Project Code: AAE24

THE HONG KONG POLYTECHNIC UNIVERSITY

BEng(Hons) in Aviation Engineering

2023/2024

AAE4002/AAE4012 Capstone Project Interim Report

Development of Diversion Airport Advice System regarding to Emergency Landing

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Date of Submission:	2 January 2024

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1. <u>Introduction</u>

1.1. Research Background

1.1.1. *Aviation Industry Overview*

There are estimated that over 100,000 commercial aircrafts fly in the world each day. In 2018 (HKCAD,2023), there were in total 427766 take-off or landing recorded in the Hong Kong International Airport. Before the cockpit crew starts the aircraft, flight planning would be conducted to establish the details such as route, flight path, schedule time, and fuel. The cockpit crew would also make pre-flight briefing and checks to ensure all the members know the estimate conditions, restrictions, and relevant information (e.g., Notice to Airman NOTAM) of the flight and make sure the aircraft is airworthy. Throughout the flight, the cockpit crews and the air traffic controllers in different sections continue to communicate to ensure safe and efficient operation.

1.1.2. Cooperation Between Cockpit Crew and Air Traffic Controllers (ATC)

To perform safe and efficient operations of aircraft, in controlled airspace, ATC use designated radio frequency to communicate with cockpit crew. The cockpit crew coordinates the flight plan and reports position, altitude, and intention to ATC, who in turn provides clearance, information, and instructions to maintain appropriate distances for safe aircraft operation. If an emergency occurs, air traffic controllers provide guidance and assistance to the cockpit crew while coordinating with other related parties to resolve the issue safely.

1.1.3. Possible Failure Model

Throughout the flight, there are a variety of situations that can cause a loss of control, so an immediate safe landing is the top priority. These situations include single or dual engine failure, abnormal on flight control surfaces, and fuel starvation. When there is soul on board requires medical assistant, or any event that does not affect aircraft performance but is potentially hazardous, the cockpit crew might need assistance to divert into the best airport as soon as possible. Cockpit crews are not expected to calculate the precise performance of the aircraft in these emergency situations.

1.2. Problem Description

1.2.1. Human Reaction Time Under Emergency or Abnormal Situations

The Human Reaction Time varies differently depending on the specific situation and the individual proficiency of the cockpit crew. A team of well-trained and experienced of cockpit crew should have high sense of situational awareness and have high familiarity with the procedures, to adopt the real time situation and make correct decisions quickly. However, there are still a gap of time which might be crucial to safety of aircraft. In the case of Hudson Miracle, pilots in simulator could successfully land in all nearby runway when they eliminate all the human reaction time in the simulations.

1.2.2. Standard Procedures Under Emergency or Abnormal Situations

When there the aircraft is abnormal, the cockpit crew first need to determine the situation, then settle a consensus before deciding which the final decision would be endorsed by the captain. Then the cockpit crew would make distress or urgency call as required the ATC to gain support from them. The ATC will then enquire information and situation in the radio while discuss the solution, such as available alternate airport/runway with the cockpit crew. The pilot then attempts referencing the procedures of the Quick Reference Handbook and Flight Manual to eliminate existing problem. If there is lack of time, the pilots would attempt to look for a nearby safer ground to make an emergency landing.

1.2.3. Limitation On Real Time Communication in Emergency or Abnormal Situations

ATC and cockpit crew uses Very High Frequency (VHF) as their communication radio. However, radio signals might still be distorted or weaken due to distance, terrain, or weather situation, etc. Clear and reliable communication between cockpit and the ground might be difficult to establish in emergency situations. At the same time, radio congestion might be occurred when there is high volume of radio transmissions in the same channel. This could delay the request and support between the cockpit and the ground. Although there may be emergency frequencies in some areas for use in emergencies, these channels still cannot guarantee smooth communication between pilots and the ground. Simplicity in conversation might be crucial when quality of radio communication is limited.

1.2.4. Support To Cockpit Crew Under Emergency or Abnormal Situations

In emergency or abnormal situation, the cockpit crew are busy to gain control of the aircraft or executing emergency procedures as mentioned above, which the communication between ATC and cockpit crew should be simple and direct to reduce workload and distractions. Furthermore, commercial flight could be flying in non-controlled airspace (Class G Airspace), where ATC are not available to assist and give recommendations to the aircraft in emergency situations. Moreover, aircraft in emergency situations also need to coordinate with other nearby aircraft in Class G Airspace, which greatly increases the workload of the cockpit.

1.3. Scope

This paper studies on real time diversion airport advice system regarding to emergency landing. The current plan of A320 pilots to handle abnormal situation is to reference the Emergency and Abnormal procedures (EAC) in the Quick Reference Handbook (QRH). The system based on the initial aircraft conditions, convert them into parameters, and determine the possible flying route while create possible trajectories to the runways nearby. It could lower the workload of the cockpit crew as pilots could save the time to found nearby airport and available runway. Cockpit crew could use suggest the ideal runway to ATC and gain support from the ground while focusing on the emergency or abnormal procedures to eliminate the unsafe issue.

This paper reviews the concept of the Air Traffic Management and human factors when cockpit crew handling abnormal and emergencies. The development of the algorithm and parameters references from Base of Aircraft Data (BADA) developed by Eurocontrol and Open Model for Aircraft Performance and Emissions developed by Dr. Junzi Sun.

1.4. *Objectives*

This project mainly focuses on the following objectives:

- ➔ To collect and analyse real-time aircraft status data.
- ➔ To examine the farthest effective flight distance using the real time data of the aircraft to determine
- ➔ To develop algorithm calculating the best landing airport option and its flight path through real-time flight data
- ➔ To determine whether the system could reduce human reaction time when facing emergency.

1.5. *Expected Deliverables*

A real time diversion airport advice system will be proposed in this research. The system is based on the condition of the aircraft to suggest the possibility of landing in nearby runways.

The framework includes the following:

- Conduct literature review in human reactions during emergencies
- Develop program to obtain and analyses real-time aircraft mechanical and dynamical data
- design algorithm method to compute the most appropriate and effective flight path for the available airport design and develop a panel for display
- Test the program and invite personnels to conduct flight with the panel in the simulator
- Analyse the result by comparing the performance between simulations

2. Literature Review

2.1. Human Factor in Aviation

2.1.1. Task Management

Aviate, navigate, and communicate are the three important elements of flight implementation in search of the flying instinct (Katerinakis, T., 2014). Aviate refers to the pilots use the skills to maintain the control of the aircraft; Navigate refers to the pilots know where the aircraft is and find out where it intends to go as destination; Communicate refers to pilots communicate with third parties such as Air Traffic Controllers, Companies, Ground Services. The most important and prioritize part is Aviate, which pilots must control the aircraft in emergency or abnormal situations before complying other action, then would be navigate, knowing where the aircraft land should, and finally to communicate with the ATC. The diversion advisory system could assist pilots in Navigation stage, reducing the time required to explain the situation to ATC and looking for possible runway one by one.

2.1.2. Human Error

Human error is one of the contributing factors in around 70% to 80% of aviation accidents (Sarter, N. B., & Alexander, H. M. ,2000). There are a few types of human errors, including skill-based errors, knowledge-based errors, and rule-based errors.

Skill-based error in aviation refers to pilots making mistakes related to the procedure skills or physical abilities without conscious thinking. It happened when the pilots doing their well-practiced tasks, such as practiced-emergency situations and it is more likely to happened when pilots are fatigue, distracted or under stressful circumstances.

Knowledge-based errors in aviation refers to pilots has no knowledge available to handle an unusual situation. They could only resort to first principles and experience to solve problem with limited understanding and awareness of the situation. These errors are more likely to happened among the less experience pilots when they are facing abnormal or emergency situations airborne.

Rule-based errors in aviation refers to the pilots apply diversly from rule that had been established. These errors are more likely to happened when the rules or procedures are ambiguity, and pilots in time pressure, or without sufficient training in the specific procedure.

These 3 types of errors are not mutually exclusive, when the working environment is not ideal, such as in abnormal or emergency situations, the pilots would be in pressure and loads of procedures would have to followed. No matter experienced or less experienced pilots, they would have a chance to make one or few above errors and mistakes, such as lapse and slips.

According to the study of pilots facing emergency by Bezerra, F. G., & Ribeiro, S. L. (2012), less difficult tasks require higher physical demand while more difficult tasks require more mental demand.

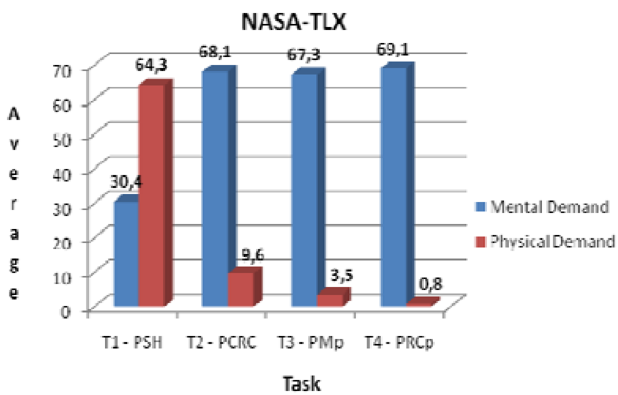


Figure 1 Demand Level in Different Tasks

(Adopted from Bezerra, F. G., & Ribeiro, S. L. ,2012)

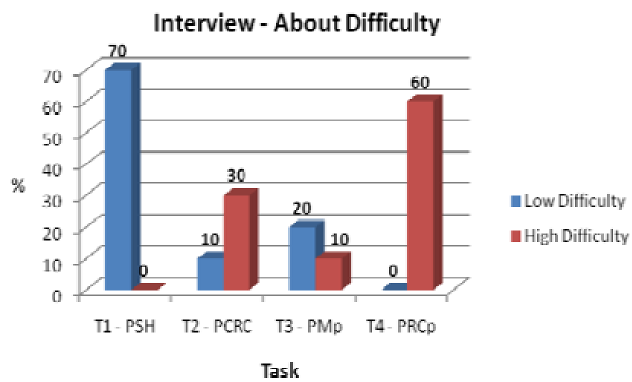


Figure 2 Difficulty Level in Different Tasks

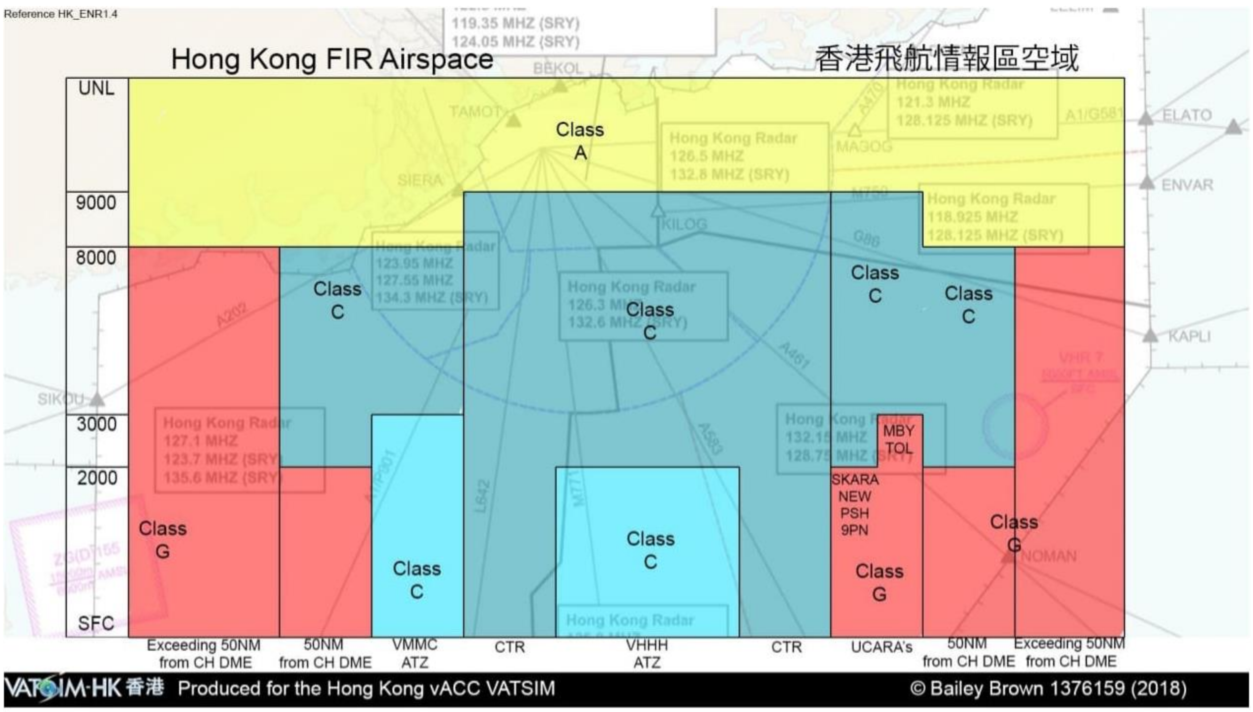
(Adopted from Bezerra, F. G., & Ribeiro, S. L. ,2012)

In aviation, physical ability could be significantly increased by training and experience gained, while mental ability relies more on natural abilities. Although there were selection progress such as aptitude tests for future pilots to determine whether they had enough mental ability to due with high intense situations before hiring them, there still differences between pilot and pilot that could not be fixed by training. Therefore, to reduce stress for pilots when they are facing emergency or abnormal situation, systems should be made to reduce tasks for them to worry. This project could reduce workload of pilots in emergency or abnormal situation and hence reduce the possible errors made by the pilots.

2.2. *Airspaces and Standard Approach/Departure Procedures*

2.2.1. Class G Airspace

Class G airspace is the uncontrolled airspace that present the absence for air traffic controllers to provide air traffic management services, only traffic information about other IFR and known VFR fights as far as practicable. According to Federal Aviation Administration (2023), exists wherever that portion of airspace has not been designated as Class A, Class B, Class C, Class D, or Class E airspace. In Hong Kong Flight Information Region, class G airspace exist in the airspace indicated below.



Note: [1]Two-way communication required. [2]Two-way communication not required south of Hong Kong TMA.

(Source: ENR 1.4 of AIP Hong Kong)

Figure 3 Class G Airspace in Hong Kong Flight Information Region

(Adopted from VATSIM, 2021)

In Class G airspace, since there is lack of ATCs to assist the emergency aircraft for avoiding separations, the pilots on board are required to indicate the situation, position and intension to all nearby aircraft via radio. This highly increases the workload of pilots.

2.2.2. Standard Instrument Departures (SIDs)

Standard Instrument Departures (SIDs) are used to provide standard route of departure from the terminal control areas to area control area. In Hong Kong International Airport (IATA: HKG, ICAO: VHHH), the terminal control areas implement RNP 1 SIDs, where aircraft using SIDs in Hong Kong should have RNP 1 capability. For runway 07L/R, here is the SIDs (HKCAD, 2023).

SID	Runway	Remarks
BEKOL3A	RWY 07R	Between 1500-2300 UTC expect ATENA2A
BEKOL1E	RWY 07L	Between 1500-2300 UTC expect ATENA2E
LAKES3A	RWY 07R	Between 1500-2300 UTC expect VENGO1A
LAKES1E	RWY 07L	Between 1500-2300 UTC expect VENGO2E
OCEAN2A	RWY 07R	Between 1500-2300 UTC expect RASSE3A or SKATE3A
OCEAN1E	RWY 07L	Between 1500-2300 UTC expect RASSE2E or SKATE2E
PECAN1A	RWY 07R	May be used H24
PECAN1E	RWY 07L	May be used H24

Figure 4 Runway 07 SIDs

(Adopted from HKCAD, 2023)

There are also 18 noise mitigating SIDs for runway 07R/L, which are normally for use between 1500-2300 UTC. In this project, we simulate a flight from Hong Kong (VHHH) to Sydney (YSSY), referencing a Cathay Pacific flight number CX111’s trajectory, it uses OCEAN2A SID from runway 07R. The requirement of OCEAN2A SID includes:

1. Initial climb to 5,000 ft. Expect further climb when instructed by ATC, but cross PORPA at 5,000ft or below.
2. Minimum climb gradient of 4.9% until leaving 1,400ft is required.
3. Speed restrictions of 205 KIAS or greater at PORPA and 220 KIAS until TD DVOR.

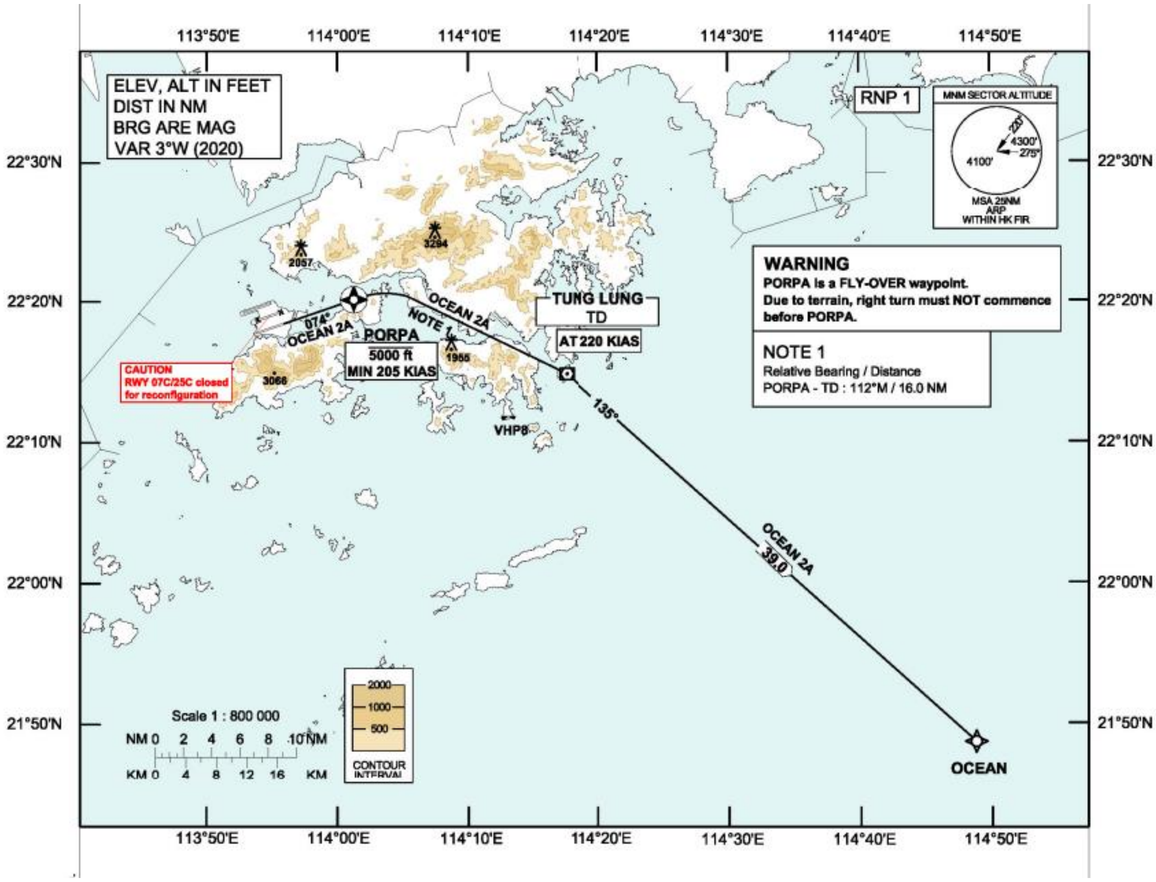


Figure 5 Chart of OCEAN2A SID

(Adopted from HKCAD, 2023)

2.2.3. Standard Terminal Arrival Routes (STARs)

Standard Terminal Arrival Routes (STARs) are used to provide standard flight procedures of arrival from the area control areas to terminal control area just before reaching a destination airport. In Sydney (Kingsford Smith) Airport (IATA: SYD; ICAO: YSSY), there are 6 STARs procedure include BOREE3A, BOREE3P, MARLN5, ODALE7 and RIVET3 using RNAV approach (Airservices Australia, 2022). The usual STAR procedure for a commercial aircraft from Hong Kong is BOREE3P if using the runway 16R, a Cathay Pacific flight number CX111's trajectory.

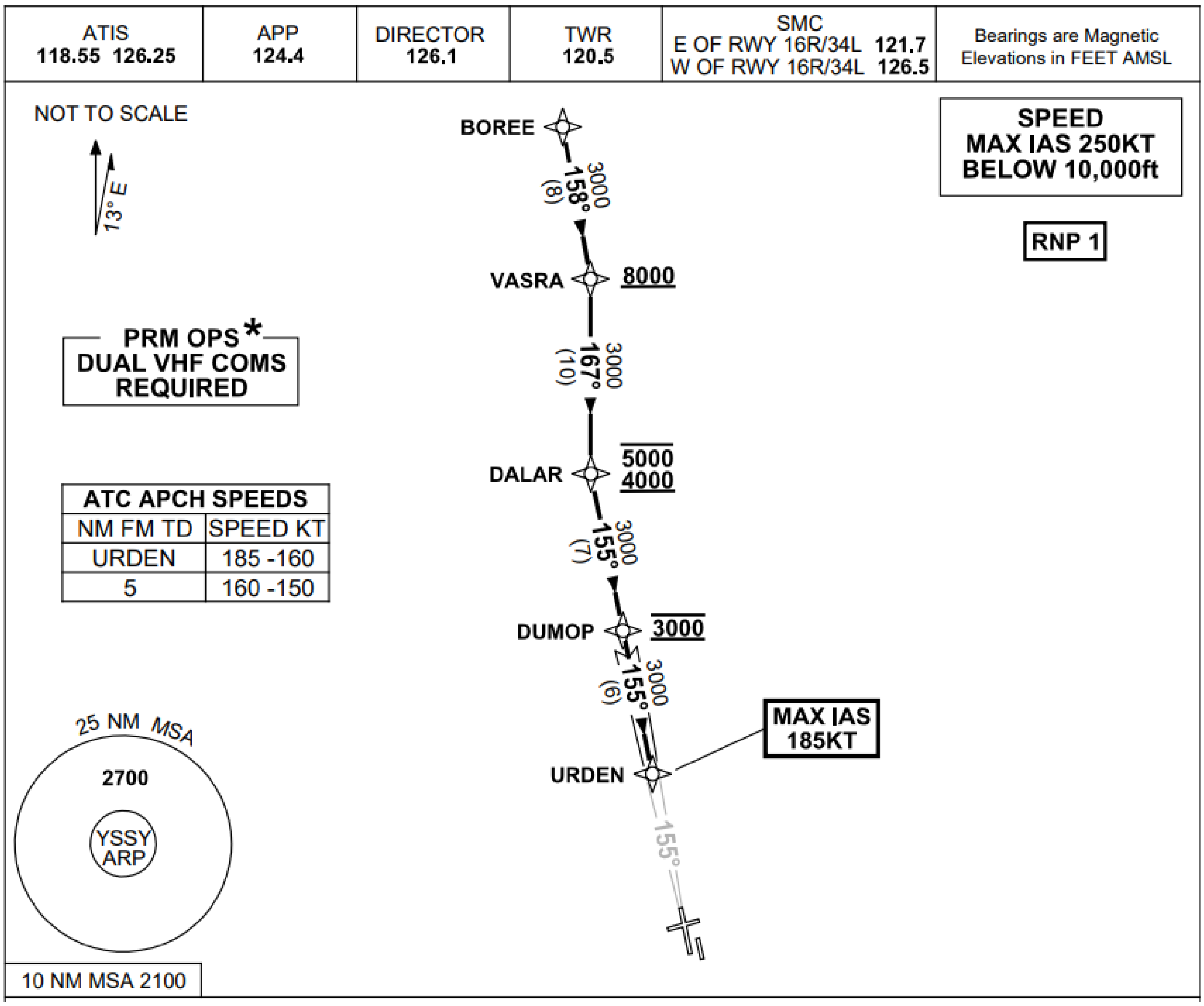


Figure 6 Chart of BOREE3P STAR

(Adopted from Air Services Australia, 2022)

2.3. Emergency landing technologies

2.3.1. Brief introduction to emergency landing

When an aircraft enters into emergency situation and it is not able to continue its normal flight or otherwise may lead to serious accidents, it has to land for assistance within a short period. Some examples of emergency landing are, failure of critical parts such as engine and hydraulic system, fire onboard and urgent medical service is needed.

After the emergency is identified by the flight crew, they have to perform the emergency procedures, for example, contacting ATC with details of emergency and finding for assistance (FAA, n.d.), also consideration of emergency landing. Once the pilots confirmed that the plane is no longer to be suitable to maintain normal operation, it has to land at the nearest possible airport or landing zone. The factors for landing spot consideration shall include the ability and performance of the aircraft, remaining fuel, runway length and weather conditions. While some information and instructions may be provided by the ATC.

2.3.2. Standard Procedure for Emergency (Airbus, 2008)

In the Flight Crew Training Manual, abnormal situations are suggested, and procedures are recommended. In case there are smoke in cabin, the main steps include anticipate and initiate diversion and smoke origin identification and fighting. “LAND ASAP” as the one of the most significant point in the Quick Reference Handbook (QRH) in this situation. The procedure is shown below.

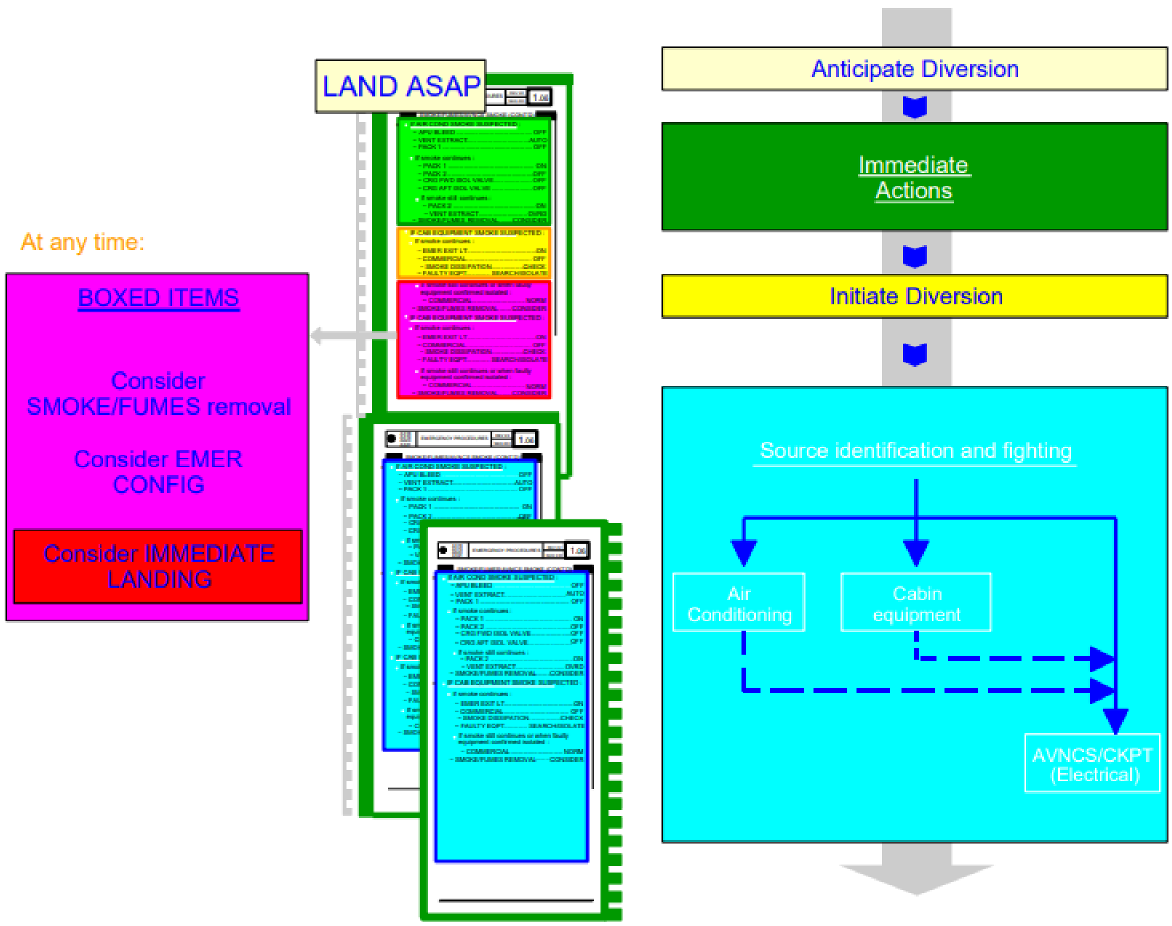


Figure 7 SMOKE/ FUMES/ AVNCS SMOKE procedure presentation in QRH

(Adopted from Airbus, 2008)

In the event of an engine failure, Autoland may still be used without one engine operating and AP utilization should be maximized to minimize crew workload. If necessary, it is traditional to conduct a manual approach and landing with one engine inoperative.

As soon as the engine failure is recognized, the PF will simultaneously:

- Set MCT on the remaining engine (largest power on remaining engine)
- Disconnect auto throttle
- Select the speed according to the strategy
- If appropriate, select a heading to keep clear of the airway, preferably heading towards an alternate. Consideration should be given to aircraft position relative to any relevant critical point.

With all engines shut down, cockpit indications will change dramatically as the generators are disconnected. The RAT was deployed to power the emergency generator and pressurize the blue hydraulic circuit. The left-seat pilot must immediately take control of the aircraft and establish a safe flight path.

For fuel leak, the crew should be doing fuel checks when sequencing a waypoint and at least every 30 minutes. When an engine failure occurs, the fuel leak are more difficult to detected and required high situational awareness of pilots to identify the problem. If fuel leak is suspected, the flight crew should follow the flowing procedure.

• If the leak is positively identified as coming from the engine, the affected engine is

shut down to isolate the fuel leak and fuel cross-feed valve may be used as required.

• If the leak is not from the engine or cannot be located, it is imperative that the cross-feed valve is not opened.

Under all the above abnormal circumstances, not only the pilots should focus on execute the tasks in the ECAMs or in the flight manual, at the moment the pilot should also identify the best airport for landing as soon as possible. When convenient, emergencies will be reported to ATC using VHF1. Depending on the situation, ATC may provide assistance with other aircraft locations, safe directions, etc. However, if the pilots are busying handling the incoming situation, the communication between the pilots and ATCs might be less prioritized, shorter and clearer communication should be established. This project might advise pilots for a clearer and direct conversation to ATCs under emergency or abnormal situations.

2.3.3. Technologies applicable for emergency landing

Besides the normal emergency procedures suggested and set by the authorities or the operators, some advanced technologies are useful to the pilots for performing successful emergency landing.

Modern aircrafts are equipped with instrument landing system (ILS), which ground signals from the runway is sent to the aircraft, leading the plane to descent in correct heading and glide slope (Civil Aviation Safety Authority Australia, n.d.). Pilots can land the plane in low runway visual range with the aid of this technology. As guidance is provided, errors due to incorrect decisions are reduced, so it is practicable to apply ILS during emergency landing, if flight systems are running in good condition. Pilots are able to focus more on the emergencies that happened.

To specifically tackle emergency landings, some technologies are developed or under experimentation, ensuring the safety and efficiency of such landings.

Automated Emergency Landing System (AELS) is developed and tested with fixed wing unmanned aerial vehicle (UAV) and Cessna 172R by Warren et. al. (2015). The key component of this system is the guidance, navigation and control (GNC). To achieve this. A path planner is developed to form possible trajectories and control systems of the aircraft are simplified to reduce excessive controls and leading to more severe errors. A motion model that is widely applicable for most of the aircrafts is built for the system. Also, compensation to wind factors is put into consideration, During the test, the throttle of the aircraft is set to idle as to simulate lost in thrust due to engine failure.

The system collects, analyzes and compute the real-time data and parameters, such as its speed, altitude, motion and its location obtained from the instruments of the aircraft. These data and parameters will then be input into equations to generate desirable outcomes.

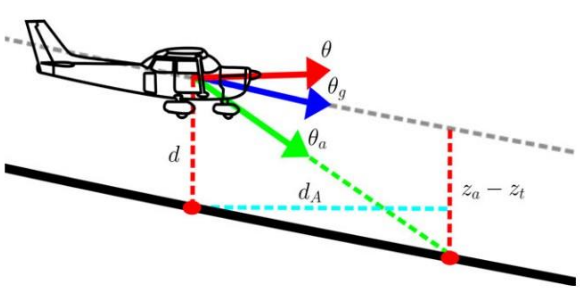


Figure 8 Pitch control model of AELS

(Adopted from Warren et. al., 2015)

Pitch control is demonstrated according to the above figure. The current pitch and glide angle, θ and θ_g is collected from the flight computer, and the required approach angle θ_a is computed by the distance between the plane and the desirable path. Then the angles, and the current airspeed V_a are input into the equation of the model to calculate best pitch angle θ_U as follow.

$$\theta_U = P_p\left(P_{descent} \times \left(\theta_a - \theta_g\right) + \min(P_{anti-stall} \times (V_a - V_g), 0)\right)$$

For the system input, the best glide speed V_g and the gains from secondary controller, which are pitch gain P_p, descent gain $P_{descent}$ and proportional gain $P_{anti-stall}$ when the best glide speed is larger than current speed. The pitch is then controlled to a desirable level by following the result of the calculation. The roll control is also computed with similar flow. As observed in this example of pitch control, the motion model seems applicable to other aircrafts as no specific parameters for a particular aircraft are needed.

Although suitable commands are given by the AELS system, this paper also emphasizes the importance of human situational awareness and actions as emergency situations do not only limit to engine failure, also the emergency in reality is uncertain, such as, the idle thrust setting in the experiment is different from actual engine failure.

2.3.4. Currently adopted landing technologies

The AELS is not approved to be put in service, while technology company GARMIN has developed a similar system and had been approved by the FAA and already installed in several small aircrafts.

According to GARMIN (2020), Autoland system enables the plane to land automatically even if the pilot is unable to control. Once the pilot or passenger presses the Autoland button, a suitable landing spot will be identified by the system and navigation starts. Besides navigation and control, Autoland can also send the current location, altitude and details of emergency to the ATC. The system works automatically until the plane comes to full stop at the landing spot, engines will also shut down automatically. The following figure shows the interface of Emergency Autoland

(GARMIN, 2020). In this interface, distance to the landing spot and the remaining flying hours according to the amount of remaining fuel are shown.

Figure 9 GARMIN Autoland system

(Adopted from Garmin, 2020)

If the aircraft is controllable, Autoland is not a compulsory measure to be adopted. An alternative technology is the Emergency Descent Mode (EDM) developed by the same company. It is mainly used when the pressurized system of the aircraft is failed and rapid descent to lower latitude that people onboard are able to breath normally is needed (GARMIN, 2020). Autopilot will act automatically and the plane will descend to a safe altitude. The pilot can control the plane again at this level.

2.3.5. Limitations of landing technologies

The systems mentioned above are adopted and tested in some small aircrafts only. One key reason is that most small aircraft require only one pilot, if that pilot is not able to continue the flight, it directly leads to loss of control to that aircraft, so it is essential to develop automatic systems for these aircraft. As large commercial aircraft require at least two pilots, the above problem is eliminated, also, the mechanics, failure mode and emergency situations of these planes are more complicated, so there are no similar systems developed for them for now. Further developments and experiments in these technologies to examine the possibility of applying these technologies into large commercial aircrafts are required.

According to the General Aviation and Commercial Division of FAA (n.d.), the Autoland system do not consider the NOTAM and other aerodrome information, also it does not take actions to avoid traffic, and most importantly, the system is not able follow ATC instructions, which may pose harm to surrounding aircrafts. It illustrates that these landing technologies are not comprehensive, in which pilot decisions and actions are still essential to maintain safety.

To perform emergency landing without excessive actions which may lead to human errors, considerations of using the landing technologies should be carefully carried out by the pilots. Also, it is beneficial to perform flight path planning as an assistance and suggestion for pilots when practicing emergency landing (Hassan et. al., 2022).

2.4. Flight path planning

2.4.1. What is flight path planning?

To maintain sufficient safety level and efficiency during the whole flight process, a comprehensive flight path should be planned before commencement of flight. A complete flight path planning of a commercial flight should include the starting position and the destination, desired route with waypoints, and desirable aircraft performance such as speed and altitude, with a consideration of ATC and meteorological restrictions.

Flight path plan is produced by flight operations department of the airlines and approval from Local Aviation Authority should be obtained (Ataman, 2023). Flight paths estimation can be generated based on different models and computer programs. Some prebuilt models are Base of aircraft data (BADA) and OpanAP with WRAP models. These models are accumulated with records retrieved from actual flights (Uzun et. al., 2018). Operators may also generate the plan with their own program. The plan is then introduced to pilots before departure. The pilots onboard enter the flight path into the Flight Management System (FMS) and perform the flight according to the desired path. While alternations and deviations during flight are anticipated due to the temporary ATC instructions and changing weather.

By adopting different flight path planning methods with accordance to relevant instructions and limitations, flight safety can be ensured. Also, optimal flight paths can be generated with fulfilling the desirable outcomes set by the operators and pilots, especially the fuel consumption and shortened flight time, which can reduce operation and fuel cost.

2.4.2. Elements of flight path planning

Flight path planning can be produced as the dynamic flight trajectory throughout the whole flight from takeoff to landing, and it can be divided into several sections or phrases, as the performance of the aircraft differs during these phrases, suitable inputs are essential for achieving the maximum efficiency with complying ATC instructions and without exceeding design limitation. the trajectory describes the flight path and position in three-dimensions (lateral, vertical and horizontal). With the addition of time measurement as a dimension, a 4D trajectory can be plotted (Delahaye et.al., 2014).

Normal flight phases include takeoff, climb, cruise, descent and landing. Climb can be divided into initial climb and normal climb, and descent can be divided into normal descent and final approach. As ground movements are mostly directed by ATC, and it post little effect to efficiency, the rolling before takeoff and after landing is not put in consideration into planning.

The basic flight path planning can be divided into vertical and horizontal segments and used for vertical navigation (VNAV) and lateral navigation (LNAV) respectively. Performance according to takeoff, climb, descent and landing are mostly included in the vertical segment. The consideration of choosing waypoints and appropriate courses is computed in the horizontal segment. In some models, velocity trajectory will also be generated (Jiang et.al., 2021).

2.4.3. Vertical flight trajectories

Takeoff and climb can be computed together from the takeoff position to the top of climb. After takeoff, the plane starts climbing. While the plane cannot directly climb and descent to the desired cruise level due to fuel efficiency, separation scheme and altitude limits, and avoid steep climb angle leading to discomfort. Different climb phases can be applied to fulfill the desirable outcomes. Also, descent and landing can be combined and computed with several descent phases.

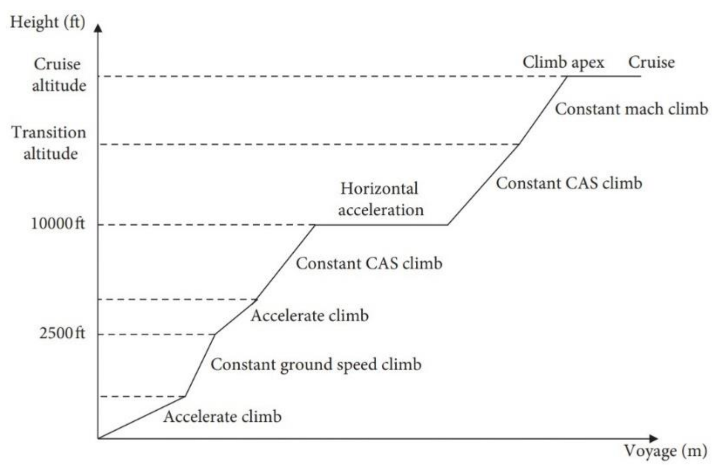


Figure 10 Example of phases of takeoff and climb

(Adopted from Jiang et.al., 2021)

As observed in the figure above (Jiang et.al., 2021), the phases of ascending are not computed with a straight line but with some steps and horizontal movement, similar approach is used for descent. This phase model is adopted in several performance and simulation model, such as OpenAP.

2.4.4. *Horizontal flight trajectories*

The consideration of flight route regarding the starting and ending positions, and the waypoints are defined as horizontal flight trajectories. During path planning, the cruise phase, which is the flight phase between top of climb to top of descent, is the main component of horizontal flight trajectories. Unlike climb and descent, this phase contains fewer alternation of altitude, while the factors affecting this phase is mainly weather, especially wind (Félix Patrón & Kessaci, 2014). As aircraft in this phase is at highest speed and altitude, the wind direction and magnitude variation post great impacts to airspeed, varying fuel efficiency. Also, alternation of course and direction is needed in accordance with airspace restrictions and ATC requirements. To determine the performance during cruise, different flight path calculations is needed to be adopted among waypoint by using different inputs.

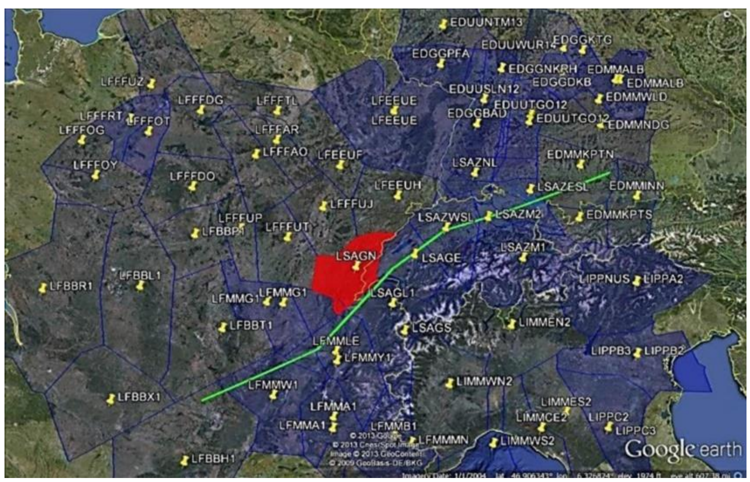


Figure 11 Example of horizontal trajectories

(Adopted from Gardi et.al., 2016)

2.4.5. *Parameters of flight trajectories*

To generate appropriate fight path for a particular aircraft, correct parameters are chosen and input for accurate estimation. Each parameter has its own maximum, minimum value based on aircraft design limitations, and mean value, which can be assumed as the optimal values accumulated from previous flights.

Basic parameters of aircraft include takeoff and landing weight, altitude, distances for takeoff and landing, fuel quantity and fuel flow, airspeed and vertical speed and the range. Different values and units of the parameters are used during different flight phases due to the expected performance, while there is no common standard to decide what values should be used (Koyuncu et. al., 2018).

For example, different airspeed values and units are used for different phases. For takeoff, climbing, descending and landing, calibrated airspeed (CAS) and true airspeed (TAS) are used for estimation as the aircraft performance is mostly affected by engine output and this speed accurately represent it. When the plane is reaching or in cruise phase, besides CAS and TAS, airspeed in Mach can be used, as the plane is at high speed, also Mach number is more suitable for describing the airspeed in situation under varying air density, hence more accurate estimation on engine performance, also calculation on fuel flow. While the Mach number cannot be directly measured but calculated by the airspeed equation as follow.

$$M = \frac{V_{tas}}{a_0\sqrt{\frac{T}{T_0}}}$$

After obtaining the TAS from the aircraft, with the ISA temperature and speed of sound (T_0 and a_0), also with the current temperature at level, Mach number can be estimated.

2.4.6. Mathematical models for flight path planning

To plan a complete flight path with essential aircraft dynamic movements, suitable parameters are put into equations for computation. Basically, integrations are used as the flight path is a combination of continuous estimation, and matrixes are used to determine the motion of the aircraft (Soler et. al., 2015). While different calculations and equations are adopted in separate models, as each model have their own outcomes.

For basic trajectory estimation, the following equation can be used.

$$l(\gamma) = \int_a^b ||\gamma'(t)||dt$$

The length of the trajectory $l(\gamma)$ can be estimated by the change of time of the movement from point a to b (Delahaye et.al., 2014). This is the optimal curvature path without consideration of other factors, so it may not be absolutely applied in all models. For example, in WRAP model used in this project, straight line segments between waypoints are adopted to reduce calculation time.

An approach to estimate the trajectory with its total fuel flow at that segment for assessing the flight cost, which is Compromised Aircraft performance model with Limited Accuracy (COALA) is as follow.

$$T_i = \{lon_i, lat_i, alt_i, TAS_i, Phase_i, \dot{m}_{f,i}, m_{gas,i}\}$$

In this function, longitude, latitude, altitude, TAS, the specific value for each flight phases, the fuel flow rate and the gas emissions are utilized to estimate the path (Rosenow et.al., 2021). This approach is more feasible to be used in computer programming as only numeric inputs, which are the values at the particular flight phase are required.

As observed in these two examples, it is assumed that with similar outcomes, calculation methods between different models are varying, it is essential to focus on the methods in the particular model that is chosen for this project, which is the WRAP model, to reduce bias and errors.

In WRAP model, the parameters are described by the continuous probability density functions (PDF), the parameter values can be represented in curvature graphic format, and the overall description of the parameter is as follow.

$$\{\hat{\psi} | \psi_{min}, \psi_{max} | * pdf\}$$

The $\hat{\psi}$ is the optimal value, and ψ_{min}, ψ_{max} are the minimum and maximum values respectively (Sun et.al., 2018). Suitable values are selected to be input into the functions. Combinations of parameters are collected through the programming process and hence trajectory can be generated.

In WRAP model, as to achieve efficient calculation, simple calculations are used. One example is that the distance of takeoff, D_{tof}, can be calculated as follow.

$$D_{tof} = R \times \arccos[sin\phi_1 \times sin\phi_N + cos\phi_1 \times cos\phi_N \times \cos(\lambda_N - \lambda_1)]$$

With the R is the radius of the earth, ϕ and λ are the latitude and longitude in radian, 1 and N is the position of the start and the end of takeoff according to the data retrieved from ADS-B (Sun et.al., 2018).

As WRAP model is a package with sufficient built-in mathematical models and equations, also with the basic information and parameters of the aircraft, its engines and the properties of the airports, it is more important to identify the flight phases and segments and select the correct parameters to input into the functions.

2.4.7. Estimated outcomes of planning

After selecting and inputting sufficient and correct parameters, with the estimated aircraft condition, such as payload, a complete flight path plan with essential predictions is made. The graphs and curves generated depend on the desirable outcomes.

The following example is the complete trajectory from takeoff to landing of an aircraft, with the consideration of altitude as and distance, also with the waypoints (Jiang et. al., 2021). The total flying distance and maximum cruising level can be observed in this trajectory. The three trajectories in different colors represents that the usage of data, and the process of simulation will make the trajectory different from the actual performance. Also, as observed in the optimal and actual paths, some waypoints are eliminated from the actual flight comparing to the desired track.

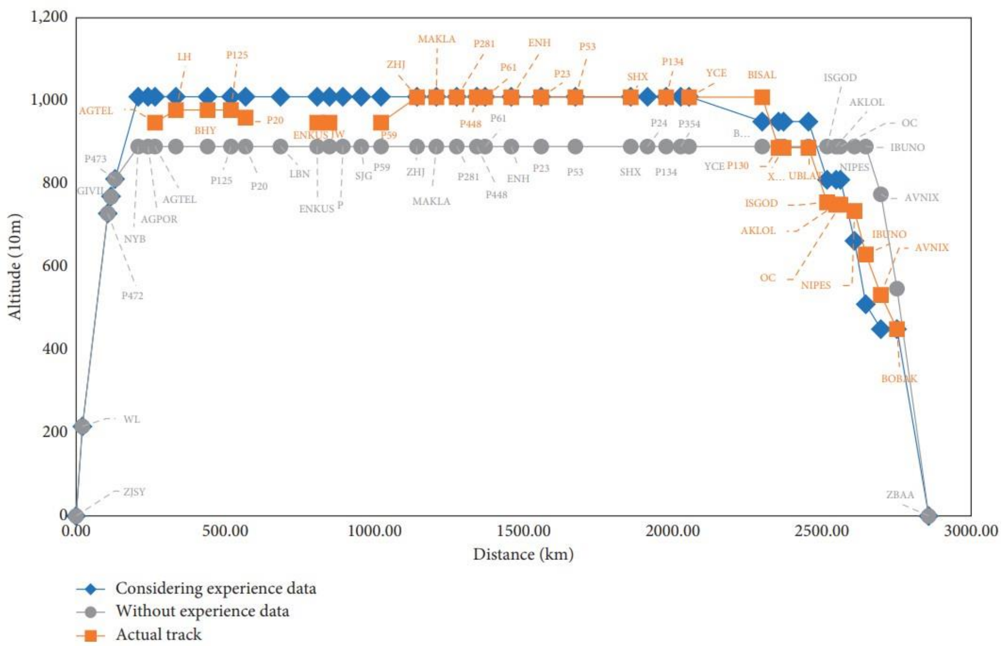


Figure 12 Flight trajectory with altitude and distance

(Adopted from Jiang et. al., 2021)

Another example made by Patrón and Botez (2015) represents both the horizontal and vertical trajectories with waypoints recorded of an aircraft during its top of climb (TOC) and top of descent (TOD). The example illustrates the horizontal paths used for LNAV with latitudes and longitudes, and vertical paths used for VNAV with the altitude. The 3D trajectory is generated by combining the horizontal and vertical paths. Similar to the example above, the optimal and actual trajectories are shown in different colors. It is observed that the altitude control of the pilot deviates from the optimal path.

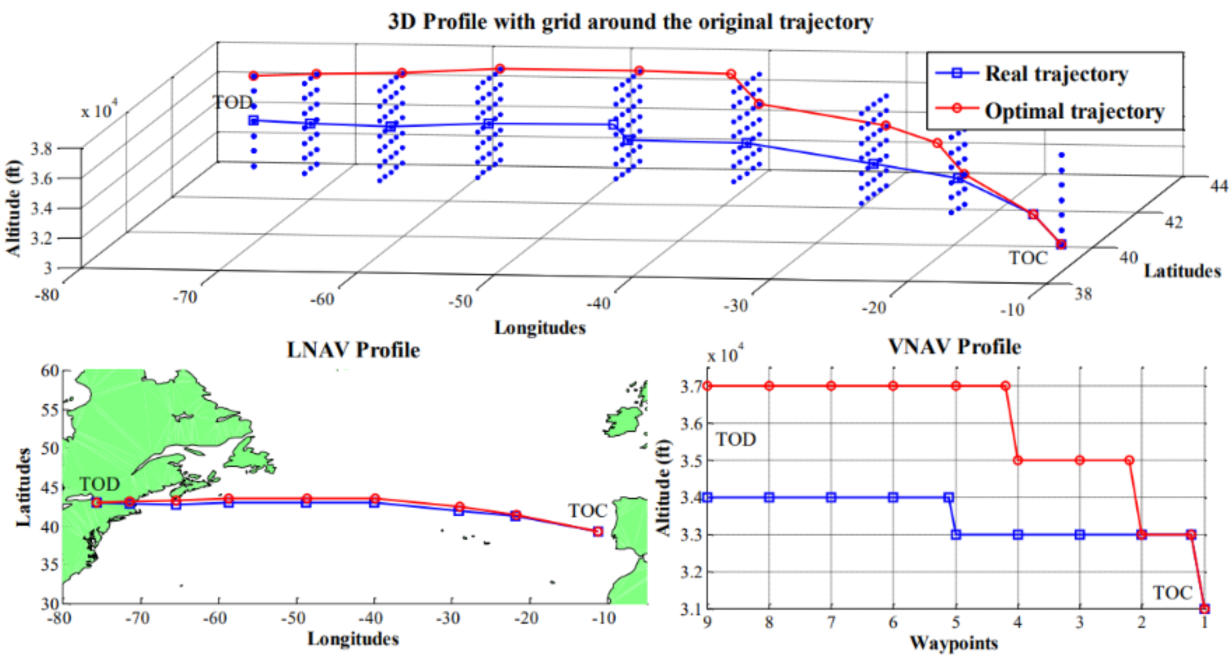


Figure 13 Completed 3D trajectory combined with horizontal and vertical trajectories

(Adopted from Patrón and Botez, 2015)

As observed in both examples made by different expertise, trajectories are integrated with the optimal trajectory, which is calculated and generated with existing experience data, also the real trajectory which is performed by the aircraft is shown. These two trajectories differ from each other and may give different values on fuel consumption and flight time. The estimated, optimized trajectory may deviate due to actual restrictions such as traffic, unexpected weather such as turbulence at level which alternation of altitude is needed, and the onboard decision of the pilot according to the situation mentioned above. Course, waypoints passing through, airspeed and altitude in actual flight are not necessary to be completely followed according to the desirable path due to these factors. Also, emergency procedures will result in severe deviation on optimal flight path, as additional control in large scale, such as emergency descent with great slope, will be applied.

2.4.8. Summary on flight path planning

The publications with their results and discussions reveal that flight path planning provides clear scope to the operators and pilots on how to maximize the performance of the aircraft by analysis of data and estimation. While this plan is not the only basis for the pilots to complete a flight, but also the real situations and instructions, especially when the plane enters into emergency.

2.5. Failure mode for modern commercial aircrafts

To consider whether emergency landing is needed, the type of failure must be identified. For modern aircrafts, most of the emergency landing cases are caused by serious system or equipment failure and threat of human onboard (Ezzat, 2020).

Some common system or equipment failures during flight include hydraulic loss (Palomeque, 2017), fuel leak, single/dual engine failure or fire, Electronic Centralized Aircraft Monitor (ECAM) failure (for Airbus aircrafts), smoke or fire onboard (Haroon, 2023). These failures may affect the normal operation of the aircraft and may lead to difficulty in control by pilot.

Once the component is found failed, cautions and warning signals will be active to alert the pilots. Also, flight control systems, such as Fly-by-wire, also detect and receive failure signals (Dolega & Rogalski, 2008). These signals are helpful to determine the required parameters to be input for the flight path planning if available.

Among the parameters of the flight path planning, the engine performance parameters are the most vulnerable to failures, as most of the severe abnormal or emergency situations are related to engine failures.

Parameter	Notation	Remarks
name	-	engine common identifier
manufacture	-	-
bpr	λ	bypass ratio
pr	-	pressure ratio
max_thrust	T_0	maximum static thrust, sea level (unit: N)
fuel_c3	C_{ff3}	fuel flow coefficient, 3rd order term (unit: kg/s)
fuel_c2	C_{ff2}	fuel flow coefficient, 2nd order term (unit: kg/s)
fuel_c1	C_{ff1}	fuel flow coefficient, 1st order term (unit: kg/s)
cruise_thrust	T_{cr}	thrust at the top of climb (unit: N)
cruise_mach	M_{cr}	cruise Mach number for the thrust condition
cruise_alt	h_{cr}	cruise Mach altitude for the thrust condition (unit: ft)

Figure 13 Engine parameters in OpenAP model

(Adopted from Sun et.al., 2018)

From the above figure, it is assumed that under the abnormal situation, the engine parameters will not be at their optimal level. If there is fuel leak, the fuel flow coefficient can be assumed be at its minimum value. For the engine malfunction, the thrust parameter can be assumed as minimum.

It is not guaranteed that the parameters are affected with this intensity, or the minimum parameters are not enough to represent the emergency situation. It is better to obtain the most updated data and information from the flight control system for precise computing for the flight plan. Also, pilots are needed to maintain awareness throughout the whole emergency process.

3. Methodology

3.1. Aim of the research

Human failure is one of the major reasons that failure occurs in operation. With the evolution of the AI technology, less experienced pilots are more likely to perform weaker in emergency situation due to the dependance on technology. Integrating the model with the aircraft system can provide optimal solutions for pilot during emergency landing. In emergency or abnormal situation, every second is crucial. To enhance the pilot performance, such as reaction time and decision making, during emergency situation by reducing the possibility of having human error, we aim to simulate the parametric model of the aircraft motion in several phases by using the open-source kinematic aircraft performance model, WRAP. Using the model, an optimal path for the pilot can be estimated by visualizing the flight path and providing the essential information for emergency situation, for example: required fuel amount, distance with nearest airport.

3.2. OpenAP

OpenAP is an open-source aircraft performance model for air transportation studies and simulations (available at: https://github.com/tudelft-cns-atm/openap). It provides OpenAP packages with python packages and model data. In the packages, it includes the aircraft data, engine data, kinematic data and navigation data such as airport and waypoint. For the python library, it includes 11 python coding packages.

Packages	
Prop	Accessing aircraft and engine properties
Thrust	Computing aircraft thrust
Drag	Computing aircraft drag
Fuel	Computing fuel consumption
Emission	Computing aircraft emission
Kinematic	Accessing WRAP data
Aero	Common aeronautical conversions
Nav	Accessing navigation information

Segment	Determining climb, cruise, descent, level flight
Phase	Identify the flight phases
Traj	Tools for trajectory generation.

3.3. Trajectory simulation

Situation	
Flight	CX111
Destination	HKG-SYD
Duration	8.5 hours
Aircraft type	A350

In this paper, we will focus on exploring a A350 flight CX111 flying from Hong Kong to Sydney. It is an 8.5 hours flight passing above ocean and small islands. A long haul flight allows us to perform a more precise simulation with different terrain and more airport option for emergency situation. To simplify the simulation routine of the flight CX111. Path will be cut into pieces by the waypoints to estimate the flight path in each phase such as climb and cruise. The picture below shows the flight path of CX111 in normal situation. The path will be cut into 8 parts to calculate the variation in each section. As the model only allow point to point calculation, each part is divided to be straight line as possible to minimize the calculation error. Flight will be separate into 8 phases, which are takeoff, climb, initial climb, climb, cruise, descent, final approach and landing. Default flight data from the WRAP model will be used as the input parameter of the formular.

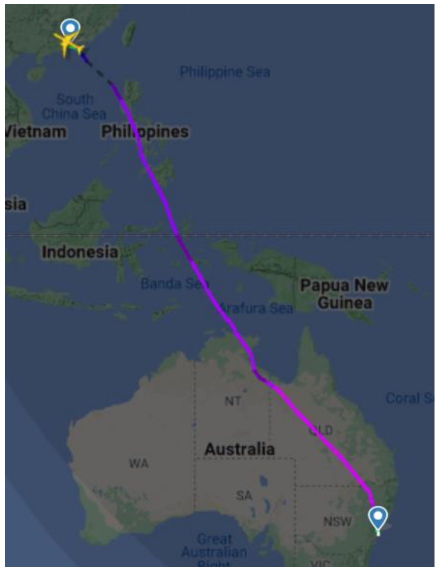


Figure 14 Flight path (Flightradar24)

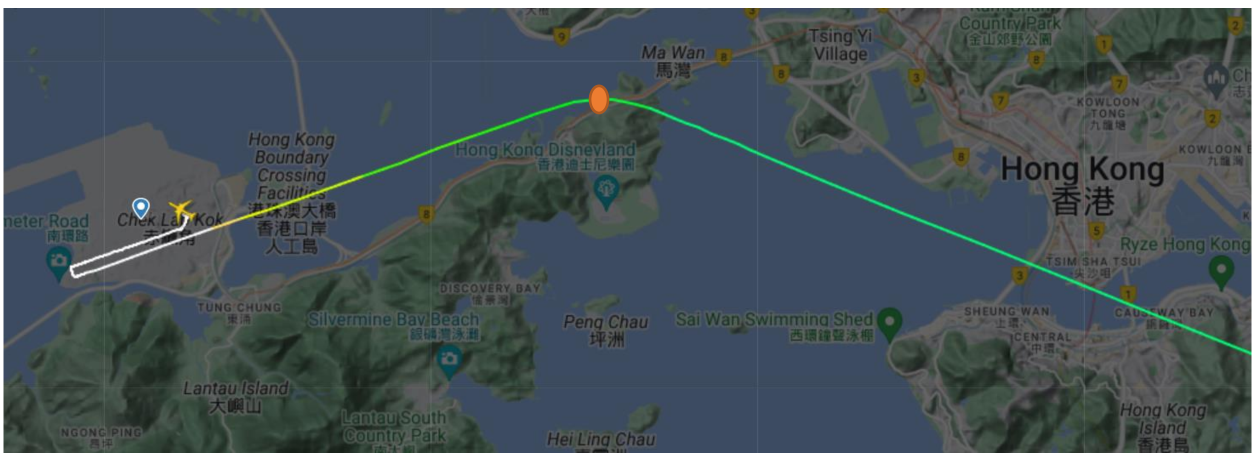


Figure 15 Waypoint: PORPA (Phase 1) (Flightradar24)

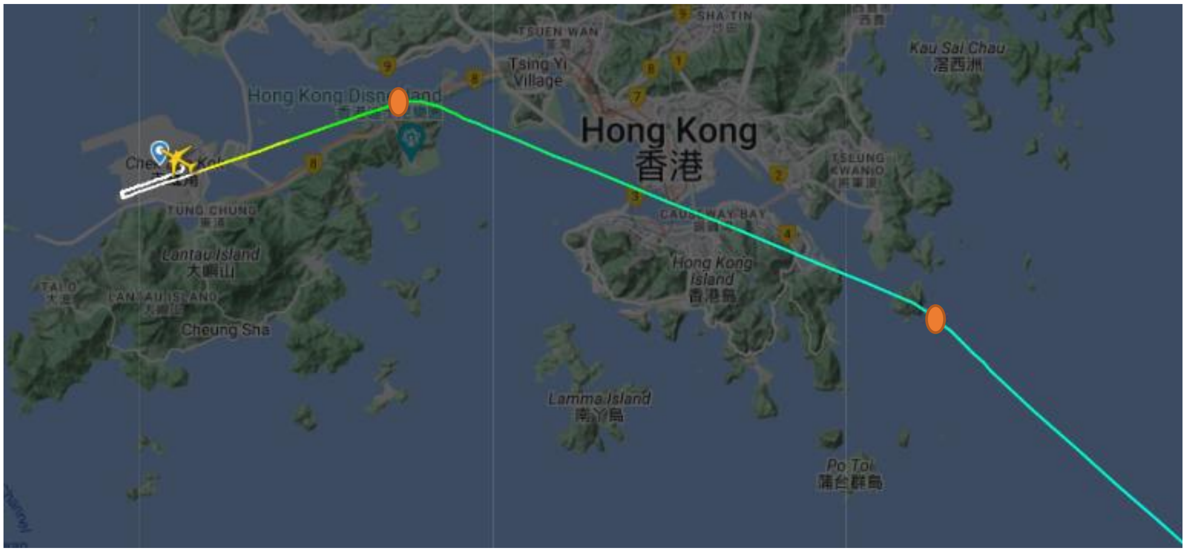


Figure 16 Waypoint: TD (Phase 2) (Flightradar24)

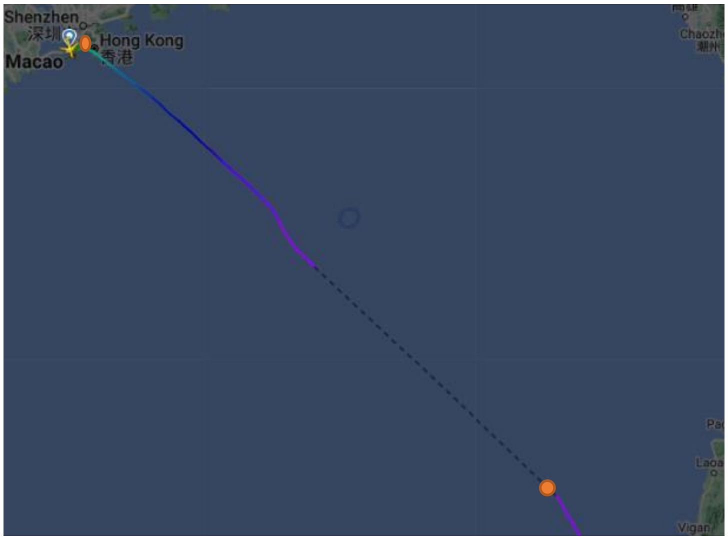


Figure 17 Phase 3 (Flightradar24)

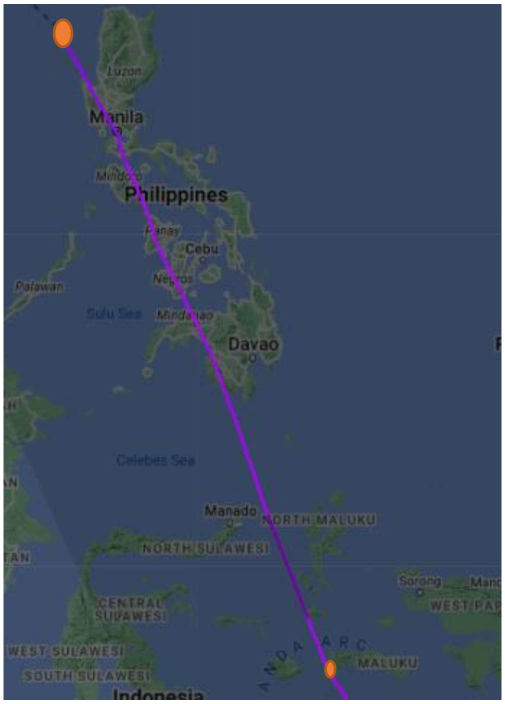


Figure 18 Phase 4 (Flightradar24)

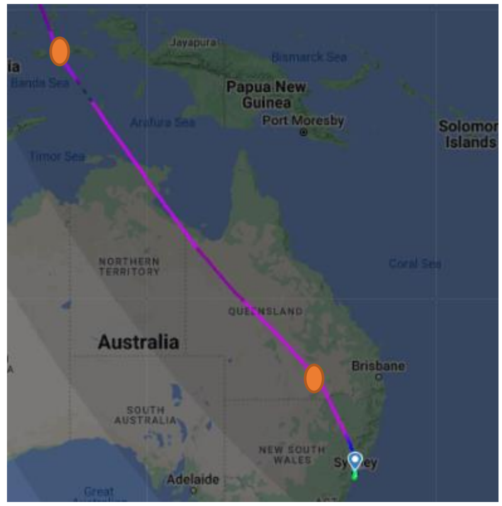


Figure 19 Phase 5 (Flightradar24)

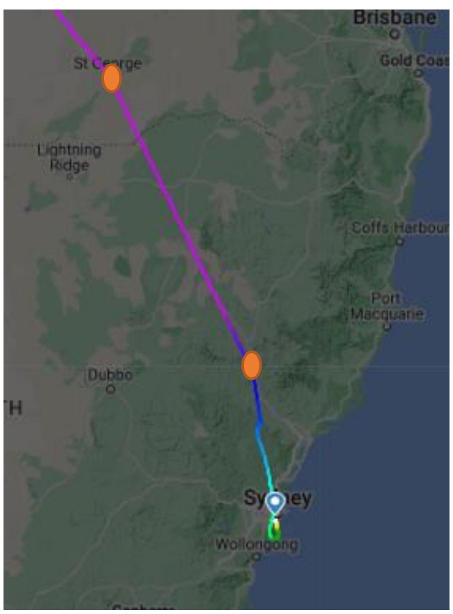


Figure 20 Phase 6 & 7 (Flightradar24)

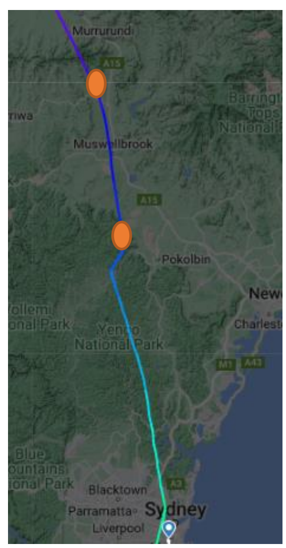


Figure 21 Phase 8 (Flightradar24)

3.3.1. Normal situation

Trajectory of flight in normal situation will be made and compared with the real flight data from Flightradar24 to ensure the simulation is accurate and precise. WRAP model will be used to help generate coding for the trajectory and calculation of the crucial information for pilot.

3.3.2. Emergency or abnormal situation

After ensuring the coding is precise for calculation and path simulation, abnormal situation will be added to the model to simulate the new flight path according to the current aircraft situation. Three Abnormal situations will be added to estimate the real situation during the flight. They are one engine failure, two engine failure and fuel leakage. To simplify the simulation, each failure has its assumption.

Failure	Assumption
One engine failure	Half of the thrust loss
Dual engine failures	Full thrust loss
Fuel leakage	Constant leakage rate

3.4. Information for pilot

As mentioned before, the simulation is used to reduce the human error made during flight especially emergency situation. Therefore, after simulating the aircraft condition during the emergency situation such as amount of fuel needed until the aircraft arrive at the airport, distance that aircraft can go on in this situation, the system will calculation and display the top 3 nearest airport nearby. Airport that located at latitude ± 2 and longitude ± 2 will be selected into calculation. The location of the airports and distance between the aircraft and the airport will be displayed for the pilot consideration. Information likes fuel amount needed and estimated arrival time will also be shown for pilot reference. Path will be visualized for the pilot for further elaboration.

4. ***Preliminary progress***

For aviation accidents, almost 80% of the fatal general aviation accidents are caused by pilot error. (*Nasa, 2013*) There are numerous factors that pilots have to face in emergency situations. For example, communication with another pilot, navigation and workload. Hence, we aim to design a flight performance model that estimates the optimal flight path for the pilot in an emergency situation.

4.1. Research

Before designing the model, we have done research on the factors that will affect the pilot performance by focusing on studying the literature regarding to the emergency in flight such as human factor, emergency landing procedure, current technology for emergency landing. It allows us to understand the possible supports pilot needed for urgent situations. Then, we can decide which essential information we need to display to reduce the information process workload for pilots in urgent situations. For instance, the distance of current location and the nearest airport, estimated time arrival, the location and code of the nearest three airports and estimated fuel amount for landing.

4.2. WRAP Model

In this paper, we integrate the OpenAP model python code (available at: https://github.com/tudelft-cns-atm/openap) along with our own code to form a model for emergency. In the model code, there are countless functions used for modeling the aircraft performance. To familiar with the model coding, we have chosen a shorter path for aircraft performance in the preliminary stage.

Situation	
Flight	HX606
Destination	HKG-NRT
Duration	3.5 hours
Aircraft type	A320

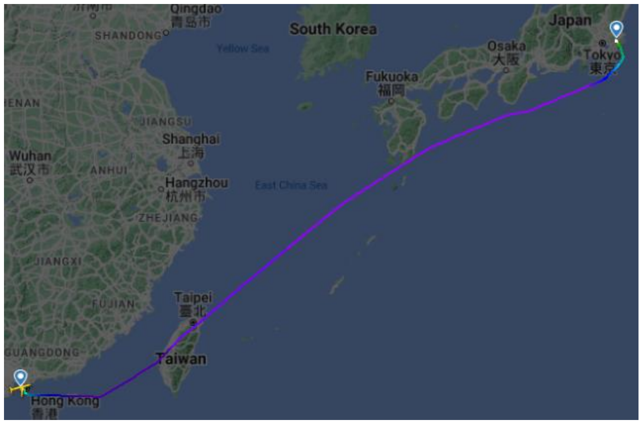


Figure 22 Flight path: HKG-NRT (Flightradar24)

4.3. Coding for navigation and trajectory

With the python packages, we try to generate coding for forming the flight path. As mentioned previously, OpenAP provides performance parameters based on real flight data, Enhanced Mode S Surveillance (EHS) data and ADS-B data. Default value will be used for each parameter in the coding as the mass of each flight and engine performance are different. Coding is attached to Appendix I.

```
Aiport location 22.31048 113.89639
current location 18.595 120.545
      icao       lat        lon  alt country       name   location
6921  RPLI  18.16364  120.52987   25      PH  Laoag Intl  Nagbacalan
6964  RPUZ  16.61909  121.24670  820      PH     Bagabag     Bagabag
6956  RPUO  20.44828  121.97533  291      PH       Basco       Basco
6957  RPUQ  17.55016  120.35436   16      PH       Vigan      Fuerte
6963  RPUY  16.93369  121.74722  200      PH     Cauayan     Cauayan
6963  RPUY  16.93369  121.74722  200      PH     Cauayan     Cauayan
```

Figure 23 Navigation result

In the current progress, the location of the selected airport can be shown in radian. With OpenAP packages, we can list the nearby airports of a certain location. As shown in the figure, we use latitude 18.595 and longitude 120.545 as the current location of an aircraft. Airports that are located at [Equation] of latitude and longitude. Other information such as the airport name, location and altitude of the aircraft will also be shown for pilot reference.

```
Takeoff phase
takeoff speed 85.3 m/s
fuel rate 2.431408188164194 kg/s
fuel rate 2.4293439255435088 kg/s
take off distance 1.65 km
takeoff time 19.343493552168816 s
total amuont of fuel needed 46.991998559751345 kg
Initial climb phase
Climb CAS 83.0 km/s
```

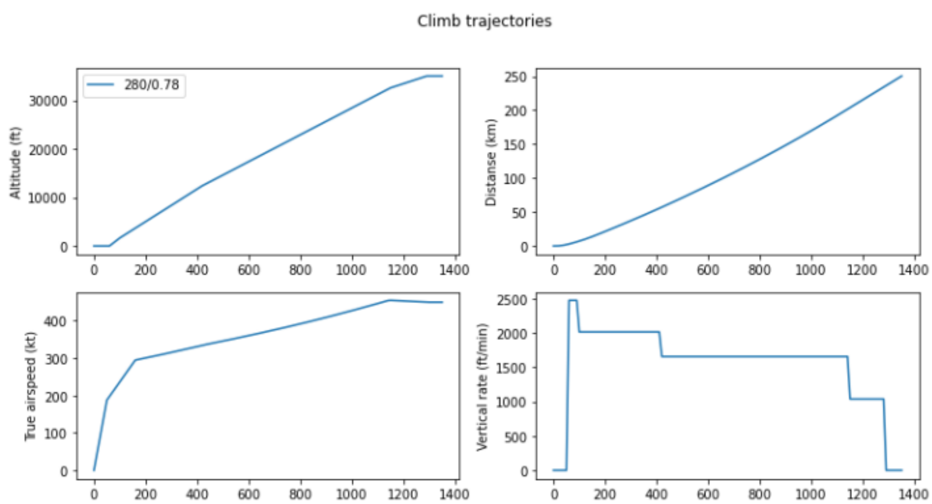


Figure 24&25 Trajectory result

From the coding in Appendix I, default performance parameters are used for further calculation for the phase. In the takeoff phase, we calculated the fuel rate at altitude = 0ft and altitude = 50ft. As the fuel rate at altitude = 0ft is larger than altitude = 50ft, to avoid the situation of underestimating the fuel usage, larger value should be used to play safe. Hence, we encountered a problem when we are calculating the climb phase. We are confused about what parameters we need to be calculate in order to generate the trajectory. From the second picture, there is a climb trajectory generated from the python packages provided in OpenAP.

```
#climb situation
data_cl = gen.climb(dt=10, cas_const_cl= 280, mach_const_cl=0.78, alt_cr=35000)
```

Figure 26 Coding from Appendix

To use the coding in OpenAP, we first need to input the climb situation of the aircraft so that WRAP model can help to calculate the phase data. However, as the input data is constant, we need to revise the coding again to understand the calculation in the coding and correct parameters we needed for simulation. Therefore, in the preliminary progress, we are still studying the python packages in OpenAP. We believe that once we acquire the knowledge inside the packages, we will have a rapid growth in designing the diversion airport advice system.

5. ***Succeeding progress***

5.1. Navigation section

In the next stage, we are going to calculate the distance between the current location and the selected airport. Then, we can further calculate the fuel amount needed and estimate arrival time. These information can be used to provide more precise navigation data for the pilot.

5.2. Trajectory of each phase

We will also need to generate the trajectory of each phase for calculating the fuel usage, change of bearing and traveling distance. To ensure the accuracy and precision of the generated trajectory, the generated trajectory will be used to compare with the real time data from flightradar 24. After confirming, we can estimate the location of the kinematic aircraft using the data calculated above. Then, we can apply the navigation part for finding the nearest airport.

5.3. Visualization

After finding the nearest airport, we aim to visualize the flight path for the pilot in 3D in the cockpit panel. An example is shown below.

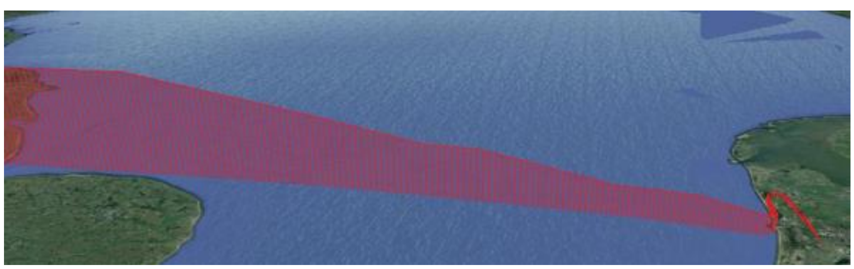


Figure 27 Visualized 3D flight path

(Adopted from Stackoverflow, 2016)

5.4. Emergency or abnormal situation

Subsequently, we can input the emergency data to the finished model and simulate the situation. As mentioned before, there will be three emergencies included in this paper. They are single, dual engine failure and fuel leakage. For a single engine failure, half of the thrust will be lost. For dual engine failure, all thrust will be lost. Lastly, fuel leakage will be at a constant rate.

With this system, it will help to decrease the workload for pilot in emergency situations and the possibility of human error.

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7. Appendix I

Flight_path_try1

```
import os

import numpy as np

import skfuzzy as fuzz

import csv                                # read excel

import matplotlib.pyplot as plt           # plot graph

from openap import FlightPhase            # flight phase

#from openap import CruiseOptimizer       # optimal situation for time and fuel (opt)

from openap import nav                    # find the location of the waypooint/airport

from openap.traj import Generator         # for gen traj

from openap import WRAP                   # kinematic

from openap import FuelFlow               # fuelflow

from openap import Thrust                 # thrust

from openap import aero                   # unit in SI unit

from math import sin, cos, sqrt, atan2


"""unit

1 knot = 1.852 km/h

"""


#initial every used Class (_init_)

fuel= FuelFlow(ac='A320', eng='CFM56-5B4')

wrap= WRAP(ac='A320')

thrust= Thrust(ac='A320', eng='CFM56-5B4')

phase= FlightPhase()

gen= Generator(ac='A320', eng='CFM56-5B4')
```

```
#takeoff 0ft-50ft (0-35ft)

#speed & change

print('Takeoff phase')

takeoffspeed= wrap.takeoff_speed()["default"]

print('takeoff speed',takeoffspeed,'m/s')

fuel_rate= fuel.takeoff(tas=takeoffspeed*1.94384449, alt=0, throttle=1) #knot, ft, 0-1 (1 full thrust)

print('fuel rate',fuel_rate,'kg/s')

fuel_rate= fuel.takeoff(tas=takeoffspeed*1.94384449, alt=50, throttle=1)

print('fuel rate',fuel_rate,'kg/s')

takeoffdistance= wrap.takeoff_distance()["default"]

print('take off distance',takeoffdistance,'km')

takeofftime= (takeoffdistance*1000)/takeoffspeed

print('takeoff time',takeofftime,'s')

Total_fuel_amount_takeoff = takeofftime*fuel_rate

print('total amuont of fuel needed',Total_fuel_amount_takeoff, 'kg')


# intial climb (35-15kft) (15-454.5m)

print('Initial climb phase')

climb_cas= wrap.initclimb_vcas()["default"]

print('Climb CAS',climb_cas, 'km/s')


# climb (10k-50k)

#generating 4 graph for climb trajectories

fig, ax = plt.subplots(2, 2, figsize=(12, 6))

plt.suptitle("Climb trajectories")

for i in range(1):

    #climb situation

    data_cl = gen.climb(dt=10, cas_const_cl= 280, mach_const_cl=0.78, alt_cr=35000)
```

```
    #graph 1
    ax[0][0].plot(
        data_cl["t"],
        data_cl["h"] / aero.ft,
        label="%d/%.2f" % (data_cl["cas_const_cl"], data_cl["mach_const_cl"]),
    )
    ax[0][0].set_ylabel("Altitude (ft)")
    #graph 2
    ax[0][1].plot(data_cl["t"], data_cl["s"] / 1000)
    ax[0][1].set_ylabel("Distanse (km)")
    #graph 3
    ax[1][0].plot(data_cl["t"], data_cl["v"] / aero.kts)
    ax[1][0].set_ylabel("True airspeed (kt)")
    #graph 4
    ax[1][1].plot(data_cl["t"], data_cl["vs"] / aero.fpm)
    ax[1][1].set_ylabel("Vertical rate (ft/min)")
    #label position
    ax[0][0].legend()
plt.show()


# cruise (For A320, max= )
# descent ()
# Final aproach (last 1000ft)
#landing (alt=0)
```

Navigation

```
from openap import nav
import os
import pandas as pd
import numpy as np
from openap.extra import aero
import csv

#Location of airport
airportloc= nav.airport("VHHH")
airport_lat= airportloc["lat"]
airport_lon= airportloc["lon"]
print('Aiport location',airport_lat, airport_lon)

#lat and lon calculation (find out nearest airport)
lat= 18.595
lon= 120.545

print('current location',lat,lon)
airports = pd.read_csv('P:/FYP/openap-master/openap/data/nav/airports.csv')
df = airports[airports['lat'].between(lat-2, lat+2) & airports['lon'].between(lon-2, lon+2)]
coords = np.array(df[['lat', 'lon']])
dist2 = np.sum((coords - [lat, lon])**2, axis=1)

#get all airport
idx = np.array(dist2)
ap = df.iloc[idx, :]
print(ap)
```