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Some Key Technologies on Subminiature Boom-Tail Fixed Wing UAV

Candidate: Liu Wufa
Major: Mechatronic Engineering
Supervisor: Gong Zhenbang
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答辩委员会对论文的评语

论文结合反恐防暴低空侦察的需要，开展了超小型双垂尾定翼飞行器的研究，关键技术涉及空气动力学、飞行力学、结构设计、飞控与导航等学科，属于交叉学科前沿研究，是当前国际上的研究热点之一。故选题具有重要的学术意义和应用价值。

该论文在超小型双垂尾定翼飞行器研究方面有以下几点创新：

(1) 导出了面元法计算气动力系数公式，对低雷诺数下的翼型进行了气动力优化设计，流场分析，得到了不同雷诺数下附面层分离的攻角。

(2) 采用 CFD 方法系统地计算出了超小型定翼飞行器的稳定性系数和稳定性导数。并设计了模糊自适应整定 PID 控制器。

(3) 将地图投影理论应用于导航参数计算、导航算法设计及航线跟踪。

(4) 上述关键技术在超小型双垂尾定翼飞行器翼型选择、机翼设计、空气动力学分析、飞控与导航方面得到了系统的应用。

论文反映出作者具有扎实的基础理论及系统深入的专门知识，独立科研能力强。论文写作条理性好，层次分明，实验结果可靠。在答辩过程中能正确回答。

答辩委员会表决结果

经答辩委员会表决，一致同意通过张颖同学的博士学位论文答辩，建议授予工学博士学位。

答辩委员会主席：**赵锡芳**

2006年1月11日

摘　要

本文针对国家高技术研究发展计划项目“飞行机器人系统研究”中超小型定翼飞行器 SUAV(Subminiature Fixed Wing Unmanned Aerial Vehicle)的低雷诺数空气动力学、结构设计、飞行力学、飞行控制与导航方面的问题进行了较为深入系统地研究,主要研究内容归纳如下:

在空气动力学方面,为了提高超小型定翼飞行器在低雷诺数下的升力,本文以 NACA2145 翼型为基础翼型,以翼型厚度、最大厚度位置及弯度为优化变量,采用计算速度较快的面元法计算气动力系数,对翼型进行了气动力优化,XFOIL 软件计算出的优化翼型的升力和 CFD(Computational Fluid Dynamics)分析计算出的优化翼型的升力一致性很好,并且优化翼型的气动力性能得到改善;CFD 计算得到了翼型的湍流强度分布图、湍流强度迹线图、湍流强度粘度图、壁面应力、速度梯度图及压力分布图,据此分析了低雷诺数下翼型附面层,得到了附面层分离的攻角,而且其分离特征参数附和附面层分离的理论;用 CATIA 建立所设计机翼的三维曲面模型并用 CFD 计算了机翼绕流场,获得了机翼的空气动力参数;由垂直尾翼和水平尾翼 CATIA 所建立的模型,CFD 计算出其升阻力系数;根据 CATIA 建立的超小型定翼飞行器模型,计算获得了静态稳定性分析、动态性能分析和飞行控制等所需要的气动力系数、稳定性导数和控制导数。

在结构设计方面，首先根据超小型定翼飞行器任务要求、起飞重量及由翼型气动力参数估算的三维机翼气动力参数，用CATIA 设计了机翼，并对机翼性能进行了计算，结果表明所设计机翼满足任务要求；其次根据机身所装载的设备、飞控与导航系统、燃油及回收降落伞，发动机和机身的安装方式，机翼和机身的连接方式，起落架和机身的连接方式等，用 CATIA 设计了机身；然后根据对现有飞机和无人机的尾翼结构形式分析和归纳，选择了本文超小型定翼飞行器尾翼的结构形式；再者用CATIA 对整个飞行器按结构进行了实体建模；最后由 CATIA 的分析功能对实体模型分析得到了飞行器的重心位置、惯性矩和惯性积等重要参数。

在飞行力学方面，飞行器的静态稳定性是很重要的，本文阐述了静态稳定性的概念并推导出了静态稳定性条件，根据飞行器惯性参数和气动力参数，判定所设计的飞行器纵向和横侧向静态都是稳定的；在飞行器动态性能方面，较为详细地介绍了飞行器刚体运动方程及小扰动情况下线性运动方程，以及纵向和横向运动状态空间方程和运动的近似方程，并求出了运动的精确解和近似解，结果表明纵向模态、横向模态、滚转模态和荷兰滚模态都是稳定的；传递函数是表征飞行器动态特性和对飞行器实施控制的重要依据，根据超小型定翼飞行器的稳定性导数及运动方程，推导出了其传递函数。

飞行控制和导航系统是实现飞行器姿态稳定和导航的根本保证。本文基于对现有小型无人机飞控与导航系统的组成、功能的分析对比，选择了微处理器，并提出了飞控与导航系统的层次结构和系统方案，据此设计制作了飞控与导航硬件系

统;在控制算法方面,首先采用 PID 算法实现了超小型固定翼飞行器飞行控制与导航,然后又研究了模糊自适应整定 PID 控制器,设计了基于舵机 PWM 模糊控制,使得模糊控制在微处理器上能够实现;根据地图投影之圆柱投影的基本理论,提出并建立了基于地图投影理论的导航参数计算原理及根据设定航线真北方位角差判断转弯转向的方法。建立了基于真北方位角差航线导航的方法,航路点到达的判断方法,及基于平面解析几何的航线跟踪方法。

针对所设计的超小型定翼飞行器硬件及软件系统,进行了姿态控制和导航地面测试和调试。最后进行了飞行试验,实现了预期的目标。

总之,本文就超小型定翼飞行器的若干关键技术开展了研究。借助 CFD 对超小型定翼飞行器涉及的低雷诺数空气动力学进行了较为系统深入的研究,设计了超小型定翼飞行器结构,分析结果表明静态和动态特性都是稳定的,根据飞行器传递函数实施姿态控制和基于地图投影理论完成导航控制,实现了超小型定翼飞行器基于航路点导航的自主飞行。

关键词 超小型定翼飞行器,低雷诺数,稳定性,地图投影,飞控与导航

Abstract

This article has conducted more systematic research on the questions about low Reynold's number aerodynamics, the structural design, the flight mechanics, the flight control and the navigation involved in Subminiature Fixed Wing Unmanned Aerial Vehicle (SUAV), which is part of the project "Flying Robot System Research" financially supported by National Hightech Research and Development Program. The main research contents are as follows:

In the aerodynamics aspect, in order to increase lift force of the Subminiature Fixed Wing UAV under the low Reynold's number, based on NACA2415 airfoil, this article makes aerodynamic optimization on the airfoil thickness, the position of max airfoil thickness and the airfoil camber with fast panel methods to compute aerodynamic coefficients, it is nice consistent with the optimized airfoil lift forces computed by XFOIL software and CFD, respectively, and aerodynamic performances of optimized airfoil has improved; The CFD computations obtain the contours of the airfoil boundary layer turbulence intensity, the turbulence intensity path lines, the contours of the turbulence intensity viscosity, the wall surface stress, the velocity gradient charts, and pressure contours. According to the above, this article has analyzed the airfoil

boundary layer under the low Reynold's number, and obtains the angle of attack which the boundary layer starts to separate, moreover, the separation characteristic parameters accord with the separation theory of boundary-layer; The 3D surface model of the designed wing has been constructed with CATIA, and its flow field is calculated with CFD, so that the wing aerodynamic coefficients are obtained; The coefficients of lift and drag of vertical and horizontal tails are calculated out by CFD with CATIA constructed models; According to the Subminiature Fixed Wing UAV model established by CATIA, the computations have got the aerodynamic coefficients, the stability derivatives and the control derivatives which are used to analyze the static stability, the dynamic performances and flight control.

In the structural design aspect, first according to the Subminiature Fixed Wing UAV missions, the total weight and three-dimensional wing aerodynamic parameters estimated by the wing airfoil aerodynamic parameters, the wing is designed with CATIA, and its performances are computed, results indicate that the wing satisfy the mission requirements; Next the fuselage has been designed with CATIA based on equipments loaded in fuselage, flight control and navigation system, the fuel oil and the recycling parachute, the fixed way of the engine and the fuselage, the connection way of wing and the fuselage and the connection way of landing gear and the fuselage, and so on; Then according to the analysis and the induction about tail wing structural styles of the

existing airplanes and UAVs, the tail wing structural style is chosen for SUAV; Furthermore the entire flight vehicle's solid model is constructed with CATIA according to its structure; Finally this solid model is analyzed by CATIA analysis functions, and gets the flight vehicle center-of-gravity, moments of inertia and products of inertia and so on.

In the flight mechanics aspect, the static stability is very important for flight vehicle, the present article illustrates the concept of the static stability and infers the condition of static stability, according to the inertia and aerodynamic parameters of this SUAV, it can be judged that the SUAV is longitudinal and lateral static stable; In the flight vehicle dynamic performance aspect, this article introduces in detail the flight vehicle rigid motion equations and the small perturbation linear motion equations, as well as longitudinal and lateral state-space equations and the motion approximate equations, and has got the exact and approximate solutions of motion, the results show that they are all stable for longitudinal mode, lateral mode, rolling mode, and Holland mode; The transfer functions not only express the flight vehicle dynamic characteristics, also are important basis of the flight vehicle control, according to the stability derivatives and the motion equations of the Subminiature Fixed Wing UAV, the transfer functions are inferred.

The flight control and the navigation system are the basic guarantees of realization the flight vehicle attitude stability and navigation. Based on the analysis and contrast of

compositions and functions of the existing small UAV flight control and navigation system, microprocessor has been chosen, and hierarchy architecture and composition are proposed for flight control and navigation, According to the above, the hardware system of flight control and navigation is designed and manufactured. First the flight control and navigation of the SUAV are realized by the PID algorithm, then the fuzzy auto-adaptive trim PID controller is studied and designed based on the servo PWM to enable the fuzzy control to be able to realize on the microprocessor; By cylindrical projection elementary theory of the map projection, this article proposes and establishes the navigation parameter computation principle based on the map projection theory, and the method of judging turning direction depending on the north azimuth error of set flight route, and establishes navigation method based on the north azimuth error, the judging method of waypoint arrival, and route track method based on plane analytic geometry.

In view of the designed Subminiature Fixed Wing UAV hardware and software system, test and debugging are carried on the attitude control and ground navigation. Finally, the flight tests are carried, and realized the anticipative goal.

In brief, this article does research on some key technologies of Subminiature Fixed Wing UAV. The low Reynold's number aerodynamics involved in Subminiature Fixed Wing UAV has been conducted more systematic research with the aid of CFD, the structure of Subminiature

Fixed Wing UAV is designed, the analysis results indicate that the static and dynamic characteristics all are stable, the attitude and navigation controls are realized according to the flight vehicle transfer functions and the map projection theory, respectively, the Subminiature Fixed Wing UAV realizes autonomous flight based on waypoint navigation.

Key words Subminiature Fixed Wing UAV, Low Reynold's number, Stability, Map projection, Flight control and navigation

目　录