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# SKY-Scanner: time-critical decision support system surveilling aircraft landing and take-off

Kristina Lapin
Faculty of Mathematics and Informatics
Vilnius University
Vilnius, Lithuania
kristina.lapin@mif.vu.lt

***Abstract*—The paper describes an experimental work conducted within the FP6 SKY-Scanner project. The project is aimed at developing a new lidar (laser radar, LIght Detection And Ranging) equipment. One work package is devoted to decision support model design and development. The decision support adopts the capabilities of lidar and facilitates the tasks of the air traffic controller in aerodrome traffic zone. The SKY-Scanner can contribute to (1) aircraft surveillance improvement within aerodrome traffic zone and (2) the visual estimation of the current situation by the controller without mental calculations of altitude and distance. The proposed method is illustrated with an application to Napoli Capodichino airport in Italy.**

***Keywords – 3D; 2D; visualization; displays, controllers' needs; situational awareness; air traffic control; naturalistic decision–making approac; cognitive workload***

## I. Introduction

The SKY-Scanner system is a novel laser technology that aims at detecting and tracking aircraft up to at least 6 nautical miles from the aerodrome traffic zone (ATZ) barycentre [1], [2]. The proposed technology is a new generation air traffic management (ATM) paradigm based on primary radar and lidar tracking data fusion. It enables the controller to track the flight from the beginning till the end. One component of the SKY-Scanner system is a decision support system (DSS) that estimates possible risks for aircraft and proposes corrective actions to the human decision maker – the controller.

Radar and lidar data flows are fused, and then the aircraft position is calculated. The position is analyzed according to airport landing and take-off procedures. In case more than one aircraft are tracked the vertical and horizontal separations are checked as well. DSS output provides the fused aircraft position and the estimated violation risks. The current situation is visualized on the desktop as well (Fig. 1).

Current air traffic control (ATC) systems based on primary radars hardly distinguish aircraft targets and background clutter at a low altitude. In most cases in ATZ, radars cannot determine the height to the needed accuracy. The lidar is more precise when directed to the target. An approximate position received from the radar can help direct the lidar. When the target is found, the lidar switches to the tracking mode and provides the exact target position for the SKY-Scanner system. This position is used to determine the potential risks and recommend appropriate actions.

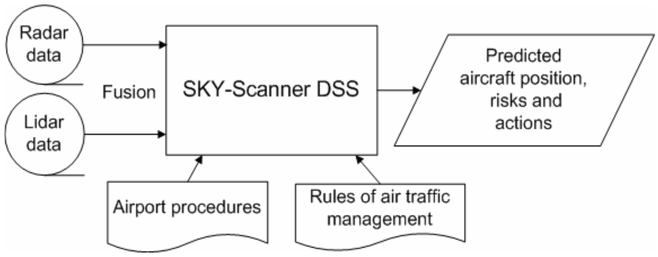


Figure 1. The scope of SKY-Scanner

According to NASA technology readiness framework [3], the developed prototype corresponds to Level 3 stage of the 9-level Technology Readiness Level (TRL) scale. TRL-3 means that active research and development (R&D) is initiated. These studies and experiments should constitute the "proof-of-concept" validation of the applications/concepts formulated at TRL-2. The SKY-Scanner DSS adopts the ideas from 3D-in-2D Planar Displays for ATC project [4].

Major causes of the ATM-related accidents in 1980-2001 were low visibility and incorrect or inadequate instruction/advice given by ATC [5]. A frequent event factor in landing accidents was non-adherence to procedures by flight crew. The SKY-scanner system aims at facilitating the controller to track the aircraft trajectory.

The four future air traffic scenarios defined by SESAR predict the growth of air traffic in various scopes [6]. Constantly rising air traffic requires more information to display on the controller's screen. Current systems present the recent situation in 2D plan view. Here an aircraft horizontal position is shown. The third dimension (altitude) and speed are presented with an aircraft label. In order to follow the actual situation and to indicate possible future troubles, the controller performs mental calculations of the altitude and speed.

Dealing with growing information amounts the ways to reduce controller's cognitive workload are studied [7]. We propose to visualize the altitude dimension. This reduces a cognitive workload as the controller will monitor rather than interpret alphanumerical characters and hold them in his mind.

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The controller needs constant decision support as ATZ situation is constantly changing. According to the SKY-Scanner requirements, the DSS has to perform risk prediction each second. Therefore time critical decision support models are needed. Such models are used mostly in military domains.

The contribution of this paper lies in the interactive, real-time demonstration of several concepts that we have not seen previously demonstrated in the ATC environment and in the lessons learned about these ideas. Our goal is to elaborate a new visualization concept for the ATC domain.

Running user studies on incremental improvements from traditional 2-D ATC displays is out of scope of our research. We adopt promising ideas from the projects which performed user studies. The primary goal of the SKY-Scanner project is the construction of new lidar equipment. The resulting ATM paradigm serves to illustrate lidar's potential. Advanced user studies are set aside for future.

The present paper is organized as follows. In the second section we examine time critical decision support models and reason the choice for the SKY-Scanner DSS. The third section describes visualization alternatives. The fourth section presents the SKY-Scanner ATM paradigm. Then, conclusions are drawn.

## II. Decision support in time critical systems

Decision making is the process of selecting a choice or course of action from a set of alternatives. The human cognitive processes underlie the most decision making models. In this section we analyze human cognitive processes and time critical decision-making models in order to define the paradigm of the SKY-Scanner DSS.

### *A. Human cognitive processes*

Attention and working memory are involved in human decision-making. Attention is how the brain, consciously or automatically, selects information for cognitive processing. Human memory has the capacity to encode, store, and retrieve information. Working memory is closely involved in executive control tasks, the conscious ability to switch between tasks, contexts, and intentions [8].

Human decision making processes are facilitated using a variety of reasoning techniques. One such technique is analogical reasoning where novel solutions are inferred via analogy to known solutions and methods. Analogical reasoning includes the following serial procedures [9]:

1. Encoding: translating stimuli to internal (mental) representations.
2. Inference: determining the relationship between problems.
3. Mapping: determining correspondences between new and old items.
4. Application: execution of the decision process.
5. Response: indicating the outcome of the reasoning process.

Since the steps in this reasoning process proceed in a serial manner, temporal ordering and timing of decision support is critical to improving time-critical decision-making. Regardless of the stimuli, the encoding step is the largest single component of the reasoning process, taking about 45% of the overall reasoning time [10]. For example, the encoding of words takes longer than the encoding of schematic pictures, implying that reducing text in displays will facilitate faster decision-making. Thus, in general, time critical decision making displays should concentrate on facilitating quicker encoding, possibly by more intuitive visualization.

### *B. DSS models for time critical systems*

Time critical decision making models are studied mainly in military context. Most models describe the human process of decision making as serial staged processes that include steps centered on information gathering, likelihood estimation, deliberation, and decision selection [10].

There are two philosophical approaches toward decision-making: the rational (or logical, or analytical) approach vs. the naturalistic (or action-based, or recognition-primed) approach.

The rational decision-making model assumes that a clear set of alternative choices can be generated and their likely outcomes predicted with a significant degree of confidence. It relies on (1) experience or past results to generate the predicted outcomes, and (2) on belief that the information on which the decision is based upon is reliable. This model presumes to be objective, by establishing criteria, weighting them, and then choosing the best "score" or highest utility.

The action-based or naturalistic model based upon imposing an interpretation of an ambiguous situation [11], [12]. This model assumes that knowledge results from actions, from observing consequences. There is an inherent assumption that after a point, too much information can be detrimental. The naturalistic model assumes it is not feasible to fully quantify the situation and find a solution mathematically. A human decision maker makes a decision based on observed subject actions.

Summarizing, the rational model is objective but requires calculating the utility of each alternative, whereas the naturalistic model highlights the need to provide the human with relevant information. Avoiding unnecessary details facilitates stimuli encoding process.

### *C. Decision support for ATM*

Any decision-making model cannot be applied for each situation. Many models share common aspects and attributes but differ in the order, area of emphasis or underlying assumptions. A significant aspect is limited or ample time to consider and analyze the situation before making decision [10]. Following are the criteria for the landing and takeoff:

- time for decision making,

- decision optimization level,
- the level of efforts that should be performed analyzing decision outcomes,
- how experience is involved in decision making.

Simple decisions are taken during landing or takeoff, for example, turn left or right. There is no place for trial and errors. Optimization level is important as corrections are not possible.

Landing procedures are based on strict rules; therefore previous experience is not involved in decision-making. Thus, situational awareness must be presented from the perspective of airport procedures: whether rules are met or violated. This can be done by presenting the aircraft actual position with respect to the visualized landing/take-off procedure. Terrain peculiarities adjust the formal procedures to the natural airport context (Fig. 2).

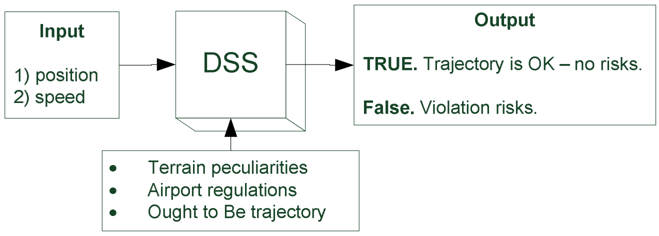


Figure 2. SKY-Scanner decision support

The analysis of the human cognitive processes and time critical decision-making models revealed the key features for the developed DSS. First, from the human cognitive perspective, quick encoding is a key factor that facilitates human decision-making. This is achieved by providing an intuitive visualization. Since pictures are encoded faster than symbols, a requirement is to present information graphically. Second, naturalistic decision-making models in the context of tracking trajectories require presenting the formal procedures intuitively.

From the modeling perspective, the landing and takeoff procedures define the relation between aircraft track, distance from the runway threshold and altitude. Thus, the proper visualization of this relation is needed.

## III. Related Work on DSS Visualization

Considering an increasing amount of information made available, a traditional 2D radar representation becomes overloaded [13]. A 2D radar display combines graphical and symbolic information. The geographical aircraft position is shown on 2D plan while the altitude and speed is presented by symbols. The novel 3D visualizations enable presenting the altitude as the third dimension and reducing the amount of symbolic information. There is no need to present speed. Landing and takeoff procedures define only maximal speed for certain phases. This value could be monitored internally in the DSS. The appropriate warning is provided when the value exceeds the allowed range.

A 3D view requires significantly less cognitive effort to interpret altitude information. It supports more informed decision-making on the vertical dimension. However, pure 3D visualizations make distance estimation inconvenient due to perspective distortion effects. The direction of camera restricts the view to a certain sector [14]. It is easy to clutter 3D view with unimportant details aiming to render as realistic picture as a view through the controller's window. 3D interfaces should be minimalistic and abstract despite the temptation to provide the beautiful realistic landscapes.

According to the SKY-Scanner requirements DSS output has to be implemented on traditional 2D displays. Therefore, augmented reality and other beyond the desktop techniques are not considered.

3D visualizations in aeronautics and geographical domains address the following sources:

- Space-time cub representations where two planar dimensions represent geographical space and the third vertical spatial dimension is time [14]
- Strict 3D visualization of air traffic concepts developed for free flight in Hughes Research Laboratories [15]
- Visualizations proposed in the project named "3D-in-2D Planar Displays for ATC" [7].

### A. *Space-time cube visualizations*

Space-time cube (STC) is a structure that is used to depict the target activities in a space-time context. STC adopts a 3-dimensional orthogonal viewpoint [16], [17]. The horizontal axes are used to record the position and location changes of objects. The vertical axis is used to provide an ordered and synchronized sequence of events. In its basic appearance these images consist of a cube with geography on its base (along the x- and y-axis), while the cube's height represents time (z-axis) [18].

A typical STC contains the space time-paths of an object moving in time (Fig. 3). According to this technique, points in three-dimensional space, where the vertical dimension corresponds to time, represent the positions of an object at different time moments. Lines connect the points corresponding to consecutive moments.

The cube' contents can be created automatically from the database. Interactiveness enables viewing from any direction [18]. STC facilitates event visualization and analysis and supports a task of searching for spatio-temporal patterns [16].

This visualization is suited for the analysis of large data sources. According to this technique, airport plan is on the bottom of the cube, aircraft horizontal positions are shown by points in three-dimensional space with the vertical dimension corresponding to time. Besides trajectories, STC display helps the user to explore the speed: sloping segments indicate fast movement, while steep segments correspond to slow motion.

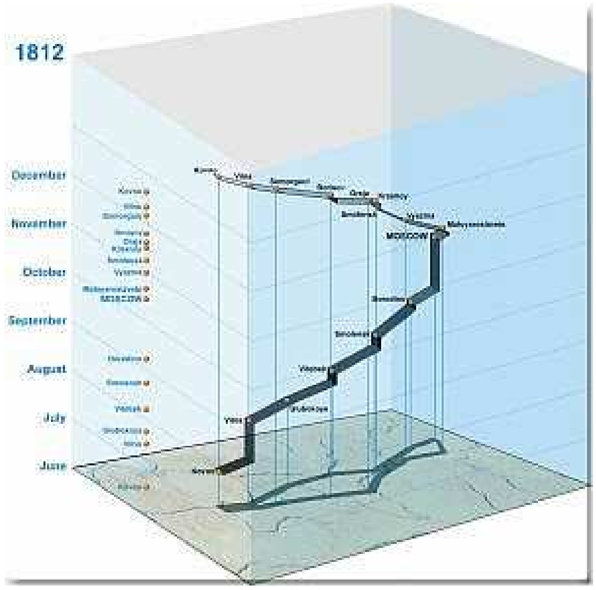


Figure 3. The space-time cube representation of the Napoleon's Russian campaign in1812 [18]

STC is a proper choice representing the relationship between the horizontal position, time and speed. However, SKY-Scanner needs to visualize the track, distance and altitude. Thus, STC does not meet the requirements.

### B. *Pure 3D visualization of aircraft trajectories*

A strict 3D was used to detect conflicts in the terminal area of Boston Logan Airport [19]; see Fig. 4. Airspace mode represented a set of linked wireframe rings in space. They draw a tunnel in the sky that aircraft appears to fly towards. This is useful in conflict detection by showing whether the airspace of two aircraft will intersect in the future, indicating a potential conflict.

In the landing/takeoff visualization, such a tunnel presents a formal procedure. It helps to detect where aircraft adheres to the assigned procedure.

To reduce controller's overload, this solution requires filtering. Each zone requires a different mode of visualization. Pure 3D has certain disadvantages. Just to mention a few, there is no possibility to oversee the global traffic out of the camera view; then a difficulty to locate traffic at the far end of the scene [20].

This method can be adapted to visualize the relationship between horizontal position, distance and altitude. The tunnel can represent a formal procedure. The violation is detected when the aircraft is located outside the rings.

### C. *Combined 3D and 2D visualizations*

Combined visualizations are based on the idea that pure 2D visualizations are no longer sufficient whereas pure 3D visualizations have significant drawbacks. The combination gives a chance to exploit their positive aspects, for example, to see both contextual and altitude information at the same time. 3D visualizations suit better for integrated attention tasks, such as instructing an aircraft to descend and turn to intercept the localizer. 2D suits better for focused attention tasks, such as estimating the exact aircraft altitude in a moment [7].

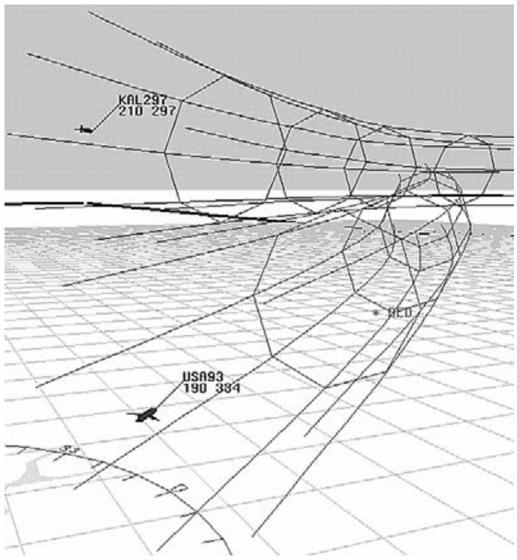


Figure 4. Visualization of highways in the sky [19]

A 3D display supports the development of an accurate mental model of traffic and terrain, effective decision making for aircraft maneuvering on the vertical plane and at glance assessment of consistency of implemented maneuver with the original one as intended by controller [7].

The following strategies are proposed in the 2D and 3D integration method [4]:

- select a portion of the main 2D view and represent it in 3D;
- show 2D projections (walls) in the 3D display with the projections of the aircraft.

The first strategy enhances a part of the main 2D view by representing it in 3D. Though Fig. 5 depicts a visualization of the enroute phase, it can be also adapted for landing and takeoff.

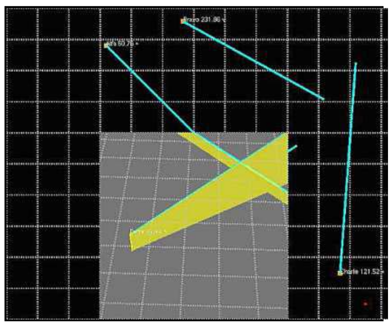

Figure 5. Picture within a picture [20]

The airport procedure and the aircraft's actual horizontal position are shown in 2D while an altitude dimension is shown in 3D. This method preserves continuity of the trajectory. It is easier to identify which aircraft is which within the 3D picture.

The second strategy can be implemented in various phases. In the enroute phase, the task of the human operator is to ensure appropriate horizontal and vertical separations. Wall View for Stack Management window proposes a vertically oriented gradation called the "altitude ruler" (Fig. 6).

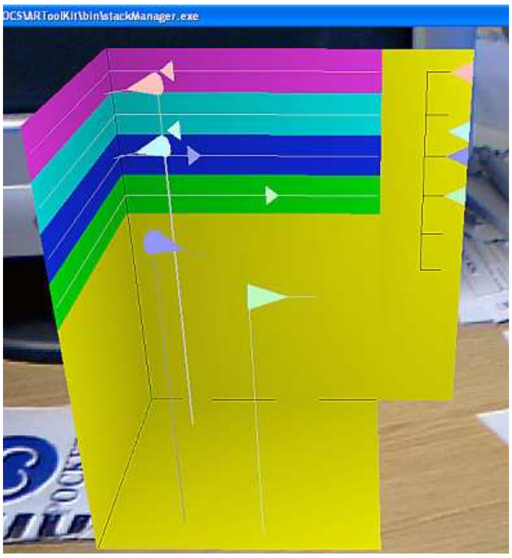

Figure 6. The Wall View for Stack Management[7].

The projections of aircraft horizontal position and altitude are depicted on 2D walls. Thus, exact information is provided. The altitude rulers visualize formal separation rules. This provides the user with precise data needed to immediate assess the traffic situation or guide aircraft accurately [7].

The Wall View of Approach Control (Fig. 7) enables the controller to check whether an aircraft adheres the assigned climb/descent procedures. The view shows unambiguously whether the procedure is strictly followed.

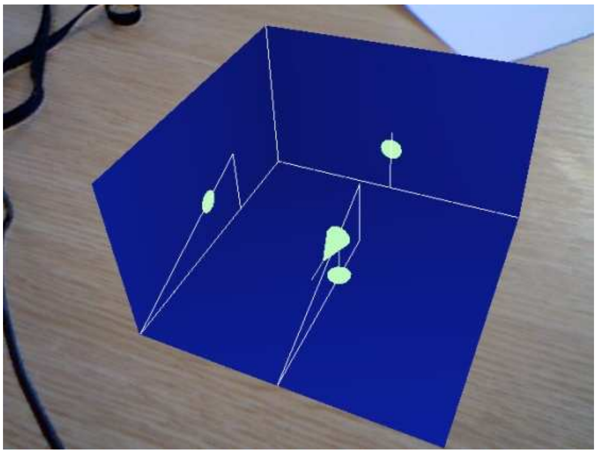

Figure 7. Wall View of Approach Control [7]

The latter method requires having the precise aircraft position that cannot be achieved with the sole radar equipment. Current surveillance technologies cannot implement those visualizations because of inaccuracy of radar devices. The SKY-Scanner system calculates exact position. Therefore this visualization can be implemented.

The proposed approaches offer two combination types: 3D within 2D and vice versa. Though the first strategy is universal and presents the needed data, the latter (2D in 3D) is more intuitive. Hence, this method better meets SKY-Scanner requirements.

## IV. VISUALIZATION MODEL IN SKY-SCANNER

The DSS visualization subsystem enables controllers to perceive and interact with the following information:

1. aircraft positions
2. the ought to be trajectories
3. detected risks.

Minimizing clutter and distractions is vital to controllers. Hence, on the one hand, it is important to show all the required information. On the other hand, this should be done with minimal means in order to avoid the clutter.

### *A. The SKY-Scanner Method*

The SKY-Scanner DSS prototype combines walls with stack control and approach control. Approach charts present a trajectory constraints in a profile view (Fig. 8).

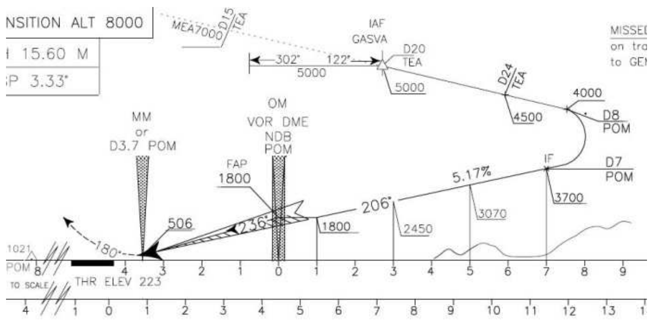


Figure 8. Example profile view of an approach chart [21]

Aeronautics professionals are accustomed to reading approach charts. Therefore, we choose this approach in SKY-Scanner. In the approach charts, flight constraints are presented with alphanumeric texts; in the Wall View with Approach Control (Fig. 7) – graphically. The latter view facilitates stimuli encoding. However, nontransparent Wall View with Approach Control covers a significant area of the screen and hides the context. Contrary, in SKY-Scanner, semitransparent curtains preserve visibility of the whole space (Fig. 11).

Airport zone is divided into two vertical spaces (Fig. 9). The space below a determined altitude (transitional altitude) is allowed for aircraft which obtained landing clearance.

Approach/departure procedures are visualized with regard to this space.

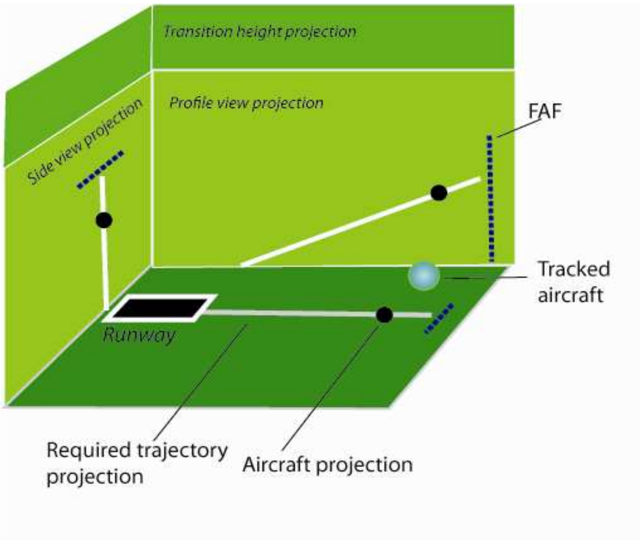


Figure 9. The SKY-Scanner visualization model

The space above a determined altitude is intended for aircraft which approach the airport from outside. In this space, the controller ensures appropriate horizontal and vertical separations. Therefore the altitude rulers are combined with vertical curtains. The number of rulers depends upon waiting loops in an airport. The rulers enable the controller to monitor a holding stack of landing aircraft.

The transition height is represented with a different color – like in the Wall View with Stack Management. Trajectories are represented with projection lines on the curtains. Figure 9 shows three projections and black indicators that represent the exact aircraft's position. Following are other features of this model (Fig. 9):

- FAF is visualized for the procedure; notice dashed lines.
- The profile view projection in 3D is parallel to the runway.
- The trajectory in 3D is not shown but projections only. The reason is that due to the selected viewing angle a representation is imprecise and brings little information.

*B. Terrain visualization*

Human cognitive processes require intuitive visualizations. Therefore, 3D view would benefit from airport procedures representation on the 3D ground surface. However, a realistic map provides too much detail that is not needed managing landing. Instead, a generalized 3D terrain with highlighted orientation features is shown [23].

Important terrain peculiarities are large and high objects in ATZ such as mountains or see line (Fig. 10). The presentation is helpful for orientation; it improves intuitiveness and does not clutter the display.

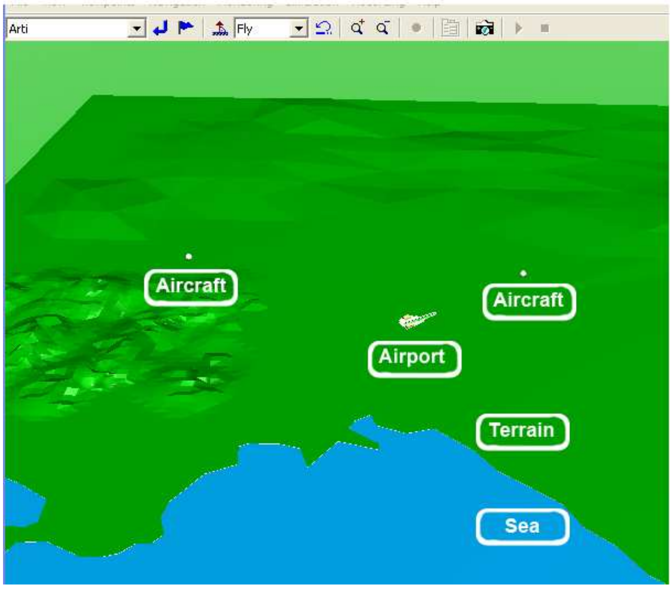


Figure 10. Generalized terrain model. The airport is presented with a white icon in the center. Small white indicators depict two aircraft.

*C. A Decision Support Scenario for SKY-Scanner*

A situation is presented in 3D with a generalized landscape and tracks detected by the SKY-Scanner system (Fig. 10). This screen imitates the situation seen from the tower but without distracting details. Violations are visualized in 3D and explained on the message board (Fig. 11).

The whole zone under observation is divided into two areas:

1. A soft control area; here the collision risk between the detected aircraft is tracked and the altitude is monitored.

2. A strict control area; here a landing procedure is assigned and the constraints (altitude, speed, track) are tracked.

In the soft control area the aircraft altitude is tracked. The longitudinal and vertical distances between aircraft are calculated. The main 3D window presents a context view (Fig. 10).

Two aircraft are depicted in a sample situation in Fig. 10: the first is landing and the second is taking off. If the distance is less than the allowed minimum, a collision risk is fixed and the aircraft icon becomes red. In case the minimal safe distance is calculated from predicted positions, the risk indicator on the DSS control panel becomes yellow and an appropriate message appears on the message board.

The strict control area is defined within 6 nautical miles, between Final Approach Fix (FAF) and Touchdown Point (TP). The assigned procedure is presented on the curtains (Fig. 11). The indicators (black) on the curtains present aircraft's projections. The transition altitude is presented with a different tone on the top of the curtains. The white lines present the projections of the approach procedure. The lines (dashed) present the projections of the main approach milestone, the FAF fly-over point.

Aircraft position validity can be easily detected visually and confirmed with colors. The tracked aircraft is depicted in green if it follows the assigned procedure. The projections on the walls enable tracking until the touchdown point.

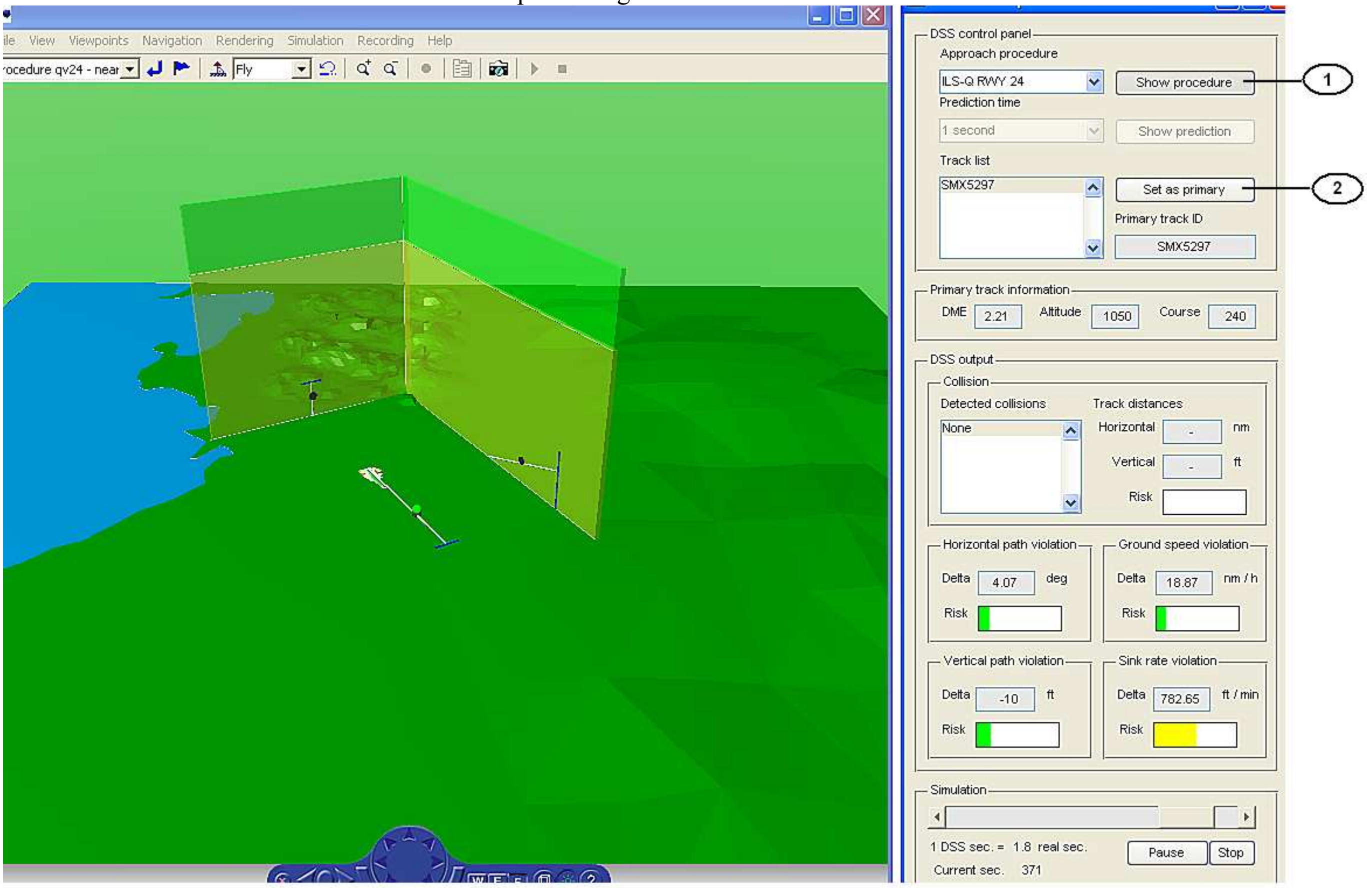


Figure 11. 3D view with control panel and message board. Button 1 turns on the curtains. Button 2 selects an aircraft to track. Violations are visible in the real time. The green indicator depicts the tracked aircraft. Three black indicators show the projections.

The DSS control panel presents the current information about the actual tracks and possible risks. 2D window comprises user interface buttons and the message board.

When an aircraft receives a clearance for landing, the DSS scenario comprises two steps (Fig. 11).

1. Assign a landing procedure: the projections appear on the curtains.
2. Observe the situation: aircraft position should be on the projection lines.

A path violation is immediately detected viewing on the projection walls or color indicators on the message board. Path and separation violation risks are shown with colors. The numerical value is shown above the indicator.

Green means that risk is evaluated zero. Yellow means a risk in the future. Red means that a violation has already occurred; aircraft position is out of the safe funnel.

## V. CONCLUSIONS

The paper reports on the ongoing study of a new ATM paradigm of the SKY-Scanner system. The contribution highlights, first, the paradigm of aircraft surveillance on a low altitude using the developed lidar equipment. Second, it proposes a decision-making scenario based on a naturalistic way of decision-making which is adapted from the military domain. Third, the decision support system expands a current limited control over the aircraft in landing/takeoff phases.

The DSS prototype provides laboratory implementation, which advances TRL 1-2 ideas to Level 3. Human operator needs are satisfied in the following way. 3D display improves situational awareness as the airport environment is depicted with essential terrain obstacles. Projection walls with airport procedures and the aircraft position reduce the cognitive workload. The controller is enabled to observe graphical information instead of interpreting alphanumerical symbols.

The model of the prototype is derived mainly reviewing scientific literature. In the future, user studies are needed to validate the concept and to get experts' feedback.

The prototype is implemented in MATLAB. This symbolic mathematical tool suits for demonstration purposes. However, another programming tool shall be chosen for industrial implementation. The reason is that MATLAB is too slow for real time applications. Consider scalability issues.

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