

Spaceborne Autonomous Relative Control System for Dual Satellite Formations

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Autonomous formation flight is a technical challenge of great interest for many scientific missions. Among other applications, the design of synthetic apertures is a promising benefit of using distributed spacecraft. Even if numerous studies exist in the literature, the formation flying concepts and applications were until now rather theoretical. The TanDEM-X Autonomous Formation Flying system presented in this paper will be implemented in the upcoming TanDEM-X mission and contributes as such to increase the readiness level of this technology. The paper focuses on the design of a guidance, navigation, and control system enabling the autonomous relative control of two spacecraft flying on near-circular orbits. Emphasis is given to the practical implementation within an onboard embedded computer, which requires a simple, resource-sparing, and robust design of the system. Therefore, the algorithms are tailored to minimize the usage of onboard resources and to allow the harmonious integration of the relative control system within the space segment. The validation of TanDEM-X Autonomous Formation Flying performed using a hardware-in-the-loop testbed shows that control performance at the meter level is expected.

Nomenclature

a	= semimajor axis
B	= ballistic coefficient
e	= eccentricity
e_N	= unit vector in normal direction
e_R	= unit vector in radial direction
e_T	= unit vector in along-track direction
i	= inclination
J_2	= geopotential second-order zonal coefficient
K	= Kalman gain
M	= mean anomaly
n	= mean orbit motion
R_\oplus	= equatorial radius of the Earth
r	= inertial position
r_{EF}	= Earth-fixed position
T	= control period
t	= time
u	= mean argument of latitude
v_{EF}	= Earth-fixed velocity
v	= inertial velocity
Δa	= relative semimajor axis
Δe	= relative eccentricity vector
Δi	= relative inclination vector
Δu	= relative mean argument of latitude
Δr	= relative position
$\Delta \alpha$	= relative orbit elements
Δv	= relative velocity with respect to Hill's comoving frame
δi_T	= variation of Δi_y over one control period
$\delta \Delta u_d$	= variation of Δu over one control period due to the drag
$\delta \Delta u_{J_2}$	= variation of Δu over one control period due to J_2

$\delta \Delta u_{\Delta v}$	= variation of Δu over half an orbit period caused by a maneuver
δe	= size of the relative eccentricity vector
δi	= size of the relative inclination vector
$\delta \varphi_T$	= phase variation of Δe over one control period
ε	= size of the tolerance window
θ	= phase of the relative inclination vector
μ	= Earth's gravitational parameter
ρ	= atmospheric density
φ	= phase of the relative eccentricity vector
Ω	= right ascension of the ascending node
ω	= argument of perigee
ω_\oplus	= Earth-angular velocity

I. Introduction

FORMATION flying is one of the most promising technologies for future space missions. The distribution of sensors and payloads among several spacecraft allows higher redundancy, flexibility, and new applications that would not be possible with a single spacecraft. Among others, one may mention the design of virtual telescopes at a libration point [1], a laser interferometer for the detection of gravitational waves [2], or an interferometric synthetic aperture radar (SAR) for Earth observation [3]. However, the high scientific gain potentially afforded by these new missions comes at the expense of a higher system complexity and costs. As a consequence, few ideas have been already concretized even if theoretical studies about formation flying abound.

The first formation flying missions to make use of a set of satellites to achieve a scientific goal were Earth observation missions. They belong to a class of missions for which the technical difficulties are usually well known and, thus, are natural candidates to gain the necessary experience in designing and operating formations of satellites. The Gravity Recovery and Climate Experiment (GRACE), composed of two low-Earth-orbit satellites flying on the same orbit with a separation of 200 ± 50 km, has already demonstrated the successful use of a ground-in-the-loop controlled formation for scientific purposes [4]. Future missions will, however, most likely use autonomously controlled formations that reduce the need for ground station visibility. In addition, autonomy provides better control performances, reactivity in case of contingency, and a reduction in the ground support and costs.

This paper presents a complete guidance, navigation, and control (GNC) architecture able to enable the autonomous relative control of a generic low-Earth mission composed of two satellites equipped

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