

論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Joint Optimization of Structure and Control for Fully Actuated UAVs Based on Value Function Minimization
著者(和文)	田所祐一
Author(English)	Yuichi Tadokoro
出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第11423号, 授与年月日:2020年3月26日, 学位の種別:課程博士, 審査員:三平 満司,藤田 政之,井村 順一,山北 昌毅,早川 朋久
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第11423号, Conferred date:2020/3/26, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

論文要旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	システム制御 システム制御	系 コース	申請学位 (専攻分野)： Academic Degree Requested	博士 Doctor of	(工学)
学生氏名： Student's Name	田所 祐一		指導教員 (主)： Academic Supervisor(main)	三平 満司 教授	
			指導教員 (副)： Academic Supervisor(sub)		

要旨 (英文 800 語程度)

Thesis Summary (approx.800 English Words)

This dissertation investigates a joint optimization scheme of the structure and control for fully actuated unmanned aerial vehicles which can achieve general motion in 3-dimensional space. The control performance such as energy consumption and settling time is heavily affected by both the control law and the plant parameters of the controlled object. However, regular optimal control problems consider optimization only over the control input and fail to utilize the plant parameters to further improve the performance. Given this problem, the objective of this work is to simultaneously acquire both the optimal control input and optimal plant parameters that minimize an objective function. To achieve this goal, the optimal value function which corresponds to the minimum cost of optimal control is reinterpreted and further minimized as a function of plant parameters. This method is called “joint optimization” of the structure and control as the two optimization problems are connected via the same objective function. Both analytical and numerical methods are developed in this work, and they can be used to determine the optimal plant parameters for different control tasks which are specified by the objective function and the set of initial states.

First, a fully actuated hexarotor is introduced as the main application of joint optimization in this dissertation. A fully actuated hexarotor has six rotors fixed on its body, and they are tilted so that the vehicle can generate force and torque in every direction and around every axis. The vehicle dynamics is modeled based on aerodynamics and rigid body dynamics, and the model is then transformed into a second-order system on the special Euclidean group $SE(3)$. A theorem shows that non-planar structures can be transformed into planar structures without changing the force and torque acting on the center of mass. This property greatly simplifies the subsequent discussion because considering only planar structures is sufficient for the analysis of the force and torque. Moreover, related research is classified by using this simplification method, and it is shown that there exist two standard classes of fully actuated hexarotors. To measure the full-actuation performance, the dynamic manipulability of hexarotors is then defined and analyzed for the two classes of hexarotors. Theorems prove that the dynamic manipulability is suitable for the evaluation of directional characteristics of acceleration. It is suggested that the structural design of the hexarotor should be considered with its control task because the acceleration characteristics change according to the position and orientation of rotors. An overview of the experiment system is given, and a preliminary experiment is also conducted.

Secondly, an analytical method for joint optimization is presented based on an analytical optimal controller for rigid body dynamics. Before developing the optimal control method, a double-geodesic PD controller on $SE(3)$ is described, which provides the basis of the optimal controller. The closed-form solution of the optimal control input and the corresponding value function are then shown for the cases where the vehicle is under zero gravity or the force of gravity is compensated by an input transformation. Theorems prove the optimality of the present control law and stability of the closed-loop system via the Hamilton-Jacobi-Bellman equation and the Lyapunov theorem. An analogy to linear optimal control is also given. The analytical value function is then minimized with respect to the plant parameters. An application to a fully actuated hexarotor shows that the optimal design for non-gravity cases corresponds to the maximization of the dynamic manipulability, and it is validated also by simulations.

Finally, a numerical method for joint optimization is studied to consider more general dynamics and objective functions. In particular, we tackle the application to a fully actuated hexarotor considering the input energy cost for gravity compensation. A nonlinear model predictive control method is proposed based on an exact discretization of the rigid body dynamics using a geometric integrator via the Cayley map for $SE(3)$. The exact discretization allows picking a coarse sampling period without losing the precision of the integrated dynamics. Moreover, the recursive discretization technique is combined with the geometric integrator to drastically reduce the computational effort of optimization. On-board simulations of flight control show that the present numerical optimal control method runs on a low-cost single-board computer in

real time while considering the gravity compensation cost. The numerical controller is then reused to calculate the value function for the specified plant parameters and initial states. Parameter optimization of rotor tilt angles is then carried out by using particle swarm optimization so that the simulated value function is minimized to the nearly global optimum. The result shows that the fast numerical control method not only provides a real-time controller but also is meaningful for reducing the computation time of the parameter optimization. It is also demonstrated that parameter optimization based on dynamic manipulability maximization is not energy-efficient when considering the cost of gravity compensation. An experiment using the fast model predictive controller further validates the effectiveness of the proposed methods of this work.

備考：論文要旨は、和文 2000 字と英文 300 語を 1 部ずつ提出するか、もしくは英文 800 語を 1 部提出してください。

Note: Thesis Summary should be submitted in either a copy of 2000 Japanese Characters and 300 Words (English) or 1 copy of 800 Words (English).

注意：論文要旨は、東工大リサーチリポジトリ(T2R2)にてインターネット公表されますので、公表可能な範囲の内容で作成してください。

Attention: Thesis Summary will be published on Tokyo Tech Research Repository Website (T2R2).