UAVBook Supplement
Total Energy Control for Longitudinal Autopilot

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One of the disadvantages of the longitudinal autopilot discussed in the book is the number of required loops and the state machine for altitude control shown in page 113. In this note we will describe a simplier scheme based on the energy states of the system. The ideas in this supplement are motivated by [1, 2].

The longitudinal control system is complicated by the fact that both altitude and airspeed need to be regulated, but that these quantities are strongly coupled. If we assume a low level autopilot on the pitch angle, then the primary control signals are the throttle and the commanded pitch angle. Both of these quantities have a significant effect on both altitude and airspeed. Rather than attempt to decouple these effects by operating different loops in different flight regimes, the total energy control method changes the regulated outputs from altitude and airspeed to total energy and energy balance, which produces a natural decoupling in the longitudinal motion.

The kinetic energy of a body in motion is given by $K = \frac{1}{2}m\|\mathbf{v}\|^2$. If we use the velocity of the aircraft relative to the air mass, then $K = \frac{1}{2}mV_a^2$. The reference kinetic energy is given by $K_{\text{ref}} = \frac{1}{2}m(V_a^c)^2$. Therefore, the error in kinetic energy is given by

$$K_{\text{error}} \stackrel{\triangle}{=} K_{\text{ref}} - K = \frac{1}{2}m((V_a^c)^2 - V_a^2).$$

The potential energy of a body with mass m is given by $U = U_0 + mgh$ where U_0 is the potential of ground level when the altitude $h = 0$. The reference potential energy is given by $U_{\text{ref}} = U_0 + mgh^c$. Therefore, the error in potential energy is given by

$$U_{\text{error}} = mg(h^c - h). \tag{1}$$

The total energy (error) is given by

$$E = U_{\text{error}} + K_{\text{error}}.$$

The energy (error) balance is given by

$$B = U_{\text{error}} - K_{\text{error}}.$$

As mentioned previously, the throttle is used to control the total energy using a PI controller:

$$\delta_t(t) = k_{p_E} E(t) + k_{i_E} \int_{-\infty}^{t} E(\tau)\, d\tau.$$

The pitch command is used to regulate the energy balance using a PI controller:

$$\theta^c(t) = k_{p_B} B(t) + k_{i_B} \int_{-\infty}^{t} B(\tau)\, d\tau.$$

As a matter of practical consideration, the TECS scheme works better for large deviations in altitude if the altitude error in (1) is saturated as

$$U_{\text{error}} = mg\ \text{sat}_{\bar{h}_e}(h^c - h),$$

where $\bar{h}_e > 0$ is the largest altitude error used to compute U_{error}, and sat is the saturation function.

References

[1] L. F. Faleiro and A. A. Lambregts, "Analysis and tuning of a total energy control system control law using eigenstructure assignment," *Aerospace Science and Technology*, no. 3, pp. 127–140, 1999.

[2] A. A. Lambregts, "Vertical flight path and speed control autopilot design using total energy principles," in *Proceedings of the AIAA Guidance and Control Conference*, pp. 559–569, http://dx.doi.org/10.2514/6.1983-2239, 1983.