Development of a Methodology for Flight Data Reproduction in a Simulation/Visualization Software

Graça Alves São Pedro
gracaalvessaopedro@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

June 2022

Abstract

Safety is a pillar of aviation. To ensure that aircraft are operated with a desirable level of safety and the risk is reduced to an acceptable level, operators have a Safety Management System (SMS) dedicated to managing the necessary structures, responsibilities, policies and procedures. Flight Data Monitoring (FDM) falls within an operator's SMS. FDM usually relies on graphical and statistical analysis, but flight data animation, consisting of the representation of the flight data in a dynamic visual format, can also be a powerful FDM tool. The objective of this work is to develop a flight data animation tool based on X-Plane to be used at Portugália. The animations are fed with data from the airborne Quick Access Recorder (QAR). The parameters undergo a conversion process that creates a file formatted according to X-Plane's specifications. Then, the animations are run on the simulation software, allowing for a thorough and immersive analysis of the events. It was found that these animations reproduce the flight data as expected, although X-Plane presents some limitations in terms of data input, which result in inconsistencies or simplifications. Nevertheless, the animations proved useful in the analysis of events, as they provide a fast, efficient and dynamic medium to represent the flight data.
Keywords: Flight Data Monitoring, Quick Access Recorder, X-Plane, Flight data animations.

1. Introduction

The International Civil Aviation Organization (ICAO) defines safety in *Annex 19 to the Convention on International Civil Aviation* as "the state in which risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level" [1]. In order to make sure that level is met, ICAO also stipulates, in *Annex 6*, that operators should implement a flight data analysis program as a part of their safety management system if their aircraft have a certificated take-off mass in excess of 27 000 kg [2]. To assist operators in implementing flight data analysis programs, ICAO has also developed the *Manual on Flight Data Analysis Programmes (FDAP)*, which describes how an effective FDAP should be established to help airlines achieve the required safety levels [3].

In Europe, the European law EU-OPS 1.037 published in the *Official Journal of the European Union* in 2008 defines and requires the establishment and maintenance of a flight safety program, including a flight data monitoring program in accordance with ICAO Annex 6 [4]. In the United States, in 2004, the Federal Aviation Administration (FAA) issued the Advisory Circular 120-82 to provide guidance on the development of Flight Operational Quality Assurance (FOQA) programs, which are analogous to the FDM programs in use in Europe, although not mandatory [5].

Under the aforementioned legislation and documentation, airlines throughout the world have been implementing flight data monitoring programs, with the purpose of achieving higher levels of safety in their operations. These FDM programs employ quick access recorders to retrieve hundreds of aircraft performance parameters and provide easy and quick access to the data. The proper contextualization and interpretation of this information are fundamental to a profitable FDM program, but also pose a challenge to safety departments.

Flight data can be represented in a variety of different formats, particularly time-series graphs and cockpit and aircraft simulations [3]. On the one hand, time-series graphs are useful in the representation of the evolution of data over a period of time and are advantageous to the numerical estimation and prediction of trends and future data [6]. Nevertheless, they usually do not allow the visualization of the interactions between different sets of parameters and are generally harder to interpret without a context. On the other hand, modern flight simulating software that allows the input of external data may prove to be useful in the visualization of QAR data, because it allows the reconstruction of a flight. This way, every event, warning and instrument reading can be reproduced and interpreted in its context. This type of technology can be used not only by the safety department of airlines for data monitoring purposes, but also by their training department to acquaint pilots with both typical and atypical operations and also in crew debriefings to review events during flights and the crew's response to them.

1.1. Objectives

The objective of this work is to develop a methodology that imports the QAR data into a flight simulation software, within the scope of Portugália's Safety Department's FDM program. The final product is a program that receives QAR data, rearranges it into a readable file by the flight simulator and inputs that file into the simulation software to allow the reconstruction and visualization of flight data. In order to develop the desired product and achieve the main goal of this work, the development process follows the steps listed below:

1. Evaluation the QAR data frame, with the purpose of determining and extracting the relevant data to be imported into the simulation.
2. Analysis of the requirements of the simulation software regarding the input of flight data and the structure of the file containing that data.
3. Development of a methodology that routinely converts the QAR data into a readable format by the simulation software and loads it into the program to run the flight simulation.
4. Validation of the developed process using test cases, with data from actual flights performed by the airline.

2. Background

A Safety Management System is, according to *Annex 19*, a "systematic approach to managing safety, including the necessary organizational structures, accountability, responsibilities, policies and procedures" [1]. ICAO issued the *Document 9859 - Safety Management Manual* (SMM), which provides a basis for the establishment of safety management systems in accordance with *Annex 19.* The FDM program is part of an operator's SMS.

Flight data analysis (FDA), also known as Flight Data Monitoring or Flight Operations Quality Assurance, is described by ICAO in *Annex 6* as a process in which flight data is analyzed with the sole purpose of enhancing the safety of flight operations [2]. A flight data analysis program must be non-punitive and provide the means to periodically collect and analyze flight data in order to yield information that can be used for improvement in crew performance, training, maintenance and even air traffic control purposes. According to the *Manual on Flight Data Analysis Programmes*, the objectives of FDM are the following [3]:

- determine standard and non-standard behavior in operations and anomalies in aircraft performance, including hazard identification;
- identify trends in flight data and conduct predictive analysis;
- aid in event investigation, by comparing the flight data with standard behavior and determining whether it is an isolated event or a systematic issue;
- suggest adjustments in operations and monitor the efficacy of the applied changes;
- support crew training through Evidence-based Training (EBT);
- enhance the economical efficiency of operations, due to the optimization of fuel consumption and the cutback in avoidable maintenance and repairs.

In order to implement an effective FDAP, an operator must employ the proper devices to record, download, process and store the data. On board the aircraft, there are recording systems that continuously capture and store hundreds of flight parameters. The best-known recorder is the Flicht Data Recorder (FDR), used in accident investigation, but its recording duration, recorded flight parameters and ease of access to the data may be insufficient for FDM purposes. As a consequence, non-crash recorders such as the QAR are employed by operators to retrieve the necessary flight data for analysis. These recorders supply additional recording capacity in terms of duration, number of parameters and increased sampling rate. They also provide an easy access to the data, through USB, memory cards or wireless connections. Afterwards, the data uploaded into the ground-based system is analyzed using specialized software that processes the information.

The transmission of data in an aircraft from the sensors to the recorders is done through specific data buses, which depend on the manufacturer. Figure 1 represents the flight data flow in the aircraft belonging to the Embraer E-jets family. In these aircraft, the Honeywell Avionics Standard Communications Bus, Version D (ASCB-D) establishes the communication between the aircraft's Modular Avionics Units (MAU) and the other systems. The MAUs feature data input and output (I/O) modules. To communicate with the Digital Voice Data Recorder (DVDR), which is the FDR in these aircraft, and the QAR, two types of data buses using Aeronautical Radio, Incorporated (ARINC) standards are used: the ARINC 717 and the ARINC 429. These standards define the data frames that carry the messages through avionics data buses. The Custom I/O module in the MAU 3 feeds the necessary flight data to the DVDR through the ARINC 717 data bus and a copy of this information is transmitted to the QAR. Similarly, the Generic I/O module in the MAU 3 sends additional flight data to the QAR through ARINC 429 data buses. In the QAR, flight data is stored in a PCMCIA card working in continuous mode, that is, when the memory is full, the oldest data is overwritten with the new data [7].

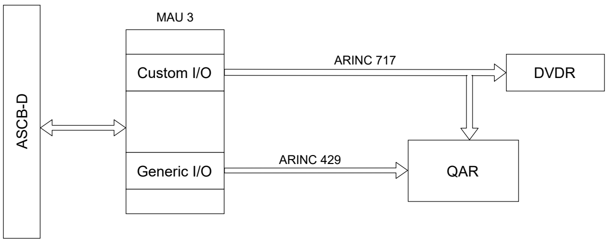

Figure 1: Data flow within the E-jets family aircraft (adapted from [7]).

2.1. FDM at Portugália

At Portugália, FDM is performed by the Safety Department, where flight data is gathered and analyzed and safety reports are issued. The FDM procedure is guided by the document *P-DS-06 - Flight Data Monitoring Procedure* [8], which details all the rules and steps that constitute the FDM program.

The flight data from an aircraft is recorded by the QAR and stored in a PCMCIA card. The binary QAR files are uploaded into Analysis Ground Station (AGS), a data management system used for flight data analysis, which splits the data into individual flights, computes statistics and the relevant information about each flight, scans the data for events and exceedances and then adequately stores all the data. Then, one can choose a flight from the database, analyze and compare the time evolution of its parameters and view associated events.

Although AGS is the main FDM tool employed at Portugália, the team also uses Google Earth to visualize the path and the profile of a flight superimposed with the globe. In addition, labels and text are shown in specific locations to identify events and the sequential positions of the aircraft are connected to recreate the flight path.

2.2. X-Plane as an FDM tool

Although the FDM procedures currently in use at Portugália are already thorough and effective, the introduction of an animation software to aid in data analysis was proposed, since this method can provide new perspectives on the evolution of the data and the occurrence of events. As such, X-Plane 11 was chosen as the platform to reproduce and animate the flight data recovered from the recorders.

X-Plane 11 is a highly reliable, accurate and complete simulator, as well as an adequate choice for the development of this project. Not only does it allow the use of a customized aircraft model corresponding to the ones operated by Portugália, it also provides a wide library of airports that covers the company's operations and simulates flights as similar to real life as possible, which is an important asset in simulations used for flight data analysis. Furthermore, X-Plane also offers the option to save and replay flights. In particular, it is possible to load data from a flight data recorder and recreate a flight, provided that data is organized in a format that can be read and processed by X-Plane. This feature is especially relevant for the development of this work, thereby motivating the choice of X-Plane 11 as the simulation platform for the animation of the flight data.

3. Implementation

The data flow from an aircraft's QAR to X-Plane is represented in Figure 2. It shows that the data fed to AGS by the QAR can be exported as a comma-separated values (CSV) file, which then undergoes data conversion to create the FDR file that is uploaded into X-Plane to run the simulations.

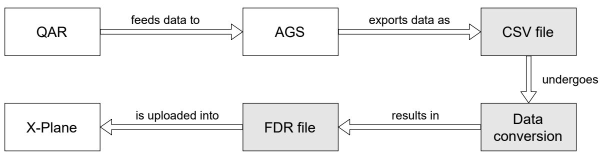

Figure 2: Data flow from the QAR to X-Plane.

In order to develop an adequate data conversion process, it is first necessary to analyze the data frames on the AGS and X-Plane sides.

3.1. Analysis of the AGS data frame

Since over 2000 parameters are recorded every flight by the QAR, it is necessary to choose which ones to analyze. AGS provides the option to define a parameter list and export the data from the parameters that are being analyzed into a CSV file, a feature that is employed in the development of this work. The period of the parameters written on

CSV file can also be defined and, for this work, a period of 0.125 s, corresponding to a sampling rate of 8 Hz, was chosen. Figure 3 presents an excerpt of an example CSV file exported from AGS, like the ones meant to be used with the developed program. Only a few lines are shown and some data was omitted to fit in the page.

```
SAT_PIL,SAT_COP,SAT_FDC_CL,LONPC,LONP1,(...),DATE_R
,,,,,,,,,,,-0.9,,,,,,,,,,-0.61111,(...),,7.8,,0,,,,
,,,,,,,,,,,,,0.63,0.00,,11.92,,,,(...),36.42188,,,,
32.3027,38.8340,,,,,,,,,,,,,,-0.60356,(...),,,,,,,,
,,,,,11.2002201,,,,,63,0.03,,,-0.03,(...),,,,,,,,,,
,,,,,,,,,,,,,,,-0.60493,,,,,,,,,,,,0.0000,(...),,,,,
,,,,,,,0.66,0.00,11.98,,,,-0.07,,,,-20.4,(...),,,,,
,,28.75,,,,,,,,,,,-0.599,112.50,,,,226.0,(...),,,,,
,,,11.2002,,0.0000,-27570.5,(...),00:00:00,23/08/20
,,,,,,,0.66,0.00,11.98,,,,-0.07,,-20.6,(...),,,,,,,
,,28.75,,,,,,,,,,,-0.60837,,112.50,(...),200,,,,,,,
,,,11.2002,,0.0000,-27570.5,(...),00:00:00,23/08/20
```

Figure 3: Example of a CSV file exported from AGS containing the QAR data for the animations.

Additionally, it is also possible to define the exported files' name. This work adopted a structured filename format based on an aircraft's registration number, flight number, date and time, which uniquely identifies a flight, because it bears fundamental data to fill some of the fields present in the FDR file structure. An example of the resulting format is shown in Figure 4, where the four parts that constitute the name are highlighted and identified.

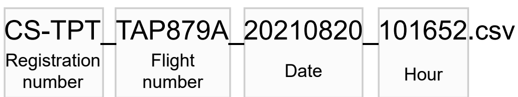

Figure 4: Format of the CSV files' name.

The first step of the work was to evaluate the data recorded by the QAR and available in AGS. It is necessary to know the meaning behind the values presented and exported from AGS, in order to choose the adequate parameters to convert the data into the FDR format. With this goal in mind, the documents *Parameter Report* [9] and the *QAR Database Specification* [7] manual were consulted and the main findings are presented below.

- Each parameter is identified by a unique mnemonic related to the type of information it stores. For instance, information about the selected heading is stored in the parameter HEAD_SEL.
- The data from the captain's and the first officer's instruments is available under different parameters.
- Both the units and the meaning of positive and negative values are well defined for each parameter, when relevant.
- Some parameters also have upper and/or lower limits, which are also defined in the aforementioned documents.
- Some data is discrete and the corresponding parameters take values from a finite set of options. In AGS, the possible values of a parameter are represented by integer numbers and each number has a specific meaning within that parameter, which is defined to ensure the correct interpretation of the data.
- The parameters recorded by the QAR are sampled at 0.25 Hz, 0.5 Hz, 1 Hz, 2 Hz, 4 Hz or 8 Hz. This information is specified for each parameter and is an important factor when choosing the period of the data written in the FDR file.
- The bus source of each parameter - ARINC 717 or ARINC 429 - can also be found in the QAR data frame.

3.2. Analysis of the X-Plane FDR data frame

As previously stated, X-Plane is capable of loading data from real flights and replay them in a simulation. The flight data input file format is called Flight Data Recorder and its file extension is `.fdr`. X-Plane FDR files are plain text files, but they are structured in a specific way, which allows the simulator to properly identify to which parameter each value refers.

There are several different fields allowed in an FDR file. The first word of each line is a four-letter code that identifies the type of information conveyed by that line of the file, including aircraft model, tail number, time and date of the flight, among others. The lines that contain the actual flight data to be reproduced by the simulator begin with the word `DATA`, each line corresponding to a time instant. They hold a total of 79 parameters in a structured fashion, although some of them appear more than once for multi-engine aircraft. A total of 118 values are written in each `DATA` line. The flight parameters to be included in these lines, as well as their order, are also fixed and defined by X-Plane. All data is numeric and the values are separated by commas. If the original QAR data does not include a particular parameter, the fields must be populated with a dummy value, such as 0.

Every single line must end with a comma, except `DATA` and `COMM` lines, and they can appear in any order, with the exception of the `TAIL` line, that must come after the ACFT line. The lines PRES, TEMP and WIND represent an oversimplification of what happens in a real flight, because sea-level pressure, sea-level temperature and wind during the flight are all volatile parameters that can change instantaneously. This format does not account for those possible changes and instead considers these values constant.

At the beginning of the file, before any flight information, two additional lines are written. The first line either shows 'A' or 'I', referring to Apple or IBM carriage returns, respectively, ensuring the software properly manages the document. The second line must be '2', in reference to the version number of the FDR format.

An example FDR file is shown in Figure 5, with some data omitted in the DATA lines to fit in the page.

```
A
2
ACFT, Aircraft/Embraer E195 v2.5 - TAP/E195.acf,
TAIL, CSTPT,
DATE, 20/08/2021,
TIME, 10:16:52,
PRES, 29.92,
TEMP, 59,
WIND, 0,0,
DATA, 0, 17, -9.206, 38.65, 2685.0, (...), 0, 0,
DATA, 1, 17, -9.206, 38.651, 2668.0, (...), 0, 0,
DATA, 2, 17, -9.205, 38.652, 2653.0, (...), 0, 0,
DATA, 3, 17, -9.205, 38.652, 2638.0, (...), 0, 0,
DATA, 4, 17, -9.204, 38.653, 2623.0, (...), 0, 0,
```

Figure 5: Example of an X-Plane FDR file containing the formatted data to be used in the animations.

3.3. Conversion of the AGS data to FDR format

After analyzing the two implicated data frames, the next step is to determine which parameters of the AGS data correspond to the parameters in the FDR files. To do so, the *Parameter Report* [9], the *QAR Database Specification* [7] manual and the *AGS Method for Database Programming* [10] manual, which list all the available parameters provided by the QAR and AGS at Portugália, were used. The list of required parameters, available in X-Plane's *Knowledge Base* [11], was used in this step of the work, to navigate the numerous parameters in the QAR data frame.

After determining the correspondence between the parameters on both sides, the conversion algorithm was developed. Some of the parameters were similar in both data frames. However, most required some form of manipulation, namely unit conversion, nondimensionalization and comparison with other parameters. The conversion process was implemented in Python, due to the language's data management and analysis capabilities. The algorithm is divided into three main parts: initializing the variables, converting the parameters and writing the FDR file.

Variable initialization consists of the creation of the variables that will store the data in the computer's memory. Each parameter that populates the DATA lines is stored in a list containing all its values from the beginning of the flight until its end, with a sampling rate of 8 Hz. Therefore, and for organization purposes, all variables are initialized before starting the conversion process.

Afterwards, the CSV file exported from AGS is opened and read using Python's *pandas* library, which includes a function that reads a CSV file and transforms the data into an organized table called DataFrame, similar to an Excel sheet, where each column corresponds to a parameter and each line to an instant in time. Sometimes, there may be errors that make a parameter's column in the DataFrame fully empty. Thus, all such columns in the DataFrame are dropped and deleted, so they do not interfere in the conversion process. Then, the length of the DataFrame is retrieved, informing of how many instants of time were recorded in that flight. Afterwards, the DataFrame containing all the data from AGS is used to extract the necessary information to fill the FDR file.

The title of the CSV file also provides information to build the FDR file. Because the format of the CSV files' name is constant, the conversion software can read it to extract information regarding the flight. Taking this into consideration, the registration number of the aircraft, the date and the hour of the flight included in the CSV name are respectively used to fill the TAIL, DATE and TIME fields in the FDR file. Additionally, the FDR file is named after the CSV file from which it is created, for coherence.

Regarding the ACFT line, which defines the path within the X-Plane folder for the aircraft model to be used in the simulation, an E-195 model developed by X-Crafts was downloaded, as well as Portugália's livery for the model. Therefore, this line shows the path for this model's files inside the X-Plane folder. Additionally, the PRES, TEMP and WIND lines are also included in the FDR file. However, because they take constant values throughout the entire flight, they do not faithfully represent what happens in a real flight, where wind and sea-level pressure and temperature are constantly varying in time and space. In the FDR file, the TEMP and WIND lines are set 59 ° F and 0 kt and 0°, respectively, but the pressure at sea-level is defined as equal to the barometric pressure dialed into the altimeter during that part of the flight.

After all the parameters are computed and the variables are all set, the information is written in the FDR file, using Python's built-in file writing function. Although the CSV data is sampled at 8 Hz, the data in the FDR files is written with a sampling frequency of 1 Hz, to reduce continuity errors in the parameters with an original sample rate of less than 8 Hz.

3.4. Parameter calculation

The data that comes from the QAR is sampled at various rates and samples from different parameters can be acquired at different instants in time. This means that the data in the CSV file - and, consequently, in the DataFrame - has empty spaces between every two measurements, if the sampling rate is lower than 8 Hz. Also, the time instant at which the first value is recorded varies with the parameter and is not necessarily at 0 s. Therefore, data must be adequately manipulated to account for these situations. The generic algorithm that reads the DataFrame columns and sets the variables with the data to be written on the FDR file is represented by the flowchart of Figure 6. In this figure, `aux_var` is a variable that is updated every time a new value is found when iterating a column, `ctrl_var` is used to determine whether the first value in the column has been found and `num_data` indicates the number of instants of time recorded in the CSV, which corresponds to the number of rows in the DataFrame.

Since the CSV file is written with a sampling rate of 8 Hz, the variables containing the data to be written on the FDR file will also be sampled at 8 Hz, even if their corresponding parameters have lower sampling rates. In these cases, the empty spaces between two consecutive samples have to be replaced with some value, in order to set the variables correctly. This process corresponds to the section in the blue rectangle in Figure 6. The algorithm iterates through the selected DataFrame column and, at each time instant, if it finds a value, it uses it to compute the value that will be written in the FDR and saves the resulting value in an auxiliary variable (`aux_var`). If, on the other hand, the cell is empty, `aux_var` keeps its previous value. In either case, in every iteration the value of `aux_var` is appended to the end of the list, so that all lists have a length equal to `num_data`. This process goes on until the last recorded time instant is reached.

It was also pointed that the first measurement may not necessarily be recorded at 0 seconds. The

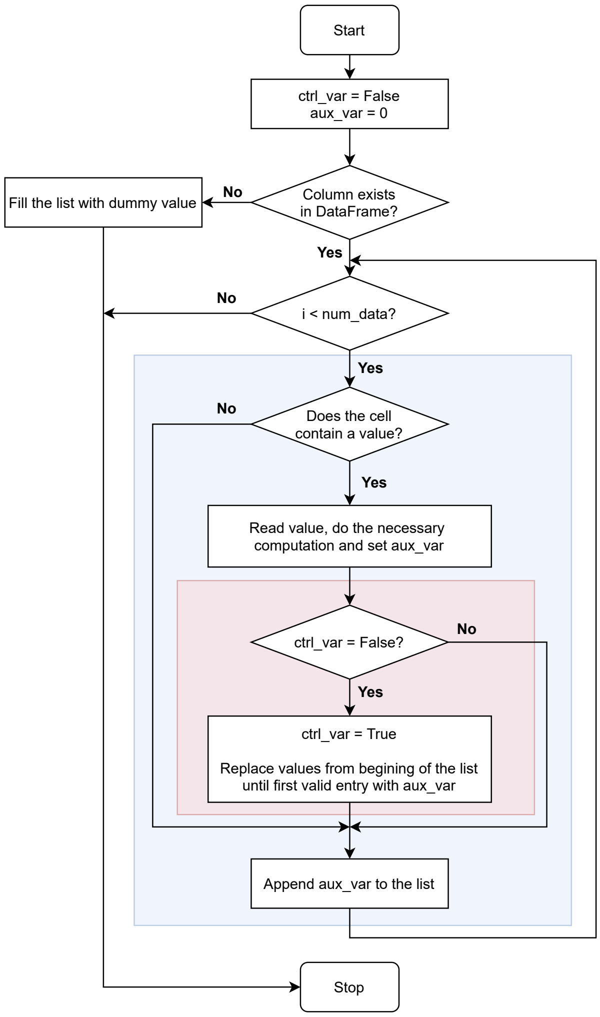

Figure 6: Flowchart of the algorithm that sets the variables with the parameters used to fill the FDR file.

red block in Figure 6 corresponds to the part of the algorithm where this situation is addressed. A previously stated, the variable `crtl_var` is a boolean that is initialized as False and receives the value True once the fist value in a column has been reached. Until then, the value 0 is appended to the list. As soon as the first value in the column is found, all the previous entries in the list are replaced with that value.

The generic algorithm used to calculate all the parameters in the FDR file represented in Figure 6 was adapted to the requirements of each parameter. For instance, if there is no information available on the DataFrame regarding a specific parameter, its list is filled with a dummy value, usually 0. However, if more than one column in the DataFrame provides information for a parameter, the existence of that column is tested and the conversion algorithm is applied before resorting to filling the list with dummy values. This is done because, in an aircraft, more than one sensor may be measuring a parameter or the values may be conveyed through different data buses or they may be recorded at different sampling rates, originating several entries in the QAR that record information about the same parameter of the flight. Nevertheless, in some cases it is useful and more robust to use more than one available column to compute a parameter, in which case a function merges all available data. This function verifies which columns are available and computes their average value in case more than one source of data is available.

Finally, the data that comes from the CSV file is discrete, but the parameters it represents can be either discrete or continuous. For example, the latitude and longitude of an aircraft are in fact continuous in time and space, but they are sampled when recorded by the QAR. When writing their values in the FDR, it was noted that there were continuity errors, introducing jumps in the position of the aircraft in the simulations. This was due not only to the natural noise in readings but also to sensor resolution and the computation process previously described. To solve this problem, a Savitzky-Golay smoothing filter was applied to the continuous parameters, in order for the simulations to be smoother and more accurate. The Savitzky-Golay is a digital filter that fits subsets of adjacent points to a polynomial of a defined degree, using the least-squares method [12]. In this project, the data was smoothed using windows of 10 seconds and second-degree polynomials. It was found that these parameters smoothed the data in a satisfactory way, while also keeping it faithful to the unprocessed data that originated it.

4. Results

After the data conversion is performed and the resulting file is automatically saved to X-Plane's folder, the simulator can be launched to replay the flight. In order to validate the animations, two events were analyzed, using data from two flights performed by the company: a go around and a localizer deviation.

Go Around

A Go Around is a maneuver performed when the crew decides not to continue an approach, when it is deemed not possible to continue the approach to a successful landing [13]. According to the company's Standards and Operating Practices (SOP), a go around must be performed under certain circumstances, such as an unstable approach, the obstruction of the runway or the absence of a landing clearance, among others. The SOP manual defines the sequence of actions to be taken during a go around.

The go around that was chosen to analyze happened during an approach to runway 03 at Lisbon airport. The Air Traffic Control instructed the crew to discontinue the approach at around 200 ft above aerodrome level because another aircraft that had just landed was slow to exit the runway. As a result, the crew performed a go around according to the company's SOP and landed successfully after a few minutes. Figure 7 represents the path described by the aircraft during the two approaches and go around, as seen on Google Earth.

Figure 7: Top view of a go around during the approach to Lisbon represented on Google Earth.

The study of a go around includes the analysis of the altitude, the status of the autopilot and autothrottle, the vertical speed, the engaged modes, the TO/GA button, the thrust, the landing gear and the flaps during the event. In this specific case, the analysis showed that the go around was fully performed according to the company's standards.

The analysis performed so far can be complemented by the visualization of the event through an animation. It shows the exact location where each step of the two approaches and go around took place, enabling a dynamic analysis of the sequence of events. The animation shows that, during the first approach, the aircraft is fully configured to land and the approach is stable according to the standard procedures at the company. Then, some meters before reaching the runway threshold, the go around is initiated. At this instant, the instrument panel indicates that the approach mode becomes armed and the rotational speed of the engines (N1) is increased to TO/GA values - around 80% - once the go around is initiated. As the aircraft starts climbing, the landing gear is retracted and the flaps are cleaned. These actions are displayed in Figure 8. Then, the aircraft describes the go around trajectory without any relevant event or irregularity and attempts a second approach to Lisbon airport.

This second approach is stable and culminates in a safe landing.

(a) Retraction of the landing gear. (b) Retraction of the flaps.

Figure 8: Retraction of the landing gear and the flaps after initiating the go around.

Localizer deviation

The localizer is a system that provides lateral guidance relatively to the runway axis, during an approach. The deviation of the aircraft from it is shown on the instruments in dots. When the aircraft is aligned with the runway, the deviation equals 0 dots. A localizer deviation occurs when the aircraft is not aligned with the runway during the approach. It can happen when the aircraft is capturing the signal from the LOC or after the signal capture if, for any reason, the aircraft deviates horizontally from the intended path.

The localizer deviation that is analyzed in this section happened during an ILS approach to runway 06 at Amsterdam Schiphol Airport, due to repeated disconnections of the LOC lateral mode, which resulted in deviations from the glidepath. Subsequent FDM analysis showed that the event culminated in a stable visual approach, because it was not possible to successfully conduct the initially cleared ILS approach. The trajectory of the aircraft is represented in Google Earth in Figure 9.

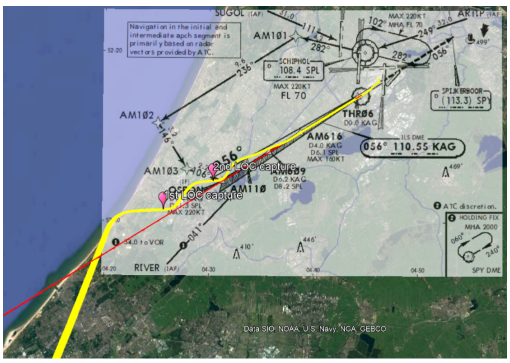

Figure 9: Localizer deviation during the approach to Amsterdam represented on Google Earth.

In the analysis of this event, AGS was used with the purpose of determining the exact localizer deviation throughout the approach, the actual and selected heading, the active autopilot modes, the altitudes at which the events occurred and other relevant numerical data. Although the graphs from AGS and the trajectory observed in Google Earth are enough to analyze this event, the analysis can benefit from an animation, because one can not only observe the evolution of the active and armed autopilot modes, but also the movement of the aircraft throughout the approach and landing. An image from the animation of this event is reproduced in Figure 10.

(a) Cockpit view. (b) Primary Flight Display.

Figure 10: Still image from the animation of the localizer deviation in Amsterdam.

The animation shows that the approach is initiated with the HDG lateral mode active and the LOC and G/S armed (Figure 10). The autopilot and autothrottle are engaged, although the state of the autopilot is not visible in the animations, as there is no field regarding this parameter in the FDR file structure. As the aircraft approaches the glidepath from the left, the localizer signal is captured and the LOC mode is engaged - represented by the green letters that read “NAV” -, but he aircraft starts turning left, deviating form the intended path. After a few seconds, the crew engages HDG once again and corrects the aircraft's trajectory. With the approach mode armed, the aircraft captures the LOC mode again, only to start turning left, deviating once again from the glidepath. Due to this misbehavior, the crew corrects the trajectory with the HDG mode active and then disengages the autopilot and flies a manual approach, which is performed safely. It is also worth mentioning that the artificial horizon does not follow the bank and pitch angles of the aircraft, because there is no information about this instrument on the FDR input file.

4.1. Comparing the three analysis methods

The two examples studied show that each one of the three analysis methods has its own advantages and they complement each other, as they represent the same data under different formats.

On the one hand, the graphical analysis done with AGS provides the most accurate and mathematical perspective, because numbers and data are directly accessed and analyzed using time-series graphs. This is the most adequate method to examine the evolution of each parameter throughout the flight. It is also particularly useful to analyze parameters that are usually not accessible by the crew and in providing the value of any parameter at any given instant in time. This method is also an important tool to establish the magnitude and duration of events and exceedances, which is fundamental in activities such as determining whether a maintenance task is required. Graphical analysis is the preferred method to analyze events such as high speed approaches, high rates of climb and descent, and landing gear and flap exceedances.

On the other hand, visual methods such as the geographical analysis supported by Google Earth and the animations are useful at contextualizing the events, although the data is not as accessible as in time-series graphs. These methods focus on showing the surroundings of the aircraft, the interaction of the crew with the instruments, and the flow of actions performed in a particular period of time. The greatest advantage of representing the flights on Google Earth is that it is possible to analyze the trajectory of the aircraft and compare it with a reference path or set of positions. One can also add the navigation charts corresponding to the portion of the trajectory that is under assessment. This is an important asset for the analysis of glidepath deviations, such as the localizer deviation studied. The analysis of taxiway and runway incursions also benefits from this method.

Unlike the static representation of the trajectory of the aircraft on Google Earth, animations show the flight in a dynamic medium, combining two characteristics of the aforementioned analysis methods: the ability to contextualize the events, like in Google Earth, and the possibility of assessing the evolution of parameters during the flight, like in graphical analysis. The analyst can visualize the flight from different perspectives, manipulate the time and speed of the animation, observe the evolution of the information shown on the instruments and analyze the events from a pilot's point of view. One can also draw conclusions about the flow of actions performed by the crew and the aircraft. These features are what makes animations such versatile, complete, powerful and innovative analysis tools.

Despite the observed advantages, the animations produced with the method developed in this work naturally have some limitations and inconsistencies with what would be expected during a real flight. Some of these may be solved with further development and analysis, but others are rooted in the characteristics of the simulation software. Some limitations of these animations are listed below.

- Some instruments do not behave as expected in the animations. For instance, the artificial horizon does not reflect the movement of the aircraft. This is the case for other instruments and parameters too, such as thrust reversers and spoilers, and it is due to the fact that they are not considered in the FDR file format.
- Due to the limitation pointed in the previous paragraph, the animation always initiates with a master warning - *FUEL PRESSURE LOW*. This happens because there is no information about the fuel pressure and the software assumes that it is 0. However, the warning can be turned off by clicking on the corresponding button on the instrument panel.
- Aircraft are equipped with redundant systems, sensors and instruments. In the animations, however, there is no distinction regarding these various data sources and, therefore, there is no redundancy.
- Control surfaces are often divided into smaller portions, each one associated with a parameter in the QAR data frame that measures its deflection. However, in the FDR file, their deflection is represented by a single value. Although these smaller surfaces usually move harmoniously, this representation is not the most accurate, as it considers each surface as a whole.
- In addition, surfaces may not always deflect symmetrically, which is the case of the ailerons. In this work, this was simplified to consider only symmetrical small-angle deflections, which may not be fully accurate in the case of higher angles.
- Furthermore, there is no way of determining which member of the crew performed each action, as their interactions with the instruments are not included in the FDR file.

5. Conclusions

The overall goal of this work was to develop a method for flight data reproduction in a simulation software. The resulting product will be used at Portugália within the scope of the Safety Department's activities, namely in the analysis of events, as a part of the FDM program.

At the moment, FDM is performed at Portugália using two tools: AGS for graphical data analysis and event detection, and Google Earth for geospatial analysis. The animations bring a new dimension to these analysis, as they provide new perspectives of the data, namely the pilots' point of view. The retrieval of the data for FDM is done with Quick Access Recorders, small data recorders, with large storage capacity and easy to access. The animations developed in this work also use data from the QAR. With the purpose of determining the necessary QAR parameters, the data frames on both the QAR and the X-Plane sides were analyzed.

The X-Plane FDR data frame was first reviewed and compared to the available parameters on the QAR. After choosing the QAR parameters for each FDR entry, taking into account the necessary conversions and computations, the algorithm that builds the FDR file was developed.

Afterwards, the animations were validated using data from flights operated by Portugália. A go around maneuver and a localizer deviation event were reproduced. It was determined that the animations confirm the analysis performed with AGS and Google Earth, but provide a more in-depth and immersive perspective of the events. They also help contextualize and explain events in a quick, efficient and dynamic way, as text and graphs are often too reductive.

In conclusion, the four objectives established for this work were fulfilled: the QAR and X-Plane's data frames were examined, the conversion process was successfully developed and the animations were validated using flight data from the airline. The main goal - developing the method for flight data reproduction - was, therefore, also met, and the animations will now be used at Portugália to support FDM and other related activities at the company, such as crew training.

References

[1] International Civil Aviation Organization. *Annex 19 to the Convention on International Civil Aviation - Safety Management*, 2^{nd} edition, July 2016. ISBN: 978-92-9249-965-5.

[2] International Civil Aviation Organization. *Annex 6 to the Convention on International Civil Aviation - Operation of Aircraft. Part I: International Commercial Air Transport — Aeroplanes*, 9^{th} edition, July 2010. ISBN: 978-92-9231-536-8.

[3] International Civil Aviation Organization. *Manual on Flight Data Analysis Programmes (FDAP)*, 1^{st} edition, 2014. ISBN: 978-92-9249-416-2.

[4] Commission Regulation (EC) 8/2008 of 11 December 2007 amending Council Regulation (EEC) 3922/91 as regards common technical requirements and administrative procedures applicable to commercial transportation by aeroplane. OJ L10/1, 2008.

[5] Federal Aviation Administration. *Flight Operational Quality Assurance (Advisory Circular 120-82)*, December 2004.

[6] R. A. Kumar, S. Balaji, T. V. S. Manoj, K. S. Kumar, and E. Geetha. Predictive analytics on aviation data. *International Journal of Advanced Research in Computer and Communication Engineering*, 5(2):106–108, October 2016.

[7] Embraer. *Quick Access Recorder Database Specification*, no date. Report no. 190EBD203.

[8] Tobias Pereira. *Flight Data Monitoring Procedure*. Safety Department, Portugália Airlines, 5^{th} edition, March 2021. Procedure P-DS-06.

[9] Portugália Airlines. *Parameter Report - QAR frame PGA*, 2018.

[10] Sagem. *Analysis Ground Station V12 - Method for Database Programming*, 2^{nd} edition, December 2008.

[11] Jennifer Roberts. FDR Files in X-Plane 11. X-Plane, 2017. `https://www.x-plane.com/kb/fdr-files-x-plane-11/`. Accessed: 11-05-2021.

[12] Abraham Savitzky and Marcel J. E. Golay. Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry*, 36(8):1627–1639, July 1964. doi:10.1021/ac60214a047.

[13] Portugália Airlines. *Standard Oprating Procedures Manual*, 9^{th} edition, March 2021.