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A QUASI-REAL-TIME GROUND-BASED TRAJECTORY OPTIMIZATION TOOL FOR GREENER OPERATIONS

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Abstract

This paper describes the methodology adopted in designing a quasi-real-time ground-based trajectory optimization tool for use by air traffic control officers. The tool is primarily intended for the optimization of aircraft trajectories during the climb and descent phases in which the user can define the trajectory in four dimensions. The optimized trajectories would then contribute to a reduction in fuel burn and emissions. The designed tool takes into account different aircraft types and sub-types through BADA performance and engine coefficients.

A simple case study for an approach in Malta International Airport has also been presented to illustrate the use of the tool.

Nomenclature

AGTD	*aircraft general type definitions*
ANSP	*air navigation service provider*
AAEM	*aircraft and engine models*
ATC	*air traffic control*
ATCO	*air traffic control officer*
CAS	*calibrated air speed*
CI	*cost index*
ETA	*estimated time of arrival*
FL	*flight level*
FMGS	*flight management guidance system*
FMS	*flight management system*
GRIB	*general regularly-distributed information in binary form*
LMML	*ICAO code for Malta International Airport*
MCDU	*multifunctional control display unit*
RTA	*required time of arrival*
SID	*standard instrument departure*
STAR	*standard terminal arrival route*
ToC	*top of climb*
ToD	*top of descent*

1 Introduction

Consistently rising fuel prices and, more recently the introduction of carbon trading schemes, have driven airlines into rethinking their business models, adopting approaches that reduce costs as well as the impact of their operations on the environment. An approach that offers great potential and has attracted the attention of the aviation industry is the management of trajectories for green operations. Traditionally, the preferred operating point of a flight, a balance between fuel consumption and flight time, is selected through the Cost Index (CI) function within the flight management system (FMS) on board most modern commercial airliners. This system has, to date, served its purpose well, but is a concept that is over 25 years old and, in its present implementation, is limited in terms of selecting a truly efficient flight profile. This is particularly true for operations in the climb and descent phases of flight, where aircraft are operating in and out of terminal areas and often have their flight trajectory altered due to air traffic control (ATC) constraints. Such constraints, which occur at a tactical level, generally do not address fuel burn and emissions in an efficient manner and, as a result, aircraft often fly highly sub-optimal trajectories. This situation can be addressed by the introduction of a trajectory optimization tool in the Air Traffic Control Cente (ATCC), with features similar to the CI function onboard aircraft, thus allowing the tactical planning of more efficient trajectories whilst maintaining the current philosophy of airline flight operations.

A number of tools and algorithms have already been developed to increase the throughput into the terminal airspace whilst facilitating better flight trajectories. For example, the En route Descent Advisor (EDA) developed by NASA ensures that the flight trajectories generated are conflict free to eliminate vector changes issued by ATC [1, 2]. Such tools are of significant value within busy aerodromes, but in small to medium sized airports, where traffic will be more widely spaced, aircraft management can be handled efficiently by the air traffic control officer (ATCO) with relative ease without the use of such tools. In such conditions, the optimization of individual trajectories, maximizing fuel reduction for a particular required time of arrival (RTA) becomes feasible.

Kai Virtanen *et. al* [3] and Janne Karelahti *et. al* [4] present visual interactive solutions to automate the process of aircraft trajectory optimization. However the user is expected to have a background in mathematical modeling since their design was not intended for use by pilots or ATCOs.

The mission of an aircraft is described by a flight plan, which contains a list of predefined waypoints with corresponding altitudes and airspeeds. The speed-altitude schedule (and corresponding time of flight) is today generally defined by the CI, which is selected by the airline at planning stage according to its business model. The flight plan, of course, does not take into account tactical considerations relating to other traffic. Neither can it take into account variations in weather conditions that may be encountered en-route. This results in the need for the tactical recalculation of the preferred (optimal) trajectory during flight, allowing for the introduction of ATC constraints and updating of operating conditions. The tool presented herein is envisaged to be used primarily for climb and descent, which is where the major potential gains are anticipated to be. The optimisation process can be performed a few minutes before the start of the relevant flight phase, allowing the use of up-to-date tactical information such as that associated with the weather and ATC constraints. The optimized trajectories can then be communicated to the flight crew.

The concept of using the flight plan data, issued by airlines, as the basis for trajectory optimization has already been exploited to optimize climb trajectories [5]. Ballin and Wing also use the flight plan data for optimizing trajectories, but the tool they propose is placed inside the cockpit [6]. This advisory tool uses an ADS-B link to receive timely and accurate traffic data to formulate a feasible trajectory. The data link established through the ADS-B receiver was intended to ensure the proposed new trajectory is free of traffic conflicts, facilitating its acceptance by ATC.

Following internal feedback from representatives of the ANSP, pilot and airline communities, it became evident that a ground-based tool for use by ATC in cooperation with the crew of the aircraft in question was a preferred approach. The merits of a ground-based optimization tool become evident when considering the operational environment as well as certification aspects of technology. Currently, ATC instructs flight crew with constraints, as explained above. Such constraints are based on the need for aircraft separation and naturally upset the CI calculations and business model of the aircraft operator. Furthermore, ATC personnel currently do not have objective means with which to introduce constraints that are sensitive to the airline business model and, as a result, often issue such constraints that result in unnecessary additional cost to the operator. Consequently, an ATC tool that is sensitive to such issues would be highly beneficial.

This paper describes the methodology adopted in designing a quasi real-time ground-based trajectory optimization tool for use by ATCOs. The tool is primarily intended for the optimization of aircraft trajectories during the climb and descent phases in which the user can define the trajectory in four dimensions as suggested by the European Strategic Aviation

Research [7]. The optimized trajectories would then contribute to the overall reduction in fuel burn and emissions. The designed tool takes into account different aircraft types and sub-types through BADA performance and engine coefficients [8]. This paper builds on previous work by the authors, integrating revised procedures around Malta International Airport (LMML) [9] with vertical profile optimization algorithms [10] implemented in the said ground-based tool.

2 Tool Design and Architecture

The top level ATC tool architecture is presented in Fig. 1.

The tool contains a graphical user interface (GUI), through which the user interacts with the system. The GUI is connected to the various databases, allowing the retrieval and storing of data associated with the databases. The optimizer is triggered via the GUI, which then runs the optimization process using data from the relevant models and databases. The output, an optimized flight trajectory or flight plan, is then passed on to the GUI for use by the user.

2.1 The AGTD Database and the Aircraft Models

A database is required to link the aircraft with its respective aircraft and engine models. The aircraft general type definitions (AGTD) database has been designed in SQL to provide this link. It contains fleet information for different airlines that choose to collaborate with ATC in using such an optimization tool to obtain optimized trajectories. The AGTD database contains a table for each airline. Each table includes aircraft information specifying the aircraft manufacturer, general type (referred to as the aircraft model), series for each general type, and the aircraft registration that is unique to each aircraft and is used as the primary key. For each aircraft specified within the AGTD database, a link is created to the aircraft and engine models (AAEM) suite, thus mapping the chosen aircraft with the appropriate (specific) aircraft and engine model. The selected aircraft and engine model is then used by the optimizer.

In this work, the optimizer uses pseudo-spectral optimal control methods. Consequently, models defined in state-space form are used. These are developed from Base of Aircraft Data (BADA)[8], using the coefficients provided by Eurocontrol.

The Aerodrome Configuration Database

The aerodrome configuration database contains a number of comma separated variables (CSV) files, each containing information that define the aerodrome, the airspace surrounding it and the arrival and departure routes. The aerodrome file consists of a table containing the airport's name together with the IATA code and the ICAO code, the geographic aerodrome reference point (ARP) specified in latitude and longitude in decimal degrees, the aerodrome elevation above mean sea level (AMSL), the runway designation which identifies the runways at the aerodrome and their orientation, the latitude and longitude co-ordinates at the runway thresholds, the elevation AMSL at the threshold of each runway and the country name and identifier as allocated by the International Telecommunications Union (ITU).

The airspace file contains data that defines the airspace surrounding the aerodrome in which trajectories will be optimized. The airspace database includes a table listing the airspace name, the airspace lower and upper limits and the airspace area shape, which, in turn, defines the edges of the area volume. The corners of the airspace area are defined in latitude and longitude, with the last in the series being connected to the first to close the polygon. The position of the entry and exit points are also specified, these marking the start and end of STARs and SIDs respectively. All the waypoints up to the top of climb (ToC) or top of descent (ToD) point are specified.

The arrival and departure routes are also defined within the aerodrome configuration file. Arrival and departure routes consist of a table specifying the name, the type of procedure being arrival, departure or approach, and whether it should be followed by RNP-AR approved aircraft. The route is defined by a series of waypoints, each specified by a latitude

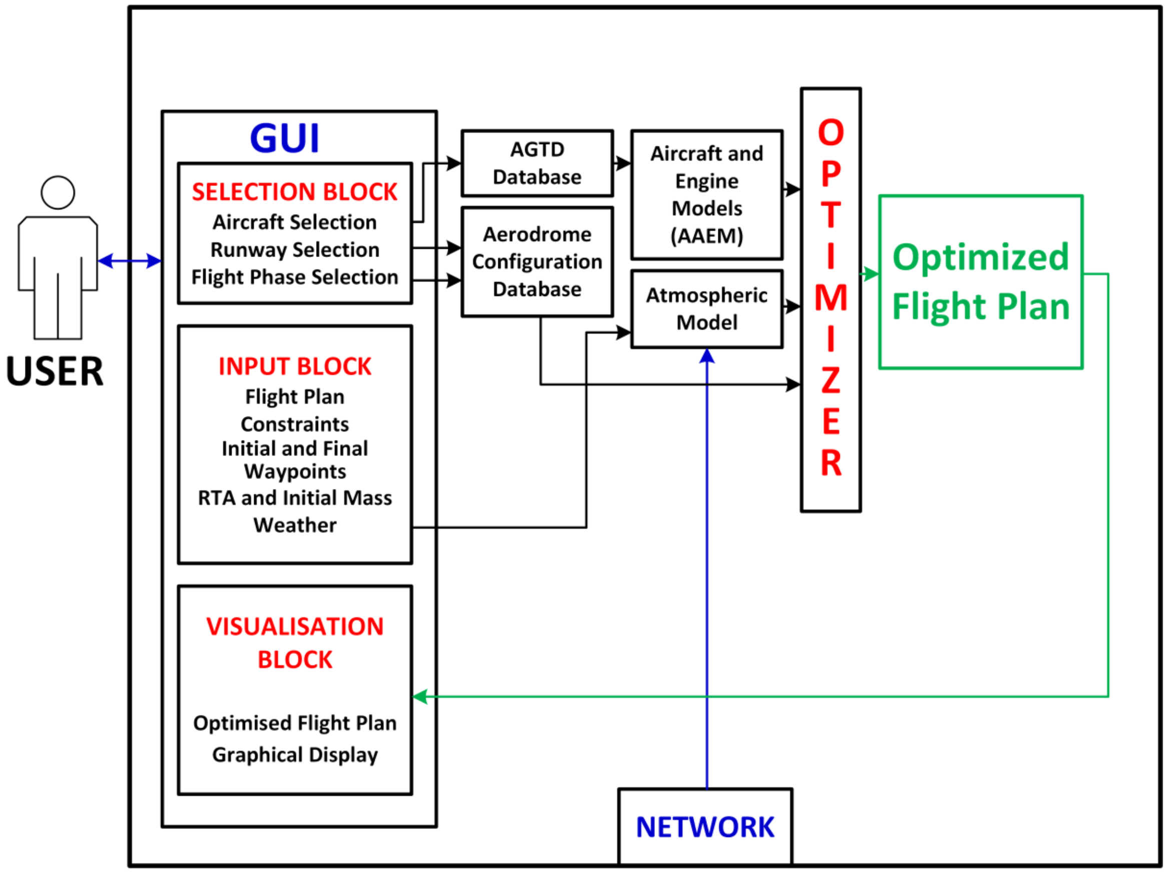

Fig. 1 The ATC Tool Architecture

and longitude, along with any speed and altitude constraints and the path termination at each waypoint as defined by the ARINC-424 database. In the case of a waypoint having an RF path termination, the previous waypoint must specify the direction of the turn, choosing between a left turn or a right turn and the circle identification number. The circle identification number is the primary key used to specify the properties of the fixed turn radius within another separate table that lists the center of the turn and the turn radius.

Arrivals (STARs) can either be closed or open. In case of open STARs, track guidance to a downwind track position is provided, from which the aircraft is tactically guided by ATC to intercept the final track position. In the case of closed STARs, the procedure provides guidance up to the final approach track, through which the aircraft intercepts the ILS, if available. Waypoints associated with T-bar or Y-approaches are listed in a separate file.

The aerodrome configuration database is designed to support easy updating, rendering the ATC tool portable to any aerodrome or flight information region (FIR) sector.

2.1 The Atmospheric Model

In order to generate good optimized trajectories, deviations from International Standard Atmosphere (ISA) conditions need to be taken into account. This, in turn, requires the use of accurate weather forecast or reporting data. Consequently, the atmospheric model developed in this work, which is based on the ISA model and then adapted to take into account local conditions, uses forecast or reported winds and temperatures at different altitudes. Such data is normally obtained through meteorological offices and agencies but is also available through Aircraft Meteorological Data Relay (AMDAR) reports from aircraft in the vicinity of the aerodrome. The process of data entry from meteorological reports is automated, using forecast data provided by NOAA via their website. This data is in General Regularly-distributed Information in Binary (GRIB) concise data format, as standardized by the

World Meteorological Organization (WMO) [11]. A major advantage of the GRIB format is that it is self-describing, with each record including information such as the resolution of the grid, the time, the atmospheric variables contained within the GRIB file and the pressure level. A decoder is needed to decode data in the GRIB format. The decoder used for the ATC tool is the Degrib executable application, also available from NOAA[1]. GRIB data is organized in a grid layout over a particular area of interest with spatial resolution defined in degrees of latitude and longitude. The Degrib application returns the temperature and wind forecasts at each point on the grid for various pressure levels and at the mean sea level. The Degrib application also returns the pressure reduced to mean sea level (PRMSL). The PRMSL allows the determination of the altitude at each isobaric pressure level for each grid point within the GRIB file. For finding the forecast values at specific geographical locations within a particular isobaric level between grid points, the Degrib application provides a bilinear interpolation method using the forecast values at the grid points around the point of interest.

In this work, the GRIB files are obtained from the Global Forecast System (GFS) model from NOAA through the ZYGRIB website, and stored within the file structure of the ATC tool. At startup and every six hours, and when the ATC is restarted, the tool automatically obtains the latest GRIB files with any updated forecasts available and updates the internal atmospheric data accordingly. The spatial resolution provided by the GRIB file is 0.5° by 0.5°, at the following isobaric pressure levels of 200mb, 300mb, 500mb, 700mb, 850mb, 925mb and at mean sea level.

In addition, weather data may be entered manually via the GUI.

2.3 The Optimizer

Trajectory optimization is a multi-disciplinary process involving relatively complex mathematical computations for tactical use. Optimizer qualities such as ability to converge and speed of convergence depend on the problem at hand as much as on the optimization technique used. In this work, the optimizer relies on pseudospectral techniques developed in previous work [10]. The optimizer generates optimised vertical profile trajectories meeting the criteria set by the user, including the initial and final operating conditions and any speed-altitude constraints along the trajectory.

2.4 The GUI

The GUI provides the human-machine interface and therefore handles inputs by the user and displays the outputs of the optimizer (data pertaining to the optimized trajectory in graphical and tabular format). Human factor considerations have been taken into account in the design to ensure that the GUI will have satisfactory visual performance. The application has been implemented in JAVA to facilitate the use of windows-based techniques whilst remaining platform independent (and, in particular, independent of operating system).

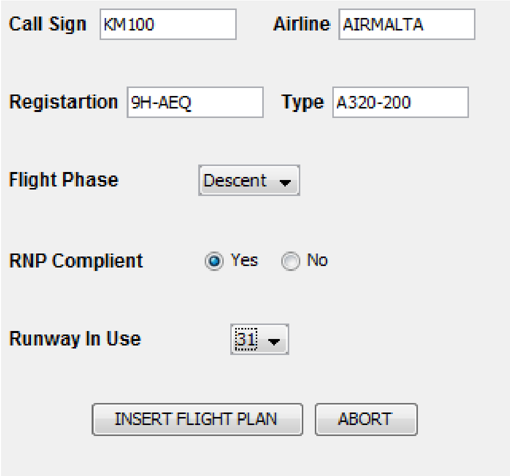

Fig. 2 The Flight Information Window

The GUI contains a menu bar with tabs, a map to show the lateral path defined by the flight plan with zoom and pan functions, and an option to display all the waypoints defined within the aerodrome configuration database on the map. The aircraft for which the flight path is to be optimized is identified by clicking the aircraft tab that opens the Flight Information Window, as illustrated in Fig. 2. Within this

[1] http://www.nws.noaa.gov/mdl/degrib

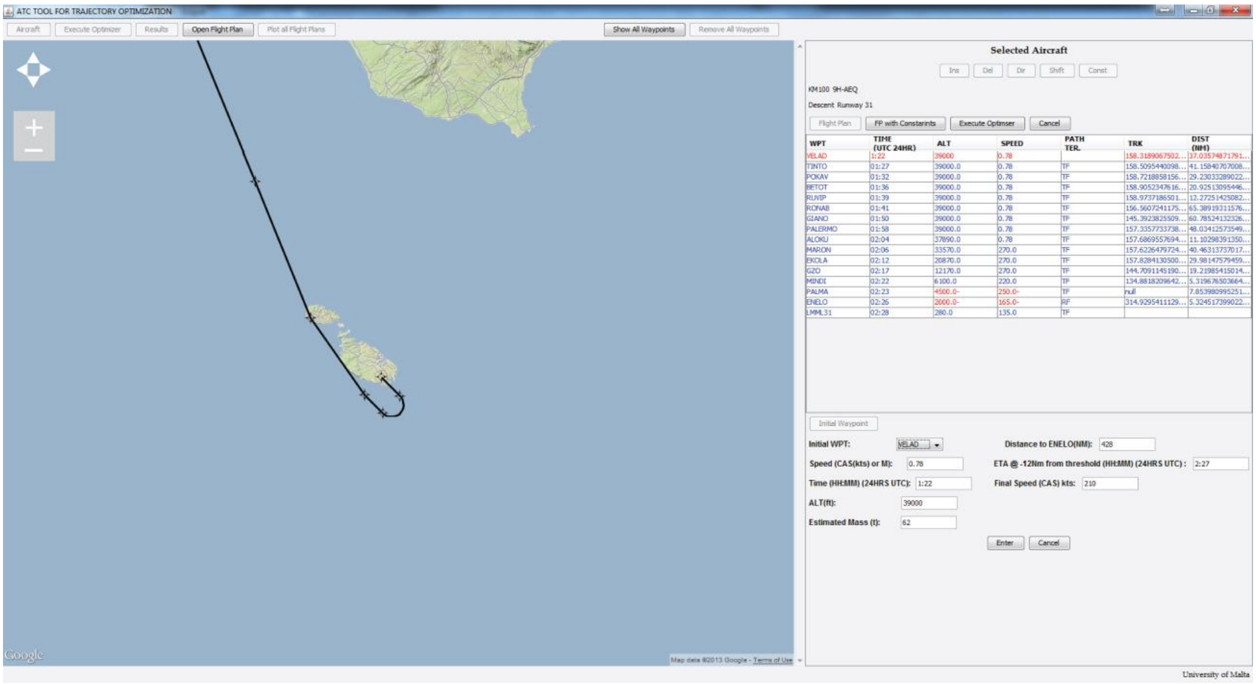

Fig. 3 The Main GUI Window with an Example Flight Path.

window, aircraft and flight details such as the call sign, airline, registration and type of aircraft are inputted and this allows the system to point to a particular entry within the AGTD database. Other details, such as selection between climb and descent, and the runway in use are also entered in the said window. The flight phase and the runway in use are used to query the aerodrome configuration database for the data pertaining to the maneuver of interest. Fig. 2 illustrates a facility to insert a flight plan manually. When the INSERT FLIGHT PLAN button is selected, a pane on the right hand side of the screen is generated for the user to input the flight plan.

The flight plan for the chosen aircraft can be entered manually within the table of the side pane of the GUI main window as shown in Fig. 2. The flight plan table consists of seven columns, indicating the waypoint name, planned time of arrival, altitude, speed, path termination as specified by ARINC-424, the track heading to the next waypoint and the track miles to the next waypoint. Whilst the user enters the first five entries, the last two are populated automatically as successive waypoints are being entered. The default path termination at each waypoint is a track to a fix (TF), which, however can be changed by the user. The resulting plan path is automatically displayed on the map as shown in Fig. 3.

Selection of an existing SID or STAR stored in the Aerodrome Configuration database is also possible by typing the name of the route within the cell where waypoints are normally entered. The specific waypoints making up the route are then automatically entered in the flight plan table. Standard speed and altitude constraints and path termination method of each waypoint associated with the route are also entered automatically as listed within the database. The flight plan table allows rows (that is, specific waypoints) to be deleted and new ones to be inserted and the tool runs a validity check to validate the entries. On successful completion, the flight plan is accepted by the system. Time, speed and altitude constraints can have the form of AT OR ABOVE, AT OR BELOW, or AT specific values and thresholds. Finally, the GUI allows changes to the flight plan to be discarded at any time.

When the user is satisfied with the flight plan and constraints, the initial and final points of the trajectory to be optimized, identified by the selection of two waypoints with specific speed and altitude values, are selected. With valid weather and operational data (including aircraft weight) entered into the system, the

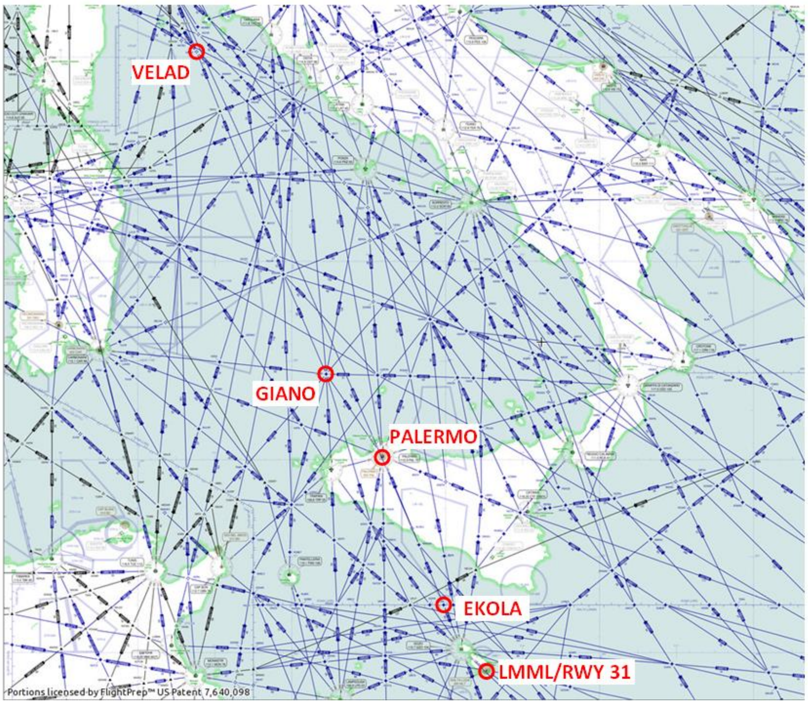

Fig. 4 Salient Waypoints of the Case Study Route.

setup will be ready for the optimization of the defined trajectory segment. This process is initiated by the user via the selection of the *'Execute Optimizer'* button (not shown in Fig. 3) that becomes active only when the setup is complete.

The GUI also has a window to facilitate the interpretation of the data associated with the optimized trajectory. To this effect, the data is displayed in both tabular and graphical format. In tabular format, speed and altitude schedules are listed for each waypoint together with the ToD or ToC point as appropriate, whilst in graphical format, various performance graphs can be displayed. Once the optimization is complete, the ATCO can relay speed schedules and the ToD/ToC point to the flight crew using standard voice radio communication means or otherwise.

3 Trajectory Optimization Case Study

A simple trajectory optimization problem was set up and solved using the tool. The problem involved a typical descent from cruise level and approach towards a runway at Malta International Airport (LMML) from the north-west. Accordingly, waypoints starting from the new approach to Runway 31 MINDI-1A proposed in previous work [1] to keep the track miles flown to a minimum was used in this work. On start-up, the tool loaded the latest atmospheric model automatically via internet and fictitious A320 aircraft data was entered into the system.

A typical flight plan was input for an aircraft flying from the waypoint VELAD, located approximately 400 NM roughly north-by-north-west of the threshold of Runway 31. Subsequent waypoints to the approach MINDI-1A were also entered. Salient waypoints of the route are shown in Fig. 4. After EKOLA, the flight path proceeds to GZO and follows the left hand down wind approach to Runway 31 defined by MINDI-1A as shown in Fig. 3.

For the purpose of the case study, the operational parameters entered at VELAD were the following:

- Time: 01:22 UTC
- Altitude: 39,000 ft
- Speed: 0.78 Mach
- Mass: 62 tons

The trajectory was optimized from VELAD to the final approach fix at ENELO, 5.3 NM from the threshold of runway 31. Air traffic control procedures into LMML require aircraft to decelerate to flap extension speed at 12 NM away from the threshold. This corresponds to approximately 210 kts for a Category-C aircraft such as the Airbus 320. Thus, the final conditions defined for ENELO were the following:

- RTA: 02:27 UTC
- Altitude: 2,000 ft
- Speed: 210 kts CAS

No further constraints other than those related to performance models were added to the problem formulation. The optimization was then executed. This took approximately 10 minutes to complete using a standard PC. Data pertaining to the resulting trajectory optimized for minimum fuel burn for the required time of flight is presented in tabular format Table 1.

Waypoint	Speed (Mach/CAS)	Altitude	Time (hh:mm)
VELAD	0.78	38,999	01:22
TINTO	0.77	38,992	01:27
POKAV	0.77	38,992	01:32
BETOT	0.78	38,985	01:36
RUVIP	0.77	38,987	01:39
RONAB	0.77	38,991	01:40
GIANO	0.77	38,981	01:49
PALERMO	0.77	38,835	01:57
ALOKU	0.63	35,657	02:04
MARON	0.58	33,538	02:05
EKOLA	197.3	21,760	02:13
GZO	200.9	12,723	02:20
MINDI	203.1	6,622	02:25
PALMA	215.6	4,376	02:26
ENELO	210.0	2,000	02:27

Table 1 Salient Data of the Optimized Trajectory, Defining the Speed and Altitude Schedules for the Different Waypoints.

The results show that in cruise, the aircraft was required to decelerate slightly from M0.78 to M0.77 and then slow down in the descent, which commences at PALERMO. In the descent, the optimal speed translates to 206kts CAS between PALERMO and MARON and about 199kts CAS between MARON and GZO.

4 Conclusion

This paper presents a prototype software tool developed primarily as a ground-based system to optimize flight trajectories with ATC constraints in the vertical profile (i.e.: speed and altitude constraints). A simple case study for an approach into Malta International Airport has also been presented to illustrate the use of the tool.

The experience obtained indicates that it can be of value in operation, particularly within the context of 4D Trajectory Based Operations. In this scenario, the tool could be beneficial in generating minimum fuel burn trajectories for a given flight time. It is concluded that the tool merits further development and use in trial operations.

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