

Juntang Yang

**Sliding Mode Control for
Spacecraft Proximity Operations
Based on Dual Quaternions**

Sliding Mode Control for Spacecraft Proximity Operations Based on Dual Quaternions

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Abstract

This dissertation focuses on the six-DOF control problem of spacecraft proximity operations. Sliding mode control (SMC), as a robust control method, is chosen to handle external disturbances. Dual quaternion parameterization, which can represent the translation and rotation of a rigid body simultaneously, is used to model the coupled relative motions during proximity operations. The basic research methodology is to explore the similarity between unit quaternion-based description of the relative rotational motion and unit dual quaternion-based description of the relative translational and rotational motion.

The main contributions of this dissertation are as follows. Firstly, a potential field-based sliding surface design method is proposed for spacecraft attitude maneuvers. The proposed method unifies sliding surface designs based on different attitude parameterizations (i.e., unit quaternions, Rodrigues parameters, and modified Rodrigues parameters) in the same framework. The classical results of sliding surface design are shown to be special cases of the proposed general form. Secondly, the potential field-based sliding surface design is applied in the spacecraft reorientation with both attitude forbidden zones and mandatory zones. The proposed sliding surface is novel in that attitude constraints are taken into consideration in its design. In the sliding mode, the desired attitude can be achieved while attitude constraints are satisfied automatically. An analysis on critical points of the potential field is conducted for the sliding mode. Thirdly, an adaptive dual quaternion-based SMC with a new sliding variable is proposed for spacecraft proximity operations. By implementing the potential field-based sliding surface design, the new dual quaternion-based sliding variable is obtained without introducing the logarithm of dual quaternion. The unwinding phenomenon and uncertainties in mass property of the chaser are taken into consideration. The stability of the closed-loop system under the proposed SMC is proven using the Lyapunov method based on dual quaternion algebra. The proposed dual quaternion-based SMC outperforms the dual quaternion-based PD-plus controller in the literature with shorter settling time and less energy consumption. Lastly, a potential field and dual quaternion-based SMC is proposed for spacecraft proximity operations with motion constraints. Motion constraints, including the approach path constraint and the field-of-view constraint, are considered in the sliding surface design in form of dual quaternions. The problem of critical points in the sliding mode is analyzed. The stability of the closed-loop relative motions under the proposed controller is proven using the Lyapunov method based on dual quaternion algebra.

Zusammenfassung

Diese Dissertation konzentriert sich auf das Sechs-Freiheitsgrade-Regelungsproblem von Raumfahrzeug-Näherungsoperationen. Als robuste Regelungsmethode wird die Sliding-Mode-Control (SMC) gewählt, um externe Störungen zu behandeln. Zur Modellierung der gekoppelten Relativbewegungen bei Annäherungsoperationen wird eine duale Quaternion-Parametrisierung verwendet, die gleichzeitig die Translation und Rotation eines starren Körpers darstellen kann. Die grundlegende Forschungsmethodik besteht darin, die Ähnlichkeit zwischen der einheitsquaternion-basierten Beschreibung der relativen Rotationsbewegung und der einheitsdualquaternion-basierten Beschreibung der relativen Translations- und Rotationsbewegung zu untersuchen.

Die Hauptbeiträge dieser Dissertation sind wie folgt. Erstens wird eine potenzialfeldbasierte Gleitflächenentwurfsmethode für Lagemanöver von Raumfahrzeugen vorgeschlagen. Die vorgeschlagene Methode vereinheitlicht Gleitflächendesigns, die auf verschiedenen Lageparametrisierungen basieren (d.h. Einheitsquaternionen, Rodrigues-Parameter und modifizierte Rodrigues-Parameter), im selben Framework. Es wird gezeigt, dass die klassischen Ergebnisse des Gleitflächendesigns ein Spezialfall der vorgeschlagenen allgemeinen Form sind. Zweitens wird der potenzialfeldbasierte Gleitflächenentwurf bei der Reorientierung des Raumfahrzeugs sowohl mit lageverbotenen Zonen als auch mit obligatorischen Zonen angewendet. Die vorgeschlagene Gleitfläche ist insofern neuartig, als bei ihrem Entwurf die Lagebeschränkungen berücksichtigt werden. Im Gleitmodus kann die gewünschte Lage erreicht werden, während die Lagebeschränkungen automatisch erfüllt werden. Eine Analyse der kritischen Punkte des Potentialfeldes wird für den Gleitmodus durchgeführt. Drittens wird eine adaptive Dual-Quaternion-basierte SMC mit einer neuen Gleitvariablen für Raumfahrzeug-Nahbereichsoperationen vorgeschlagen. Durch die Implementierung des potenzialfeldbasierten Gleitflächendesigns wird die neue duale Quaternion-basierte Gleitvariable erhalten, ohne den Logarithmus des dualen Quaternion einzuführen. Das Abwicklungsphänomen und Unsicherheiten in der Masseneigenschaft des Chaser werden berücksichtigt. Die Stabilität des Closed-Loop-Systems unter der vorgeschlagenen SMC wird mit der Lyapunov-Methode basierend auf der Dual-Quaternion-Algebra nachgewiesen. Der vorgeschlagene Dual-Quaternion-basierte SMC übertrifft den Dual-Quaternion-basierten PD-plus-Regler in der Literatur mit kürzerer Einschwingzeit und geringerem Energieverbrauch. Schließlich wird eine Potentialfeld- und Dual-Quaternion-basierte SMC für Raumfahrzeug-Annäherungsoperationen mit Bewegungseinschränkungen vorgeschlagen. Bewegungsbeschränkungen, einschließlich der Annäherungspfad-Beschränkung und der Sichtfeld-Beschränkung, werden im Gleitflächenentwurf in Form von Dual-Quaternionen berücksichtigt. Das Problem der kritischen Punkte im Gleitmodus wird analysiert. Die Stabilität der Relativbewegungen im geschlossenen Regelkreis unter dem vorgeschlagenen Regler wird mit Hilfe der Lyapunov-Methode auf Basis der Dual-Quaternion-Algebra nachgewiesen.

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