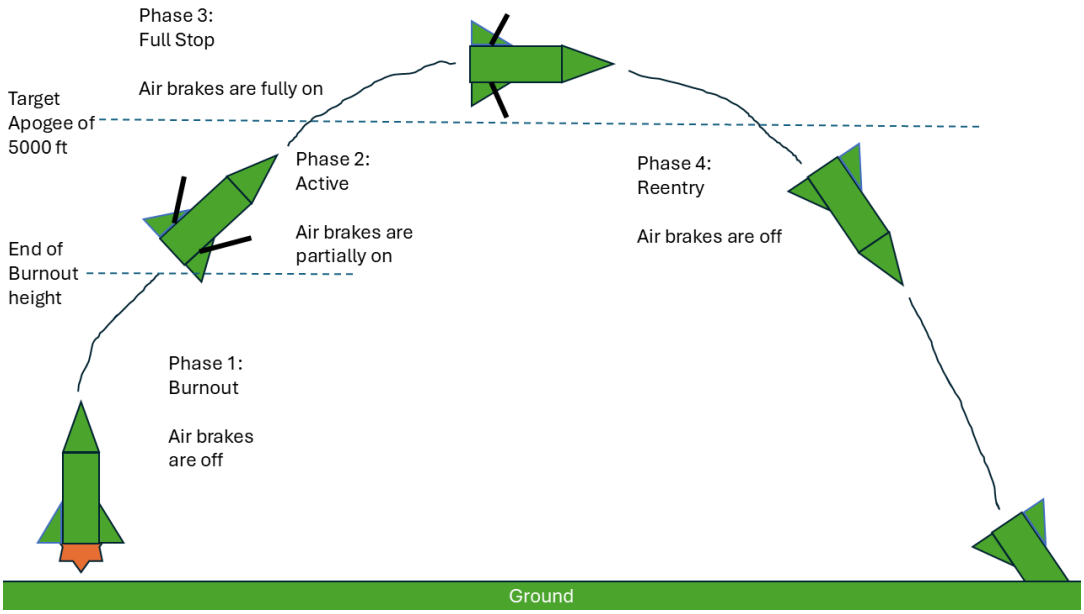
Christopher Kilroy
Alan Guyster
Chiara DeAngelis

Introduction

This document outlines the development of a state machine for air brakes. We provide a simplified breakdown of the trajectory/rocket phase & brake phases. The rocket & brake phases are then used to develop a state machine that returns the state of the air brake system based on flight altitude, velocity, and acceleration. Considerations made during development are also included. An appendix provides the code and code output.

Trajectory/rocket phase & brake phase diagram

This section explains rocket trajectory, when air brakes are active, and why air brakes are active. It also explains the basic concepts for the state machine.

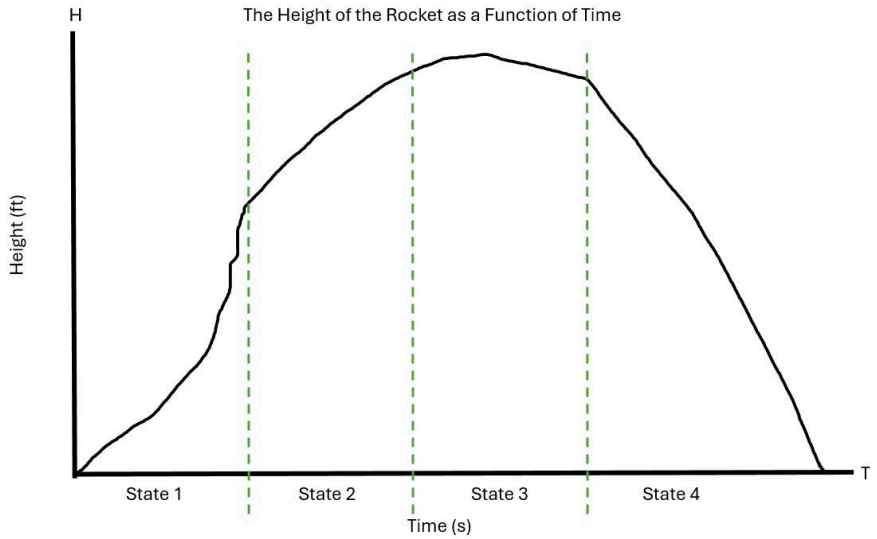


In the burnout phase (state 1), the rocket has an active forward thrust propelling it into the air. In this state, the air brakes are not active as we want the forward upward thrust to be maximized. The rocket's linear y position (altitude) is increasing exponentially as vertical velocity and acceleration are positive. The burnout phase ends when the rocket is no longer exhausting hot gas to thrust it forward, which will happen when the vertical acceleration becomes negative.

When the burnout phase ends, the active phase (state 2) begins. In this state, the air brakes are partially out and fluctuate based on the PID predictions of when the rocket will reach the target apogee of 5000 feet. During this phase, the rocket's change in altitude is starting to wane because while vertical velocity is still positive, the vertical acceleration is now due to gravity and thus negative. The active phase ends when the rocket reaches 5000 ft.

When the active phase ends, the full stop phase (state 3) begins. In this state, the air brakes are fully out as we want to make sure the rocket doesn't go too far away from the apogee. During this phase, the rocket's altitude will transition from increasing to decreasing as velocity transitions from positive to negative. The full stop phase ends when the rocket's altitude becomes less than 5000 ft.

When the full stop phase ends, the reentry phase (state 4) begins. In this state, the air brakes are now inactive again and an assumed parachute becomes active. During this phase, the rocket will continue to fall while a parachute initiates to lessen the impact force when it hits the ground.



Four states were defined for the rocket: burnout, active, full stop, and reentry. In the burnout stage, no air brakes are to be used. The active phase requires active control of the air brakes (some percentage out), with airbrakes 100% out during full stop. Upon reentry, the air brakes will be off.

State	Rocket phase	Brake phase
1	Burnout	No air brakes
2	Active	Controlled percentage out
3	Full stop	100% out
4	Reentry	No air brakes

Data description

This section describes data sources that were considered during development. We identified two data sources that provide parameters for time, altitude, acceleration, and velocity. These can be used as inputs into the state machine code.

https://raw.githubusercontent.com/usfsoar/NSL_24-25_EECS/refs/heads/main/TESTING_DEV/platformio_av_bay_test/**imu_data.csv**?token=GHSAT0AAAAAACX7OHPRJRQBTAUUXQNQPPTIZZGMVZA

Time,**Altitude**,Pressure,**Velocity**,Temperature,Events,Voltages
0.00,1.936287E-05,991.30,0,91.22, -,9.023726
0.05,8.33699,991.00,7.952381,91.22, -,9.023726

https://github.com/usfsoar/NSL_24-25_EECS/blob/main/TESTING_DEV/platformio_av_bay_test/**imu_data.csv**

time, **accel_x**, **accel_y**, **accel_z**, **linear_x**, **linear_y**, **linear_z**, gravity_x, gravity_y, gravity_z, quat_w, quat_x, quat_y, quat_z, gyro_x, gyro_y, gyro_z
14929 , 0.20 , -9.86 , 0.00 , 0.00 , 0.00 , 0.00 , -0.33 , -9.79 , 0.19 , -0.70 , 0.03 , -0.00 , 0.71 , 0.13 , -0.06 , -0.19
14948 , 0.19 , -9.84 , 0.00 , 0.04 , -0.05 , 0.00 , -0.33 , -9.79 , 0.19 , -0.70 , 0.03 , -0.00 , 0.71 , 0.13 , 0.37 , -0.25

Methodology

This section describes the state machine on a conceptual level using tables and pseudocode. The actual code implemented is included in the appendix.

State Machines

Our solution utilizes two state machines. The first state machine, M1, determines the stage of rocket flight. The second state machine, M2, determines the state of the air brakes. The state of M1 is used to determine the state of M2. The transition tables for the state machines are shown in the tables below.

M1

Start state	*End state* 1	2	3	4
->1	v>=0	a<=0		
2		v>=0	H>=h2	
3			H>h2	v<=0 or H<=h2
4				H<h2

M2

Start state	*End state* 1	2	3
->1	M1 = 1 or M1 = 4	M1 = 2	
2		M1 = 2	M1 = 3
3	M1 = 4		M1 = 3

Pseudocode for the air brake state machine

```
# Determine the current state of the rocket
M1(previousM1state, currentV, currentH, currentA):{
        previousM1state == 1 & currentV >= 0 : 1,
        previousM1state == 1 & currentA <= 0 : 2,
        previousM1state == 2 & currentV >= 0 : 2,
        previousM1state == 2 & currentH >= h2 : 3,
        previousM1state == 3 & currentH >= h2 : 3,
        previousM1state == 3 & currentV <= 0 | currentH <= h2 : 4,
        previousM1state == 4 & currentH < h2 : 4
}

# Determine the current state of the air brakes
M2(previousM2state, currentM1):{
        previousM2state == 1 & (previousM1state == 1 | previousM1state == 4): 1
        previousM2state == 1 & previousM1state == 2: 2,
        previousM2state == 2 & previousM1state == 2: 2,
        previousM2state == 2 & previousM1state == 3: 3,
        previousM2state == 3 & previousM1state == 3: 3,
        previousM2state == 3 & previousM1state == 1: 1
}

# Uses current velocity, acceleration,and height to determine rocket stage
# Uses rocket stage to determine braking state, calculates percentage ON
# Returns percentage ON of air brakes
AirbrakeState(previousM1state = 1, previousM2state = 1, currentV, currentH, currentA):
        currentM1 = M1(previousM1state, currentV, currentH, currentA)
        currentM2 = M2(previousM2state, currentM1)
        If M2 = 2 then X = RunPID()
        Else if M2 = 3 then X = 100%
        Else X = 0%
        Return X
```

Considerations

Would it be better for the Air Brakes to remain active in the Reentry phase to slow the rocket down more when it lands on the ground? If it lands at a terminal velocity without anything slowing it down, would the data still remain intact from the force of landing? If the air brakes are open during descent then the rocket will impact the ground with less force which would help ensure the data survives the experiment and doesn't get corrupted. For this study, we are assuming that reentry velocity is being controlled via parachute. This means that the rocket is already being slowed down but with air brakes it could slow the rocket down even more and ensure that the data remains fully intact.

If air brakes are implemented into the reentry, then another issue arrives where if the parachute and air brakes were fully active simultaneously, the sudden decrease in velocity may be so great that the rocket is torn apart by the air it is displacing (or another way of thinking of it as a rapid unscheduled disassembly of the rocket). If the air brakes were to be implemented, the percent active and when it is active can be determined by the PID and a potential additional state where the parachute is active to ensure both don't activate at the same time.

The burnout phase was considered to end at some predicted height. The height would be calculated using an equation for burnout height based on a given amount of time. This phase was determined to also correspond to the acceleration becoming negative. Instead of predicting the transition height, we decided to use acceleration. Height could be implemented as a control parameter using an OR statement of *height = arbitrary value* or *a<=0*, whichever happens first. However, a concern arises when the rocket exceeds the burnout height and continues to exude thrust as the rocket would still be in burnout phase, but the air brakes would initiate. If this is a concern while using this OR statement, it would be better to make use of an AND statement where both conditions must be filled. If we go this route, it may delay air brake implementation due to physical delays of the IMU sensor. Due to these concerns, we chose to limit the transition condition to be based only on the acceleration.

At any stage of flight, the air brake state machine might need to be manually overridden. This could be performed by some other operation, by using exceptions, etc. It may be possible to accomplish this by adding an extra state within M2 that manually sends the state to 0% or 100% ON. However, it could provide greater control to implement overriding functionality outside of the AirbrakeState function.

References

[1] Geeks for Geeks. 2024. Introduction of Finite Automata. Geeks for Geeks website. Accessed 3 November, 2024 from https://web.archive.org/web/20240331182324/https://www.geeksforgeeks.org/introduction-of-finite-automata/

Appendix

Code

```
import numpy as np
import csv

# Open the CSV file
with open('imu_data.csv', mode='r') as file:
    reader = csv.DictReader(file)  # Read CSV into a dictionary for easier
column access
    acceleration = []

    # Extract columns
    for row in reader:
        acceleration.append(row[' accel_y'])

with open('University_of_South_Florida (2) (1).csv', mode='r') as file:
    reader = csv.DictReader(file)  # Read CSV into a dictionary for easier
column access
    velocity = []
    altitude = []

    # Extract columns
    for row in reader:
        velocity.append(row['Velocity'])
        altitude.append(row['Altitude'])

def RunPID():
    x = np.random.rand()
    return x

# Initial parameters
for A in range(1000):
    while (0 < A < 1000):
        previousM1state = 1
        currentV = int(float(velocity[A]))  # initial upward velocity
        currentA = int(float(acceleration[A]))  # initial acceleration
```

```
        currentH = int(float(altitude[A]))    # starts from the ground
        h2 = 4000       # target height for transitioning to state 4
        statesM1 = np.array([1, 2, 2, 3, 3, 4, 4])

        # History to track state transitions
        history = []

        # Simulation loop
        for t in range(1):  # Adjust steps as needed
            # Set states and conditions without modification

            M1 = np.array([
                (previousM1state == 1) & (currentA >= 0) & (currentV > 0)
& (currentH < h2), # Stage 1 to Stage 1
                (previousM1state == 1) & (currentA < 0) & (currentV > 0) &
(currentH < h2), # Stage 1 to Stage 2
                (previousM1state == 2) & (currentA < 0) & (currentV > 0) &
(currentH < h2), # Stage 2 to Stage 2
                (previousM1state != 2) & (currentV > 0) & (currentA < 0) &
(currentH > h2), # Stage 2 to Stage 3
                (previousM1state == 3) & (-300 < currentV < 300 ) &
(currentH > h2), # Stage 3 to Stage 3
                (previousM1state == 3) & (currentA < 0) & (currentV < 0) &
(currentH <= h2), # Stage 3 to Stage 4
                (previousM1state != 4) & (currentA < 0) & (currentV < 0) &
(currentH < h2) #Stage 4 to Stage Stage 4
            ])

            # Determine the current state based on conditions
            currentM1State = statesM1[np.argmax(M1)]
            previousM1state = currentM1State  # Update state


            # PID section
            if currentM1State == 2:
                X = RunPID()
            elif currentM1State == 3:
                X = 1
```

```
            else:
                X = 0

            # Record the state for later analysis
            history.append((currentM1State, currentV, currentA, currentH,
X))

            # Update velocity, height, and potentially stop if the ball
has landed
            currentH += currentV
            currentV += currentA

            if (t > 10) & (currentA > -10):
                currentA -= 1

            if (t > 0) & (currentH <= 0):  # Ball hits the ground
                currentH = 0
                currentV = 0
                currentA = 0
                break  # End simulation when the ball lands
            # Print simulation results
            for step, (statesM1, V, A, H, X) in enumerate(history):
                print(f"Step {step}: Rocket Stage={statesM1},
Velocity={V}, Acceleration={A}, Height={H}, PID State = {X}")
```

Simulation Output

Step 0: Rocket Stage=1, Velocity=7, Acceleration=0, Height=8, PID State = 0
Step 0: Rocket Stage=1, Velocity=18, Acceleration=0, Height=19, PID State = 0
Step 0: Rocket Stage=1, Velocity=23, Acceleration=0, Height=25, PID State = 0
Step 0: Rocket Stage=1, Velocity=31, Acceleration=0, Height=33, PID State = 0
Step 0: Rocket Stage=1, Velocity=45, Acceleration=0, Height=47, PID State = 0
Step 0: Rocket Stage=1, Velocity=52, Acceleration=0, Height=55, PID State = 0
Step 0: Rocket Stage=1, Velocity=58, Acceleration=0, Height=61, PID State = 0
Step 0: Rocket Stage=1, Velocity=68, Acceleration=0, Height=72, PID State = 0
Step 0: Rocket Stage=1, Velocity=82, Acceleration=0, Height=86, PID State = 0
Step 0: Rocket Stage=1, Velocity=90, Acceleration=0, Height=94, PID State = 0
Step 0: Rocket Stage=1, Velocity=106, Acceleration=0, Height=111, PID State = 0
Step 0: Rocket Stage=1, Velocity=119, Acceleration=0, Height=125, PID State = 0
Step 0: Rocket Stage=1, Velocity=132, Acceleration=0, Height=139, PID State = 0
Step 0: Rocket Stage=1, Velocity=151, Acceleration=0, Height=158, PID State = 0
Step 0: Rocket Stage=1, Velocity=172, Acceleration=0, Height=181, PID State = 0
Step 0: Rocket Stage=1, Velocity=185, Acceleration=0, Height=195, PID State = 0
Step 0: Rocket Stage=1, Velocity=196, Acceleration=0, Height=206, PID State = 0
Step 0: Rocket Stage=1, Velocity=207, Acceleration=0, Height=217, PID State = 0
Step 0: Rocket Stage=1, Velocity=223, Acceleration=0, Height=234, PID State = 0
Step 0: Rocket Stage=1, Velocity=236, Acceleration=0, Height=248, PID State = 0
Step 0: Rocket Stage=1, Velocity=252, Acceleration=0, Height=265, PID State = 0
Step 0: Rocket Stage=1, Velocity=257, Acceleration=0, Height=279, PID State = 0
Step 0: Rocket Stage=1, Velocity=257, Acceleration=0, Height=290, PID State = 0
Step 0: Rocket Stage=1, Velocity=263, Acceleration=0, Height=301, PID State = 0
Step 0: Rocket Stage=1, Velocity=268, Acceleration=0, Height=315, PID State = 0
Step 0: Rocket Stage=1, Velocity=268, Acceleration=0, Height=329, PID State = 0
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