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# Spacecraft formation flying: A review and new results on state feedback control

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**Abstract**

This paper presents a review of previous work within the field of spacecraft formation flying, including modeling approaches and controller design. In addition, five new approaches for tracking control of relative translational motion between two spacecraft in a leader–follower formation are derived. One PD controller with feedback linearisation is derived and shown to result in an exponentially stable equilibrium point of the closed loop system. Four nonlinear controllers are derived and proved by using Lyapunov theory and Matrosov's theorem to leave the closed loop system uniformly globally asymptotically stable. Results from the simulation of the system with the derived controllers are presented, and compared with respect to power consumption and tracking performance.


*Keywords:* Spacecraft formation flying; State feedback; Uniform stability

## 1. Introduction

### 1.1. Background

Spacecraft flying in formation are revolutionising our way of performing space-based operations, and this new paradigm brings on several advantages in space mission accomplishment, and new opportunities and applications for such missions. Spacecraft formation flying is a technology that includes two or more spacecraft in a tightly controlled spatial configuration, whose operations are closely synchronised. The distributed spacecraft structure appears as a single sensing system for the user, whose physical size largely exceeds the barriers imposed by a single body. The concept makes the way for new and better applications in space industry such as monitoring of the Earth and its surrounding atmosphere, geodesy, deep space imaging and exploration, and in-orbit servicing and maintenance of spacecraft. The replacement of traditional large and complex spacecraft with an array of simpler micro-satellites introduces a multitude of advantages regarding mission cost and performance. The major advantage of formation flying of spacecraft lies in flexibility and modularity. The development of formation flying technologies for spacecraft applications will enable the use of a modular spacecraft structure where multiple distributed spacecraft could be coordinated to act as one. The life span of the mission can be prolonged with the possibility of adding new units to replenish or augment the formation. The initial instrument baseline can evolve by implementing new measurement concepts at a later time, without requiring

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a complete replacement of all the spacecraft in the formation. This also entails system redundancy at a large scale, and not only in subsystems.

### 1.2. The control problem

The advantages of using spacecraft formations come at a cost of increased complexity and technological challenges. Formation flying introduces a control problem with strict and time-varying boundaries on spacecraft reference trajectories, and collisions between spacecraft should of course be avoided at all costs. The rise of spacecraft formation flying as a new technology has resulted in new areas of research, and the concept requires detailed knowledge and tight control of relative distances, velocities and orientations for participating spacecraft. A challenge for tight spacecraft formation flying lies in the coordination of the spacecraft motions relative to each other, to avoid inter-satellite interference and collisions and achieve mission goals, whilst minimising the required control efforts. In addition, tight spacecraft formations will be sensitive to perturbations due to external disturbances caused by atmospheric and solar drag, and variations in the gravity field of the Earth, and a solution to the control problem must be able to suppress such perturbations.

### 1.3. Previous work

#### 1.3.1. Modeling

The possibility to provide optimal and robust control to participating spacecraft is highly dependent on detailed mathematical models of the formation including the perturbations mentioned above. The simplest model of relative motion between two spacecraft is linear and multi-variable, known as Hill equations [1] or Clohessy–Wiltshire equations [2]. This model originated from the equations from the two-body problem, based on the laws of Newton and Kepler, and has inherent assumptions that the orbit is circular with no orbital perturbations, and that the distance between spacecraft is small relative to the distance from the formation to the centre of the Earth. An extension to elliptic Keplerian orbits, yet still assuming no orbital perturbations, is what is known as the Lawden equations [3] or Tschauner–Hempel equations [4]. Both models were originally presented for solutions of the problem of orbital rendezvous, but has been adopted later for the very similar and more general spacecraft formation flying control problem. As the visions for tighter spacecraft formations in highly elliptic orbits appeared, the need for more detailed models arose, especially regarding orbital perturbations. This resulted in nonlinear models as presented in, e.g. McInnes, and Wang and Hadaegh [5,6], and later in Manikonda et al. and Yan et al. [7,8], derived for arbitrary orbital eccentricity and with added terms for orbital perturbations.

Other mentionable approaches for modeling spacecraft formations are orbit element differences [9–11] and Theona theory [12,13]. The first stems from Lagrange and Gauss equations, and is based on the thought that each spacecraft in the formation will have a desired orbit described by a specific set of orbit parameters. The orbital perturbations will then cause the orbital parameters for each spacecraft to drift away from the desired parameters, and this is known as orbit element differences. The strength of this method in a control perspective is that the spacecraft are controlled relative to their natural orbits, instead of keeping the formation fixed as in the Newtonian approach. However, control of orbit element differences requires orbit determination and global positioning, which can often be computationally demanding, and the accuracy needed for close formation flying is hard to achieve. In Newtonian models, control is only dependent of relative positions and velocities in the formation, which can be acquired with high accuracy by means of optical or radar-based inter-satellite links (ILS).

The numeric-analytic Theona satellite theory is a computationally efficient orbit propagation method used with success for optimal manoeuver and station keeping of spacecraft formations. Similar to orbit element differences, this approach is based on orbital parameters, but Theona theory is a mathematical extension that can include more corrections in satellite motion.

#### 1.3.2. Controller design

Several approaches have been suggested as a solution to the formation control problem in previous reported research. Linear feedback control was the topic in Yan et al. [14], where pulse-based controllers were presented, based on a discrete model of the Clohessy–Wiltshire equations. By using constant gain in the control design, the author showed that the closed loop system was stable, and asymptotically stable with periodic gain. The control design framework was also extended to the case of trajectory tracking. Solutions to the formation control problem via $H_2/H_\infty$ control was found by Naasz et al. [15], again based on the Clohessy–Wiltshire equations. In the same paper, a nonlinear controller based on Lyapunov theory was derived and claimed to provide global asymptotical stability in the absence of orbital perturbations. This was also the case, but the proof