# Control of Satellite Formation Flying Using Space Environmental Forces

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## 論文内容の要旨

In this thesis, the practical feasibility of space environmental forces in the various orbit control missions is examined. It looks insight the rectilinear representation of the relative motion for the satellite formation flying (SFF) using high fidelity dynamics equations of relative motion. The investigated model, which is referred to by Scheiwghart-Sedwick (SS), has been developed from Hill-Clohessy-Wiltshire (HCW) equations by incorporating the secular effects of the second-order zonal harmonic perturbations $(J_2)$ for the Earth. The thesis implements various terminologies to analyze the controllability of each space environment force. Furthermore, it elaborates on the full controllability of the system with low constraints by exploiting the minimum configuration of hybrid control action. It estimates the controllable and uncontrollable states of space environmental forces for different orbit configurations. The design of practical control algorithms using only space environmental forces considering the real constraints of these forces is the main objective of this research. Therefore, the parameterized output regulation (POR) algorithm is designed to invoke high performance in various practical formation maneuver missions considering input saturation. The stability of the POR algorithm is approved using the parametric Lyapunov algebraic equation (PLAE) with low-conservative constraints. The performance of the SFF in the presence of external perturbations is analyzed using a high-precision orbit propagator (HPOP). The POR control algorithm is enhanced by incorporating a conditional anti-windup integral controller to deal with the drawbacks of low-gain feedback for the POR algorithm in the steady-state region. The high fidelity procedures are investigated to validate the practicality of the control algorithms, which is analyzed by testing various control algorithms' stability and performance analytically with uncertain parameters. The numerical results assured the low performance-deterioration of the derived control algorithm with various uncertainty sources and nonlinear dynamics using the HPOP environment.

The dynamics of the relative equations are discussed in Chapter 2. In Sec. 2.1, the nonlinear relative equations of motion are presenting, defining the relative position and velocity of the follower satellites w.r.t the leader satellite. The linearized forms of the rectilinear states are stated in Section 2.2 with the assumption of a low formation radius. Section 2.2.1 presents the linear formulation of Hills-Clohessy-Wiltshire (HCW) equations for circular orbits and its analytical solution. The Scheiwghart-Sedwick (SS) model derivation is illustrated with the main differences between its formulation and the HCW model in Sec. 2.2.2.

Chapter 3 states the space environmental forces and their formulations for various circular orbits' configurations. In Sec. 3.1, the formulation of linearized differential atmospheric drag is presented.

Section 3.2 illustrates the derivation of a new linear time-variant (LTV) form for the solar radiation pressure (SRP) with various circular orbits configurations. The derivation for the Lorentz forces control action is invoked in Sec. 3.3.

The controllability analysis of various space environment forces is illustrated analytically and numerically in Chapter 4. Section 4.1 outlines the analytical controllability analysis for separate and hybrid control actions. It analyzes the controllability of different forces for discrete systems with various time intervals. Furthermore, it estimates the controllable and uncontrollable states of continuous and discrete systems using the Kalman decomposition approach for various space environmental forces. The numerical controllability analysis of the bounded control actions is stated in Sec. 4.2. It investigates different solutions for the algebraic and the periodic time-variant Riccati equations to generate control actions for sun-synchronous orbits.

Chapter 5 presents the preliminary steps to derive analytic form for the finite-time reachability of the relative dynamics models by using the bounded differential atmospheric forces. This analysis involves the requirements of the reachability sets for dynamics models to achieve the final states within finite time. Therefore, a new formulation of the differential atmospheric force is derived based on the implementation of the atmospheric lift and drag forces simultaneously in Sec. 5.1. Section 5.2 analyzes the boundary sets using two main approaches to estimate the maximum boundaries for the in-plane states. The first approach is defined by the applied formulation of finite-time reachability analysis, which is illustrated in Sec. 5.2.1 by using the optimum solutions of Hamilton-Jacobi (HJ). The second approach is called the analytical representation, which is stated in Sec. 5.2.2. It is derived by using the Eigen structure of the state matrix. Thus, it investigates the time-reversed formulation of the null controllable system to acquire the boundary closures of the reachability sets.

Chapter 6 outlines the derivation of the parameterized output regulation (POR) algorithms. It is designed to formulate a less-conservative and stable way for tracking problems using the output regulation algorithm with bounded control inputs. Section 6.1 presents the objectives and structure of the output regulation algorithm. The derivation of the parameterized output regulation (POR) algorithm is illustrated in Sec. 6.2. The comparison between the numerical results of the POR and the parametric linear quadratic regulator (PLQR) algorithm is presented in Sec. 6.3. The types of uncertainty sources in relative dynamics using differential atmospheric drag are classified based on origin and nature in Sec. 6.4. It outlines the stability and the performance analysis of the POR algorithm for various types of uncertainties using analytical stability analysis and numerical results. The final section discusses the enhancement of the POR algorithm to improve steady-state errors with low-gain feedback by incorporating an integral controller with an anti-windup scheme. The simulation results of the enhanced algorithm are illustrated in the final Section. It approves that the enhancement in the POR algorithm can handle the uncertainties in the control action without high performance-deterioration.

The validation process of the new control algorithms is investigated in Chapter 7. It provides the validation procedures for various control algorithms by testing their performance in HPOP. The numerical simulation results of the POR algorithm and the integrated control algorithm in the HPOP environment is presented. The results clarify the robustness of the parameterized control algorithms when implemented in real space environmental conditions with precise and nonlinear inertial-dynamics models.

Finally, Chapter 8 contains the conclusions of the study and recommendations for future work.