

Validation of an innovative experimental safety assessment for virtual control tower HMI designs

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Abstract—Current aerodrome control procedures rely essentially on the availability and quality of the controller’s out of window view. The safe perception of visual cues focusing on aircraft motion, vehicles and weather conditions is mandatory to afford at least the current level of safety and capacity at the aerodrome. The substitution of the out of window view by display systems is the subject of research in various research projects as e.g. Advanced Remote Tower (ART) by Saab AB and the Swedish ANSP LFV, Remote Airport Traffic Control Center (RAiCe) by German Aerospace Center and Virtual Control Tower Research Studies (ViCToR) by Deutsche Flugsicherung GmbH. The chosen design of the virtual control tower console (VCT) consisting of a set of well selected display systems seems to be a valid candidate to deliver an equivalent level of safety compared to conventional operations. Assuming optimal sensor surveillance availability, the consoles design impacts safety in operation significantly by inadequate perceptibility of surveillance data that results in a corrupted or incomplete virtual representation of the real situation. Our console design was experimentally derived through an experimental correlation analysis between common consoles layouts and their probability to generate severe consequence occurrences according to ESARR 2. The implemented experimental VCT console environment is scalable, allows to be validated individually by using of proposed safety metrics and related hazard event indicators. Those homogenously cover the area of responsibility of the tower controller. The validation methodology also comprises triggering of the safety metrics by providing typical threat events such as runway incursions or blocked runways at the airport which shall be handled through professionals as a real time experiment.

Keywords- air traffic control, aerodrome control, safety assessment, visual information evaluation, fault tree analysis, human-in-the-loop validation, distributed interactive simulation.

I. INTRODUCTION AND STATE-OF-THE-ART

The tower controller monitors the traffic situation, confirms or reorganizes sequences of departing and landing aircraft and controls vehicle movements on the airport’s maneuvering area according to ICAO PANS ATM Doc 4444 [1]. The need for visual information is multifaceted and consists of both local positions, heading and velocity of ground vehicles and aircrafts and a large amount of system specific information such as e.g. weather information, surface conditions and wild life observations. The authentic and immediate availability as well as the diversity of visual information turns the

out of window view today into a mandatory requirement for the control work. A comprehensive overview about control tower operations and tasks is given at [22].

The idea to substitute the common out of window view by means of display systems in a virtual control tower (VCT) was already and still is subject of various projects such as the Advanced Remote Tower (ART, figure 1) [2], Remote Airport Traffic Control Center (RAiCe) [5][6] and Virtual Control Tower Research Studies (ViCToR) [8] and [9]. A short overview of systems substituting the out of window view is summarized in table 1.

TABLE I. OUT-OF-WINDOW-VIEW SUBSTITUTE SYSTEMS

Project	Systems that substitute the out of window view
ART [2]	Video-Panorama Projection (360°), Radarscreen, Pan-Tilt zoom, weather and status monitor [3]
RAiCe [7]	Video-Panorama Screen (180°), Radarscreen, Augmented Tower Vision, Pan-Tilt zoom

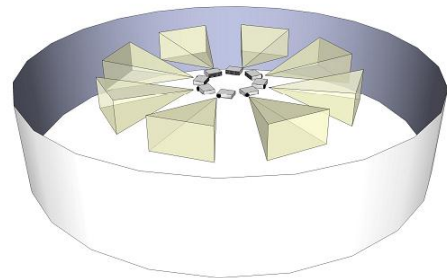


Figure 1. Advanced Remote Tower environment, with a camera array of the 360 degree panorama display [3].

As often happens, the selected console design concepts have yet not been finally validated by means of a reliable safety assessment that include the visual cues. All ideas circling around virtual towers claim for advantages in increased flexibility and efficiency in human resource allocation, safety aspects are seen as a secondary, downstream problem. Especially at airports with limited traffic demand, to remotely perform aerodrome control services and further to centralize control services of various aerodromes seems to be attractive. From the overall system development problem, the separated

development of functional and safety requirements could be fatal in several ways: efficiency, development time and safety assurance [21]. Dino Piccione, FAA human factors technical lead, explained

“We have to consider the window as a surveillance mechanism, which may not be so simple to replace with hanging a bunch of video cameras and having the controller check television screens.” [10].

The use of synthetic display systems may bear risks that consist of limited availability, reliability, continuity and integrity, all metrics of safety critical system certification processes that include a mandatory safety assessment according to Commission Regulation (EC) N° 1315/2007 [11] and N° 2096/2005 [12] that demands the compliance with the Target Level of Safety (TLS) defined by ESARR4 [19]. The minimum goal of any VCT console design is consequently at least to maintain the current level of safety in aerodrome control operations, which in turn is not yet measurable objectively and in a standardized way. Our research will provide first ideas to initiate an efficient and safe system development.

The first major issue concerns about the ability to cover the diversity of visual information cues by a sensor driven surveillance environment and a quantitative display processing. A set of visual cues for aerodrome control procedures has been determined in [13] and these are assumed by the tower controller as mandatory to assure safe control services. Concerning the safety relevance of visual information cues, hazards are commonly identified by means of experts statements in the scope of workshops with tower controllers [14][15]. The safety relevance of cues has been demonstrated by determining the degree of severity that results when visual cues are not present on the console displays when demanded. A more technical view has been chosen in the safety assessment of the ART project [4].

The second important issue concerns about the qualitative aspect of presenting available information with respect to the human perception (physical capabilities and constraints) and the corresponding situational awareness. It is assumed that the console design and layout can significantly contribute to the probability of severe consequences. In this case design and layout issues have to be part of the risk mitigation in the scope of the Preliminary System Safety Assessment [17].

As an initial approach and to cover common display systems, the following display systems have been chosen for our experimental VCT:

- Video display system covering the airport maneuvering area extending to parts of the apron.
- Ground surveillance movement radar system (SMR) presenting a synthetic picture of the ground traffic at a quality comparable to today secondary surveillance radar (SSR) display systems such as PHOENIX.

- Secondary surveillance radar system presenting a synthetic picture of the air traffic within the control zone (CTR) also equivalent to today radar displays.

The video display system therein offers the capability to reproduce the out of window view best in the panoramic view as used in [2] and [5]. This traditional approach meets the controller requirements and habits, so the VCT environment can be integrated best into the existing operational procedures.

Alternatively, the possibility of distributing the video cameras at any location on the airport movement field could offer the potential to increase the probability of detecting objects of operational and safety interests. Our proposed configuration is presented in figure 2 and points out the capability to reduce the required time for detecting ground movements (e.g. aircrafts, ground vehicles) and key events with a higher accuracy.

The chosen example is defined by an exocentric runway crossing view that promises the advantage of a close distance to the lineup and vacating points (points of interests) compared to the panoramic view. Additionally, the visual angle is smaller (raised zoom), that induces a larger projection of objects on the displaying monitor. Thus the number of observation points as well as their visual direction was selected as significant parameters of the VCT console design.

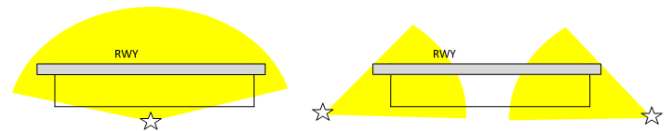


Figure 2. Two possible video display configurations of the point of view (left: egocentric/ panoramic, right: exocentric/ runway crossing).

The most common approach to assess the proposed console design of the VCT is to use expert's statements that estimate the contribution of specific design parameters to the current level of safety. The affection of expert's statements by limits of the abstract imagination e.g. how future work might be with new system functions and new display systems. Further, the characteristic subjectivity often results in inconsistent statements among the experts and consequently imprecise conclusions about VTC design solution. For this reason, we propose an experimental approach from the safety assessment point of view that promises the ability to estimate safety contribution and affection by system function more objectively. Finally, we expect to gain reliable statements of future system users (test persons) that are more specific for the assessment of safety of VTC.

The aim of this research is to verify our contribution of required design parameters against the probability of occurrences of severe events. In reference to sensitivity analysis methodologies, we use a reliable approach to back trace the varying frequencies of the occurrences of severe events to contributing design parameters as e.g. position and direction of points of view. It further effects information redundancy offered by ground surveillance units and varying

points of view in the video system. Thus, the results of our research will contribute reliable indications for efficient and safe VTC designs regarding to a significant visual information perception.

II. METHODOLOGY

Our methodological approach is based on the Safety Assessment Methodology (SAM) provided by Eurocontrol [16] to reflect the best practices for safety assessment of air navigation systems. The SAM development in the context of the EATMP (European Air Traffic Management Programme) provides an aviation standard procedure to reflect the high potential of damage for both the aircraft and uninvolved third parties. An obligation on the providers of Air Traffic Management services to ensure the safety of air traffic is demanded at the ICAO Annex 11 [24]. The “burden of proof” for the ATC is to satisfactorily demonstrate safe procedures and systems by obtaining an acceptable level of safety [25]. In prior research projects we gain sustainable experiences on safety assessment and we proposed a model-based approach to improve the standard assessment methods to ensure, that safety relevant results will significantly enhance the system development process [21]. The SAM defines three steps to assess air navigation systems (ANS) to assure safe operations. A short summary introduces the main objectives

1) Functional Hazard Assessment (FHA):

The first step outputs safety objective for identified hazards respecting system definitions, functional requirements and the target level of safety during system definition phase.

2) Preliminary Systems Safety Assessment (PSSA):

The second step outputs safety requirements enhanced by the application of risk mitigation to the system architecture respecting the safety objectives during the design phase.

3) System Safety Assessment (SSA):

The finally step validates the compliance of implemented functions to safety objectives and the assurance of the target level of safety when operating during implementation phase and start up.

A. Development of the safety model

The severity class scheme of ESARR 2 [18] determines indicators for events which possess the potential of injured persons and damaged aircraft. This scheme introduces severity classes for incidents/accidents. The following table 2 provides a short overview of the severity classification scheme and the some corresponding examples linked to the VTC safety assessment. We assume that the occurrence of hazards and its severe consequences can be fully or partly caused by specific design attributes (design parameters) which are capable to contribute to the probability of the occurrence of severe consequences

TABLE II. SEVERITY CLASSIFICATION SCHEME [18]

Severity Class	Description	Target level of safety (TLS) per operating hour [20]	Example
A	Accident	1.55E-8	Physical contact between objects (e.g. a/c, ground vehicle)
B	Serious Incident	1.0E-5	Runway incursion, violation of separation minima by more than a half.
C	Major Incident	1.0E-4	Violation of separation minima by less than a half.
D	Significant Incident	1.0E-2	Increased workload

Our approach is to investigate in how much an independent design parameter will influence the output of the experiment by means of changing the frequency of the occurrence of severe consequences. The additional benefit of the safety assessment is generated by the systematic identification of parameters that significantly contribute to the resulting risk. Thus, the list of available parameters will be reliably reduced to relevant parameters. For validation purposes of our approach the parameters listed in the following table 3 were selected as varying input of the causal model shown in figure 3.

TABLE III. DEFINITION OF INPUT DESIGN PARAMETERS

Parameter	Description
#1	Point of view of the video system (figure 2) 1. Panoramic view 2. Distributed exocentric view (crossing view)
#2	Number of active display systems 1. With ground surveillance 2. Without ground surveillance

In reference to fault tree and event tree models, figure 3 shows the assumption of causal relationships between design parameters and potential consequences according to events defined in table 2.

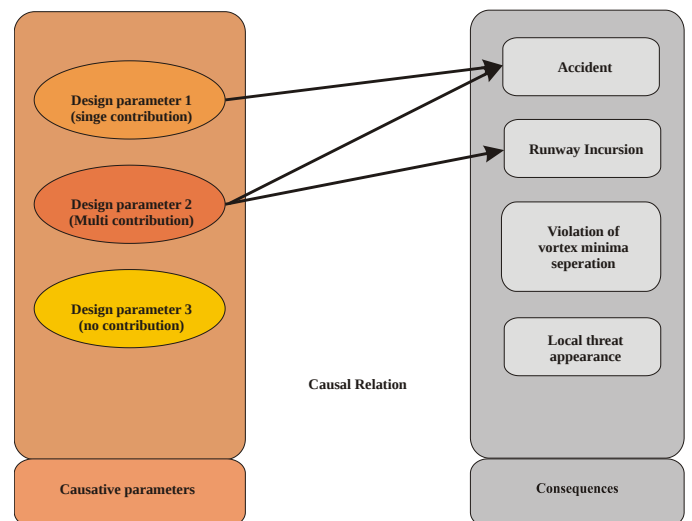


Figure 3. Assumed causal relation between design parameter and safety relevant consequences according to the severity scheme table 2.

III. EXPERIMENTAL DESIGN

A. Experimental tasks

The experimental environment is designed for an interactive mode in which the person shall perform the primary task consisting of giving lineup and take-off clearances to:

- departing traffic respecting the inbound traffic and ground vehicles and
- friction test ground vehicles considering the presence of inbound and/or outbound traffic.

Other clearances such as start-up, pushback, taxi, landing and entry clearance are automated and are not taken into account for the working environment. Instead of the standard radio telecommunication (R/T), the test person has to use digital communication (keyboard).

The secondary task consists of monitoring the behavior of aircrafts and ground vehicles as well as the occurrence of local threats (e.g. appearance of wild live on the air field)

For indicating the performance of the secondary task, the following key events of table 4 are designed and shall be detected by the test person. In case of non-detection, the key event induces the occurrence of a hazard that is related to severe consequences (table 2) according to the proposed hazard identification [15].

TABLE IV. KEY EVENTS

Key event #	description	Severity class in the case of non-perception [15]
1.	animal appearance	A
2.	unauthorized entry of the runway by a ground vehicle (ground vehicle overrun)	B
3.	unauthorized entry of the runway by an aircraft (aircraft incursion)	B
4.	Go-around	C

The test person is instructed to use the display systems and to perform its tasks by stroking the corresponding key at the keyboard with respect to the primary and secondary task. This pressed key immediately generates a feed back to the traffic situation by giving the corresponding clearances. The resulting human-in-the-loop principle is illustrated in figure 4, where the detection of key events (brown) is directly indicated by the test persons keystrokes, the occurrences of the consequences (blue) results of the inadequate clearances in the primary task only and is automatically triggered.

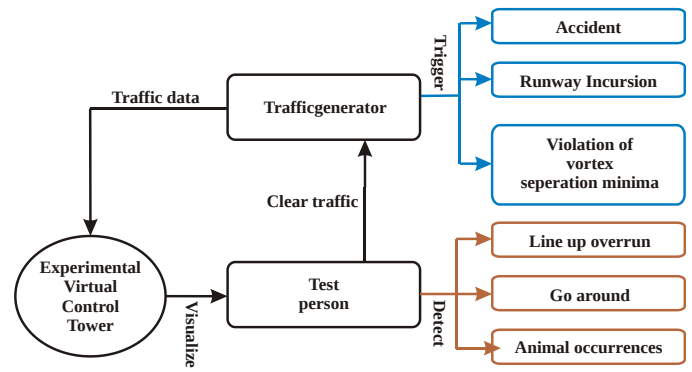


Figure 4. The diagram illustrates the concept of the experimental environment.

All movements and clearances are periodically recorded for detailed investigations of the VTC efficiency. Additionally, the elapsed time from key event occurrence till the moment of keyboard indication (controller's reaction) is gathered as well.

B. The scenario

All scenarios take place at Dortmund Wickede Airport (ICAO code: EDLW) with a single runway layout (directions 06/24). The inbound and outbound movements consists of a mixed traffic characteristics with

- 50% - light traffic with a maximum ground speed (GS) of 90kn.
- 50% - medium traffic with a maximum GS within the control zone (CTR) of 250kn.

Further, the operational scenario is characterized by the following attributes (table 5).

TABLE V. TRAFFIC MOVEMENT QUANTITIES

attribute	quantity	embedded key event
Traffic outbound (overrun)	13 (3)	3
Traffic inbound (go-around)	12 (4)	4
Friction test vehicles (overrun)	4 (2)	2
Animal occurrences	4	1
Scenario endurance	34 minutes	

The inbound traffic is sequenced into blocks with 3-4 movements paused with up to 3 minutes of no inbound traffic in between. Figure 5 shows the trajectories of inbound and outbound traffic.

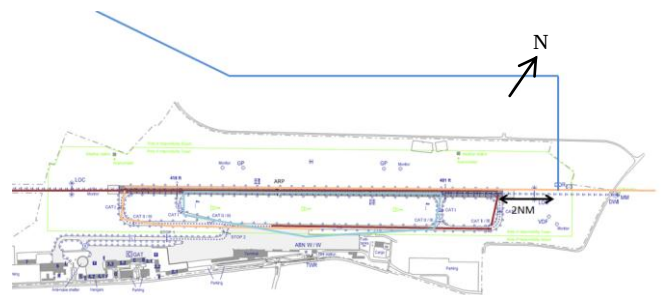


Figure 5. Trajectories of inbound (blue/light orange) and outbound traffic (red).

C. Experimental design configurations

Based on the design parameter schemes as presented in table 3, the following configurations (table 4) were selected for the experimental application. Configuration A represents a baseline scenario with the most common case of having the conventional panoramic view. The configurations B and C are the corresponding variations of the proposed design parameters. A potential configuration D that unifies the variation of both design parameters is not defined, but will be taken into account at further investigations. The contribution of each design parameter shall be identified by relative comparison with the baseline configuration A.

TABLE VI. EXPERIMENTAL DESIGN CONFIGURATIONS

Configuration	design parameter 1	design parameter 2
A	Panoramic view	With ground surveillance
B	Panoramic view	Without ground surveillance
C	Crossing view	With ground surveillance

D. Control groups

Thirteen test persons with an age of 22-25 years (non-professionals) take part at the VTC validation trials. Concerning the monitoring and detection of visual information, it is assumed that the experimental environment downgrades the habitual workflow of professionals which ensures a comparable performance of the test persons. The test persons are familiar with aerodrome control procedure in theory and are instructed in the functions of the experimental environment. For training purposes, every test person trained his capability during a “warm-up” scenario, lasting for 1 hour. The secondary task (key event observation) was hidden and consequently not trained beforehand.

IV. IMPLEMENTATION OF THE EXPERIMENTAL CWP

The implementation was done at the Chair of Air Transport Technologies and Logistics of the Technische Universität Dresden. The test bed consists of four 22” monitors with each one having a resolution of 1680 by 1050 pixel. The monitors are located side to side and focused on the operator (figure 6).



Figure 6. The experimental display set up.

The display systems and its software system architecture works with four software modules:

- traffic generator: produces the corresponding traffic data according to a predefined flight plan, distributes the data to peripheral visualization modules and listens to keystrokes of the operator (figure 7).

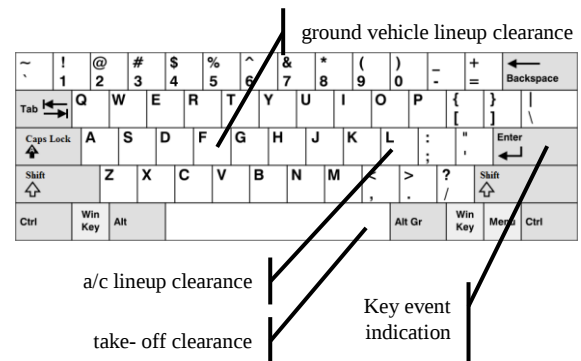


Figure 7. Keyboard configuration to formulate ATC clearances and event indication.

- ground surveillance radar monitor: (figure 8, shows the airport layout of Dortmund airport (DTM))
- air surveillance radar monitor: Figure 9, shows the corresponding runway of DTM (yellow) and the dashed centerline. The blips represent aircraft positions labeled by call sign, altitude and speed.

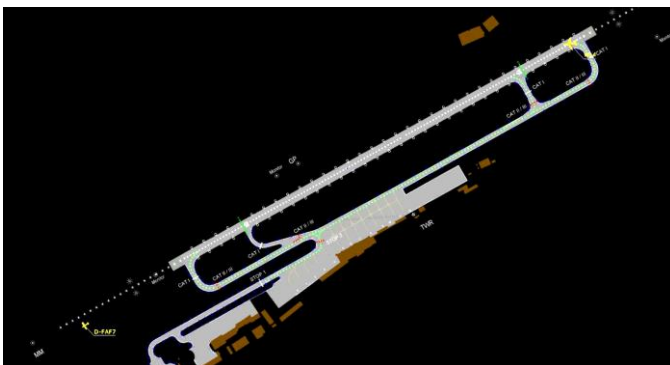


Figure 8. The ground surveillance radar monitor.

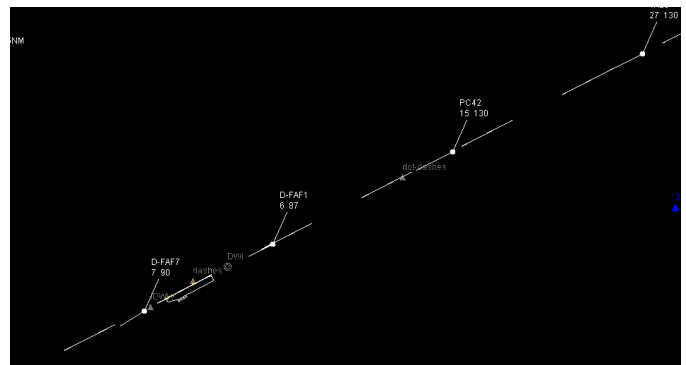


Figure 9. The air surveillance radar monitor.

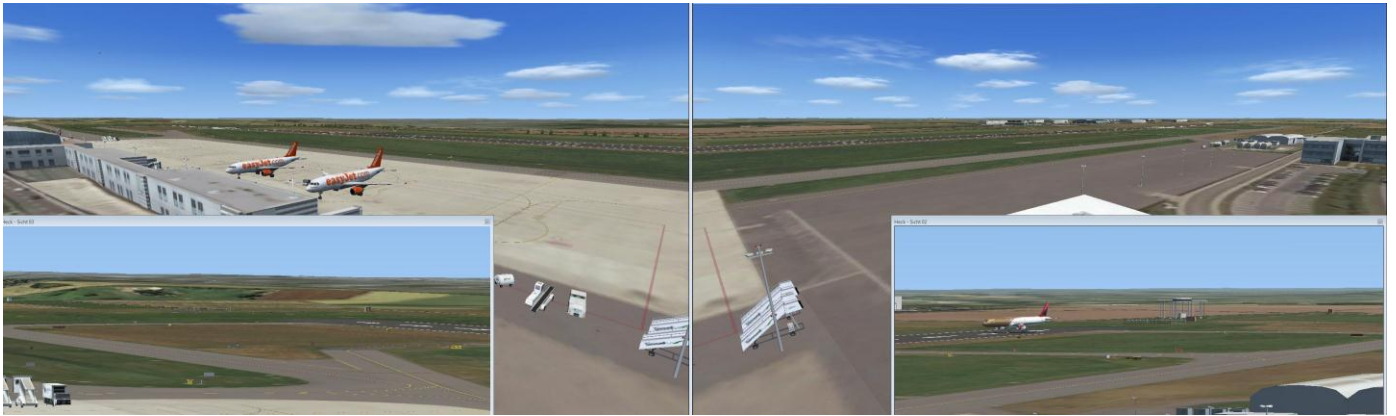


Figure 10. Panoramic video view (design configuration A and B).

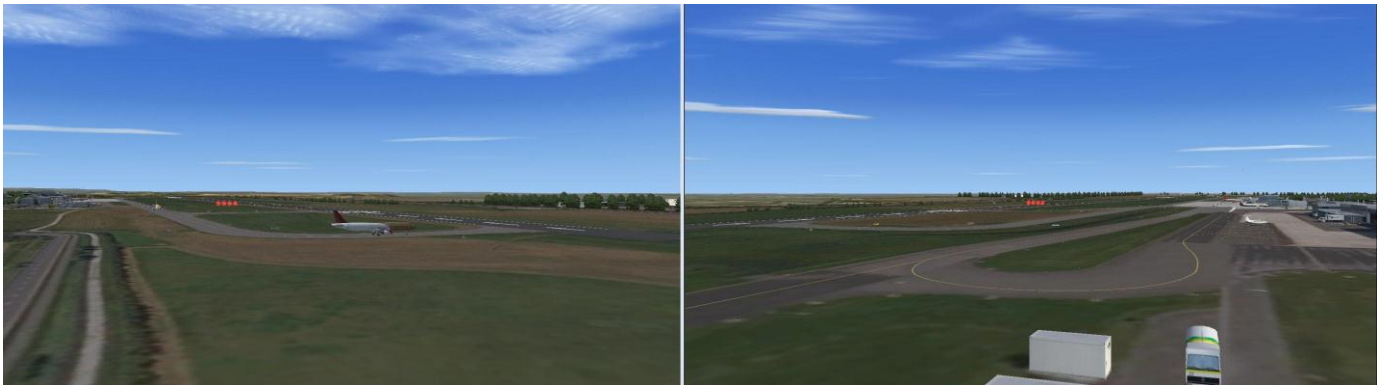


Figure 11. Runway crossing video view (design configuration C).

- visualization of the airport environment: similar to a video camera was achieved by using Microsoft Flight Simulator X SP2 (FSX). The video display is divided into 2 monitors (figure 10 and figure 11) that cover most of the movement area of DTM Airport¹.

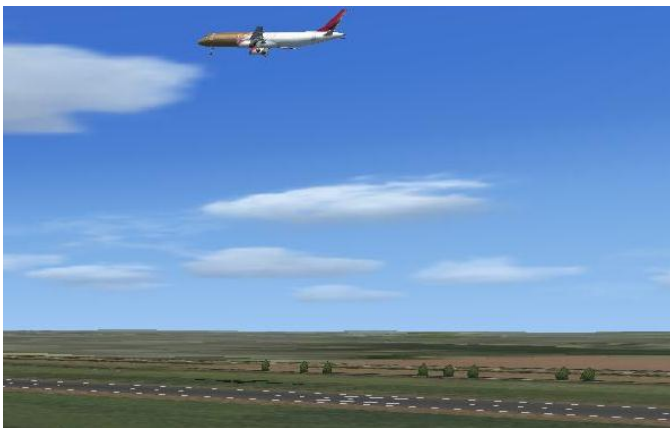


Figure 12. Go-around of an inbound a/c.

The appearance of key events that represents threats to the operating traffic is realized by means of a traffic generator logic excepting the animal occurrences. The traffic generator therefore executes the flightplan to sequence the aircraft or ground vehicle on an alternative route and holding points. Figure 12 shows the go-around of an aircraft. The appearance of animals takes place on the movement area with a predefined route (giraffe on figure 13).



Figure 13. Animal appearance on taxi

¹ For augmenting the scenery (buildings, movement area, airport environment), the scenery expansion pack “German Airports 2” of Aerosoft has been installed.

V. RESULTS

The experiments were performed with 13 test persons, each lasting 2 hours including a warm up for primary task training.

A. Qualitative findings

To derive the qualitative findings we used the common box-plot metric, defined by the following characteristics:

- the generated box covers 50% of all measurements ($Q_{0.25}$ and $Q_{0.75}$ quantile),
- the box is surrounded by an upper and lower whisker, which state the boundaries for a coverage of 80% ($Q_{0.1}$ and $Q_{0.9}$ quantile),
- outline values (above the $Q_{0.9}$ and below $Q_{0.1}$) represent 20% percent of the measured values, and
- the expected value is highlighted inside the box with a black bar surrounded by white separators.

In the presented research we actually focus only on the characteristics of the expected value, observations resulting from the specific characteristics of the variance will be a major part of our ongoing investigations of the VTC environment [15].

According to the post interrogation, the test persons had no problems to use the keyboard functions. The interrogation also delivered many qualitative statements about the acceptance and usability of the design configurations. The judgment of test persons about advantages and causes of hazards and consequences are summarized as followed:

In his primary task to give lineup and take-off clearances the test person cleared 13 outbound aircrafts and 2 ground vehicles. The following bar figure 14 shows the average frequency of violation occurrence that can be backtracked to the decision of the test person in the scope of the primary task. Accidents were not detected and occurred not once, thus it is excluded from further discussions.

The design configuration B without ground surveillance is identified as the most contributing to the consequence occurrence of severity B and C (cf. table 2). The test persons stated that the missing ground surveillance in design configuration B caused:

- a downgraded accuracy of the perceptibility of the a/c position particularly when aircrafts are vacated,
- a downgrading of the situational awareness concerning the traffic situation (position of aircrafts and ground vehicles), and
- a downgrading of the precise velocity estimation.

Design configuration C also shows a higher contribution to the frequency of runway incursion and to the violation of wake vortex separation minima. The test persons stated that the crossing view causes

- a confusing situational picture of the air field situation which increases the time to percept and deduct the traffic situation mentally.

Further the secondary task was to detect key events that shall indicate the ability to monitor the entire environment of the moving area and air space. The diagram figure 15 points out the different detection frequencies of events.

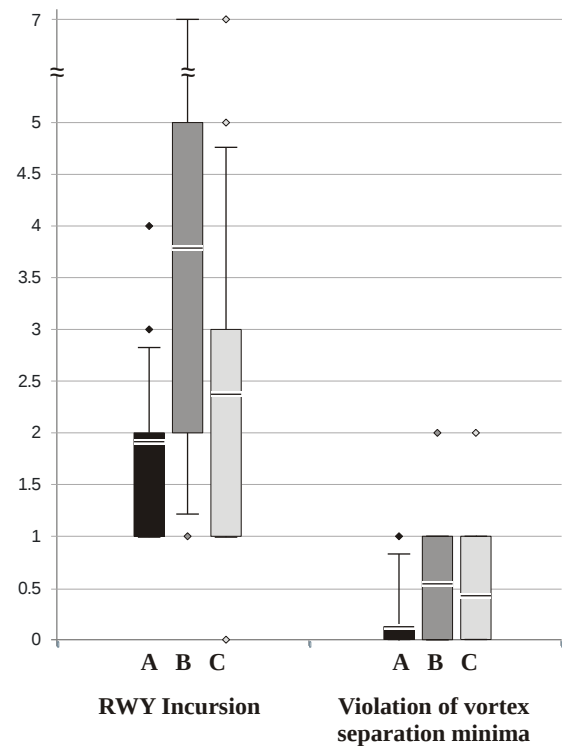


Figure 14. Average violations of the primary task by the operator.

The detection rate of overrun events is generally reduced when turning off the ground surveillance system. The reduced detection frequency of the crossing view for overrunning aircrafts was first surprising, as the crossing view should have its advantage in the low distance to the lineup holding point. The test persons then stated malfunctions in the behavior of aircraft that are intended to overrun the stop bar just before the event occurs. This malfunction is observable from the panoramic view and not from the crossing view. The result is consequently not valuable for assessing the crossing view for aircraft observation purposes.

Turning off the ground surveillance system (B) contributes more to the probability of detecting go-around and animal occurrences compared to A. The test persons stated that the missing ground surveillance has been adjusted by monitoring the video display more intensively. The crossing view contributed little to the detection probability of go-around events compared to the effect when turning off the ground surveillance.

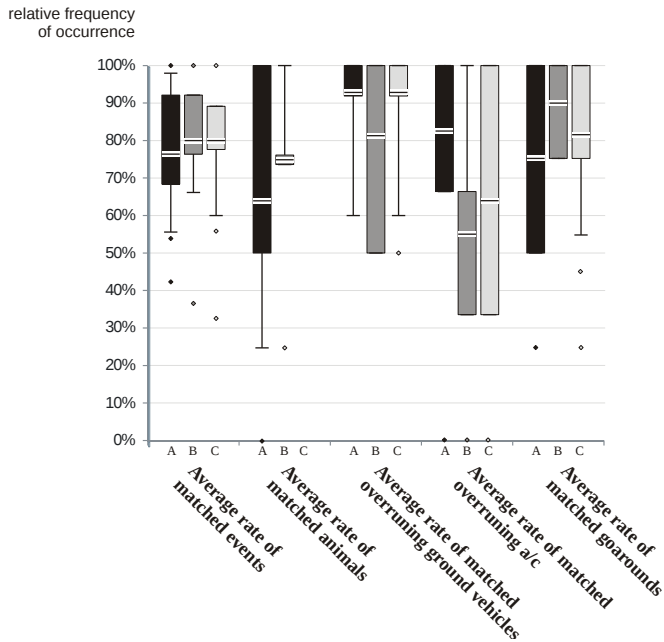


Figure 15. Average rates of matched events

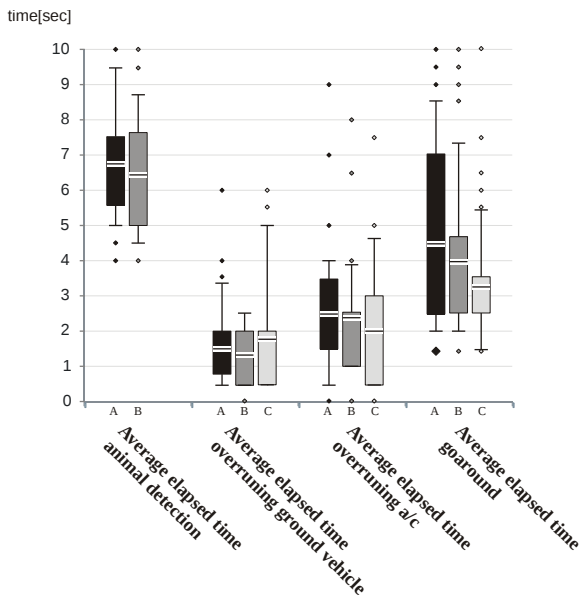


Figure 16. Elapsed time for key event detection

In case of having successfully detected the key events, a detection time was calculated. The average time values are summarized in figure 16.

The most obvious is the design configuration B inducing a lower detection time compared to A in any case. The difference of overrunning events is insignificant but points out a trend. The greatest acceleration effect is observable in the detection of animals and go-around events. The effect is similar to the detection rates, which result of the head down time caused by the availability of the ground surveillance (cf. [23]).

The design configuration C is characterized by an enormous acceleration effect in detecting go-around events compared to A in spite of the ground surveillance being active. The overrunning a/c event is affected by the observable malfunction right before the event occurred. The test persons stated a more clear observability of go-arounds due to the pointed angle to the runway direction 24 that causes a low time of localization on the video display. Thus the beginning climb of the inbound aircraft is recognized faster. The increased detection time of overrunning ground vehicles compared to A and B has been assessed as the result of object shading. The visibility in crossing view mode on ground vehicles was obstructed by aircrafts. The panoramic view had a clearer overview on the movement area.

VI. CONCLUSION

A methodology for assessing HMI design configurations was developed and tested for validation purposes. The causal relation of design adjustments (design parameters) to the probability of consequence occurrences could be demonstrated by comparing resulting frequencies of severe consequence occurrences when varying design parameters systematically. The results show heterogenic sensitivities of design parameter with the following aspects.

- The availability of the ground surveillance contributes to the mitigation of risk, concerning the perceptibility of the traffic situation.
- The availability of the ground surveillance contributes to the risk, concerning the perceptibility of local threats as wild live observations.
- The usage of the exocentric runway crossing view has low acceptance by the test persons.

The selection of design parameters for defining the applied design configurations A, B and C was quite simple and the objective to validate the methodology. A possible alternative choice of e.g. the variation of a different spatial adjustment of the monitors might induce bigger variations in the output frequencies.

Additionally, an identification of hazard causes is possible by a post interrogation of the test persons. The identified causes are characterized by the association to a specific operational situation and thus the identification results more specific.

This approach identifies parameters in the design that can contribute to risk by determining a sensitivity of output values when varying design configurations. Enhancing the methodology to determine a probability of consequence occurrence that satisfies absolute claims due might be difficult. It is assumed that an event selection that partly covers realistic and daily operational events limits the validity of frequencies in an absolute context.

An advantage is the versatility of different kinds of input parameters that might include

- Varying aerodrome control procedures
- Operator training
- Clouding of consciousness

This methodology can contribute to perform the PSSA [17] and potentially improve the ability to mitigate risk by identifying parameters that have the biggest effect on the frequency of severe consequences. By the help of this identification, safety requirement can be derived that have a verified effect on mitigating risk. This contributes to achieve a valid system that is compliant to the TLS of ESARR 4 [19] and EUROCAE [20].

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