# NETWORK CONTROLLED TRACKING OF SPACECRAFT FORMATION FLYING WITH COMMUNICATION DELAYS

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***Abstract***— In the networked control systems (NCSs), the formation tracking problem of multiple spacecraft is considered. This paper presents a digital control technique for spacecraft formation keeping in the presence of variable network-induced communication delays and external disturbances. A digital controller is developed to guarantee the exponentially uniformly ultimate boundedness (UUB) of the tracking errors and to ensure desired formation objectives. The proposed digital controller is successful in achieving desired circular formation flying of spacecraft.

***Index terms:*** **Networked Control Systems, Network-based Tracking Control System, Spacecraft Formation Flying, Multiple Spacecraft Formation, Uniformly Ultimate Boundedness , Variable Communication Delay.**

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## I . INTRODUCTION

Spacecraft formation flying (SFF) is an enabling technology that includes two or more spacecraft in a tightly controlled spatial configuration whose operations are closely synchronized. Today, formation flying is a critical technology for planned and future missions of NASA, the Department of Defense and other national space agencies. Significant interest in formation flying started to develop in the late 1990s. The tracking control problem of relative position is a significant research topic in current LF literature. Formation flying of multiple spacecraft is an enabling technology for many future space science missions including enhanced stellar optical interferometers and virtual platforms for Earth observations beyond those of a single spacecraft. Controlling a formation will require several considerations beyond those of a single spacecraft. Formation flying is the coordinated motion control of a group of vehicles where the vehicle positions relative to each other are very important. These vehicles may be groups of trucks, aircraft, or spacecraft. The results are for prototype spacecraft, but all of these vehicle formation applications share common sensing and control research issues. Formation flying technologies for spacecraft will enable the use of a `virtual spacecraft bus' where multiple distributed spacecraft could be coordinated to act as one. This will enable new scientific missions involving coordinated but distributed measurements, leading to improved stellar interferometry, gravimetry, and synthetic aperture radars. Spacecraft formation control will require a measure of the formation states, i.e., the relative attitude and positions of the vehicles; The most prominent centralized control scheme is the leader-follower coordination scheme. In a leader-follower scheme, the spacecraft in the formation are divided into leaders and followers. The leaders in the formation are tasked with tracking a given reference condition, while each of the followers track one of the leaders in the formation.

## II. LITERATURE SURVEY

Control approaches have been developed based on the liberalized relative position dynamics known as Hill's equations or Clohessy -Wiltshire equations and nonlinear dynamics.Linear quadratic (LQ) control was adapted for formation-keeping control. The application of fuzzy technique was considered by Meng, et al, where a low-thrust fuzzy controller was presented on the basis of Hill's equations. In Mitchell and Richardson applied an invariant manifold method for controlling first-order nonlinear Hill's equations. Model predictive control of formation position and attitude, in conjunction with feedback linearization, where the control method was limited by singularities and coordinate frame switching was utilized. The tracking control has also been examined based on sliding mode approach to provide asymptotically stable nonlinear tracking. Nonlinear adaptive tracking control was developed to ensure asymptotic tracking errors. Using the adaptive output feedback controller, Wong, et al. in proved the asymptotic convergence of relative translation errors for multiple SFF. Spacecraft formation control can be divided into four control architectures: multiple-input multiple-output (MIMO), leader-follower (LF), virtual structure (VS), and behavioral. The LF control architecture is the most studied SFF architecture and is applied to NASA's Earth Orbiter-I and the New Millennium Interferometer programs, U.S. Air Force's TechSat-21 program, etc.

### *A. Spacecraft Formation Flying (SFF)*

Spacecraft Formation Flying (SFF) is an end-to-end system including two or more space vehicles and a cooperating infrastructure for science measurement, data acquisition, processing, analysis and distribution .It deals with the tracking or maintenance of a desired relative separation, orientation or position between or among spacecraft. An-Min Zou et al. [1] considers the attitude coordination control problem for spacecraft formation flying when only a subset of the group members has access to the common reference attitude. Kristianian et al. [2] presents a review of previous work within the field of spacecraft formation flying including modeling approaches and controller design. Al W.Beard et al. [3] addresses the problem of coordinating multiple spacecraft to fly in tightly controlled formations. Kourosh Rahnamai et al. [4] investigate the advantages of using an intelligent fuzzy supervisory unit to modify the optimal regulator developed to maintain the relative position between spacecraft.

### *B. Networked Control Systems:*

A Networked Control System (NCS) is a control system where in the control loops are closed through a real-time network. The defining feature of an NCS is that control and feedback signals are exchanged among the system's components in the form of information packages through a network.In the broadest terms, these systems are comprised of actuators, sensors, and controllers whose operation is coordinated through some form of communication network.

## III. PROPOSED DESIGN

This paper focuses on developing a digital control technique for spacecraft formation keeping in the presence of variable network-induced communication delays and external disturbances. A reference trajectory is generated by the force-free Hill's equations. When a control loop is closed via a communication channel, the interconnection is referred to as an NCS. In this paper, a sampled-data representation of the NCS is considered for the tracking control of relative translational motion between two spacecraft in an LF formation. By adding a buffer which is longer than the worst case delay and augmenting the system model to include past values of system input as additional states, a new discrete time-invariant model is formulated, and a digital controller is developed to guarantee the exponentially uniformly ultimate boundedness (UUB) of the tracking errors and to ensure desired formation objectives with limited control authority.Numerical simulations are presented to demonstrate the effectiveness of the proposed controller.It provides an analytic result of UUB for spacecraft formation keeping while integrating the exact nonlinear equations of motion and taking into account the effect of communication delays and external disturbances.

### *A. Relative Dynamics*

We present the nonlinear equations of the relative motion between spacecraft in an LF formation. The spacecraft are modeled as point masses.A schematic representation of SFF is shown in Fig. 1. The motion of the follower spacecraft is described relative to the leader spacecraft by the local-vertical-local-horizontal (LVLH) frame fixed at the center of the leader spacecraft.

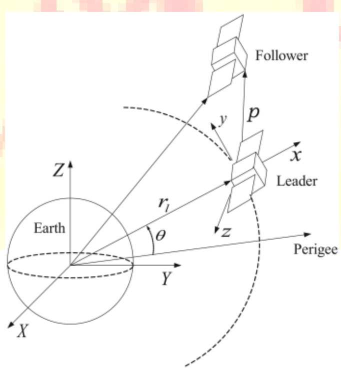


Fig. 1. Schematic representation of SFF system.

### *B. The Networked SFF Model with Delays*

The hardware of networked spacecraft formation control systems consist of samplers, controller,zero-order hold (ZOH) actuators and a communication channel basically. The control arithmetic is executed in the flight control computer. There are two sources of delays in the communication channel: the delay from the sampler to the controller , and the delay from the controller to the ZOH . Without loss of generality, any controller delay can be absorbed into either delay. For time-invariant controllers, both delays can be lumped together. The problem has been converted into designing a control law to make the tracking error system achieve desirable control performance (stability or ultimate boundedness).It is assumed that the measurements of the sampler are transmitted in a single packet, which means that the sample data are lumped together into one packet and transmitted over the communication channel at the same time.

We consider the following setup: a clock-driven sampler, that periodically samples the system states; an event-driven controller, which calculates the control signal as soon as the sample data arrive; and an event-driven ZOH, that changes the system inputs as soon as the controller data arrive. Develop a digital controller to guarantee the UU of the tracking error e in the closed-loop system and to drive the follower spacecraft to the desired formation trajectory in the presence of variable network-induced delays, bounded external disturbances.

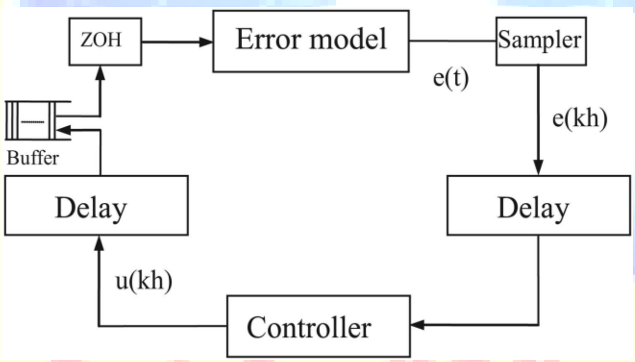


Fig. 2. Setup of error model with network-induced delays.

### *C. Stability Analysis*

We present the stability analysis of the networked SFF control system in the presence of time delays and external disturbances. The robust boundedness result is established to guarantee the exponentially UUB of the tracking errors.The tracking error model with network-induced delays is shown in Fig. 2. The closed-loop system consists of the tracking error model (10) and a discrete-time controller. u(kh) = -Ke(kh), where the state-feedback control gain K is of compatible dimension and h, a positive real constant, is the sampling period. Because the delays are randomly changing, the system is time varying, which makes design and analysis of the system complex. The use of buffers is an effective method to handle the time-varying delays and has been used for linear systems. In our setting, a buffer which is longer than the worst case delay is added before the node of ZOH.The control u is piecewise continuous. The timing of signals of this setup is shown in Fig. 3.

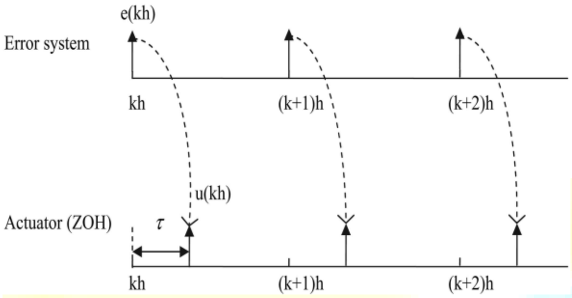


Fig. 3. Timing mechanism of network-induced delay.

### *D. Simulations*

The simulation results using non-linear equations are produced to illustrate the effectiveness of the proposed controller. The leader spacecraft is assumed in a circular reference. The reference trajectory used here is a projected circular formation, in which the leader and the follower spacecraft maintain a fixed relative distance on the y-z plane. We first consider the system performance without control input. The initial position and velocity components for this numerical simulation are computed by substituting t =0. We now examine the system response in conjunction with the proposed control scheme. In the numerical simulations, the network-induced delays are generated randomly.

## SIMULATION RESULT

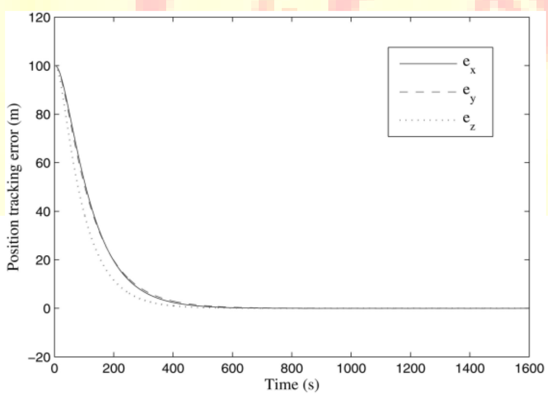


Fig. Position Error.

## IV. CONCLUSION

This paper focuses on formation tracking control for multiple spacecraft while taking into account the effect of variable network-induced delays and bounded external disturbances. An SFF system consisting of a leader and a follower spacecraft is considered for the case when the leader spacecraft is in a circular orbit. A reference trajectory is generated by the force-free Hill's equations. The tracking problem is solved by employing a sampled-data control scheme. By adding a buffer which is longer than the worst case delay and augmenting the system model to include past values of system input as additional states, a new discrete time-invariant model is formulated, and a digital controller is developed to guarantee the exponentially UUB of the tracking errors and to ensure desired formation objectives. The performance of the proposed controller is examined through numerical simulations of the governing nonlinear system equations of motion. The controller is successful in establishing projected circular formation within limited control authority. The steady-state tracking errors remain low and bounded under several diverse conditions including different initial conditions and different magnitudes of external disturbances. Finally, it is worth mentioning that this paper also determines the maximum allowable time delays to guarantee good performance of the closed-loop control system, as demonstrated through the numerical simulations.

## REFERENCES

[1] Kristiansen, et al. "Spacecraft formation flying: A review and new results on state feedback control",*Acta Astronautica*, (2009).

[2] Kapila, V., et al. "Spacecraft formation flying: Dynamics and control." *Journal of Guidance, Control, and Dynamics*, (2002).

[3] Scharf, D. et al, "A survey of spacecraft formation flying guidance and control (Part II): Control." *Proceedings of the 2004 American Control Conference*,Boston, MA, 2004.

[4] Vassar, R. H et al, "Formation keeping for a pair of satellites in a circular orbit." *Journal of Guidance, Control, and Dynamics*, (1985).

[5] Meng, Q.,et al "Low-thrust fuzzy formation keeping for multiple spacecraft flying."*Acta Astronautica*, (2004).

[6] Manikonda, V., et al. “A model predictive control-based approach for spacecraft formation keeping and attitude control.” *Proceedings of the American Control Conference*, San Diego, 1999.

[7] Liu, H.et al “Terminal sliding mode control for spacecraft formation flying.” *IEEE Transactions on Aerospace and Electronic Systems*,(2009).

[8] De Queiroz, et al,“Adaptive nonlinear control of multiple spacecraft formation flying.” *Journal of Guidance, Control, and Dynamics*, (2000).

[9] Wu, J.,et al “Model predictive control for networked control systems”. *International Journal of Robust and Nonlinear Control*, (2009).

[10] Zhang, et al “Stability of networked control systems”. *IEEE Control Systems Magazine*, (2001).