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Formation Control of Spacecraft under orbital perturbation

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Abstract: The novel concept of multiple spacecraft formation flying as a substitute for a single large vehicle will enhance future space mission performance. The benefits of a spacecraft formation include more cost effective synthetic aperture radar for observations, flexibility of the satellites altering their roles, reduction of cost owing to the reduction of mass launched into orbit etc. A significant challenge in the domain of control design is to contrive a formation maintenance controller that will enable the member spacecrafts to maintain a desired relative orbit with optimal propellant expenditure while maintaining the desired formation. This paper examines a low earth orbit formation control methodology, with the aim of evaluating formation from a propellant budget, thrust level and error dynamics standpoint. A State feedback controller has been applied on J_2 perturbed Clohessy-Wiltshire dynamics, and the system is checked for its stability and performance.

Keywords: Formation flying, State feedback control, Optimal control, J_2 Perturbation.

1. INTRODUCTION

The major reason for formation of satellites is the desire to distribute the functionality of large satellites. The ability of small satellites to fly in precise formation will make a wide array of new applications possible, including next-generation internet, space-based radar and ultra powerful space telescopes. There is also an economic aspect to this; often it is more expensive to place one big satellite with all the functions built-in into orbit than several smaller ones of the same collective weights. Therefore, as the number of missions that use spacecraft flying in formation, proposed or under development, increases, one can imagine assembly lines of standardized spacecraft, thus drastically lowering the cost of building them. These standardized spacecraft will be fully equipped with proper instruments for their mission.

The concept of multiple satellite formation flying is drastically transforming Earth and Space science. This technological revolution heralds novel technique in spacecraft guidance, navigation, and control, and the manner information is shared between space borne vehicles and ground. The formation constituted by NASA's Earth Observing-1 and Landsat-7 carry instruments to create high-resolution images for the study of climatic trends in the Earth's environment.

The literature on the subject is divided into five architectures:

- Multiple-input, multi-output:- The research on FFC is not restricted to spacecraft formations only. Extensive literature exists on achieving formation in a group of robots and UAV's and similar autonomous vehicles. A recent paper (Zhang-2008) presents the Lyapunov type controller based on feedback linearization approach.
- Leader-Follower:- The leader/follower(L/F) architecture is the most studied formation flying control(FFC) architecture, also termed as chief/deputy or master/slave. Extensive literature exits on this subject. The best part of these approaches is that sufficient conditions for stability are available for general L/F formation, and these stability conditions are broadly classified as mesh stability.
- Virtual structure:- In the virtual structure architecture, the spacecraft behave as points embedded in a virtual rigid body. Spacecraft states are coupled through the template fitting step(Lamy-1993) considers Earth-orbiting formations.
- Behavioral:- In behavioral architecture the output of multiple controllers designed for achieving different and competing behavior is combined. Anderson et. al(1998) provides an excellent example of a Behavioral FFC algorithm. They consider velocity-commanded aircraft with collision avoidance, obstacle avoidance, move to goal and formation maintenance behaviors.
- Cyclic:- In a cyclic FFC algorithm, the spacecraft are connected in a cyclic or ring structure. The spacecraft share information with their neighbors in the cyclic topology and generate the control law based on the local information.

Existing literature is quite rich with respect to formation flying, though the inclusion of orbital perturbation is still not completely explored. The paper aims at examining low earth orbit formation control under orbital perturbations. A State feedback controller has been applied on J_2 per-

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turbed Clohessy-Wiltshire dynamics. Major contribution from current work is :

- Formulation and implementation of control algorithm that achieves precise formation maintenance, since the formation must be maintained in the face of external disturbances, robustness of the controllers is an essential feature.
- Evaluation of the performance of this control law with respect to its fuel consumption , thrust required and transient behaviour.

The flow of paper is as follows, next session briefly introduces the translational dynamics of spacecraft. Section further introduces the J2 perturbation as the unmodeled force and discusses the ways to incorporate it in the translational dynamics.
Section 3 and 4 explain the control law and proves the system's stability under J2 perturbation. Simulation based verification of the control law is presented in section 5 followed by conclusion in section 6.

2. BACKGROUND

2.1 Kepler's law and Energy and Momentum associated with Spacecraft

Kepler's laws of motion describe satellite's motion with respect to the earth(general two body motion)Vadali(2009),

$$\ddot{\boldsymbol{r}} + \frac{\mu.\boldsymbol{r}}{r^3} = \mathbf{0} \tag{1}$$

where, $r = [X, Y, Z]^T$ is the position vector of the spacecraft in the ECI frame and μ is the gravitational constant of earth.

2.2 The translational dynamics of spacecraft

The trajectory of the satellite cannot be chosen arbitrarily, but is constrained by the laws of physics. One of the big challenges is to find appropriate paths for all the satellites in a formation, so that the desired functionalities are achieved, both with a view to fuel efficiency and to fulfil the predefined mission. As discussed in section 2.1 , Kepler's laws govern the motion of any spacecraft in inertial frame. Consider two spacecraft, where one is the leader and the other is the follower. The most common linear passive relative orbits of the followers with respect to leaders are the solutions to the Hill-Clohessy-Wiltshire Equations. These equations were introduced in Clohessy(1960). Though it's worth noticing HCW equations do not consider the eccentricity of the orbit, and the same has not been considered for the work carried out in this paper. Let the subscripts $i = l, f$ denote the leader and the follower satellite respectively. The position vector from the leader to the follower satellite can be expressed as

$$\begin{aligned} \boldsymbol{\rho} &= \boldsymbol{r}_f - \boldsymbol{r}_l \qquad (2) \\ &= x\boldsymbol{e}_r + y\boldsymbol{e}_\theta + z\boldsymbol{e}_z \end{aligned}$$

where x, y and z are the components of $\boldsymbol{\rho}$ in the Hill frame. Using Kepler's law and following the derivation as in Clohessy(1960) under linearized approximation, the equations will be given by:

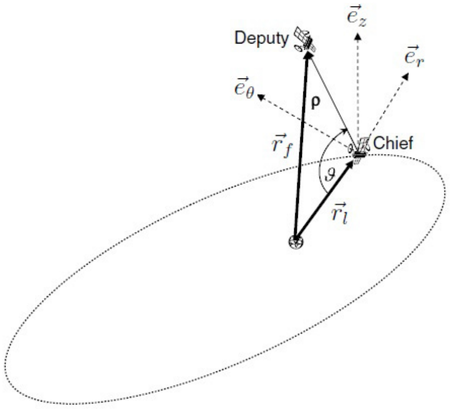

Fig. 1. Rotating Euler-Hill frame, centered at the leader spacecraft. This figure also shows the follower spacecraft, whose position vectors in the rotating and inertial reference frames are denoted by ρ and r_f, respectively (Vadali 2009).

$$\ddot{x} - 2n\dot{y} - 3n^2x = u_x \tag{3}$$

$$\ddot{y} + 2n\dot{x} = u_y \tag{4}$$

$$\ddot{z} + n^2z = u_z \tag{5}$$

where, (x, y, z) are the coordinates of spacecraft in Hill's frame or LVLH frame and (u_x, u_y, u_z) is the control input and n is $\dot{f}$, where f is the true anomaly of the leader satellites orbit.

2.3 Perturbation due to non-spherical Earth

HCW equation(3-5) is the linear version of original dynamics and does not account for the oblateness of the earth surface. This oblateness leads to important consequences in practical spacecraft orbit design.The most pronounced effect on Low Earth orbits is caused by the second harmonic of the Earth potential, which reflects the oblateness of Earth Samuel(2002).

Incorporating J2 Perturbation in HCW Equations In Samuel(2002), the authors show that the equations of motion relative to circular non-Keplerian reference orbit and including the J_2 term are well approximated by the linear system:-

$$\begin{aligned} \ddot{x}_i &= 2nc\dot{y}_i + (5c^2 - 2)n^2x_i + \frac{3}{4}K_{J_2}Cos(2\bar{k}t) \\ \ddot{y}_i &= -2nc\dot{x}_i + \frac{1}{2}K_{J_2}Sin(2\bar{k}t) \\ \ddot{z}_i &= -q^2z_i + 2lqCos(qt + \phi) \qquad (6) \end{aligned}$$

where, i_{ref} and r_{ref} are parameters of the reference orbit, R_e is the nominal radius of the earth, $s = \frac{3J_2R_e^2}{8r_{ref}^2}(1 + 3\cos(2i_{ref}))$, $c = \sqrt{1+s}$, $K_{J_2} = \frac{3n^2J_2R_e^2}{r_{ref}}\sin^2(i_{ref})$, $\bar{k} = c + \frac{3J_2R_e^2}{2r_{ref}^2}\cos^2 i_{ref}$, q is approximately equal to cn, and ϕ, l are time varying functions of the difference in orbit inclination (see Samuel(2002) and Yeh(2002) for the details).