‘Sky Crane’ platform state estimation - final project description (updated - 11/29/17)

ASEN 5044

Fall 2017

1 Introduction

The ‘Sky Crane maneuver’ was used as a deployment method for the Curiosity rover upon its arrival and descent near the surface of Mars, as an alternative to the air bag method used in previous missions. Thrusters were used to stabilize the MSL Descent Stage System (aircraft) to zero horizontal velocity and to slowly guide the system to 20 m above the ground to deploy the rover. A (highly) simplified model of this latter stage’s longitudinal dynamics will be used to perform vehicle state estimation just prior to rover deployment.

2 Physical system

Figure 1 depicts a simplified 2D longitudinal dynamics model of the MSL Descent Stage aircraft. The system will be modeled as a rectangular box with two thrusters , one each on the bottom corners of the aircraft mounted at angle β to the vehicle $z-$axis.

The simplified vehicle states consist of the inertial translation ξ (in m), altitude above surface z (m), pitch angle θ (rad), and rates $\dot{\xi}$ (m/s), $\dot{z}$ (m/s), and $\dot{\theta}$ (rad/s). The control inputs are $\mathbf{u} = [T_1, T_2]$, where T_i is the thrust produced by the ith thruster (in N). Sensors for state estimation will consist of a simplified ideal single-axis IMU, i.e. an accelerometer and rate gyro pair which provide noisy measurements of inertial ξ accelerations and pitch rotations about the inertial $\eta-$axis (going into the page). The sensor data also include onboard barometer readings to gauge altitude. Image-based tracking measurements from an overhead passing satellite are also converted into noisy ξ platform position reports.

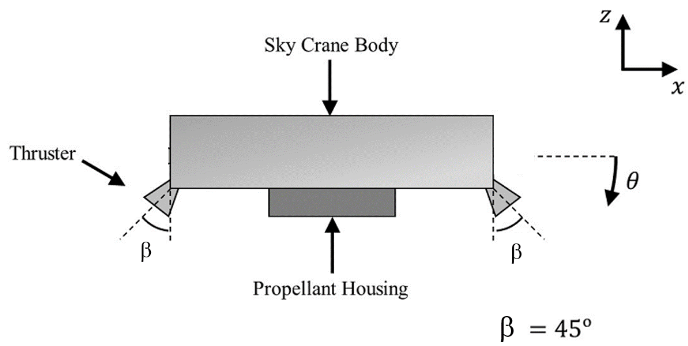

Figure 1: Sky Crane aircraft schematic.

3 Dynamical system model

The equations of motion are derived here by considering only gravity, thrust, and drag forces (the vehicle is assumed not to generate significant lift in this phase). Drag will be modeled as $F_{drag} = \frac{1}{2}C_D \rho A v^2$, where C_D is the drag coefficient, ρ is the atmosphere density, v is the magnitude of the velocity, and A is the approximate cross-sectional area of the vehicle in the direction of motion. Let m_b is the mass of the Sky Crane aircraft and payload, m_f is the mass of the fuel, w_b and h_b are the width and height dimensions of the Sky Crane body as shown in Fig. 1 (assuming the full payload is completely housed inside the body), w_f and h_f are the dimensions of the propellant housing, and h_{cm} and w_{cm} are the dimensions for the vehicle center of mass. To simplify analysis, assume changes in m_f can be ignored here. The non-linear equations of motion are then

$$
\begin{aligned}
\ddot{\xi} &= \frac{[T_1(\cos\beta\sin\theta + \sin\beta\cos\theta) + T_2(\cos\beta\sin\theta - \sin\beta\cos\theta) - F_{D,\xi}]}{m_b + m_f} + \tilde{w}_1, \\
\ddot{z} &= \frac{[T_1(\cos\beta\cos\theta - \sin\beta\sin\theta) + T_2(\cos\beta\cos\theta + \sin\beta\sin\theta) - F_{D,z}]}{m_b + m_f} - g + \tilde{w}_2, \\
\ddot{\theta} &= \frac{1}{I_\eta}\left[(T_1 - T_2)\cos\beta \cdot \frac{w_b}{2} + (T_2 - T_1)\sin\beta \cdot h_{cm}\right] + \tilde{w}_3, \\
I_\eta &= \frac{1}{12}\left[m_b(w_b^2 + h_b^2) + m_f(w_f^2 + h_f^2)\right], \\
F_{D,\xi} &= \frac{1}{2}C_D\rho[A_{side}\cos(\theta - \alpha) + A_{bot}\sin(\theta - \alpha)] \cdot \dot{\xi}\sqrt{\dot{\xi}^2 + \dot{z}^2}, \\
F_{D,z} &= \frac{1}{2}C_D\rho[A_{side}\cos(\theta - \alpha) + A_{bot}\sin(\theta - \alpha)] \cdot \dot{z}\sqrt{\dot{\xi}^2 + \dot{z}^2}, \\
\alpha &= \tan^{-1}\left(\frac{\dot{z}}{\dot{\xi}}\right),
\end{aligned}
$$

where I_η is the moment of inertia about the η-axis, β is the fixed thruster angle, A_{bot} is the bottom/top area, A_{side} is the side area, and each $\tilde{w}_i$ is process noise.

The combined system state, control inputs, and disturbance inputs are thus

$$\mathbf{x}(t) = \begin{bmatrix} \xi & \dot{\xi} & z & \dot{z} & \theta & \dot{\theta} \end{bmatrix}^T,$$
$$\mathbf{u}(t) = \begin{bmatrix} T_1 & T_2 \end{bmatrix}^T,$$
$$\tilde{\mathbf{w}}(t) = \begin{bmatrix} \tilde{w}_1 & \tilde{w}_2 & \tilde{w}_3 \end{bmatrix}^T$$

The sensing model for this system is

$$\mathbf{y}(t) = \begin{bmatrix} \xi \\ z \\ \dot{\theta} \\ \ddot{\xi} \end{bmatrix} + \tilde{\mathbf{v}}(t),$$

where $\tilde{\mathbf{v}}(t) \in \mathbb{R}^4$ is the sensor error vector (which can be modeled by AWGN).

4 Nominal system parameters

The nominal system state/equilibrium is at zero vertical velocity and horizontal velocity, with zero pitch angle and pitch rate for nominal thrust values (at fixed hover at $z_0 = 20$ m altitude above the ground, holding a constant horizontal position). Assume the following parameter values:

- $\rho = 0.020 \frac{kg}{m^3}$ and $g = 3.711 \frac{m}{s^2}$ (Mars surface atmosphere density and gravity),
- $\beta = \frac{\pi}{4}$ rad (as shown in figure),
- $C_D = 0.2$,
- $m_f = 390$ kg, $w_f = 1$ m, $h_f = 0.5$ m, $d_f = 1$ m (propellant housing depth into page)
- m_b=1510 kg, $w_b = 3.2$ m, $h_b = 2.5$ m, $d_b = 2.9$ m (vehicle body depth into page)
- $h_{cm} = 0.9421$ m, $w_{cm} = \frac{w_b}{2}$
- $A_{side} = (h_b \cdot d_b) + (h_f \cdot d_f)$,
- $A_{bot} = (w_b \cdot d_b) + (w_f \cdot d_f)$.
- $T_{1,nom} = T_{2,nom} = 0.5 \cdot g \cdot \left(\frac{m_b + m_f}{\cos \beta}\right)$ (nominal thrusts for static hover)