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COURSE TITLE: **Navigation and Control of Unmanned Aerial Vehicles (UAVs):** ***A Comprehensive Approach***

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COURSE LEVEL: **Graduate - MSc and PhD Student Level**

Course Summary: The course objective is twofold: i.) Provide a comprehensive study of unmanned fixed-wing and rotorcraft navigation and control techniques, including a review of kinematics, dynamics and equations of motion, sensors, identification, controller design and implementation, as well as advances in unmanned aviation technology. When focusing on multi-rotor UAVs, a detailed modeling approach based on Lagrange formulation is followed, which also accounts for rotor dynamics, gyroscopic effects, all types of drag, disturbances, and abrupt changes of mass. A comprehensive presentation of linear, linearized, nonlinear and soft-computing based controller designs are discussed, the focus being on helicopter, rotorcraft, and fixed-wing navigation and control designs. A comparison of advantages and limitations of implemented techniques follows, subsequently introducing a generalized 'one-fits-all' flight control system (FCS) in which the specific controller design approach is a plug-in-plug-out module. Implementation details and how to guarantee task execution given strict timing requirements is detailed. Case studies include simulation and experimental results for several prototype UAVs. ii.) Present a detailed methodology for designing and navigating/controlling a new type of fixed-wing aircraft with enhanced aerodynamic performance based on the concept of Circulation Control, which allows for lift enhancement, reduced takeoff and landing distance, delayed stall and increased effective payload. CC based aircraft design is followed by controller design that also includes identification of stability and control derivatives. Simulation results, experimental/wind-tunnel and flight tests validate and verify the proposed methodology. Consequently, a general framework for controller design of a class of nonlinear systems with unstructured, time-varying uncertainties (aerodynamic uncertainties) is proposed, 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, Mechanical and Systems Engineering.

COURSE OUTLINE

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

First Component

- *Introduction*
    a. Brief History of Unmanned Aviation
    b. Types of Unmanned Aircraft
    c. Current state-of-the-art
    d. Challenges

- *Review of rigid body motions, homogeneous transformations, coordinate frames for aided navigation*
    a. Fixed-wing aircraft
    b. Rotorcraft (helicopters and multi-rotors)
- *6-DoF Rigid body dynamics and kinematics*
    a. Derivation of Lagrange and Newton-Euler equations
    b. Position and orientation dynamics
    c. Derivation of forces and moments
    d. Moment of inertia and the inertia tensor
- *Unmanned Fixed-Wing and Rotorcraft*
    - Definition and types/configurations
    - Rotor heads
    - Rotorcraft components/subsystems
        - Rotors
        - Rotor head and swash plate
        - Engine
        - Servos/actuators
        - Fuselage
        - Tail stabilizers (vertical and horizontal fins)
        - Feedback gyro (single-axis yaw and 3D gyro)
    - Pilot input mapping to control surfaces
    - Forces generated / Aerodynamics
    - Equations of motion (EOM)
    - State space approach (Linear EOM, Linearized and nonlinear EOM)
    - Different flight modes (hover, aggressive, non-aggressive)
- *Sensors and communication*
- *UAS Navigation controller technology*
- *System 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 for Unmanned Rotorcraft and Fixed-wing aircraft*
    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

- *Comprehensive Navigation-Control Architecture*
    a. Modularity
    b. Add-on components (Fault-tolerance, etc.)
    c. Timing requirements
- *Applications and case studies*

<u>Second Component</u>

- *Fundamentals of Aerodynamics and Fluid Mechanics*
    b. Importance of Aerodynamics
    c. Aerodynamic Forces and Moments
        i. The Aerodynamic Coefficients - Magnitude and Variations
        ii. Airfoil Nomenclature
        iii. Airfoil Characteristics
        iv. Applied Aerodynamics: Flow Over an Airfoil – The Real Case
        v. Classical Thin Airfoil Theory:
            The Symmetric Airfoil
            The Cambered Airfoil
    d. Vorticity Equation / Kelvin's Circulation Theorem / Helmholtz's Vortex Theorem
    e. Circulation
        i. Kuta, Joukowski, and the Circulation Theory of Lift
        ii. Prandtl's Classical Lifting - Line Theory
        iii. Boundary layer control
        iv. Supercirculation
    f. Wing and Tail designs
    g. Aerodynamics and Forces generated
        i. Fuselage
        ii. Control surfaces
- *Circulation Control Wings (CCWs): From Design to Implementation and Testing I*
    Definition of Circulation Control
    Coandă Effect
    History of Upper Surface Blowing
    Circulation Control (CC) Fundamentals
    CCWs
        iii. Airfoil shapes for CC
        iv. Trailing Edge (Coanda Surface) Design
        v. Flap design
        vi. Aileron Design
        vii. Flow Uniformity at the Slot-Exit
        viii. Plenum Design
        ix. Air Supply Unit (ASU)
    NASA focus on CC
- *Circulation Control Wings (CCWs): From Design to Implementation and Testing II*
    Wind Tunnel & Instrumentation
    Experimental Setup
        x. CCW
        xi. Plenum
        xii. Air Supply Unit
    CFD Results

Experimental Results
The Future of CCWs

- *Controller Design*
  Modeling assumptions
  Modeling of uncertain systems
  Longitudinal and Lateral Controller
- *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. K. Dalamagkidis, K. P. Valavanis, L. A. Piegl, On Integrating Unmanned Aircraft Systems in to the National Airspace System: Issues, Challenges, Operational Restrictions, Certification, and Recommendations, *International Series on Intelligent Systems, Control and Automation: Science and Engineering*, Volume 54, Springer, 2nd Edition, 2012.
5. 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. ***(Also translated and published in Chinese)***.