Procedure and Interface Design for Continuous Descent Approaches Under End Time Constraints

Master of Science - Thesis

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TU Delft

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by

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Preface

With this report, my Master studies, which started in September 2018 and were spent between The Netherlands, Germany and Greece, come to an end. Starting with my courses, I had the chance to substantiate my background in the domain of Control & Simulation through the lectures of motivating Professors and the assignments that made me grow individually, but also as a team member, by tackling diverse challenges. Then, during my Internship in Max Planck Institute for Biological Cybernetics, I had the unique opportunity to work in a renowned research institution and expand my horizons.
I would like to firstly thank Prof.dr.ir. M. Mulder for bringing me in contact with my Internship Supervisor in February 2019, then in February 2020 providing me with this interesting and multifaceted Thesis topic and being eager to guide and assist me through this project. It was a privilege to discuss together the development of my project during our weekly group calls. Moreover, I was grateful to work on this project under the supervision of Dr.ir. C. Borst and Dr.ir. M. M. van Paassen, who I had the chance to meet at first in their insightful lectures during my first year in TU Delft. I really appreciated to hear their points of view and getting ideas of ways to move forward. In addition, I would like to thank Dr.ir. A. C. in 't Veld for providing a pilot's perspective into this project and Ir. O. Stroosma and ing. E. H. H. Thung for their assistance during the experimental period.
I would like also to express my gratitude to my friends and roommates, in both Athens and Delft, who supported me during the challenging times of my studies. Last but not least, I would like to thank my family, who was always standing by my side during this demanding journey and providing me with the means to accomplish my goals.

Viktoras Georgios Vasilopoulos
Delft, 29^{th} June 2021

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Nomenclature

α	Angle of Attack
γ	Flight Path Angle
ρ	Air density
θ	Pitch Angle
C_D	Coefficient of drag
C_L	Coefficient of lift
D	Drag
g	Acceleration due to gravity
H	Altitude
L	Lift
m	Mass
P_a	Atmospheric pressure
q	Pitch Rate
S	Wing area
T	Thrust
V	True airspeed
V_{sound}	Velocity of sound

Abbreviations

ACDA Advanced Continuous Descent Approach.

ADS-B Automatic Dependent Surveillance - Broadcast.

AGL Above Ground Level.

ATC Air Traffic Control.

ATD Along Track Distance.

CDA Continuous Descent Approach.

CSE Cognitive Systems Engineering.

CWA Cogntive Work Analysis.

DASMAT Delft University Aircraft Simulation Model and Analysis Tool.

DME Distance Measuring Equipement.

EID Ecological Interface Design.

ETA Estimated Time of Arrival.

FAF Final Approach Fix.

FMS Flight Management System.

G/S Glideslope.

GPS Global Positioning System.

GUI Graphical User Interface.

IAF Initial Approach Fix.

IAS Indicated Airspeed.

ILS Instrumental Landing System.

NAP Noise Abatement Procedure.

NDB Non-Directional Beacon.

NLR Koninklijk Nederlands Lucht- en Ruimtevaartcentrum.

PFD Primary Flight Display.

PID Proportional–Integral–Derivative.

PLA Power Lever Angle.

RTA Required Time of Arrival.

SESAR Single European Sky Air Traffic Management Research.

SRK Skills, Rules, Knowledge.

STAR Standard Terminal Arrival Route.

TAS True Airspeed.

TMA Terminal Maneuvering Area.

ToD Top of Descent.

TSD Time Space Diagram.

VOR Very high frequency Omnidirectional Range.

VSD Vertical Situation Display.

I

Paper

Procedure and Interface Design for Continuous Descent Approaches Under End Time Constraints

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***Abstract*—The Continuous Descent Approach (CDA) offers reduced aircraft noise emissions and fuel consumption, but the main issue limiting its use to low traffic conditions, is the lack of predictability in terms of the trajectory and Estimated Time of Arrival (ETA). A suggested solution is to develop a pilot support interface to facilitate the execution of a fixed flight path angle CDA with an end time goal. This project proposes that thrust level is not bounded to idle, thus being flexible to follow a velocity profile, which will lead to the selected ETA. Initially, the trajectory of CDA was investigated from a kinematic point of view with the equations of motion. Then, the solution space of the ETA, and the calculation method of the stepwise velocity profile were defined. Following the analysis of the pilot's role in this process, a two-fold pilot support interface was designed based on the principles of Ecological Interface Design (EID), with a Vertical Situation Display (VSD) playing a central role in both aspects of the interface, namely planning and execution. The interface was prepared to be tested in a setup of MATLAB®/Simulink® and five pilots were recruited to execute simulations over different wind conditions. Their performance in terms of meeting the time goal, was satisfactory, while they worked with the provided cues and suggested some changes for the interface to accommodate their strategy. The validation of the proposed approach can lead to adopting the CDA in more airports, as a widely accepted approach procedure.**

***Index Terms*—Continuous Descent Approach (CDA), Vertical Situation Display (VSD), Ecological Interface Design (EID)**

I. Introduction

The common procedure, that an aircraft follows from the Top of Descent (ToD) until the interception of the Glideslope (G/S), includes step-down descents and level flight segments. This logic is shaped according to Air Traffic Control (ATC) commands, in order to create traffic flows with uniformly decelerating aircraft and facilitate the aircraft sequencing [13]. Going beyond the established navigational aids and procedures of the past decades, the research done in the aerospace industry has enhanced the aircraft's capabilities regarding navigation with the Global Positioning System (GPS) and the Flight Management System (FMS), and can execute more complex procedures and trajectories [2].

A related concept that has been proposed, investigated and applied in some airports is the Continuous Descent Approach (CDA), with the initial goal to mitigate the noise footprint of air traffic. One of the first analyses of CDA took place at the National Aerospace Laboratory NLR [7], as a possible Noise Abatement Procedure (NAP) for Schiphol International Airport (AMS/EHAM). This approach trajectory is executed in the Terminal Maneuvering Area (TMA) at higher altitude than the conventional approach and the aircraft intercepts the G/S without performing level flight segments. CDA is defined as [9]:

"Continuous Descent Approach is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and ATC instructions."

After the initial presentation of CDA, it has been proven that CDA reduces the noise level and fuel consumption along the approach routes, using different research methods. This concept was tested in computer simulations using aircraft performance data [14], [15], [18], [30] in European airports varying in traffic load. In addition, more realistic conditions were examined in actual flight tests [4], [6], [10], [23] and sessions in flight simulators [6], [12], [13].

The procedure of CDA has been adapted to different forms, by modifying its parameters. For instance, the flight path angle of CDA was kept constant at $-3°$ (Three Degree Decelerating Approach) and the flap schedule, in combination with the thrust cutback altitude (thrust set to idle), were subjected to optimization to reduce the noise footprint and maintain aircraft separation [6]. In addition, the effect of the flight path angle to the noise footprint has been considered in flight tests [4], namely for $-2°$, $-2.5°$, $-3°$, but the angle's impact did not result to be significant. The possibility of splitting the CDA into two different flight path angle segments has been investigated with a constant flap schedule [24], provided an additional flexibility during planning of the approach and led to an acceptable time performance. In the case of having both the flight path angle and flap velocities as free variables, it was proposed that the pilot can use the aircraft's total energy, which is converted to the available control space, to define the decelerating strategy [11]. A modified $-3°$ CDA was also tested [11], which makes the trajectory prediction easier, since the aircraft in this case intercepts the "extended" $-3°$ G/S and initially maintains its velocity and as it flies closer to the airport, it starts decelerating.

However, in the first stages of the development of CDA, it was noted [8] that the execution of this approach results in the extension of the planned landing interval from 1.8 minutes to 4 minutes, due to the uncertainty concerning the Estimated Time of Arrival (ETA). Flight tests [4] likewise concluded that this procedure cannot be applied in peak traffic times, due to the lack of accurate trajectory prediction. The goal of this project is to propose a new agile approach to this problem, by modifying the initial concept of CDA, which has thrust as a free variable, in contrast with the aforementioned projects, and therefore will be able to follow a velocity profile that leads to the desired ETA, thus the Required Time of Arrival (RTA).

The transition from a 3-D approach, hence the trajectory in space, to a 4-D concept, with the addition of time, has already been implemented [22], as the Advanced Continuous Descent Approach (ACDA). A research project [18], which applied the ACDA concept, added some flexibility to the parameters of the approach, such as the flight path angle and thrust setting. However, this trajectory is fully executed by the FMS, which leaves the pilots without maintaining an appropriate situation awareness and it will be difficult for them to intervene if needed [17].

Therefore, the other dimension of this project comes into place, namely engaging the pilot into this procedure. The concept of this approach concerns controlling the aircraft's trajectory from the Initial Approach Fix (IAF) to the Final Approach Fix (FAF) at the landing runway's threshold. The pilot can define the deceleration and descent trajectory of the aircraft, starting from the choice of the CDA's flight path angle. During this execution, the pilot remains on a supervisory role and interacts with the aircraft through automation, the autopilot. The information, such as the future trajectory, the ETA limits and the commands to be followed to achieve this goal, can be either presented as cues in an existing display, like the Primary Flight Display (PFD) [6], [13], [23], or a new interface can be designed for this purpose [5], [10], [11], [24].

The design of this pilot support interface will be based on previous work that took place for the CDA explicitly [5], [24] or in general for 4D trajectories [16] and flight envelope visualization [26]. All these projects had, as a common framework the Ecological Interface Design (EID) [21], [28], which guides the design process towards supporting human cognition, in terms of depicting the abstract properties and the constraints of a system in an easily perceptible way for the pilot.

This article continues with Section II, starting with the analysis of previous work that has been executed on the concept of CDA that leads to defining the parameters of this approach. Then, the development of this project breaks down in its two main components, the trajectory calculation and the interface design. After finalizing the development of these aspects, the experimental procedure is described in Section IV, its results and implications are analyzed in Section V and finally Section VI concludes the findings of the project and poses future suggestions.

II. Background

Having shaped the outline of the taken approach, hence to modify the initial definition of CDA and be flexible in terms of thrust, in pursuing of achieving a desired ETA, the next step is to define the rest of the parameters. At first, the flight path angle γ of the CDA has been considered to be constant [4]–[6], [12], but also a free variable [11], but the latter is not adopted, since it may complicate more the task of separation by the ATC. An example of this type of trajectory is presented in Figure 1. At $2,000$ ft, the interception of the G/S can be noted, where the flight path angle changes from $-2°$ to $-3°$. A range for the flight path angle of a CDA is proposed to be from $-2°$ to $-3°$ [4], and in general higher angles are preferred, for less noise emissions, as long as the aircraft can decelerate without deploying the speedbrakes. Therefore, with a constant

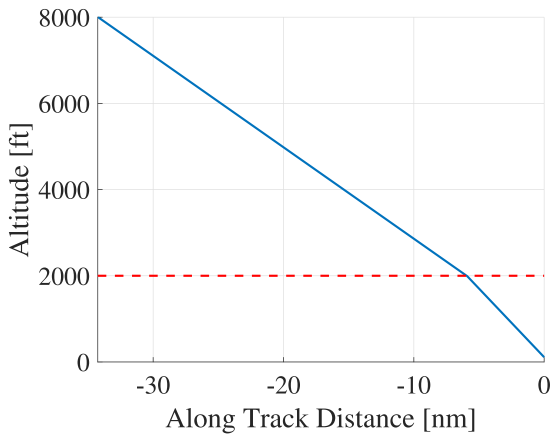

Fig. 1: Overview of a CDA trajectory

flight path angle, the last parameter, the flap schedule, which has been subject to modification and optimization [6], [11], remains fixed, since it is preferred to keep flap deployment velocities at a narrow range for the convenience of the pilots [29]. In addition, when flaps are extended close to their corresponding maximum operating velocities, it can lead to extensive wear. The primary analysis, that is needed for this project, is the calculation of the aircraft's trajectory from the IAF to the FAF and consequently estimating the ETA. The other perspective that is needed, is the application of the trajectory calculation methods into the final interface design.

A. Trajectory calculation

The trajectory calculation follows the logic of an aerodynamic model, considered as a point mass, whose trajectory is calculated in 2-D (longitudinal and vertical axes) [6], [13], assuming that the effect of the lateral axis does not impact the ETA. The aircraft type that is used to calculate its trajectory for this approach is a Cessna Citation I, which is the basis of Delft University Aircraft Simulation Model and Analysis Tool (DASMAT). DASMAT's main goal is to assist flight dynamics and control research and it contains the aerodynamic and propulsion characteristics of Cessna Citation I. The basic specifications of this aircraft are mentioned in Table I.

TABLE I: Cessna Citation I Specifications

Model Specification	**Value**
Length	13.26 m
Wingspan	14.33 m
Wing Area	24.99 m^2
Empty Weight	3,338 kg
Maximum Takeoff Weight	5,375 kg
Maximum Mach number	0.705
Range	2,460 km

The computational model consists of twelve nonlinear equations of motion, assuming a rigid aircraft with constant mass and a flat non-rotating earth. In addition, it incorporates an atmospheric model and optional capabilities, such as wind and turbulence, and it has already provided a platform to perform similar studies [6], [11], [13]. This simulation tool operates in Simulink®/MATLAB® and can perform both offline and online simulations.
Since DASMAT is a nonlinear model in Simulink®, it is not favorable to use it in performing multiple trajectory calculations in a short period of time. However, this ability is crucial for a pilot support interface which is based on future trajectory calculations. Therefore, a point mass model was implemented to structure these calculations [6] and DASMAT was used firstly as a validation of this model and then in the subsequent experiment setup. The formulation of this model includes also the wind velocity on the longitudinal axis, hence for nonzero wind conditions a deviation between the kinematic flight path angle γ_k and the aerodynamic flight path angle γ_α ($\Delta\gamma = \gamma_k - \gamma_\alpha$) is created.
In Figure 2, the forces acting on the aircraft (Thrust T, Drag D, Lift L, Weight mg), along with the flight path angles and the basic velocities, are depicted, so the equations of motion can be established afterwards. Regarding the velocities, the True

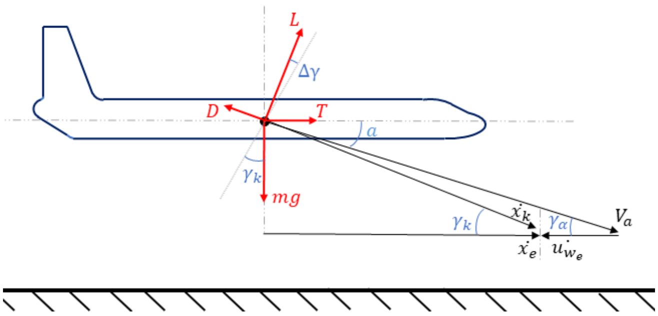

Fig. 2: Force diagram and related velocities/angles

Airspeed (TAS) V_α with the wind velocity u_{w_e} compose the groundspeed $\dot{x_e}$, which are defined in the North-East-Down reference frame F_e. The γ_k is the desired flight path angle of the aircraft during the CDA and the G/S, while the γ_α can be derived from the velocities:

$$\gamma_\alpha = \arccos\left(\frac{\dot{x_e} - u_{w_e}}{V_\alpha}\right) \quad (1)$$

The V_α is calculated as:

$$V_\alpha = \sqrt{(\dot{x_e} - u_{w_e})^2 + (\dot{x_e} tan(\gamma_k))^2} \quad (2)$$

By making a small angle approximation for the angle of attack α, the equations of motion on the longitudinal and vertical axes of the kinematic frame of reference F_k are:

$$Lcos(\Delta\gamma) - mgcos(\gamma_k) + Tsin(\Delta\gamma) - Dsin(\Delta\gamma) = 0 \quad (3)$$

$$-Lsin(\Delta\gamma) + mgsin(\gamma_k) + Tcos(\Delta\gamma) - Dcos(\Delta\gamma) = m\ddot{x_k} \quad (4)$$

For the vertical axis, the components multiplied with $sin(\Delta\gamma)$ can be neglected, so L is easily derived and its coefficient C_L is calculated. Then, in the longitudinal axis, the coefficient of drag C_D is estimated by a second order polynomial as a function of C_L, whose coefficients depend on the value of C_L and the aircraft configuration [6]. The last component to define in the Equation 4, so it can be solved, is either the value of T or the acceleration $\ddot{x_k}$. In the previous applications of this trajectory calculation [6], [13], only idle thrust was used as input and in this project it is approximated as a percentage of the maximum thrust, which is a function of Mach number and atmospheric pressure. However, the main difference of this project is to create the capability to follow a velocity profile. Therefore, if a velocity profile is imposed, the value of $\dot{x_k}$ is known for the next time step, so $\ddot{x_k}$ can be calculated and used as input to the Equation 4. If the output of this equation, T, is less than the corresponding idle thrust, then the input to the equation switches to thrust for that particular time step. All of these components, that lead to the general trajectory calculation algorithm, are arranged in a flowchart in Figure 3. The planning of a CDA, from the IAF in the TMA (H_{IAF},

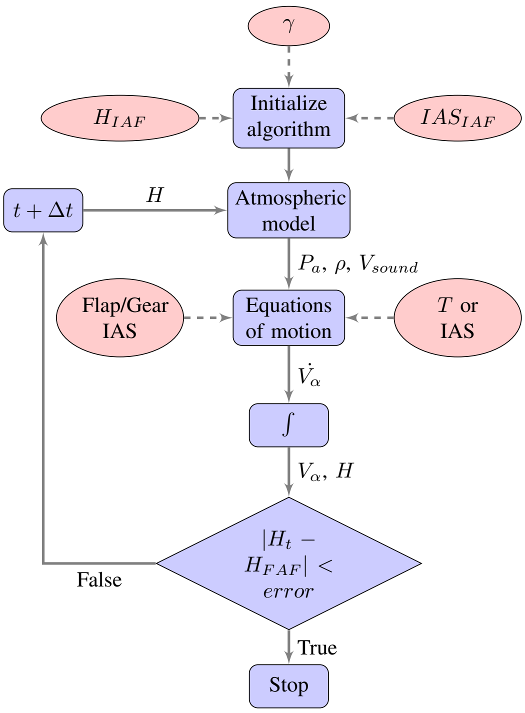

Fig. 3: Trajectory algorithm flowchart

IAS_{IAF}) up to the FAF close to the landing runway (H_{FAF}, IAS_{FAF}), is based on this general algorithm, and having set the flap/gear schedule, aircraft's mass and wind velocity, three different calculation applications were developed to accommodate its needs. The first application of this algorithm, calculates the maximum ETA from the IAF to FAF for a given γ_{CDA}. In detail, starting at the IAF, the input to the algorithm is idle thrust, which is kept at that level until the aircraft decelerates to IAS_{FAF}. Then, the input to the algorithm changes to IAS and the appropriate value for thrust to maintain the IAS_{FAF} is calculated until the aircraft's altitude reaches H_{FAF}.

The second application of this algorithm concerns the calculation of the minimum ETA to reach the FAF from the IAF. In particular, the aircraft begins its descent from IAF, but the input to the algorithm remains the velocity IAS_{IAF}, until the latest possible time step to start decelerating. Consequently, the goal of the second algorithm, before calculating the minimum ETA, is to find the time, where the input to the algorithm will have to shift to idle thrust and allow the aircraft to reach H_{FAF} with the desired velocity IAS_{FAF}. A straightforward solution to estimate this time step is to start checking iteratively all the possible time steps starting from $t = 1s$ with a step of $\Delta t = 1s$.

However, this can lead to a high execution time, so a calculation logic using the bisection method was developed for this purpose. For the first iteration, the first point to calculate the trajectory is the earliest deceleration T_{min}, hence at $1s$, the third point is the latest point for deceleration T_{max}, so an extreme time point is taken (for example $3,600s$) and the second point is the average of the first and third time points T_{mid}. In this logic, each trajectory is checked whether it provides a valid solution, hence if it reaches H_{FAF} with IAS_{FAF}. The first point will always deliver a valid solution, since it is the earliest deceleration. Then, if the second point also delivers a valid solution, it means that the time step that results to the latest possible deceleration is located between the second and third time points and in the next iteration the three calculation points are arranged accordingly. If the second point does not result in a valid solution, that means that the solution is positioned between the first and second points and in the next iteration the calculation points are adapted in the same manner. The logic of each iteration is presented through a flowchart in Figure 4. When the time to start decelerating is found, then the general trajectory algorithm is executed by imposing velocity (IAS_{IAF}) as input until that time step, and then switching to idle thrust and the minimum ETA can be defined.

The third application of this algorithm is to calculate the IAS profile that will lead to a selected ETA, hence a RTA, which will be between the calculated time limits. Since the project's aim is to keep the pilot engaged in this process, the IAS profile is chosen considering this fact and limiting its complexity to a stepwise profile representing the pilot's commands to the autothrottle. However, the velocity profile, in the form of multiple steps, that leads to the RTA can not be calculated directly in a deterministic way.

By having the boundary conditions and setting the constraints, this application can be shaped as an optimization problem.

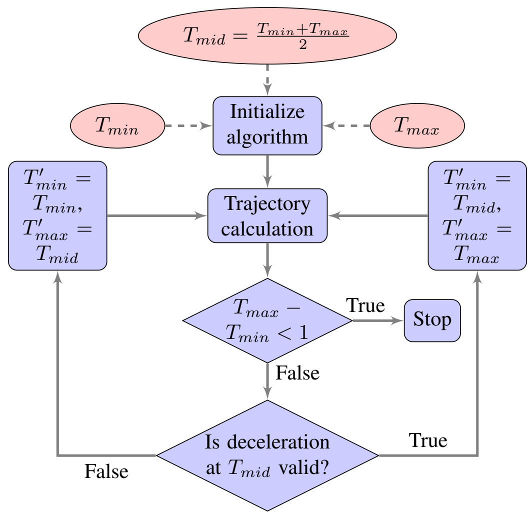

Fig. 4: Minimum ETA calculation flowchart

Since the two aforementioned trajectory calculation cases are programmed in MATLAB®, the built-in non-linear optimization functions of MATLAB® are considered for this problem to facilitate its implementation. The decision variables of this optimization procedure are the values of the n intermediate IAS steps, given that all the steps have equal duration and the first and last steps are IAS_{IAF} and IAS_{FAF} accordingly. To that end, a function is created that has as its main input the IAS values, calculates the trajectory for the selected RTA and its output is the objective function. The two-fold objective function J (Equation 5) has as its first segment the squared difference of H_{FAF} and the altitude at the last time step of the calculated trajectory $H_{t=RTA}$ and the second segment being the inverse of the sum of the decision variables.

In detail, apart from the main goal of being time punctual at the specified altitude, it is preferable not to decelerate early to the final velocity, in order to be able to compensate for any unforeseeable factors during the approach, such as a wind velocity change. So, the values of the design variables are forced to be as high as possible, by using the second segment of the objective function to maximize their value. The two objectives to be minimized, have the same weights in the optimization procedure, since favoring one side or the other did not converge to a different solution.

$$J = \begin{bmatrix} (H_{FAF} - H_{t=RTA})^2 \\ \frac{1}{\sum_{n=1}^{N} IAS_n} \end{bmatrix} \tag{5}$$

The constraints of this optimization can be formulated as inequalities. The main constraint that is imposed is that the calculated velocity values corresponding to each step would not exceed the initial velocity or be less than the final velocity.

$$IAS_{FAF} \leq IAS_n \leq IAS_{IAF} \tag{6}$$

The results from the three different applications of the trajectory calculation algorithm can be observed in terms of the IAS profiles and the corresponding response from the point mass model. Then, the third application's response (RTA goal) is compared to the response of nonlinear model of DASMAT for the same IAS input, with the intention of validating the accuracy provided by the simpler point mass model. The conditions for these simulations are presented in Table II and the trajectory of the aircraft is depicted in Figure 1.

By implementing the first and second applications of the trajectory calculation, the two IAS profiles are defined, as well as the ETA bounds. For the selected conditions, the minimum ETA is 619 s and the maximum ETA is $1,002$ s. In this time range, a RTA of 720 s is selected and four IAS steps are used for the optimization algorithm, whose solution indicates that the intermediate IAS steps are 184 kts, 161 kts and 139 kts. The outcomes of the three applications are presented in Figure 5, which are used as the input for the point mass model and the IAS responses are presented in Figure 6.

TABLE II: Simulation conditions

Variable	Value
H_{IAF}	8,000 ft
IAS_{IAF}	200 kts
H_{FAF}	100 ft
IAS_{FAF}	110 kts
γ_{CDA}	$-2°$
$\gamma_{G/S}$	$-3°$
H for G/S intercept	2,000 ft
Flaps 15° IAS	165 kts
Flaps 40° IAS	125 kts
Gear Down IAS	135 kts
Mass	4,696 kg
Wind velocity	0 kts

The last demonstration of the point mass model is performed against the response of the DASMAT model for the stepwise profile in order to achieve the RTA of 720 s. In DASMAT model, a flight path angle hold loop, with an integrated pitch damper, and an airspeed hold loop were implemented, so the desired flight path angle and IAS profile can be tracked. The PID gains of these controllers are constant and were manually tuned by using the linearized symmetric model of the aircraft.

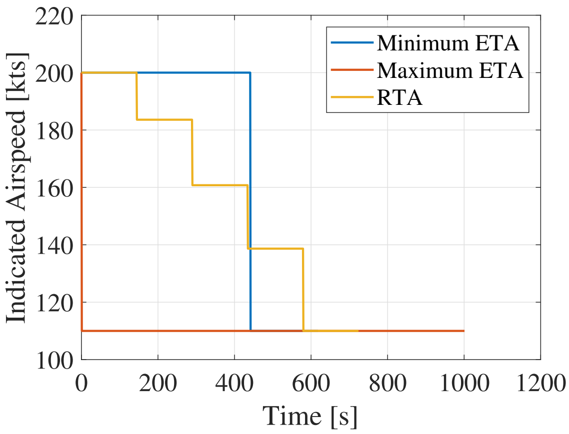

Fig. 5: Input IAS profiles

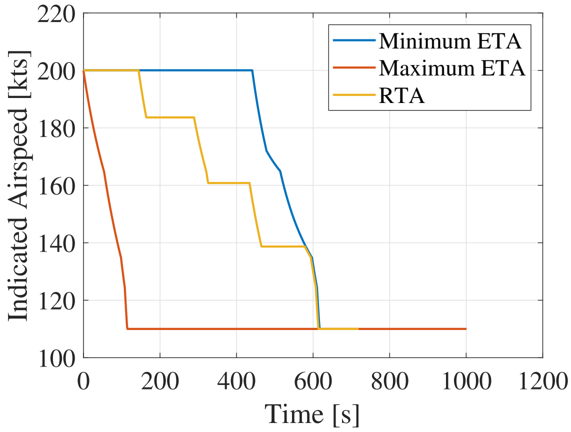

Fig. 6: IAS responses for minimum/maximum ETA and RTA

For the same input profile of Figure 5, a deviation of the response of the point mass model from one of the nonlinear model, is noticeable in the last velocity step in Figure 7, but it does not have an impact on the overall performance, since the ETA differs by 5 s. An additional comparison is performed between the thrust response of the point mass and DASMAT models, to demonstrate the accuracy of the former model. As it is depicted in Figure 8, the steady state values of thrust for each IAS step are nearly identical, while the DASMAT model, due to its modeling, is able to capture the transient phenomena. In addition, the distribution of maximum thrust proves that although this CDA is not entirely performed with idle thrust, as in its principal form, the thrust level remains low during the approach.

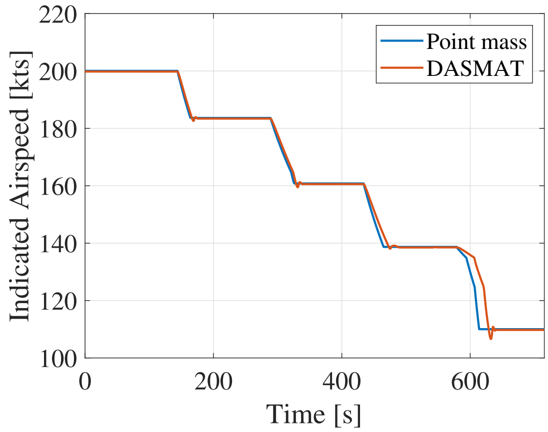

Fig. 7: IAS responses for the point mass and DASMAT models

III. Interface Design

The interface that is needed to support the pilot's mission, is developed by considering which variables can facilitate this task, that are not provided by the standard flight instruments. The depiction of this information on a display is based on previously applied concepts [16], [24], [26], which have as a

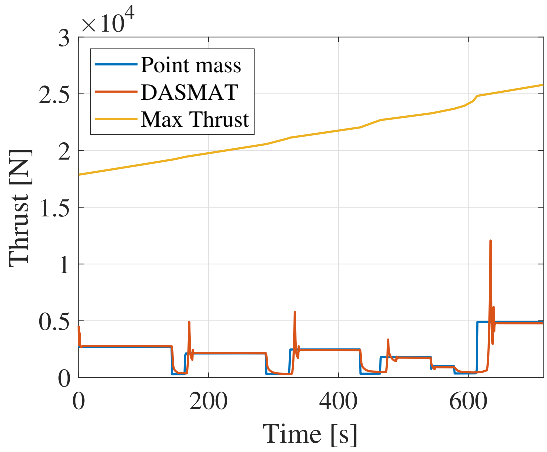

Fig. 8: Thrust responses for the point mass and DASMAT models and the corresponding maximum Thrust

common base the EID, which is suited towards planning and controlling a system [27].

The execution of a CDA with an end time goal requires solid planning and, during its progress, monitoring, so the calculated commands are followed timely and further corrective actions can be taken, if required. Following the principles of EID [28], it was pursued to design an interface, which has integrated the necessary information of the work domain in a way that its constraints are directly perceivable [1], [3]. Therefore, the trajectory analysis is suitable for this goal, since by applying the fundamental kinematic equations [16] and the aircraft's performance data, the higher order variables can be approximated for the operation of the interface.

In particular for this setup, the pilot, when planning the CDA with the IAF and FAF being constant, needs to know what is the range of the CDA flight path angle and then, after choosing one value, which are the ETA bounds. This logic can be followed also in the reverse order, if the pilot has a RTA to be met from the ATC, then the flight path angles that can accommodate this requirement can be estimated. Then, during the execution, a typical procedure is that the pilot uses the autopilot to insert the commands for the target state, and in this case the autothrottle is the function of interest. However, this supervisory role of the pilot requires some additional information to confirm that the CDA is being executed as planned and the RTA will be met. This information mainly concerns the time performance, hence the ETA for the current state of the aircraft and its deviation from the RTA. This led to developing a new display that provides the necessary time performance information and possible solutions to deal with deviations from the goal.

A. Main display type

The basic display type to incorporate in the interface is the Vertical Situation Display (VSD), which has been adopted in similar projects of CDA planning and execution and it was used in presenting an example CDA trajectory in Figure 1. Some of the initial studies concerning VSD were carried out [19], [20] to enhance the situation awareness of the pilots for the vertical axis and provide a better grasp of the operation of automation. In these projects, the VSD was integrated on the lower part of the Navigation Display screen, which provides guidance on the lateral axis. Then, VSD's use was expanded [25] to offer terrain avoidance capabilities and display the space for potential maneuvers. Recently, the VSD was adopted with a visualization feature concerning the flight envelope and the changes in this envelope caused by the deployment of flaps and gear [26]. Therefore, VSD has demonstrated its agility and can contribute to structure a pilot support interface to be utilized for CDA planning and execution.

In the subsequent step of this project, this interface is tested in an experiment to evaluate its effectiveness to achieve the RTA goal. Therefore, the VSD was not developed as an independent entity, but as a part of a complete experimental platform in MATLAB®/Simulink®, having as a base the DASMAT model. Taking into account that during a simulation, the pilot has to interact with the interface, in terms of planning the CDA, as well as to execute the IAS/flaps/gear commands and monitor the performance in parallel, led to splitting the pilot support interface into two sections. The basic layout of the VSD is used as a concept to be augmented in both sections, which are notably the CDA Graphical User Interface (GUI) and the CDA monitoring display. The VSD of the GUI presents the possible combinations of flight path angle and ETA, while during the flight simulation it assists the interaction with the pilot and the CDA monitoring display provides information about the current position of the aircraft, the future trajectory and the space of possibilities, regarding the ETA.

B. CDA Graphical User Interface (GUI)

In App Designer of MATLAB®, a GUI was structured gradually, starting from the need to plan the CDA for the given conditions, by presenting the possible solutions to the pilot during this process. Afterwards, the next goal of executing a simulation of a CDA, by using the DASMAT model, led to creating an accompanying platform to provide the interaction between this model and the pilot, thus inserting the IAS/flaps/gear commands during the flight and assess the remaining trajectory.

The GUI is divided into three areas, following the logic of the simulation, as presented in Figure 9. At first, for a constant flap/gear schedule, IAF and FAF, on the left area of the GUI, the pilot selects the aircraft's mass and the wind velocity, so that the feasible range of the CDA flight path angle is calculated and presented in the light green region of the VSD. Then, the pilot selects the desired flight path angle, which is highlighted with a magenta line on the VSD and the range of the ETA is given in the corresponding slider, by using the minimum and maximum ETA algorithms. The last step to fully define the approach plan is to choose the ETA and the number of IAS steps. Then, the optimization algorithm calculates the IAS commands and their position on the trajectory is indicated on the VSD. They are presented with vertical lines on the VSD

[16], [24] with their labels being above the plot.
When the CDA is fully defined, the pilot initiates the simulation from the GUI and, by tracking in real time the CDA monitoring display, can enter, in the centre section of the CDA GUI, the IAS/flaps/gear commands. If, during the simulation, there is a deviation of the calculated ETA from the RTA, the pilot may opt to re-plan the rest of the approach, for the same flight path angle, on the right area of the CDA GUI, thus a new ETA and number of IAS steps can be defined.

C. CDA monitoring display

During the simulation, the pilot's main focus is to use the designed VSD, which is continuously updated with the background calculations, for achieving the RTA goal. The aim of these calculations is not only to provide a new ETA, using the aircraft's current position and the IAS profile, but also to support the ecological aspect of the interface. This functionality concerns the depiction of the system's bounds and the affordances, such as ETA limits, the RTA and the effect on the ETA of changing the timing of the IAS commands.
In Figure 10, a screenshot of the VSD is presented, following the CDA plan of Figure 9. The aircraft position is represented with a magenta triangle on the upper left corner of the display and stays constant at that position, so the axes of altitude and Along Track Distance (ATD) are updated, as the flight simulation is executed. The IAS commands are displayed in the same way as in the CDA GUI, and move towards the aircraft symbol (triangle) during the simulation. A main characteristic of this VSD is the right panel, which is independent from the trajectory plot [26], and concerns the space of possibilities regarding the time performance. The upper and lower limits of the axis, are the minimum and maximum ETAs accordingly, and they are calculated using the current state of the aircraft. The ETA, based on the future IAS commands and the state of the aircraft, is depicted with a magenta circle on the axis, which has been suggested as an important cue for this type of mission [24]. Finally, the RTA, as defined during the CDA planning, is represented with a green circle of larger diameter and around this value an error bar of $\pm$30s has been placed.
Therefore, the first augmentation of the basic VSD concept with the adoption of EID, is the presentation of the space of possibilities for the ETA and the estimate for the aircraft's current performance in this interval. The subsequent augmentation of the VSD concerns supporting the pilot's cognition, in case of a deviation from the RTA. Since the flap/gear schedule and the values of the IAS commands are constant, then a considered degree of freedom is modifying the nominal timing of the next IAS command and observing the result of this action on the ETA cue. However, the development of mental model for the pilot for this strategy requires the creation of cues that correlate the magnitude of the deviation from the nominal IAS schedule, with the effect on the ETA.
In detail, the background calculations estimate for the upcoming IAS command, the position of the cues that will result to a ± 15 s and ± 30 s change on the ETA. This is achieved by structuring a loop and starting to reposition, in terms of time, the next IAS command from the nominal time step, so when the desired values of ± 15 s and ± 30 s are achieved, the loop is terminated. These cues move towards the magenta triangle, along with the initial IAS commands, and the pilot decides either to enter the new IAS to the autothrottle at the nominal time or to change the timing of this command, if the ETA needs adjustment. Moreover, above the aircraft symbol, a text cue will appear, in order to alert the pilot when the aircraft's velocity is close to deploying flaps/gear. As mentioned in Section III-B, if the pilot cannot reduce a possible time deviation with the assistance of the cues on the trajectory line, then there is the possibility to re-plan the remaining approach in the CDA GUI by taking into account the new wind velocity and the new plan is transferred to the CDA monitoring display.

IV. Experiment Design

An experimental plan was created to get some initial comments from pilots, regarding the usability of the support interface and evaluate if they manage to achieve the RTA goal with the means they are given.

A. Participants

The five Participants of the experiment had licences for different aircraft types, such as Boeing 737/777/787, Fokker 70/100, Cessna Citation II and Single Engine Piston. An ethics approval was granted by the Human Research Ethics Committee of Delft University of Technology. A within-participants experiment design was selected, given the small number of Participants, and the trials had the same order for everyone.

B. Independent Variables

The chosen independent variable is the wind velocity profile used in each trial. During the CDA planning, the pilot is given for each trial a specific wind velocity to use in the GUI and calculate the IAS profile. Then, during the simulation, the wind velocity is either staying constant, hence allowing the pilot to easily achieve the goal, or a deviation from the initial wind velocity starts being imposed at 20% of the total ATD and reaches the final value at 30%. In this way, the ETA cue will diverge from the RTA cue, and the pilot will be forced to use the cues on the VSD to modify the timing of the IAS commands or, as a last resort, to re-plan the approach with the updated wind velocity. The four wind velocity Scenarios that were applied in the main experiment are (the negative values correspond to headwind):

- Scenario 1: Initial -5 kts, Final -5 kts
- Scenario 2: Initial -15 kts, Final -10 kts
- Scenario 3: Initial -10 kts, Final 0 kts
- Scenario 4: Initial 0 kts, Final -15 kts

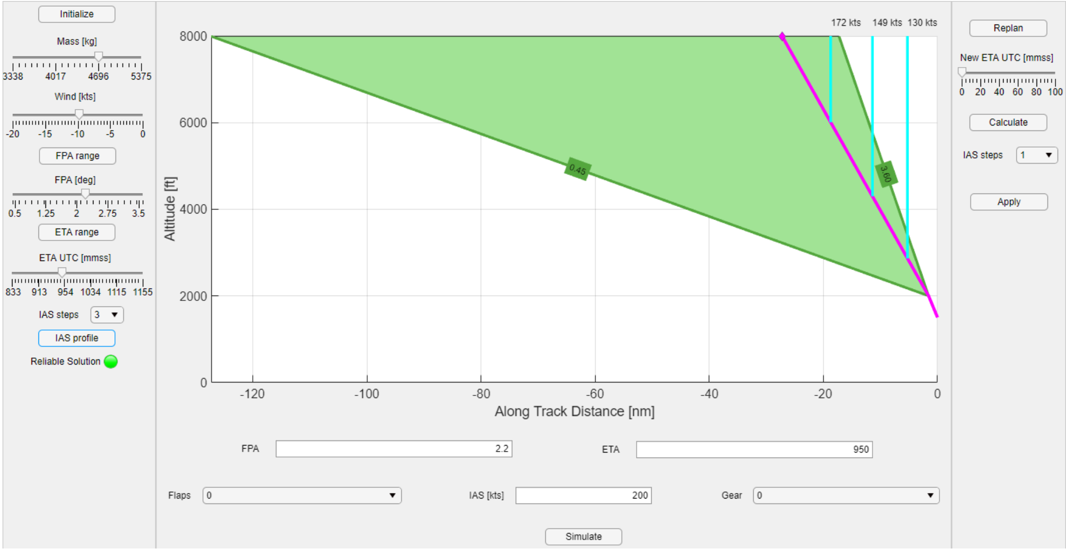

Fig. 9: Example case for the CDA GUI

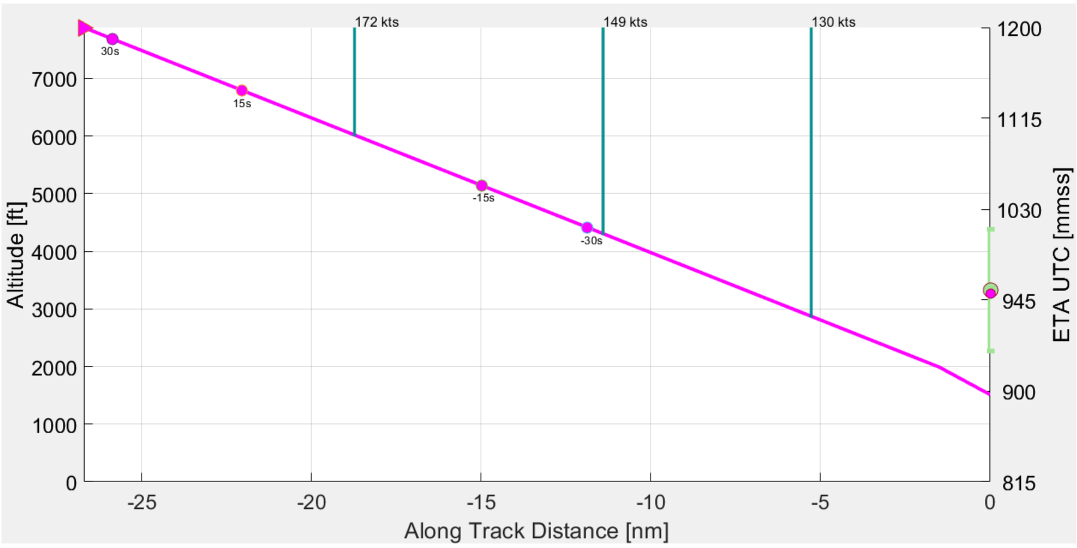

Fig. 10: Example case for the CDA monitoring display

C. Apparatus

The experiment was conducted in the ATM lab at Delft University of Technology. A dual display setup was used at a conventional desktop computer to accommodate the two sections of the pilot support interface, within MATLAB®/Simulink®. In the right screen an altimeter and an airspeed indicator complemented the CDA monitoring display during the simulation, whereas the left screen included the CDA GUI. The aircraft model of the simulation was the same as in the Section II, the Cessna Citation I.

D. Procedure & Scenarios

The experiment started with signing the informed consent form and then reading the briefing document, which includes basic information regarding the displays and then a detailed walk-through of the first training trial. The experiment included five training trials, where for a given aircraft's mass and wind velocity, the pilot had the freedom to select the flight path angle, the RTA and the number of IAS steps, from a provided range. Then, after any questions that the pilot may have and a break, the four experiment trials took place.

Both training and experiment trials included a range of wind velocity (headwind) from 0 to 15 kts, and in particular for the wind velocity deviation, the ratio of the wind deviation to the initial velocity was different for each Scenario. In this way, the divergence of the ETA from the RTA did not have the same magnitude for each of these Scenarios. The experimental conditions are the same as in Table II, apart from the wind velocity that varies depending on the Scenario and the FAF which is at $1,500$ ft with IAS 130 kts. In the main experimental conditions, the RTA was the same (600 s) and the pilots needed to be at the FAF as close as possible to the time goal, ideally within the ± 30 s error interval.

E. Dependent Measures

All the variables associated with the aircraft performance, such as altitude, IAS and time, to determine the Actual Time of Arrival (ATA), are saved, as well as the pilot's inputs during the simulation. In addition, before beginning the experimental trials the pilot was asked to declare any experiences regarding flying a CDA and using a VSD in a flight deck, by completing a questionnaire. After each trial, the questionnaire followed by asking the pilot which cues and functionalities were found to be helpful during the simulation, if a re-plan was performed and how the pilot would rate his/her mental load with the Rating Scale Mental Effort (RSME) (Range: $0 - 150$) [31]. At the end of the experiment, further open questions were addressed to the pilot, regarding the CDA GUI usability, the comprehension of the cues of the VSD and further comments/suggestions for the interface.

F. Hypothesis

It is hypothesized that the pilot will not deviate more than 30 s from the RTA goal in all the Scenarios. Moreover, if there is a deviation from the initial wind velocity and the pilot does not re-plan the approach, the mental load will be higher than the cases, where a re-plan does not take place. Finally, the case where there is not wind deviation, the mental load will be the lowest.

V. Results & Discussion

The results of this experiment come from the flight performance data, which are indicative of the pilots' strategies to meet the end time goal, and from the questionnaire they were asked to fill before the experiment, after each trial and at the end of the experiment. Although the number of Participants is not sufficient to perform a formal analysis, these initial results offer an insight of a potential application of this interface in the flight deck.

A. Flight performance analysis

In the initial overview of the flight performance results, two trials out of the twenty executed (five Participants with four Scenarios) are not considered successful, since at the termination of the simulation they were not below $2,000$ ft with IAS of 130 kts. The first variable that is examined is the ATA that was achieved for each Scenario. The time performance of each trial is presented in Table III. As mentioned in Section IV-D, the approach is planned for an RTA of 600 s, but the trial may stop between $2,000$ ft and $1,500$ ft, so it should be taken into account that all the pilots will be approximately 20 s earlier than the RTA. During the analysis of each pilot's IAS commands, it was noted that they did not use the re-plan function, except from one of the two trials, which has already been excluded. In addition, three out of five pilots opted to

TABLE III: ATA [s] for each Scenario and Participant

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Participant 1	570	588	-	588
Participant 2	590	588	590	589
Participant 3	576	591	573	582
Participant 4	570	570	570	576
Participant 5	567	-	564	582

skipping an intermediate IAS command in order to delay their deceleration and compensate for a time deviation. In addition, one pilot used IAS commands between the nominal values. These strategies were not preferable, although it was not mentioned explicitly in the briefing document. For example, in the first Scenario, since there is no wind velocity deviation, the pilots did not deviate significantly from the nominal IAS profile, as it is demonstrated in Figure 11. On the other hand,

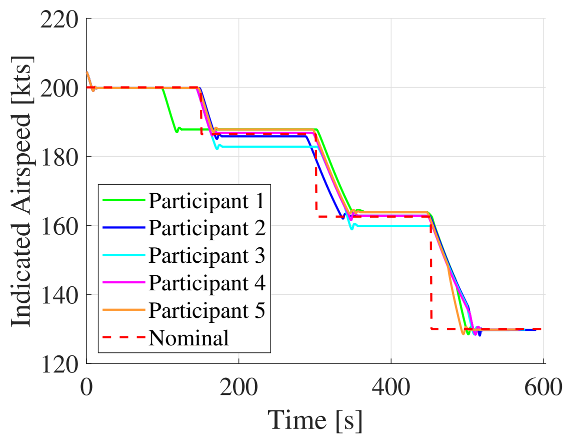

Fig. 11: Nominal IAS profile and corresponding aircraft response for Scenario 1

for the Scenario 4, where there was the highest wind deviation from 0 kts to -15 kts, only Participant 2 used the second IAS command, while Participant 4 decelerated directly to the final IAS. Moreover, in Figure 12, it is demonstrated that all pilots delayed the first deceleration to compensate for the increased headwind, which caused the ETA to increase. For the second Scenario of Figure 13, Participants 2 and 4 have a uniform performance with similar deviations from the nominal IAS profile, while Participant 1 follows the same strategy, except from the last deceleration which is executed earlier than the other Participants. In addition, it is noted that Participant 3 skipped the third deceleration to $158kts$ and selected the final IAS. In the third Scenario, Participant 3 decelerated directly to a velocity close the third IAS command of 162 kts and then to 130 kts. Participants 2 and 5 have a similar IAS response, as it is presented in Figure 14, while Participant 4 seemed to have a different approach to this case.

B. Questionnaire analysis

In the initial part of the questionnaire, the pilots were asked to provide their past experience with flying a CDA and also if they have used a VSD. All of them have performed a CDA,

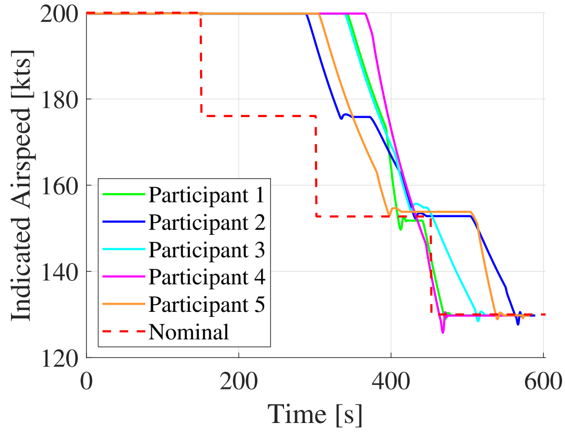

Fig. 12: Nominal IAS profile and corresponding aircraft response for Scenario 4

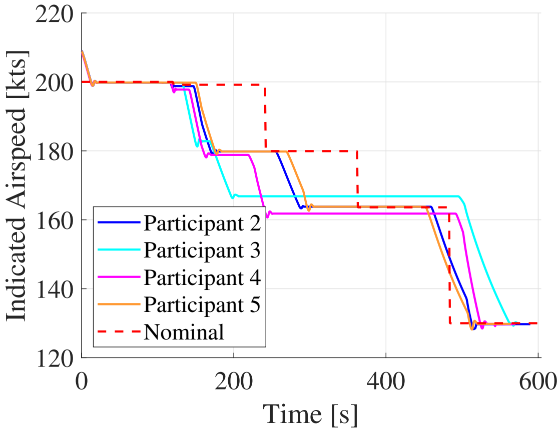

Fig. 14: Nominal IAS profile and corresponding aircraft response for Scenario 3

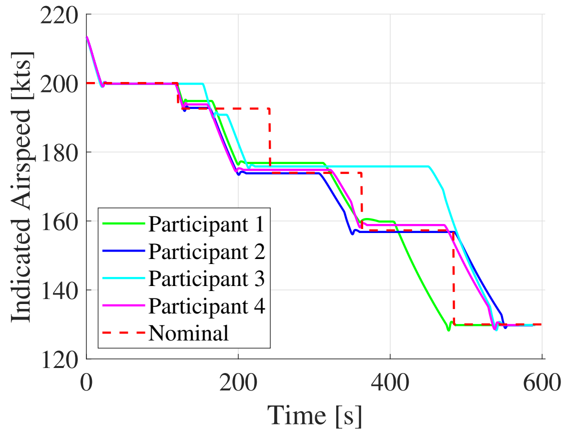

Fig. 13: Nominal IAS profile and corresponding aircraft response for Scenario 2

either for commercial flights with Boeing 737/787 or during past experimental projects with a Cessna Citation II (PH-LAB) and they mentioned that CDA is becoming standard, but it takes place in non-peak traffic hours, without a strict RTA. In addition, one pilot mentioned that each approach is aimed to be a CDA, but the ATC may ask the flight crew to deviate from the optimal flight path. Regarding the VSD, one pilot had not used it in the past, while the others mainly interacted with this type of display in previous experiments for terrain and weather depiction. In addition, this display has been installed in some Boeing 737, but it has found limited use, and in Boeing 787 for the full flight envelope visualization to assist correcting flight path deviations.

After each trial, the pilots were asked some closed questions regarding their performance and strategy during the simulation. In 16 out of the 18 valid trials, the pilots declared that they used the cues on the trajectory line for the early/delayed deceleration and a re-plan of the remaining trajectory was not preferred. When questioned regarding the cues that proved to be more useful to achieve the RTA goal, the pilots indicated the information presented of the right panel (RTA and errorbar, ETA) and the cues on the trajectory line. A subsequent question concerning whether the pilots believed that they achieved the goal of the simulation, the result indicated that, regardless of the Scenario, the pilots agreed that they were successful. Finally, they were presented with the RSME scale and they provided an overall mental load rating for the past trial, as it is presented in Figure 15.

After all the trials, the pilots filled some closed and open questions regarding the overall experience interacting with the two sections of the pilot support interface. It was indicated by their feedback in the closed questions, that they strongly believe in the usage of the time cues on the right panel, while for the cues for IAS and the early/delayed deceleration are also somewhat helpful to achieve the time goal. In addition, it was declared that the CDA planning application gave a moderately good overview of the solution space depicting the flight path angle and the ETA.

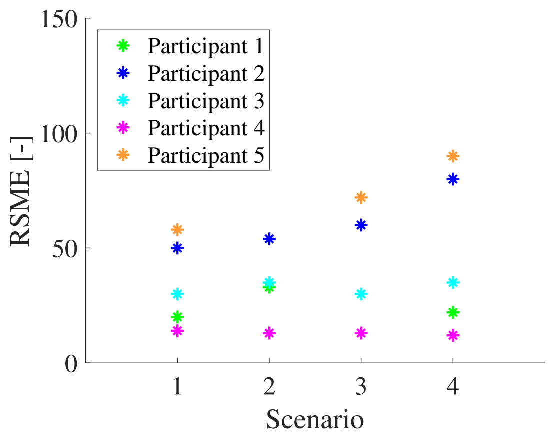

Fig. 15: RSME for each Scenario and Participant

Regarding the open questions, at first the pilots were asked about the CDA GUI and how it can be improved. A pilot indicated that rounded values of IAS could be more easy to use. Furthermore, it was suggested that the selection of the flight path angle should be done for discrete values (i.e. $-2°$, $-2.2°$, $-2.4°$) for the convenience of the pilot and ATC and the number of IAS steps should be decreased to 3 to avoid excess workload. An additional proposal, is to create a wind velocity profile depending on the altitude and not assume a constant wind velocity for the full approach.

The last open questions focused on the CDA monitoring display, as the most complicated object of the experiment and which elements of it were not used or needed to be altered. It was mentioned that the flap/gear text cue was easy to be missed and the errorbar around the RTA may have been superfluous. In addition, on the time axis, the ETA value and its deviation from the RTA could be also printed as numerical values and it was proposed, from the majority of the pilots, that is more convenient to have a fixed time scale and not continuously adapt the axis limits and consequently the intermediate values. Moreover, it was noticed that as soon as the next IAS command reached the aircraft symbol, its cues for a delayed deceleration would disappear, so that the calculations for the upcoming command can take place and be presented, but this proved not to be convenient. On this topic, it was also recommended that a single cue on the trajectory line, which will minimize the time deviation, can be depicted to avoid confusion and show a trend arrow on the ETA cue to demonstrate the immediate effect of a pilot's IAS command. In terms of general presentation of the trajectory, it was recommended to have the flexibility to zoom in/out on the ATD axis and it was proposed to investigate if the VSD is definitely needed for this mission, or the cues can be incorporated in the existing displays of flight deck.

C. Discussion

The main goal of each simulation, being in FAF at the set RTA, is achieved in accordance with the hypotheses, as it is demonstrated in Table III, since an ATA of 580 s is expected. The earlier termination of the simulation is attributed to the fact that the trajectory calculation algorithms, may not converge to the desired final state when the aircraft is very close to the calculation stopping point ($1,500$ ft) and the simulation will terminate between $2,000$ ft and $1,500$ ft. Although at that point in flight, the future trajectory and the ETA bounds will be of limited use, a potential solution could be a higher time discretization for this segment of flight or stop updating the VSD in the last $1-2$ nm.

Regarding the performance of the pilots, as depicted by the aircraft's IAS response, it is concluded that apart from the alterations of the nominal IAS values, the pilots had, in general, similar strategies in the experimental Scenarios. Moreover, if Table III is correlated with the IAS responses, then it is noted that two pilots may follow the same strategy in a Scenario, but they can have a different ATA, due to the fact that their corresponding simulations ended at different altitudes, within the $1,500-2,000$ ft interval.

One of the aims of the experiment was to use the calculated IAS commands and manipulate their execution timing if needed, but not to change the number or the values of these steps or skip a command, as mentioned in Section V-A. In addition to this practice that was observed in 3 pilots, nearly all the pilots asked whether their usual practice of adapting the flap/gear schedule in the pursue of managing the deceleration can be applied in this experiment, but also this tactic was contradictory with the main assumptions of the project.

The CDA, as it is becoming more common in commercial flights, according to the pilots' supportive feedback, demonstrates again that there is a need of executing this approach in a timely manner. While the VSD is not yet widely incorporated in flight decks, the pilots seemed to be a bit skeptical about its use and insist on fully defining its role in the flight procedures. During the simulation, the pilots proved that they can work with the augmented VSD and by adopting their experience and the logic of the IAS and time cues, were able to fulfill their role. In the end of each trial, the usage of the RSME, as a subjective indicator, resulted in a wide range of scores for the same Scenario, proving that each pilot has a different perception and thresholds regarding the mental effort and the workload in general. Participants 2 and 5 had an upward trend of their workload as the Scenarios proceeded, since the deviation from the initial wind velocity was increasing and it could pose additional difficulties to manipulate the ETA.

During the simulation, the pilots experienced firsthand the interaction with this novel display and in combination with their past commercial and research flying experience, provided remarks and suggestions. As it is mentioned in Section V-B, the time axis has an important role in meeting the RTA goal, but it needs some improvements in terms of its cues, their exact position and the scaling of the axis. A first solution could be to have a constant time scale and create minimum/maximum ETA cues able to move, as the ETA cue. Moreover, it was recommended that the flap/gear cues should be more discernible, and maybe they can be presented on the PFD [23]. In addition, the cues on the trajectory line, regarding the early/delayed deceleration, should be reconsidered, so a cue leading to the optimum solution may be presented too or to provide a shorter solution space for all the IAS commands, not just for the next one. Therefore, as the next step for this project could be the adaptation of the pilot support interface in a regular flight deck setup, the distribution of more cues in the standard displays can be performed. In addition, this implementation has to accommodate both segments of the pilot support interface (planning and execution) and, as suggested by a pilot, if the VSD concept is maintained, it should be aimed to fit it on the Navigation Display.

VI. Conclusion

In this project, the concept of executing a CDA with an end time goal was facilitated, by creating a pilot support interface. While keeping the flap/gear schedule and the flight path angle constant, further possibilities were investigated to define the solution space for the ETA and the IAS commands that lead to a RTA. This trajectory was analyzed through its fundamental equations of motion, which proved their accuracy, in terms of the ETA, and created the basis to structure the pilot support interface.

An augmented VSD for both planning and executing the CDA was designed by depicting the space of possibilities for the flight path angle for the former and for the latter focusing on depicting the ETA and the time performance constraints. An experimental session took place to evaluate the effectiveness of the interface to achieve the end time goal, through a simple experimental setup allowing to plan the CDA and then, during the flight, to monitor the VSD, while interacting with the autothrottle and the flap/gear settings. The overall time performance of the pilots was satisfactory, without experiencing high mental effort during their task. Moreover, the participating pilots followed the logic of the provided cues during the simulation, and showed in general a flexibility to adjust to a different strategy in approach procedures, but proposed some changes in the depiction of the cues for future iterations of the interface. This proved that the main frame of augmenting the basic VSD accommodated the needs of executing this approach, in particular the elements of presenting the time constraints, the deviation from the goal and the potential changes to the nominal IAS command timing. Having the developed trajectory calculation algorithms and the calculation logic of the VSD elements as a starting point, this pilot support interface can have its two segments combined in the next phase of development. This will be done by considering the current avionics capabilities in the flight deck and possible extensions of their basic operation. In addition, the already encountered trajectory calculation limitations and assumptions can be addressed, in order to substantiate the robustness of the interface and ensure its reliability. In addition, the optimization procedure that took place during the planning phase of the CDA to define the IAS profile, can be further developed, so it can be executed also during the simulation and its outputs will correspond to the current state of the aircraft and the external conditions. A higher level of interaction between the pilot and the display during planning and execution can be considered and alternative forms of velocity profiles for the selected RTA can be evaluated, for instance to have a different time duration of each IAS step. Then, the suggestions from the pilots' side and more improvements of the underlying codes can be incorporated to the interface, so it can be installed into the flight deck and perform a full scale flight simulation experiment. Therefore, the participating pilots will be in a familiar setup and extract more accurate metrics in terms of their performance.

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II
Preliminary Report, previously graded under AE4020

1
Abstract

This literature study addresses the concept of Continuous Descent Approach (CDA), which, as it was proven in research projects of the last 20 years, can reduce aircraft noise emissions and fuel consumption. The main issue, concerning CDA and limiting its use to low traffic conditions, is the lack of trajectory predictability and eventually the time of arrival, thus imposing an increase in landing intervals. A suggested solution is to develop a pilot support interface with the objective of facilitating the execution of a fixed flight path angle CDA under a set time of arrival. This project separates itself from previous work, since thrust level is not bounded to idle, as in a classic CDA, and this adds the flexibility of planning and following a velocity profile which will lead to a target Estimated Time of Arrival (ETA). Initially, the trajectory of CDA is investigated from a fundamental kinematic point of view and the solution space in terms of ETA is defined. Following the validation of this system modelling, using the response of a full aircraft model, the subsequent step is to analyze the human-machine interaction and the work environment, in the frame of Cogntive Work Analysis (CWA). CWA facilitates the identification of the system's constraints, the tasks to be executed and the distribution of roles between humans and automation. This thorough analysis leads to designing a pilot support interface based on the principles of Ecological Interface Design (EID), which focuses on presenting the space of possibilities and supporting human cognition. The validation of this proposed approach can lead to the potential application of CDA in real life flight conditions, without limiting itself to low traffic airports or certain time frames.

2
Introduction

This chapter sets the foundation for the development of this Literature study project, beginning, in Section 2.1, with the explanation of the conditions that led to the formulation and analysis of of Continuous Descent Approach (CDA). Then, in Section 2.2, the incentives and the results of further understanding and testing in real life conditions this type of approach are mentioned, as well as, what differentiates this project. Finally, the main research questions and the resulting subquestions are formulated in Section 2.3 and the Literature Study's structure is mentioned in Section 2.4.

2.1. Background

Nowadays, the air traffic density in Europe is steadily increasing and many airports/hubs operate at (nearly) full capacity, as stated in a recent report by EUROCONTROL et al. [2019]. Each civil aviation authority, that experiences this traffic surge, tries to balance the assigned time slots (taking into account the separation minima) and respect the regulations regarding noise effects and engine emissions. Regarding the emissions, in the Paris Agreement, the main commitment was to keep below $2°C$ the increase of the global average temperature, and as estimated by Terrenoire et al. [2020], staying aligned with this goal, in 2050 the impact of aviation of the total human-caused warming will be $1.4-2\%$, instead of 5.2%. In terms of noise effects (airframe and engine noise), as summarized by Girvin [2009], there are different categories of restrictions, targeting at first the manufacturers during the certification phase of an aircraft and then the airports' side, for instance imposing a noise limit per aircraft movement, cumulative noise limits or a noise tax. The impact of the aforementioned effects is more apparent, when the aircraft is closer to the ground, hence during takeoff and approach/landing, therefore these phases are a common subject of further investigation and optimization.
Taking into account that during takeoff, the aircraft gains altitude with a high rate, the attention is shifted towards the approach where the aircraft flies at a lower flight level for a longer period of time. However, the approach procedures of an aircraft from cruise level until touchdown use, in general, the same navigational aids for the past decades such as Instrumental Landing System (ILS), Very high frequency Omnidirectional Range (VOR), Non-Directional Beacon (NDB) and Distance Measuring Equipement (DME). This fact did not impact the research done in the aerospace industry, which has enhanced the aircraft's capabilities regarding navigation, for example the Global Positioning System (GPS) and the

Flight Management System (FMS), and can execute more complex procedures and trajectories. In this domain, Avery [2011] mentions that the current research goals of the main FMS manufacturer, Honeywell, are related with the Single European Sky Air Traffic Management Research (SESAR) program and include 4-D navigation, trajectory optimization and usage of Automatic Dependent Surveillance - Broadcast (ADS-B) for autonomous aircraft separation. The usual path, that an aircraft follows from the Top of Descent (ToD) until the interception of the ILS Glideslope (G/S), includes step-down descents and level flight segments and it is shaped according to Air Traffic Control (ATC) commands, in order to create traffic flows with uniformly decelerating aircraft. This logic is convenient for ATC, since it facilitates the aircraft sequencing towards the final descent, as it is described by In 't Veld et al. [2004].
Another concept that has been proposed, investigated and applied in some airports is the Continuous Descent Approach (CDA), with the initial goal to mitigate the noise footprint of air traffic. One of the first analyses of CDA took place at the National Aerospace Laboratory NLR by Erkelens [1998], as a possible Noise Abatement Procedure (NAP) for Schiphol International Airport (AMS/EHAM). CDA is defined by EUROCONTROL [2008] as:

> *"Continuous Descent Approach is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and ATC instructions."*

In this approach trajectory, the aircraft's trajectory maintains higher flight levels for a longer period of time and intercepts the G/S without having level flight segments, as it is depicted in Figure 2.1.

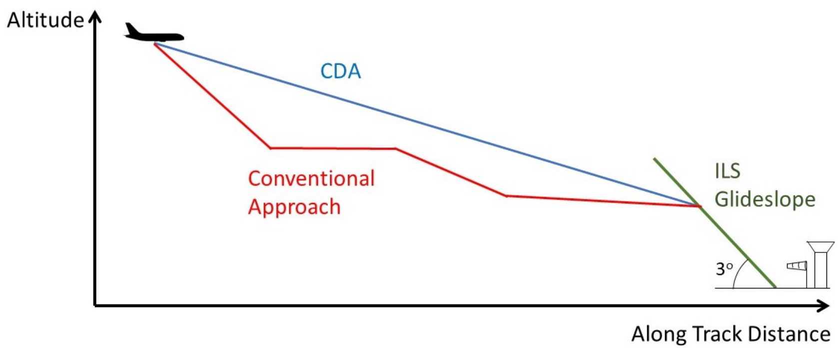


Figure 2.1: CDA and conventional approach trajectories

These trajectories are executed within the Terminal Maneuvering Area (TMA), which is a circular control area around the airport and its ceiling can reach 10500 ft. The radius of TMA depends on the altitude and it is narrower close to the airport, as described by Janssen [2019], so it has a conical shape. An aircraft reaches the TMA through a predefined approach route, as it is assigned by the ATC, the Standard Terminal Arrival Route (STAR). These maneuvers, that happen closer to ground level and have the highest impact concerning the noise and emissions footprint, led to the development of alternative solutions, such as the CDA.

2.2. Incentives to apply CDA

After the initial presentation of CDA, it has been proven that CDA mitigates the noise level and fuel consumption along the approach routes using different research methods. This concept was tested in computer simulations using aircraft performance data by Inaad [2016], Janssen [2019], NLR et al. [2001], Wubben and Busink [2000] in European airports varying in traffic load. In addition, more realistic conditions were examined in actual flight tests by Clarke et al. [2004], De Prins et al. [2007], Gerber et al. [2020], Schippers et al. [2005] and sessions in flight simulators by De Prins et al. [2007], In 't Veld et al. [2004, 2009].
Janssen [2019] reported that through an optimization procedure, including the approach trajectory and arrival scheduling for a CDA, the total fuel consumption can be reduced by 2.2 – 4.8%. That project was set up as a simplified problem of Schiphol International Airport (single runway) using aircraft performance data with the goal of fuel economy and time punctuality. In another study, conducted by Inaad [2016], CDA simulations were executed for specific flights and aircraft types, having as the main target the fuel economy, and then the results were compared to actual flight data from conventional approaches. The comparison revealed that the fuel saving was quantified as 92 kg up to 500 kg per flight and using the example of Schiphol International Airport this summed up to 39 million kg of fuel per year. In the early stages of the development of CDA, the computational model of Wubben and Busink [2000], which used actual flight data, had as an outcome a 25 – 40% reduction of fuel consumption and a 30 – 55% lower noise footprint. In terms of noise effects, the research program of NLR et al. [2001] expanded the initial concept of CDA with more options and capabilities, such as manipulating the flight path angle, velocity profile and thrust level. In these simulations, NLR et al. [2001] used aircraft performance data from the manufacturers, executed trajectory simulations for four European Airports and demonstrated that the noise footprint is reduced up to 50%.
Clarke et al. [2004] validated this result, where after the preliminary design of their project, at first the designed flight path was flown in a flight simulator to determine the FMS settings and pilot procedures of a conventional approach and the CDA and afterwards the actual flight tests were executed. That project revealed even better performance (reduction of 3.9 – 6.5 dBA, where −3 dBA is -50%) in Louisville International Airport, where the frequent cargo flights during the night provoke noise complaints from the neighbouring areas. Recently, Gerber et al. [2020] executed 70 CDAs in Zürich International Airport (ZRH/LSZH) and compared the performance between a baseline case, where the pilot tried to execute a CDA with the goal of being eco-friendly and quiet, and flying with an assistance display (Low Noise Augmentation System), which calculated the optimum trajectory and configuration to achieve that. It was demonstrated that the trajectories flown with the assistance display were more consistent, as well as having enhanced fuel consumption and lower noise emissions.
As it has been done by the flight tests of Clarke et al. [2004], Gerber et al. [2020], the operational details of CDA have been examined in terms of the actual steps that the pilot has to take, mainly concerning the flight path angle, energy management and deployment of flaps. So far, the main principle of CDA was to execute the trajectory while having the thrust levers set to idle. Therefore, the free variables, that are left to be manipulated/optimized are the flight path angle, the time at which the pilot will reduce thrust to idle and the velocities at which flaps will be deployed. However, in some studies by De Prins et al. [2007], In 't Veld et al. [2004, 2009], Janssen [2019], Schippers et al. [2005] there is the additional parameter

of tracking the preceding aircraft's trajectory in order to maintain safe separation, but in this project this issue will not be examined.
De Prins et al. [2007], computed a 3° CDA trajectory by using a simple point mass kinematic model and optimizing the flap velocities and thrust cutback altitude (thrust set to idle) to reduce the noise footprint and maintain safe separation. Then, the validation took place in three stages, firstly with Monte-Carlo simulations of the optimization algorithm, which demonstrated a good performance and robustness in wind, mass and flight characteristics estimation. Then, with the assistance of cues in the flight displays (PFD and navigational display), flight tests in an actual aircraft, as well as in a flight simulator, were conducted and demonstrated that the computational model can be applied to real life and the developed pilot support interface reduces the pilot's workload. Clarke et al. [2004] examined three cases of flight path angle in the preliminary simulations, namely $2°, 2.5°, 3°$, but the difference of impact in noise footprint, which was the objective of the experiment, at their corresponding results was not significant and the 2° was chosen.
It has also been considered in another case study by Sopjes et al. [2011], that the flap velocities can be constant, but then the flight path angle is a free variable. This methodology can be more convenient for the pilot, who prefers to keep flap deployment velocities at a narrow range and secondly if flaps are extended close to their corresponding maximum operating velocities, it can lead to extensive wear. In that project, Sopjes et al. [2011] performed a flight simulator experiment to test the effectiveness of a Vertical Situation Display (VSD) to show the range of flight paths that the pilot can take during the CDA. In the case of having the flight path angle and flap velocities as free variables, Gernaey [2005] proposed that the pilot, with the assistance of a new display, will be able to know the available control space and decide on the decelerating strategy depending on the aircraft's total energy. Considering the additional difficulty of the free flight path angle, Gernaey [2005] examined a modified 3° CDA which can make easier the trajectory prediction. The aircraft in this case intercepts the "extended" 3° ILS G/S and initially maintains its velocity and as it gets closer to the airport, it starts decelerating so the landing configuration can be implemented. Then, de Beer et al. [2008] used this concept of modified 3° CDA and altered the total energy display to a VSD to support the pilot.
However, in the first stages of development of CDA, it was noted by Erkelens [2000] that the execution of this approach results in the augmentation of landing interval from 1.8 minutes to 4 minutes, due to the uncertainty concerning the Estimated Time of Arrival (ETA). The flight tests of Clarke et al. [2004] concluded too that this procedure cannot be applied in peak traffic times, due to the lack of future trajectory prediction. A solution to this problem was proposed in the work of De Prins et al. [2007], Schippers et al. [2005] using a 3° CDA with a flap scheduling algorithm to appropriately space the incoming aircraft, but as it was already mentioned, it is preferable to use a nominal flap schedule. In another version of CDA, the incoming aircraft have the freedom to change their flight path angle during approach, as tested for example by Sopjes et al. [2011] to meet an end time goal, but then as it is pointed out by Gernaey [2005], the task of ATC to maintain separation becomes more difficult and the landing intervals have to be increased. In detail, EUROCONTROL [2019] proposes that the predictability can be analyzed in two ways: from the ATC point of view, which does not know if their command will be executed immediately by the pilot or how the deceleration profile of a particular aircraft will be. In addition, from the pilots' point of view, it can be concluded that it is not always up to them to decide when they can

start their descent or which approach route they will follow. This can lead to uncertainty of whether safe separation can be maintained and the exact time of arrival that will eventually be achieved.

2.3. Problem Statement

Taking into account the already applied concepts, the benefits concerning the noise emissions and fuel economy and their results concerning the flight operation, it can be concluded that there are some ambiguous points in order to come up with a more pilot/ATC friendly and time punctual execution of CDA. The transition from a 3-D approach, hence the trajectory in space, to a 4-D concept with the addition of time has been implemented by Ruigrok and Korn [2007], as a version of Advanced Continuous Descent Approach (ACDA). This trajectory is fully executed by the FMS, which takes into account the initial conditions, the aircraft's performance, the present and forecasted wind conditions and leads the aircraft from ToD to the interception of G/S and ultimately reaching the RTA goal. However, some uncertainties, such as different weather conditions, traffic conflicts or even an automation malfunction can occur during this approach and the aircraft cannot follow accurately the originally planned path, so the pilot will have to take action. In this case, if nearly all the procedures are taking place in the background without maintaining an appropriate situation awareness, then it will be difficult for them to intervene if needed, as it is analyzed by Mulder et al. [2017]. A suggestion for this timing issue is to modify the strict CDA definition of having idle thrust and explore different velocity profiles, thus giving the pilot extra freedom. Indeed, the research project of NLR et al. [2001], which applied the ACDA concept, added some flexibility to the parameters of the approach, such as the flight path angle, velocity profile and thrust setting. In particular, NLR et al. [2001], confirmed that if variable thrust is used to follow a designated velocity profile, then the trajectory of the aircraft can be calculated beforehand, hence having an accurate ETA.
The concept for the operation of this approach concerns controlling the aircraft's trajectory starting from the IAF upon entering the TMA until the FAF at the landing runway's threshold. The ATC will have informed the pilot for the RTA at the FAF, so the pilot will be able to define the trajectory regarding the deceleration of the aircraft, starting from the choice of the CDA's flight path angle. During this process, the pilot remains on a supervisory role and interacts with the aircraft through automation, hence the autopilot. Therefore, the goal is to plan and then monitor the aircraft's descent and deceleration in order to be in at the FAF at the designated time with the appropriate aircraft configuration. During the execution, the pilot's main task is to apply new commands concerning the aircraft's IAS and lower the flaps and gear, whose deployment velocities remain around at their nominal value to avoid confusion and extensive wear. The final step before forming the research question is to define how to organise and present this information to the pilot during the approach. The information, such as the limits of ETA and flight path angle and the commands to be followed to achieve this goal, can be either presented as cues in an existing display, like the Primary Flight Display (PFD) (De Prins et al. [2007], In 't Veld et al. [2004], Schippers et al. [2005]), or design a new interface for this purpose (de Beer et al. [2008], Gerber et al. [2020], Gernaey [2005]).
Regardless of the display configuration, the analysis of this complicated human-machine interaction will follow the principles of Cogntive Work Analysis (CWA), as explained by Vicente [1999]. This methodology has been already applied in related studies, by de Beer

et al. [2008], Gernaey [2005] in the field of CDA and it is divided in five steps, which will be analyzed in a subsequent phase of this project. In addition, the analysis framework that CWA delineates, is closely related to Ecological Interface Design (EID), as it was proposed by Rasmussen and Vicente [1989] and then further substantiated (Vicente and Rasmussen [1992]). Rasmussen and Vicente [1989] elaborated EID by suggesting an approach to interface design which will depict the abstract properties and the constraints of a system in easily perceptible way for human operators. Having formulated the aspects of CWA, then elements of EID will be used to form the pilot support interface prototypes, as it is more focused on design (Amelink [2010]). In particular, Borst et al. [2015], van Paassen et al. [2018] have investigated the impact and implications of EID in aeronautical applications in the first 25 years of its application, such as ATC support tools and flight deck interfaces. van Paassen et al. [2018] concluded that EID eventually is used towards planning and controlling a system and not troubleshooting a potential anomaly and Borst et al. [2015] suggested that the advancement of technology has offered a wide range of input information, but the goal, not only from EID's perspective, is not to find a way to project all the available data to human operators, but to use this information to support them in the decision making process.
Having taken into account the aforementioned suggestions, the main research question can be posed:

> "Is a fixed flight path angle CDA under an end time goal, feasible to be performed by the flight crew, with the assistance of a pilot support interface?"

Splitting this project into sections from the analysis of a CDA trajectory to the design of the interface, then some subquestions arise:

1. What are the developments of CDA during the last 20 years?
   - Which are the benefits in terms of noise emissions?
   - Is the fuel consumption concerning this segment of the flight less than a conventional approach?
   - Which are the disadvantages of the CDA?
   - Which are the proposed enhancements to the initial concept?
2. What are the methods to analyze a CDA in terms of aircraft performance?
   - Is the trajectory studied from an energetic point of view or through kinematic equations?
   - Which are the set and free variables of the problem?
   - How the minimum and maximum ETA to FAF are calculated based upon the aircraft's state?
   - What are the differences in the trajectory analysis when using a full nonlinear aircraft model compared to a point-mass model?
3. What are the types of CDA that are applied nowadays in actual flights and how are they performed?

- What are the actions that the pilot takes to follow the fixed flight path angle CDA and in what order?
- Which are the interfaces and systems of the flight deck that the pilot uses during the CDA?
- Which are the differences from a conventional approach procedure?

4. When considering a fixed flight path angle CDA with a set end time goal (RTA), how the pilot can be assisted to execute the approach?

   - Which aircraft states and other types of information should be presented to the pilot during this phase and how these variables are presented?
   - Are both novel display(s) and cue(s) in the existing display(s) needed?
   - What should be the pilot's interaction with this novel interface while planning and then executing the CDA?

2.4. Report Structure

The subsequent Chapters of the Literature Study follow the steps that were taken in the actual project analysis. So, Chapter 3 describes the model that was applied to investigate the kinematics of the CDA in order to set up the solutions space and the target trajectory. Then, Chapter 4 includes the five step analysis required to investigate all the aspects of the human-machine interaction needed to execute successfully with time punctuality a CDA. Finally, in Chapter 5, two types of displays that have been used in similar applications are introduced and then an initial design of a pilot support interface for planning a CDA is presented.

3
Trajectory Analysis

This Chapter encapsulates the steps taken to examine the CDA in terms of the actual trajectory of an aircraft model. Firstly, in Section 3.1 the aircraft model is formulated and in Section 3.2 the main trajectory calculation algorithm is explained. Then, the two boundary cases defining the solution space, in terms of the ETA, are explained in Section 3.3, as well as the target case, which leads to the end time goal in Section 3.4. Then, two levels of simulating the aircraft's trajectory are presented with the appropriate Figures, starting from the simple point mass model in Section 3.5 and afterwards using the full nonlinear model in Section 3.6, as validation of the previous one.

3.1. Aerodynamic model

The analysis of CDA and the range of feasible solutions requires the calculation of the trajectory of the aircraft, so the ETA can be defined, given the current state of the aircraft. This calculation has been formulated with an energy dissipation approach by Gernaey [2005], as well as with the classic Newtonian equations of motion by De Prins et al. [2007], In 't Veld et al. [2004]. In general, the range of feasible solutions can be enclosed by the most gradual deceleration and the most steep deceleration, so the minimum and maximum ETAs are calculated. Moreover, the flaps and gear deployment velocities remain constant at their nominal values, as mentioned in Section 2.3.

For this project, the trajectory of an aircraft that executes a CDA can be simulated with a simple aerodynamic model. This model can be further extended to include the interception of the G/S of the ILS and ultimately reaching the runway's threshold at 50 ft Above Ground Level (AGL). In this calculation algorithm, the aircraft is assumed as a point mass and the equations of the symmetric model are considered, as performed by In 't Veld et al. [2004]. Therefore the aircraft is aligned with the runway and in addition its mass remains constant and there is no wind.

The aircraft type that is used to calculate its trajectory for this approach is a Cessna Citation I, which is the basis of the Delft University Aircraft Simulation Model and Analysis Tool (DASMAT). DASMAT's main goal is to assist flight mechanics research, as it contains the aerodynamic and propulsion characteristics of Cessna Citation I. The basic specifications of this aircraft are mentioned in Table 3.1.

Model Specification	**Value**
Length	13.26 m
Wingspan	14.325 m
Wing Area	24.99 m^2
Empty Weight	3338 kg
Maximum Takeoff Weight	5375 kg
Maximum Mach number	0.705
Range	2460 km

Table 3.1: Cessna Citation I Specifications

The computational model consists of 12 nonlinear equations of motion, assuming a rigid aircraft with constant mass and a flat non-rotating earth. In addition, it incorporates an atmospheric model as well as optional capabilities such as wind and turbulence and it has already provided a platform to perform similar studies in the past from De Prins et al. [2007], Gernaey [2005], In 't Veld et al. [2004]. This simulation tool operates in Simulink®/MATLAB® and can perform both offline simulations and online simulations.

3.2. Equations of Motion

The aircraft (as a point mass) can be depicted in descent with the forces acting on it, as in Figure 3.1.

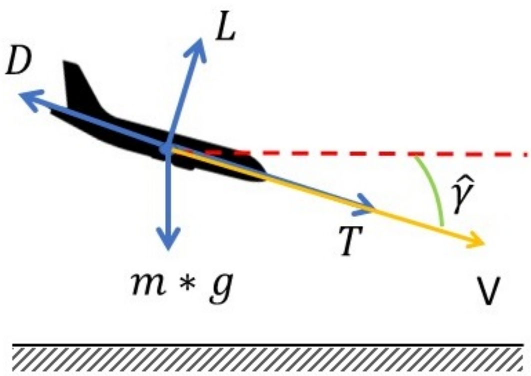


Figure 3.1: Force diagram of the point mass model

Assuming a small angle of attack α ($T \cdot cos(\alpha) = 0$, $T \cdot sin(\alpha) = 0$) and a constant flight path angle γ, then the equations of motion are:

$$\Sigma F_x : m \cdot \ddot{x} = T + m \cdot g \cdot sin(\gamma) - D \tag{3.1}$$

$$\Sigma F_z : 0 = L - m \cdot g \cdot cos(\gamma) \tag{3.2}$$

The aerodynamic forces in the Equation 3.1 need to be calculated for different flight conditions at each time step , so external data about the aircraft model are needed. The force of lift, as it is obtained from the Equation 3.2 it is used to calculate the coefficient of lift, as in

Equation 3.3.

$$C_L = \frac{L}{\frac{1}{2} \cdot \rho \cdot S \cdot V^2} \tag{3.3}$$

The flaps of the aircraft can be set in three different positions (0°, 15°, 40°) and also, during the last phase of the approach, the landing gear can be deployed.
The coefficient of drag C_D is calculated by using the coefficient of lift C_L as a parameter in different flight conditions, as formulated by De Prins et al. [2007] (Table A.1 in Appendix A). Moreover, maximum thrust for each Mach number is obtained from DASMAT (Figure A.1 in Appendix A), and it can be calculated for all flight levels as it is multiplied with the ratio $\frac{P_a}{101325}$. Having the maximum value of thrust, then in the same time a minimum value of thrust can be defined as a percentage of the maximum for the corresponding flight condition.
The calculation of the aircraft's trajectory is executed in a loop for each time step until the target altitude is reached. In addition at the target altitude, the goal is to have a final IAS within certain bounds. The logic of the algorithm is presented in Figure 3.2.

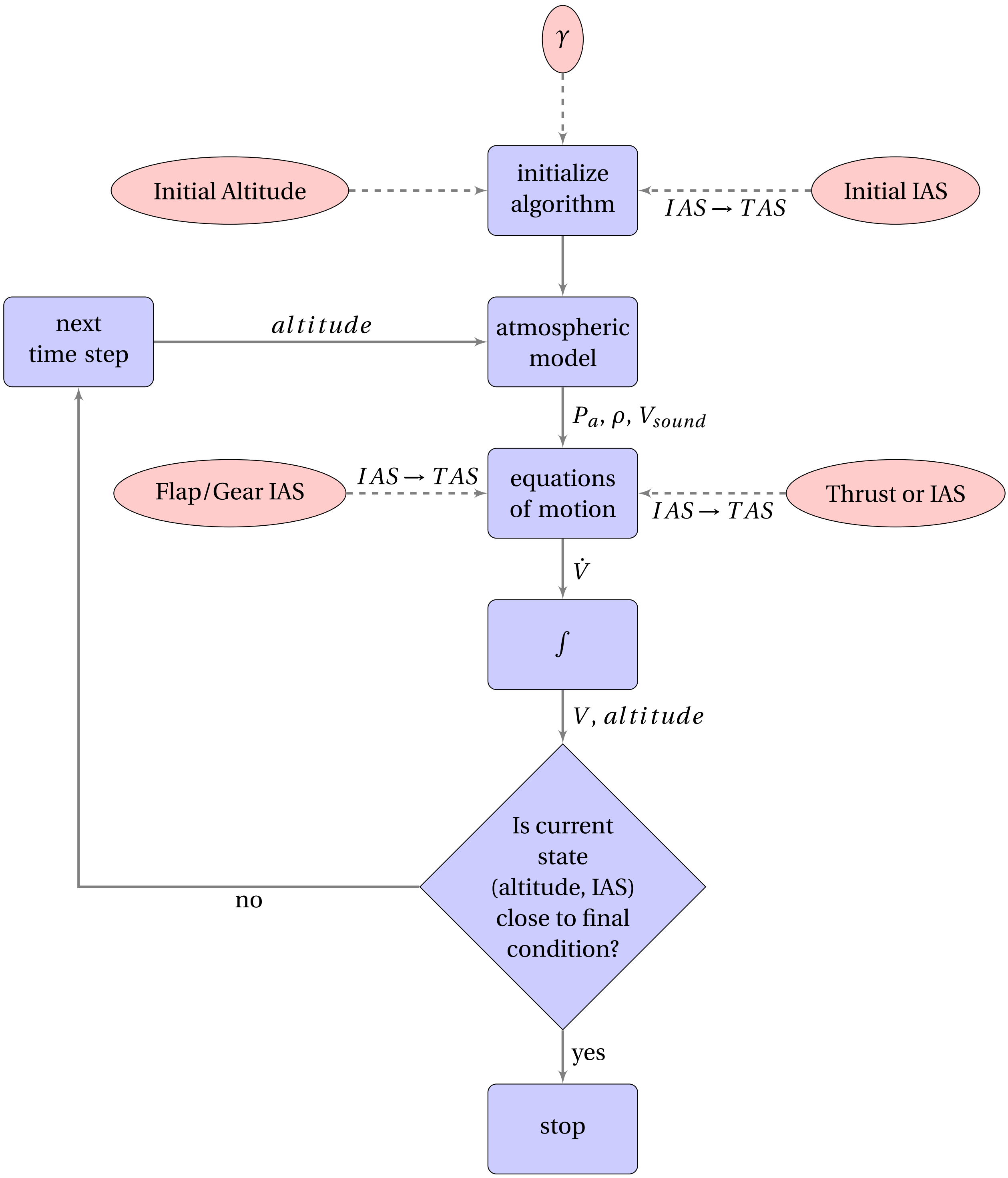


Figure 3.2: Trajectory algorithm flowchart

The difference of this algorithm compared to its previous applications by De Prins et al. [2007], In 't Veld et al. [2004] is that, in the past, the input of the algorithm was the idle thrust, as it was calculated for each flight condition, in the same way as C_D. However, in this study the thrust level can be a free variable and sometimes the algorithm should have the possibility of switching the input of the next time step from thrust to velocity and vice versa. For instance, if the aircraft during its descent decelerates to its final velocity bounds

before reaching the target altitude, then the algorithm should switch from imposing a minimum thrust value for each time step to keeping the IAS (converted from TAS) within the desired bounds until the final altitude.
Another parameter that can be adjusted for this algorithm is the calculation direction. The algorithm can start from the Initial Approach Fix (IAF) and when the Final Approach Fix (FAF) conditions are met, it stops (forward calculation) or it can start from the FAF and calculate back until the IAF conditions are reached (backward calculation). The change between the two algorithms can be easily done by switching the initial and final conditions and add a minus at the left hand side of the Equation 3.1. Both calculation directions were initially considered in this project, since they offer different advantages.

3.3. Boundary cases calculation

As it is mentioned in Section 2.3, one of the objectives of this project is to offer the pilot an overview of the possible ETA according to the current state of the aircraft. Therefore it is useful to calculate the two trajectories that result to the minimum and maximum ETA.
The maximum ETA will result from imposing immediately in the trajectory calculation the target final velocity. This will result to a steep decrease in thrust to its minimum value. Then, thrust is kept at this level until the aircraft decelerates within the desired bounds of final velocity of FAF. At this last phase, the algorithm will shift back to keep constant the IAS until the target altitude. So, in this case the moment to impose a deceleration to the target final velocity is known (next time step) and the forward calculation logic fits this concept.
However, the minimum ETA can be achieved when the current IAS is kept constant and a deceleration is imposed with the highest possible delay, which it will still result in reaching the target altitude and final velocity of FAF. This trajectory calculation can be done with a forward calculation and investigate sequentially all the possible deceleration profiles until reaching the one, which after that the final target cannot be met. However, this method will result in higher computation time. Consequently, the backward calculation can be tested, since it starts from the FAF conditions and it keeps the minimum thrust level, until it reaches the desired IAS of the IAF and then this velocity is kept until the target altitude is reached. However, the backward calculation starting from the threshold up to the IAF presented some discrepancies when a flaps change was applied, which affected the coefficient of drag, caused a drop in velocity which rolled back the flaps change. So, another method was implemented to calculate the minimum ETA, in particular applying the forward calculation but not evaluating sequentially all the possible time steps to decelerate.
This algorithm is based on the logic of the bisection method to find the last possible time step to reduce thrust to idle and be at the Final Approach Fix (FAF) with the desired velocity, so it is required for the trajectory to be calculated at three points in each loop. For the first repetition, the first point to calculate the trajectory is the earliest deceleration possible, hence at $1s$, the third point is the latest point for deceleration, so an extreme time point is taken (for example $3600s$) and the second point is the average of the first and third time points (for the first loop $\frac{1+3600}{2} = 1800.5$ s, rounded to 1801 s). In Figure 3.3, the three IAS responses are presented and it can be noted that the first trajectory (blue) reaches the target velocity and then the calculation stops, when the altitude of FAF is reached. The green and orange responses demonstrate that the trajectory ends at FAF altitude, but not with the desired IAS. Therefore, the solution is located between the blue and orange responses.

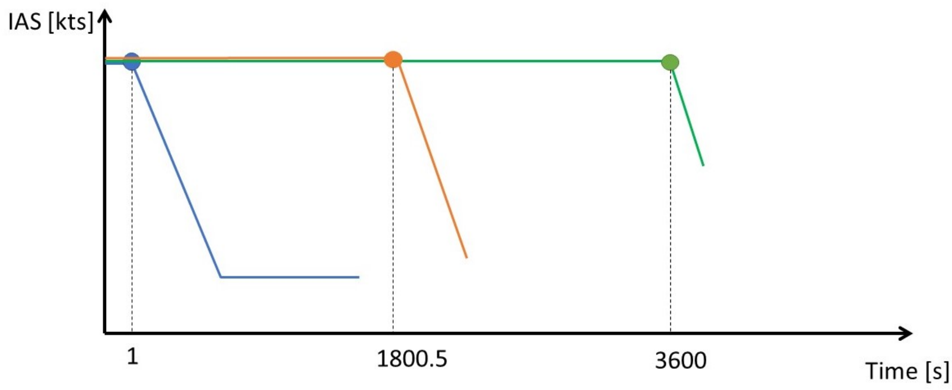


Figure 3.3: The trajectory calculation cases for the first iteration

In the algorithm, each trajectory is checked whether it provides a valid solution, hence if it reaches the Final Approach Fix (FAF) altitude with a velocity within the desired bounds. The first point will always deliver a valid solution, since it is the earliest deceleration. Then, if the second point also delivers a valid solution, it means that the time point that results to the latest possible deceleration is located between the second and third time points and in the next iteration the three calculation points are arranged accordingly. If the second point does not result to a valid solution, that means that the solution is positioned between the first and second points and in the next iteration the calculation points are adapted as well. The logic of each iteration is presented as a flowchart in Figure 3.4.

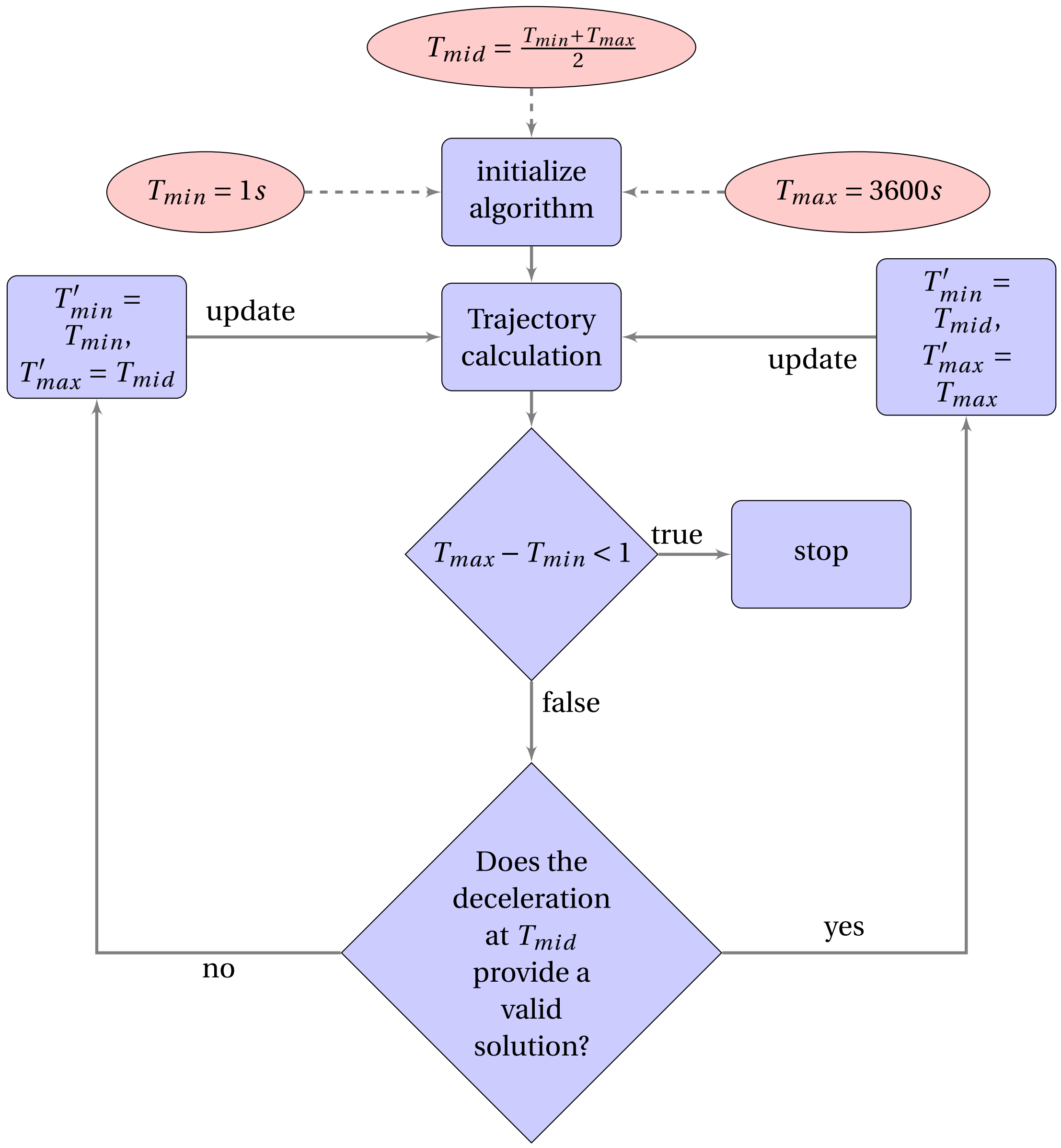


Figure 3.4: Minimum ETA algorithm flowchart

3.4. Target time calculation

When planning a CDA, the pilot will have the first indication of the solution space, hence the minimum and maximum ETA trajectories. Having this information, the pilot will have to select a target time of arrival between these bounds and follow the instructions required to achieve that goal. In order to keep the human controller engaged in the process, the IAS profile will not be non-linear or something that the FMS can only track, but it will be divided in steps. Therefore, the pilot will have to follow the calculated IAS setpoints, in combination with the flaps and gear deployment at the designated times during the approach.
The velocity profile, in the form of steps, that leads to the target trajectory can not be calculated directly as in the maximum and minimum ETA cases. By knowing the boundary conditions and setting some constraints, this problem can be shaped as an optimization prob-

lem. The difference of this problem, in comparison with the minimum ETA case, which used an adjusted bisection method, is that the design variables (IAS steps) are more than one. Since, DASMAT is programmed in Simulink®/MATLAB®, as well as the maximum and minimum ETA cases, so the built-in non-linear optimization functions of MATLAB® are considered.
The non-linear programming with constraints solver *fmincon* is an appropriate choice for this case. The fmincon minimization solver operates by feeding and evaluating a function, whose input variable is the decision variables' vector and the output is the value of the objective function. The function creates the imposed velocity vector according to the input vector and calculates the trajectory for the given target time. For this problem, the target time can be either divided in a specified number of steps or the duration of the steps can be set, with each step corresponding to velocity value that the optimization solver generated. Regarding the design variables, the formulation of the problem included that the first velocity step corresponds to the initial IAS of the aircraft and the final step corresponds to the final velocity within the desired bounds. Therefore, the design variables are the values of the intermediate velocity steps (number of decision variables N). In this problem, apart from the main goal of being time punctual at the specified altitude, it is preferable not to decelerate early to the final velocity, in order to compensate for any unforeseeable changes during the approach, such as the wind. So, the design variables are forced to be as high as possible, by using a second objective function to maximize their value.
As this problem is shaped to be multi objective, the MATLAB® multi objective optimization solver *fgoalattain* is chosen, while using the *fmincon* as a basis. The objective function is two-fold with the first segment being set as the squared difference of the altitude at the FAF and the altitude at the last time step of the calculated trajectory and the second segment being the inverse of the sum of the decision variables. The two objectives to be minimized, have the same weight coefficients in the optimization procedure, since favoring one side or the other did not converge to a different solution as the initial case.

$$J = \begin{bmatrix} (h_{faf} - h)^2 \\ \frac{1}{\sum_{n=1}^{N} IAS_n} \end{bmatrix} \tag{3.4}$$

The constraints of this optimization were formulated as inequalities. The main constraint that was imposed is that the calculated velocity values corresponding to each step would not exceed the initial velocity or be less than the final velocity.

$$IAS_{final} \leq IAS \leq IAS_{initial} \tag{3.5}$$

In addition, some optional constraints were tested but not applied in the final proof of concept, such as setting a maximum difference between two velocity steps, although this constraint can be contradicting in some cases that a few number of steps are available, but the total required deceleration is higher than the constraints.

3.5. Simulation of the point mass model

A simulation using the point mass model of the Section 3.1 is presented with its two minimum and maximum ETA solutions along with the stepwise target time solution. This approach contains the main segment of a CDA, hence a trajectory of $\gamma = -2°$, and the G/S, a $\gamma = -3°$ path leading $50 ft$ above the runway's threshold (assuming a runway at sea level).

The initial and final conditions of this simulation, along with the flaps and gear deployment velocities are presented in Table 3.2. The selected velocities for flaps and gear were chosen from the previous work on DASMAT by Gernaey [2005]. Since the bounds of ETA are needed to select the target time, the calculations of the minimum and maximum ETA precede the target time calculation, where the duration of each time step was set to 120 s.

Variable	**Value SI**	**Value**
Initial altitude	2500 m	8202 ft
Initial IAS	100 m/s	194 kts
Final altitude	15 m	50 ft
Final minimum IAS	56 m/s	109 kts
Final maximum IAS	55 m/s	107 kts
Flight path angle CDA	−0.0349 rad	−2°
Flight path angle G/S	−0.0524 rad	−3°
G/S intercept altitude	600 m	2132 ft
Flaps 15° IAS	75 m/s	146 kts
Flaps 40° IAS	60 m/s	117 kts
Gear IAS	58 m/s	112 kts
Minimum thrust percentage	3 %	3 %
Aicraft mass	5000 kg	5000 kg

Table 3.2: Conditions for the CDA and G/S trajectory simulation

The input IAS profiles that were imposed to the point mass model in these three cases are presented in Figure 3.5. In detail, apart for the aforementioned boundary cases' profiles in Section 3.3, the result of the optimization procedure of the Section 3.4 is visible with the step IAS commands that leads to the target end time.

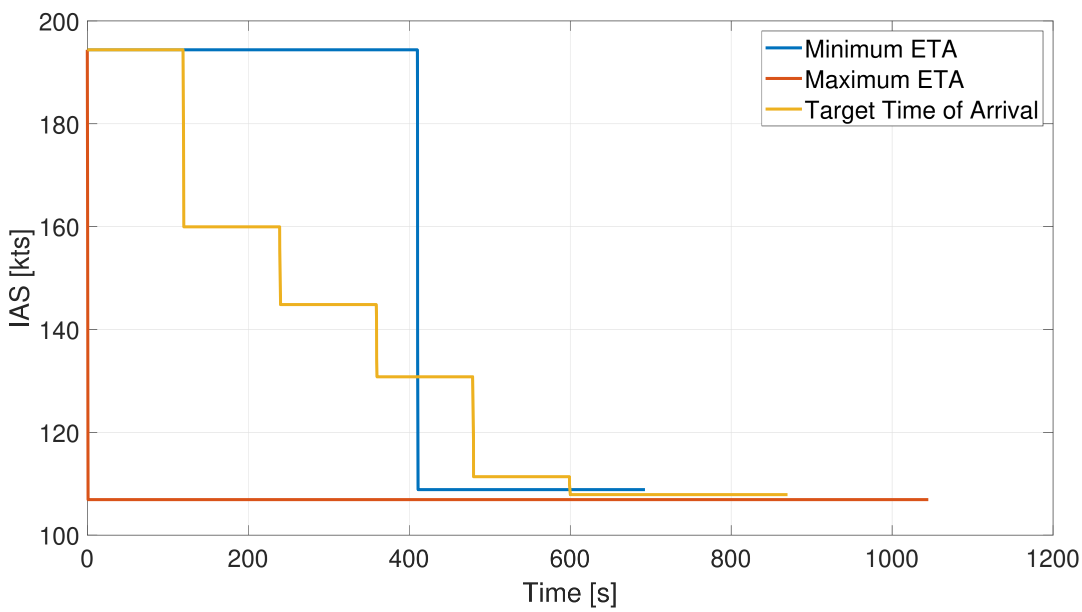


Figure 3.5: Input IAS profiles

The Time Space Diagram (TSD) of this trajectory is presented in Figure 3.6. The range of ETA and the target time of arrival are visible on the right-hand side of the diagram. Hence, the minimum time is close to 700 s, the maximum time is 1050 s and the target time was chosen to be 870 s (the average of the bounds). Finally, the slant range, between the IAF and the FAF for the selected flight path angles of CDA and G/S, is 35 nm.

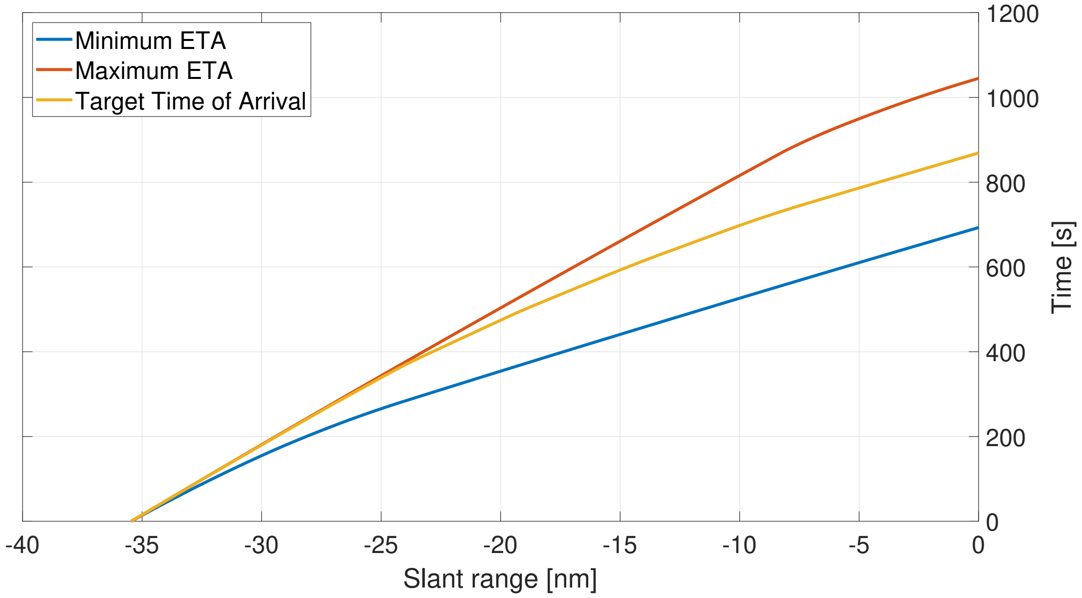


Figure 3.6: Time-space diagram of the trajectory

The IAS profiles of the minimum and maximum ETA trajectories are depicted in Figure 3.7 as well as the response of the point mass model to the calculated velocity steps of the target end time case. It is clear that the aircraft follows two completely different strategies in the boundary cases. In the fastest case, it maintains the initial IAS for 420 s and then decelerates to the upper final velocity bound, which is reached at the last time step. In the case of the maximum ETA, the lower final velocity bound is reached at 175 s and it is then kept constant until the altitude of the FAF. In addition, a change of angle in these curves resulting in a steeper deceleration at 146 kts signifies the deployment of flaps to 15° and a similar change happens when the flaps are extended to 40° at 117 kts.

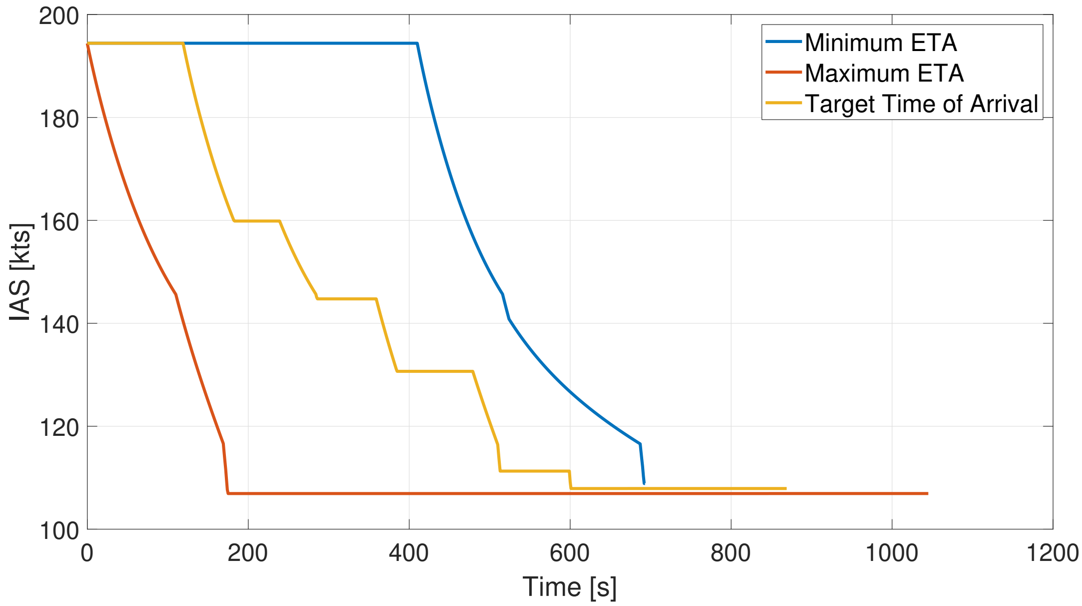


Figure 3.7: IAS profiles for the two boundary and the target cases of the CDA

The responses of the altitude, as a function of the along track distance, present a deviation in Figure 3.8 although the imposed flight path angle is the same. This can be attributed to the fact that the aircraft reduces its thrust at or close to idle in an abrupt manner, while being at a relatively high altitude to take an action like that. This is also demonstrated by the maximum ETA case, which decelerates at a later point and has a more linear response. However, this doesn't affect their ultimate goal to reach with the appropriate state the FAF with the desired flight path angle and is further investigated in the application of DASMAT.

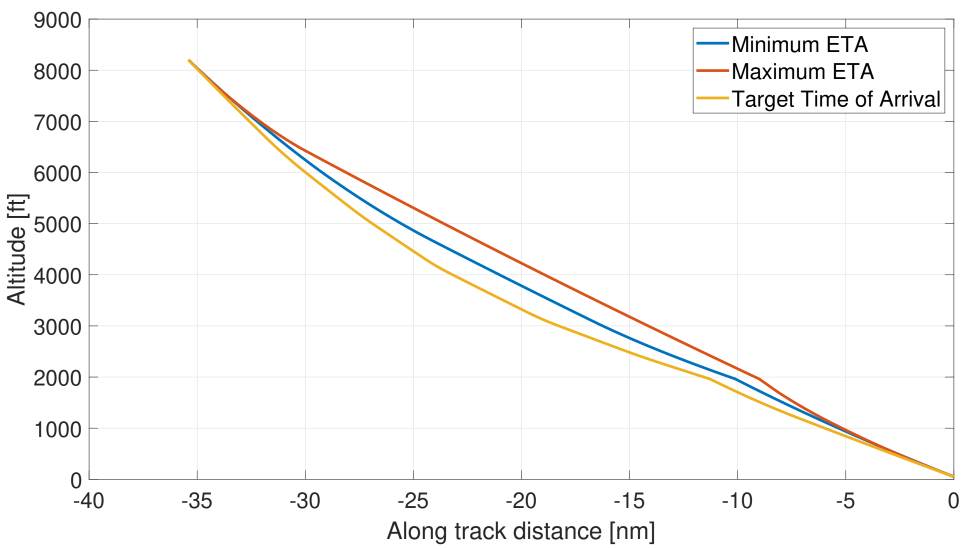


Figure 3.8: Altitude profiles for the two boundary and the target cases of the CDA

3.6. Validation of the minimum, maximum and target end time cases with DASMAT

DASMAT, as it was described in Section 3.1, encapsulates a complete non-linear model of a Cessna Citation I and serves as the basis of this validation process. Having extracted the necessary data to simulate the aircraft as a point mass model and calculate the boundary trajectories and then the target one, the next step is to examine the effect of other model parameters that have not been considered. These parameters include engine dynamics, a more accurate aerodynamic model, servodynamics and the control system. DASMAT offers the possibility to trim the aircraft model at a specified flight condition and aircraft configuration, by using an optimization function to find the steady state condition where all the rotational and translational accelerations are zero. The output file of the trimming routine is used as a starting point to execute a simulation in the Simulink® model. In addition, there is the option to create a linear state space model of the aircraft out of this trimming output file. This feature is particularly useful in the preceding task of designing a controller to implement within the model.
Since the goal is to track a velocity profile and keep the flight path angle at a desired value, then two controllers need to be designed: a flight path angle hold loop and an airspeed hold loop. The designed flight path angle loop includes two Proportional–Integral–Derivative (PID) controllers, a flight path controller and a pitch damper, as it is presented in the block diagram of Figure 3.9.

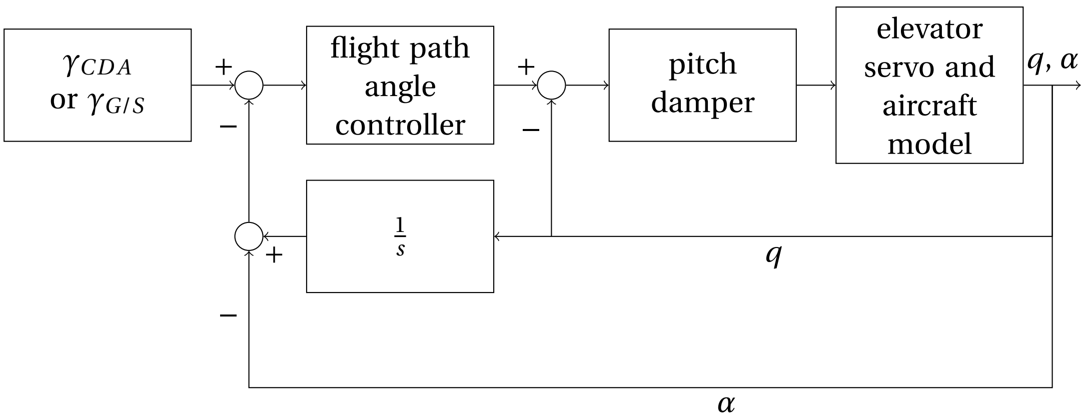


Figure 3.9: Flight Path Angle Controller Block Diagram

In this application, a full solution would be to calibrate the gains in multiple flight conditions (velocity, altitude) and configurations (flaps, gear) along the approach trajectory and then apply gain scheduling. However, in order to simplify this procedure, the gains were manually tuned in a limited number of conditions and then an average was taken for their values, albeit ensuring an acceptable performance. In the airspeed hold loop, a single PID controller is needed to convert the IAS error to Power Lever Angle (PLA) and its architecture is presented in Figure 3.10.

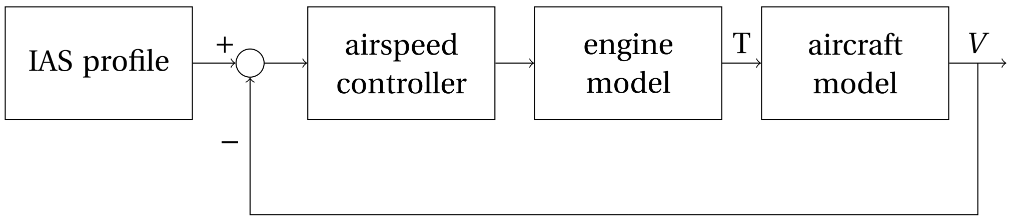
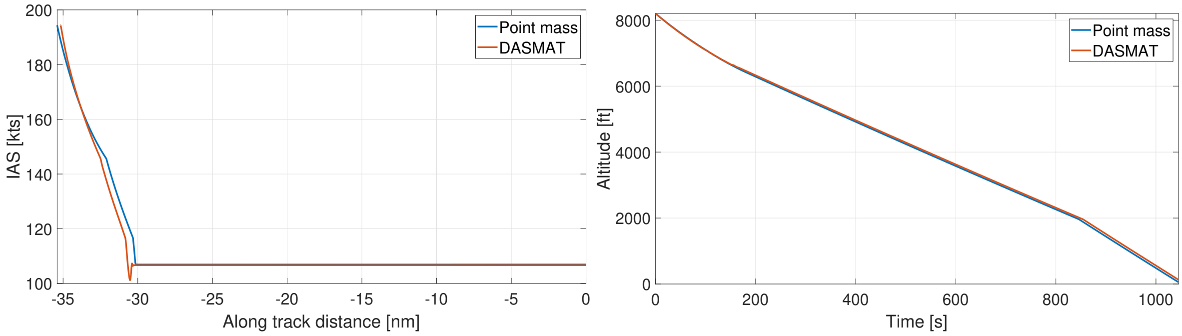


Figure 3.10: Airspeed Hold Controller Block Diagram

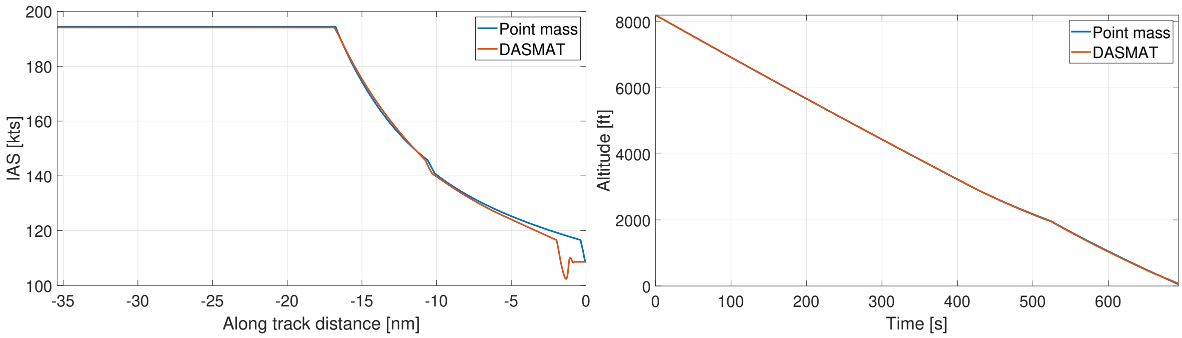
The inputs for DASMAT simulations were the same as the point mass model (Figure 3.5). The results of both models for each time case are presented on the same plot to observe how effectively the point mass model approximates the response of the nonlinear model of DASMAT. The comparison of the IAS response of the point mass model in the maximum ETA case and its execution in DASMAT is presented in the Figure 3.11a and the results show that the point mass model can produce a response that is comparable. Similarly, the altitude responses in Figure 3.11b do not have a significant difference and the aircraft arrives at 50 ft. in 1045 s in the case of the point mass model and in 1053 s in DASMAT model.



(a) IAS response of the point mass model and DASMAT (b) Altitude responses of the point mass model and DASMAT

Figure 3.11: Maximum ETA validation

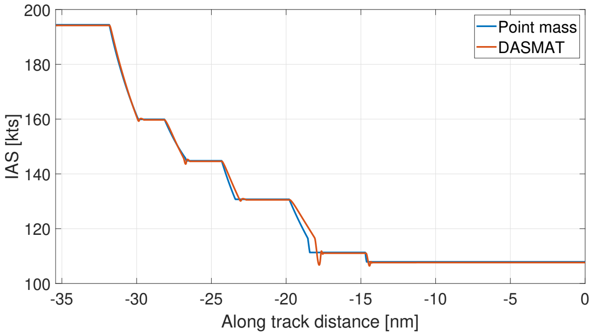
In the minimum ETA boundary case, DASMAT model is able to follow the velocity profile in the same way as the point mass model, and their end times are very close, in particular 693 s for the point mass model and 695 s for the DASMAT model. The undershoot of IAS versus the along track distance in the Figure 3.12a is caused by the flight path angle hold controller, when flaps are extended to 40°, but does not have a significant effect on the overall performance and an extensive gain scheduling strategy can possibly regulate it.



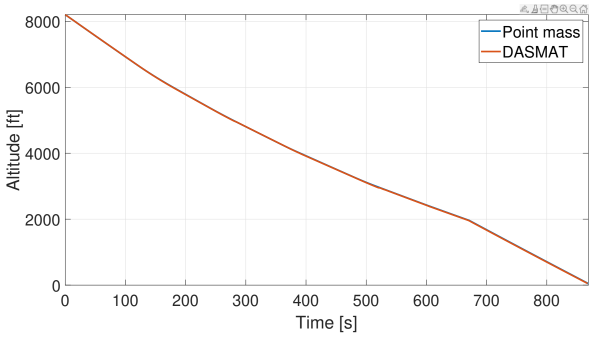
(a) IAS profiles of the point mass model and DASMAT (b) Altitude responses of the point mass model and DASMAT

Figure 3.12: Minimum ETA validation

Finally, DASMAT had as input the velocity profile containing IAS step commands, as it was generated from the optimization procedure to achieve the desired end time goal at the FAF. The point mass model executes the trajectory in 868 s, while DASMAT does it in 869 s, so there is not practical difference for this case in ETAs.



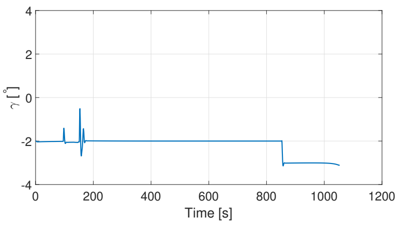
(a) IAS profiles of the point mass model and DASMAT



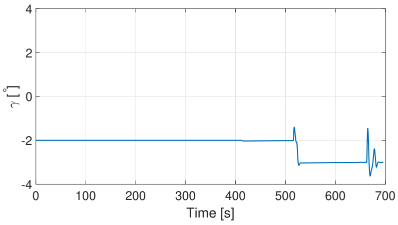
(b) Altitude responses of the point mass model and DASMAT

Figure 3.13: Target time of arrival validation

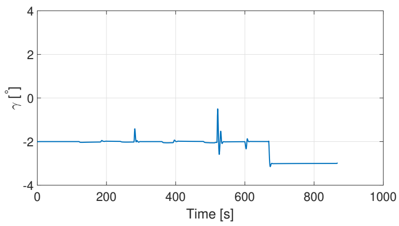
The flight path angle of DASMAT is held around the desired level of $-2°$ in CDA and $-3°$ in G/S with the assistance of the control loop of Figure 3.9. Some minor fluctuations are noted, mainly when imposing a flaps change, as it is shown in Figure 3.14a for the maximum ETA, in Figure 3.14b for the maximum ETA and finally for the target time of arrival in Figure 3.14c. However, these overshoots and undershoots do not have a considerable effect on the overall performance.



(a) Flight path angle response of DASMAT (maximum ETA)



(b) Flight path angle response of DASMAT (minimum ETA)



(c) Flight path angle response of DASMAT (target time of arrival)

Figure 3.14: Validation of the flight path angle hold controller in the three cases

3.7. Conclusion

The point mass model along with its approximations and simplifications can be used to calculate the full trajectory of the aircraft with an accuracy comparable to the full nonlinear model of DASMAT as it was demonstrated in Section 3.6. Taking into account the significantly lower calculation time of the point mass model compared to the DASMAT model which executes a simulation within Simulink®, then it can be picked as the basis of a pilot support interface.

4
Cognitive Work Analysis

This chapter contains the analysis framework for the task of performing the steps needed for a CDA with an end time goal. This analysis, the CWA, includes five explicit steps which study from a different perspective the human-machine interaction needed to accomplish this mission. In detail, Section 4.2 concerns the work domain analysis, Section 4.3 includes the task analysis, Section 4.4 concerns the strategy analysis, Section 4.5 contains the social organization and cooperation analysis and the last step of worker competencies analysis is included in Section 4.6.

4.1. Introduction

The design of an interface that will enable the pilot to plan and execute the approach, consisting of the CDA and the G/S, under a defined end time goal will follow the paradigm of EID, as elaborated in Section 2.3. However, for the initial theoretical analysis, CWA proposes a more elaborate procedure to analyze this human-machine interaction and it will be subsequently implemented. This work analysis will examine the work environment as well as the task allocation for the actors and how these tasks are dealt with. This problem is dealt with using a ecological formative approach as proposed by Vicente [1999] and applied in relevant projects, such as the aforementioned study of CDA by Gernaey [2005]. In detail, as Borst [2016] proposes, the point of view of EID goes beyond the usual dyadic approach, where in the design process the human operator's and the system's sides are considered. In detail, in the first case, the human cognitive abilities are dominant and everything is adapted to human's needs and in the second case the center of attention is the automation and how its operation can be accommodated. However, EID falls into the triadic approach, where the main focus is is the analysis and depiction of the laws and constraints governing the work domain.

In specific, the ecological perspective comes from the work of Gibson [1986] in human-environment interaction and the concept of affordance. Affordance depicts properties of the work environment that can be used by the human operator to achieve a goal. These properties, called invariants, in the case of an aircraft are the underlying laws of physics governing this system and they cannot be directly perceived by the human operator. Then, this is where the work of Rasmussen and Vicente [1989] fits in to map the invariants into a perceivable form in an interface. The formative way of analyzing this process concerns the given emphasis on the constraints of the work environment which will define the space of

possible actions of the human operator to reach a goal. These constraints are investigated and formulated during the five step process of CWA.
CWA is accomplished by using previous work and knowledge, such as from de Beer et al. [2008], Gernaey [2005], Marwijk et al. [2011] for analyzing mainly the execution of the approach. The first step is the Work Domain Analysis, which maps the workspace and the constraints it sets on the executed task. The second step is the Control Task Analysis that identifies the possible inputs, the outputs of human operator and other factors, the potential states that the system will be in and finally the desired goals. The third step is the Strategies Analysis, which considers how each task is executed regardless of who is in charge of it (human operator or automation). The fourth step is the Social Organization and Cooperation Analysis and concerns how the execution of the tasks, the areas of work domain and the strategies are distributed among the actors, hence the pilot and the autopilot. The final step is the Worker Competencies Analysis, based on the Skills, Rules and Knowledge Taxonomy as formulated by Rasmussen [1983], where the abilities and the constraints required to execute the tasks are categorized depending on the behavior of the human operator.

4.2. Work Domain Analysis

The analysis of the work domain is a crucial part in both EID and CWA and it is executed by examining the system by itself and not regarding the human operator. It is applied by forming the abstraction-decomposition space, as it has been described by Rasmussen [1986]. The abstraction-decomposition space is a two dimensional matrix, whose vertical axis represents the five levels of abstraction and the horizontal axis depicts the decomposition of the system, namely in this case the whole system, the subsystems and the components. The five levels of abstraction begin from the system's goal in the environment it operates in (functional purpose) and the next level is the abstract function, which includes the functioning of the system as defined by some basic physical laws. The third level is the generalized function, encapsulating the equations and the concepts that quantify the laws of the previous level and the fourth level is the physical function which concerns the actual physical representation of the phenomena mentioned the third level and how the components of these processes operate. Finally, the fifth level is the physical form including the physical appearance of the system, the components that is made of and any other factors affecting its operation.
Between each level of abstraction there is a means-end relation, hence the functions and components of one level are the means to accomplish the function of the higher level. As it is analyzed by Amelink [2010], Rasmussen [1986], while looking at one particular level's functions, the next higher level concerns why these functions are implemented and the next lower level describes how these functions are achieved. All the aforementioned principles of executing the work domain analysis are presented in the abstraction-decomposition space of Table B.1. The levels of decomposition (Entire System, Subsystems, Components) are not predetermined as the levels of abstraction and they are based in similar studies of this human-machine interaction, such as from de Beer et al. [2008], Gernaey [2005].
The levels of abstraction begin with the functional purpose of the entire system which is generalized to executing a successful approach to the designated runway. This target is broken down into subgoals in the next level of decomposition, namely being time punctual as far as the RTA, being able to track and follow the designed trajectory during the

descent and finally avoiding any unsafe situations (for example flying close to flight envelope limits). A successful approach consists of some tasks/actions analyzed in the next level of abstraction, the Abstract function. In detail, this concerns the task of managing the aircraft's locomotion and directing a deceleration to its final landing velocity and simultaneously a descent with a constant flight path angle of CDA and G/S, all of them being linked to physical phenomena. During the approach, the aircraft's configuration is adjusted at certain points, from clean state to landing setup, according to the calculated IAS profile. The generalized function level, quantifies, in a mathematical form, the aspects of the approach trajectory that are mentioned in the abstract function. So, the broad domain that includes the equations that describe these aspects is flight dynamics, which then can be broken down in the basic forces (Lift, Drag, Thrust, Weight) and tracking the desired flight path angle. The equations and variables of flight dynamics' system are created from the operation of the physical components of the aircraft in the atmosphere, as mentioned in the subsequent level of abstraction, the Physical Function. The Physical Function begins with the aircraft as a system and then has as components, in order to create the means-end relation with the previous level of abstraction, the parts of the aircraft that influence the approach such as the wings, the engines and the flight control surfaces. The lowest level of abstraction is the Physical Form which includes aspects of the physical implementation of the approach, which are peripheral to the system, but still have an influence in its execution and performance.

Another way to look at the Table B.1, is to identify the external and internal constraints of the work domain, as Marwijk et al. [2011] performed and Borst et al. [2010] presented as a framework. The internal constraints come from the actual physical laws and the aircraft's performance characteristics, hence starting from the higher Physical Function level of Abstraction to the lower level of Generalized function. On the other hand, the external constraints lie on the Physical form level of Abstraction and encapsulate factors that are imposed to this problem such as the weather and the ATC's instructions.

		Levels of Decomposition		
		Entire System	*Subsystems*	*Components*
Levels of Abstraction	*Functional Purpose*	Successful approach	Time punctuality Maintain designed trajectory Safety	
	Abstract Function	Physics	Deceleration Descent to runway Aircraft Configuration	
	Generalized Function	Flight dynamics	Lift Drag Thrust Weight Flight path angle control	
	Physical Function	Aircraft		Flight control surfaces Horizontal/Vertical stabilizers Wings Engines Radio navigation Flaps/Landing gear
	Physical Form			Air Traffic Landing runway Aircraft type Weather conditions IFR rules RTA requirement

Table 4.1: Abstraction-Decomposition space

4.3. Task Analysis

The task analysis step of the CWA sets the workflow that is followed in the work environment and the potential constraints that may come up, in terms of the inputs to the system. In addition, the goal of the task is defined and the information that is used by the actors to accomplish the task. This decision making process can be depicted as a type of a flowchart, namely the decision ladder, which has a general structure leading to its goal. The main concept of the decision ladder starts from the activation of the actors, observing the information regarding the system and identifying the state that the system is in and how it affects the main goal. Then, it continues with planning the next target state which will bring closer the main goal, defining the task that will steer the system's state to the target state, formulating the procedure that the task requires for its execution and finally executing the planned procedure.

As formulated by Vicente [1999], the graphical representation of the decision ladder of Figure B.1 consists of the information processing activities (rectangular), which represent the activities of the actors, and the states of knowledge (ellipsoid) as the outcomes of the information processing activities. The task that has to be performed is to bring the aircraft to the threshold of the landing runway using a CDA and then the ILS G/S. Beginning from the activation phase, it is assumed that the descent will have been planned, according to ATC requirements, and the actual activation is dealing with an unforeseen event, so this step of CWA is oriented more towards execution rather than designing. The actor uses the instrumentation to determine the aircraft's state. After observing the key data, the actor, having available the background calculations by the FMS created for this mission, has available the current position of the aircraft along the planned trajectory as well as the projected trajectory up to the runway's threshold. Then, the actor, starting from the present condition of the aircraft, can evaluate if the ETA is within the desired bounds of the RTA goal, otherwise a new RTA goal has to be set. The next step is to observe the strategy that is going to be followed to track the selected approach trajectory or if adjustments have to be made to the future trajectory plan, so the target will be met. So, there is an overview of the actions that have to be taken in the future, in terms of setting the desired IAS commands, switching from the CDA flight path angle to G/S and deploying the flaps and landing gear. Finally, when the appropriate moment for each of these actions comes, as planned with the FMS calculations, the actor proceeds with execution.

In this chain of actions and outcomes, there is the possibility of bypassing some stages and move directly to a subsequent steps, as it was discussed by Steens et al. [2008]. In particular, these shortcuts are demonstrated in Figure B.1 with arrows from information processing activities of the left side of the decision ladder pointing to states of knowledge of the right side. There could be instances, when determining the aircraft's state, that the aircraft is in the desired path and the execution of the next command of IAS/flaps/gear is imminent, so there is no need for more considerations or alterations of the goal. Similarly, in the higher level shortcut, the aircraft is set to fly on an initially designed approach, but further future projections of its course are needed to ensure that it is indeed staying in the target state and have an overview of the future actions.

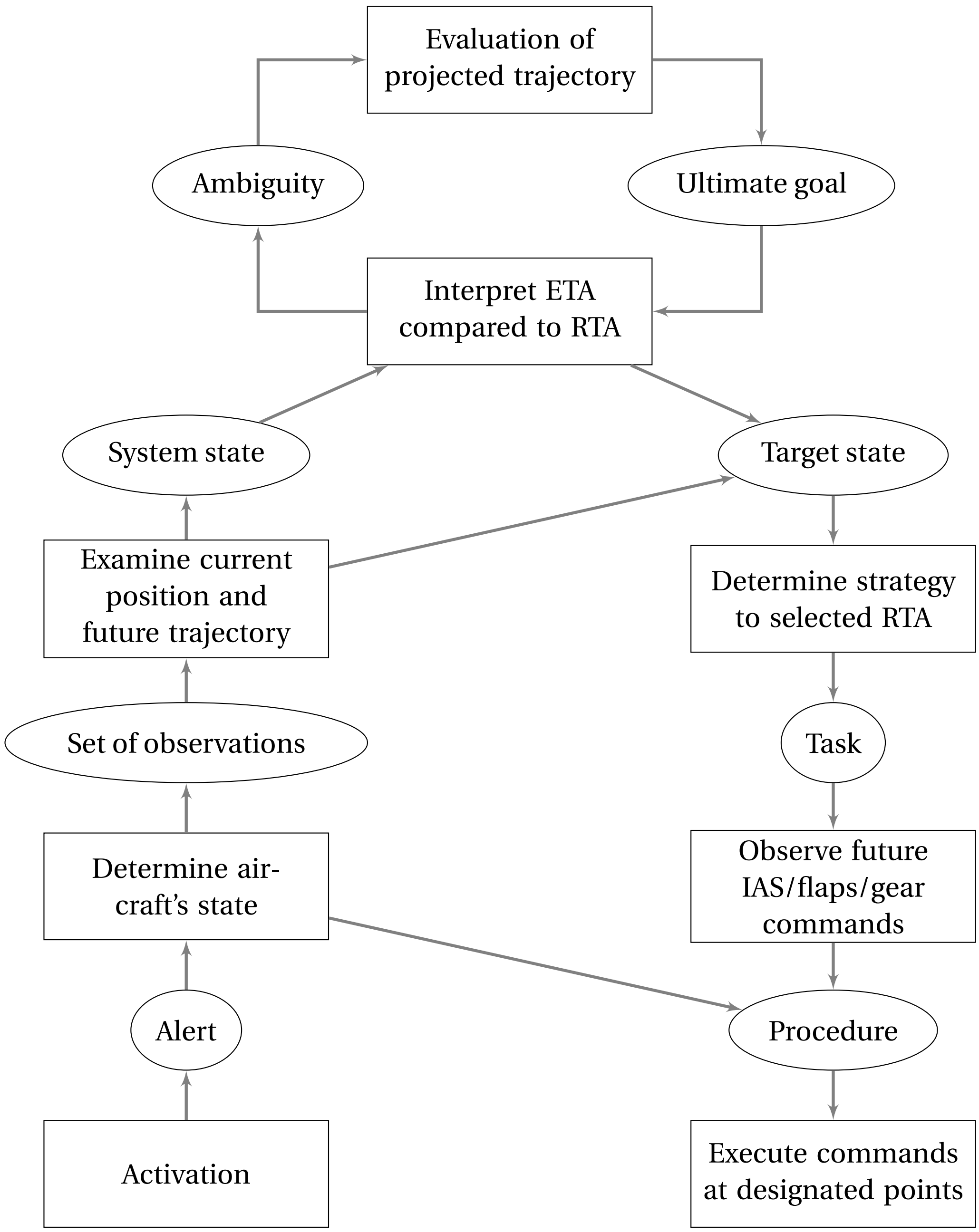


Figure 4.1: Decision Ladder

4.4. Strategies Analysis

In this step of CWA, the methodology, that will be followed to steer the system towards the target RTA, is analyzed without making a differentiation on the actor in this process (pilot/human operator or autopilot). The aircraft starts the CDA from 8000-10000 ft and descents with a constant flight path angle until the interception of the G/S and then continues to the runway's threshold. Before starting the CDA, the RTA as a time slot will be made available, so the CDA can be planned in terms of the starting altitude and velocity (IAF) as well as the flight path angle and the number of velocity steps. The FMS will calculate the minimum and maximum ETA from the IAF and the prescribed time slot should fall between these bounds. In addition, it is assumed that the aircraft is aligned with the

runway or any corrections to its lateral axis will not influence the main mission.
For the selected RTA, the IAS profile consisting of steps/commands, will be calculated as well as the flaps/landing gear deployment points, taking into account the point mass model of Section 3.5. Therefore, if this profile and the other actions (flaps/landing gear) are followed as expected the aircraft will be at the FAF within the desired time slot. During the procedure, the ETA will be iteratively calculated by the FMS and the IAS profile, that leads to that, will be fine tuned so that the aircraft will not deviate from its target. If for some reason (for example air traffic), the RTA goal changes during the procedure then the FMS calculations will accommodate the new goal, assuming that it falls between the current minimum and maximum ETA bounds. Otherwise, other measures can be considered, such as using the speedbrakes or going into holding pattern, which are not modeled in DASMAT and point mass model, and then start again planning.

4.5. Social Organization and Cooperation Analysis

This analysis uses the work on the task analysis and the strategies analysis in order to determine the roles of the human operator/pilot and the autopilot, both represented by the same entity (actor) in the previous steps and supported by the FMS for the future trajectory calculations. The FMS works in the background to track the aircraft's state and update the future trajectory estimation in the pilot support interface. This is the basis to initially plan the approach and set its parameters, such as the flight path angle and the RTA. During the execution of the approach, the human operator maintains the required situation awareness regarding the basic variables of flight and the aircraft's position in the trajectory. Then, the human operator interprets the information provided by the instruments and the pilot support interface to insert the IAS/flaps/gear commands, when needed, and conclude whether the aircraft maintains its nominal path and meets the end time goal. The autopilot, on the other hand, is tracking the desired flight path angle of the CDA and afterwards the G/S, as well as the autothrottle follows the IAS commands of the human operator.

4.6. Worker Competencies Analysis

The worker competencies analysis is directly related to the three level categorization of the human information processing, the Skills, Rules, Knowledge (SRK) taxonomy (Rasmussen [1983]). The Skill Based Behavior contains actions that are triggered unconsciously by signals and require zero or nearly zero mental workload. The intermediate level of this taxonomy corresponds to Rule Based Behavior, which requires the execution of a rule (or a set of rules) that does not require any further knowledge and they may have been taught, learnt from past experiences or prepared, for when a sign will trigger this behavior. The highest level of human information processing is the Knowledge Based Behavior, that relies on reasoning, and concerns a mental model that is employed to face an unfamiliar situation. It is consequently a slower procedure, that takes into account the goal and the model of the system and the symbols, which represent its properties, and it can lead to finding a solution but also to making errors.
Borst et al. [2008] used the decision ladder, as the Figure B.1, and divided into three domains the information processing steps using the SRK taxonomy. The lower levels of the decision ladder, hence the activation (tracking the performance) and the execution of the tasks towards the target state, correspond to skill based behavior. These actions of the hu-

man operators are done without high mental load and are repeatedly executed during a flight. The next level are the intermediate information processing actions such as identifying the current state and position of the aircraft in the approach trajectory and on the other side to define and plan a strategy to reach the target state. These actions rely on Rule Based Behavior, since the human operator has to follow specified guidelines and checklists during planning and executing the approach. Finally the upper level of the decision ladder, in particular the interpretation of the current state in terms of accomplishing the final goal and checking if it feasible, corresponds to the Knowledge Based Behavior. This procedure requires a more creative way of thinking, since the human operator is trained in the general procedures, but each situation can present some differences that require different solution. The goal of designing this procedure and the accompanying interface is to reduce the human operator's cognitive load, hence to employ more Skill and Rule information processing activities and facilitate the Knowledge based behavior when facing an unfamiliar situation.

4.7. Conclusion

The steps of CWA contributed to create a comprehensive overview of the human-machine interaction that is needed to execute a CDA approach. The abstraction-decomposition space revealed the means-end relations between systems, subsystems and components, so it is clear what is needed to control each level of abstraction. Then, the decision ladder laid down the path that is needed to be taken and the required information for each action to reach the system's goal, when an unexpected incident occurs during execution. The strategy analysis, without yet delegating the tasks between the human operator and the autopilot, describes a potential strategy that begins with planning the approach with a set end time goal, using the background calculations of the FMS, executing the CDA and then continuing with the G/S. Finally, the social organization and cooperation analysis proposed a separation of the tasks between the pilot and the autopilot, assisted by the FMS and in the last step of CWA the pilot's tasks are classified to the three levels of SRK taxonomy. Overall, this analysis will assist the subsequent step of designing the aforementioned pilot support interface.

5

Interface Design

In this Chapter, a brief presentation of the links between EID, CWA and the trajectory analysis of Chapter 3 are presented in Section 5.1. Then, two types of displays, that have been used in research projects for the flight deck, are introduced in Section 5.2 and finally in Section 5.3 a proposal for a potential pilot support interface is analyzed and demonstrated with an example.

5.1. Introduction

The execution of a CDA with an end time goal requires beforehand solid planning and, during its progress, monitoring, so the calculated commands are followed timely and further corrective actions can be taken quickly, if required. These tasks require the usage of an interface consisting of one or more displays, so the needs of planning and monitoring the CDA approach can be accommodated. Following the principles of EID, as elaborated by Vicente and Rasmussen [1992], it is pursued to design an interface, which has integrated the necessary information of the work domain in a way that its constraints are directly perceivable. Moreover, SRK behavior of the human operator is better supported, for instance it can facilitate the creation of a mental model of the system, when Knowledge based behavior is required in an unfamiliar situation, as suggested by Marwijk et al. [2011]. As Borst et al. [2010] analyzed in a theoretical level, the steps of this Cognitive Systems Engineering (CSE) approach start from the CWA and then, by using each step's contribution, an interface using the EID can be created.

As described in Chapter 4, the concept of affordances of the work domain is adopted to represent the space of action to achieve a goal, and in this case to control locomotion. Abeloos et al. [2002] mention that the affordances, as an initially vague notion, in each application are quantified in more specific properties, but in complex and dynamic fields such as the aeronautical applications, they cannot be perceived directly and here the role of EID becomes active. Having the CWA completed, the content and the structure of a potential interface can be extracted from this analysis and then the next step is to depict these constraints on the display(s) in a manner to lower the cognitive load and focus on perception. Borst et al. [2010] stated that the pilots mainly work with aspects of the Physical function of the Abstraction-Decomposition space (Table B.1) and they cannot directly grasp the higher order or long term impact of their control actions, for instance the impact of the flight path angle of the CDA on the ETA performance. Therefore, the trajectory analysis of Chapter 3 is suitable for this goal, since by applying the fundamental kinematic equations and the aircraft's performance data, the higher order variables can be approximated for the operation of the interface.

5.2. Types of Displays

A pilot support interface can facilitate the task of the pilot to perform locomotion control ranging from short term, in terms of seconds, to long term, in terms of hours, as van Paassen et al. [2018] present. In particular, for this case the pilot plans the CDA to be executed and redesigned, if needed, during its execution, therefore focusing mainly on the aspect of navigating of the triplet "Aviate, Navigate, Communicate". However, the novel pilot support interface will be structured with displays that are currently used in commercial aviation or have been used in experimental projects in the past. In particular, as Borst et al. [2010] mentions, they already had favorable results for the pilot's performance and a minor familiarization from their side will be needed to the new setup.

5.2.1. Vertical Situation Display

The first display to incorporate in the interface is the Vertical Situation Display (VSD), which has been used in similar projects of CDA planning and execution, as it is mentioned in Section 2.2 and used in presenting the trajectory analysis (Figure 3.8). Some of the initial studies concerning VSD were carried out by Prevot [1998], Prevot and Palmer [2000], to increase the situation awareness of the pilots for the vertical axis and provide a better grasp of the operation of automation. In these projects, that included also an experimental part, the VSD was integrated on the lower part of the navigation display screen, which provides guidance on the lateral axis. Following these initial projects, VSD's use was expanded by Suijkerbuijk et al. [2005] to present information regarding terrain obstacles and aircraft performance, hence to offer terrain avoidance capabilities and display the space for potential maneuvers. In addition, Heylen et al. [2008], by applying the framework of EID, used this display as a separation assistance tool, posing a second source of constraints, apart from the aircraft's performance. As a consequent project, Rijneveld et al. [2010] combined the two aforementioned concepts into a VSD depicting terrain obstacles and traffic constraints. In parallel, de Beer et al. [2008] modified the concept of VSD to design a pilot support interface for CDA, where the altitude axis was replaced by an axis representing the total energy of the aircraft. Recently, van Geel et al. [2020] used the concept of VSD, as it was enhanced by Rijneveld et al. [2010], Suijkerbuijk et al. [2005], and added a visualization feature concerning the flight envelope and the changes the deployment of flaps and gear is causing to it. Therefore, VSD has demonstrated its agility and can contribute to structure a pilot support interface to be utilized for CDA planning and execution.

5.2.2. Time Space Diagram

The second display that is being adopted in the pilot support interface is the Time Space Diagram (TSD), as it has been initially presented for the trajectory analysis (Figure 3.6). TSD has been applied in the past for aeronautical applications in ATC context to provide 4-D information about an aircraft approaching a runway, in the controlled airspace. This display has as its vertical axis the ETA of the aircraft to the runway and the horizontal axis represents either the slant range or the along track distance to the runway. The slope of the curve represents the corresponding velocity vector of the aircraft, so if it flies with constant velocity the curve is straight and if IAS increases, the slope becomes less steep. Tielrooij et al. [2010] presented the concept of TSD as a tool for ATC to manage the incoming traffic executing a CDA, by predicting their trajectories. The incentives of Tielrooij et al. [2010] to facilitate the execution of CDA were the same, as presented in Chapter 2.2, while trying to deal with maintaining aircraft separation and not sacrificing airport capacity. After this proposed design, de Leege et al. [2013] used the initial TSD, enhanced it with more dynamic capabilities, combined it with a conventional ATC display and then proceeded with an experiment, validating the hypothesis. Recently, Mulder et al. [2019] used the TSD, beyond CDA, in an ATC experiment regarding managing traffic consisting of different types of aircraft and alternating weather conditions. Therefore, TSD has proven its effectiveness in the aeronautical field and is incorporated in planning a CDA by the pilot.

5.3. Initial Concept for Pilot Support Interface

In this project, VSD and TSD are applied in a static form in the pilot support interface, to present for the former possible trajectories from the IAF to FAF for a range of flight path angles and the range of ETAs for the latter, in terms of planning a CDA. Then, while executing a CDA, a VSD can be placed below the navigation display to have a continuous overview of the future trajectory of the aircraft, along with cues regarding the future commands for IAS, flaps and gear in combination with cues in the PFD. This 4-D point of view has been also evaluated by Marwijk et al. [2011], where a VSD was used along with a horizontal situation display to present the affordances to the pilot and interact with the interface in real time. The difference of this present study is that the CDA planning pilot support interface is separated from the interface configuration that is used to monitor the execution of CDA. While designing a potential pilot support interface for planning a CDA in graphics software, it can be counterproductive to sketch interfaces, but not being able to actually operate them. Since the trajectory analysis of Chapter 3 took place in MATLAB®, the application App Designer of MATLAB® was chosen to built a prototype Graphical User Interface (GUI) depicting the pilot support interface. This would give the possibility of having the algorithms of Chapter 3 working in the background and present the results in the interface, therefore simulating the way that the pilot is going to interact with the interface. Firstly, the design of the interface needs some elements from the CWA of Chapter 4, such as the system and its component that the pilot is interacting with, the strategy followed to plan beforehand a CDA (or reconsider the plan in case of unexpected circumstances during the execution) and how the SRK behavior can be facilitated. Then, for each stage of planning a CDA, the inputs of the pilots, the expected output of the background calculations and how these outputs are presented in the interface are considered. For the presentation of the outputs, the displays of Section 5.2 are implemented and adjusted for this project to depict in an easily perceivable way the system's constraints and affordances.

The background calculations, which have as basis the trajectory algorithm of Figure 3.2, need at first the initial and final conditions of the trajectory. In particular, these variables are the altitude and IAS at these positions, as well as some other variables, whose majority remains constant during the planning phase, such as the aircraft's mass, the flaps/gear deployment velocities, the flight path angle of the G/S and the altitude to intercept the G/S. Having this information, the range of the flight path angle of CDA can be defined, so the pilot can start evaluating different options. Once a flight path angle is selected, the next af-

fordance to be calculated and presented is the range of ETA, using the concepts described in Section 3.3. Consequently, for the chosen ETA the stepwise velocity profile can be calculated for the desired number of steps, as in Section 3.4 for more than one steps.
The layout of the interface is divided in two sections: the left side concerns the pilot interaction with text fields, sliders and buttons and the right side includes the three designed displays with the outputs of the calculations. In the interface, the coloring chosen to depict the solution space (light green), its bounds (dark green) and the selected trajectory (magenta), follows the example of Mulder et al. [2019]. In the first step of planning a CDA, the pilot support interface expects the initial and final conditions to be entered in the text fields on the upper left side of the interface, as demonstrated in Figure 5.1. A full approach is chosen from IAF (Altitude 10000 ft, IAS 210 kts) to FAF (Altitude 50 ft, IAS 110 kts).

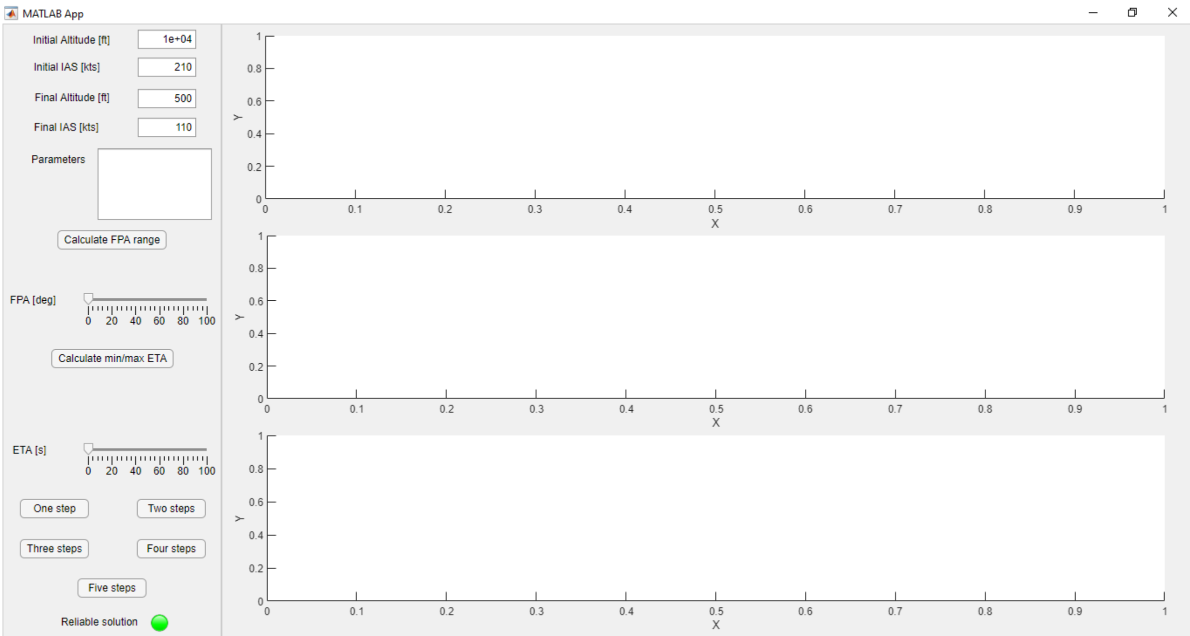


Figure 5.1: First step for CDA planning

Once the range of flight path angles is calculated, on the left side of the interface of Figure 5.2, in the Parameters text field, those variables that were used in the calculation but are rarely changing during planning, are printed. In addition, the flight path angle slider, which will be used in the next step to select the desired value, has its limits updated with the calculated ones. On the right side, the top display, as a VSD, presents the solution space with the possible trajectories, depending on the selection of the CDA flight path angle.

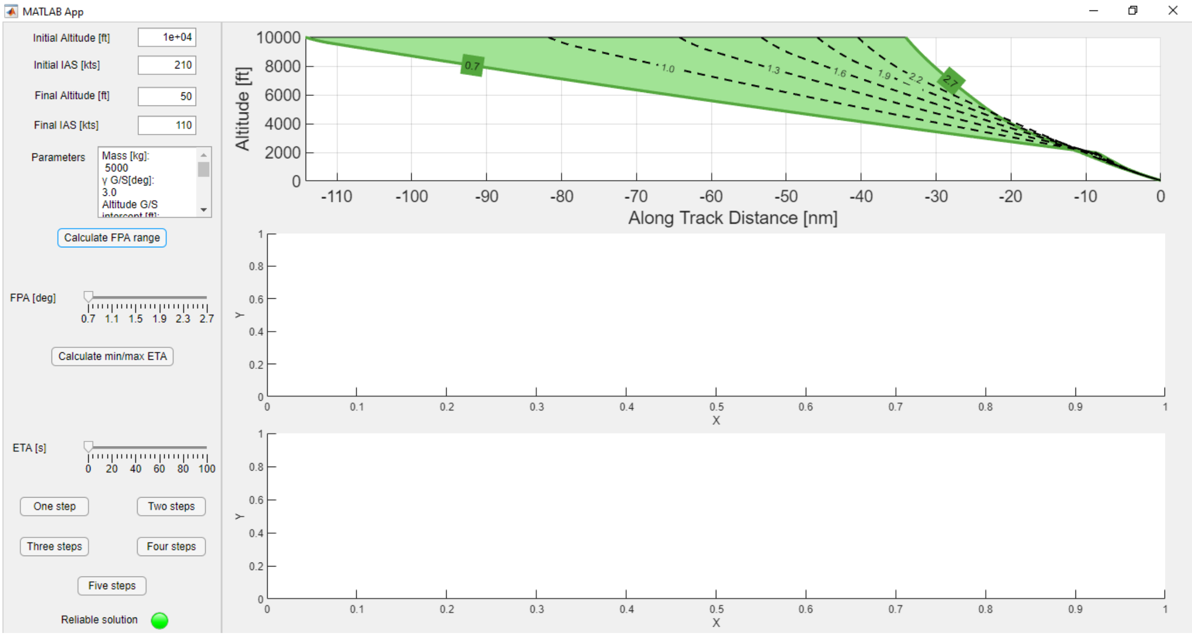


Figure 5.2: Second step for CDA planning

The selection of the desired flight path angle (1.5°) leads to the calculation of the ETA bounds, depicted in a TSD on the middle display of the interface. In particular, in Figure 5.3, the TSD presents the affordance for the ETA, as well as the slider for the ETA selection of the subsequent step has its limits updated. In addition, the selected trajectory is now visible with a different color on the VSD on the top display.

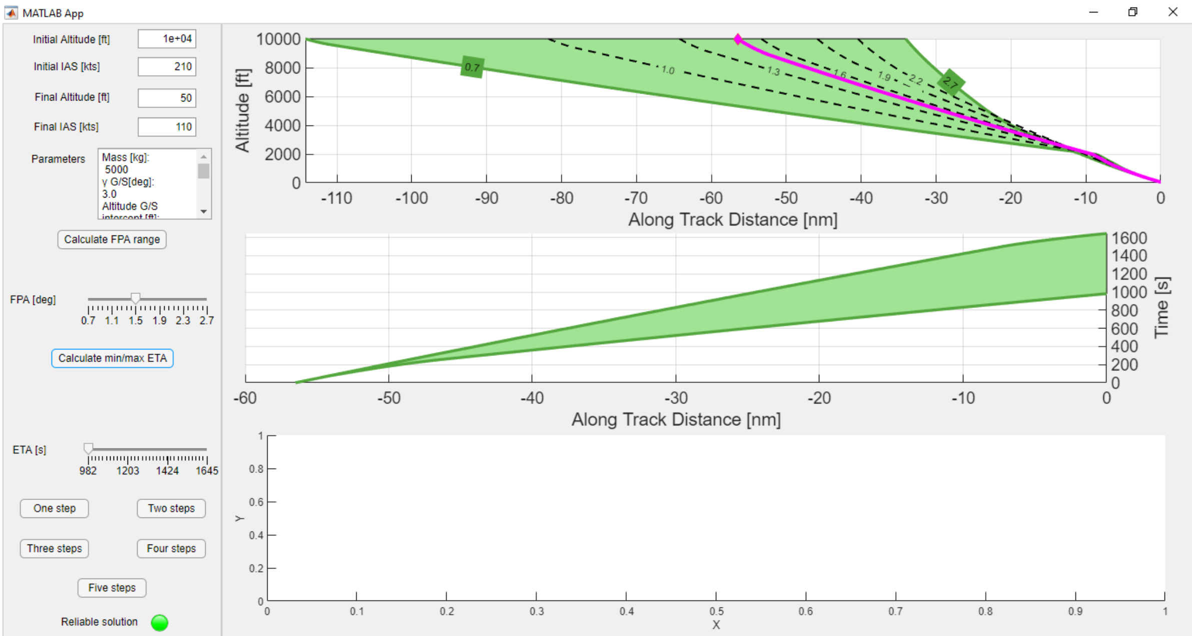


Figure 5.3: Third step for CDA planning

For the last step, the pilot has to select the target ETA (1200 s) and then the number of velocity steps (one step) that are applied to reach the final velocity from the initial one. Then, the results of the calculation are projected on the middle and bottom displays. Namely, in

Figure 5.4, the TSD indicates the selected ETA and its corresponding curve and the bottom display includes the velocity step(s) that lead to the selected ETA.

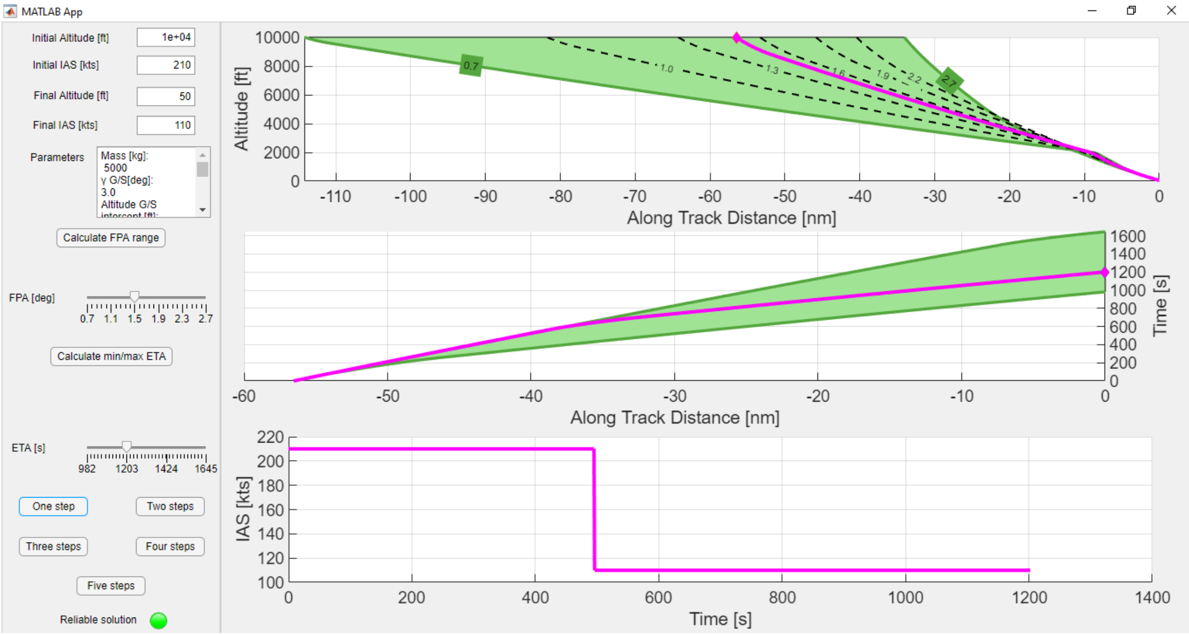


Figure 5.4: Fourth step for CDA planning

At the end of the fourth step, the pilot has a full overview of a potential CDA with its parameters defined and can further investigated alternative options, such as changing the number of steps or the flight path angle. Moreover, below the velocity steps buttons, there is an indicator to alert the pilot, by turning red, if the optimization algorithm did not converge to an acceptable solution. In this case, a proposed solution is to reduce the number of steps up to one step, which will always deliver a solution, since it examines sequentially all the possible time steps to impose the deceleration, until it finds the one which corresponds to the response of the target ETA.

5.4. Conclusion

In brief, using the principles of EID and previous work on the domain of interface design for aeronautical applications, a prototype for a pilot support interface to be applied for CDA planning was designed. This interface included a section for user interaction, hence to enter and select inputs and initiate the calculations, and a section with 3 displays, namely a VSD, a TSD and a display presenting the calculated stepwise velocity commands as a function of time. The pilot is then able, in real time, to have an overview of different approach scenarios, by examining the full range of the calculated affordances and changing the input variables.

6 Conclusion

In this Literature Study, the concept of executing a CDA with a target end time goal using a pilot support interface is analyzed, beginning from the background of this topic. CDA, has proven to be environmentally friendly in terms of emissions and less noise polluting, but in its initial form remains ambiguous regarding the ETA. There have been some studies improving the initial concept to reach an end time goal, concerning mainly flap scheduling and variable flight path angle, but a more flexible approach is to modify the definition of CDA and let thrust to be variable with a constant flap schedule and flight path angle. Therefore, a velocity profile, that has been calculated to lead to a target end time, can be followed with the pilot being engaged in the procedure through a support interface.
The development of this new approach requires at first to understand the kinematics and calculations needed for this approach in order to define the solution space and the target trajectory. Using a Cessna Citation I model, a proposed approach is to use a simple point mass model, while using data regarding aircraft performance from previous studies. Therefore, by applying the Newtonian equations of motion the aircraft trajectory can be simulated faster and the bounds regarding the minimum and maximum ETA are calculated. Then, an ETA can be selected and the IAS profile to accommodate this goal has to be defined. Since the pilot remains active in the process, a stepwise profile is chosen, corresponding to the commands to the autothrottle and the values of the steps are obtained from an optimization process. Finally, the performance of the point mass model compared to a nonlinear model, given the same inputs, proved to be acceptable.
The next step is to analyze this human-machine interaction from the perspective of the CWA. This analysis started by splitting down the work domain that the actors are interacting with, through the abstraction-decomposition space and how each level affects the other. Then, a task analysis took place, using a decision ladder, to lay down a road map of how to interact with the different aspects of the work domain to achieve an ETA goal and deal with issues that may occur. Then, a strategy of how to plan a CDA and then proceed with the execution is delineated and in the next step the roles of the pilot and the automation are appointed. Finally, the worker competencies analysis evaluated the behavior of the pilot in this procedure, according to the SRK taxonomy, hence revealing details of how the cognitive behavior can be assisted.
Having the elements of CWA, the design of the pilot support interface takes place, by following the guidelines of EID to present on the interface the calculated affordances and

constraints. An interface prototype was created, as a GUI with three displays and a user interaction section to enter the inputs needed for the calculations. The initial and final conditions (altitude, IAS) are used to define the range of flight path angles and present the possible trajectories in a VSD. Afterwards, using a selected flight path angle, the bounds of ETA are depicted on a TSD and finally after choosing an ETA and a number of IAS steps, the velocity profile that satisfies the goal is presented as a function of time.

The next step of this procedure includes the further enhancement of the CDA planning interface and define an interface design to monitor the execution of CDA and the commands of IAS/flaps/gear to be followed. Afterwards, pilots can evaluate the designed interfaces from an operational point of view in trials and propose more suggestions. The application of this modified type of CDA, if it proves its effectiveness and accuracy regarding the ETA, can pave the way to consider the application of this approach in more dense traffic conditions.

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III

Appendices (not graded yet)

A

Appendix A

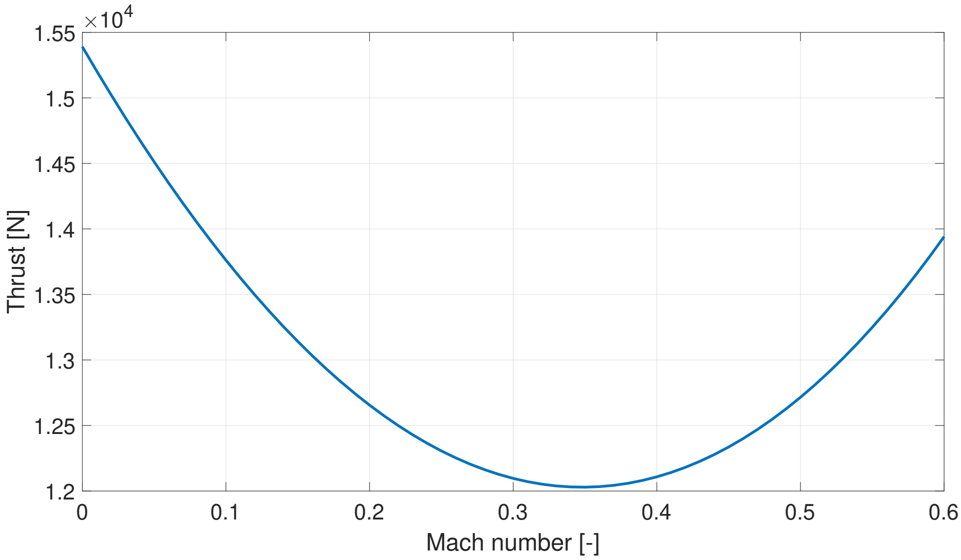


Figure A.1: Maximum thrust of one engine for a range of Mach numbers at sea level

Flap/Gear setting	c_1	c_2	c_3	**Constraints**
0°, gear UP	−0.0430	0.0202	0.0251	$C_L < 0.2823$
0°, gear UP	−0.0203	0.0241	0.0222	$0.2823 \leq C_L < 0.3702$
0°, gear UP	−0.0285	0.0458	0.0153	$0.3702 \leq C_L < 0.6$
15°, gear UP	−0.0246	0.0355	0.0281	$C_L < 0.4$
15°, gear UP	0.0345	−0.0027	0.0341	$C_L \geq 0.4$
15°, gear DOWN	0.0452	−0.0060	0.0532	-
40°, gear UP	0.0267	0.0160	0.0900	-
40°, gear DOWN	0.0327	0.0090	0.1126	-

Table A.1: Second order polynomial of the drag coefficient C_D of the Cessna Citation I ($C_D = c_1 \cdot C_L^2 + c_2 \cdot C_L + c_3$)

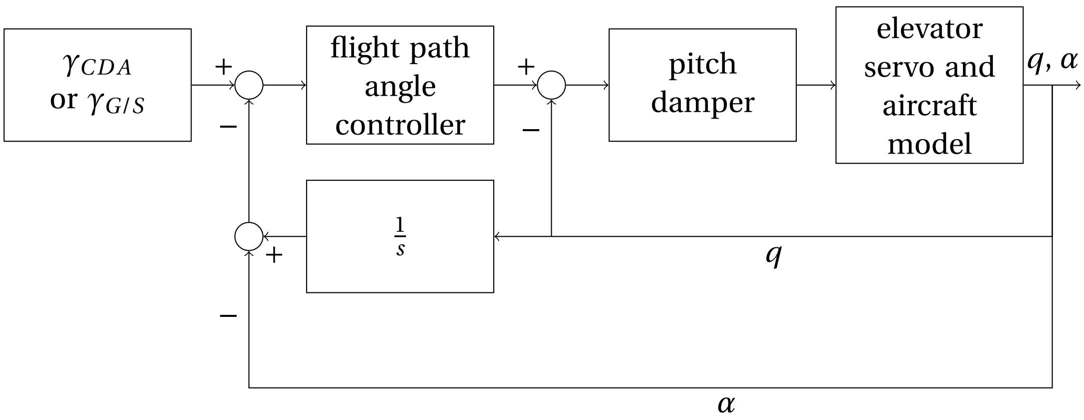


Figure A.2: Flight Path Angle Controller Block Diagram

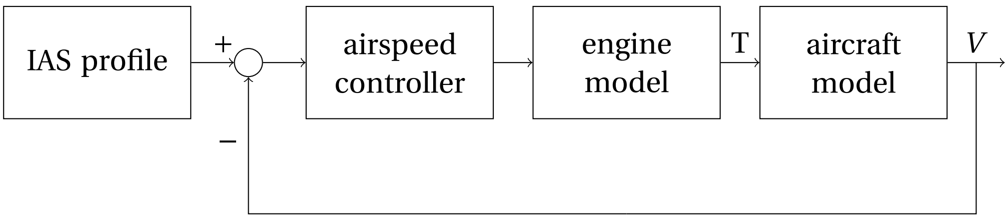


Figure A.3: Airspeed Hold Controller Block Diagram

B

Appendix B

B.1. Cognitive Work Analysis

The five-step process of CWA lays the foundation to proceed in designing an interface that will facilitate the pilot's mission. The point of view of CWA is shared with EID, namely the triadic approach (Borst [2016]), where the attention is given on the analysis of the laws and constraints of the work domain, instead of focusing only on the human operator or the automation. Through CWA these constraints are identified, so that the affordances (Gibson [1986]), i.e. the properties of the work environment that can be used by the human operator to achieve a goal, can then be presented in the interface. CWA is accomplished by using previous work and knowledge from de Beer et al. [2008], Gernaey [2005], Marwijk et al. [2011] for analyzing the execution of an approach. The five steps of CWA are: Work Domain Analysis, Task Analysis, Strategies Analysis, Social Organization and Cooperation Analysis, Worker Competencies Analysis.

B.1.1. Work Domain Analysis

The first step of CWA examines the structure of the system only, by forming the abstraction-decomposition space by Rasmussen [1986], as a 2-D matrix, in Table B.1. For the dimension of decomposition, the system can be broken down into subsystems and further components, while for the dimension of abstraction the system's goal rests on the highest level leading to the physical implementation of the system and other peripheral parameters as the bottom level. Between each level of abstraction, there is a means-end relation such as from Amelink [2010], Rasmussen [1986], hence while looking at one level's functions, the next higher level concerns why these functions are implemented and the next lower level describes how these functions are achieved. The analysis begins with the system's Functional Purpose to execute a successful approach, which is broken down into three subgoals, in terms of trajectory, time and safety. These targets can be achieved by coordinating Abstract Functions, thus tasks and actions, such as decelerating and descending. In particular, these tasks can be quantified in the form of equations of flight dynamics, in the Generalized Function level, which are dominated by the main forces acting on the aircraft and controlling its flight path angle. The influence of these variables depends on the different components of the aircraft, for example its engines and control surfaces, being the Physical Function of these phenomena, while the other peripheral aspects of the system who can also affect its operation, consist its Physical Form.

		Levels of Decomposition		
		Entire System	*Subsystems*	*Components*
Levels of Abstraction	*Functional Purpose*	Successful approach	Time punctuality Maintain trajectory Safety	
	Abstract Function	Physics	Deceleration Descent to runway Aircraft Configuration	
	Generalized Function	Flight dynamics	Lift Drag Thrust Weight Flight path angle control	
	Physical Function	Aircraft		Flight control surfaces Horizontal/Vertical stabilizers Wings Engines Radio navigation Flaps/Landing gear
	Physical Form			Air Traffic Landing runway Aircraft type Weather conditions IFR rules RTA requirement

Table B.1: Abstraction-Decomposition space

B.1.2. Task Analysis

During the Task Analysis, a sequence of actions is proposed that will lead the actor (pilot/autopilot) to achieve the set goals and the necessary information inputs to accomplish these actions are defined. This logic is depicted in the form of a decision ladder by Vicente [1999] in Figure B.1, which is consisted of information processing activities (actions) and states of knowledge (outcomes of actions). Having planned the CDA, this procedure is taking place during the execution of the approach and the decision ladder flowchart begins with initiating a routine check of the aircraft's state. After evaluating the key variables of flight that confirm the normal state of the aircraft, the actor continues by using the background calculations to examine the current position of the aircraft in terms of its designed trajectory, as well the future trajectory. Then, it is decided if the system's state (future trajectory/ETA) is aligned with the goal (RTA), or a new target should be established. With a set RTA, then the strategy to meet this end time goal is determined and the tasks that have to be completed in the future (IAS/flaps/gear) are specified and their execution is completed at the designated points. In addition, there is the possibility of bypassing some stages of the decision ladder (Steens et al. [2008]), if an action is about to be executed or the aircraft is on the desired state and path and no adjustment have to be made.

B.1.3. Strategies Analysis

The Strategies Analysis concerns the methodology that is taken to steer the system (aircraft) to its goal state (FAF at RTA) from the IAF, without making a differentiation on the actor in this process (pilot or autopilot). The CDA is planned by taking into account the timeslot given by the ATC, the estimated wind velocity and the IAF and other parameters to be selected concern the flight path angle and the number of IAS steps. Then, during the execution of the approach, the background algorithms will use the current position of

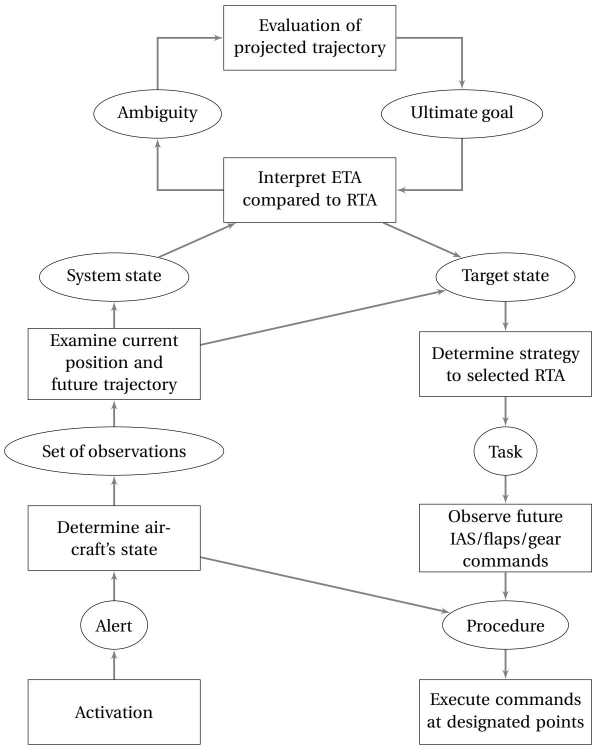


Figure B.1: Decision Ladder

the aircraft to continuously calculate the remaining trajectory and ETA and if the flap/gear schedule and the IAS profile are followed and there are no unforeseen factors, the time of arrival will be close enough to the RTA. However, in case of a deviation from the estimated wind velocity, then the next IAS steps can be executed earlier or later than initially calculated to adjust the ETA, or a re-planning of the remaining trajectory can be performed using the new wind data.

B.1.4. Social Organization and Cooperation Analysis

This analysis uses the work on the task analysis and the strategies analysis in order to determine the roles of the human operator/pilot and the autopilot, both represented by the same entity (actor) in the previous steps and supported by the future trajectory calculations. During the execution of the approach, the pilot maintains the required situation awareness regarding the safe flight status and the aircraft's position in the trajectory. Then, the pilot interprets the information provided by the instruments and the pilot support interface to insert the IAS/flaps/gear commands, when needed, and conclude whether the aircraft maintains its nominal path and will meet the RTA. The autopilot, on the other hand, is tracking the flight path angle of the CDA and afterwards the G/S, as well as the autothrottle follows the IAS commands of the pilot.

B.1.5. Worker Competencies Analysis

The worker competencies analysis is directly related to the three level categorization of the human information processing, the Skills, Rules, Knowledge (SRK) taxonomy by Rasmussen [1983]. The Skill Based Behavior contains actions that are triggered unconsciously by signals and require very low mental workload. The intermediate level is the Rule Based

Behavior, which includes the execution of rule(s) that do not require further knowledge and they may have been taught or learnt from past experiences. The highest level is the Knowledge Based Behavior, that relies on reasoning, and concerns a mental model that is employed to face an unfamiliar situation and it can lead to finding a solution but also to making errors.

Using the decision ladder, as in the Figure B.1, and dividing into three domains the information processing steps, the SRK taxonomy is applied (Borst et al. [2008]). The lower levels of the decision ladder, hence the activation and the execution of the tasks towards the target state, correspond to skill based behavior. These actions of the human operators are done without high mental load and are repeatedly executed during a flight. The next level are the intermediate information processing actions, such as identifying the current state and position of the aircraft in the trajectory and on the other side to define a strategy to reach the target state. These actions rely on Rule Based Behavior, since the pilot follows guidelines and checklists during planning and executing the approach. Finally the upper level of the decision ladder, in particular the interpretation of the current state in terms of accomplishing the final goal and checking if it feasible, corresponds to the Knowledge Based Behavior. This procedure requires a more creative way of thinking, since the pilot has been trained, but each situation can present some differences that require an alternative approach. The goal of designing this procedure and the accompanying interface is to reduce the human operator's cognitive load, hence to employ more Skill and Rule information processing activities and facilitate the Knowledge based behavior.

C

Appendix C

C.1. Experiment Briefing

Experiment briefing

Introduction

The noise that a flying aircraft creates, both from the engines and the airframe, can be a substantial nuisance in the neighborhoods around airports. It has been noted that an aircraft at take-off gains altitude at a high rate and their impact is lower, whereas the main noise source comes from the landing aircrafts, which fly at lower flight levels for longer periods, with their flaps extended which cause additional airframe noise. Combining this issue with the mitigation of the aircraft's gas emissions, in different research projects it is proposed to adopt new approach methods for the Terminal Maneuvering Area (TMA) and go beyond the traditional Air Traffic Control (ATC) sequencing and navigational aids.

One proposed solution is the Continuous Descent Approach (CDA), which in a general sense, concerns a descent towards the interception of the Glideslope (G/S), without horizontal flight segments and the minimal use of thrust.

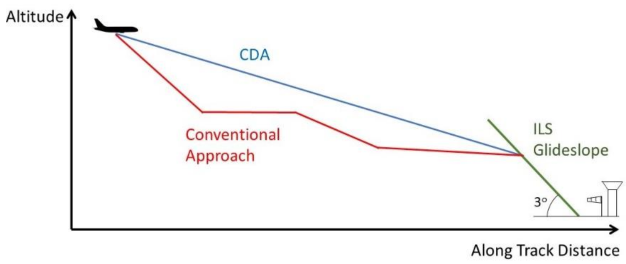


Figure 1 – CDA vs conventional approach procedures

The main issue with this approach concept, as it has been proven in both real flight experiments and simulations, is the low predictability of the time of arrival, either at the runway's threshold or at the interception of the G/S. This can hinder the implementation of the CDA at busy airports with tight landing slots and limit its use to low traffic hours.

Proposed concept

This project proposes the execution of a CDA that has some differences from the previously developed concepts. Firstly, the CDA has a constant flight path angle, as it is preferred by the ATC, and in addition, a goal concerning a Required Time of Arrival (RTA) is set to be achieved by following a pre-calculated velocity profile that fits these conditions. Therefore, thrust level is not bounded (close) to idle, but it is free to vary in the pursuit of tracking this velocity profile.

These functionalities need to be accommodated by a new interface that calculates the approach and presents it appropriately to the pilot. Then, the pilot can interact with this interface and be supported during this trajectory. We want to test this interface in the experiment.

The role of the pilot in this concept is like the usual approach procedure, hence the pilot maintains a supervisory role and interacts with the Autothrottle (A/T) and the flaps/gear setting. In the experiment, the tracking of the flight path angle of the CDA and the G/S is done by the automatic flight control system and the pilot does not interfere with this parameter after the initiation of the approach. In this approach, the velocities for selecting flaps settings and gear extension are fixed.

General principles of the experiment

The experimental procedure starts with the training session, where the first trial is going to be guided step by step through this document. Then, you can continue with the rest 4 training trials, where you can experience the functionalities of the interface and address any question to the experimenter. After a 10-minute break, you can continue with the main 4 experimental trials, where after each trial you will be asked to complete a brief questionnaire about your feedback and mental load. Depending on the selected CDA parameters, each trial can take from 8 to 11 minutes of flight time, but in this simulation scheme the actual time is shorter than that. At the end of the experimental session, you will complete the final questionnaire for any general remarks and suggestions regarding the interface.

Before the execution of the CDA, a planning process takes place, where all the parameters of the CDA are defined, given the Initial Approach Fix (IAF) and the Final Approach Fix (FAF), and the velocity profile that leads to the RTA is calculated. The approach uses stepwise changes in velocity, which can be implemented with discrete commands to the A/T.

Your task in each trial is to plan a CDA, according to the given guidelines, and then initiate its simulation. During the simulation, your goal is to take as a starting point the calculated velocity profile and reach the FAF with the minimum possible deviation from the RTA.

The experimental setup that you are about to use, consists of two computer displays, a mouse and a keyboard.

- The left display includes an application to design the CDA and define its parameters in the planning phase. Then during the simulation, in the lower part you can enter the IAS commands to the A/T and deploy the flaps/gear. Finally, on the right side there is the functionality to replan the remaining trajectory, if needed. This application is built around a Vertical Situation Display (VSD), which gives an overview of the possible trajectories, and then when the desired CDA trajectory is chosen, the IAS steps are being printed on that trajectory with their corresponding cues.
- The right display concerns the actual tracking of simulation and incorporates an altimeter, an airspeed indicator and a VSD, which is continuously updated with the remaining trajectory and the IAS/flaps/gear commands.

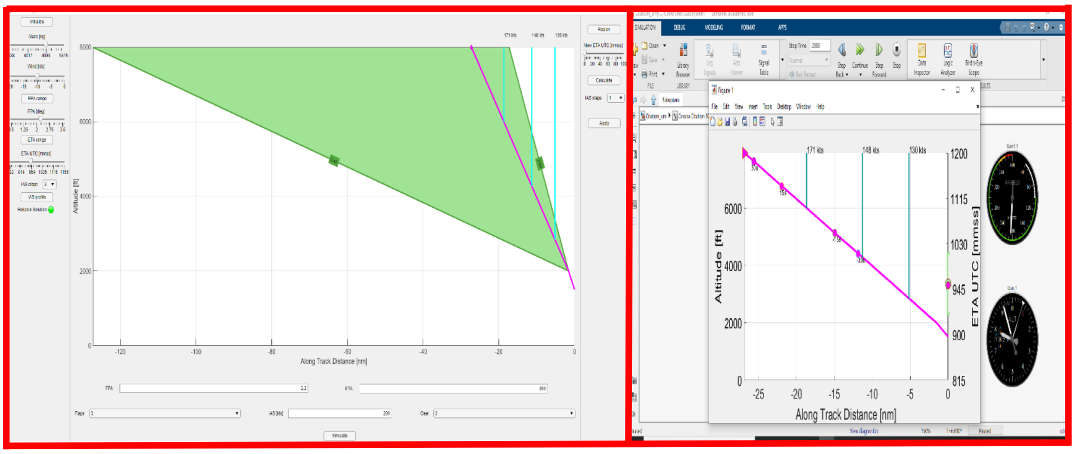


Figure 2 – Screenshot from the described setup

The IAF and the FAF of both the training and main experimental trials remain the same, along with the aircraft's mass, the flap/gear schedule, and the G/S parameters. The only variable that changes for each trial is the wind velocity.

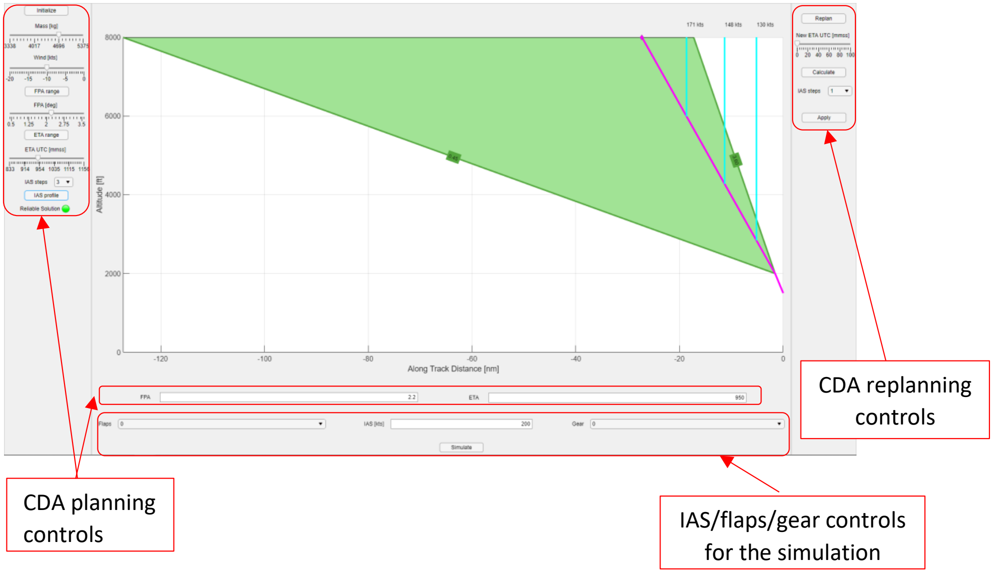
The aircraft, that was available to be used as a model in the project, is a Cessna Citation I.

Variable	**Value**
IAF Altitude	8000 ft
IAF IAS	200 kts
FAF Altitude	1500 ft
FAF IAS	130 kts
Mass	4696 kg
IAS for Flaps 15	165 kts
IAS for Flaps 40	120 kts
IAS for Gear Down	135 kts
Flight Path Angle of the G/S	3º
Altitude to intercept the G/S	2000 ft

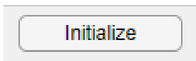
Table 1 – Experimental conditions

You can now let the experimenter know if you have any questions up to this point, so he can proceed to starting up your first training trial.

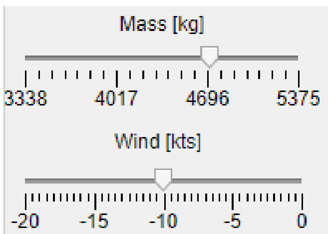
1st training trial walkthrough



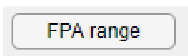
You can start using the CDA planning application by pressing the ***Initialize*** button, to setup the subsequent sliders of mass and wind velocity.



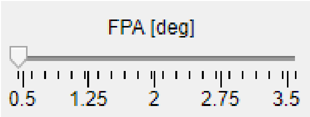
Then, you can select the value of mass (4696 kg) and the wind velocity for this trial (-10 kts).



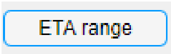
Having this input data, along the variables of the Table 1, the background calculations to define the feasible range of flight path angles for the CDA can begin by pressing the ***FPA range button***.



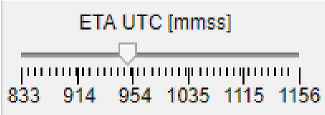
Therefore, the slider to select the desired flight path angle is updated with the calculated limits and the VSD of the application presents the range of possible solutions.

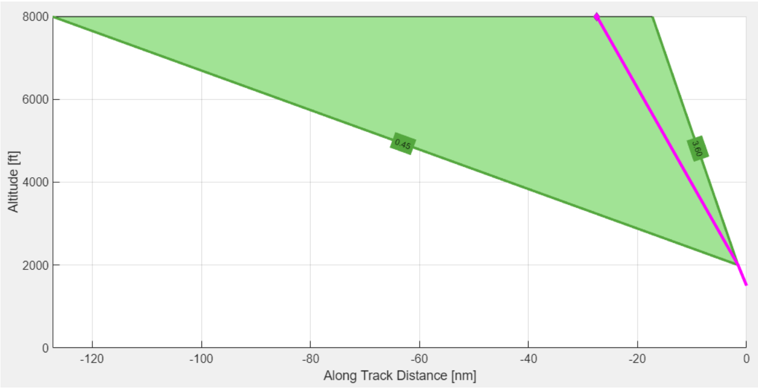


The selection of the flight path angle is free, within the range of 2º – 2.5º (steeper flight path angles will result in shorter in time trials). You can also see the exact FPA value that you selected on the slider on the corresponding textbox at the lower central section of the interface. For this demonstration, a value of 2.2º is selected and the button ***ETA range*** is pressed.

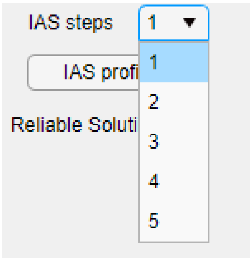


Consequently, the limits of the achievable ETA are calculated and displayed as the corresponding limits of the ETA slider, and the selected trajectory is printed on the VSD. You can also see the exact ETA value of the slider, on the corresponding textbox. The ETA slider and all the time indications in the experiment are converted into minutes and seconds and presented as [mmss].

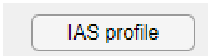




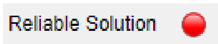
The last step for the CDA planning is to select the desired value of ETA and the number of IAS steps that you will have to execute, hence, to enter the IAS value to the A/T, during the simulation. During the calculation of these IAS values, an algorithm works in the background and it may take a few seconds for the solution to appear on the VSD, with the last IAS value always being the set IAS at FAF. For this trial, the ETA value can be in the range of 7 to 11 minutes (0700 to 1100) and a value of 0950 is selected. The number of velocity steps is free to choose in the drop-down list.



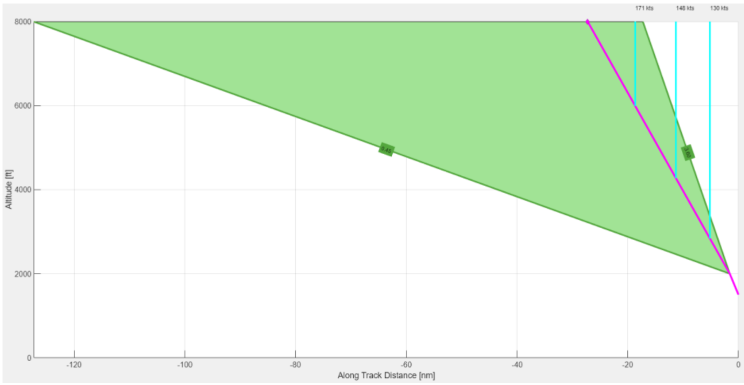
3 steps are selected and by pressing the ***IAS profile*** button the calculation of the IAS steps begins.



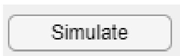
If the calculated solution, is not feasible, then the indication *Reliable Solution* will turn red. In that case, you can reduce the number of steps and/or select an earlier ETA and press again the ***IAS profile*** button, until it turns back green again.



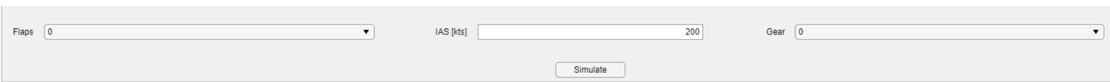
For the selected parameters, the IAS steps ATD positions are printed on the VSD, hence the deceleration will happen from the initial IAS to 171 kts, then to 148 kts and finally to 130 kts.



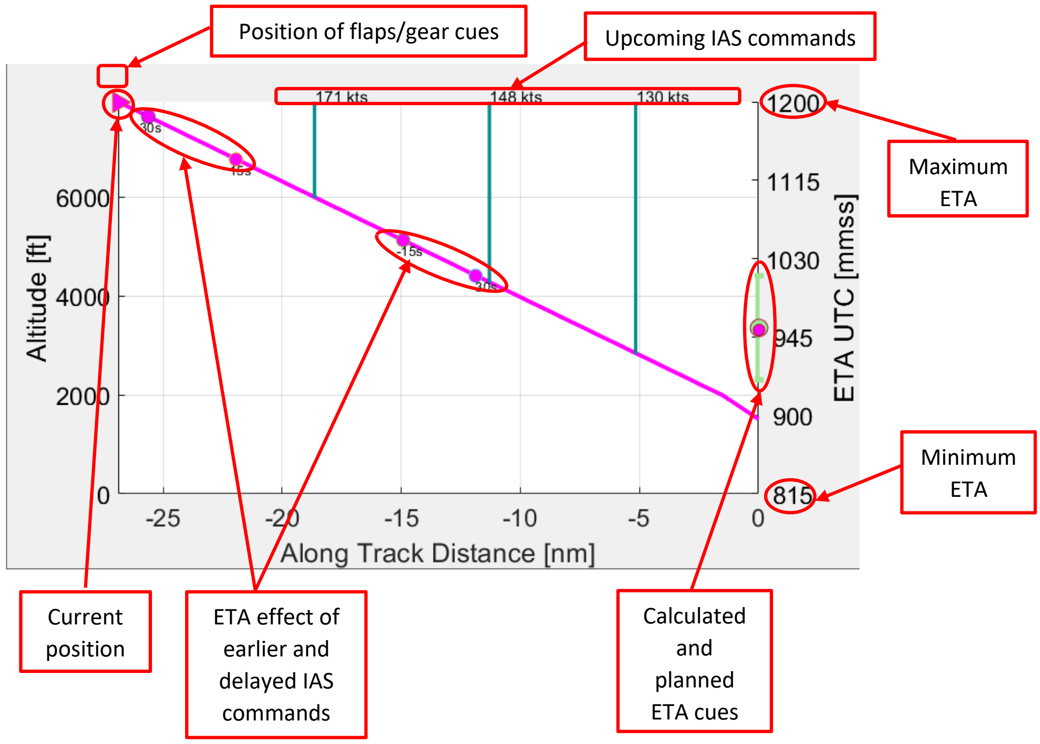
Having calculated the velocity profile, the flight simulation can begin, by pressing the ***Simulate*** button.



Above this button there are the controls to use during the simulation, which are initialized for the IAF configuration. Thus, there is the A/T where you can type the IAS value at the appropriate time and select using the drop-down lists the flaps and gear settings.



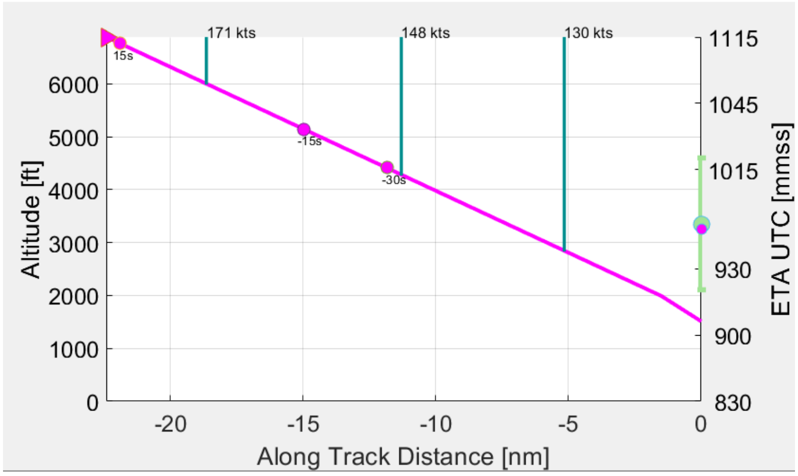
Having pressed the ***Simulate*** button, you can shift your attention to the right display with the airspeed indicator, the altimeter and the VSD, that has been enhanced with cues to accommodate this type of approach.



In this VSD, which is continuously updated during the flight simulation, you will notice that the magenta triangle, representing the current position of the aircraft, is stable at its position. Therefore, the altitude and ATD axes are being updated and in parallel the cues of the upcoming IAS/flaps/gear commands move to the left getting closer to this triangle.

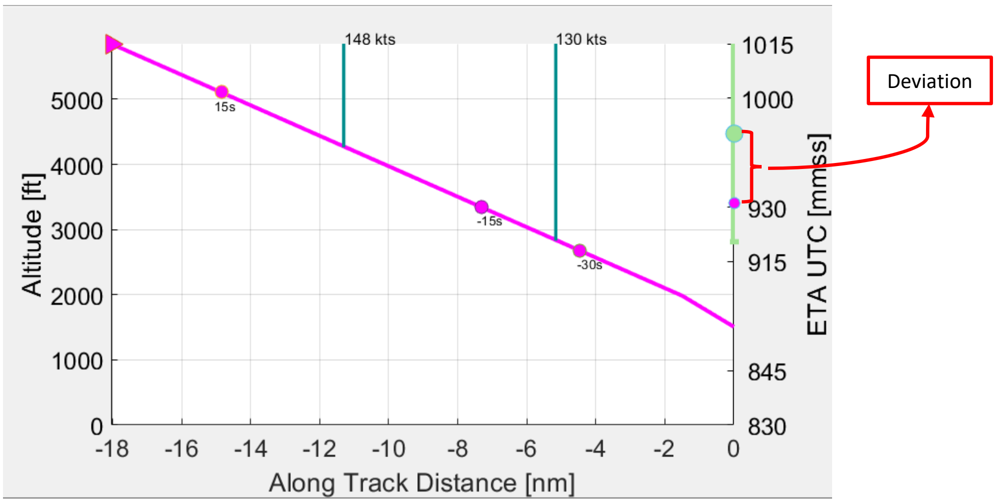
One of the main enhancements to a basic VSD design was the presentation of the different possibilities in terms of the ETA. In detail, on the VSD there are cues on the right vertical axis regarding the calculated ETA depending on the current aircraft's state (magenta circle) and the planned ETA (RTA), considering the time that has passed (green circle) with an error bar of ±30 s. The limits of the ETA axis are the minimum and maximum values of ETA according to the current state of the aircraft. On the trajectory line, there are cues (magenta circles) before and after the next IAS command, which represent the effect on the ETA of an earlier or later execution of that IAS command.

As the simulation continues the next command to the A/T (171 kts) is getting closer to the current position symbol, that means that you should prepare your strategy.



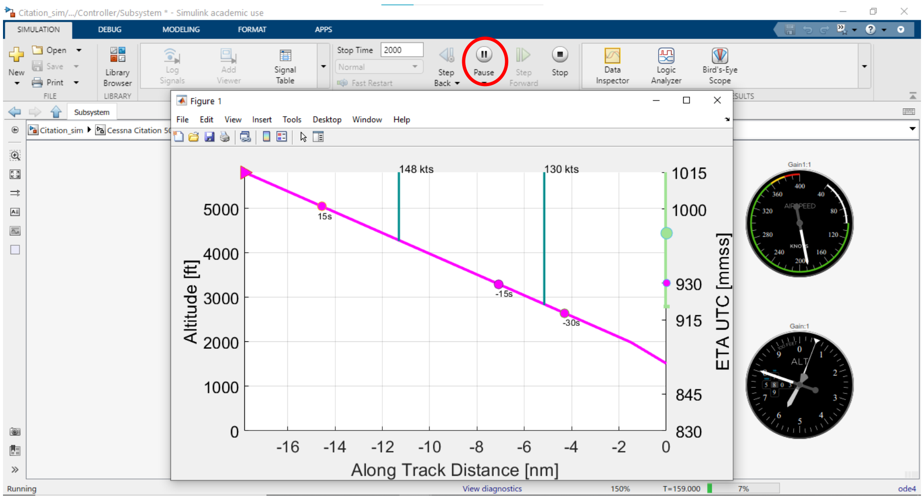
In detail, you can check the relative position of the estimated ETA cue compared to the planned ETA cue. In this case, they are very close, so the initially calculated ATD position to reduce the velocity to 171 kts is still valid.

After entering the next IAS command to the A/T, and deselecting the field to enforce your command, you can see that indeed the aircraft slows down according to the airspeed indicator. As the aircraft moves forward, you may notice that there is a higher deviation between the two ETA cues, approximately 20 s. That can be attributed to a deviation of the actual wind velocity from the planned one, that was used for planning the CDA.



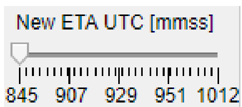
That gives you two options to resolve it and reduce the deviation. The first solution is to use the ETA cues on the trajectory line. In this case, the estimated ETA is earlier than the planned ETA, so you need to increase the estimated ETA by decelerating earlier to the next IAS. So, if you decelerate to 148 kts when the +15s cue reaches the aircraft's position, then the ETA estimate will get closer to the planned ETA.

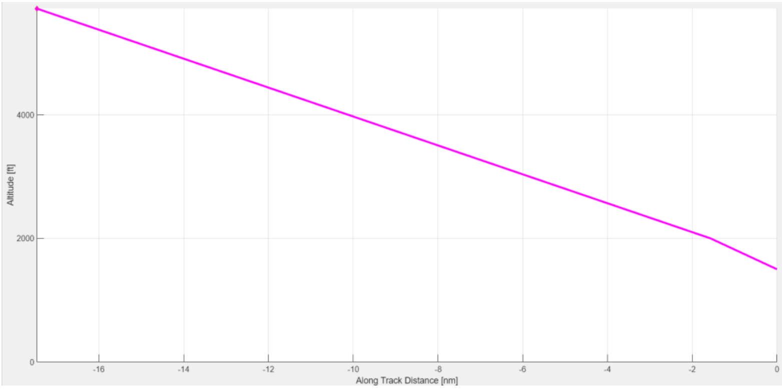
If this strategy does not produce the desired results, or does not fit your approach method, you can press the ***Pause*** button on the upper part of the right display.



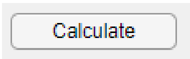
Then, you can use the left display, where on the right side of the CDA planning application, you can replan the remaining of the approach by taking into account the new wind velocity. However, this solution is advised to be used as a last resort. You can start the process, by pressing the ***Replan*** button. This replan procedure should be as quick as possible (under 1 min).

The application will update the New ETA slider with the achievable limits of the ETA, considering the current state of the aircraft and will plot the remaining trajectory on the VSD.

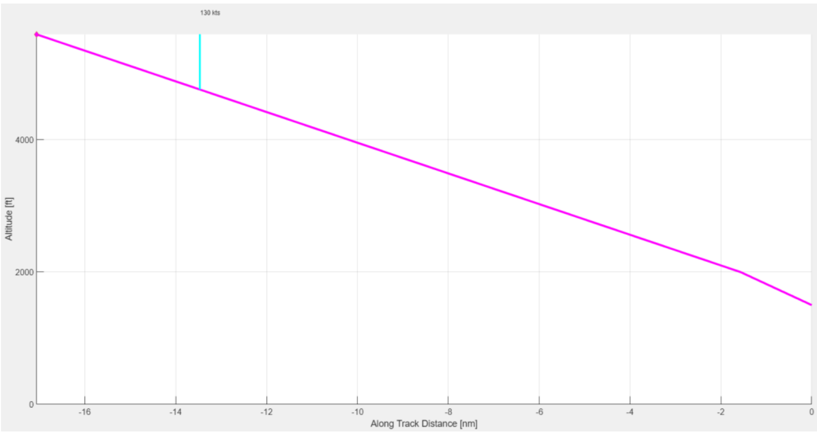




Therefore, you can select the new ETA as close as possible to the initially planned ETA, at 0950, and the number of IAS commands you wish to do until the end of the simulation. The new velocity profile is consequently calculated by pressing the ***Calculate*** button.

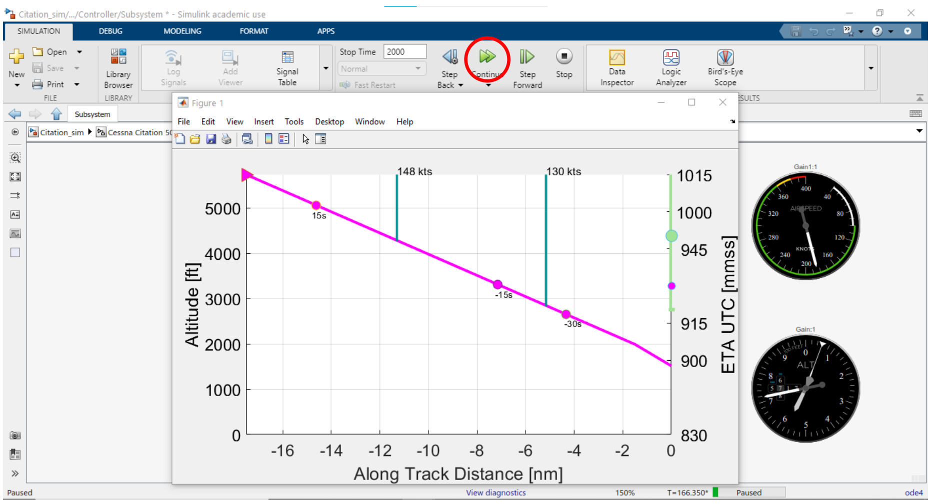


With 1 IAS change, the ATD position of this command is presented on the VSD.



If the *Reliable Solution* indicator remains green, the solution is valid, and you can press the ***Apply*** button to transfer the changes to the simulation.

Then, you can continue the simulation by pressing the ***Continue*** button, on the upper part of the right display.



When you are 500 ft above the FAF, the simulation will stop automatically. Then, you can continue with the next training trials.

C.2. Trials

Trials

For the training phase of the experiment, you can have the first interaction with the setup and have a clear picture of its functionalities, while you are encouraged to share with the experimenter any questions and concerns. At the end of each experimental trial, you will be asked to fill an electronic questionnaire regarding your experience and mental load.

Training

Training Trials:

- 1st trial
    - Wind velocity: -10 kts
    - Flight path angle: 2° – 2.5°
    - ETA: 0700-1100
    - Velocity steps: free selection
- 2nd trial
    - Wind velocity: 0 kts
    - Flight path angle: 2° – 2.5°
    - ETA: 0700-1100
    - Velocity steps: free selection
- 3rd trial
    - Wind velocity: -5 kts
    - Flight path angle: 2° – 2.5°
    - ETA: 0700-1100
    - Velocity steps: free selection
- 4th trial
    - Wind velocity: -5 kts
    - Flight path angle: 2° – 2.5°
    - ETA: 0700-1100
    - Velocity steps: free selection
- 5th trial
    - Wind velocity: 0 kts
    - Flight path angle: 2° – 2.5°
    - ETA: 0800-1100
    - Velocity steps: free selection

Experiment Trials:

- 1st trial
  - Wind velocity: -5 kts
  - Flight path angle: 2º
  - ETA: 1000
  - IAS steps: 3
- 2nd trial
  - Wind velocity: -15 kts
  - Flight path angle: 2º
  - ETA: 1000
  - IAS steps: 4
- 3rd trial
  - Wind velocity: -10 kts
  - Flight path angle: 2º
  - ETA: 1000
  - IAS steps: 4
- 4th trial
  - Wind velocity: 0 kts
  - Flight path angle: 2º
  - ETA: 1000
  - IAS steps: 3

Variable	**Value**
IAF Altitude	8000 ft
IAF IAS	200 kts
FAF Altitude	1500 ft
FAF IAS	130 kts
Mass	4696 kg
IAS for Flaps 15	165 kts
IAS for Flaps 40	120 kts
IAS for Gear Down	135 kts
Flight Path Angle of the G/S	3º
Altitude to intercept the G/S	2000 ft

C.3. Questionnaire

Introductory questions

Participant number

Have you ever flown a CDA either in real conditions or in a flight simulator? If yes, please specify what are your experiences and thoughts on this procedure?

Have you ever used a VSD? If yes, please specify which circumstances you were using it and your opinion on this type of display.

Experiment trial

Did you use the cues on the trajectory line concerning the early/delayed deceleration for this trial?

- Yes
- No

Did you perform a replan of the remaining trajectory?

- Yes
- No

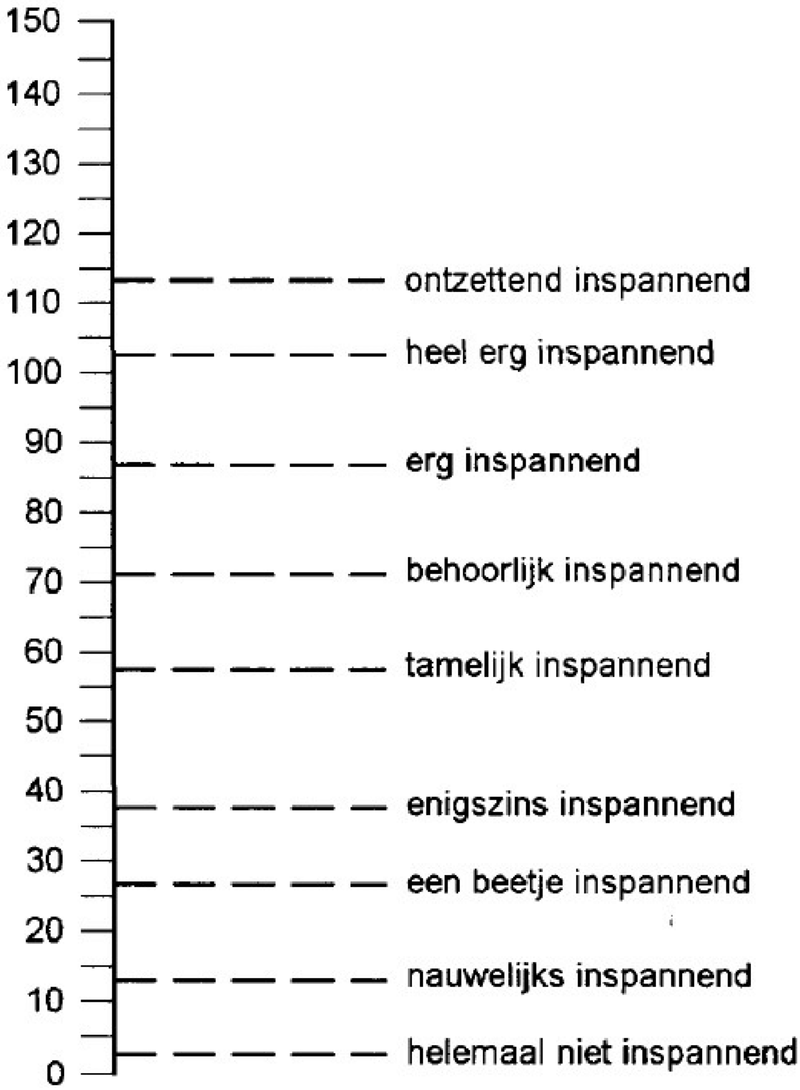
If you performed a replan, what forced you to this option?

Which functionality(ies) of the VSD proved to be more useful to achieve the RTA goal?

- ☐ Early/Delayed deceleration cues on the trajectory line
- ☐ Replan function
- ☐ I didn't need to use something else besides the initial IAS commands
- ☐ ETA cues on the right axis
- ☐ ________ Other

Do you think that you achieved the goal of the approach (be at FAF with the minimum deviation from the RTA goal)?

- ○ Definitely yes
- ○ Probably yes
- ○ Might or might not
- ○ Probably not
- ○ Definitely not



Please rate your mental load:

	0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150	
Rating Scale Mental Effort		☐

Final questions

The CDA planning application gave you a good overview of the upcoming approach trajectory and the required steps to be taken.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

The cues of IAS commands and the flaps/gear deployment were understandable and helpful during the simulation.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

The early and delayed deceleration cues on the trajectory line provided a convenient solution to manipulate the velocity commands and reach the RTA goal.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

The right axis of the VSD (ETA axis) was important for understanding the min/max ETA boundaries.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

The ETA errorbar and the planned ETA cue (RTA) were helpful additions to the ETA axis.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Was there any information on the VSD of the flight simulation that you did not particularly use?

Do you think that there is a lack of information for the timely execution of this approach, given the setup of the experiment?

Do you have any suggestions regarding the planning phase of the CDA?

Do you have any suggestions regarding the execution of the CDA using the VSD?

Any further comments/suggestions

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D

Appendix D

D.1. Introduction to the developed codes/models

From the beginning of the project, the developed codes for the trajectory calculations have been shaped around DASMAT model. Then, the three trajectory calculation cases were used in the development of the CDA GUI and in the CDA monitoring display. In parallel, the Simulink model of DASMAT was adopted firstly for the validation of point mass model, without needing an interaction during simulation, and then a second version of the Simulink model was created to accommodate the needs of the simulation of the experimental phase. In all of the trajectory calculations, the SI units were used and the conversion to the units of the aviation domain took place only during plotting of the corresponding results.

D.2. Trajectory Analysis

The trajectory analysis needed at first some functions in order to calculate all the variables for each time step. An atmospheric model was adapted from Gernaey [2005], in order to create a function (*atm*), which for a given altitude, calculates the atmospheric pressure P_{α}, the air density ρ and the velocity of sound V_{sound}. Moreover, two functions were adopted from this atmospheric model to convert the IAS to TAS (*VIAS_VTAS*) and vice versa (*VTAS_VIAS*). The C_D was calculated through a function (*cd_calc*), that used as input the C_L for a second order polynomial from De Prins et al. [2007], whose coefficients depend on the input and the flap/gear setting. Another variable to define for a trajectory calculation was the idle thrust, which was approximated by a percentage of the maximum thrust (3%) of one engine (JT15D). This percentage was calibrated by comparing the deceleration responses of the point mass model and DASMAT model. The maximum thrust was defined by the ratio of the atmospheric pressure at the current altitude to the atmospheric pressure at sea level multiplied by a third order polynomial as a function of Mach number, which was obtained from the corresponding DASMAT model input matrices and a least squares regression was adopted for the coefficients. Finally, the error bounds for the altitude and velocity are set in order to check at the end of each iteration, whether the aircraft has reached the FAF.
Then, the trajectory calculation follows either an IAS profile, which has been already defined for each time step, or it uses the idle thrust until it reaches the final velocity, when the

input to the equations switches to velocity. The principal script that contains the three trajectory algorithms (*solver*) begins with initializing the aircraft data, flap/gear schedule and the IAF/FAF, and then continues with the maximum ETA calculation case, the minimum ETA case and finally the target ETA case comes. In the latter case, an if-condition is applied to separate the case with a single IAS step, where the unknown variable of deceleration time is found by checking iteratively all the possible time steps, or more than one IAS step, where the optimization algorithm is adopted. For the optimization algorithm, a function was created (*traj6*), which takes as input the parameters of the IAS profile, such as the number of steps, the target ETA, the duration of each step, the initial and final IAS step values and the intermediate IAS step values, which are subjected to the optimization process. The output of the function is the objective function vector with the two goals. Once the optimization converges to objective function values less than a threshold (50% of the error bound), the calculation stops, otherwise a message is printed on the screen for a non-reliable solution. Finally in this script, the input IAS profiles and the responses of the three trajectory calculation cases are plotted to be compared.

D.3. Simulink models

The first Simulink model (*Citation*) was edited from its original form, but only as far as the Controllers block (Citation/Cessna Citation 500/Controllers), which included the flight path angle controller, the airspeed controller and the flap/gear deployment schedule and execution, and the Wind/Turbulence block (Citation/Cessna Citation 500/Citation model DASMAT/AIRCRAFT MODEL/WIND/TURBULENCE) for the wind velocity. The Simulink is using as input several variables from the workspace, such as the wind velocity, the flap/gear schedule, the IAS profile and the flight path angle settings (γ_{CDA}, $\gamma_{G/S}$, altitude to intercept the G/S). The gains of the controllers were tuned manually using the PID Tuner App of MATLAB with linear models of DASMAT in different trimming conditions and an adequate combination of constant gains was obtained for the range of the simulations. To begin a simulation, at first the *solver* script should be executed to initialize the basic variables and define the desired IAS profile, and then execute the initialization script of DASMAT (*initcit*) to define the starting point of the simulation from the trimming file (*simulation_new*).
The second Simulink model (*Citation_sim*) is an adapted version of the first model, with the difference of removing the inputs of the IAS profile and the flap/gear schedule and adding in their position a constant input block which the pilot can change during the simulation through the CDA GUI. Moreover, a function to calculate the wind velocity at each time step depending on the experimental scenario was created (Citation_sim/Cessna Citation 500/), which uses as input the scenario number, the initial wind velocity, the current ATD and the total ATD from the IAF. Finally, a function was coded in order to create and update the CDA monitoring display (Citation_sim/Cessna Citation 500/Controllers/Controller/Subsystem).

D.4. CDA GUI

The GUI has been shaped in blocks of code, which are executed when a button is pressed or a value in a textbox is entered, hence following an object-oriented logic. Some variables, such as the basic trajectory calculation parameters, as well as the calculated ETA bounds and the selected trajectory are used in multiple blocks, therefore they were declared as global variables.

The *InitializeButtonPushed* block is connected to the Initialize Button and sets up the GUI sliders for the mass and wind selection. The *FPArangeButtonPushed* block is executed from the corresponding button and calculates the limits of the flight path angle of the CDA. Therefore, two iterative procedures are applied starting from a very low angle (0.1°) until the first feasible solution is found and then starting again from the found solution, the iterations continue with increasing the flight path angle until the trajectory algorithm does not terminate at the desired state. Then, the bounds are printed as simple trajectory lines on the VSD and the corresponding slider is updated.
The *ETArangeButtonPushed* block calculates the ETA limits for the selected flight path angle by applying the already mentioned trajectory algorithm cases and then for the desired value of ETA and number of IAS steps, the *IASprofileButtonPushed* block defines the IAS profile. Once the trajectory is fully defined, the *SimulateButtonPushed* block initializes the pilot's controls (IAS textbox, flaps/gear selector), saves the needed variables in the main MATLAB workspace so they can be used by the Simulink model and initializes the one-dimensional input blocks in the Simulink model that may change during the simulation if a re-plan is executed. The multi-dimensional inputs that may change during the simulation, hence the parameters of the IAS profile, are saved as a structure array (str), which is read at every time step of the simulation. Finally, the simulation is initiated by updating the Simulink model and starting the execution.
During the simulation, the pilot's input of IAS in the textbox activates the *IASktsEditField-ValueChanged* block which transfers this input to the Simulink model airspeed controller and accordingly if the flap/gear setting changes the *FlapsDropDownValueChanged* and *GearDropDownValueChanged* impose this input to Simulink. Finally, if the simulation is paused and the Replan button is pushed, at first the *ReplanButtonPushed* plots the remaining trajectory on the VSD of the GUI and calculates the new ETA limits. Then, for the new ETA and number of IAS steps, the IAS profile is defined by the *CalculateButtonPushed* block and if the solution is accepted by the pilot, then by pressing the Apply button, the *Apply-ButtonPushed* block updates the inputs of the Simulink model with the new conditions.

D.5. CDA monitoring display

The CDA monitoring display is updated every 3 seconds and needs a vector of inputs, plus the ETA and the minimum ETA of the previous time step to facilitate the execution. In this function, at first the input variables are read, the IAS profile for the remaining trajectory is created and the current IAS step is estimated by comparing the horizontal position of the aircraft and the ATD position of the IAS commands. Then, the ETA is calculated, followed by the calculation of the ETA cues on the trajectory line (±15s, ±30s). In these calculations, at first the modified IAS profile is defined with the upcoming IAS command being displaced with a step of $\Delta t = 1$ s until the desired deviation from the initial ETA is found. Finally, the bounds for the ETA are determined, by firstly calculating the maximum ETA and its difference from the minimum ETA of the previous iteration. If the difference is higher than 75 s, then a new minimum ETA is defined, since it was noted that close to the FAF the minimum ETA trajectory calculation may deteriorate, not converge and cause an error to the simulation. At the end of the function, the results are arranged and plotted on the VSD.