פיתוח אלגוריתמים לטיסות מקבץ של לוויינים תחת שגיאות דחף

Development of Satellite Cluster Flight Algorithms Under Thrusting Errors

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Background

Satellite cluster flight has been examined recently in many aspects. One of the most widely considered topics is cluster keeping, which is the control of the relative positions among the satellites in the cluster. In general, satellite cluster flight is intended to keep the satellites in a specific range of distances [1]. In order to maintain relative distances within given bounds, maneuvers are required.

One of the ongoing projects implementing cluster keeping algorithms is SAMSON [2]. In SAMSON, three autonomous nano-satellites form a cluster and perform autonomous cluster keeping maneuvers using warm-gas thrusters.

Satellite clusters are intended to replace large and expensive satellites using a few smaller vehicles. Therefore, minimizing the mass is very important. Unnecessary fuel consumption should be avoided by optimizing the maneuver in order to decrease the satellite's mass.

The thrust used during a maneuver is often not as precise as could be expected. Errors can occur in the desired magnitude of the thrust as well as in its direction, as shown by [3]. These errors are usually caused by the uncertainty of operating conditions in space. Furthermore, during the launch the thruster can undergo unexpected variations.

Researchers have been attempting to find ways to model the thrusting errors. For example, Ref. [3] used a random range of thrust values and others [4] used Monte-Carlo analysis in order to model the thrust errors.

Moreover, ways to overcome the thrust errors during the maneuver had been examined. Ref. [5] divided the trajectory into equal time intervals. In every time interval the change of mass was minimized and thus the total change of mass was decreased. Ref. [6] used sliding mode control in order to overcome thrust errors. In addition, different algorithms to optimize the maneuvers in a cluster flight had been found [7].

Research Objectives

The main purpose of this research is to extend the orbit control methods under thrust error uncertainty discussed above to cluster flight and minimize the effect of thrusting errors on the evolution of relative distances and on the consumption of fuel.

In particular, this research will deal with the effect of thrust errors on a satellite cluster flight mission. Due to thrust pointing and magnitude errors, the satellites do not actually follow the desired maneuver. The main purpose is to develop algorithms that will minimize the fuel consumption during the maneuver as well as minimize the time of the maneuver in spite of thrusting errors. Specifically, a control law robust to thrust errors in magnitude and direction will be developed. This control law may be implemented in the SAMSON project in order to verify its validity.

To achieve the research goals, a model that will predict the thrust errors will be developed. Then, an investigation of different ways of mitigating the thrust uncertainty effect will discover the optimal way of dealing with those errors.

Technical Description

The following control law is implemented in the SAMSON project so as to minimize fuel consumption:

$$\mathbf{u}_k = -\frac{\mathbf{G}\left(\mathbf{x}_k, t\right)^T \mathbf{P}_k \left(\mathbf{x}_k - \mathbf{x}_j\right)}{\left\|\mathbf{G}\left(\mathbf{x}_k, t\right)^T \mathbf{P}_k \left(\mathbf{x}_k - \mathbf{x}_j\right)\right\|} T_{max} \tag{1}$$

where k is the index of the satellite in the cluster, $\mathbf{x}_k = \left[\bar{a}, \bar{e}, \bar{I}\right]$ is the state vector of satellite k ($\bar{a}$ is the mean semi-major axis, $\bar{e}$ is the mean eccentricity and $\bar{I}$ is the mean inclination), $\mathbf{x}_j = \left[\bar{a}_{ref}, \bar{e}_{ref}, \bar{I}_{ref}\right]$ is the target state, $\mathbf{G}\left(\mathbf{x}_k, t\right)$ is the Gauss Variational Equations (GVE) matrix, $\mathbf{P}_k$ is the gains matrix and T_{max} the maximal thrust of the propulsion system.

As can be seen in [1] the thrust model is

$$\mathbf{T_k} = T_k \begin{bmatrix} \cos\left(\alpha_k\right)\cos\left(\delta_k\right) \\ \sin\left(\alpha_k\right)\cos\left(\delta_k\right) \\ \sin\left(\delta_k\right) \end{bmatrix} \tag{2}$$

where T_k is the thrust magnitude and α_k and δ_k are the azimuth and elevation angles of the thrust vector in the satellite body fixed frame with respect to a reference frame.

The main interest is a mean $\{a, I\}$ control. The GVE for these elements are:

$$\dot{\bar{a}}_k \simeq \dot{a}_k = \frac{2a_k^2 v_k}{m_k \mu} T_k \cos(\alpha_k) \cos(\delta_k) \tag{3}$$

$$\dot{\bar{I}}_k \simeq \dot{I}_k = \frac{r_k}{m_k h_k} \cos(f_k + \omega_k) T_k \sin(\delta_k) \tag{4}$$

where $v_k = \|\mathbf{v}_k\|$ is the velocity, $r_k = \|\mathbf{r}_k\|$ is the radius of the orbit, m_k is the mass, f_k is the true anomaly, ω_k is the argument of periapsis, $h_k = \|\mathbf{h}_k\|$ is the angular momentum and μ is the gravitational parameter.

To start, the errors will be modeled as random constants. The thrust model, including the errors, becomes

$$(\mathbf{T_k})_{err} = (T_k + \Delta T_k) \begin{bmatrix} \cos(\alpha_k + \Delta\alpha_k)\cos(\delta_k + \Delta\delta_k) \\ \sin(\alpha_k + \Delta\alpha_k)\cos(\delta_k + \Delta\delta_k) \\ \sin(\delta_k + \Delta\delta_k) \end{bmatrix} \tag{5}$$

where ΔT_k , $\Delta\alpha_k$ and $\Delta\delta_k$ are the errors in the thrust magnitude, the azimuth angle and elevation angle, respectively. These errors will be chosen randomly from a given range of values, so that

$$\begin{cases} \Delta T_k \in \left[\begin{array}{ccc} -T_{err} & , & T_{err} \end{array} \right] \\ \Delta\alpha_k \in \left[\begin{array}{ccc} -\alpha_{err} & , & \alpha_{err} \end{array} \right] \\ \Delta\delta_k \in \left[\begin{array}{ccc} -\delta_{err} & , & \delta_{err} \end{array} \right] \end{cases} \tag{6}$$

These errors induce parasitic fuel consumption, Δm, and longer maneuver times, Δt .

One of the solutions to handle thrust errors is to divide the maneuver into intervals and to solve the control law for each of the intervals. This way in each interval i, the fuel consumption, Δm_i, will be estimated and corrected during subsequent maneuvers.

Another possible solution can be a sliding mode control scheme. The sliding variable can be chosen as

$$\mathbf{s} = \ddot{\mathbf{e}} + c_1\dot{\mathbf{e}} + c_2\mathbf{e} \tag{7}$$

$$\mathbf{e} = \mathbf{X}_d - \mathbf{X} \tag{8}$$

where $\mathbf{X}_d$ is the expected relative position and $\mathbf{X}$ is the real relative position. On the sliding mode, the following condition must be fulfilled:

$$\dot{\mathbf{s}} = 0 \tag{9}$$

Using this control scheme [6], the overall fuel consumption during the maneuver and the maneuver total time can be potentially reduced.

These solutions will be examined and the results of the best solution will be chosen. The solutions will be verified using numerical simulations.

References

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