COURSE TITLE: **UAS Modeling and Control**: ***A Comprehensive Approach***

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COURSE LEVEL: Graduate, PhD Student Level

Course Summary: The course objective is to provide a comprehensive study of unmanned fixed-wing, rotorcraft, and multirotor vehicle modeling and controller design techniques. Course modules include a review of kinematics, dynamics, equations of motion, parameter identification techniques, linear, linearized, and nonlinear controller design approaches, implementation, and testing – along with their advantages and limitations. A software-based platform for simulated experiments is introduced and used to compare performance of implemented techniques under nominal and detrimental conditions. Case studies include simulation and experimental results for several prototype UAVs. Consequently, a general framework for controller design of a class of nonlinear systems with unstructured, time-varying uncertainties (aerodynamic uncertainties) is proposed and implemented, and it is supported by obtained results.

Prerequisites: Knowledge of feedback control systems is required. Knowledge of fundamentals of robotics is desirable, but not necessary. All required background information will be presented in class.

Intended Audience: The course is suitable for graduate and doctoral students in the areas of Aeronautical, Electrical and Computer, Mechanical and Systems Engineering and Computer Science.

Schedule: To be decided.

COURSE OUTLINE

The list of topics to be covered and course modules are as follows:

First Part

- ***Introduction – course objectives***
- ***Review of rigid body motions, homogeneous transformations, coordinate frames for aided navigation and control***
    a. Fixed wing aircraft
    b. Rotorcraft (helicopters and multirotors)
- ***6-DoF Rigid body dynamics and kinematics***
    a. Derivation of Newton-Euler equations
    b. Derivation of Euler-Lagrange equations
    c. Position and orientation dynamics

d. Derivation of forces and moments
e. Moment of inertia and the inertia tensor
f. Gyroscopic effects
g. Drag modeling
h. Analytical proof of the Newton-Euler and Euler-Lagrange formulations

- ***Fixed wing, rotorcraft, and multirotor UAVs***
  - Definition and types/configurations
  - Fixed wing
  - Rotorcraft components/subsystems
  - Multirotor configurations
  - Equations of motion (EOM)
  - State space approach (Linear EOM, Linearized and nonlinear EOM)
  - Different flight modes (hover, aggressive, non-aggressive)
- ***System and parameter identification***
  - System ID general process
  - Parameter vs. Experimental
  - Time vs. Frequency
  - Frequency response method (Mettler), MOSCA (CMU)
  - Parameter based (Alberta)
  - Tools for flight testing/data collection
  - Simulation tools
- ***Control fundamentals*** (State space vs I/O approaches)
  - i. Model-based, model-free methods
  - ii. State space explanation
  - iii. Linearization of EOM
  - iv. Linear versus nonlinear versus model-free
  - v. Continuous versus discrete time
  - vi. Linear systems (PID, LQG/LQR, H-∞, Gain Scheduling, etc.)
  - vii. Nonlinear systems
  - viii. Feedback linearization
  - ix. Backstepping
  - x. Adaptive/MPC
  - xi. Controller tuning/optimization
  - xii. State-space approach
- ***Controller Design***
  - a. Linear/Non-linear
  - b. From design to implementation and testing
    - i. (Design, Simulation, Processor-In-the-Loop (PIL), Hardware-In-the-Loop (HIL), Flight testing/implementation
- ***A comprehensive control architecture***
  - a. Modularity
  - b. Add-on components (Fault tolerance, etc.)
  - c. Timing requirements
- ***Applications and case studies***

Second Part

- ***Introduction to the Koopman operator***
- ***Koopman-based modeling and control of multirotor UAVs***
    - *Position dynamics and control*
    - *Attitude dynamics and control*
    - *Controllability and Stability*
- ***Koopman-based controller design***
- ***Controller comparison***

Third Part

- ***Fundamentals of aerodynamics and fluid mechanics***
    a. Importance of Aerodynamics
    b. Aerodynamic Forces and Moments
    c. Vorticity Equation / Kelvin's Circulation Theorem / Helmholtz's Vortex Theorem
    d. Circulation
    e. Wing and Tail designs
- ***Circulation control wings (CCWs): From design to implementation and testing***
    Definition of Circulation Control
    Coandă Effect
    CCWs
    Wind Tunnel (WT) testing
- ***Controller Design***
- ***Implementation and results***

Course Material

Course material includes detailed power point presentations; survey papers; copy of *eBooks*.

1. Power Point Presentations (.pdf) and papers (.pdf).
2. M. Michailidis, K. P. Valavanis, M. J. Rutherford, Nonlinear Control of Fixed-Wing UAVs with Time-Varying and Unstructured Uncertainties, Springer 2020.
3. K. Kanistras, K. P. Valavanis, M. J. Rutherford, Foundations of Circulation Control Based Small- Scale Unmanned Aircraft: *A Comprehensive Methodology from Concept to Design and Experimental Testing*, Springer, 2018.
4. I. A. Raptis, K. P. Valavanis, Linear and Nonlinear Control of Small-Scale Unmanned Helicopters, *International Series on Intelligent Systems, Control and Automation: Science and Engineering*, Volume 45, Springer 2011.

PROJECT TEMPLATE

PROJECT REPORT LAYOUT TEMPLATE

General Outline of a Lab Project Report

Scientific writing is just as important as scientific investigation or experimentation. Although a major part of scientific investigation may be in a laboratory and/or in front of a computer, a great deal of time is spent to present the results in a concise, objective, critical and conclusive format, like writing a research paper.

A well-organized lab/project report is much more effective and influential than one without a structure. Advantages of a well-structured report include, among others: i.) influence your reader; ii.) impact on promotion and career advancement; iii.) draw the attention of the scientific community; iv.) archive the work/results so that the work will not have to be done in the future. A tentative structure of a lab/project report should include: Title; Abstract; Introduction; Procedures; Results and Discussion; Conclusions; Appendices. However, this template may not fit all labs/projects; you should pay attention to the specifics of the lab/project and modify the report structure accordingly.

Abstract

The abstract should be written concisely in normal rather than highly abbreviated English. The author should assume that the reader has some knowledge of the subject but has not read the paper. Thus, the abstract should be intelligible and complete in itself; particularly it should not cite figures, tables, or sections of the paper. The opening sentence or two should, in general, indicate the subjects dealt with in the paper and should state the objectives of the investigation. It is also desirable to describe the treatment by one or more such terms as brief, exhaustive, theoretical, experimental, and so forth.

The body of the abstract should indicate newly observed facts and the conclusions of the experiment/argument discussed in the paper. It should contain new numerical data presented in the paper if space permits; otherwise, attention should be drawn to the nature of such data. In the case of experimental results, the abstract should indicate the methods used in obtaining them; for new methods the basic principle, range of operation, and degree of accuracy should be given. The abstract should be typed as one paragraph. Its optimum length should not exceed 200 words.

Introduction

It identifies the project/experiment/study to be undertaken, the objectives of the project or experiment or study, importance, and overall background for understanding the project, study, experiment. The objectives are important to state because these objectives are usually analyzed in the conclusion to determine whether the project/study/experiment succeeded. The background often includes theoretical predictions for what the results should be.

Procedures

Procedures, often called the Methods, discuss how the experiment/study occurred. Documenting the procedures is important not only so that others can repeat your results but also so that you can replicate the work later if the need arises. Historically, procedures have been written as first- person narratives as opposed to second person sets of instructions. Because your audience expects you to write the procedures as a narrative, you should do so.

Achieving a proper depth in discussing procedures is challenging. In general, you should give the audience enough information so that they can replicate your results. For that reason, you should include those details that affect the outcome. Consider as an example the procedure for using a manometer and strain indicator to find the static calibration of a pressure transducer. Because calibrations are considered standard, you can assume that your audience will have access to many details such as possible arrangements of the valves and tubes. What you would want to include, then, would be those details that might cause your results to differ from those of your audience. Such details would include the model number of the pressure transducer and the pressure range for which you calibrated the transducer. Should you have any anomalies, such as unusual ambient temperature, during your measurements, you would want to include those. When the procedure is not standard, the audience would expect more detail including theoretical justification for the steps.

Results and Discussion

The heart of a project/laboratory report is the presentation of the results and the discussion of those results. In some formats, Results and Discussion appear as separate sections. Use your judgment. For instance, combine these sections when the discussion of your first result is needed to understand your second result, but separate these sections when it is useful to discuss the results, after all results are reported. In discussing the results, you should not only analyze the results, but also discuss the implications of those results. Moreover, pay attention to the errors that existed in the experiment, both where they originated and what their significance is for interpreting the reliability of conclusions.

Conclusions

A Conclusion section often appears. Whereas the Results and Discussion section has discussed the results individually, the Conclusion section discusses the results in the context of the entire project/experiment. Usually, the objectives mentioned in the Introduction are examined to determine whether the project/experiment succeeded. If the objectives were not met, you should analyze why the results were not as predicted. Note that in shorter reports or in reports where Discussion is a separate section from Results, you often do not have a "Conclusion" section.

Appendices

One type of appendix that appears in reports presents information that is too detailed to be placed into the report's text. For example, if you had a long table giving voltage-current measurements for an RLC circuit, you might place this tabular information in an appendix and include a graph of the data in the report's text. Another type of appendix that often appears in reports presents tangential information that does not directly concern the experiment's objectives.

If the appendix is formal, it should contain a beginning, middle, and ending. For example, if the appendix contains tables of test data, the appendix should not only contain the tabular data, but also formally introduce those tables, discuss why they have been included, and explain the unusual aspects that might confuse the reader. Because of time constraints, your instructor might allow you to include "informal" appendices with calculations and supplemental information. For such "informal" situations, having a clear beginning, middle, and ending is not necessary. However, you should still title the appendix, place a heading on each table, place a caption beneath each figure, and insert comments necessary for reader understanding.