Can LiDAR Point Clouds effectively contribute to Safer Apron Operations?

Results of an experimental controller-in-the-loop study

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***Abstract*—The current system of conventional and remote airport ground control still largely relies on the direct visual contact between the ATCO and his area of responsibility. Despite supporting video cameras and dedicated radar applications, sudden occurrences in the ATCO`s picture may deteriorate safety without further risk mitigating tools or sensors in place. Especially low visibility conditions and also darkness regularly give rise to capacity backlogs, incidents and accidents. At the same time, LiDAR sensors and computer vision algorithms have made considerable progress in recent years. A combination of both offers the unique capability to allow for the detection of small unknown objects and simultaneously to enable the classification of known objects for distances of up to several hundred meters. This work describes the experimental assessment of the corresponding potential safety benefits for apron operations when using LiDAR sensing to improve the controller`s picture. The experiment was designed as a controller-in-the-loop study and was conducted with academic students in an apron control tower simulator. The central metrics gathered were the number of (emerging) hazardous situations that could be recognized by the test person with associated reaction times. Compared to conventional apron control, the hazard recognition rates increased by 18% on average whereas reaction times decreased by 45% for an ideal LiDAR configuration. With regard to individual hazard categories, the contribution to safety was largest for Foreign Object Debris (FOD) scenarios with increased hazard recognition rates of 33%.**

Keywords- airport ground surveillance, apron control, apron safety, LiDAR, Laser scanning, point cloud, controller-in-the-loop study

I. INTRODUCTION

After the world`s first Remote Tower Service (RTS) became operational in 2015 in Sweden and with a continuing implementation of the International Civil Aviation Organization`s (ICAO) A-SMGCS concept [1], the need for real-time generation of highly precise, error-free and robust sensor data has become far stronger than ever before. The availability of data capturing the traffic situation and the operating conditions on the movement area[1] is deemed essential for today`s airport surveillance system and for a more automated airport surveillance in the future.

In contrast to this development the current system of airport ground surveillance still largely relies on the controller`s Out-The-Window-View (OTWV), partly supported by video cameras and Surface Movement Radar (SMR). These information sources contribute to the controller`s situational awareness (SA), which is defined as "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" [2]. The first level of Endsley`s three-stage model of SA [3] tackles the controller`s "picture" (see [4]) set up, comprising "[…] the status, attributes, and dynamics of relevant elements in the environment". Consequently, this level deems to have a high impact onto safety as missing or incorrect information can potentially lead to reduced "comprehension of the current situation" (level 2) and/or limited "projection of future states" (level 3).

Some task analyses [5], [6], [7] and a large number of legacy operational control procedures requiring a direct visual contact to an object underline the crucial role of the OTWV for building and maintaining the controller`s picture. Even the aforementioned RTS concepts and their practical implementations continue to stick to the paradigm of the (artificially reproduced) OTWV (e.g. [8], [9], [10]). The OTWV, however, is apparently greatly dependent from weather/lighting conditions (e.g. fog, precipitation, darkness) and obstacles in the line-of-sight. In situations where such view-obstructing factors are present, a reduction in the amount of handled traffic to compensate for the insufficient controller`s picture will most likely occur [11], e.g. due to the application of Low Visibility Operations in Air Traffic Control. A more critical case arises if this insufficient picture leads to a reduced ability to recognize conflicts and to poor decision making. In this context, it was found in [12] that 72.4% of all safety-relevant occurrences from the Aviation Safety Reporting System (ASRS) constitute situational awareness level 1 failures („Fail to perceive information or misperception of information") of the Air Traffic Controller (ATCO).

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[1] According to ICAO Annex 14 [12] the movement area consists of the maneuvering area and the apron area.

We would like to thank the DFG (German Research Foundation) most sincerely for funding the research presented in this paper (FR 2440/4-1).*)*

These figures apply in particular to the apron, which ICAO terms “A defined area […] intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fueling, parking or maintenance” [13]. Moreover, the apron is commonly referred to as an unstructured, dynamic and therefore hazardous working environment [14], [15], [16] and thus hardly to be fully covered with current sensor systems. In view of these preconditions, a degradation of the apron controller`s picture is even more likely to affect apron safety. One exemplary, yet important problem is the timely and reliably detection of Foreign Object Debris (FOD) on the movement area (including the apron), which is not possible up to now with SMR (X and K_u band) due to limited resolution. The comparably high resolution Millimeter Wave Radar (MWR, W band) showed detection rates of 100 percent for typical FOD test objects in some studies, but suffers from low range performances of 30m [17] and 35m [18] respectively.

Various risk analyses underline the need for action to mitigate the current risks of incidents and accidents on airport movement areas for both the maneuvering area (e.g. Runway Incursion Prevention [19]), and in particular for the apron area (e.g. [16], [20], [21], [22], [23], [24]). Parallel to this the SESAR consortia targets for total risk mitigation in the ATM domain by the factor 10 [25] and, therefore, also addressing the movement area including the apron. To achieve an effective reduction of risk for operations on the apron the authors aim at establishing a constant, appropriate picture on the side of the apron controller, since he represents the central authority to create and maintain operational apron safety [13]. In order to implement this approach three dimensional (3D) sensor data from LiDAR was found to be the most promising candidate to meet these new requirements regarding information quality and quantity (for details see [26]).

LiDAR is a Laser-based method which measures distances between the sensor and any reflecting object. In conjunction with an efficient data processing current LiDAR devices for solid target detection have the unique capability to detect unknown, very small objects on the floor (like FOD) and at the same time they are able to classify known, rather larger objects (e.g. class “Aircraft”) from distances of up to several hundred meters. For example it is possible to type-classify most general aviation traffic aircraft (e.g. instance “Cessna 172”) thanks to LiDAR`s high spatial resolution compared to common SMR and MWR, even if not equipped with a Mode S transponder. These capabilities are achieved by the following specific LiDAR characteristics: Non-cooperative environmental scanning, high pulse repetition rates (PRR) with high pulse intensities, pulse frequencies reaching into petahertz range (≙Extremely High Frequency, EHF), high precision and accuracy in millimeter range[2] (for details see [27]). The above characteristics also result in an independency from light conditions (day/night) and in a reduced sensitivity against adverse weather conditions compared to the human eye and standard video cameras [28]. Meanwhile, researchers from Ohio State University have also recognized the potential of LiDAR sensing for ATM surveillance tasks like the detection of aircraft centerline deviations on runways [29] and the heading estimation of taxiing aircraft [30].

In conclusion, the chosen mitigation approach foresees to overcome an insufficient picture by providing information on present or emerging hazards to the controller. Based on this information the controller shall be enabled to take corrective actions in time so as to avoid or at least manage hazardous situations. Visual indicators that represent typical causes of an emerging hazard or that make an already existent hazard visible will be content of this information. In the first development stage of the concept implementation, a simple visual presentation of these indicators at the default apron Controller Working Position (CWP) is envisioned. At a later stage, automated hazard pattern recognition interprets these indicators based on model-knowledge to assist the controller. Independent from the stage of development, the concept relies on LiDAR 3D point data and requires the following basic functions: object detection[3], object classification[4] and object tracking (see Figure 1).

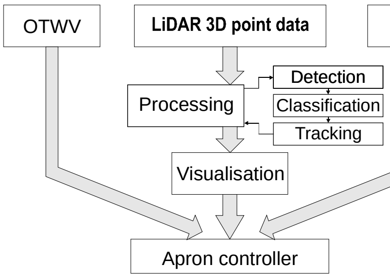

Figure 1. LiDAR point cloud surveillance concept for an apron CWP [27]

In this paper the authors report on the experimental assessment of their LiDAR point cloud surveillance concept [31], [32] in terms of its potential risk mitigation effect for apron operations. To answer this central research question, a controller-in-the-loop (CITL) simulation study was designed, carried out and evaluated using various safety-relevant metrics.

In section II, the methodological basis for the development and validation of a LiDAR point cloud surveillance concept, in fact a Risk Assessment (RA) is briefly sketched using Dresden airport (DRS) as a reference example. Building on this, section III describes the development of an experimental design for a CITL simulation study that is able to make potential safety effects of a LiDAR support at the apron CWP measurable. Section IV reports on the translation of this experimental design into a physical setup. Section V evaluates the data that was collected in the experiments and discusses the results with regard to the central research question. Section IV

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[2] At the example of the LiDAR Neptec OPAL 360 which is available to the authors: Horizontal-Field-of-View (HFOV): 360°, Vertical-Field-of-View (VFOV): 45°, PRR: 200kHz@200m, 25kHz@1100m, precision: 5mm, accuracy: <10mm, azimuthal resolution: ≈0.0057°, Laser Class 1 (eye safe)

[3] According to Johnson`s theory of discrimination [45]“detection” is about perceiving the “presence of an object”.

[4] According to Johnson`s theory of discrimination [45] “classification” is about recognizing the “class to which (an) object belongs […]”.

summarizes the findings of this work and concludes with an outlook on the next steps to be taken in this research.

II. METHODOLOGICAL BACKGROUND

This paper reports on the experimental assessment of a LiDAR point cloud surveillance concept for reducing risks in apron operations. It is therefore necessary to provide an overview of the overall Risk Assessment (RA), where the Eurocontrol Safety Assessment Methodology (SAM) served as methodological framework [33]. The main purpose of the RA was to capture the current risk situation on airport aprons (Functional Hazard Assessment, FHA) to identify potential causes and to develop a corresponding concept to mitigate these risks using LiDAR sensing (Preliminary System Safety Analysis, PSSA). Finally, the effectiveness of this concept was assessed in terms of its contribution to apron safety (System Safety Assessment, SSA). The RA used the Dresden airport as a reference example.

A. Hazard Analysis

As a first step of the SAM, an FHA was conducted to assess the contribution of an apron controller`s potentially insufficient picture to the risk of airport apron operations. Based on the apron control`s manual of operations, field observations and interviews with controllers an abstract description of the whole system of apron control regarding surveillance tasks, processes, information demand and information sources was created. A Hierarchical Task Analysis (HTA) [34], [35], [36] served as methodical framework and Task Layer Maps (TLM) [37] were used for the visualization of the results. The TLM is available in [38].

For the purpose of hazard identification, a hazard was defined as “An insufficient information acquisition on the part of the controller in a specific situation demanding for specific information to safely execute the control and surveillance task of the apron control” [27]. The list of hazards was created by systematically applying key words to the TLM that describe potential states of an insufficient picture (“failure modes”): a) *required information completely unavailable* b) *incomplete information* and c) *cognition of corrupt information*. Additionally, suitable hazards from completed safety assessments were reviewed and added to the list (e.g. a subproject to *innovativer Flughafen*, iPort [39]). The actual hazard identification process involved multiple brainstorming sessions with apron controllers and safety experts from Dresden airport. For each of the 50 hazards that had been identified before the possible “consequences” for apron operations and their associated highest imaginable severities (Severity Class, SC) were determined and joined to an event tree. Finally the FHA was completed by allocating Safety Targets (ST) for each hazard to define a limit for its overall maximum frequency of occurrence. As a result of the lack of quantified probabilities of occurrence for each of the consequences, the “prescriptive method” was applied in the allocation process (pursuant to Eurocontrol SAM FHA Chapter 3 Guidance E).

B. Cause Analysis and Risk Mitigation Concept

The assignment of apparent and/or presumed causes to the identified hazards within the PSSA (2nd step of SAM) resulted in individual fault trees for each hazard. This cause analysis was realized through the investigation of about 500 incident and accident reports (e.g. NTSB, AIDS, ASRS, OCR, ASRS) involving ground occurrences on the movement area (except for the runway). All hazard-cause relations (fault trees) and their associated consequences and corresponding severities (event trees) were linked to hazard-wise Bow-Tie models. From these Bow-Tie models the authors extracted those visual cause and hazard indicators that make emerging and already present hazards visible to the apron controller. A list of indicators is provided in Table 1 using hazard H-3 as an example.

TABLE 1: CAUSE AND HAZARD INDICATORS FOR HAZARD H-3

Hazard No.	**Hazard**	**Cause indicators**	**Hazard Indicators**
H-3	Aircraft (AC) position misperceived	• Two or more taxiways in close proximity to each other • Short-term changes in the standard routing • Direct view to AC (partly) hidden by other objects	• AC overruns holding point without clearance • AC taxis on wrong taxiway

In the scope of the PSSA, the assumed capability to reliably detect these indicators using LiDAR sensing and their subsequent visualization at the apron CWP is understood as central measure to limit the risks that had been identified before in the FHA. In detail this approach aims at reducing both the frequency of occurrence of hazardous events (“hazard avoidance”) and the severity of the hazard consequences (“hazard control”). As an initial step towards a future highly automated hazard pattern recognition based on machine interpretation of visual indicators the authors derived a list of basic requirements from this set of indicators. These requirements (see Table 2) comprise the basic functions of object detection, classification (including instance recognition as submethod) and tracking and are aimed at a future LiDAR system for apron surveillance[5]. Since moving objects are also covered by these basic functions a near real-time capability[6] is needed as well.

TABLE 2: BASIC REQUIREMENTS FOR A LIDAR-SYSTEM FOR APRON SURVEILLANCE FROM A RISK MITIGATION PERSPECTIVE

Basic Functions	**Relevant Target Objects**	**State of Movement**
Detection	All objects that are not part of the static apron scenery	stationary & in motion
Classification	Aircraft (AC), ground vehicles (GV), pedestrians (PED), turnaround equipment (EQ), FOD	stationary & in motion
Instance Recognition	AC: e.g. Airbus 319-100, Boeing 737-700; GV: e.g. follow me, fuel truck	stationary & in motion
Tracking	All objects from line “Classification”, all object types from line “Instance Recognition”	in motion

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[5] “LiDAR system” is referred to as the combination of a LiDAR sensor and several raw data processing methods.

[6] According to ICAO A-SMGCS concept [1] this requires an update rate of ≤1s.

Based on the above requirements and under consideration of ergonomic design criteria and findings from a controller workshop a concept for a prototypical LiDAR Graphical User Interface (GUI) was designed (see Figure 4). In parallel Computer Vision methods for object detection and object classification/instance recognition were developed in accordance to the basic requirements and have already been partly tested (see [26] and [30]).

C. Concept Validation

In line with the 3rd step of the SAM, which is the SSA, the compliance between the achievable safety level for apron operations under LiDAR surveillance and the "Safety Targets" of the FHA needed to be demonstrated. Adapted to our methodology, the aim was to prove significant contributions to the "hazard avoidance" and "hazard control" strategies. For this reason it was decided to conduct a controller-in-the-loop (CITL) simulation study assessing selected metrics that appropriately represent the overall achieved safety level.

III. EXPERIMENTAL DESIGN

A. Hypotheses

To answer the main research question whether and to what extent a LiDAR support at the apron CWP will reduce risks for apron operations, a hypothesis testing study was chosen as analysis method. This method allows for the analysis of relationships between independent input variables and dependent output variables. The "(non-)availability" of a LiDAR GUI at the apron CPW was defined as independent input variable with a further differentiation into two assumed LiDAR performance levels (see subsection B). Based on the main research question the following hypotheses were tested within the experimental simulation study:

H1: The availability of a LiDAR GUI at the apron CWP increases the controller`s hazard recognition rate.

H2: The availability of a LiDAR GUI at the apron CWP increases the controller`s situational awareness.

H3: The availability of a LiDAR GUI at the apron CWP decreases the controller`s workload.

H4: The risk mitigation effect of a LiDAR GUI at the apron CWP is higher when poor visibility conditions are present than under good visibility conditions.

H5: The higher the performance level of the LiDAR system (sensor, raw data processing), the higher the risk mitigation effect for apron operations.

B. Experimental Configurations

To find answers for these hypotheses, the experiment should allow for a comparison between a common apron CWP with standard video camera support (control condition, referred to as "Default apron CWP") and a CWP that is additionally equipped with a LIDAR GUI (experimental condition, referred to as "LiDAR Apron CWP"). The two performance levels for "LiDAR Apron CWP" were shaped by the assumed time delay between the physical appearance of a specific target object in the coverage area[7] and its visual presentation on the LiDAR GUI depending on the individual basic function (see Table 2). The performance level "Real Time", which represents a future most advanced developed LiDAR system, assumes a delay of 0.5s for all functions and all kinds of targets (see Table 3). In contrast, "Case Study" reflects the current performance level of the LiDAR system available to this research project, for instance preventing the execution of the "tracking" function. The delay times of "Case Study" originate from measurements at Dresden airport with a real LiDAR sensor [27], [40], [41] or were extrapolated based on these measurement data and known geometric-physical relationships (see Table 3). Potential misdetections and misclassifications were not simulated in the experiment.

TABLE 3: DEFINITION OF LIDAR PERFORMANCE LEVELS

Performance Level	**Time Delay Detection**	**Time Delay Classification**	**Time Delay Tracking**
Real Time	All objects: 0.5s	All objects: 0.5s	All objects: 0.5s
Case Study	AC: 2s GV/EQ: 10s PED: 25s FOD: 50s	AC: 2s GV/EQ: 10s PED: 25s FOD: 50s	No tracking

In conclusion, the following configurations were applied and assessed within the simulation study:

- Configuration 1: "Default Apron CWP"
- Configuration 2: "LiDAR Apron CWP" with performance level "Real Time"
- Configuration 3: "LiDAR Apron CWP" with performance level "Case Study"

C. Dependent Variables

First, suitable dependent output variables had to be selected to ensure that all hypotheses could be answered properly. The primary variables were the "Hazard Recognition Rate" and the "Reaction Times for Hazard Recognition" as they directly represent the potential risk mitigation effect by (timely) recognizing cause and hazard indicators (see subsection II.B). "Situational Awareness" (SA), "Workload" (WL) and "Frequency of Camera Usage" were given a secondary status as they might be considered as side-effects contributing to the hazard recognition task or that help to explain observed effects. Table 4 summarizes all dependent variables and transfers them into metrics that could be captured with the study`s experimental design.

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[7] Assumptions: The LiDAR sensor`s field of view comprises the complete apron area of Dresden airport and, additionally, all taxiways of maneuvering area but not the runway. Further, the availability of a sufficiently large number of LiDAR sensors at Dresden Airport is assumed, allowing for a permanent monitoring. In addition, also shadowing effects that may occur due to occlusions by other objects or buildings are neglected.

TABLE 4: DEPENDENT VARIABLES AND MEASUREMENT METHODS

Dependent Variables	Measurement Method
Hazard Recognition Rate (HRR)	Number of recognized hazards→ via keyboard input (where 17 of 17 is the highest)
Reaction Times for Hazard Recognition (RTHR)	Time span between the occurrence of a hazard and the controller`s reporting →via keyboard input
Situational Awareness (SA)	Self-assessment via SART → via post-interview (where -14 is the lowest, +46 is the highest)
Workload (WL)	Self-assessment via ISA → via post-interview (where 1 is the lowest value, 5 is the highest)
Camera Usage Intensity (CUI)	Number of camera changes and camera motions →via keyboard input

Unlike all other dependent variables and their corresponding metrics, “Situational Awareness” and “Workload” were not measured by objective methods but by subjective self-assessment using SART and ISA, respectively.

D. *Groups of Subjects*

To compare each of the two LiDAR configurations with “Default apron CWP” by means of a CITL simulation study, a total of 18 subjects was divided into two groups (see Table 5). Each group consisted of eight novices (university students with a theoretical ATM background, aged 20 to 25) and one apron controller from Dresden airport (in their early thirties).

Subjects of group 1 had to pass through the experiment once without any LiDAR support (configuration 1) and once with a supporting LiDAR GUI at the “Real Time” performance level (configuration 2). Also the subjects of the second group had to pass through the experiments once without any LiDAR support (configuration 1), and then once with a supporting LiDAR GUI at “Case Study” level (configuration 3). The order of control and experimental conditions was systematically varied within each group to compensate for potential training effects (“counterbalanced order”).

TABLE 5: GROUPS OF SUBJECTS

	Control Condition	Experimental Condition
group 1	Configuration 1	Configuration 2
group 2	Configuration 1	Configuration 3

E. *Experimental Tasks*

In the scope of this CITL simulation study the subjects had to perform the principal surveillance and control tasks of the Dresden apron control unit. Key priority was to ensure safe traffic movements by creating safety distances and to avoid conflicts between aircraft and ground vehicles, pedestrians, turnaround equipment and FOD. In detail, the subjects’ tasks consisted in:

- Issuing taxi clearances for inbound and outbound aircraft and for some ground vehicles on the apron.
- Issuing pushback clearances for aircraft parked nose in at the terminal building.
- Recognition and reporting of emerging or already present hazardous situations on the apron.

Via the playback of ATC communication standard phrases the simulated traffic automatically made acoustic requests when passing specific route points. To issue a requested clearance the subjects had to press a dedicated clearance button on a keyboard. An issued clearance would then be acoustically read back by the respective aircraft resulting in further movements. If a subject would recognize a (emerging) hazard, he had to press a certain key immediately stopping the scenario. If the controller did not recognize any hazard the scenario would continue until the hazards’ consequences finally occurred. In order to ensure a uniform performance level of the subjects, each subject had to complete a theoretical and practical training before the commencement of the actual experiment.

F. *Scenarios*

As it is more likely that potential benefits of a LiDAR support will be even clearer if controllers’ traffic load is rather high the maximum traffic capacity of Dresden airport was used for the scenario design (one aircraft movement every two minutes). The simulation traffic comprised the following aircraft types:

A320, Lufthansa	(call sign: LH12)
B737, Germanwings	(call sign: GW56)
Fokker 50, Air Canada	(call sign: AC34)
A340, Virgin Atlantic	(call sign: VI89)
Piper PA-18/Pa-30	(call sign: DEAB)

Furthermore, as a distinct advantage of LiDAR sensing over the OTWV and the camera apparently lies in its independence from lighting conditions and its reduced sensitivity against adverse weather conditions, the following environmental conditions were integrated into the experimental design (see Table 6):

TABLE 6: ENVIRONMENTAL CONDITIONS USED IN THE SIMULATION STUDY

Designator	Environmental Characteristics
CAVOK	day, ground visibility ≥ 10km, cloudless
CAT IIIa	day, ground visibility ≤ 210m, mist, overcast
CAT IIIa & night	night, ground visibility ≤ 210m, mist, overcast

The hazard scenarios had to contain cause and hazard indicators to allow for the principal recognition of (emerging) hazards by the subjects. These indicators would emerge in a time span of approximately 3 to 5 minutes after the scenario had started. From this reason the complete list of hazards and their causes (see section II) was used to construct the scenarios. Finally, the following four thematic groups of hazard were represented in the 17 hazard scenarios.

- Hazards that relate to aircraft movements.
- Hazards that relate to movements of ground vehicle and turnaround equipment.
- Hazards that relate to the presence of FOD.
- Hazards that relate to the presence of pedestrians.

Altogether, the subjects had to handle 21 scenarios comprising of 17 hazard scenarios and four standard scenarios that did not contain any hazard at all. The purpose of integrating these standard scenarios was to reduce the subjects' expectations to be only confronted with hazardous situations in every scenario.

IV. EXPERIMENTAL SETUP

A. *Apron Controller Working Position*

The experimental apron CWP was set up at TU Dresden. Three projection screens were used to artificially reproduce the OTWV from the apron tower at Dresden airport. A graphic tablet (size 27") stood centered in front of the subjects and was used for visualizing the LiDAR GUI. The LiDAR GUI was surrounded by two computer monitors (size 22") that showed switchable video camera views (see Figure 2).

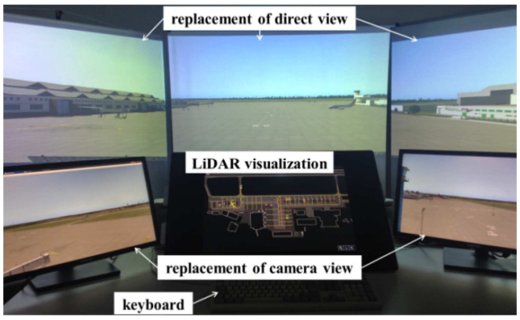

Figure 2. Experimental CWP at TU Dresden

A computer keyboard served as interface between the subjects and the simulation environment. The keyboard was equipped with six clearance buttons where five of them addressed the simulated aircraft and with one button corresponding to a ground vehicle. Buttons on the NumPad were used to switch between different cameras and to pan/tilt the individual camera devices. A recognized hazard would be reported by pressing the space bar (see Figure 3).

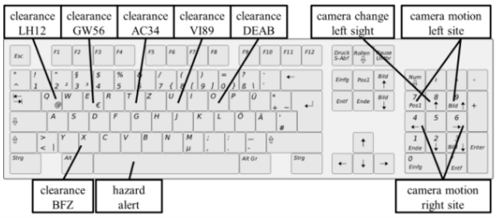

Figure 3. Keyboard layout of experimental CWP

B. *Implementation of the LiDAR GUI*

The prototypical LiDAR GUI developed in the concept phase (see subsection II.B) was used for the experimental CWP. In accordance to this concept, those objects that were already detected but not yet classified were depicted as a red bounding box, whereas classified objects were represented by the icons shown in Table 7:

TABLE 7: LIDAR GUI ICONS REPRESENTING ALL TARGET OBJECTS

AC	GV	EQ	PED	FOD
✈	⬜	▭	🟥	🟠

By using the zoom function of the LiDAR GUI, subjects could select between three different magnification levels. Figure 4 exemplarily shows the LiDAR GUI with pre-set magnification level 2, fully covering the apron area of Dresden airport.

Figure 4. LiDAR GUI at the experimental CWP

V. ANAYLSIS OF EXPERIMENTAL RESULTS

A. *Evaluation Methodology*

For the visualization and interpretation of experimental data on "Reaction Times for Hazard Recognition", "Situational Awareness" and "Camera Usage Intensity" box-and-whisker-plot diagrams are used. For the measurement data regarding the "Hazard Recognition Rate" and "Workload" the databases are too small to do so. In this work, the box-and-whisker-plot diagrams are defined as follows:

- The generated box is limited by upper and lower quartiles ($Q_{0.25}$ and $Q_{0.75}$) covering 50% of all measured data.
- The median is represented by a black bar in the box.
- Upper and lower whiskers surround the box and represent both the maximum and minimum value of the measured data.

B. *Quantative findings*

Table 8 shows the results for the primary dependent variables (on an arithmetical average of all subjects) which are assumed to represent the potential risk mitigation effect best:

TABLE 8: RESULTS FOR THE PRIMARY DEPENDENT VARIABLES

	Default Apron CWP (config. 1)	**LiDAR Apron CWP with "Real Time" (config. 2)**	**LiDAR Apron CWP with "Case Study" (config. 3)**
Number of recognized hazards (max. 17)	$\mu = 13{,}9$ $\sigma = 1{,}65$	$\mu = 16{,}8$ $\sigma = 0{,}42$	$\mu = 14{,}9$ $\sigma = 1{,}85$
Hazard Recognition Rate (HRR) [%]	81%	99%	88%
Reaction Times for Hazard Recognition (RTHR) [s]	$\mu = 34s$ $\sigma = 10s$	$\mu = 19s$ $\sigma = 10s$	$\mu = 38s$ $\sigma = 11s$

As the subjects had to handle a total of 17 hazard scenarios, a maximum of 17 (developing) hazardous situations was to be reported in each configuration. According to Table 8, the subjects assigned to configuration 2 were able to recognize nearly all hazardous situations (mean value μ=16.8 out of 17) and required the lowest reaction times[8] to do so (μ=19s). In a direct comparison with configuration 1 the “Hazard Recognition Rate” (HRR) for configuration 2 significantly increased by 18%. The potential benefits of LiDAR are less clear in configuration 3: Although more hazards were recognized in comparison to configuration 1 (a plus of 7%), the reaction times of the subjects to report these hazards did also increase (see Figure 5). Apparently the defined high delays of the LiDAR performance level “Case Study” for detection and classification lead to a delayed but still timely hazard recognition. Based on this the hypothesis H1 (see subsection III.A) was verified for both LiDAR-configurations 1 and 2.

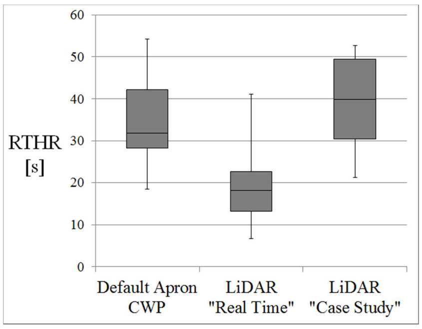

Figure 5. Reaction Times for Hazard Recognition, RTHR (Box-and-whisker-plot)

In an additional analysis, the variables of Table 8 were assessed separately with regard to four main hazard groups (see subsection III.F). The results revealed the particular capability of the LiDAR system to recognize hazards associated with the presence of FOD. As such, the HRR improved by 33% for configuration 2 and by 24% for configuration 3 compared to configuration 1.

The results for the self-assessed “Situational Awareness” (arithmetical average of all subjects, see Table 9/Figure 6) emphasize the positive contribution of a LiDAR support on the subjects’ picture. Again, configuration 3 shows a rather marginal improvement compared to configuration 1. The fact that moving objects could yet not be detected/classified at all might be a possible cause for this discrepancy between the respective outcome for configuration 3 and 1.

TABLE 9: SITUATIONAL AWARENESS
(SART SCALE:-14 IS LOWEST, +46 IS HIGHEST)

	Default Apron CWP (config. 1)	**LiDAR Apron CWP with “Real Time” (config. 2)**	**LiDAR Apron CWP with “Case Study” (config. 3)**
SA	μ = 32 σ = 5	μ = 36 σ = 5	μ = 33 σ = 6

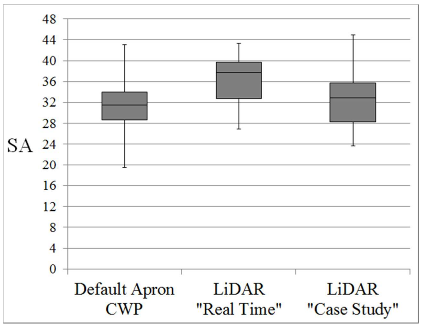

Figure 6. Results for Situational Awareness (Box-and-Whisker-plot)

The same effect can be observed for the data regarding “Workload”, which were collected through a subjective self-assessment (see Table 10):

TABLE 10: WORKLOAD (ISA SCALE: 1 IS HIGHEST, 5 IS LOWEST)

	Default Apron CWP (config. 1)	**LiDAR Apron CWP with “Real Time” (config. 2)**	**LiDAR Apron CWP with “Case Study” (config. 3)**
WL	μ = 3,6 σ = 0,5	μ = 4,1 σ = 0,4	μ = 3,7 σ = 0,6

Summarizing, the use of both LiDAR-configurations 1 and 2 slightly increases the SA and decreases WL. Hypotheses H2 and H3 have thus been confirmed.

Furthermore, the intensity of the “Camera Usage” significantly decreased for configuration 2 compared to configuration 1 (see Table 11/Figure 7). As such, the subjects of configuration 2 invoked 75% less camera changes and motions compared to configuration 1 whereas configuration 3 resulted in a smaller reduction of 24%. For configuration 2 it can be assumed that the subjects were able to acquire most of the demanded information from the OTWV and the LiDAR GUI to such an extent that video camera sources became less important for them. However, the one-sided use of the LiDAR GUI may also be seen as critical, for instance when considering that not all of the hazard and cause indicators can be (reliably) captured through LiDAR sensing (e.g. smoke).

TABLE 11: CAMERA USAGE INTENSITY

	Default Apron CWP (config. 1)	**LiDAR Apron CWP with “Real Time” (config. 2)**	**LiDAR Apron CWP with “Case Study” (config. 3)**
Number of camera changes and motions	μ = 148 σ = 47	μ = 34 σ =35	μ = 105 σ = 46

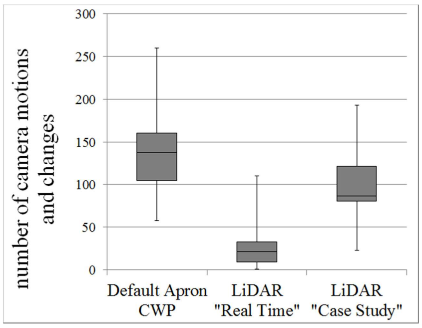

Figure 7. Camera Usage Intensity (Box-and-whisker-plot)

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[8] Only those reaction times for hazard recognition were considered that had been recognized by a subject for both the control and experimental condition.

The evaluation of all three configurations under different environmental conditions (see subsection III.F) did not reveal any major differences in terms of HRR, RTHR, WL and CUI, which was not expected by the authors but could be attributed to simulation-related limitations and simplifications. Only the difference in SA between configuration 1 and the configurations 2/3 was, in relative terms, higher under adverse weather/lighting conditions (Δ20% and Δ3.3%, respectively) than under optimal conditions (no differences). For this reason, hypothesis 4 is rejected, at least for the current experimental setup.

Finally, we observe that configuration 2 was superior to configuration 3 in all analyzed metrics. Since the difference between both configurations is based on the assumed performance levels (see subsection III.B), hypothesis 5 is confirmed.

C. Methodological Aspect

In view of the measurement data, the significant variances around the mean values are a major concern for all metrics. The problem here is that some differences between the mean values of one configuration to another configuration are in parts smaller than the individual standard deviations from that mean value (e.g. situational awareness, see Table 9). Nevertheless, the application of a method to find outliers beyond three standard deviations (3σ) from the mean value provided no satisfactory results.

The causes for this "measurement noise" are likely to be found in the experimental design. An exemplary issue in terms of the internal validity of the study is the use of novices as test persons who were confronted with demanding surveillance and control tasks in a multi-tasking environment. From this reason it seems plausible that the novices might have needed more training to achieve a homogenized performance level, even though this is not in line with the results from the questionnaire: Here the novices stated that they felt well-prepared for the tasks. In conclusion, a possible future solution can consist in the exclusive use of professional controllers or to significantly increase the amount of training before conducting the actual experiments.

Finally it should be noted that the subjects did only recognize hazards on the basis of detected hazard indicators which is a finding from the post-interviews conducted with every subject. Probably related to the experimental design the mere presence of a cause indicator did not result in any hazard report. Therefore, this study successfully proved the risk mitigation effect of LiDAR sensing for the "hazard control" strategy whereas no effect in terms of "hazard avoidance" could be demonstrated.

VI. CONCLUSION & OUTLOOK

This work reported on an experimental assessment of a LiDAR point cloud surveillance concept aimed at mitigating the substantial risks of today`s apron operations. This concept was the result of the authors' previously performed risk assessment on apron safety where Dresden airport served as a reference example. Within this scope, a CITL study was designed and carried out to verify/falsify hypotheses on the potential contribution of a LiDAR GUI to the apron controller`s picture and thus ultimately to apron safety. The subjects' capabilities to recognize emerging or present hazardous situations and the reaction times required to do so were considered as primary metrics to compare between a common apron CWP (control condition) and two CWP configurations additionally equipped with a LiDAR GUI at different performance levels (experimental conditions). To complement this, also situational awareness, workload and usage intensity of the camera were recorded to support the interpretation of the observed effects. For the actual experiment 18 subjects were divided into two groups and allocated to the control and experimental configurations. Their task consisted in the safe management of ground traffic for a total of 21 scenarios comprising of 17 hazard scenarios and four standard scenarios.

The analysis of the experimental data largely verified the hypotheses. It has been shown that the combination of a state-of-the-art LIDAR sensor and powerful raw data processing methods increases the probability to recognize (emerging) hazardous situations on an airport apron. Besides this, also situational awareness and workload benefit from the availability of such a system. The intensity of the risk mitigation effect, however, is primarily determined by the performance level of the LiDAR system. In this experimental study configuration 2, which was assigned the performance level "Real Time" and which represented a future most advanced LiDAR system, was superior to configuration 3 (performance level "Case Study") in all analyzed metrics.

Even though there were a lot of efforts to ensure a high degree of internal and external validity, the overall results of the study are only generalizable to a limited extent. In particular, the sensor model was strongly simplified and will be replaced in the future by a model that takes laser physics and the geometric pulse propagation into account. In addition, the generalizability of the results to other airports, e.g. to Frankfurt airport, has yet to be proven.

In late 2016 we will evaluate the LiDAR point cloud surveillance concept at Dresden airport also in practical terms. Here we will simulate and then record selected hazardous situations with the LiDAR sensor installed at the terminal overlooking the apron. The simultaneous processing of the raw data by means of our detection and classification methods will generate a picture on the LiDAR GUI, which will be finally assessed by professional apron controllers on its potential benefits for apron surveillance.

ACKNOWLEDGMENT

Our thanks go to Dresden airport for their extraordinary willingness to support our research throughout the whole project duration. We also thank Neptec Technologies for their support.

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