PHY407 Final Project: Simplified Flight Simulator in Circuit

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December 16 2021

Abstract

Simulation of aircraft motion is one of the most important topics in the aerospace field. Autopilots are designed based on these simulations. In this project, I have tried to simulate a typical Cessna 172 aircraft flying in a normal left-hand circuit pattern. In the first phase, I developed a method for the aircraft to simply do an ideal circuit. In the second phase, I added wind and demonstrated its effects on the aircraft's trajectory. In the third phase, I simulated how pilots counteract the effects of wind by crabbing. In this project, I have used multiple computational methods such as integration, solving ODEs, and random processes to simulate aircraft movement and wind.

1 Introduction & Motivation

A professional flight simulator is a complicated system that provides a simulated flight from take-off to landing for pilots. Flight simulators simulate aircraft dynamics and subsystems in detail to replicate aircraft behavior. To make this project more feasible, I used a greatly simplified model of aircraft dynamics.

The motivation of this project is to provide a useful tool to student pilots and instructors to learn to fly in a circuit under different wind conditions. For this purpose, flight simulators are not a good visual tool. The first disadvantage with them is that flight simulators do not provide an external visual overview, making it harder to see what the aircraft is doing as seen from the outside. Secondly, unlike in flight simulators, this simulation excludes irrelevant material such as the details of flight control and instead focus on how wind affects circuit flying.

From my personal experience, the lack of visual aids to demonstrate normal flying in a circuit pattern, whether with or without wind, makes it difficult for instructors to explain these concepts to students. This project can provide a great objective tool to simulate circuit flying for any type of wind condition.

More specifically, the early focus of this project was to simulate flying a standard circuit with zero wind. Later on, I applied two different types of wind conditions: gusty and constant. By integrating a random wind acceleration over time and adding noise, I generated a gusty wind. By comparing the reference trajectory and the simulated flight trajectories, we can understand the different wind effects on the path. By visualizing this, the student can understand what they have to expect if they do not compensate for the wind. I have additionally added functionality in order to counteract the wind factor and reduce trajectory error relative to the standard pattern.

2 Background

For understanding how this simulation works, first we need to introduce what is a typical flying in a circuit look like and how, later on, we can use some references to implement the coding part for the project.

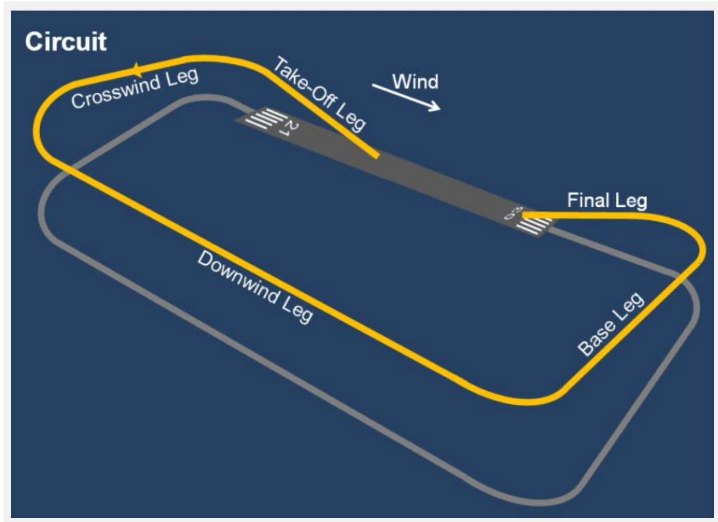


Figure 1: Standard Circuit Pattern

From figure 1, the circuit has been divided into different sections. The transition from takeoff leg to crosswind leg, typically happens at 300 feet or approximately 100 meters. Transition for cross wind to downwind happens at 1000 feet or 300 meters. Transition from downwind leg to base leg happens typically based on the aircraft position, after moving 2 runway lengths beyond the runway threshold. In real life, the transition from base to final involves aligning the aircraft with the center line of the runway. In our simulation, we mostly followed this pattern, but for the base to final transition we simply turned onto the runway heading and did not try to follow the center line. we used a coordinate system where x and y are horizontal dimensions and z is vertical. The positive x direction is the direction the aircraft points during takeoff. The runway is a line segment where -1000 < x< 0 and y and z are 0.

2.1 The Leg transition mode

In our model, we used the following rules to transit between the legs:

Leg Transition	Condition
Take-off to crosswind	Z coordinate > 100 m
Crosswind to downwind	Z coordinate > 300 m
Downwind to base	X coordinate < -2 * Runway Length
Base to final	Y coordinate < 1000 m

For the turn from base to final, we set the turn when the Y-coordinate is the same as the aircraft turning radius. This setting helps the aircraft to finish the turn by the time it is aligned with the runway.

3 Methods

General approach

To simulate aircraft motion in 3 dimensions, we decoupled vertical motion from horizontal motion as a simplification. At each simulation time step, a new velocity vector was calculated from position, previous velocity, and an additional state variable storing the current leg of the circuit. This model does not attempt to directly find and simulate forces acting on the aircraft to limit complexity.

The simulation contains a model of how a pilot behaves while flying a circuit pattern. This model determines, according to the current leg and the current state of the aircraft, what rotation rate to apply in the horizontal plane and what vertical speed to apply in the vertical plane.

Numerical integration

The position of the aircraft at the end of each time step is determined by numerical integration of velocity relative to the ground. For every time step, velocity relative to the air is first calculated by applying the pilot behavior model according to the previous state of the aircraft. Velocity relative to the ground is then determined by adding a wind vector to velocity relative to the air.

Then, position and time are recorded, the part of the pilot behavior model that determines whether to switch to the next leg is run, and the time step is finally advanced. In total, this method functions as an ODE solver.

$$x(t+h) = x(t) + h\frac{dx}{dt} + \frac{h^2}{2}\frac{d^2x}{dt^2} \quad (1)$$

$$x(t+h) = x(t) + hf(x,t) + O(d^2) \quad (2)$$

Where $O(d^2)$ is negligible. For finding the position we only need to solve the Euler method.

Wind model

In aviation, especially in maneuvering in relation to an airport as must be done in a circuit, wind and its variations are important considerations. To maintain motion in a desired direction relative to the ground in the presence of different types of wind, pilots use a technique called crabbing in which they fly relative to the air at an angle from the desired direction of motion to compensate for wind.

The program is capable of using two wind models: a simple one in which wind is a given constant vector and another in which wind varies randomly over time.

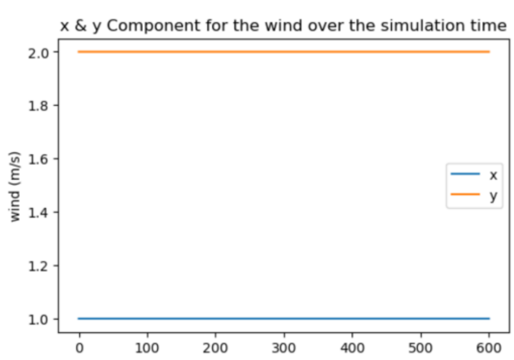
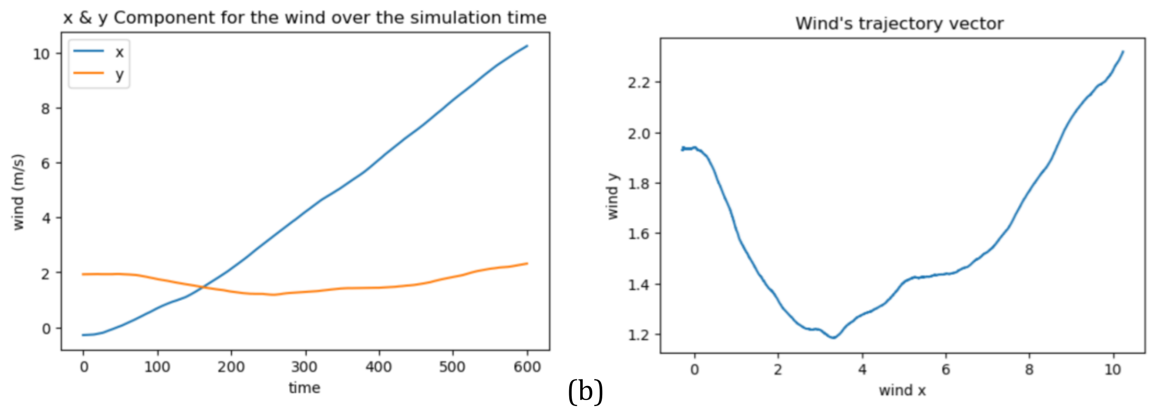


Figure 2: constant velocity wind model

In the model in which wind varies, an initial wind vector is randomly generated. A persistent rate of change is initialized to a zero vector. Then, for each time step, the rate of change is changed by a random number and is then applied to the wind. An additional small random change is then separately added to the wind. This combination of a changing rate of change and small random changes produces a smooth variation of wind over time perturbed with noise.

All uses of randomness in this model use **Gaussian distributions** to better represent the statistical behavior of physical phenomena in real life and to control the gust factor.



(a) (b)

Figure 3: These plots demonstrate a random variable gusty wind model. (a) A plot over time of wind components generated randomly using gaussian functions. (b) The overall trejectory of the wind vector, plotted in space instead of time, indcates the gradual and smooth gusting of the wind.

Pilot behavior model

Our model of pilot behavior considers the circuit as a series of legs, each of which is followed by another leg in a fixed circular order. The ideal trajectory is provided in figure 3, when the pilot experiences zero wind velocity and does not need to compensate for it. We run the simulation for approximately one circuit and a half to give enough time observe the different consequence for the following cases.

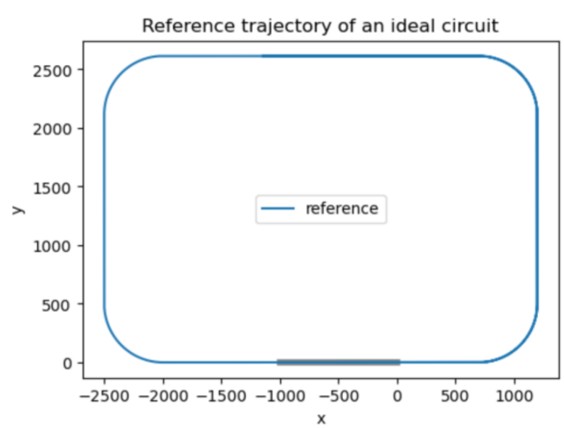
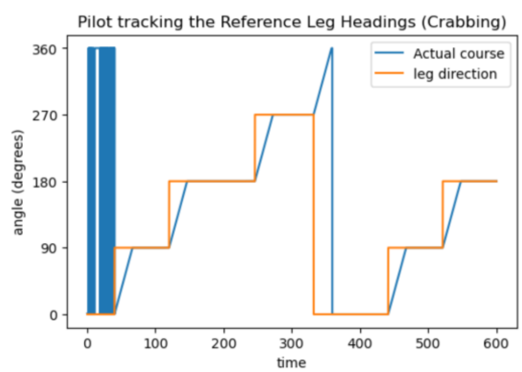


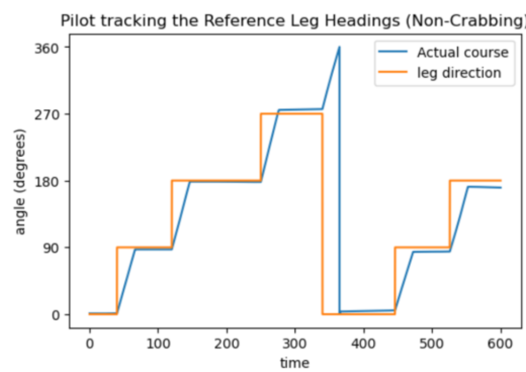
Figure 4: Ideal circuit pattern with zero wind condition.
Runway has been indicated in a gray line

In each run of the program, a total of three simulations are performed. One is a reference simulation under an ideal condition in which wind is zero. The other two simulations use the same pre-generated wind data.

The crabbing technique is used in everyday flying during windy conditions. As a part of flying lessons, students have to understand what crabbing is and how this can affect their desired path. In the second simulation, the pilot uses crabbing to maintain desired courses in the presence of wind. This is implemented by making the pilot model navigate using velocity relative to the ground as the aircraft's velocity. In this mode, the pilot turns such that the direction of the aircraft's motion relative to the ground matches the desired heading for each leg. In the third simulation, the pilot does not use crabbing. Instead, the pilot simply points the aircraft toward the desired heading. This causes the aircraft to travel in the desired direction relative to the air, but not relative to the ground. In figure 5, we can observe that in



(a)



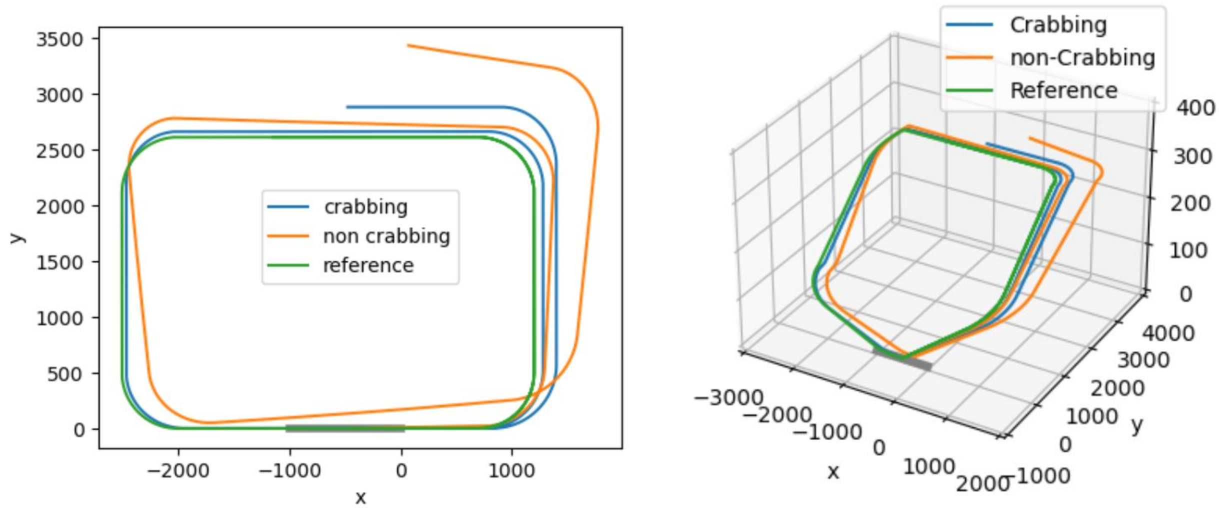
(b)

Figure 5: Plots of how the course of the aircraft along the ground tracks the target headings for each leg. Oscillation between 0 and 360 degrees are artifacts of considering the same value for 0 and 360 in degrees (a) applying crabbing technique (b) Not applying crabbing technique;

As you can see, in the non-crabbing case, the direction of travel of the aircraft relative to the ground drifts away from the desired track which resulted in drifting from the reference path which means that the deviation from the actual course and the leg direction is larger in non-crabbing case in comparison with the crabbing case. Although, in both cases, the is some drifting, in the non-crabbing case, the drifting is much more severe.

3 Results

Knowing what differs between the crabbing and non-crabbing cases, and considering figure 5, we expect that the trajectory of the aircraft when crabbing is closer to the reference trajectory than when not crabbing. This is confirmed by the results shown in figure 6. As can be seen there, crabbing allows the aircraft to move in the desired directions and remain near the ideal location of the circuit. Some drift still occurs during turns. Meanwhile, the trajectory without crabbing shows dramatic drift even during straight segments.



(a) (b)

Figure 6: A plot of reference, crabbing and non-crabbing trajectories after applying a gusty wind (a) A plot of 2D model in x & y coordinate (b) 3D plot of the same case

4 Discussion

By the previous method and by considering figure 7, we can see that the difference behaves consistently at each turn. Although the crabbing technique provided us a much more accurate circuit following, the deviation from the actual path still existed due to the wind effect during the turns. A possible next step is to implement a third pilot behavior in which the pilot follows lines in space instead of headings. This would be similar to how autopilots behave when following routes and would bring the aircraft back to the reference trajectory after each turn, even further limiting trajectory error.

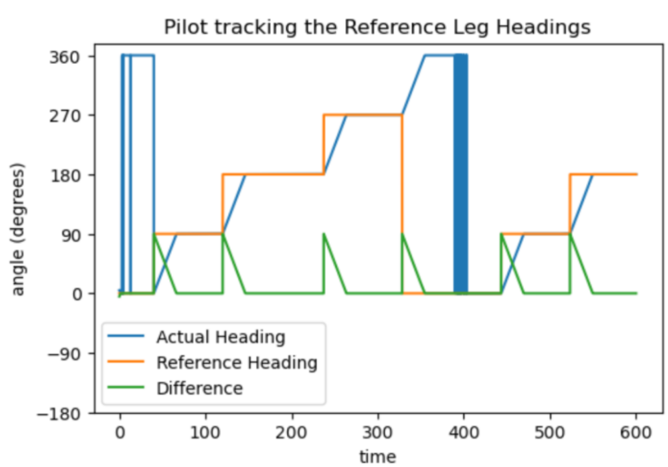


Figure 7: Plots of how the course of the aircraft along the ground tracks the target headings for each leg. Oscillation between 0 and 360 degrees are artifacts of considering the same value for 0 and 360 in degrees. The green line is the difference between the current coarse of the aircraft and the desired direction

Another fundamental concept that was ignored for this project was the coupling between vertical and horizontal motion. For the next step of this project we can couple them in order to simulate aircraft dynamics more realistically.

In general, this project has provided the foundations for an illustration tool for pilot training. The crabbing and non-crabbing concepts have been covered and instructors can also set the wind to constant and gusty conditions to illustrate different expected trajectories with and without compensation.

References

Newman, Mark. 2013. *Computational Physics.* Michigan: University of Michigan.

Transport Canada. 2004. *Flight training manual.* Ottawa: Transport Canada.