

Valbal Trajectory Planning

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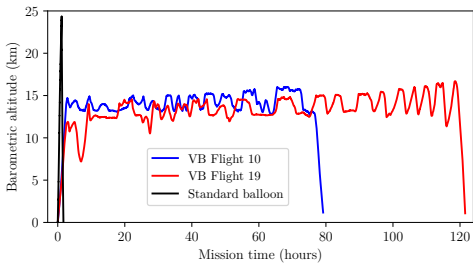
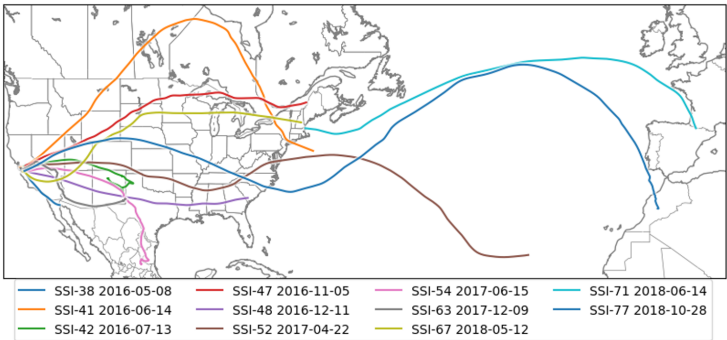
Stanford Student Space Initiative

December 6, 2018

ValBal

- ▶ Research project by the Stanford Space Initiative (undergrad student club).
 - ▶ High altitude latex balloon platform that controls its altitude by venting lifting gas and dropping ballast mass.
 - ▶ Very cheap (sub thousand dollars), long endurance (5 days demonstrated).
 - ▶ Potential applications: hurricane data collection, radar probing of Greenland ice, lightning research, data relay. . .
 - ▶ Control: in altitude (remain between bounds while minimizing control effort), in space (pick altitude to get good winds).
1. A. Sushko, A. Tedjarati, J. Creus-Costa, S. Maldonado, K. Marshland and M. Pavone, "Low cost, high endurance, altitude-controlled latex balloon for near-space research (ValBal)," 2017 IEEE Aerospace Conference, Big Sky, MT, 2017, pp. 1-9.
 2. A. Sushko et al., "Advancements in low-cost, long endurance, altitude controlled latex balloons (ValBal)," 2018 IEEE Aerospace Conference, Big Sky, MT, 2018, pp. 1-10.





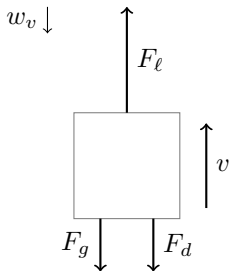
System Dynamics

► Assumptions

- $F_d \propto v$ i.e. drag is linear.
- $F_\ell - F_g = F_d$ i.e. the balloon is always at terminal velocity

► Equations of motion

- let $\ell = F_\ell - F_g$ be the net lift on the balloon
- $\dot{\ell}$ is commanded by controller
- $\dot{v}(t) = k_d(\dot{\ell}(t) + w_\ell(t))$
- $\dot{h}(t) = v(t) + w_v(t)$
- $\mathcal{L}\{h(t)/\dot{\ell}(t)\} = k_d/s^2$



F_d : Force of drag

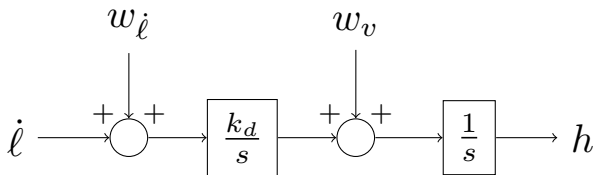
F_g : Gravity

F_ℓ : Buoyant force

v : vertical velocity of balloon

w_v : vertical velocity of surrounding air

Plant Block Diagram



$\dot{\ell}$: commanded change in lift (valve and ballast actions)

$w_{\dot{\ell}}$: atmospheric lift disturbance

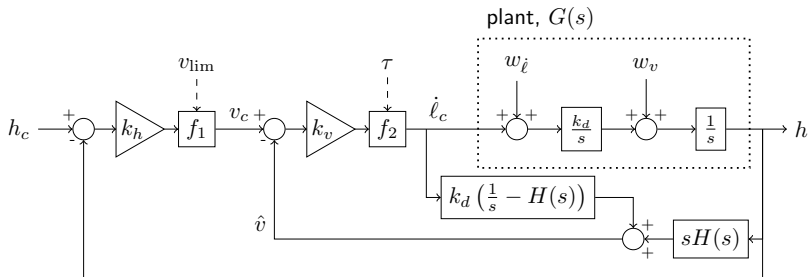
w_v : atmospheric velocity disturbance

h : altitude

$$x = \begin{bmatrix} h \\ v \end{bmatrix} \quad u = \dot{\ell}$$

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ k_d \end{bmatrix} u + \begin{bmatrix} w_v \\ k_d w_{\dot{\ell}} \end{bmatrix}$$

Controller Block Diagram



$H(s)$ low-pass filter

$f_1(v; v_{lim})$ clamp on the velocity commanded by the altitude loop set by v_{lim}

$f_2(\dot{\ell}; \tau)$ deadband on the controller effort set by τ

h_c commanded altitude (set by Flight Controller)

v_c commanded velocity (output of position loop)

$\dot{\ell}_c$ commanded change in lift per unit time (output of velocity loop)

$w_{\dot{\ell}}$ atmospheric disturbances that change balloon lift (heating/cooling)

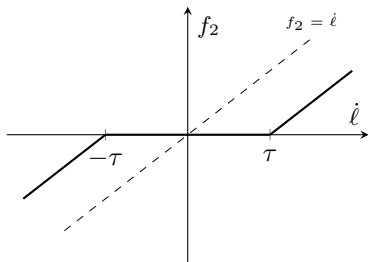
w_v atmospheric disturbances that change balloon velocity (turbulence)

h balloon altitude

\hat{v} estimate of velocity

Controller Deadband

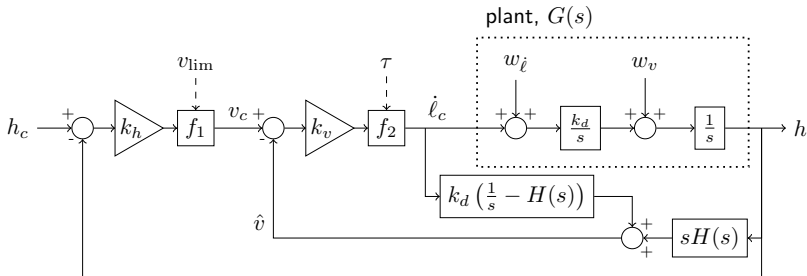
Since we typically command a target altitude and an allowable region, we add a deadband to the controller output. Let $\dot{\ell}_o$ be the output of the nonlinearity. Deadband:



$$f_2(\dot{\ell}; \tau) = \begin{cases} 0 & |\dot{\ell}| < \tau \\ \text{sign}(\dot{\ell})(|\dot{\ell}| - \tau) & |\dot{\ell}| > \tau \end{cases}$$

To set bounds on the altitude, we set $\tau = e_{\text{tol}} k_v k_h$, where e_{tol} is the allowable distance from the altitude command.

Controller Block Diagram



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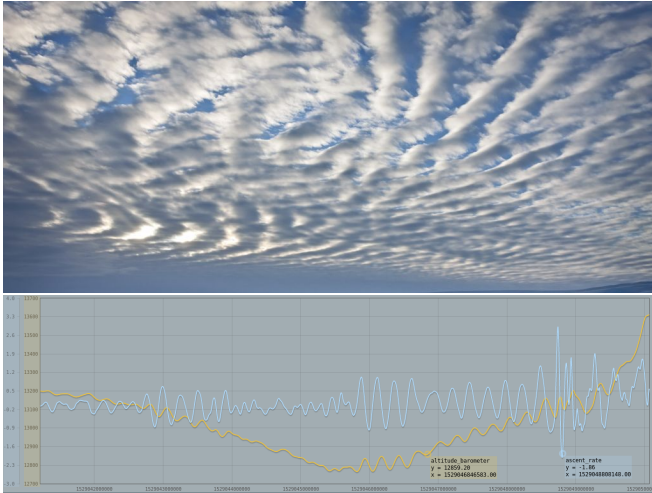
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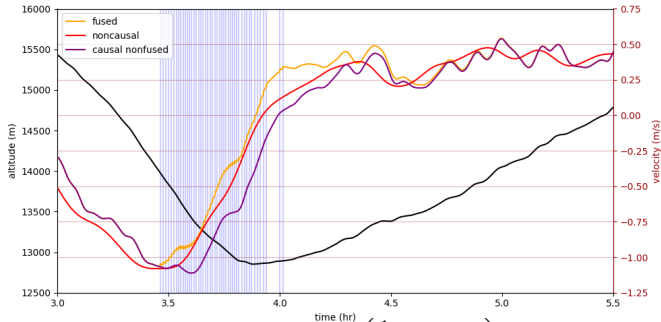
\hat{v} estimate of velocity

Atmosphere Waves



Velocity Estimator

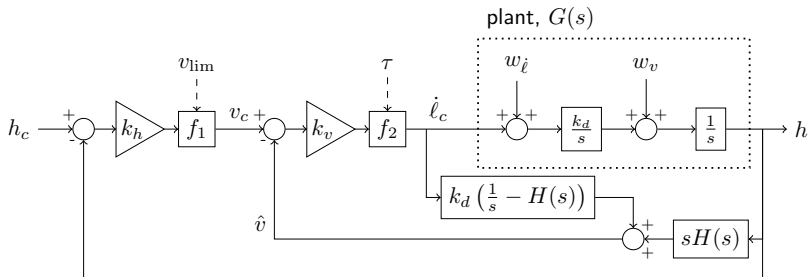
Low pass filtered velocity estimate uses a 2nd order filter to remove the effect of atmospheric waves



$$\mathcal{L}\{\hat{v}\} = sH(s)\mathcal{L}\{h\} + \left(\frac{1}{s} - H(s)\right)\mathcal{L}\{\dot{i}_c\}$$

$H(s)$ a 2nd order lowpass filter

Controller Block Diagram



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\hat{v} estimate of velocity

Picking gains

note: while the deadband makes the controller non-linear, it still peicewise linear, thus linear analysis can be used.

Transfer function for the linear system is

$$T(s) = \frac{k_h k_v k_d}{s^2 + k_v k_d s + k_h k_v k_d}.$$

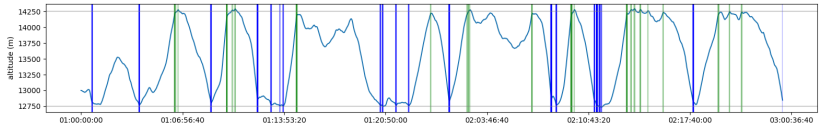
So damping ratio is $\zeta = \frac{1}{2} \sqrt{\frac{k_d k_v}{k_h}}$.

- ▶ We choose gains such that $\zeta > 1$ and we have over damping.
- ▶ This gives ratio between k_v and k_h , but what about magnitiude?
- ▶ high gain \rightarrow controller waits and acts aggressively near e_{tol}
- ▶ low gain \rightarrow controller acts cautiously before e_{tol}

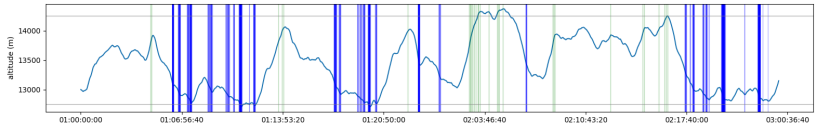
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High vs Low Gain

Plots of simulation shown
high gain

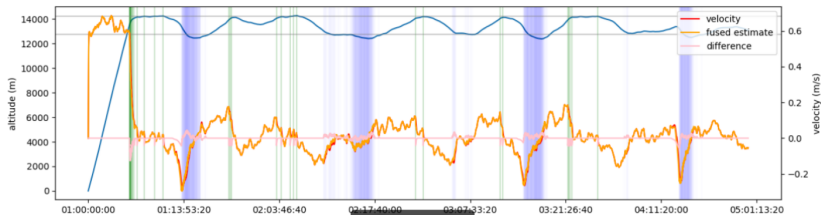


low gain

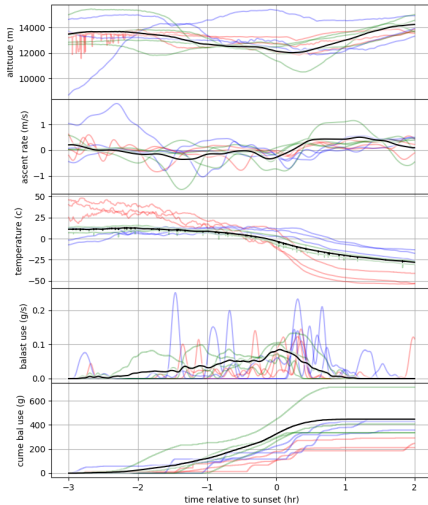


High gain performs better but can't tolerate uncertainty, low gain is worse but performs better under uncertainty

Simulations



Nightfall



- ▶ Left plot shows 10 sunsets across various flights (each flight different color).
- ▶ plot blow shows a fit to the data using convex regularization and constraints

