for low lighting conditions, which can cause major problems in pixel characterization. Cameras used in existing surveillance systems require additional auxiliary lightings, such as lasers or infrared light for night surveillance. In turn, this requires a large amount of infrastructure in the airport using this system, which increases the cost.

2.3 Runway Contamination

According to ICAO [1], runway contaminants are associated with extreme weather conditions (e.g., snow, ice, slush, frost, or water). Such adverse weather, resulting in the runway surface being contaminated, is responsible for 35% runway-landing incidents/accidents [5]. These overruns have occurred on grooved and smooth runways during periods of moderate to heavy rain. The analysis of these events shows that the braking friction coefficient in each case is significantly lower than expected, and if the runway changes from a wet state to a contaminated state based on rainfall intensity or reported data, it may take 30% to 40% % extra stopping distance. The water contaminated value is within the threshold shown in Table 1.

When 25% of the runway surface area (regardless of whether it is in an isolated area) is covered by standing water with a depth of more than 3 mm or an equivalent amount of snow or loose snow, the runway is considered to be contaminated. As mentioned in Sect. 1, when the average friction value of any 152-m section of the runway is below the recommended minimum friction level, the runway is also considered to have been contaminated with rubber deposits or other materials that degrade friction.

Table 1. Parameter considered by ICAO for Runway Contamination.

Standing water	Slush (Mud)	Loose wet snow	Loose dry snow
3.2–6.4 mm	3.8–7.6 mm	7.6–15.2 mm	15.2–30.5 mm

The type of runway contamination covered by the MPP project is focused on detecting water-sheets, which are generally associated with the risk of aquaplaning. The thickness of the water sheet can affect the operating conditions of the runway, which may lead to aquaplaning phenomena, leading to loss of control of the aircraft in the ground, with the risk of excursion. Monitoring such water-events is essential not only for the detection of drainage problems but also to identify areas at higher risk of occurrence on the runway.

Several types of descriptive terms can be used to report runway surface conditions, such as the type and depth of pollution, readings from runway friction measurement equipment, and aircraft braking action reports. The investigation of reported runway safety incidents found that the accuracy and timeliness of the runway surface condition report were insufficient, which contributed to many runway deviations. Such shortcomings include the lack of standardization in the aggregation and reporting of runway surface conditions to end-users (e.g., airport operators and crew), especially the use of different terminology, formats, and timeliness of reporting.

In order to overcome the lack of standards for reporting runway pollution, ICAO has developed the Global Runway Condition Assessment and Reporting Format (GRF). As shown in Table 2, the method includes the evaluation of the runway and the allocation of RWYCC, ranging from 0 for a very slippery surface to 6 for a dry surface. The code is supplemented on the basis of a description of surface contaminants based on their type, depth and coverage, for every third of the runway.

The runway condition assessment matrix provides a common standardized terminology for runway surface condition description. An agreed set of criteria used, in a consistent manner, for runway surface condition assessment [5, 10]. Within the scope of the MPP project, we particularly want to monitor conditions related to water events (i.e., situations where stagnant water may encourage water skiing). The presence of water reduces the braking coefficient to that of an icy or "slippery" runway [11]. In this case, due to the formation of a water wedge between the runway and the tires, the tires can no longer provide directional control or effective braking, causing the aircraft to be completely water-borne. There are three types of aquaplaning:

- **Dynamic aquaplaning** (also called hydroplaning) is related to speed and tire pressure. High speed and low tire pressure are the worst combinations, with the lowest aquaplaning speeds. When dynamic aquaplaning occurs, the tiers of the aircraft rise from the water and ride on the water wedges like water skis.
- **Viscous aquaplaning** occurs on all wet runways and describes the abnormal slipperiness or lubricating action of the water. Typically, it corresponds to a small amount of water mix with surface contaminants. Compared with dynamic aquaplaning, a much thinner layer of a contaminant is required in the event of viscous aquaplaning. It appears in the same way as dynamic aquaplaning but on abnormally

smooth surfaces such as touchdown zones contaminated with excessive rubber deposits, which may start and continue at any ground speed.

- **Reverted rubber aquaplaning** occurs when the water is thin, and the surface of the runway is smooth. Dynamic or viscous aquaplaning is usually done with the wheels locked. The locked wheels generate enough heat to vaporize the water film underneath, thereby forming a steam cushion, which eliminates contact between the tire and the surface and begins to restore part of the rubber on the tire to an uncured state. This is the only type of aquaplaning which leaves physical evidence on the runway surface. Before anti-skid devices were widely used, this situation was much more common, and usually only happened on aircraft with such emergency brakes.

Table 2. The runway condition assessment matrix, source [4].

Assessment criteria		Downgrade assessment criteria	
RWY Code	Runway (RWY) surface description	Aeroplan deceleration or directional control observation	Pilot report RWY braking action
6	- Dry	---	---
5	- FROST - WET (the runway surface is covered by any visible dampness or water up to and including 3 mm depth) **Up to an including 3 mm depth:** - SLUSH - DRY SNOW - WET SNOW	Breaking deceleration is normal for the wheel braking effort applied AND directional control is normal.	GOOD
4	**- 15º C and Lower outside air temperature:** - COMPACTED SNOW	Breaking deceleration OR directional control is between Good and Medium.	GOOD to MEDIUM
3	- WET ("slipper wet" runway) - DRY SNOW or WET SNOW (any depth) on top of COMPACTED SNOW **More than 3 mm depth:** - DRY SNOW - WET SNOW **Higher the -15º C outside air temperature:** - COMPACTED SNOW	Breaking deceleration is noticeably reduced for the wheel braking effort applied OR directional control is noticeably reduced.	MEDIUM
2	**More than 3 mm depth of water slush:** - STANDING WATER - SLUSH	Breaking deceleration OR directional control is between Medium and Poor.	MEDIUM to POOR
1	- ICE	Breaking deceleration is significantly reduced for the wheel braking effort applied OR directional control is significantly reduced.	POOR
0	- WET ICE - WATER ON TOP OF COMPACTED SNOW - DRY SNOW or WET SNOW ON TOP OF ICE	Breaking deceleration is minimal to non-existent for the wheel braking effort applied OR directional control is uncertain.	LESS THAN POOR

The LIDAR solution proposed by MPP (TLS-Ground Laser Scanning) constitutes an innovative method that overcomes the challenge of automatic runway contamination inspection and provides indicators about the target runway condition (i.e., deformation, foreign bodies, and contamination) while allowing the visualization of a high-precision 3D representation. In this domain, information visualization combined with visual analytics provides an interdisciplinary field that seeks to combine the advantages of human perception and the processing power of computers in establishing the extent of information governance. This means that information governance encompasses more than traditional records management. It incorporates information security and protection, compliance, risk management, data security, knowledge management, and business operations.

3 Project Context – Automated Runway Inspections

MPP will implement a non-intrusive web-based solution, based in LIDAR technology (TLS - Terrestrial Laser Scanning) to perform inspections and to report measurements on the conditions of the runway, namely the identification of risks related to aquaplaning (caused by water sheet thickness), deformations in the pavement and detection of foreign objects. MPP addresses an automatic runway surface condition assessment and reporting of runway contaminants for improved safety and operational efficiency. The goal is to streamline the visualization of events according to three criteria:

- Foreign Object Debris (FOD)
- Cracks & Deformation (CD)
- Runway Contamination (RC)

MPP follows a user-centric design approach, covering the entire process of acquiring sensoring data, processing those (raw) data at the service layer to enhance the information by integrating the collected data with additional operational data provided by existing systems within the airport. In the end, an interactive dashboard provides decision-makers with accurate and real-time information about runway safety conditions. The goal is to increase understandability and to create a product that provides the best possible user experience. During the project execution, informational artifacts will be specified in close collaboration with the end-user group and compliance with existing standards, namely:

- ISO/IEC/IEEE 42010:2011: Systems and software engineering, this standard addresses the creation, analysis, and sustainment of architectures of systems through the use of architecture descriptions. A conceptual model of the architecture description is established.
- ISO9241–210:2019: Ergonomics of human-system interaction, this standard provides requirements and recommendations for human-centred design principles and activities throughout the life cycle of computer-based interactive systems. It also improves ergonomics and enhances the conceptualization of interactive dashboards co-designed with end-users to address relevant concerns and information needs.

The project consortium strengthened cooperation in research and innovation, establishing productive partnerships with airport stakeholders to co-design a smart solution for the surveillance of the runway conditions in Lisbon airport.

MPP architectural challenges address the need to support increased scalability – because of real-time and web-scale demands introduced by the LIDAR sensor for surveillance of the runway active segments –, tighter safety events and increased usage of ICAO standards [12]. It embraces and supports a strong API-based philosophy, providing the means to drive decoupling communication between the system software components. With decoupling and segmentation, we can engage effectively with the ideas expressed by the concept of shearing layers, integrating an event-driven architecture with microservices using event sourcing and CQRS[3]. The advantages of CQRS integrated with event sourcing, and microservices are:

- Leveraging microservices for modularity with separate databases. Having separate models and services for read and insert operations.
- Leveraging event sourcing for handling atomic operations. Read operations can be faster as the load is distributed between read and insert services.
- Maintain historical/audit data for analytics with the implementation of event sourcing.

The MPP presentation layer (i.e., client-DAS[4]) was designed to support workflows providing spatio-temporal context awareness, combined with advanced data analytic capabilities. Data governance and collaboration diagrams describing coherent and compliant messages flow between the stakeholders are specified according to ICAO requirements using BPMN[5]. This strategy paves the path to a system prototype for operation in a relevant environment - such as the Lisbon airport. Apart from listing technological challenges, the implementation of tiny cycles of participatory reflection and co-create usage scenarios, discussing factors that facilitate or impair the acceptance and use, according to the user's perspective and user requirements elicitation, will be critical to ensure acceptance.

3.1 Project Context Diagram

Figure 1 presents a high-level view of the system being modeled, establishing the boundaries of the system and its environment. It shows the entities (stakeholders) that interact with the system. By defining and clarifying the boundaries of the system, we can identify flows of information between the system and the external entities. The entire system is shown as a single process.

[3] Command and Query Responsibility Segregation (CQRS) pattern maximizes performance, scalability, and security. The flexibility created by CQRS allows a system to better evolve over time and prevents update commands from causing merge conflicts at the domain level.

[4] Data Analysis & Surveillance (DAS), this is a client interface designed to act as a command centre where a set of functionalities to keep decision-makers well informed about the runway condition, enabling them to act when an event requiring their intervention is triggered.

[5] BPMN - Business Process Model and Notation (https://www.omg.org/spec/BPMN).

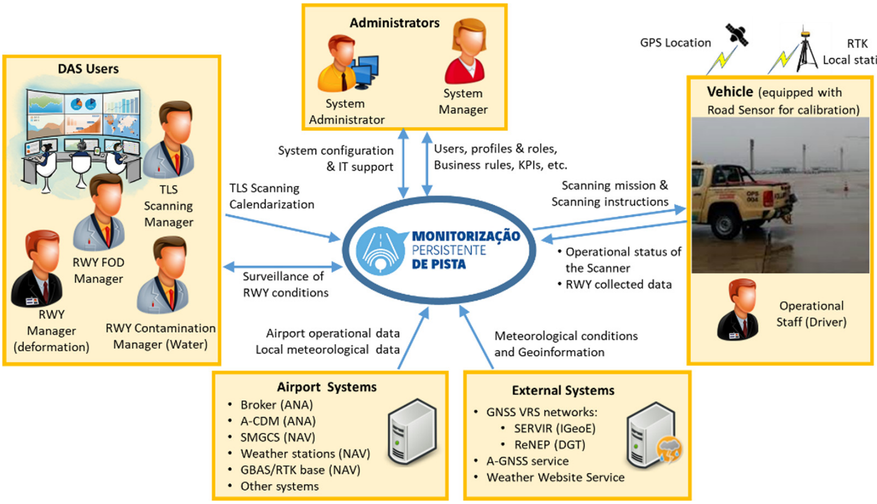

Fig. 1. MPP context diagram.

Although the TLS equipment is responsible for collecting data about the runway status (i.e., runway automatic inspection), for adequately assessing the runway operational condition the MPP system has to interact with multiple airport systems, each one with a specific role in providing information used by the MPP system to analyze the runway status according to airport regulations, the number of movements, weather conditions and the airport operational status (e.g., NVO/LVO[6], maintenance work or any other aspects that might influence airport movements). The MPP system has, therefore, to interact with external systems when assessing the runway status, namely:

- The Airport Collaborative Decision Making (A-CDM), providing (just-in-time) information about aircraft movements.
- The Broker [16], providing information regarding the flight scheduling system (SCORE).
- Local weather stations installed at the airport, providing information useful to improve the TLS scanning context, namely with parameters such as precipitation/rainfall, temperature, humidity, dew/frost point, air pressure, wind speed and direction, and visibility conditions (compliance with ICAO weather parameters requirements).
- Weather web service, providing global meteorological information and forecast services to be used as additional weather-context to enhance the accuracy of the runway inspection report performed by the TLS equipment.

[6] NVO/LVO, these two acronyms define the level of service of the airport, meaning Normal/Low Visibility Operations. LVO are usually defined as a set of procedures established at an airport when either surface visibility is sufficiently low to prejudice safe ground movement without additional procedural controls or the prevailing cloudbase is sufficiently low to preclude pilots obtaining the required visual reference for a safe landing.

The calibration of the TLS equipment is performed by a mobile Road Sensor based on spectral analysis. This calibration process uses a vehicle equipped with the Road Sensor, fusing the spectral analysis with a set of additional data, namely the Position Navigation and Timing (PNT) provided by a GNSS Real-Time Kinematic (RTK) receiver for location accuracy. The MPP system also incorporates data from the ReNEP and SERVIR systems, external systems held by Portuguese governmental entities, providing geo-positioning public services with a precision lower than 10 cm, enabling MPP to improve location precision to a larger scale. In this process (whenever required), the Driver of the vehicle equipped with the Road Sensor can be instructed to drive the vehicle to specific areas of the runway.

The runway diagnosis is based on the spectral analysis of light reflected from the pavement. The spectral analysis method utilizes diodes to capture the reflecting behavior of the runway surface at specific segments. Due to the different spectral properties of the runway surface (in particular, for situations favoring the formation of water sheets), the spectral analysis can deduce the characteristics of the pavement state based on the current environment/context conditions [12].

Both sensors (i.e., the TLS equipment and the Road Sensor) can be controlled by the TLS manager directly from the client-DAS interface. Whenever a runway risk event is detected by the MPP system, at the back-end (i.e., the MPP Server-OKM[7]), the system automatically notifies the corresponding runway manager. The format of the notification message follows the SNOWTAM format (see Sect. 4.1 for more detailed information). In the case of an unlikely lack of communication between the MPP system with the TLS equipment, the Driver using a proprietary operator mobile console will be able to access the road sensor or execute any configurations instructions requested by the TLS manager.

3.2 Characteristics of the Laser Equipment

The use of a commercial of the shelf (COTS) TLS equipment is nowadays a common practice in research projects for non-intrusive solutions, mitigating the development costs and contributing simultaneously to increase the technological maturity level, in particular for critical tasks requiring precision. The approach enabled researchers to focus their effort on what is core/innovative. After defining the specifications of the equipment, a market search for possible suppliers with equipment that best complies with the project requirements was performed. The marker survey also considered a solution with a range of flexibility by supporting external peripherals and accessories (e.g., equipment coverage for outdoor installation, power supply/consumption requirements, flexibility in operating the equipment remotely, compliance to existing 3D scanning and types of standards interfaces provided by the equipment).

[7] **Operational Knowledge Management (OKM)**, includes a set of software modules at the server side (i.e., system back-end) responsible to compute the raw data reported by the TLS and analyse them based on the business logic valid at the time the data were collected, which requires knowing the environmental condition (e.g., airport operational data) and traffic loads, including weather information to assess the risk of runway excursion.

Two potential types of equipment were identified (Carlson Scan2K and Riegl VZ-400i). The corresponding suppliers were contacted, and after presenting the project goals, they were mostly interested in collaborating. A set of demo sessions were scheduled to provide a quick overview of each equipment specific capabilities. Both suppliers agreed to leave the equipment for laboratory tests (during a short period). The possibility to perform laboratory tests with samples of the runway from Lisbon airport enabled us to get a better notion of the TLS capabilities. Site-tests at the Lisbon airport also provided outcomes with a very high-resolution level and topography accuracy.

The preliminary field tests were relevant to verify possible locations to position the equipment to analyze the runway pavement in specific areas, analyze the response time between the laser scan. These tests also provided concrete data to be used to configure/train the MPP system (in an early phase of the project execution) regarding the characteristics of the runway pavement, generating a 3D cloud (x, y, z) and "intensity" (the intensity i of the reflected laser signal) referred by some authors as "4D laser scanning".

During the preliminary tests, the TLS equipment was able to generate dense clouds (high-resolution). The Riegl VZ-400i equipment was more performant (complying to its specifications, which state accuracy of 5 mm, precision of 3 mm, and angular step of 0.0015º or less, depending on laser pulse rate using in a range from 250 m to 800 m). Figure 2 presented a TLS' view of a runway slice at Lisbon airport (with moving objects in the runway).

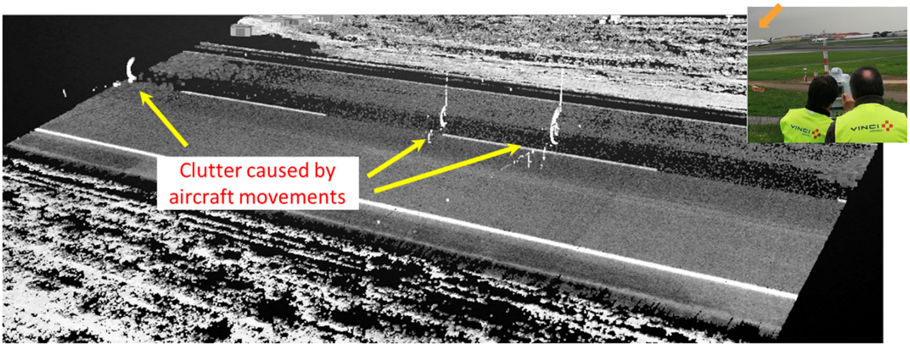

Fig. 2. Lisbon Airport Runway TLS image (runway slice).

The scan presented in Fig. 2 corresponds to a processed image, with the TLS equipment positioned in a way that allows us to analyze the details. The field tests were accomplished in a raining day with the runway wet, during a long period (over 2 h) to analyze the possible impact caused by movements at the runway during the execution of the field-tests. In Fig. 2, we can see the presence of the clutter, managed by the passing planes. However, it did not produce significant shadows to affect the image of the track. This clutter is well identified and can be easily eliminated by software.

4 Smart Airport Runway Safety Process

Automated runway inspections provide fast, accurate, and non-subjective options for manual inspections. Compared with traditional manual qualitative surveys, they can also perform a quantitative analysis of the runway pavement condition, thus providing an additional dimension [13]. The use of TLS instrumentation for monitoring the runway conditions is nowadays a state-of-the-art approach, providing reliable and precise information [14]. The technology can be used to perform inspections and to report measurements on the conditions of the runway, identifying risks related to aquaplaning, pavement deformation, and the presence of foreign objects, simultaneously allowing the visualization of the collected data in a 3D high precision [15].

Information governance provides a holistic approach for managing this type of information by implementing processes, roles, controls, and metrics that treat data as a valuable business asset. The goal is to make data assets available to those who need it while simplifying management and ensuring compliance with the types of events being monitored. Another important goal is to provide airport staff with data they can trust and easily access, while making business decisions to deal with risks associated with unmanaged or inconsistently managed information, thereby becoming more agile. The information governance framework includes defining who will specify the information workflow related to runway safety incidents and the types of data that the information governance program aims to manage. This means that information governance includes more than traditional records management. It integrates data security and protection, compliance, risk management, knowledge management, and business operations.

In addition, data governance also involves (usually a person or a specific team) the responsibility of understanding how data is collected, how it is maintained, how it is interpreted, how users use data, and why it is so valuable. If the data is inconsistent or incomplete, what steps can the organization take to change it? This means that governance needs to include management to achieve better self-service. Data stewards usually manage data catalogs, glossaries, and metadata repositories, and protect the resources required to maintain them. They promote the reuse of data and try to improve collaboration around data and analysis.

4.1 Business Scenario for Runway Contamination

The status of the runway must be regularly assessed, especially in extreme weather conditions, which may affect the runway surface. The condition of a wet runway can be measured by the depth of water in the touchdown zone. ICAO has defined standard terminology to describe the runway as dry, wet, wet, wet, or full of water [1]. In such contaminated conditions, the risk of aquaplaning is high.

When the wheels are running with water, aquaplaning may occur. This situation may also occur in some cases when water and wet snow are mixed. Aquaplaning on a runway surface with typical friction characteristics is unlikely to start at a water depth of 3 mm or less. Therefore, a depth of 3mm is used in Europe as a means to determine whether the runway surface is contaminated by water so that the assumption of aircraft performance is easily affected. When it is detected that the water depth in most areas of the runway is 3 mm (or higher), the airport operator must immediately inform all involved stakeholders of the status of the runway.

Figure 3 outlines the use case responsible for notifying the Airport Operator (with the role of RC manager) about the runway status, alerting for the risk of aquaplaning. A new notification will be issued whenever there is a significant change in the runway conditions (e.g., whenever a water-event is detected). The system infers the information at the business logic layers (i.e., by the Central Decision Management). Each time the TLS provides updated data about a runway inspection, the system will compute the data and pass the results to be analyzed. Activity five (A5) is responsible for correlating the collected data with the data about the airport operational status (provided by existing airport systems) to generate the inspection report. In case a runway event is detected, then a specific sequence flow is triggered to alert the airport operators promptly.

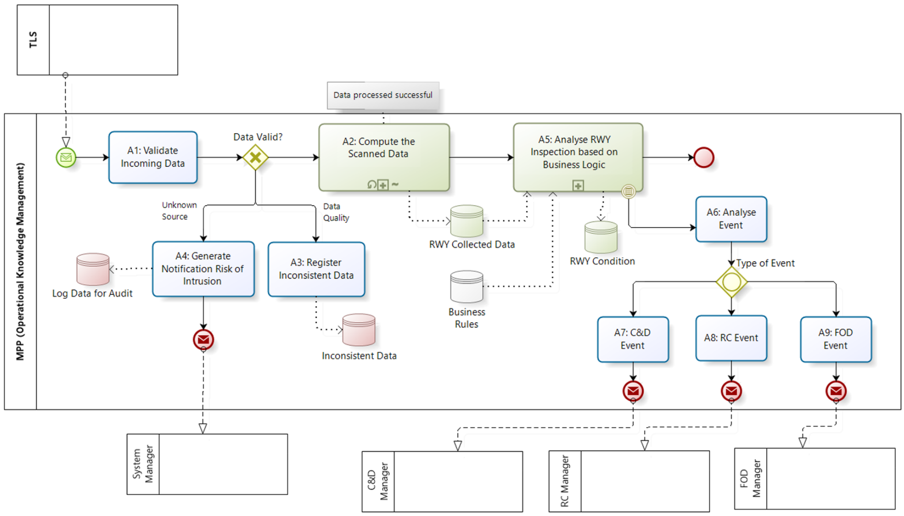

Fig. 3. The workflow associated with runway events.

The same scenario is outlined in Fig. 4 with a different viewpoint. The use case diagram highlights the system behavior from the perspective of the user. The purpose of the use case diagram is to capture the dynamic aspect of a system, meaning that when the requirements of a system are analyzed, the functionalities are captured in use cases. Business use cases should produce a result of observable value to a business actor. A key concept of use case modeling is that it can help us design a system from the perspective of the end-user. By specifying interactions with external systems (defined as actors in UML notation), this is a useful technique for communicating system behavior in the user's terms. Use case six (UC6) is responsible for notifying the RC manager about the presence of hazardous conditions due to the runway condition. Such a notification message follows the format defined by ICAO for SNOWTAM[8].

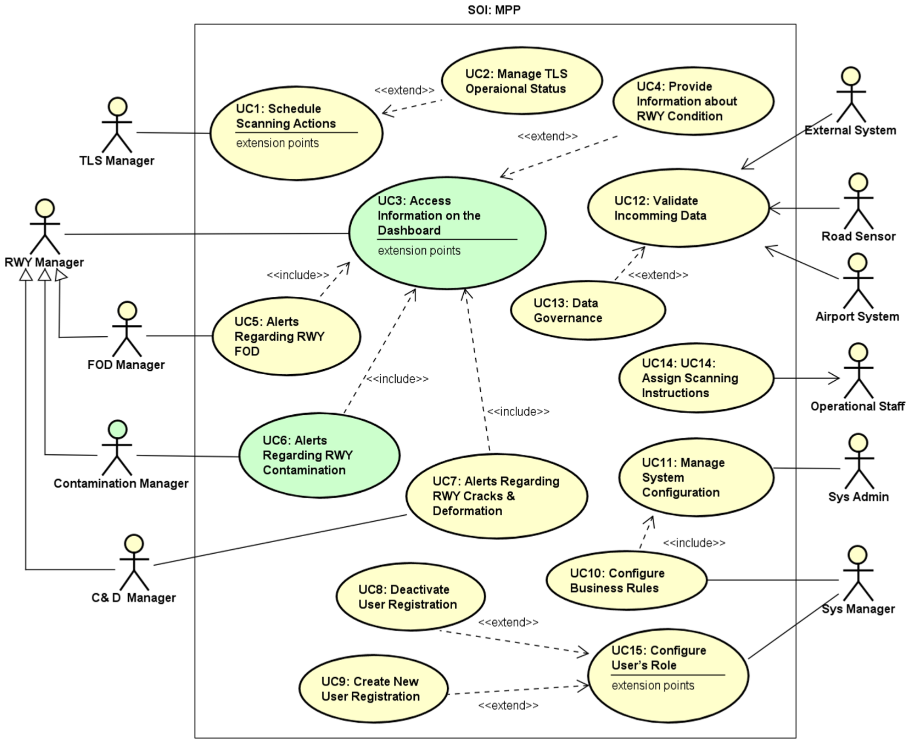

Fig. 4. Use case scenarios associated with the MPP project scope.

Within the scope of MPP, the preliminary tests were performed at the Touchdown Zone segment of the Runway in Lisbon airport. In this area, the runway condition can be affected to some degree by rubber deposits from landing aircraft. These deposits should be regularly removed to achieve a stated minimum dry friction level, mitigating the risk of viscous aquaplaning.

In most situations, raw data has no value in itself; instead, we need to extract the information contained in it. This is the first step in the discovery of knowledge to aid in decision making. End-users should be empowered to exploit the data; as such, the user experience when interacting with the system is determinant to motivate the user in

8 SNOWTAM is a special series NOTAM notifying the presence, or removal, of hazardous conditions due to snow, ice, slush or standing water associated with snow, mud and ice on the movement area. A NOTAM (notice to airmen) is a notice containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations.

exploring the system capabilities to extract information from the data. The knowledge gained can be used to elaborate policies, to make decisions, or to define rules of behavior in a way that is well informed and legitimized by its fairness and transparency.

The acquisition of raw data is no longer the driving problem: it is the ability to identify methods and models, which can turn the data into reliable and comprehensible knowledge. In Visual Analytics, the central driving vision is to turn the information overload into an opportunity, making the way of processing data and information, transparent for an analytic discourse.

The big trend we see in our research is to with the need for an event-driven model were the data collected by TLS is fused with airport operational data to make the data a more significant part of decision-making. With this approach, we hope to reduce errors and in order to convert data into actionable insights and to provide the end-user with good data quality and trusted data. At the same time, the airport wants to empower more personnel to discover and share data insights to more users. This increase in self-service analytics, however, means that we must find a good balance between giving freedom to the users and providing the right oversight and data governance.

4.2 User Interface Specification

Using interactive dashboards to visualize information can create a means for end-users to be more aware of undergoing (critical) events. People normally respond better to visuals telling a clear story than a long table or description that needs interpretation. Nowadays, the combination of information visualization and visual analysis has become the medium of the semi-automated analysis process. In this process, humans and machines work together to obtain the most effective results. The user has the ultimate authority when specifying the analysis direction related to a specific task. Besides, the visual representation sketch can describe the path from data to decision, providing a reference for user group collaboration across different tasks.

Figure 5 presents a high-fidelity prototype of the proposed interactive dashboard. It relies on data visualization best practices. The interface offers a set of role-based and interactive features to support the management of runway operations and monitoring activities, promoting situational awareness to the users. Figure 5 depicts three interactive areas of the interface: header toolbar left sidebar and a (geo)workspace container. On the right side, the notification wizard keeps the user well informed about current events, enabling the user to configure the type of events (s)he wants to keep monitoring.

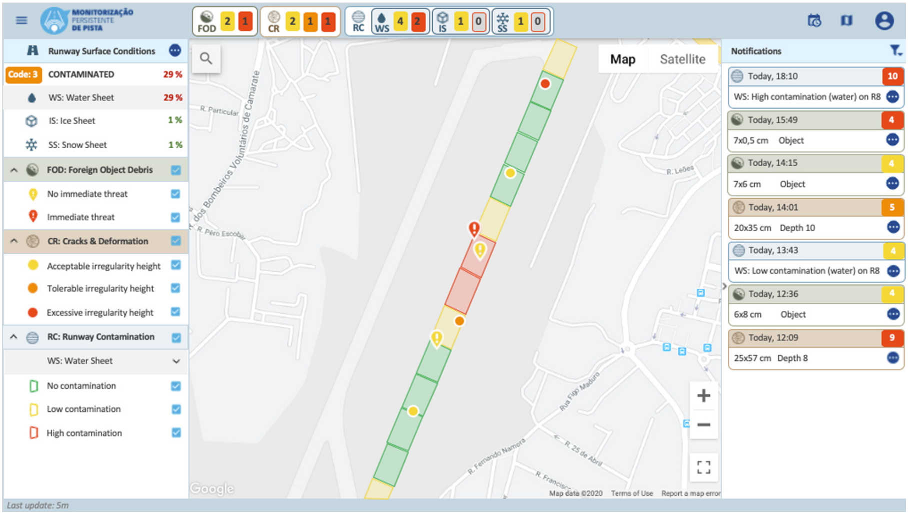

Fig. 5. The high-fidelity prototype of the runway surface conditions surveillance.

The interface supports the management of information regarding runway status, promoting situational awareness to the users. The application was designed to streamline the visualization of data related events according to three criteria:

- Foreign Object Debris (FOD)
  - Yellow, a FOD event that represents no immediate threat;
  - Red, a FOD event that represents an immediate threat that should be removed;
- Cracks & Deformation (C&D)
  - Yellow, a C&D event that represents acceptable irregularity height;
  - Orange, a C&D event that represents tolerable irregularity height;
  - Red, a C&D event that represents excessive irregularity height;
- Runway Contamination (RC), with a focus on water sheet events
  - Yellow, a runway segment classified as low contamination (between 10–25%);
  - Red, indicates the runway segment classified as high contamination (above 25%).

Runway surface conditions depend on a variety of factors, including state changes due to surface temperature effects, chemical treatment, or run-off and removal. The Runway Surface Conditions in the MPP, adopted from ICAO (see Sect. 2), are classified as:

- Dry, a runway is considered dry if its surface is free from visible moisture and not contaminated within the area intended to be used;
- Wet, a runway is considered wet when it is covered by any visible dampness or water that is above 3 mm in depth;
- Contaminated, a runway is considered contaminated when any fluid contaminant is above 3 mm, and when the contaminants represent an area above 25%. Ice and snow are not fluids; nevertheless, they are considered as contamination as well:

– Water Sheet, water depth with more than 3 mm;
– Ice Sheet, any form of ice/compacted snow, the depth is irrelevant;
– Snow Sheet, snow above 3 mm.

The information presented at the user interface in Fig. 2 is compliant to the requirements defined by ICAO for the runway condition assessment matrix (see Table 2 for a detailed list of the runway condition codes). If the runway is classified as contaminated, then the corresponding segment is marked accordingly, providing a visual context-awareness streamlining the user-perception of the risk level. The report is complemented with metadata clarifying the type of contaminator (e.g., water, ice, or snow), presenting a map-based interface for the visualization of the reported event(s). Whenever applicable, the localization of the event (e.g., FOD and C&D) is represented as a georeferenced point over the cartographic layout.

A new notification is generated if in the next cycle of the Runway inspection, new events are detected or if the existing ones persist (i.e., not solved). This is particularly relevant for FOD events. The total of unread events (or new events) is presented as an indicator to call the attention of the user. The user can configure the system to show a specific behavior for events requiring his/her immediate attention.

5 Conclusion and Future Work

To help mitigate the risk of excursion, ICAO has developed a unified method for assessing and reporting runway surface conditions. This methodology, called GRF, aims to cover requirements under all climatic conditions. GRF involves evaluating the runway through manual observation (usually done by airport operators) and using a runway condition matrix. The purpose is to establish a unified reporting system on the condition of the runway surface. In this article, we introduced the MPP project's approach to ICAO assessment of the runway surface conditions during dry/wet/contaminated conditions and the procedures/formats for reporting to all intervenient stakeholders. This project introduced an innovative method of using TLS as an automatic runway inspection. The solution applies spectrum analysis to infer the characteristics of the pavement surface, and sends the collected data to the server-side for processing, and integrates with other airport data.

Although TLS equipment monitors the runway status, other data about the airport's operating status needs to be considered when assessing the runway status. The MPP system interacts with multiple airport entities, and each entity plays a specific role in providing information. This information is used by the system to report runway status according to airport regulations, flight numbers, weather conditions, and operational status. The system accesses public services to improve the positioning accuracy of identified runway safety events. The next step in the execution of the MPP project is to implement a high-fidelity prototype and use a continuous data stream test system collected by the TLS equipment installed at Lisbon Airport. In this phase, the end-user will actively participate in verifying the information displayed for each interactive dashboard, its compliance with ICAO recommendations, and, most importantly, the usability of the system interface to handle critical runway safety-related events.

References

1. ICAO: State of Global Aviation Safety. ICAO Safety Report (2019)
2. EUROCONTROL: European Action Plan for the Prevention of Runway Incursions, ed. 1 (2017)
3. European Union Aviation Safety Agency (EASA): Easy Access Rules for Aerodromes (2019)
4. ICAO: The New Global Reporting Format for Runway Surface Conditions. https://www.icao.int/safety/Pages/GRF.aspx. Accessed 21 May 2020
5. Adamson, P.: Runway Surface Conditions: The Global Reporting Format, Uniting Aviation. https://www.unitingaviation.com/news/safety/runway-surface-conditions-the-global-reporting-format. Accessed 10 June 2020
6. European Union Aviation Safety Agency (EASA): Runway safety, Opinion No 03 (2019)
7. Vorobyeva, O., et al.: Assessing the contribution of data mining methods to avoid aircraft run-off from the runway to increase the safety and reduce the negative environmental Impacts. Int. J. Environ. Res. Public Health **17**, 796 (2020)
8. Davies, R.: Real-time runway monitoring: ICAO's new global reporting standard. Airport Technology (2019). https://www.airport-technology.com/features/real-time-runway-monitoring. Accessed 21 May 2020
9. Manzi, N.M.: The Runway Condition Report. ICAO Regional Seminar on Implementation of the New Global Reporting Format for Runway Surface Condition, 17, 796 (2019)
10. Huijbrechts, E.-J.A.M., et al.: Using Vmcg-Limited V1, controllability issues on contaminated runways and in crosswind. J. Aircr. **56**(4), 1342–1352 (2019)
11. Daidzic, N.E., Shrestha, J.: Airplane landing performance on contaminated runways in adverse conditions. J. Aircr. **45**(6), 2131–2144 (2008)
12. ICAO. Doc9981, Procedures for Air Navigation Services, Aerodromes, 2nd edn. (2016)
13. Mathavan, S., Kamal, K., Rahman, M.: A review of three-dimensional imaging technologies for pavement distress detection and measurements. IEEE Trans. Intell. Transp. Syst. **16**(5), 1524–9050 (2015). https://doi.org/10.1109/TITS.2015.2428655
14. Li, Q., et al.: Laser imaging and sparse points grouping for pavement crack detection. In: 25th European Signal Processing Conference - EUSIPCO (2017)
15. Ragnoli, A., Blasiis, M.R., Benedetto, A.: Pavement distress detection methods: a review. Infrastructures **3**, 58 (2018)
16. OutSystems, S.A.: Interface between Resource Broker and Client Systems, ANA Aeroportos de Portugal, SA, 16th July (2007)