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DEVELOPMENT OF FLIGHT GUIDANCE CONTROL LAWS FOR A WEB BASED AIR TRAFFIC CONTROL SIMULATOR

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Air Traffic Control (ATC), Flight Guidance, Point-Mass Aircraft Model, Fast-Time Simulation

ABSTRACT

ENAC (École Nationale de l'Aviation Civile), the French civil aviation university, offers a comprehensive training program for aspiring air traffic controllers. The program combines theoretical classroom-based instruction with practical hands-on experience using simulators and real-time scenarios. ENAC's proprietary software, ELSA (ENAC Light Simulator for Atc), plays a crucial role in providing online air traffic control simulation exercises for training purposes. This paper focuses on the implementation of trainee clearances in ELSA, specifically how these clearances are converted into commanded values which feed dedicated guidance control loops for a point-mass aircraft model. The simplicity and realism of the point-mass aircraft model contribute to an effective Air Traffic Control (ATC) training experience.

INTRODUCTION

ENAC (École Nationale de l'Aviation Civile), the french civil aviation university, offers a wide range of training programs and courses that cover all aspects of civil aviation, such as air traffic management, air navigation, aviation safety, airport operations and air transport systems. The school provides initial training programs for aspiring pilots, engineers in air transport and aeronautics, air traffic controllers, as well as continuing education for aviation professionals. It also conducts research programs and collaborates with numerous stakeholders in the aviation industry and international organizations. The training program for air traffic controllers at ENAC aims to provide and assess trainees with the knowledge and skills needed to begin training as a trainee controller in an Air Traffic Control (ATC) center (airports or en-route control centers) on a real operational system with real air traffic. This program includes a comprehensive curriculum that covers various aspects of air navigation and traffic management.

The architecture of the training program consists of both theoretical and practical components. The theo-

retical part involves classroom-based instruction, where trainees learn about air traffic control concepts, aviation regulations, airspace management, communication procedures, navigation systems, as well as safety and emergency procedures. They also gain understanding in meteorology, aviation technology and human factors that may impact air traffic control operations. The practical component of the training program involves hands-on experience using simulators and real-time scenarios. Students have the opportunity to apply their knowledge in simulated environments that replicate air traffic control operations. They learn how to handle different air traffic situations, make critical decisions, communicate with pilots, and ensure safe and efficient movement of aircraft within assigned airspace. Several tools are available to bring students to master the requested competencies. Among them we can cite ESCAPE, ROSE and ELSA.

ESCAPE (Eurocontrol Simulation Capabilities and Platform for Experimentation) is the scalable Eurocontrol Air Traffic Management (ATM) real-time simulation platform (Eurocontrol 2023). It supports small and large-scale simulations, controller training and research & Development (Evaluation of new operational concepts and controller tools for example). At ENAC ESCAPE is used as a High-Fidelity simulator to train controllers on electronic en-route environments. It is a highly realistic environment very close to the last generation of en-route operational centers. ESCAPE requires both hardware and software installations as well as an entire maintenance team to run simulations.

ROSE (Radar Operation Simulator & Editor) is a customizable radar simulator developed by ROSE simulation (Rose 2023). This simulator is scalable to allow for complex networked simulations, briefings in classroom and Part Task Training (PTT). It also requires a specific installation by ROSE engineers and strong knowledges in Air Traffic Control (ATC) and aeronautical procedures to build environments and exercises.

ELSA (ENAC Light Simulator for Atc) is a software solution developed by ENAC and Kéléo Solution since 2016 and owned by ENAC. This software is used to publish and operate online air traffic control simulation exercises for air traffic controllers training purposes. ELSA's main strengths and differences compared with ESCAPE and ROSE essentially lie in its ease of access

both for trainees and simulation developers. Indeed it enables both online and autonomous simulations via either a standard web browser or on site with pseudo-pilots simulations via a local area network and standard computers.

This paper is organized as follows: in the next section, ELSA functionalities are overviewed. Then the point-mass aircraft model used in the simulator is presented. This aircraft model is controlled through dedicated flight guidance control laws. The specific control law dedicated to the flight level clearance provided by the aspiring air traffic controller is then outlined and illustrated. The same type of description will then be done for the control law dedicated to the tracking of a DME (Distance Measuring Equipment) arc, which takes the flight plan as an input. Finally, conclusion and perspectives will be drawn.

ELSA OVERVIEW

The main objective of ELSA simulations is to practice specific skills before beginning applying the working method on High-Fidelity simulators. Those simulators are located in simulation rooms equipped with replicas of Controller Working Positions (CWPs) including all equipment: hardware, software and connectivity enabling full functioning/interaction of the CWP and their environment. Prepared with ELSA, High-Fidelity simulation sessions are more efficient for trainees. Part Task Training (PTT) tools help trainees to reach a highest level and save instructors, pseudo-pilots and High-Fidelity simulators time.

At ENAC, ELSA is used as an online and autonomous Air Traffic Control (ATC) simulator through its Learning Management System(LMS). Students have an access 24/24 hours and 7/7 days to simulation exercises via an internet connection and a standard web browser. ELSA is capable of running simulations with a light embedded flight guidance module and provides pilots readbacks through a dedicated messages panel. It monitors clearances according to aircraft performances and also calculates key performance indicators to provide live and post-session feedback to trainees. Its installation is also easy as it only needs the Microsoft Windows operating system to run the exercise editor and is compatible and based on web technology. Moreover the software provides realistic aircraft models based on tabular performance data which can easily be modified by developers. An example of a tabular performance data is provided in Figure 1: the tables indicate the rate of climb and descent, the true airspeed during climb, descent and cruise for each flight level and aircraft type. Graphics below illustrate the figures in those tables. Those figures have been tuned by ENAC’s training designers from BADA data sets developed by Eurocontrol(Poles et al. 2010). In addition to the simulation server, ELSA is composed of a WYSIWYG (What You See Is What You Get) edi-

tor, which enables the training designer to quickly create and view games or drills in an edit mode, and a simulation engine.

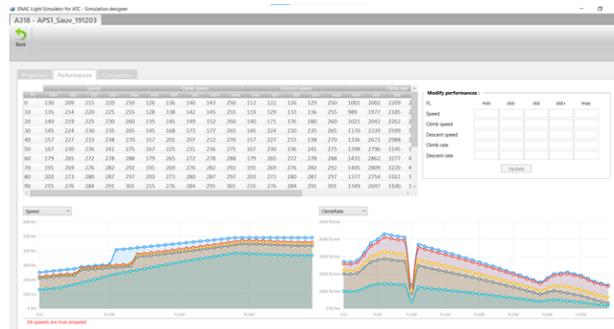


Figure 1: ELSA tabular performance data

As far as the simulation engine is concerned, its functionalities consist in:

- Presenting an interface including various action commands. It enables learners to play the simulation exercises or drills produced for learning or testing purposes;
- Calculating aircraft movement based on an aircraft model using tabular performance data. This module translates each clearance given by the trainee into a specific commanded value which feed dedicated guidance control loops for a point-mass aircraft model. This paper focuses on this point;
- Calculating trainee’s key performance indicators in real time;
- Recording and saving simulation exercises for revisiting.

In the following of this paper we will present how flight guidance instructions coming either from the flight plan of the aircraft or from the aspiring air traffic controller are translated into specific commanded values which feed a point-mass aircraft model through dedicated flight guidance control loops.

AIRCRAFT MODEL

The main motivation to introduce an aircraft model within ELSA software was to achieve an High-Fidelity simulator with the constraint to remain very economic in computational time for compatibility with a web application.

Consequently ELSA works with a simple point-mass aircraft model, which will be described in this section. A point-mass aircraft model is sufficient because it provides a realistic aircraft response from an ATC point of view.

Kinematics equations

In the following, we will use the following notation: x is the position of the aircraft with respect to the North, y the position of the aircraft with respect to the East, z the height from the ground, ψ the heading of the aircraft, V_p the true airspeed of the aircraft, γ the flight path angle of the aircraft, i.e. the angle between the true airspeed V_p and the horizontal axis, W the speed of the wind and ψ_w the direction from which the wind is blowing. Assuming a flat Earth and that the vertical component of the wind is zero, kinematics equations read:

$$\begin{cases} \dot{x} = V_p \cos(\psi) \cos(\gamma) + W \cos(\psi_w + \pi) \\ \dot{y} = V_p \sin(\psi) \cos(\gamma) + W \sin(\psi_w + \pi) \\ \dot{z} = V_p \sin(\gamma) \end{cases} \quad (1)$$

Point-mass aircraft dynamics

The flight dynamics equations are those derived from point mechanics. When the aircraft is modeled as a point of constant mass m , and assuming no sideslip, flight dynamics equations read (Etkin 2005):

$$\begin{cases} m\dot{V}_p = T - D - mg \sin(\gamma) \\ mV_p\dot{\gamma} = L \cos(\phi) - mg \cos(\gamma) \\ mV_p \cos(\gamma)\dot{\psi} = L \sin(\phi) \end{cases} \quad (2)$$

where T is the thrust, D the drag, g the acceleration of gravity ($g = 9.80665 \text{ m/s}^2$), L the lift and ϕ the bank angle of the aircraft.

State equations

The following controls will be used for the point-mass aircraft model defined in (2):

- The longitudinal load factor $n_x = \frac{T-D}{mg}$;
- The vertical load factor $n_z = \frac{L}{mg}$;
- The bank angle ϕ of the aircraft.

Note that the use of n_x and n_z as controls makes it possible to overcome the knowledge of the aerodynamic coefficients needed to compute lift L and drag D .

Taking into account the expressions of the controls, the dynamics equations (2) finally reads as follows:

$$\begin{cases} \dot{V}_p = g(n_x - \sin(\gamma)) \\ \dot{\gamma} = \frac{g}{V_p}(n_z \cos(\phi) - \cos(\gamma)) \\ \dot{\psi} = \frac{g}{V_p} \frac{\sin(\phi)}{\cos(\gamma)} n_z \end{cases} \quad (3)$$

Then the control problem consists in setting the expression of controls n_x , n_z and ϕ so that the flight plan of the aircraft as well as the clearances provided by the trainee can be tracked.

As far as automatic control theory is concerned, the control laws will be designed using feedback linearisation technique (Isidori 1995). Moreover a cascaded structure of the control laws will be obtained through singular

perturbation theory (Kokotović et al. 1999). Basically, it consists in choosing the time constants of the feedback loops such that the time response of the inner loop is faster than the time response of the outer loop. When such conditions are satisfied, the commanded value driving the outer loop can be identified to its actual value. Last but not least the Runge-Kutta method of order 4 is used to integrate the sets (1) and (2) of non-linear differential equations (Butcher 2008).

In the following, we present how are implemented the flight guidance control laws dedicated to the following use cases: Flight level clearance and Tracking a DME (Distance Measuring Equipment) arc.

FLIGHT LEVEL CLEARANCE

The way to achieve a flight level clearance coming from the aspiring air traffic controller is presented hereafter.

Flight path angle hold mode

From the second equation of (3), and assuming $\phi \approx 0 \Rightarrow \cos(\phi) \approx 1$, we get the expression of the vertical load factor n_z according to $\dot{\gamma}$:

$$\dot{\gamma} = \frac{g}{V_p}(n_z - \cos(\gamma)) \Rightarrow n_z = \dot{\gamma} \frac{V_p}{g} + \cos(\gamma) \quad (4)$$

The dynamics of the flight path angle is then chosen as follows, where γ_c is the commanded flight path angle and τ_γ a time constant to be set:

$$\dot{\gamma} = \frac{\gamma_c - \gamma}{\tau_\gamma} \quad (5)$$

Altitude hold mode

The commanded flight path angle γ_c is obtained from the commanded vertical speed V_{zc} , which is identified to the actual vertical speed \dot{z} through an appropriate choice of the inner loop time constant and the use of singular perturbation theory (Kokotović et al. 1999):

$$\dot{z} = V_p \sin(\gamma_c) \approx V_{zc} \Rightarrow \gamma_c = \arcsin\left(\frac{V_{zc}}{V_p}\right) \quad (6)$$

The value of $\frac{V_{zc}}{V_p}$ is limited by the ELSA tabular performance data. As far as the altitude hold mode is concerned, a first-order dynamic for the altitude z is imposed to obtain the commanded vertical speed V_{zc} . Denoting z_c the commanded altitude, we get:

$$V_{zc} = \frac{z_c - z}{\tau_z} \quad (7)$$

Once the commanded vertical speed V_{zc} is set, then (6) is used to get the commanded flight path angle γ_c , which will feed (5) and then (4) to get the vertical load factor n_z which controls the point-mass aircraft model.

Use case

Altitude or Flight Level (FL) clearances are issued by Air Traffic Controllers (ATCOs) to pilots. When a FL or altitude is given in a clearance to a pilot, the aircraft has to descend (or climb) to the given FL or altitude and maintain it when reached. An example of message issued by an ATCO is: *Air France one two three four, climb level one six zero*. Once this clearance is issued, ELSA checks its validity according to the aircraft flight envelope. Then if feasible, the clearance is issued to the flight guidance engine previously described. Figure 2 shows the multiple input window presented to the trainee for such a clearance.

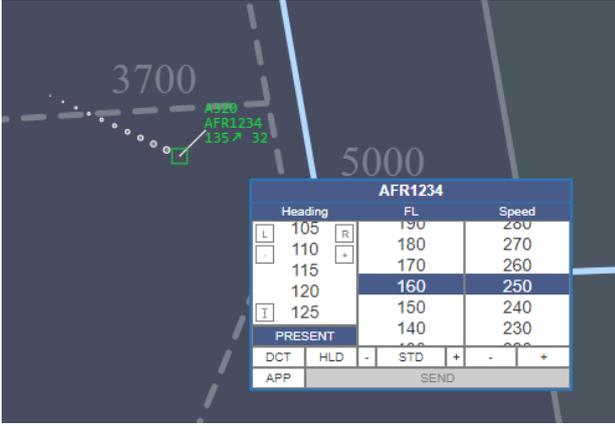


Figure 2: Flight level capture

TRACKING A DME ARC

The way to achieve the tracking of a DME (Distance Measuring Equipment) arc coming from the flight plan is presented hereafter.

Heading and track hold modes

From the last equation of (3) assuming $\phi \approx 0 \Rightarrow \sin(\phi) \approx \phi$, $\gamma \approx 0 \Rightarrow \cos(\gamma) \approx 1$ and $n_z \approx 1$, we get the expression of bank angle ϕ according to $\dot{\psi}$ and V_p :

$$V_p \dot{\psi} \approx g \phi \Rightarrow \phi = \frac{V_p \dot{\psi}}{g} \quad (8)$$

The heading dynamics $\dot{\psi}$ is then chosen as follows, where ψ_c is the commanded heading and τ_ψ a time constant to be set:

$$\dot{\psi} = \frac{\psi_c - \psi}{\tau_\psi} \quad (9)$$

Due to the wind W , the route of the aircraft may be different from its heading. The difference between route χ and heading ψ is the drift angle, which is denoted d :

$$d = \chi - \psi \quad \text{where} \quad d = \arcsin\left(\frac{W \sin(\chi - \psi_w)}{V_p \cos(\gamma)}\right) \quad (10)$$

Thus, when a commanded route χ_c is provided by the trainee, it is converted into a commanded heading ψ_c through the following relation:

$$\psi_c = \chi_c - d \quad (11)$$

Circle's tracking

A DME arc is a curved track at a constant distance around a facility. We present hereafter how the tracking of a DME arc is implemented within ELSA.

First, consider the equation of a circle with center (x_c, y_c) and radius r passing through the position (x, y) of the aircraft:

$$(x - x_c)^2 + (y - y_c)^2 = r^2 \quad (12)$$

The time derivative of this equation reads:

$$(x - x_c) \dot{x} + (y - y_c) \dot{y} = r \dot{r} \quad (13)$$

Let G_s be the ground speed of the aircraft and χ its route:

$$\begin{cases} \dot{x} = G_s \cos(\chi) \\ \dot{y} = G_s \sin(\chi) \end{cases} \quad (14)$$

We get from (13):

$$(x - x_c) G_s \cos(\chi) + (y - y_c) G_s \sin(\chi) = r \dot{r} \quad (15)$$

Then we define angle η as a function of aircraft position (x, y) and center of circle (x_c, y_c) as follows:

$$\begin{cases} x - x_c = r \sin(\eta) \\ y - y_c = r \cos(\eta) \end{cases} \quad (16)$$

Using (16) inside (15) gives:

$$\sin(\eta + \chi) = \frac{\dot{r}}{G_s} \quad (17)$$

The dynamics of convergence of radius r towards a constant radius R_c is set as a first order dynamics. Denoting τ_R a time constant to be tuned, we set \dot{r} as follows:

$$\dot{r} = \frac{R_c - r}{\tau_R} \quad (18)$$

Then the commanded track χ_c is identified to its actual value χ through an appropriate choice of the inner loop time constant and the use of singular perturbation theory (Kokotović et al. 1999). Finally, given $\sin(x) = \sin(\pi - x)$, the two possible values for the commanded track χ_c are obtained from (17):

$$\begin{cases} \chi_{cl} = \arcsin\left(\frac{\dot{r}}{G_s}\right) - \eta \\ \chi_{cr} = \pi - \arcsin\left(\frac{\dot{r}}{G_s}\right) - \eta \end{cases} \quad (19)$$

The value χ_{cl} corresponds to a counter-clockwise rotation whereas the value χ_{cr} corresponds to a clockwise rotation.

Use case

DME Arcs are most commonly found during the arrival phase, leading aircraft from a specific navigation point

called the Initial Approach Fix (IAF) onto the Final Approach Course (SIA 2012).

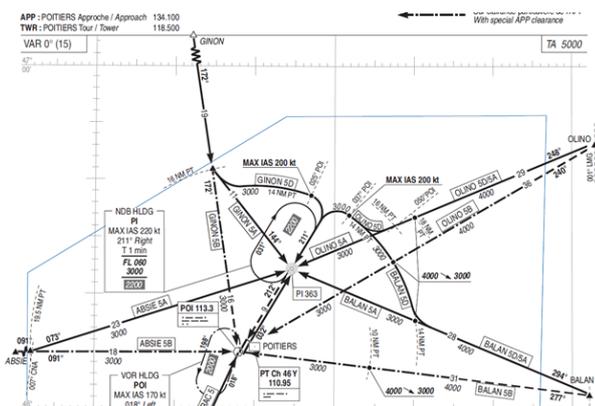


Figure 3: Poitiers Biard arrival chart showing GINON 5D arrival procedure

In Figure 3, an aircraft performing the GINON 5D (SIA 2023) arrival will fly from GINON waypoint until crossing the 16 nautical miles DME arc of POITIERS NAVD to turn left and follow the 14 nautical miles DME arc of POITIERS.

To follow and perform this arrival procedure, the pilot is generally cleared by the air traffic controller. An example of message issued by an ATCO is: *Air France one two three four, cleared GINON five delta arrival.* Figure 4 shows the corresponding window for such a clearance. It is worth mentioning that the circle's tracking control law is coupled with an axis capture control law (which is not described here) to track the entire arrival procedure.

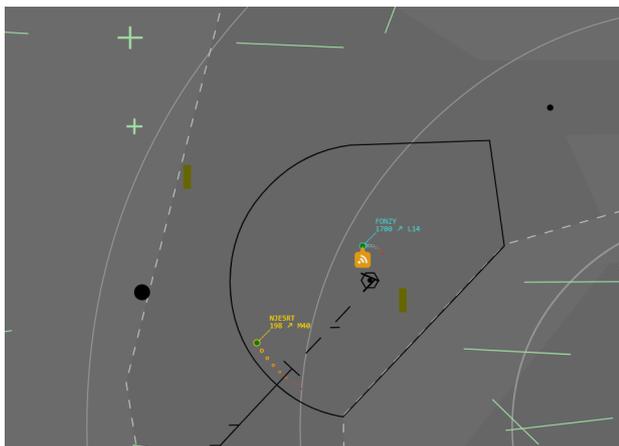


Figure 4: Poitiers Biard arrival on ELSA

CONCLUSION AND PERSPECTIVES

ELSA is a flexible tool which gives the possibility to build a complete ATC environment with its own ATC procedures, radar views, aircraft tracks, label designs

and safety nets. Thanks to the use of a light embedded flight guidance module controlling to a point-mass based aircraft model, ELSA offers both a realism equivalent to a High-Fidelity simulator while remaining compliant with an efficient web based environment. This last point ensures a wide and flexible access to ATC simulation resources for aspiring air traffic controllers.

DSNA, the French ANSP (Air Navigation Service Provider) has acquired the ELSA software license in 2020 for staff training purposes. DSNA uses ELSA as ENAC does, that is as an online part task trainer to develop specific skills. But DSNA also uses ELSA as a synthetic training device, meaning that ELSA is used to create global and complex ATC simulations thanks to ELSA server with multiple sectors, controllers and pseudo-pilots. This configuration enables controllers to train on more realistic simulations or abnormal situations to assess and maintain their ATCO license rights.

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