Unity Aircraft Simulation Design

Author: Dr. Wen Jiang

Objective

Build an aircraft in Unity which supports manual operation, autopilot operation and fully automatic operation. The dynamics of the aircraft should be as real as possible. The aircraft model and the control interface will be fit into an airport level simulation in the future. The environment, including terrain and airport is not part of this design and will be included in the future work as well.

3D Aircraft Model

The aircraft that we use in this design is in the family of Air Tractor AT-400. Its Unity .obj model Polygon Stunt Plane, which is developed by Synty Studios, is free to use. This aircraft is a taildragger, which means it consists of two main wheels forward of the center of gravity and a small wheel or skid to support the tail.

Figure 1. Air Tractor AT-400

The main components of the aircraft are:

- Fuselage
- Propeller
- left/right main wings
- Flaps
- Ailerons
- Left/right tail wings
- Elevators
- Vertical stabilizer
- Rudder
- Front wheels

- Back wheel

Dynamics

The aerodynamics logic is completely in FlightControls.cs file. The flight parameters are tuned based on the Cessna 172 model because the lift coefficient data for the Cessna model was handy.

Force Analysis

There are four main forces acting on an aircraft, thrust, drag, lift and weight. See the following figure.

Figure 1. Main forces acting on an aircraft

Thrust

Propeller generates thrust force. Thrust force is calculated by the following model:

$$T = Ct * rho * n^2 * D^4,$$
$$Ct = k * J + b,$$
$$J = V / (n * D),$$

where rho is air density and can be calculated according to Appendix 1, n is turns per second, D is propeller diameter, Ct is the dynamic thrust coefficient and is a linear function of advance ratio J, k and b are the linear function coefficients and can be determined by wind tunnel experiments, V is aircraft air speed.

Drag

Drag is the resistance force when traveling in the air and can be broken down into fuselage drag and wing drag. In this work, we model the total drag as follows,

$$total\_drag = body\_drag + main\_wing\_drag + tail\_wing\_drag$$

Lift

Lift is generated by the wings. In this work, we use the lift generated by the main wings and the tail wings. When flap is in use, it changes the lift coefficient of the wing. When the aircraft needs to make a turn, the ailerons on both sides turn in opposite directions. The aileron in use changes the lift coefficient as well.

Weight

Weight is caused by gravity, which is equal to mg, where m is the total mass of the aircraft and g = 9.81 m/s^2. The total mass of the aircraft includes the aircraft itself, fuel and load. The load is composed of the people and their belongings.
So, theoretically weight can be modeled as the following:

$$f\_weight = (m\_aircraft + m\_fuel + m\_people + m\_cargo)\, g.$$

The fuel mass is a variable of time and can be modeled as:

$$m\_fuel(t+1) = m\_fuel(t) - usage\_rate * engine\_rpm$$

In our work, we simplify the weight to be just a constant.

Control Interface

The control interface of the aircraft in our work consists of the following:
thrust, roll, pitch, flap, trim, ground brake and ground turn.

Thrust Control

Thrust is controlled through the propeller's RPM. The RPM input is a variable belonging to [0,1]. The input maps the throttle from idle to full. At time t, if the propeller's RPM is not equal to the target RPM according to the input, we use a fixed RPM changing rate to bring the actual RPM to the input target RPM.

Roll Control

Roll is controlled through the opposite directional movement of the ailerons on both sides. The input is a variable belonging to [-1, 1]. Left turn is "-", while right turn is "+". The magnitude is mapped to the aileron turning angle. When the aileron moves, it causes change on the lift coefficient of the wing. We model this effect by multiplying an additional aileron impact coefficient to the lift force. The aileron impact coefficient is calculated as follows,

$$aileron\_impact\_coef = 1 + impact\_range * roll\_input,$$

where the impact_range is a predefined constant. The other side of the lift is multiplied by 1 - impact_range * roll_input.

Pitch Control

Pitch is controlled through the movement of the elevator on the rear wing. When we want the nose up, the elevator should go up, which causes more downforce on the rear wing that pushes the tail down. The input is a variable belonging to [-1, 1]. Nose up is “-”, nose down is "+”. The magnitude determines how much angle change should be applied to the rear wing. The rear wing angle of attack is modeled as follows,

rear_wing_angle_of_attack = rear_wing_initial_shooting_angle + elevator_moving_range * elevator_input + trim_angle.

Trim angle will be introduced in a later section.

Flap Control

Flap is controlled through the flap switch, which has 4 positions, 0, 10 deg, 20 deg, and 30 deg. The input is a variable belonging to {0, 1, 2, 3}. Flap angles continuously move from one setting to the other. At time t, if the flap angle is not equal to the target angle, it will move toward the target angle at a predefined rate. Any flap setting except 0 will have an effect on the main wing’s lift coefficient as follows,

coef_due_to_flap = flap_degree / flap_moving_range,

main_wing_lift_coef = lift0_coef_table_float[angle_of_attack] + (lift30_coef_table_float[angle_of_attack] - lift0_coef_table_float[angle_of_attack]) * coef_due_to_flap;

where lift0 and lift30 means the lift lookup table at flap 0 and flap 30 deg.

Trim Control

Trim is controlled through the trim rotor. The effect of the trim on the aircraft is similar to that of the elevator. The trim adds a constant bias to the elevator angle.

Ground Turn and Brake Control

Ground turning is controlled through turning the back wheel. There is a Unity Wheel Collider attached to the back wheel. The ground turning is manipulated by the Unity engine. The input is a variable belonging to [-1, 1]. Turn left is “-”, turn right is “+”. The input is linearly mapped to -54 deg to 54 deg of the steering angle on the back wheel.

Ground braking is controlled through the braking paddle. This is an on-off control. If activated, both front wheels will receive a braking torque that will be applied to the Unity Wheel Collider.

* We focus on the aerodynamics at this moment. The ground dynamics will be addressed at a later time.

Display

The main window shows an aircraft following camera view from a 3rd person perspective.

Top middle dashboard

The most important flight data is shown in the top middle.

- PIT-pitch angle in degree
- HDG-heading in degree
- SPD-speed in knot
- ALT-altitude in feet
- VRT-vertical speed indicator in ft/min

Top left dashboard

The top left corner shows aircraft status variables.

- AOA-angle of attack in degree
- Thrust-thrust force in newton
- LeftWingLift-left wing lift force in newton
- SlideAngle-slide angle in degree
- u-vertical stabilizer input
- YawTorque-yaw torque the vertical stabilizer try to balance for
- Trim-trim angle in degree
- Autopilot, Hea, Alt, Spd, VRt-main autopilot and heading, altitude, speed, vertical speed autopilot switches indicator.

Top right dashboard

The top right dashboard shows debug info.

Middle left dashboard

Middle left dashboard shows all autopilot status and the set value.

Middle right dashboard

The middle right panel shows the control interface of the aircraft, which includes the engine switch, flap setting, yoke status(up/down, left/right) and throttle status.

Future Work

- Model the rudder dynamics.
- Ground brake using rudder paddle and using continuous braking torque instead of on-off control.
- Develop Model predictive controller for airborne controls.
- Tune the aircraft parameters according to Air Tractor AT-402 or 802 which lines up with the obj model. Currently it's tuned according to Cessna 172 due to lacking lift coefficient data at the time when developing this simulation.

Appendix

1. Air Temperature, Pressure and Density

According to NASA's Earth Atmosphere Model, the temperature, density and pressure of the air can be modeled in the following way with all metric units.

For $h \geq 25000$,

$$T = -131.21 + 0.00299 * h$$

$$p = 2.488 * [\frac{T+273.1}{216.6}]^{-11.388}$$

For $11000 \leq h < 25000$,

$$T = -56.46$$

$$p = 22.65 * e^{(1.73-0.000157 * h)}$$

For h < 11000,

$$T = 15.04 - 0.00649 * h$$

$$p = 101.29 * [\frac{T+273.1}{288.08}]^{5.256}.$$

The density is always

$$\rho = p/(0.2869 * (T + 273.1)).$$

$T = temperature\ (°C)$
$h = altitude\ (m)$

$p = \ pressure\ (KPa)$

$\rho = density\ (kg/m^3)$