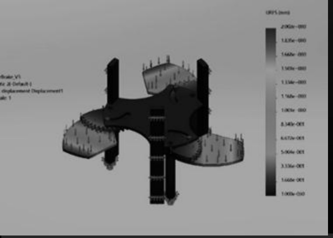   

Model Predictive Control (MPC) for a Rocket Airbrake System

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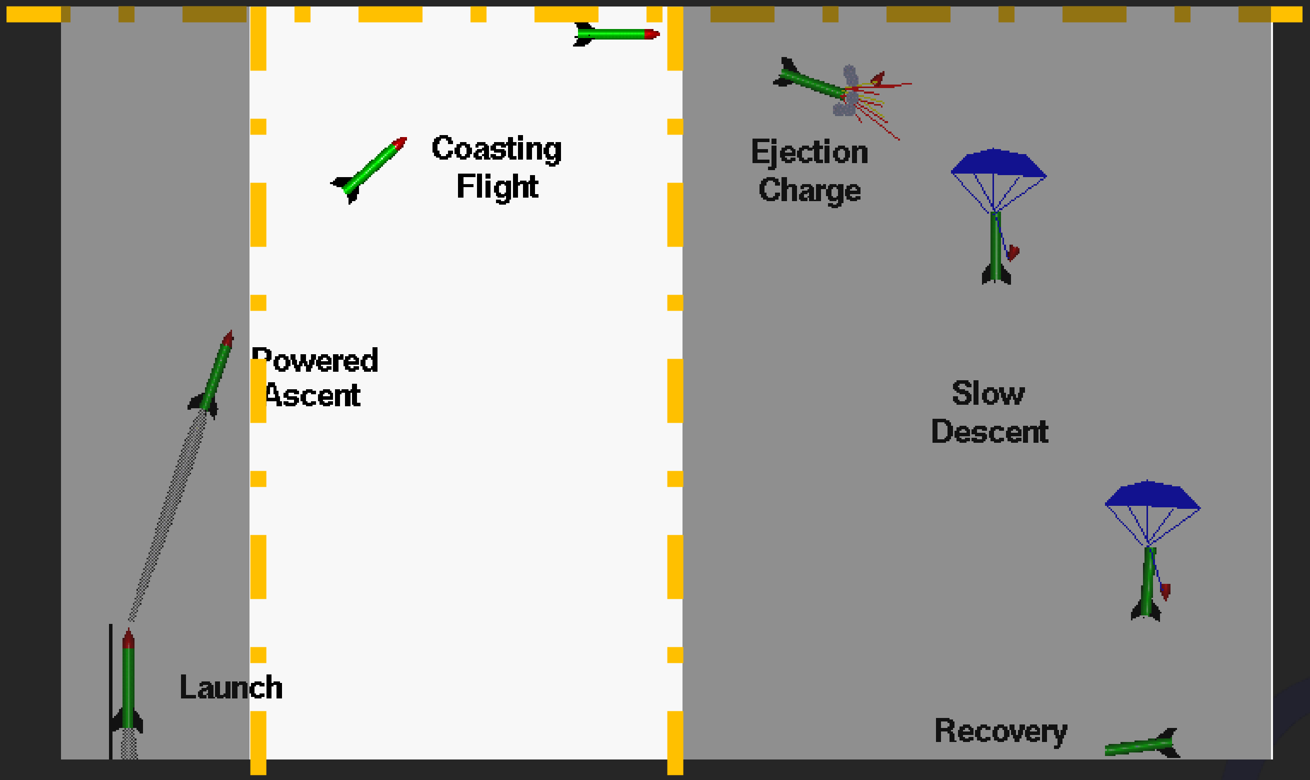
Overview of Presentation

- Part I : Some Context
  - Background of our goal
  - Relevant information about rocket design
- Part II : Control Theory & Implemented Solutions
  - Functionality of Model Predictive Control (MPC)
  - Quick mention of sensor fusion
  - State estimation
  - Model prediction
  - Error correction via physical actuation
- Part III : Demonstrations
  - Active controller performing in a simulated environment

Our Desired 'Output' (Rocket Coast Profile)

Our active control system only works during coasting flight

10 000 ft
3048 m

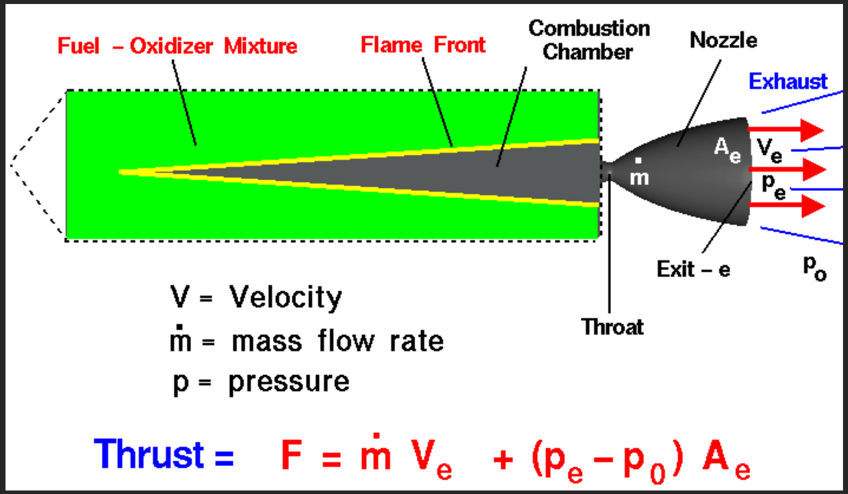


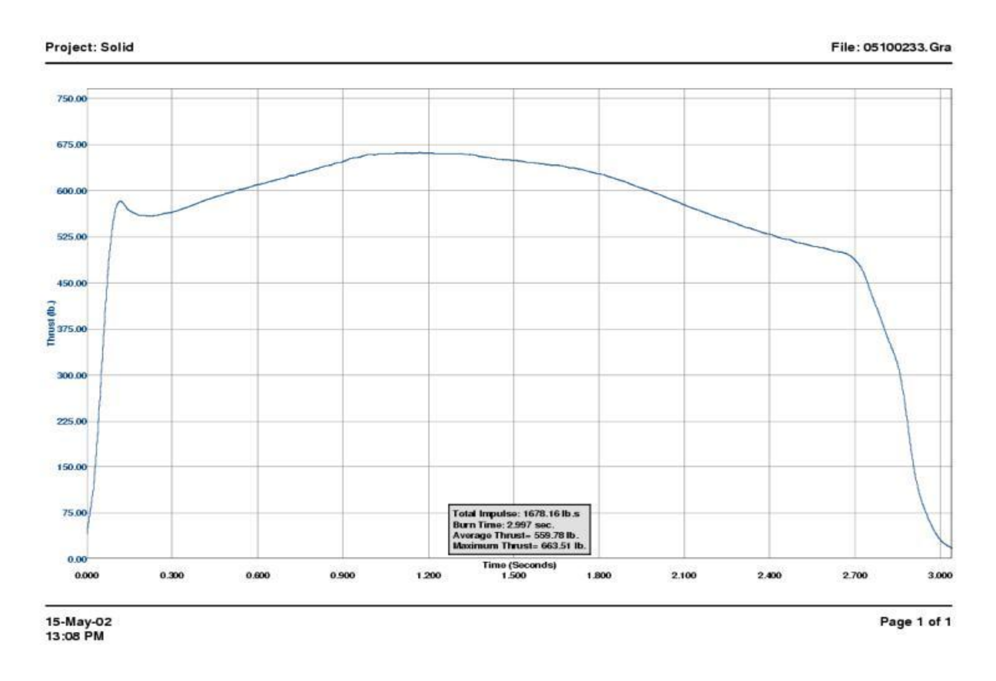
Time

Coasting is defined as the duration of rocket flight where no active thrust is present and before descent

Why no Active Control During Powered Flight?

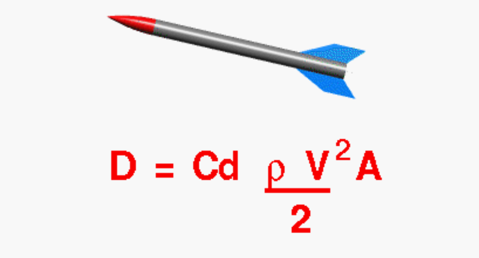
- Deploying airbrakes is more likely to destabilize powered flight
- During powered flight for our solid rocket motor
  - Max velocity w/o air resistance: 351 m/s
  - Max acceleration: 13g

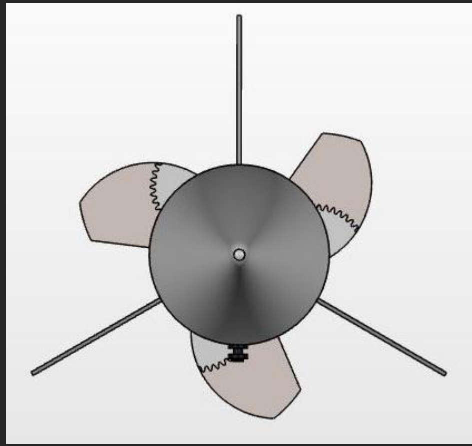




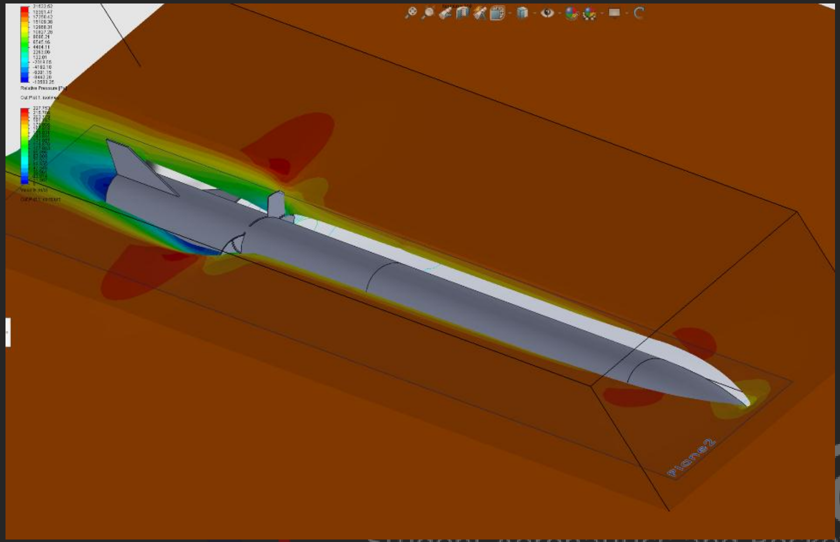
Airbrakes and Effects of Increased Drag

- Empirical drag force formula
  - Rho = air density
  - Cd = experimentally determined coefficient
  - V = velocity
  - A = reference area





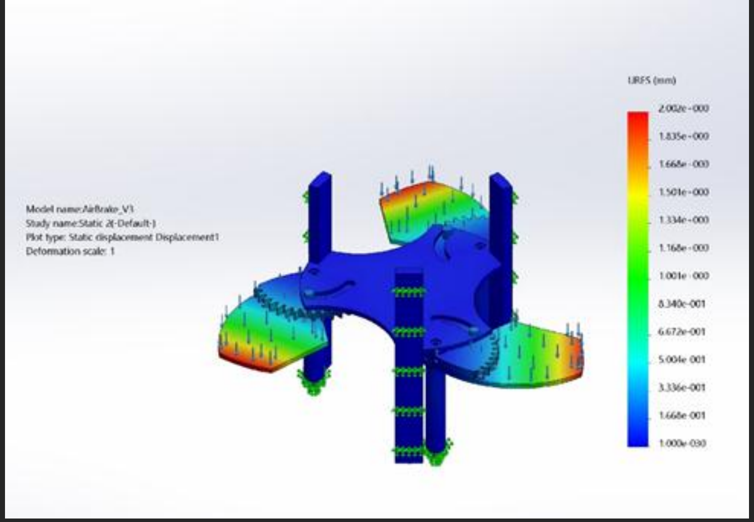
- Deploying airbrakes during coast
  - Increases reference area -> increase in overall drag
  - Increases Cd -> increase in overall drag
  - Decreases velocity -> decreased final altitude



- One servo actuates the ‘position’ of the airbrakes
  - Resolution of 5%
  - Deployment is symmetric

Refined Airbrake Design

Part	Material	Thickness	Elastic Modulus (GPa)
Top Plate	Plywood	3 mm	(See plywood prop.)
Centre Gear	Plywood	6mm	(See plywood prop.)
Leaf Gears x3	Plywood	6mm	(See plywood prop.)
Leaf x3	Aluminum	3mm	68.9
Spars x3	Aluminum	6.35mm	68.9
Standoff x3	Aluminum	12.7mm	68.9
Guide Pin	Delrin	6.35mm	
Spektrum A6180 Servo	Plastique	n/a	n/a
Bushings x6	Nylon w/ PTFE	n/a	n/a
M3x5 Screw x3	Zinc-plated Galvanized Steel	n/a	n/a



- New Airbrake design increases exposed area by 245% when fully deployed
  - New Fully Deployed Area: 110.4cm^2
  - Old Fully Deployed Area: 40.0cm^2

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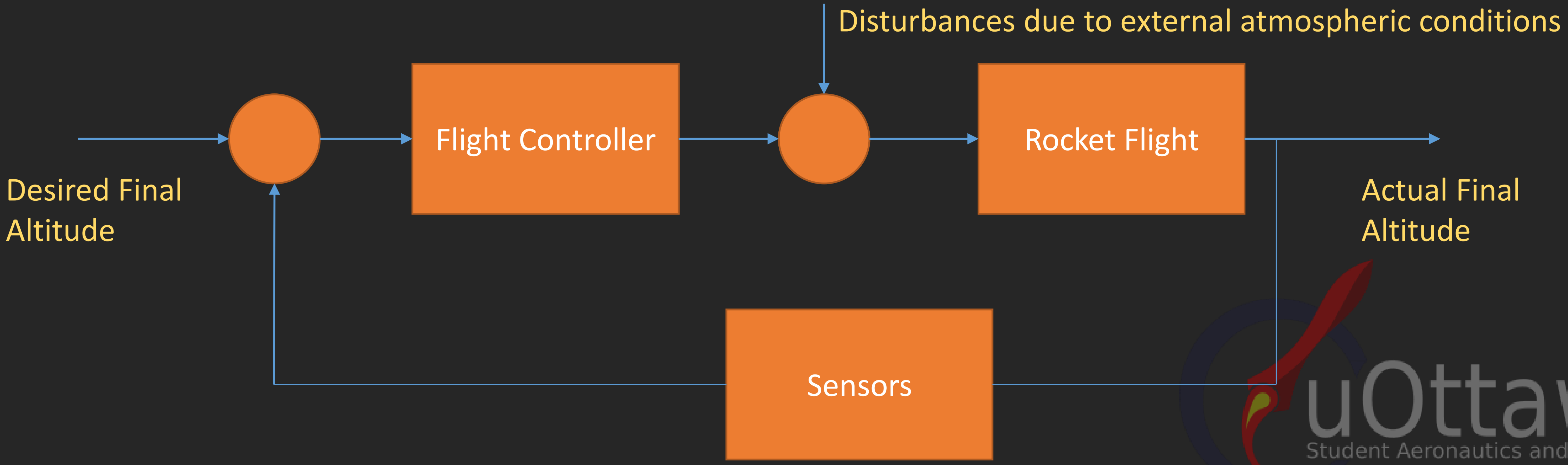
The Refined Problem Statement

- "We want to control the final altitude of our rocket flight by actively controlling the amount of airbrake area that is exposed (via a servo motor) during coast."
- A diagrammatic abstraction of the system is shown below:



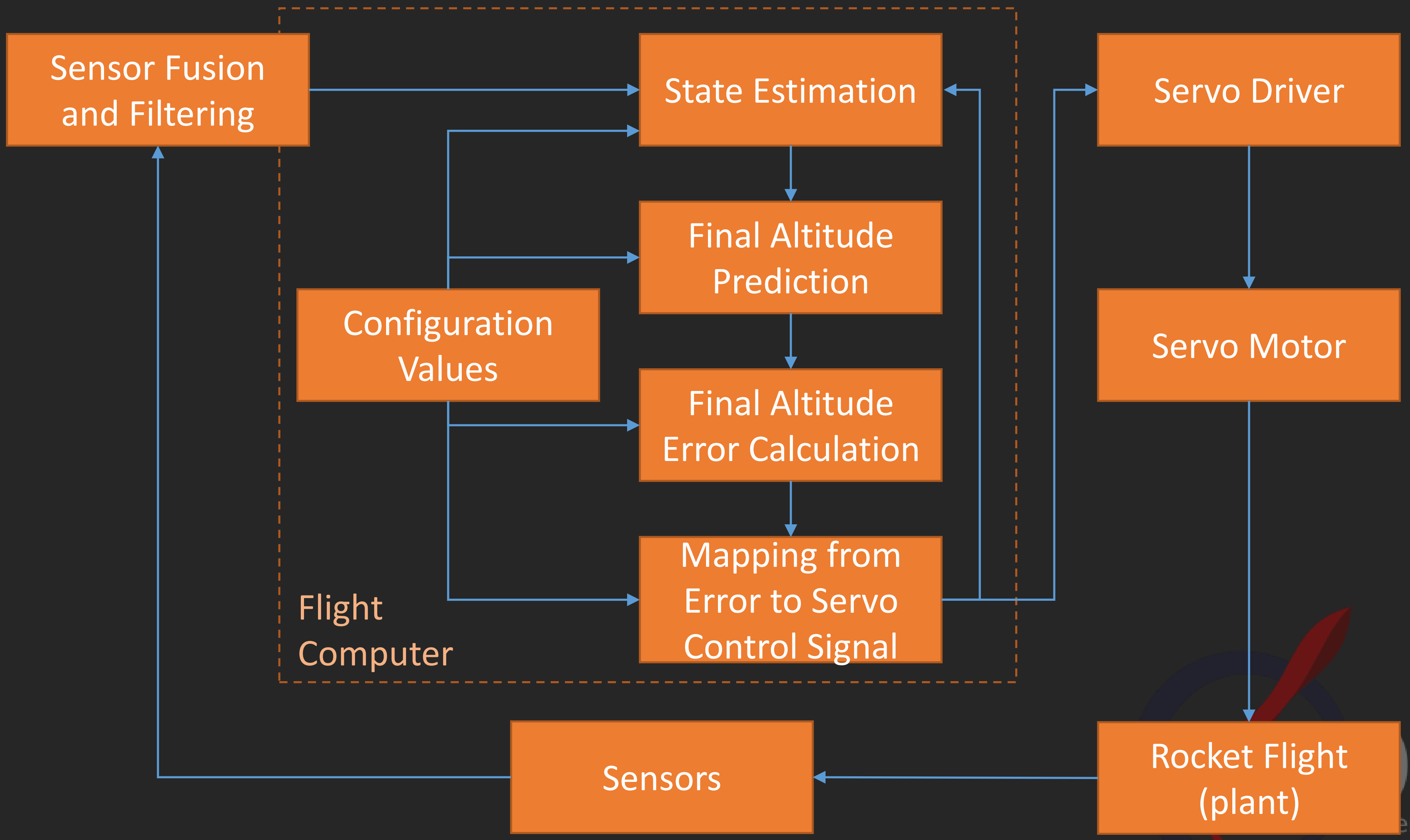
Model Predictive Control (MPC)

- Due to the speed of modern computing, it is possible to create a layer of abstraction and implement control systems based on ‘real time simulations’
- The final altitude can be ‘predicted’ by using the current states of the rocket in flight and the sensor feedback values through the use of simple kinematics equations

What is Required to Implement MPC?

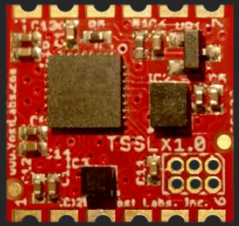
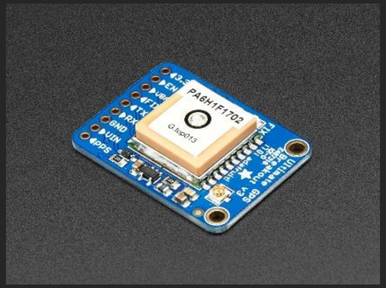
- State Estimation
  - Acceleration in 3 dimensional space
  - Linear velocity in 3 dimensional space
  - Position in 3 dimensional space
  - Orientation in 3 dimensional space
  - Servo angle
- Function to calculate predicted final altitude
- Calculation of error between predicted and desired final altitudes
- A mapping from error -> angle of deployment of servo motor

Complete Diagram of Implemented MPC System



Sensor Fusion

- Sensors on board
  - 9 DOF Inertial Measurement Unit (IMU)
    - 3D acceleration in inertial frame
    - 3D rotational velocity in inertial frame
    - 3D orientation in inertial frame
  - GPS
    - LAT-LONG Coordinates
  - Altimeter
    - Altitude from sea-level

- Usually quite difficult to filter data from IMU – we solved this by letting others solve it for us (ie. The IMU comes with advanced hardware filtering)

- Note: The data from the GPS and altimeter are used to achieve better estimates of states during state estimation

- Outputs: 3D acceleration in Non-inertial frame, GPS data, altimeter data

State Estimation

- Inputs to this block: previous states & sensor feedback values
- Outputs of this block: current states

$$v_x = \int a_x \, dt \qquad v_y = \int a_y \, dt \qquad v_z = \int a_z \, dt$$

$$v_x = a_x \Delta t + v_{x-pre} \qquad v_y = a_y \Delta t + v_{y-pre} \qquad v_z = a_z \Delta t + v_{z-pre}$$

$$p_x = \int v_x dt \qquad p_y = \int v_y dt \qquad p_z = \int v_z dt$$

$$p_x = \frac{1}{2} a_x \Delta t^2 + v_x \Delta t + p_{x-pre} \qquad p_y = \frac{1}{2} a_y \Delta t^2 + v_y \Delta t + p_{y-pre} \qquad p_z = \frac{1}{2} a_z \Delta t^2 + v_z \Delta t + p_{z-pre}$$

Final Altitude Prediction

- Inputs to this block: current state values
- Outputs of this block: predicted final altitude

$$t_{rem} = \frac{v_{z-current}}{a_{z-current}}$$

$$p_{zfinal-predicted} = \frac{1}{2} a_{z-current} t_{rem}^2 + v_{z-current}\, t_{rem} + p_{z-current}$$

Error between Desired and Predicted

- Inputs to this block: predicted final altitude
- Outputs of this block: error between predicted and desired

$$Error_{final\_altitude} = p_{zfinal-predicted} - P_{zfinal-desired}$$

$$Error_{final\_altitude} = p_{zfinal-predicted} - 3048m$$

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Mapping to Servo Control Signal PI

- **Airbrake Drag Model Method**

$$3048m = \frac{1}{2} a_{z-desired} t_{rem}^2 + v_{z-current}\, t_{rem} + p_{z-current}$$

<- Need to find values of t_{rem} and $a_{z-desired}$ that satisfy all other given states while eliminating error.

$$f_{z-total} = -f_{z-drag} - f_{z-gravity}$$

$$a_{z-desired} \times m_{rocket} + 9.81 \frac{N}{Kg} \times \cos(\theta) \times m_{rocket} = f_{z-drag}$$

<- Plug in the value found for $a_{z-desired}$ to find the drag required to achieve desired final altitude.

$$f_{z-drag} = \frac{1}{2} \rho_{air} \times Cd(A) \times A(servo\_angle)$$

<- Plug the required drag into the experimental model and isolate for servo angle

- Requires accurate drag model

Mapping to Servo Control Signal PII

Velocity	Angle of Deploy	Drag Force of Brake	Drag Force of Body
250m/s	40%	82.76 N	415.69 N
250 m/s	60 %	137.39 N	494.68 N
250 m/s	80 %	190.08 N	566.21 N
250 m/s	100%	219.9 N	608 N
200 m/s	40%	51.65 N	152.65 N
200 m/s	60 %	85.97 N	315.06 N
200 m/s	80 %	118.55 N	360.74 N
200 m/s	100%	136.88 N	396.46 N
150 m/s	40%	28.62 N	148.78 N
150 m/s	60 %	47.02 N	175.98 N
150 m/s	80 %	64.886 N	201.47 N
150 m/s	100%	74.79 N	218.49 N
100 m/s	40%	12.37 N	65.65 N
100 m/s	60 %	20.651 N	77.678 N
100 m/s	80 %	28.37 N	89.09 N
100 m/s	100%	32.6 N	96 N
50 m/s	60 %	5.71 N	13.435

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Parting Remarks

- Due to the nature of rocket flight dynamics, a classical control schema is quite difficult to properly implement
  - Model Predictive Control was used instead

- Model Predictive Control can be quite helpful as a method of abstracting the design of controllers

- A custom design for the airbrakes were derived and are implemented on the rocket today