AEM 5333: Design-to-Flight: Small Uninhabited Aerial Vehicles

Description: Designing, assembling, modeling, simulating, testing and flying of Uninhabited Aerial Vehicles. Rapid prototyping software tools for vehicle modeling. Guidance, navigation, and flight control, real-time implementations, hardware-in-the-loop simulations and flight tests.

Credits: 3 credits, A-F only

Prerequisites: AEM 4601 Instrumentation Lab, AEM 4202 Aerodynamics, and AEM 4303W Flight Dynamics and Control.

Instructor: Gary J. Balas

References

- M.V. Cook, *Flight Dynamics Principles*, Second Edition, Elsevier Ltd., Oxford, UK 2007
- B.L. Stevens and F.L. Lewis, *Aircraft Control and Simulation*, John Wiley & Sons, 1992, ISBN 0-471-61397-5
- Matlab and Simulink User's Guides

Introduction

Uninhabited Aerial Vehicles (UAVs) are defined as aircraft which fly without a human operator onboard. In recent years, there has been significant interest in the design and operation of small UAVs. It is important that the engineering workforce understands all aspects of UAV design and operation. Training this workforce requires rethinking of how aerospace engineers are educated since small UAVs are not simply miniaturized versions of large aircraft. Similarly, the design cycle for small UAVs will likely be in terms of month instead of years. Therefore rapid prototyping software tools are necessary to both improve and speed up the design, testing, and real-time implementation.

Course Description

The course is concerned with the design, building, modeling, simulation, testing and flying of UAVs. This semester the focus is on the use of rapid prototyping software tools for vehicle modeling, guidance, navigation, and flight control, real-time implementation, hardware-in-the-loop simulation and flight tests.

The prerequisites for the course will be AEM 2301 Mechanics of Flight, AEM 4601 Instrumentation Lab, AEM 4202 Aerodynamics, and AEM 4303W Flight Dynamics and Control.

Students will get hands-on experience of the entire UAV design cycle. Students will be assigned to groups. Each person in a group will learn one or more of the following skills:

1. Translate mission level specifications and requirements into vehicle level sizing, performance, reliability, and safety specifications.
2. System level design requirements for UAV systems, system architectures and cost tradeoffs.
3. Select actuators, sensors, communication systems, microcontrollers, and real-time computers to meet system level specifications.
4. Develop equations of motion for small UAVs from first principles and system identification techniques.

5. Develop linear and nonlinear models of a small UAV from the equations of motion and simulate their response to control inputs and disturbances.
6. Analyze the stability and control characteristics of the aircraft.
7. Use open-loop flight test data to identify and validate the UAV model based on first principles modeling.
8. Design flight control laws using feedback to achieve desire dynamic characteristics of the vehicle.
9. Implement and test feedback control algorithms in linear and nonlinear UAV simulation models.
10. Generate vehicle state information using Kalman filtering. An overview of Kalman filtering, GPS, inertial measurement units (IMUs), aircraft navigation and guidance will be provided.
11. Integrate guidance and navigation algorithms into the nonlinear UAV simulation.
12. Implement guidance, navigation and feedback control algorithms in real-time and verify that they execute properly in software-in-the-loop and hardware-in-the-loop simulations.
13. Perform closed-loop flight tests with real-time implementation of guidance, navigation and feedback control algorithms.
14. Compare closed-loop experimental flight test data with simulation data.
15. Redesign and flight test of flight control laws.

The course objective is for students to design, simulate, test and fly inner and outer-loop flight control laws for the candidate UAV. The control algorithms will be updated and redesigned based on software-in-the-loop, hardware-in-the-loop and flight tests. Students will work in groups of 5 or 6 to accomplish these objectives.

The course will not follow any of the texts directly and may vary from the syllabus depending on the level of the students. The homework and reports will require the students access to a computer account to use Matlab, Simulink, Control System Toolbox, Aerospace Blockset and Simulink Real-Time Workshop software products.

The course website is http://www.aem.umn.edu/courses/aem5495/spring2011/. It contains course announcements, syllabus, homework and solutions, design project information and lecture notes.

Student Responsibilities

The course will meet in one group for lectures every Monday and Wednesday. Regular attendance at lectures is strongly recommended. You are responsible for any course material, schedule changes, announcements, etc. discussed in class.

Course Outline

The following topics will be covered in this course: mission level requirements and specifications; vehicle specifications derived from mission requirements; linear and nonlinear simulation UAV model development in Simulink including wind gust modeling; simulation, trim, linearization of UAV model; extract linear models from flight test data; design, implementation and testing of longitudinal and lateral-directional axis flight controllers in a nonlinear simulation model; introduction to navigation and guidance algorithms; integration of navigation and guidance algorithm modules into nonlinear UAV simulation; generation of real-time control, navigation and guidance algorithms for integration into flight control computer; testing and validation of real-time algorithms in hardware-in-the-loop setup; real-tume systems, validation of flight test data, algorithms and models.

Week *Topics*

1. Overview of Uninhabited Aerial Vehicles (UAVs) and their potential uses; UAV mission requirements and specifications for design project; Derivation of vehicle and component level requirements. Selection of candidate UAV radio/controlled plane.
2. System level architecture description for UAV; definition of interfaces between components; basic overview of sensors and actuators, on-board computers. Overview of avionic systems. Digital/analog I/O, PWM signals, RS-232, Universal Serial Bus (USB), Ethernet, CAN Bus, CPU architectures, real-time operating systems, and communication.
3. Overview of the Ultrastick radio controlled aircraft. First principles modeling of a fixed wing aircraft. Derivation of longitudinal and lateral-directional transfer function models of candidate aircraft. MATLAB/Simulink refresher.
4. Modeling in Simulink. Development of Simulink linear aircraft models. Modeling of individual vehicle components (i.e. actuators, sensors, sample rate, filters, winds, commands, etc.). Implementation of component interface with radio-control box in Simulink. Testing and refinement of aircraft models based on flight data. Discuss how Simulink operates, Simulink blocks, masks, configurable subsystems, library blocks, inports, outports, sinks, sources, and signal flow.
5. Identification of aircraft aerodynamic coefficient s from flight tests. Flight test Ultrastick radio controlled aircraft. Extract nonparametric linear frequency response models of the UAV from flight test data and identify parametric 1st and 2nd order transfer function models with time-delays from frequency response data. (Maybe delayed based on weather.)
6. Inner and outer-loop flight control design for fixed wing aircraft.
7. Analysis and design of flight controllers for Ultrastick aircraft longitudinal and lateral-directional axes.
8. Simulink nonlinear aircraft model development based on equations of motion, wind tunnel data and flight data. Simulation, trim, linearization of nonlinear UAV model. Introduce the notion of model uncertainty, ranges of parameters, and the use of Monte Carlo simulations to validate designs. Implement and test flight control laws in linear and nonlinear Simulink aircraft equations of motion. Compare responses with flight test data.
9. Introduce navigation and guidance equations and avionic systems.
10. Integrate C subroutines into Simulink using S-functions. Integrate supplied guidance and navigation subroutines, developed in C, into nonlinear UAV Simulink model. Define trajectories and input sequences for flight tests. Test simulations. Discuss generation of real-time software using C subroutines and Simulink Real-time Workshop. Implement and test in software-in-the-loop and hardware-in-the-loop simulation control, guidance and navigation algorithms.
    a. Discussion of issues associated with hand coding versus use auto-code for real-time implementation of algorithms.
11. Validate and verify (V&V) hardware-in-the-loop (HIL) results meet vehicle and mission level specifications through Monte Carlo and worst-case simulation.
12. Flight test of complete UAV system; Verify and validate flight test results.
    a. Relate flight test results to HIL and simulation results. V&V typically consists of many Monte Carlo simulations results which verify the performance requirements are satisfied. Then a small number of flight tests are used to not only show that performance requirements are satisfied but also to confirm that the HIL and simulation models are accurate.
13. Redesign flight control algorithms, filters, trajectories, waypoints, etc.
14. Flight test redesigned algorithms and compare with simulation.
15. Compare flight test results of original and redesigned controller. Lessons learned.