MODELING PATH VIOLATION IN A DECISION SUPPORT SYSTEM FOR AIRCRAFT APPROACH AND DEPARTURE

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Abstract. The control of approaching and departing aircraft is an important function of the air traffic control. In the EU FP6 SKY-Scanner project, it has been proposed to use the lidar (laser radar, Light Detection And Ranging) for the aircraft surveillance. It will improve the situational awareness of the human decision-makers – the controllers. As part of the project a decision support system (DSS) is being developed. It is based on the radar and lidar data fusion. The DSS estimates possible risks for aircraft and proposes corrective actions to the controllers. This paper presents design decisions and advances in the DSS development. Areas of interest include representing knowledge about normative requirements for aircraft trajectories, calculating risk of path violation and visualization of detected deviations in approach and departure phases of flight. Approach data model is defined in terms of fly-over points. Eight path violation types are discerned. A method to model path violation risk is proposed. It is based on how much the observed trajectory deviates from normative requirements. An interface paradigm based on 2D and 3D view integration is defined. Finally, a two-area decision support model consisting of strict and non-strict constraint checking areas is proposed.

Keywords: knowledge representation, air traffic control, decision support model, information visualization, instrument approach procedures.

1 Introduction

Air traffic control (ATC) is a service provided by the ground-based controllers for the purpose of preventing collisions and maintaining an orderly flow of traffic [13]. One of the ATC functions is the control of approaching and departing aircraft. Surveillance equipment (primary radar, secondary radar, etc.) is used to establish the controllers’ situational awareness of their assigned airspace. In the EU FP6 SKY-Scanner project, it has been proposed to use the lidar for the aircraft surveillance to improve the controllers’ awareness and decision-making capacity. Lidar is installed on ground and, unlike other surveillance systems (secondary surveillance radar or automatic dependent surveillance broadcast), does not require additional equipment to be installed on the aircraft. Lidar is more precise than the primary radar, but it may function worse in certain weather conditions (rain, fog). So, the lidar could be used in conjunction with the primary radar [15].

Figure 1. The functions of the decision support system (DSS)

New air traffic management systems have a long requirements building cycle. Research and development projects generate ideas that are examined and elaborated in subsequent projects. Before the implementation, a solution is verified from various perspectives in different projects. Presented work is performed within the project that aims at developing a novel laser tracking technology – the SKY-Scanner system – capable to detect and track aircraft up to at least 6 nautical miles from aerodrome traffic zone (ATZ) barycenter. The primary target is demonstrating the use of lidar for aircraft detection and tracking. A decision

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support system (DSS) for aircraft approach and departure is part of the SKY-Scanner system. It performs radar and lidar data fusion, estimates possible risks and proposes corrective actions to the controller (Figure 1).

This paper concentrates on the path violation risk estimation issues. The task of the system is to evaluate if the observed aircraft trajectory (the “is” trajectory) is “correct”. The “correct” trajectory (the “ought-to-be” trajectory) is defined in terms of requirements, which are listed in normative documents that regulate flights (e.g., flight rules and terminal procedures).

Currently, the project is in the development phase. The DSS research prototype is being developed incrementally in Matlab/Simulink. Simulations are used to verify if the model is working as expected. Existing flight data is used to fine-tune the algorithms.

In the following sections, we present current issues and design decisions in modeling path violation in the DSS. Based on the study of the approach/departure regulations, the following results have been reached:

1. Conceptual approach/departure model, including flight phase models.
2. Approach/departure constraint data model.
3. Eight path violation types. They are mapped to relevant flight phases.
5. Interface paradigm with requirements for trajectories being represented on 2D projections.
6. Decision support scenario consisting of a soft control area and a strict control area.

2 DSS as a Knowledge-Driven System

We regard the DSS as a knowledge-driven system. The system receives information about an “is” trajectory and uses the knowledge about the “ought-to-be” trajectory to make a decision whether the observed trajectory is “correct” and what actions to take, if it is not. The “ought-to-be” trajectory can be extracted from normative documents.

Treating the DSS as a knowledge-driven system has some advantages:

- The system is more adaptive – only the “knowledge” part of the system has to be changed if some rules change;
- Decisions are more transparent, they are easier to understand and rely on for the domain experts that will be using the system.

There are several knowledge sources, that are taken into account in the decision making process. Besides explicit knowledge, which is found in the documents, tacit knowledge also has to be considered. For example, “the pilot knows that half-a-dot deviation on the horizontal situation indicator is still acceptable”.

Thus the main problem in the development of the DSS is representing the rules that define the “ought-to-be” trajectory (Figure 2). The rules, which are presented in a human-convenient form (e.g., charts) in the normative documents (“rules in law”), should be represented in the DSS data structures (knowledge base) and algorithms (“rules in software”).

Most reports on aviation-related systems [6, 9, 11] show the traditional “problem-solving” approach and do not look deep into knowledge representation.
3 Instrument Approach Procedures

We use instrument flight rules (IFR) as a source for the “ought-to-be” trajectory requirements, as they define constraints, which can be used to evaluate the observed trajectories. The instrument approach procedures are described in this section.

Instrument flight rules are regulations and procedures for flying aircraft by referring only to the aircraft instrument panel for navigation. Even if nothing can be seen outside the cockpit windows, an IFR-rated pilot can fly, while looking only at the instrument panel. Most scheduled airline flights operate under IFR.

Instrument approach procedure is a series of predetermined maneuvers from the initial approach fix to a point from which a landing can be completed [13]. Approaches are classified as either precision or nonprecision, depending on the accuracy and capabilities of the navigational aids used. Precision approaches utilize both lateral (localizer) and vertical (glide path) information. Nonprecision approaches provide lateral course information only.

Instrument approach procedures are depicted in the Instrument Approach Charts. All aerodromes, where instrument approach procedures are established, should issue Instrument Approach Charts [1]. The charts are prepared and designed in accordance with International Civil Aviation Organization (ICAO) requirements and recommendations. These documents graphically depict the specific procedure to be followed by the pilot for a particular type of approach to a given runway. There are different procedures for different navigational aid types – very high frequency omni-directional radio range (VOR), non-directional beacon (NDB), instrument landing system (ILS) and others. The number of controlled parameters is also different. ILS procedures provide most information about the approach. Procedures depict prescribed altitudes and headings to be flown, as well as obstacles, terrain, and potentially conflicting airspace. In addition, they also list missed approach procedures and commonly used radio frequencies (Figure 3).

Figure 3. An example of the approach procedure [7]

An instrument approach may be divided into four approach segments: initial, intermediate, final, and missed approach. Additionally, some routes provide a transition from the en route structure to the IAF [8]:

- Arrival: where the pilot navigates to the Initial Approach Fix (IAF), and where holding (keeping an aircraft within a specified airspace while awaiting further clearance) can take place.
- Initial Approach: the phase of flight after the IAF, where the pilot commences the navigation of the aircraft to the Final Approach Fix (FAF), a position aligned with the runway, from where a safe controlled descent back towards the airport can be initiated.
- Intermediate Approach: an additional phase in more complex approaches that may be required to navigate to the FAF. Intermediate Approach begins at the Intermediate Fix (IF).
• Final Approach: between 4 and 12 nautical miles (NM) of straight flight descending at a set rate (usually an angle of between 2.5 and 6 degrees).
• Missed Approach: an optional phase; should the required visual reference for landing not have been obtained at the end of the final approach, this allows the pilot to climb the aircraft to a safe altitude and navigate to a position to hold for weather improvement or from where another approach can be commenced.

4 Representing Approach Procedures

Approach phases terminate on fly-over points (Figure 4) that have associated constraints. Approach procedures determine the number of the fly-over points.

![Figure 4. Approach procedure in terms of fly-over points](image)

Two types of constraints define the approach procedure:
1. Global: defined for the whole procedure;
2. Local: defined for the particular fly-over point.

Global attributes are the following:
1. Name of the procedure;
2. Glide Path (GP in degrees or GP INOP in %);
3. Reference Datum Height (RDH);
4. Obstacle Clearance Altitude or Height (OCA/H) attribute for each airplane type;
5. Sink Rate (SR, in feet per minute) for a given Ground Speed (GS);
6. Time needed to fly between defined points for a given GS;
7. Runway orientation (in degrees).

Summarizing the fly-over point constraints the approach procedures were concluded to have the following local attributes:
1. Name of Distance Measuring Equipment (DME) device (required);
2. Name of a fly-over point (optional);
3. Lateral distance to DME (required);
4. Lateral distance to Touchdown Point (TP) (required);
5. Altitude (required);
6. Course or track (required).

Table 1 provides an example of local constrains for Napoli/Capodichino airport approach procedures through IAF “Bento” fly-over point.

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaching point type and name if available</th>
<th>ILS-P procedure for Runway 24</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DME INP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DME, nautical miles</td>
<td>Alt, feet</td>
</tr>
<tr>
<td>1.</td>
<td>IAF “Bento”</td>
<td>19</td>
<td>7000</td>
</tr>
<tr>
<td>2.</td>
<td>IF</td>
<td>16</td>
<td>5900</td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td>13</td>
<td>4830</td>
</tr>
<tr>
<td>4.</td>
<td>FAF</td>
<td>10</td>
<td>3770</td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td>7</td>
<td>2730</td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td>4</td>
<td>1646</td>
</tr>
<tr>
<td>8.</td>
<td></td>
<td>3</td>
<td>1293</td>
</tr>
<tr>
<td>9.</td>
<td></td>
<td>2</td>
<td>939</td>
</tr>
<tr>
<td>10.</td>
<td></td>
<td>0.8</td>
<td>504</td>
</tr>
</tbody>
</table>
The table is interpreted the following way: if the aircraft is flying according to the ILS-P procedure, the course should be 236°, and, for example, at the distance of 13 nautical miles to the airport, the aircraft’s altitude should be 4830 feet (see line 3).

5 Modeling the Risk of Path Violation

Based on the approach/departure procedure constraints, eight path violation types are defined and mapped to relevant flight phases:

1. Vertical position violation
   1.1. Altitude violation (Initial Climb, En-Route, Holding, Initial Approach, Final Approach and Missed Approach);
   1.2. Glide path violation (Final Approach);
   1.3. Obstacle clearance violation (Initial Climb);
2. Speed violation
   2.1. Climb gradient violation (Initial Climb and Missed Approach);
   2.2. Indicated airspeed violation (Initial Climb, Holding and Missed Approach);
3. Position violation
   3.1. Course violation (Initial Climb, En-Route, Holding, Initial Approach, Final Approach and Missed Approach);
   3.2. Maneuver area violation (Holding);
   3.3. Circling sector violation (Holding).

A DSS function is to estimate the risk of path violation. This section is devoted to risk modeling. We propose modeling with linear representation. It is based on how much the “is” value deviates from the “ought-to-be” value. Risk can be defined as a function that maps the deviation into the risk level from the interval [0, 1]. Zero means no risk, 1 means the maximum risk. Path violation risk is currently defined for vertical (altitude and glide path) and horizontal (course) violations. The “ought-to-be” values from the procedures are given some allowable deviation, like a funnel centered on the “ought-to-be” value. When the deviation of the “is” value from the “ought-to-be” value is small, the risk of path violation is zero, or small. As the “is” deviation approaches the limits of the funnel, the risk increases. When the deviation is outside the defined limits, path violation risk is denoted by 1. The result is similar to a fuzzy set [17] membership function (Figure 5).

Figure 5. Calculation of path violation risk

A narrow funnel is defined for the glide path constraint (Figure 5a). The risk function is interpreted in the following way. Path violation risk is zero only when “is” value is equal to the “ought-to-be” value, for example, 3° (i.e., the deviation is zero). The risk increases as the deviation gets close to –0.25° or 0.25°. The risk of glide path violation is 1, when the deviation exceeds these limits.

Similarly, a wider symmetrical funnel is defined for course (horizontal) violation (Figure 5b). Demonstration model allows ±5° course violation. A deviation from –2° to 2° gives zero course violation risk. Course violation risk increases for deviation values that are more than 2° (less than –2°) and approach 5° (–5°). The risk of course violation is 1, when the deviation exceeds the limits.

Funnel for altitude violation is asymmetric (Figure 5c). The approach charts depict the minimal allowed altitude value, i.e. tolerance for the negative deviation (“is” values lesser than “ought-to-be”) should be smaller.
than for the positive deviation. When the “is” altitude is less than the “ought-to-be” altitude minus 0.5% it gives an altitude violation risk of 1. A deviation from 0% to 2% gives zero violation risk. The maximal allowed deviation is 5%. Approaching the limits (–0.5% or 5%) increases the altitude violation risk.

The allowed deviation values are chosen for demonstration purposes only and are subject to fix by experts. For example, ILS instrument precision requirements may be used, as the pilot controls the aircraft according to instruments, and the DSS must not require greater precision than the equipment provides.

6 DSS Interface Paradigm

The design of DSS interface defines how controllers will perceive and interact with information provided by the DSS: aircraft positions, predicted trajectories and detected risks. People, not computers, fly the aircraft, direct the traffic, and have the final word in all decisions. Therefore, how computer systems present information to the human controllers, play a crucial role in the effectiveness of ATC systems [3].

User-need investigation showed that there are two goals to achieve: improve situational awareness and reduce cognitive workload. The system should help the controller to understand if aircraft trajectories correspond to approach and departure procedure requirements.

Recent developments in the field of visualization for ATC show that traditional 2D visualization is no longer sufficient [5, 16], and pure 3D visualization has some significant drawbacks [2, 16]. Some authors propose to use 3D in combination with the more traditional 2D display to see both contextual and required altitude information at the same time [2].

One recent project [12] analyzed innovative visualizations in ATC, Command and Control, Medical, Geographic and other fields. Based on this analysis, authors draw a conclusion that not all possibilities to integrate 2D and 3D in ATC systems have been tried. They propose several new strategies [12]. These ideas were reviewed to see how they could be used in the DSS interface:

- The user selects a portion of the main 2D view and that portion is represented in 3D. It was noted that users prefer such solutions that preserve continuity (i.e., make it easy to identify aircrafts after switching on the 3D picture) and do not use distortion.
- To show 2D walls in the main 3D view and mark projection of the aircraft position on the wall. For example, a vertically oriented gradation (“altitude ruler”) helps monitor and control the holding stack.
- To use augmented reality. In this case, a 3D view of the whole airspace is provided, and virtual tools are used to closer examine the situations of interest.

The chosen solution has to take into account the technical limitations of the system model. There will be two 21” LCD color displays: one for graphic and another for hypertext visualizations [14]. Hence, complex augmented reality or virtual reality solutions are not suitable.

![Figure 6. DSS user interface example](image)

After reviewing solutions proposed in other projects, an interface model based on 3D was selected. The system will present a pure 3D display with 2D projections (“curtains”) in relevant places, showing aircraft positions and requirements for trajectories, or rulers helping estimate distances more accurately. The prototype shown in Figure 6 meets defined user needs in the following way:

- 3D display improves situational awareness;
- “Curtains” reduce the cognitive workload.
Selection of the objects (the number of objects and the level of detail) to be visualized in the interface has to be optimal. The DSS works with a lot of data every moment – aircraft coordinates, past and foreseen trajectories, risk alerts, etc. Some information is presented in a separate display (flight data) [15]. However, switching from one display to a separate information source could be time consuming and taking attention away from the traffic situation [10]. So, some authors suggest that all required information should be shown in one display, for example, attaching information about an aircraft to its representation. On the other hand, one must consider that minimizing clutter and distractions is vital to controllers [4].

Objects that are important to represent in the DSS interface are aircraft, past and estimated future trajectories, terrain and the approach/departure requirements for the trajectories. Alternatives for object representation were considered: sphere, cone or 3D model for the aircraft, continuous or dotted lines, or a “ghost” plane for past and estimated trajectories, coloured map, generalized or photo-realistic models for terrain.

In the approach procedures, main requirements for the aircraft trajectory are shown in profile view (Figure 7). These requirements can be represented in a 2D projection – the wall (Figure 6). The profile view of the procedure could be quite long (in some procedures – more than 10 NM) and, showing it in real proportions, the scene becomes too fine to be useful. So, it was decided to try out these alternatives: represent requirements for trajectories in separate segments (i.e., with little or no possibility for the overview) or to use distortion of the projection. In other projects distortion was not accepted positively [12].

![Figure 7](image)

**Figure 7. An example of the profile view of the approach procedure [7]**

### 7 Decision Support Usage Model

Current DSS prototype proposes the following usage scenario. The overall situation is presented in 3D view window with generalized airport landscape and tracks detected by SKY-Scanner system. A 2D control panel holds user interface buttons and a message board for the text messages. Violations are visualized in 3D view using colors and explained in the message board.

The whole observed area is divided into two parts:

- **Soft control area** where only altitude control is performed;
- **Strict control area** when certain landing procedure is assigned to the current track, and procedure constraints (altitude, speed, and course) can be followed.

Strict control area is defined between IAF, FAF and TP. When track receives a clearance for landing, the landing procedure is assigned for the track. Operator turns on the DSS support and assigned procedure is presented on the projection walls. Aircraft position validity can be easily detected visually and confirmed with colours. The DSS control panel presents the current information about tracks and possible risks.

In soft control area the global parameter OCA is traced. The button “Show prediction” visualizes a predicted situation in a determined time interval.

When airplane receives a clearance for certain landing procedure, the DSS support scenario is available:

- **Turn on the projection curtains.**
- **Select the landing or take off procedure, assigned to current track.** The projections of assigned procedure appear on the curtain.
- **View the situation:** airplane position should be on the lines of the visualized procedure.

Path violation can be detected on the projection walls: airplane projection signs have to be right on the procedure lines. Path violation risk is visualized using colors:
• *Green* means that risk is equal to zero;
• *Yellow* means that current positions approaches the safe limit and path violation risk is in the interval \((0, 1)\);
• *Red* indicates a path violation, which means that position is out of the safe funnel.

8 Conclusions

The use of lidar for aircraft tracking will enable controllers to observe phases of flight that are near to the ground. The aircraft approach and departure decision support system will allow for some control over the aircraft in these phases. This is not possible using only the primary radar.

DSS is designed as a knowledge-based system. It tracks the aircraft in accordance with the requirements for trajectories provided in the approach and departure procedures.

The procedures provide a complex definition of the requirements composed of both textual and graphical descriptions. The main constraints form a series of rectangular “gates” defined at certain distances from the airport. Moreover, there are several such procedures for each airport. This makes representing the requirements in the system a challenge.

The current research has undertaken the first steps in representing the approach/departure procedure requirements and using them for path violation risk estimation and visualization. Although the model is promising, it is still far from being used in the operational environment.

Future work includes, but is not limited to, estimating future aircraft positions and using them to foresee future path violations and testing the models with existing flight data.

References