LiDAR Performance Requirements and Optimized Sensor Positioning for Point Cloud-based Risk Mitigation at Airport Aprons

A novel field of application for LiDAR-based Surveillance

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***Abstract*—In the advent of the remote tower becoming operative in foreseeable future, and along a worldwide continuing implementation of the A-SMGCS concept, the need for precise and reliable sensor-based information for the automated support of aerodrome services has become far stronger than ever before. In particular the acquisition of traffic information, which among others includes the classification of objects, has been recognized as most crucial for supporting future aerodrome control and apron management services. However, current research and development efforts have paid only little attention on achieving full surveillance coverage of apron surfaces normally concealed to the controller`s eye, as well as on the detection of objects with small dimensions. A significant issue is the timely detection of FOD, which could not yet be completely resolved by MMW-Radar, as current systems still require complex and comprehensive installations at the airport. In this scope we present our project concept aimed at the analysis of a promising surveillance solution that will be enabled by LiDAR-generated three-dimensional point clouds. We assume that this approach holds the potential to significantly enhance the capabilities of tomorrow's apron management services. By providing a precise and high-contrast picture of its environment in real-time, the non-cooperative LiDAR-technology potentially contributes to the situational picture of the apron controller, the latter being endowed with the role of the most influential risk mitigator during operations. In particular, a point cloud visualization combined with automated situation interpretation is assumed to improve the controller´s capability to recognize visual hazard indicators, and thus to prevent incidents or accidents. This paper presents first results on performance requirements for LiDAR selection and strategies regarding the sensor`s optimized positioning.**

Keywords- LiDAR; laser scanning, point cloud; airport surveillance; apron control; apron management service; foreign object debris

I. Introduction

This paper gives an introduction to our DFG-funded research with the central topic of providing an innovative visualization of the apron situation to the apron controller. The visualization will be based on three-dimensional (3D) LiDAR point cloud data, which will be post-processed to make real-time model-based situation interpretation possible. LiDAR is a non-cooperative Laser beam-based method to primarily measure distances between the sensor and reflection points from its environment. As we identified airport surface operations, and in particular the apron, as significant risk driver for inducing even severe incidents, our research`s objective is to improve the current safety level of apron operations beyond current targets (e.g. ICAO Advanced Surface Movement Guidance and Control Systems-Concept (A-SGMCS) target level of safety). This addresses the detection and classification of objects, among others Foreign Object Debris (FOD), and, implicitly, the timely and differentiated recognition of hazardous situations and their leading indicators to prevent imminent collisions of aircraft, vehicles and pedestrians. Our analysis of the potential benefits of cost-effective LiDAR technology for airport surface surveillance may also be relevant for remote tower research, development and implementation efforts (e.g. SESAR WP 6.9, WP 12.0 [1]), as well as for the continuing implementation of the *Surveillance* function of A-SMGCS [2].

Our research takes up the results of an earlier field test carried out at our department [3], in which a *Velodyne HDL-32E* LiDAR [5] was mounted at Dresden airport to capture operations at three dedicated terminal aircraft stands. This field test demonstrated the capability of a state-of-the-art LiDAR sensor to provide point cloud information to the apron controller for the visual detection and identification of moving objects on the apron, e.g. aircraft and vehicles. Interviews with apron controllers showed both benefits and drawbacks in the provision of a point cloud-based situational picture. The drawbacks were mainly related to the technical design of the

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used sensor (e.g. insufficient resolution), but also to the LiDAR measuring principle (e.g. inability to recognize colours). The here presented on-following research project is again carried out in close cooperation with Dresden airport.

This paper first focuses on the description of the concept studies' research issues derived from the current state of operations on aprons, and second on the location assignment and optimization strategy for the – significantly improved – LiDAR sensor. Hence, emphasis is placed on section II, where the current risk situation resulting from airport apron operations and the need for further action to mitigate risk of damage to human beings and material is introduced as motivation to our research. In section III, the research issues are translated into a selected research approach, which foresees the provision of 3D point clouds to directly assess and reduce hazard causes by enhancing the situational picture on the apron. This shall form the central measure of risk mitigation with the corresponding concept presented in this section, as well as the motivation for using LiDAR-based point clouds. The fourth section gives details on the requirements laid down for selecting a LiDAR sensor for our project, as well as on considerations regarding the sensor`s optimized positioning and thoughts about raw data processing. The last section concludes with an outlook on the next steps to be taken in our research.

II. Airport Apron Safety – State-of-the-art

A. *Current Risk Situation on the Apron*

Referring to aviation`s total Air Traffic Management (ATM) empirical risk of 1,55 × 10E-8 fatal accidents per flight hour [4], operations on the airport movement area contribute a significant proportion to the ATM induced risk of injuries to human health and damage to material, respectively. According to [6] nearly 60% of all aircraft accidents (including not only ATM causes) occur in the tower controller's responsibility, which is both the airspace within the runway close part of the Terminal Maneuvering Area (TMA) and the movement area on ground-level.

However, future aviation and ATM concepts, e.g. the International Civil Aviation Organization`s (ICAO) Global Air Navigation Plan for CNS/ATM Systems [7], calls for improved safety targets. The Single European Sky ATM Research Programme (SESAR) targets for a total risk mitigation in the ATM domain by the factor 10 [8].

To achieve this objective the risk situation that results from surface operations on the airport movement area is to be considered. As the movement area is subdivided into maneuvering and apron area, disparities in the particular risk profiles and the previously applied risk mitigation measures (refer to subsection *B.*) can be discerned. In particular the apron area lacks of proper risk control and mitigation, as will be explained in the following:

The ICAO defines the airport apron as *"A defined area […] intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fuelling, parking or maintenance"* [9]. Typically, a wide range of processes take place, which includes the aircraft turnaround, supervised by ramp agents (e.g. refueling, loading), and all in-block and off-bock aircraft movements, which are in the responsibility of the airport operator or the Air Traffic Service (ATC). As such, airport aprons provide a highly dynamic environment exposed to numerous, in part moving objects, e.g. apron personnel and vehicles, which are diverse in size and behavior, and which are located in immediate proximity to each other in a limited space. In line with these descriptions, the apron can be named an inherently heterogeneous area, which complies with [10], where the apron is characteristically depicted as an *"extremely congested multipath outdoor area"*.

In contrast to the maneuvering area, where complex activities may take place, too, e.g. aircraft departures and landings as well as taxiing operations from / to the runway, the apron area is less internationally regulated. Indeed, ICAO Annex 13 [11] demands for a standardized reporting system for incidents and accidents that have occurred on the maneuvering area including the apron. Even though Safety Management Systems (SMS) for airports have been established at national level [12], the ICAO however does not claim yet for a publicly accessible and standardized accident and incident register.

The following statistics, which partly refer to the movement area as a whole, shall be considered to fight against incomplete reporting of safety relevant occurrences on the apron leading to potentially higher incident/accident rate than formally reported. Whatsoever, the airport apron accounts for a significant share of the total risk in aviation [13] [14]. It can be stated that:

- the probability of the apron ground personnel to become fatally or severely injured accounts for an overall rate of 0.47×10E-6 per aircraft departure [15][16],
- ground handling accidents, e.g. the collision of two aircraft during taxi, caused material damage amounting up to \$1.9 million direct costs and \$4.9 million indirect costs, the latter resulting from e.g. delays, outage of aircraft [17][18] and,
- five of 41 recorded ground occurrences at Australian airports could be attributed to FOD [13], with typical dimensions equal to or less than approx. 6 cm^2 and of dark colour in more than 50% of all cases [19].

Especially FOD hold a significant risk for operations. The need to detect FOD quickly and reliably is therefore set forth in [9]: "*The surfaces of all movement areas including pavement shall be inspected […] with the objective of avoiding and eliminating any loose objects/debris that might cause damage to aircraft or impair the operation of aircraft systems."* Although some FOD detection systems are available on the market (e.g. the QinetiQ's Tarsier system [20], their deployment to airports is still very rare.

B. *Surveillance Solutions for the Apron Management Service*

According to ICAO Annex 14 [9] the Apron Management Service (AMS) is in charge *"to regulate the activities and the movement of aircraft and vehicles on an apron"*. The AMS is mostly performed by either the ATC unit at the respective airport (generally referred to *ground*) or by the airport operator itself (generally referred to *apron control*). Current apron processes essentially rely on the see-and-avoid principle, which applies for all involved parties operating on the apron. As such, the AMS, and in particular its task of surveillance is performed by means of the direct view. A weakness of this principle is the sensitivity against view-restricting weather conditions (e.g. rain, fog) and its dependency on the daylight and on physical visibility barriers.

The deployment and utilization of additional surveillance systems on the apron can be thus regarded as technical measures for risk mitigation. Typically, the situational picture of the controllers in charge of the AMS is enhanced by non-cooperative surveillance systems like video and Surface Movement Radar (SMR). At Dresden airport the AMS lays in the responsibility of apron control, whose workstation is depicted in Fig. 1.

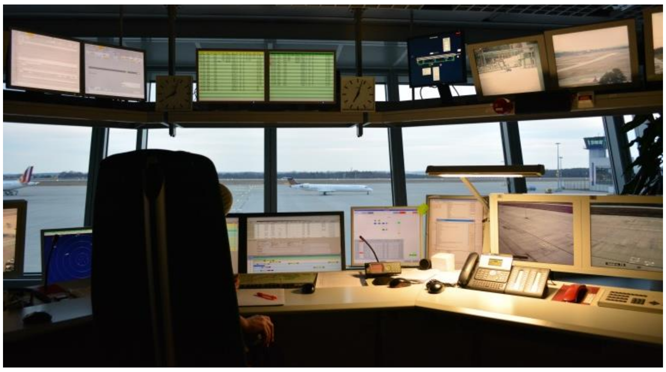

Figure 1. Apron Controller`s workstation at Dresden airport

In line with the direct view, cameras are sensitive against view-limiting factors mentioned above. Primary Radar, however, can be subject to false detections, especially in an area with pronounced object diversity like the apron [21]. Further limiting constraints when using Radar are low resolution, poor coverage and target-splitting effects [22] [23] [24].

One technological solution to overcome the above deficiencies is based on the usage of non-cooperative, high-precision Radar at millimeter wave band (MMW). As such the authors of [10] evaluated a MMW Radar, which is deployed at Madrid airport, and which is characterized by a range of 600m, 2m accuracy, 1Hz refresh rate and a 360° azimuthal field of view. In the analysis, a high probability for detecting aircraft and vehicles under various conditions was found (e.g. sunny day 99.8%, rainy day 96.9%). Recognition task without using a second sensor, however, had not been foreseen due to a still too low azimuthal resolution of 0.75 (e.g. compared to *Neptec OPAL 360* LiDAR, see Table 1). Similarly, in [23], [24] and [25] a sensor network consisting of MMW Radars was built up to improve the surveillance of the airport apron.

Another approach to actively contribute to apron surveillance was pursued in the project AVITRACK [26]. Within it, a camera network had been set up for the comprehensive surveillance of the airport apron. The focus laid on the supervision of turnaround activities, which was to be supported by automated scene understanding.

However, cooperative surveillance systems like Surveillance Radar (SSR) and Multilateration (MLAT) have been rarely deployed for the support of the AMS. MLAT and the underlying SSR-principle have been showing sensitivity to shadowing effects, multipath propagation, unwanted reflections and garbling, which particularily occurs in the apron area with its mentioned characteristics [21]. In addition, cooperative surveillance depends on active response signals, which requires a certain technical equipment level of all potential targets, thus excluding FOD detection from the beginning.

As set forth earlier, the majority of risk mitigation measures addressing surveillance were applied to the maneuvering area. The manifold examples include the *Runway Incursion Prevention and Alerting System* (RIPAS), e.g. [27], the A-SMGCS concept and its stepwise implementation, e.g. [28] and FOD detection systems, e.g. [29]. From the presented prerequisites, of which the apron area is exposed to, it may be concluded that a simple adaption of these technologies and solutions to the apron has not been possible so far.

III. RESEARCH APPROACH

The central assumption of our research is that a highly dynamic and complex environment such as the apron, which in addition holds many stakeholders with a limited situational picture, is a major contributor to risk of accidents and incidents. The synchronization of the individual pieces of information and the alignment of the situational picture follows the see-and-avoid principle, and is thus regarded as fundamental for risk mitigation on the apron. As already stated in section II, today`s airport apron processes mainly rely on the direct view, in some cases supported by video cameras and, where available, on ground surveillance. Acoustic information and voice communication contribute to the individual situational picture and help synchronizing them with other parties operating on the apron.

Our approach intends to improve the surveillance of apron operations by taking advantage of 3D point clouds. The real-time visualization of post-processed point clouds shall enable the apron`s stakeholders to act more safely, to avoid collision more effectively and to detect FOD automatically. In our approach, we chose LiDAR sensor technology to fill the role of a point cloud generator. The selection of both 3D point clouds and LiDAR is a direct result from our previous review on other domains that rely on automated object detection, recognition and tracking, and that take place in dynamic and complex environments. With reference to these conditions, we found the domain of autonomous driving at an advanced stage, which is largely attributable to the utilization of LiDAR-generated 3D point clouds, and which will be shortly explained in the following:

In the context auf autonomous driving, the stereoscopic fusion of video data and 3D LiDAR point clouds was analyzed in [30], followed by the development of concepts tackling the presentation of this data, e.g. on how to integrate visual elements into the video image [31]. The capabilities of LiDAR based perception in operation were shown during the DARPA Urban Challenge (2007) and the Civilian European Land Robot Trial (2007), where a *Volkswagen (VW) Touareg* and a *Passat*, respectively, had been equipped with a *Velodyne HDL-64E* [32]. In particular this sensor bases on the product family *Velodyne HDL* and can be found deployed in many automotive-automation applications requiring for road and object detection and recognition. The *Velodyne HDL-64* sensor has got a 360° horizontal field-of-view, which bases on a permanently spinning laser unit, and delivers 3D point cloud data in real-time. Supported by primary Radar, the same sensor type was installed on another *VW Passat* in a research project described in [33]. By the help of LiDAR, this Passat became the first car to be driven autonomously on real city roads with real surrounding traffic. In [34] a qualitative comparison of LiDAR and other sensors for automotive sensing can be found.

Besides autonomous driving, geo-referenced mobile mapping of roads and buildings is another field of application that has experienced a boost through LiDAR [35], but is less relevant for our research, as the point cloud data is not to be post-processed in real-time after capturing.

In summary, 3D point clouds from LiDAR, partly in combination with video, infrared and/or primary Radar, have become an important backbone for research and development in the field of autonomous driving. Above all, the transferability of the accumulated experiences in autonomous driving with both LiDAR and point clouds is ensured by the fact, that those automotive applications are exposed to a complex and dynamic surrounding that is similar to an airport apron.

Despite some similarities, we found one distinct difference between the autonomous driving domain and our research: In the first case, the focus has been set on methods for processing point cloud data from multiple sensors with the objective to provide these data in a converted, machine-readable format to an automat (e.g. target tracking at robot cars [36], sensor fusion in [37]). In our approach, however, raw data post-processing will be only one of two important aspects, as the appropriate visualization of the post-processed data to a human operator has to be equally considered. An example of simple point cloud visualization is shown in Fig. 2, which is a result from our preliminary study on the visual detectability of pedestrians. The raw point clouds had been provided by a *Velodyne HDL-32E* sensor and were then colour-coded in accordance to both height above ground level and target distance.

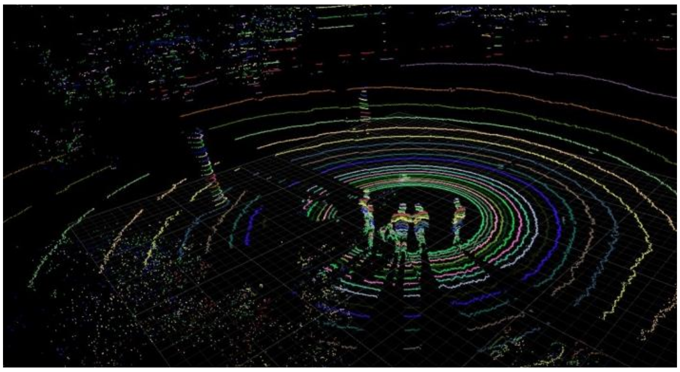

Figure 2. Visualization of point clouds applied to a segmentation filter with colour-coding

Our LiDAR demonstrator, which bases on flight simulator *X-Plane 10.0,* is another example for point cloud data processing and visualization using a segmentation algorithm from *Point Cloud Library* [38] (see Fig. 3).

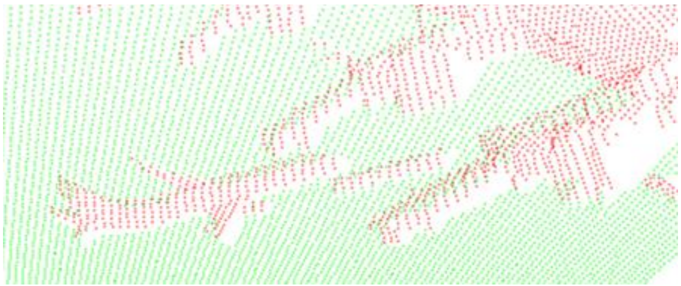

Figure 3. Point cloud-based presentation of an apron situation with colour-code segmentation algorithm applied

From our literature review on autonomous driving we extracted those features of LiDAR point clouds that seemed to be most valuable for achieving a precise and rich environmental image, which then shall be processed for visualization and, potentially, for automated situation interpretation:

- LiDAR sensors, with the exception of LiDAR line scanners (2D data), generate 3D point clouds – a property that is one major requirement for extracting 3D objects [39]. This property is an advantage over primary Radar, where only the slant range can be measured, and over video cameras, as 2D images lack of the depth information value (z).

- In parallel to this 3D property, highly dense 3D point clouds are most suitable for extracting geometric relationships from data [40], e.g. positions, orientations and spatial dimensions of objects. As such, many algorithms, e.g. for object detection, recognition and tracking, can be applied in real-time for the purpose of post-processed visualization and/or model-based situational interpretation. Some state-of-the-art 3D LiDAR sensors are able to provide the necessary high point cloud density, since LiDAR has, in comparison to the earlier presented MMW, a high temporal and spatial resolution, the letter resulting from a high pulse repetition rate (PRR). Especially in terms of the resolution, LiDAR clearly outperforms MMW, which was already mentioned in section II of this paper.

- LiDAR is independent from the target object due to the non-cooperative measurement principle. In connection therewith, not only regular objects (e.g. aircraft, vehicles, pedestrians), but also irregular objects, e.g. FOD, can be potentially detected.

- LiDAR is compared to the direct view and to video only slightly dependent from weather conditions [34]

Finally it should be mentioned, that our approach to utilize LiDAR fully complies with the SESAR ATM Target Concept D3 [42], in which research and development on non-cooperative sensors for enhancing the situational picture is expressly requested.

After having determined 3D LiDAR point clouds as enabler for risk mitigation on the apron, we chose the Apron Management Service (AMS) as the best starting point for the application of the respective risk mitigation measures. As the

AMS is in the role of the central authority to regulate movements and to prevent collisions [9], we assume that incidents and accidents can be proactively prevented through an early and differentiated indication of potentially hazardous situations. It is foreseen to conduct the respective proof of concept in two ways: First, a simulation based approach, which will require a field test with a real LiDAR sensor for parameter identification, and second, an experimental validation to be conducted at Dresden airport. The apron of Dresden airport will serve as reference operating environment for our research. To achieve transferability of our results, it is foreseen to let AMS personnel from Frankfurt Airport and/ or Munich Airport participate at certain points of our research.

IV. An Effective Risk Mitigation for Apron Operations

A. *Apron Surveillance Concept*

Our approach foresees the visualization of the apron situation to be provided to the apron controller as a first step towards evaluating a risk mitigation concept that takes advantage of point cloud-based surveillance. The apron controller, who is in charge of the AMS, is assumed to be an optimal candidate to benefit from a supporting visualization, as he occupies the position of the central authority to regulate movements and to prevent collisions. This very position enables the apron controller to act at short notice in accordance to the individual situation, and to cooperate with all relevant stakeholders. The de-escalation from hazardous situations at the apron could be effectively done by:

(1) Recognizing emerging hazard indicators, which may lead to incidents or accidents, and

(2) Informing pilots or apron personnel about a potentially critical situation development or at least terminating related operations when damage is inevitable.

Thus, our concept focuses on a visualization that provides the apron controller with the best possible support for performing the above mentioned tasks for effective risk mitigation. This support bases on a visualization design that takes inherent advantage of the processability of point clouds, and building on that, the possibility to assess a situation by applying higher-level-knowledge. This again offers the capability to visualize the situation on the apron free from any distortions, and to identify critical actions in the apron controller`s area of interest (AOI). However, a-priori knowledge regarding all cases that may occur has to be available. On the basis of the review in chapter II, the design of the surveillance concept is founded on the assumption that critical situations might end up in the following classes of incident and accidents (safety relevant events):

(1) Collision of aircraft, vehicle or pedestrians

(2) Damage caused by Foreign Object Debris (FOD)

According to the fault tree logic, these are final states of an event resulting from the causal combination of certain conditions of a situation, namely the hazard.

Indicating these hazards at the apron controller`s workstation by point cloud processing is the explicit objective of the visualization. From a theoretic point of view, our drafts for designing the visualization will be directed to two extremes:

First, a simple visualization (see Fig. 3) providing point-cloud-based ground surveillance that corresponds to a state-of-the-art Radar surveillance. In contrast, the second option will utilize state-of-the-art filters that process point clouds, allowing for the extraction of high-level information by means of applied model-knowledge. With the scope on risk mitigation, this knowledge might consist of the hazard patterns to be visually displayed to the operator. Hence, the risk mitigation will succeed if the operator will be able to recognize hazardous situation more effectively by means of higher recognition rates. Figure 4 shows this concept, which has been complemented by Radar and video in this example.

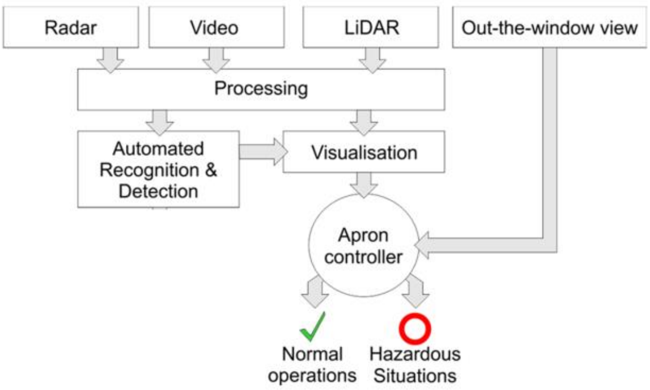

Figure 4. Sketch of the LiDAR-based surveillance concept

The most challenging task is to obtain valid knowledge that corresponds to the above mentioned definition of a hazard, the unique character of the early commencement of safety relevant events and the way the incident/accident finally occurs. For these reasons, historic incidents/accident reports are being analyzed to identify systematic pattern most contributive to the occurrence of the particular safety relevant event, which, in addition, have to comply with the hazard definition. In the following, two exemplary risk mitigation strategies are presented:

(1) The kinematic interpretation of the apron situation by classifying and tracking objects shall allow the controller for concluding on the existence of critical states in the AOI.

(2) The detection of FODs by highlighting unclassifiable obstacles on the AOI`s surface.

B. *Hazard and Cause Analysis*

In order to turn the above concept into reality, the apron controllers' tasks connected to the control and monitoring of aircraft and vehicles on the apron have to be determined in a first step. By reviewing international rules and local operating agreements a model of the controllers` tasks, including the demand for information, is set up, which is then calibrated through on-the-spot field observations and interviews with controllers. After having completed the model, a methodical hazard assessment is conducted by means of expert workshops with the aim to determine the controllers` contribution to potentially hazardous situations under the constraint of the present information situation at the control tower. On the basis of an analysis of accident and incident data, visual hazard indicators can be derived. In the sense of a Preliminary System Safety Analysis (PSSA), strategies for risk mitigation with focus on an improved situational picture enabled by point clouds will be developed.

C. *Concept for Object Detection and Recognition*

State-of-the-art 3D LiDAR sensors deliver pre-processed, time stamped position data in 3D Cartesian format (x, y, z) as well as corresponding reflection intensity of each reflection point in real-time. Our concept to utilize these raw data for object recognition consists of a two-step approach applying to each frame “n”. The first step will serve the detection of objects. This is, at first, performed by subtracting the static background from the point cloud in the AOI. This is achieved through subtracting the apron`s plan surface and the surfaces of the terminal buildings. To extract the contours from the non-static foreground, the nearest neighbor method, which searches for connected regions in the data, is applied. For the purpose of reliable object detection, the respective methods are currently being assessed, e.g. [47].

Within the second step the extracted object shall be assigned to a class. This step will be realized by mapping the extracted geometric object information to a description vector (n tuple), which shall map geometric attributes to a discriminative model. This vector is then associated to characteristic object knowledge, which is defined by areas within the discriminative model, and which contains dimensions and contour information of objects typical to the AOI, e.g. vehicles and aircraft. The above areas will be a result of a learning process, in which the discriminative model will be manually evaluated and completed by means of many samples.

In case of successfully matching an object, the object class is instantiated to a timeline, and the first match is marked as the timeline`s origin. With continuing frames, the timeline will be updated in accordance to the results of the discriminative model. By building up a continuous history of position and heading values, the functionality of object tracking is realized. The circle will terminate, when the particular object leaves the AOI.

D. *Optimized Sensor Positioning*

FODs are understood as loose objects of an unknown type characterized by unknown geometric dimension. As laid out in section IV, the detection of FODs is one decisive pillar of our risk mitigation strategy. A successful detection of these objects often depends on whether an object can be identified as “irregular” in comparison to a certain expected situation. As FODs are usually located on the ground, one major criterion to capture as many objects in the AOI as possible is the field of view. A major drawback of LiDAR-based point clouds is the fact that the detection demands for the line-of-sight. This principle is highly sensitive to shading effects potentially preventing FODs to be successfully detected. For this reason, an analytical-geometric model to calculate the area that is effectively covered by the respective LiDAR sensor was developed at TU Dresden in [46]. In this study we showed that the maximum coverage for FOD detection on ground-level will be achieved, if the sensor is mounted in the lateral extension of the diagonal line of the aircraft silhouette (assuming a geometric figure similar to a cross), and at a height that corresponds to the height of the aircraft`s wings above ground. This minimizes shadowing right below the aircraft fuselage, around the jet turbines` air inlet and the area of the critical engine exhaust, so that service vehicles and apron personnel on both sides of the aircraft will not be covered during the turnaround. As a first result, the positioning of the sensor at the intersection-points of two extended diagonal axis of two aircraft stands is to be recommended.

E. *LiDAR Performance Requirements*

The introduced strategies impose requirements on the LiDAR infrastructure, so that effective risk mitigation can be realized by utilizing the generated point cloud. We derived the following basic requirements:

- According to the results of the preliminary field test [3], the LiDAR sensor shall fully cover the “core zones” of the apron, meaning those areas where usually the widest range of (safety critical) processes take place (aircraft turnaround, all in-block/off-bock aircraft movements, and parts of the apron taxiway). For the most airports, including Dresden airport, a minimum range performance of at least 200m is considered appropriate.
- The LiDAR sensor shall also support a potential multi-sensor configuration to expand, in case of need, the full covering area for object acquisition.
- The LiDAR shall provide significant contours of the relevant objects on the apron in real-time to permit type classification within a range of at least 200m. To provide an orientation based on the experiences from [3], a point density less equal 0.16° in azimuth and 1.3° in elevation should be envisaged.

V. OUTLOOK

This paper explains the need for mitigating risks of injuries and damages that result from apron surface operations at the airport. According to this, we derive our research`s objective to improve the current safety level of apron operations. Our approach foresees to provide a point cloud-based visualization to the apron controller, who we assume is the most influential risk mitigator in the apron area. Central to this approach is a surveillance concept that is aimed at timely indicating safety-critical situations holding the potential to transform into incidents or accidents, so that corrective actions can be taken by the apron controller to prevent these undesirable end-states.

One of the next steps in our research is the preparation of a field test at Dresden airport. According to our research approach in section III, a LiDAR sensor will be installed to identify model parameters for the envisaged simulation-based validation. Therefore, the following matters will be most relevant in the near future:

A. *Sensor Choice*

Our research includes the acquisition of a 3D LiDAR sensor. The selection of an appropriate sensor bases on the requirement list presented in chapter IV. In the scope of a first selection step, we conducted a market survey, among others involving [43], that left the *Velodyne HDL-64 S2* (when leaving the requirement of 200m range performance aside, which is most likely not met) and the *OPAL 360* sensor series from *Neptec Technologies* on the shortlist (see Table 1).

TABLE 1: SELECTED PERFORMANCE FIGURES OF VELODYNE HDL-64 S2 AND NEPTEC OPAL 360 HP [41] [44]

Sensor	Horizontal Field of View	Vertical Field of View	Range	Vertical Reso-lution	Horizon-tal Reso-lution	Type of Scan Pattern
HDL-64 S2	360	26,33	120m @80% reflectivity	0,4°	0.09°	Over-lapping
OPAL 360HP	360	45	1100m @90% reflectivity	0,03°	0,0057°	Non-Over-lapping

When comparing those remaining sensor candidates, which both are designed for outdoor and all-weather use, a clear difference in the sensors scan principle can be found. The *OPAL 360* series works with a non-overlapping scan pattern, which is generated by a single 1540nm pulsed Class 1 laser and two rotating prisms. The non-overlapping scan pattern is most valuable for stationary applications in dynamic surroundings (like a fixed-based installation at the airport), since data gaps can be reduced over time. In detail, the gaps will be filled up until a certain point density required for a necessary detectability of objects is reached, given that a sufficient amount of time is granted for data acquisition (for instance 10s @ 200 kHz PRR result in 2×10E6 reflection points). The increased range of the *OPAL 360* sensor series closes a former major deficit of LiDAR compared to range performance of MMW systems, e.g. the Tarsier Radar [20]. Furthermore, it also fulfills and exceeds by far the minimum range performance requirement of section IV.

The *Velodyne HDL-64 S2*, however, was designed for mobile applications, where an overlapping scan pattern is fully sufficient as the whole sensor is moved externally. As already stated in our preliminary study [3], a stationary installation of this sensor would systematically result in blind spots in the scan pattern, which again would leave room for small objects like FOD to easily hide in between these gaps.

Complementary to the performance figures of Table 1, the *Neptec OPAL 360* series features an obscurant penetration mode, which shall enable the sensor to look through dust, fog, snow, smoke etc. by a software triggered changing of the receive logic. This mode showed promising results during helicopter operations [44].

B. Practical Sensor Positioning Issues

To take full advantage of the sensor`s features and to gain the greatest possible coverage of all relevant ground activities by reducing shadowing, an optimized sensor positioning based on a methodical approach will be required. Therefore, we will take the calculations of the analytical-geometric model presented in section IV into account.

From a practical point of view, two general mounting locations at Dresden airport seem to be appropriate: Either mounting the sensor on a light mast on the apron, or installing the sensor on the roof of the terminal building. Regarding the first option, practical implementation issues like the vibration behaviour of the masts caused by wind need yet to be assessed. The second option is sketched in Fig. 5 at the example of the *Neptec OPAL 360* series, where the theoretical coverage for the sensor`s operation at maximum PRR (200m @ 200 kHz) is shown for an exemplarily installation on the terminal`s top-right corner. Based on theoretical knowledge, it is expected that objects at the size of a car, and possibly even people, can be tracked within the green zone. In the yellow zone tracking of objects at the size of a bus should be possible. The orange zone (*OPAL SP*) and the red zone (*OPAL HP/XP*), respectively, are assumed to make tracking of large objects like aircraft possible.

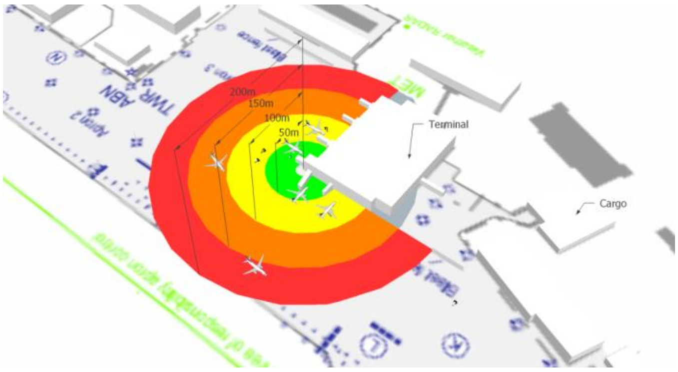

Figure 5. Theoretical coverage of OPAL 360 series at maximum PRR for an exemplary installation on the terminal roof of Dresden airport [Neptec Technologies, Canada; AIP DFS Deutsche Flugsicherung, Germany]

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