Nonlinear Robust H-Infinity PID Controller for the Multivariable System Quadrotor

J. P. Ortiz, *Member, IEEE*, L. I. Minchala, *Member, IEEE* and M. J. Reinoso

***Abstract*— This paper presents the methodology of design of a nonlinear robust controller for attitude regulation and its implementation in an experimental platform of an unmanned aerial vehicle (UAV) quadrotor. Details on the kinematic and dynamic modeling based on the Euler-Lagrange formalism are provided, as well as the particulars of the design of a nonlinear robust H-infinity PID controller to regulate the rotational moments. The performance and effectiveness of the proposed controller are tested in a simulation and an experimental platform. The performance of the proposed controller is compared with a conventional PID controller by using the integral square error (ISE) as performance parameter. Experimental results help to demonstrate the correct operation of the system for real-time applications in the presence of unmodeled dynamics and the uncertainties of the parameters.**

***Keywords*— Nonlinear system, quadrotor, robust control, attitude regulation, UAV**

I. INTRODUCCIÓN

LOS sistemas de control para vehículos aéreos no tripulados del tipo quadrotor se han desarrollado con gran rapidez en los últimos años. La necesidad de desarrollar sistemas con mayor autonomía, que puedan realizar maniobras de alta complejidad, que realicen misiones de largo alcance, que operen en entornos de alto riesgo para los seres humanos, sin duda han permitido que este campo este bajo continua investigación y desarrollo [1-3].

En [4] se establece un controlador robusto para despegue, seguimiento de trayectoria y aterrizaje, constituido por un controlador de posición y un controlador de orientación. El controlador de posición usa el método de realimentación estático para obtener la altitud deseada, mientras que el control de orientación utiliza un proporcional-derivativo (PD) con una técnica de compensación robusta. En [5] se propone agregar a la estructura del controlador PD un método robusto de sintonización de parámetros, que permite modificar en línea los parámetros del compensador durante el seguimiento de una trayectoria.

Los estudios realizados en [6] plantean un controlador robusto no lineal H_∞ para estabilizar los momentos de rotación y un control basado en el enfoque de *backstepping* para el seguimiento de trayectoria. La referencia [7] sugiere un controlador del tipo integral predictivo para resolver el problema de seguimiento de trayectoria. Ambos resultandos simulados son robustos ante perturbaciones externas del sistema.

J. P. Ortiz está con el Departamento de Ingeniería Automotriz, Universidad Politécnica Salesiana, Cuenca, Ecuador, jportizg@ups.edu.ec

L. I. Minchala, está con el Departamento de Ingeniería Eléctrica, Electrónica y de Telecomunicaciones de la Universidad de Cuenca, Cuenca, Ecuador, ismael.minchala@ucuenca.edu.ec

M. J. Reinoso está con el Departamento de Ingeniería de Control de Ask Solutions. Cuenca, Ecuador, manuelrja@hotmail.com.

En [8] se propone un controlador tolerante a fallas para planeamiento y re-planeamiento de trayectorias. En [9] se implementan y comparan dos algoritmos de control tolerante a fallas basados en: un regulador lineal cuadrático y un controlador de modelo predictivo, los resultados demuestran un desempeño aceptable de los algoritmos para el control de altura en presencia de perdidas parciales de la acción de los actuadores.

Diversas investigaciones [10-12] han realizado comparaciones entre varias técnicas de control y también usado diferentes modelos matemáticos del sistema [13-15]. Entre los controladores más usados para resolver los problemas de seguimiento de trayectoria y de regulación están: el control por linealización entrada-salida [16], el control por visión [17], el control adaptivo [18], el control por modos deslizantes [19], el control óptimo *backstepping* [20], el control robusto no lineal adaptivo [21], entre otros.

Este artículo propone un controlador robusto para afrontar el problema de regulación del subsistema de orientación de un quadrotor. El problema se divide en tres etapas: en la primera, se obtienen los modelos matemáticos, cinemático y dinámico. En la segunda etapa se presenta el diseño y la implementación del controlador robusto no lineal H_∞ que compensa las fuentes de incertidumbre en el modelo debido a dinámicas no modeladas, errores en la estimación de parámetros, perturbaciones exógenas y ruido. En la tercera etapa se realizan las pruebas de funcionamiento y el análisis de desempeño del controlador en las plataformas de simulación y experimental, usando el ISE como criterio de desempeño y obteniéndose buenos resultados en comparación con un sistema de control clásico PID.

Este documento se organiza como sigue: La sección II presenta el modelado matemático del sistema considerando dinámicas no lineales traslacional y rotacional. La sección III muestra el procedimiento para el diseño del controlador robusto no lineal H_∞ del sistema de orientación de la aeronave. La sección IV presenta los detalles de la implementación del controlador, tanto en la plataforma de simulación como en la plataforma experimental. La sección V presenta las conclusiones del trabajo.

II. MODELADO MATEMÁTICO DEL SISTEMA

A. *Consideraciones del sistema*

Un vehículo aéreo no tripulado (UAV por sus siglas en Inglés) posee la configuración de cuatro motores coplanarios, como se muestra en la Fig. 1. La variación controlada de las velocidades en los motores permite el movimiento del quadrotor. El movimiento del sistema hacia adelante (pitch) se logra disminuyendo y aumentando las velocidades de los motores delantero (F1) y trasero (F3) respectivamente. Un desplazamiento lateral (roll) demanda el mismo procedimiento

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Cheng Siong Chin

Nonlinear H Infinity Controller For The Quad Rotor:

Robotic Manipulators and Vehicles Gerasimos Rigatos,Krishna Busawon,2018-05-24 This monograph addresses problems of nonlinear control estimation and filtering for robotic manipulators multi degree of freedom rigid link robots flexible link robots underactuated redundant and cooperating manipulators and closed chain robotic mechanisms and nonlinear control estimation and filtering for autonomous robotic vehicles operating on the ground in the air and on and under water independently and in cooperating groups The book is a thorough treatment of the entire range of applications of robotic manipulators and autonomous vehicles The nonlinear control and estimation methods it develops can be used generically being suitable for a wide range of robotic systems Such methods can improve robustness precision and fault tolerance in robotic manipulators and vehicles at the same time as enabling the reliable functioning of these systems under variable conditions model uncertainty and external perturbations **New Developments and Advances in Robot Control** Nabil Derbel,Jawhar Ghommam,Quanmin Zhu,2019-01-24 This book highlights relevant studies and applications in the area of robotics which reflect the latest research from interdisciplinary theoretical studies and computational algorithm development to representative applications It presents chapters on advanced control such as fuzzy neural backstepping sliding mode adaptive predictive diagnosis and fault tolerant control etc and addresses topics including cloud robotics cable driven robots two wheeled robots mobile robots swarm robots hybrid vehicle and drones Each chapter employs a uniform structure background motivation quantitative development equations case studies illustration tutorial simulations experiences curves tables etc allowing readers to easily tailor the techniques to their own applications **9th International Conference on Robotic, Vision, Signal Processing and Power Applications** Haidi Ibrahim,Shahid Iqbal,Soo Siang Teoh,Mohd Tafir Mustaffa,2016-09-29 The proceeding is a collection of research papers presented at the 9th International Conference on Robotics Vision Signal Processing Power Applications ROVISP 2016 by researchers scientists engineers academicians as well as industrial professionals from all around the globe to present their research results and development activities for oral or poster presentations The topics of interest are as follows but are not limited to Robotics Control Mechatronics and Automation Vision Image and Signal Processing Artificial Intelligence and Computer Applications Electronic Design and Applications Telecommunication Systems and Applications Power System and Industrial Applications Engineering Education

Innovations and Applications of Artificial Intelligence in Electrical and Electronics Engineering Mohammed WADI,Mohammed SALEMDEEB,Mohammed JOUDA,2025-03-23 **Intelligent Renewable Energy Systems** Gerasimos Rigatos,2016-08-06 Focused on renewable energy systems and the development of information and communication technologies ICTs for their integration in smart grids this book presents recent advances and methods that help to ensure that power generation from renewable sources remains stable that power losses are minimized and that the reliable functioning of these power generation units is maintained The book highlights key topics and technologies for renewable

energy systems including the intelligent control of power generators power electronics that connect renewable power generation units to the grid and fault diagnosis for power generators and power electronics In particular the following topics are addressed Modeling and control of power generators PMSGs DFIGs Modeling and control of power electronics converters inverters Modeling and fault diagnosis of the transmission and distribution Grid and Modelling and control of distributed power generation units interconnected synchronous generators or photovoltaic units Because of the above coverage members of the wider engineering community will find that the nonlinear control and estimation methods presented provide essential insights into the functioning of renewable energy power systems while the academic community will find the book a valuable textbook for undergraduate or graduate courses on renewable energy systems **Recent Advances in Sliding Modes: From Control to Intelligent Mechatronics** Xinghuo Yu,Mehmet Önder Efe,2015-04-10 This volume is dedicated to Professor Okyay Kaynak to commemorate his life time impactful research and scholarly achievements and outstanding services to profession The 21 invited chapters have been written by leading researchers who in the past have had association with Professor Kaynak as either his students and associates or colleagues and collaborators The focal theme of the volume is the Sliding Modes covering a broad scope of topics from theoretical investigations to their significant applications from Control to Intelligent Mechatronics **Computer-Aided Control Systems Design** Cheng Siong Chin,2017-12-19 Computer Aided Control Systems Design Practical Applications Using MATLAB and Simulink supplies a solid foundation in applied control to help you bridge the gap between control theory and its real world applications Working from basic principles the book delves into control systems design through the practical examples of the ALSTOM gasifier system in power stations and underwater robotic vehicles in the marine industry It also shows how powerful software such as MATLAB and Simulink can aid in control systems design Make Control Engineering Come Alive with Computer Aided Software Emphasizing key aspects of the design process the book covers the dynamic modeling control structure design controller design implementation and testing of control systems It begins with the essential ideas of applied control engineering and a hands on introduction to MATLAB and Simulink It then discusses the analysis model order reduction and controller design for a power plant and the modeling simulation and control of a remotely operated vehicle ROV for pipeline tracking The author explains how to obtain the ROV model and verify it by using computational fluid dynamic software before designing and implementing the control system In addition the book details the nonlinear subsystem modeling and linearization of the ROV at vertical plane equilibrium points Throughout the author delineates areas for further study Appendices provide additional information on various simulation models and their results Learn How to Perform Simulations on Real Industry Systems A step by step guide to computer aided applied control design this book supplies the knowledge to help you deal with control problems in industry It is a valuable reference for anyone who wants a better understanding of the theory and practice of basic control systems design analysis and implementation **Government Reports**

Announcements & Index ,1993-11 **Extending H-infinity Control to Nonlinear Systems** J. William Helton,Matthew R. James,1999-01-01 H infinity control originated from an effort to codify classical control methods where one shapes frequency response functions for linear systems to meet certain objectives H infinity control underwent tremendous development in the 1980s and made considerable strides toward systematizing classical control This book addresses the next major issue of how this extends to nonlinear systems At the core of nonlinear control theory lie two partial differential equations PDEs One is a first order evolution equation called the information state equation which constitutes the dynamics of the controller One can view this equation as a nonlinear dynamical system Much of this volume is concerned with basic properties of this system such as the nature of trajectories stability and most important how it leads to a general solution of the nonlinear H infinity control problem *International Aerospace Abstracts* ,1997 *H-infinity Control for Nonlinear Descriptor Systems* He-Sheng Wang,Chee-Fai Yung,Fan-Ren Chang,2006-01-18 The authors present a study of the H infinity control problem and related topics for descriptor systems described by a set of nonlinear differential algebraic equations They derive necessary and sufficient conditions for the existence of a controller solving the standard nonlinear H infinity control problem considering both state and output feedback One such condition for the output feedback control problem to be solvable is obtained in terms of Hamilton Jacobi inequalities and a weak coupling condition a parameterization of output feedback controllers solving the problem is also provided All of these results are then specialized to the linear case The derivation of state space formulae for all controllers solving the standard H infinity control problem for descriptor systems is proposed Among other important topics covered are balanced realization reduced order controller design and mixed H2 H infinity control H infinity Control for Nonlinear Descriptor Systems provides a comprehensive introduction and easy access to advanced topics **Thomas Register of American Manufacturers** ,2002 This basic source for identification of U S manufacturers is arranged by product in a large multi volume set Includes Products services Company profiles and Catalog file **Physics Briefs** ,1981 Nonlinear H [infinity] Control W. C. A. Maas,1996 **Design of H [infinity] Stabilizing Controller for a Class of Nonlinear Systems Presented by Their Describing Functions** Shahzad Khaligh,1998 *H Infinity Control Methods in Control and Robust State Estimation for Nonlinear Systems with Sector Bounded Nonlinearities* Hua Ouyang,2011 This thesis uses H infinity symbol control methods to study robust state estimation and Lagrange stabilization of sector bounded nonlinear systems According to different stability notions and nonlinearity configurations this thesis is divided into two parts Part A considers robust state estimation for uncertain stochastic systems with slopebounded nonlinearities satisfying Integral Quadratic Constraints IQC and multipliers are used to exploit the uncertainties and nonlinearities A new approach for constructing a robust state estimator for the nonlinear system is developed Part B studies stability analysis and Lagrange stabilizing controller synthesis for pendulum like systems This part proposes two new versions of a Lagrange stability criterion one is used for stability analysis of pendulum like system with a single nonlinearity

and the other one is used for pendulum like system with multiple nonlinearities As these new Lagrange stability criteria do not require the linear part of the pendulum like system under consideration to be minimal they can be applied to more general pendulum like systems than the previous results in the literature Also a sufficient condition which ensures that a periodic in state nonlinear system is a pendulum like system is established These two results enable Lagrange stabilizing controller synthesis for pendulum like systems with multiple nonlinearities To facilitate Lagrange stabilizing controller synthesis for pendulum like systems some results in standard H infinity symbol control are generalized An extended strict bounded real lemma is developed which only requires the pair of system matrices A B to be stabilizable rather than the Hurwitz property of the system matrix A Also a pseudo H infinity symbol control theory is developed This includes a pseudo strict bounded real lemma which relates a pseudo H infinity symbol condition in which the system matrix A has n 1 eigenvalues with negative real parts and one eigenvalue with positive real part and a frequency domain norm bound condition holds to the existence of a sign indefinite solution to an algebraic Riccati equation These results can handle some system control design problems which the standard H infinity symbol control theory is not applicable This is one of the main contributions of this thesis The Lagrange stabilization problem for pendulum like systems with different version of periodic in state nonlinearities is formulated and solved in term of the solutions to game type Riccati equations These equations can be solved using available software kits In addition some examples with simulations are given to illustrate the efficacy of the proposed methods **H(infinity) Control of Nonlinear Systems: A Class of Controllers** ,1993 Abstract The standard state space solutions to the Em control problem for linear time invariant systems are generalized to nonlinear time invariant systems A class of nonlinear controllers are parameterized as nonlinear fractional transformations on contractive stable free nonlinear parameters As in the linear case the E control problem is solved by its reduction to four simpler special state space problems together with a separation argument Another byproduct of this approach is that the sufficient conditions for control problem to be solved are also derived with this machinery The solvability for nonlinear H infinity control problem requires positive definite solutions to two parallel decoupled Hamilton Jacobi inequalities and these two solutions satisfy an additional coupling condition An illustrative example which deals with a passive plant is given at the end *H [infinity] Control of Nonlinear Systems with Sampled Measurement* Sadanori Suzuki,1994 H [infinity] Controller Synthesis for Sampled-data Systems and Nonlinear Systems Qi Yu,1999 *Le guide des familles* ,1889

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