



Flight Dynamics and Control of Vertical Lift Vehicles



June 2023

Dr. Umberto SAETTI
Assistant Professor
Department of Aerospace Engineering



Presenter's Bio



Education

- **Penn State**
 - Ph.D. Aerospace Engineering (2019)
 - M.Sc. Electrical Engineering (2017)
 - M.Sc. Aerospace Engineering (2016)
- **Politecnico di Milano (Italy)**
 - B.Sc. Aerospace Engineering (2014)

Research Experience

- Assistant Professor (**University of Maryland**) 2022-Present
- Assistant Professor (**Auburn University**) 2021-2022
- Postdoctoral Fellow (**Georgia Tech**) 2019-2021
- Graduate Research Assistant (**Penn State**) 2015-2019
- Visiting Scholar (U.S. Army ADD, **NASA Ames**) 2018

Research Field

- Flight Dynamics & Control, System ID, Handling Qualities
- Human-Machine Interaction
- Time-Periodic Systems



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Extended Reality Flight Simulation and Control Lab



VR/AR Headset

- VRgineers XTAL 8K
- Resolution: 3840x2160 (4K) per eye
- 180 deg field of view
- Refresh rate: 75 hz @ 4K per eye
- Hand Tracking
 - Ultraleap Motion Rigel
 - 170 deg circular viewing angle
- Eye tracking @ 100 Hz



Full-Body Haptics

- TESLASUIT
- Haptic system
 - 80 electrostimulation channels (114 electrodes)
- Biometry (electrocardiography)
- Motion tracking
 - IMU 9 and 6 axes
 - 10 motion capture sensors



Motion-Base Simulator

- **Heave:** ± 185 mm, ± 600 mm/s
- **Surge:** ± 240 mm, ± 600 mm/s
- **Sway:** ± 240 mm, ± 600 mm/s
- **Roll, Pitch, Yaw:** ± 30 deg, ± 120 deg/s



Extended Reality Flight Simulation and Control Lab



Simulation Unit #1



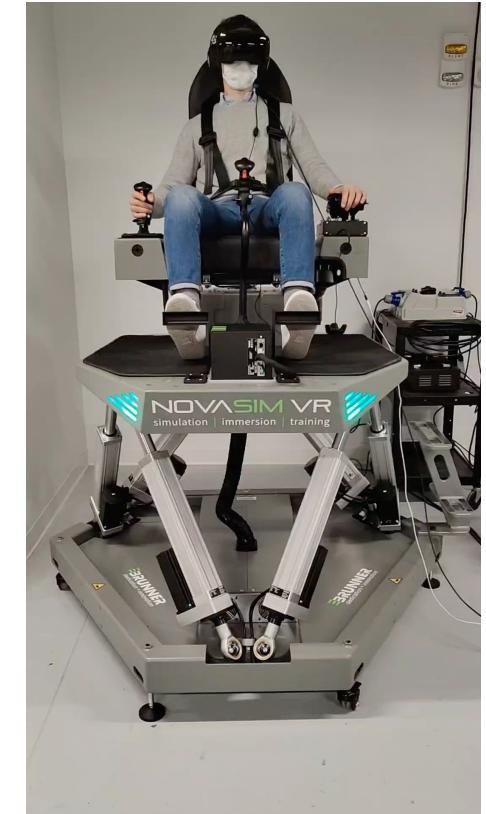
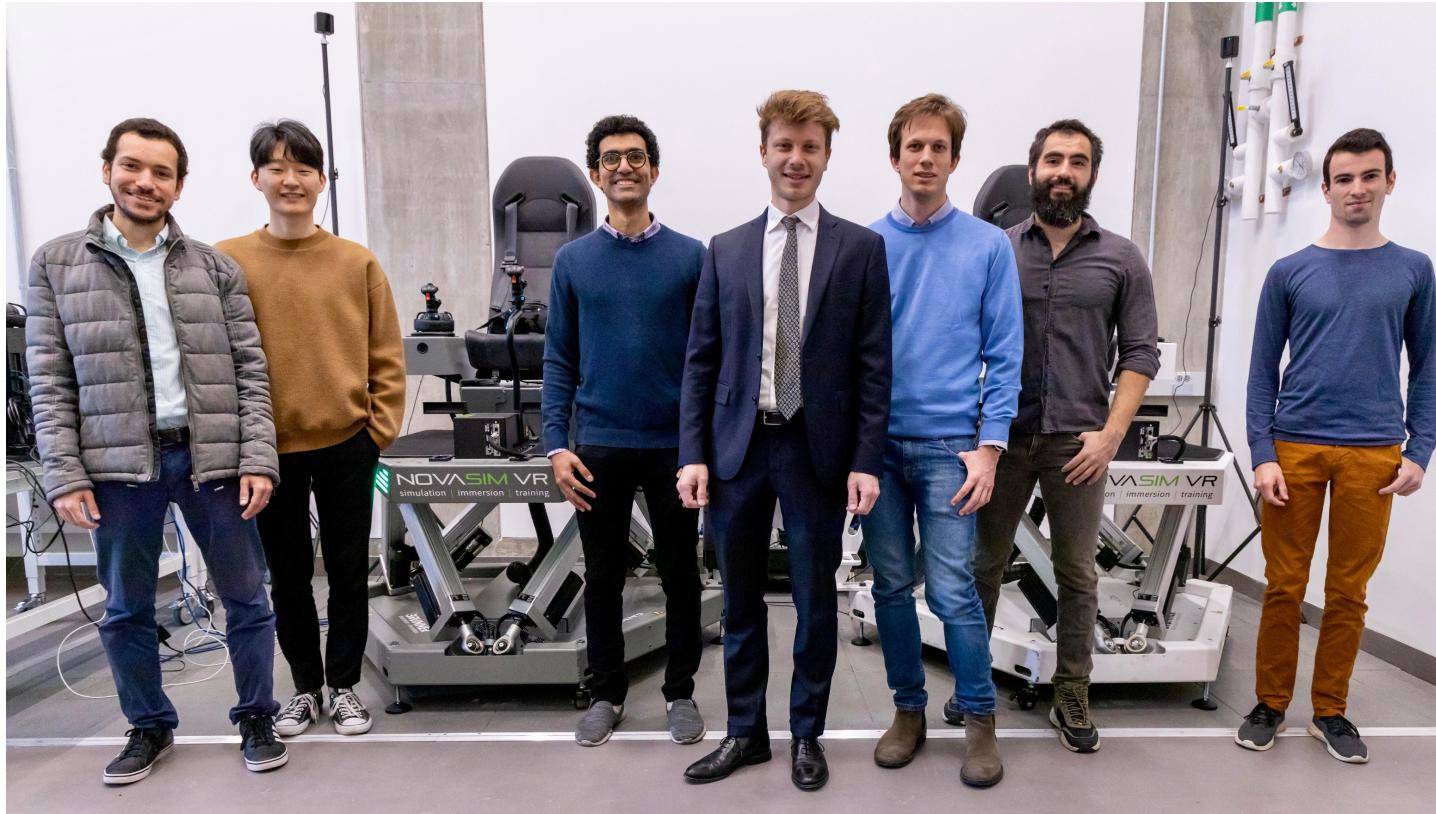
**Central
Computing Unit**



Simulation Unit #2

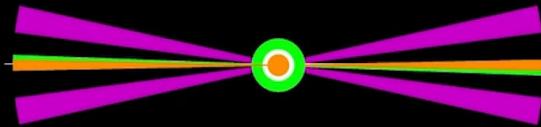
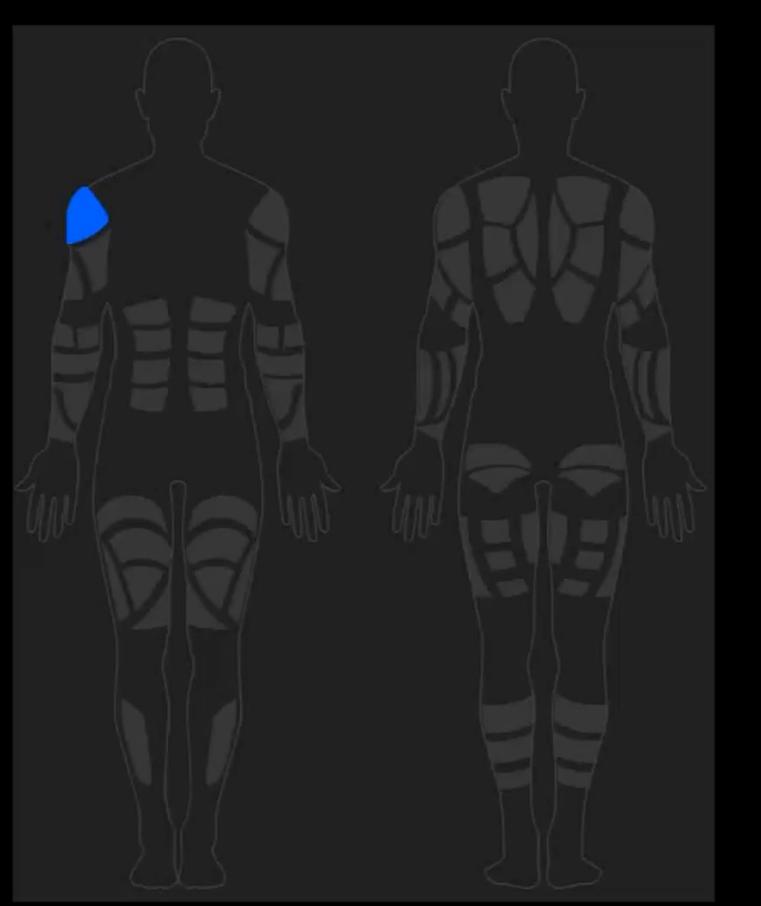


Extended Reality Flight Simulation and Control Lab





Extended Reality Flight Simulation and Control Lab





Course Overview





Course Overview



- **Lecture 1:** Course Introduction and Review of Fundamentals in Vertical Flight Aerodynamics
- **Lecture 2:** Modeling of the of Rotorcraft Flight Dynamics
- **Lecture 3:** Trim, Linearization, and Model-Order Reduction
- **Lecture 4:** Dynamic Modes of Motion in Hover and Forward Flight
- **Lab 1:** Dynamic Analysis of a Simple Helicopter Model
- **Lecture 5:** Intro to Rotorcraft Flight Control Design
- **Lecture 6:** Modern Flight Control Design I: Explicit Model Following
- **Lab 2:** Implementation of Explicit Model Following Flight Control Law
- **Lecture 7:** Modern Flight Control Design II: Dynamic Inversion
- **Lab 3:** Implementation of Dynamic Inversion Flight Control Law
- **Lecture 8:** Stability, Handling Quality, and Performance Specifications
- **Lecture 9:** Model Stitching/Tiltrotor Modeling and Simulation

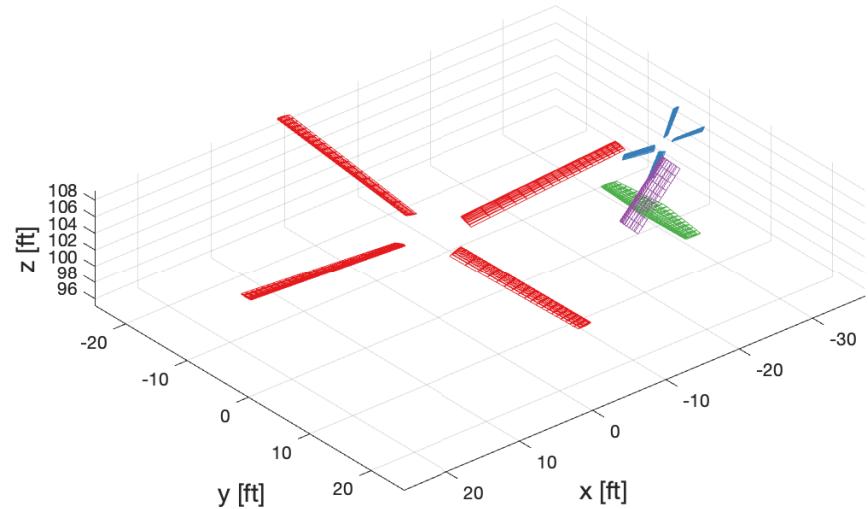


Course Overview



Course Objectives

- Provide you with fundamentals of rotorcraft flight dynamics modeling, simulation, and control
- Apply modern computational tools to rotorcraft simulation and stability analysis
- Develop scripts to be used later on in research
- Make you aware of contemporary trends in rotorcraft (drones, tilt rotors, compound rotorcraft, eVTOL)
- Inspire you to pursue rotorcraft studies or a career in rotorcraft flight dynamics and controls
- Give you a feel of what it means to work as a rotorcraft flight dynamics and control engineer





Course Overview



Prerequisites

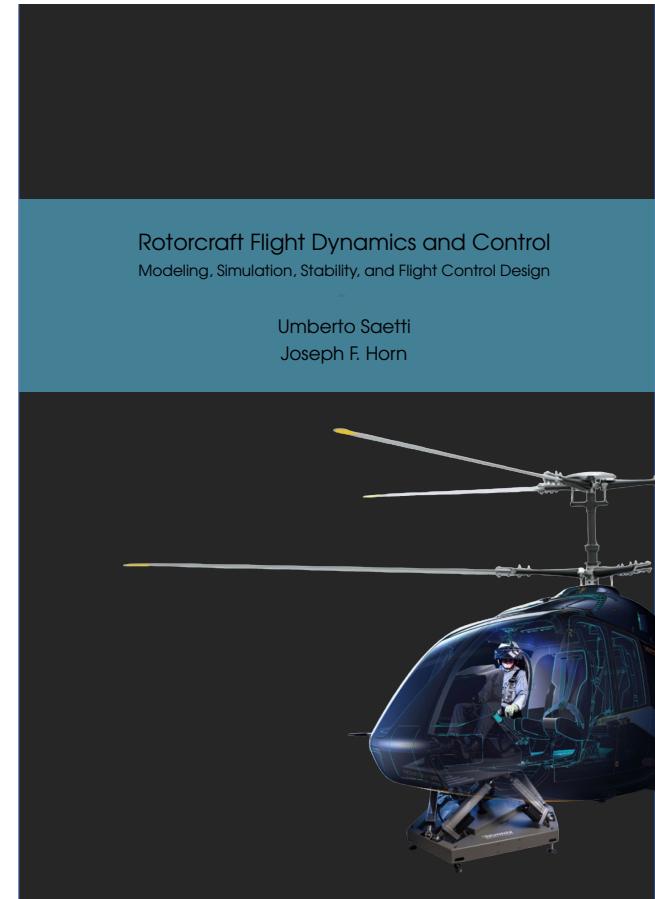
- Basic helicopter aerodynamics + system dynamics

Good to Know

- MATLAB/Simulink (tutorial:
<https://www.mathworks.com/support/learn-with-matlab-tutorials.html>)

References

- Class notes
- Padfield, G. D., "Helicopter Flight Dynamics: Including a Treatment of Tiltrotor Aircraft", Wiley, 3rd Edition, 2018, ISBN: 978-1-119-40105-6.
- Tischler, M. B. et al., "Practical Methods for Aircraft and Rotorcraft Flight Control Design: An Optimization-Based Approach", AIAA Education Series, 2017, DOI: <https://doi.org/10.2514/4.104435>.
- Stevens, B. L., Lewis, F. L., and Johnson E. N., "Aircraft Control and Simulation: Dynamics, Controls, Design, and Autonomous Systems," Wiley, 3rd Edition, 2015, ISBN: 978-1-118-87098-3.





Single Main Rotor Helicopter



Sikorsky S-64 Skycrane



AgustaWestland AW-189



Robinson R-22 Mariner



Eurocopter EC-135



Coaxial Rotor Helicopter



Kamov Ka-32



Gyrodyne QH-50 DASH



Sikorsky S-97 Raider



Sikorski SB>1 Defiant



Tandem Rotor Helicopter



Boeing CH-47 Chinook



Boeing Vertol 107-II



Piasecki YH-21 "the Flying Banana"



Yakovlev Yak-24



Synchropter (Intermeshing Rotors)



Kaman HH-43 Huskie



Kaman K-MAX



SNCAC NC.2001 Abeille



Tilt Wing



A³ by Airbus Vahana



Ling-Temco-Vought (LTV) XC-142



NASA GL-10 Greased Lightning



Tilt Rotor



Bell V-280 Valor



Bell Boeing V-22 Osprey



AgustaWestland AW-609



Tip Driven Rotorcraft



Hiller YH-32 Hornet



McDonnel XV-1



Sud-Ouest Djinn



F-Helix eVTOL Concept



Compound Helicopter



Airbus RACER



Piasecki 16H-1A Pathfinder II



Fairey Rotodyne



Sikorski X-2



Rotorcraft Manufacturers



Largest Companies

■ USA

- Bell (Dallas Fort Worth, TX)
- Sikorsky (Stratford, CT, West Palm Beach, FL)
- Boeing (Philadelphia, PA, Mesa, AZ)
- Robinson (Torrance, CA)
- Kaman (Bloomfield, CT)
- Piasecki (Ridley Park, PA)
- AugustaWestland USA (Philadelphia, PA)

■ Europe

- Leonardo Helicopters (former AgustaWestland, Italy)
- Airbus Helicopters (former Eurocopter, France, Germany)

■ Other

- Turkish Aerospace



Bell 525 Relentless



Airbus H-160



AgustaWestland AW-609



Exciting Times for Rotorcraft

US Army Army Future Vertical Lift (FVL) Program

Future Long Range Assault Aircraft (FLRAA) → Replace UH-60 Black Hawk



Sikorsky SB-1 Defiant



Bell V-280 Valor

Future Attack and Reconnaissance Aircraft (FARA) → Replace OH-58 Kiowa



AVX/L3



Bell 360 Invictus



Sikorsky Raider X



Karem AR-40



Exciting Times for Rotorcraft



Urban Air Mobility





Exciting Times for Rotorcraft



Drone Delivery



Elroy Air



Amazon Prime Air



Google Wing



Rotorcraft Research



Universities

■ USA

- Vertical Lift Research Center of Excellence (VLRCOE):
[U Maryland](#), [Georgia Tech](#), [Penn State](#)
- Auburn, Texas A&M, Rensslear Polytechnic, UT Arlington, Embry-Riddle

■ Europe

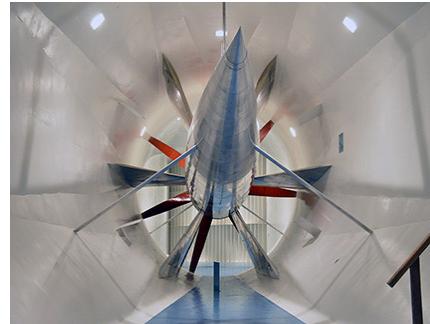
- Network for Innovative Rotorcraft Research (Nitros): Milan Polytechnic (Italy), TU Munich (Germany), TU Delft (Netherlands), University of Liverpool (UK), University of Glasgow (Scotland, UK)

Government Agencies

- NASA, Army (CCDC), Navy (ONR, NAVAIR), Air Force

Main Conferences

- Vertical Flight Society Annual Forum (May)
- European Rotorcraft Forum (September)



Glenn L. Martin Wind Tunnel



NASA Ames Research Center



Penn State's Rotorcraft Flight Simulation Facility



Rotorcraft Research at UMD



Faculty Members

- **Dr. I. Chopra** – Rotorcraft Aerodynamics, Design, Smart Structures
- **Dr. A. Datta** – Structural Dynamics, Rotor Dynamics
- **Dr. J. Baeder** – CFD, Aeroacoustics
- **Dr. U Saetti** – Flight Dynamics & Control

UMD Vertical Flight Society Chapter

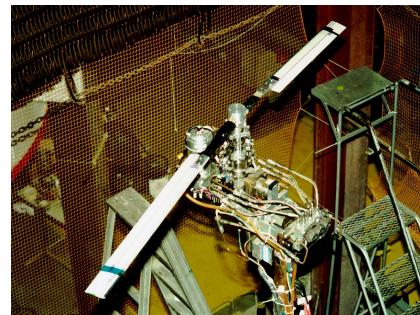
- President: Nathan O'Brien (nobrien2@umd.edu)



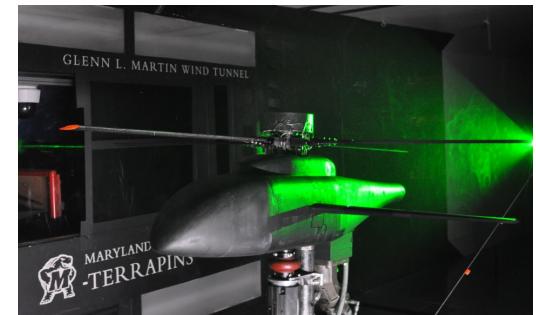
UMD Tiltrotor Rig



Extended Reality Flight Control and Simulation Lab



Hover Tower



Helicopter / Compound Rig



Definitions



Definitions

- **Trim:** An equilibrium flight condition. The states defining the aircraft dynamics are constant with time.
- **Stability:** Tendency of an aircraft to return to equilibrium (trim) following a disturbance
- **Control:** Ability of the aircraft to be maneuvered from one flight condition to another
- **Static Stability:** Tendency of an aircraft to *initially* return to equilibrium following a disturbance (does not necessarily imply stability). Static stability is a necessary but not sufficient condition for stability.



Definitions



Definitions

- **Flight Dynamics:** The study of how an aircraft responds to control inputs and disturbances. Purely objective science based on aircraft aerodynamics and equations of motion
- **Handling Qualities:** “Qualities that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.” Combination of objective and subjective sciences, a function of a number of factors:
 - Stability and control characteristics of aircraft
 - Mission requirements
 - Human factors
 - Environmental conditions
- **Flying Qualities:** Includes Handling Qualities and “Ride Qualities” (aircraft qualities that impact passenger comfort and experience)



Definitions



Definitions

- **Rotorcraft Flight Dynamics:** The study of the motion of the aircraft as it relates to handling qualities and maneuvering performance.
- **Rotorcraft Dynamics:** Usually refers to the study of the dynamics of the rotor system as it relates to loads, vibration, and rotor stability analysis.



Definitions



Rotocraft Flight Dynamics

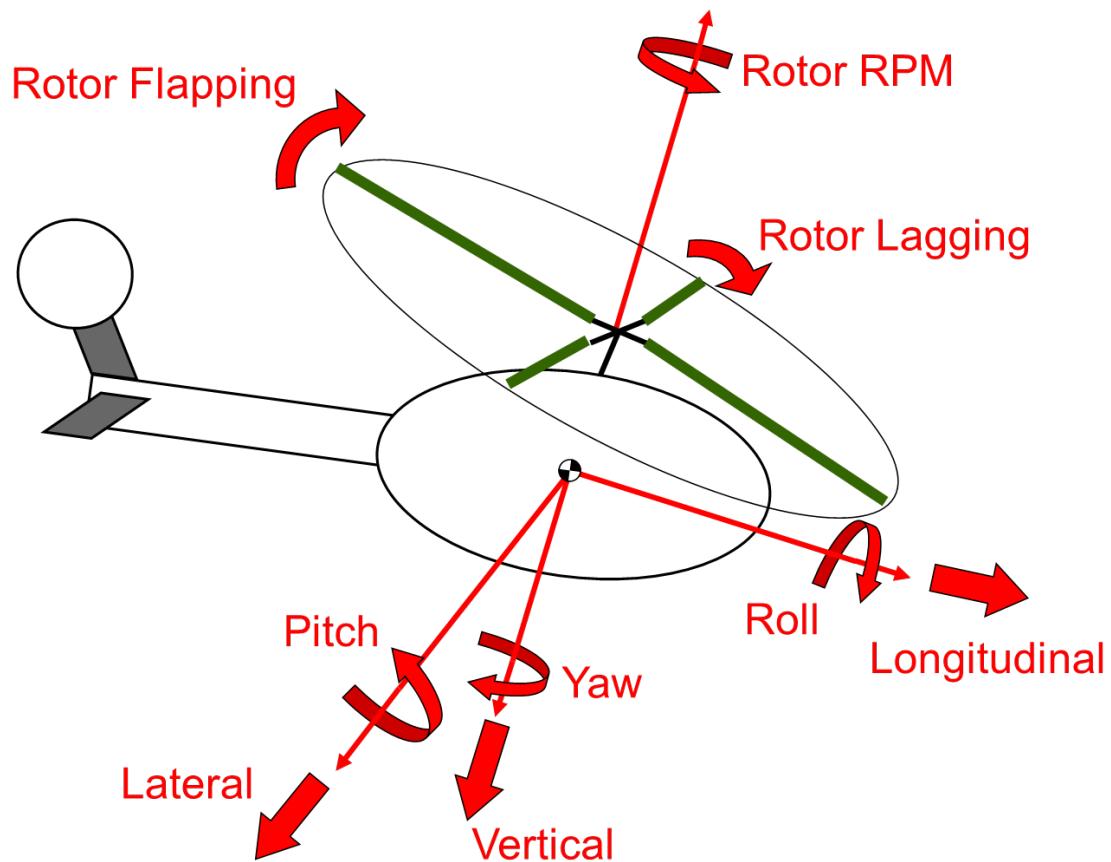
- Captures low frequency dynamics (steady-state to 1/rev)
- Usually assume rigid blades
- Usually use assume rigid fuselage
- Finite-state inflow model
- Detailed model of fuselage aerodynamics
- Detailed model of automatic flight control systems and engine dynamics
- Detailed model of aerodynamic interference effects
- Can simulate large amplitude maneuvers
- Real-time operation is desirable

Rotorcraft Dynamics

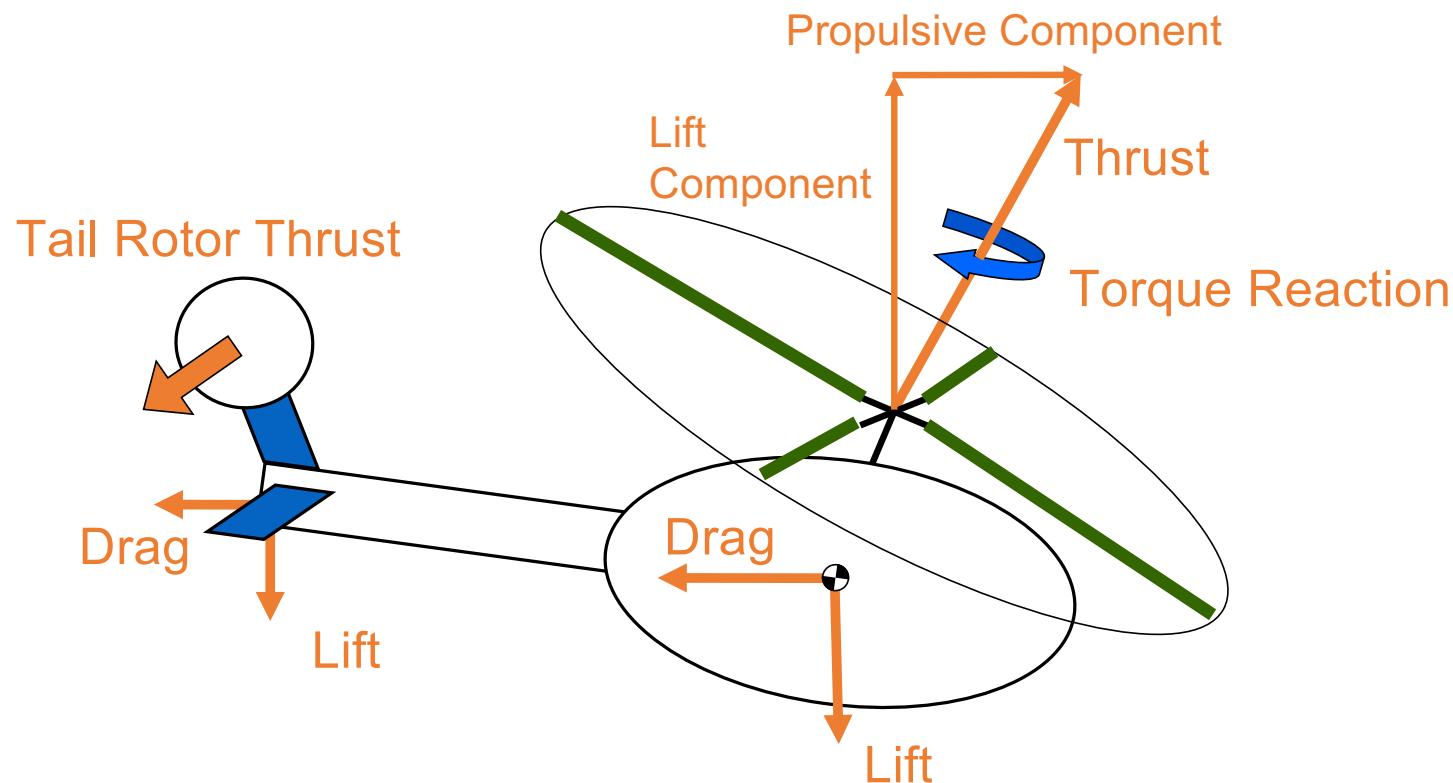
- Captures high frequency dynamics (out to n/rev and above)
- Flexible blades models
- Flexible fuselage models (sometimes)
- More complex wake models (free wake)
- Often use simple models of fuselage aerodynamics, engine dynamics, automatic flight controls, because ...
- Normally used for analysis of trimmed (or quasi-steady) flight conditions only
- Real-time operation not normally feasible



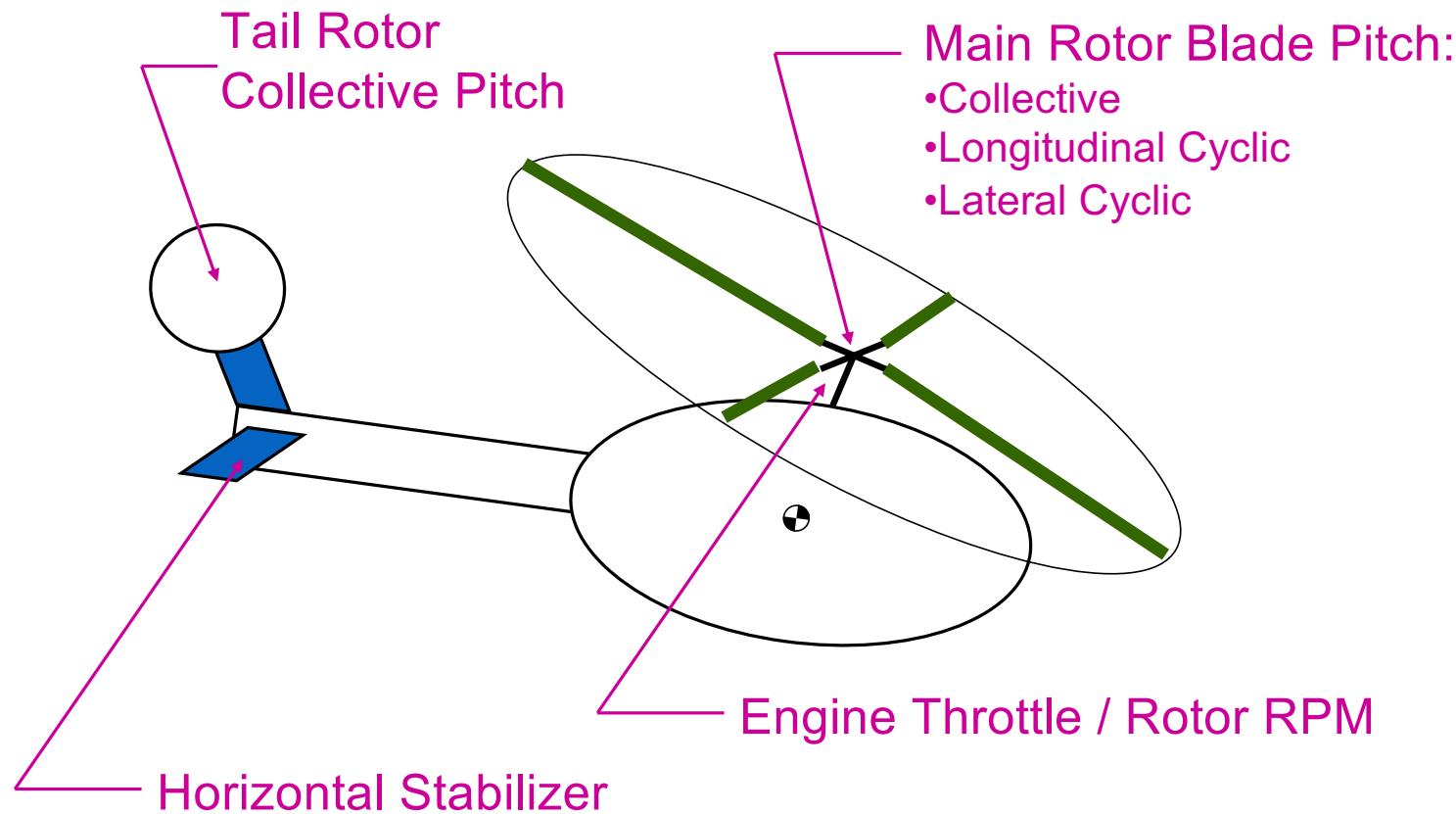
Rigid Helicopter Degrees of Freedom



Helicopter Forces



Helicopter Controls





Modeling and Simulation Challenges





Modeling and Simulation Challenges

Background

- Gap closing between
 - ❑ Rotorcraft flight dynamics simulations
 - ❑ Comprehensive aeromechanics codes
- New rotorcraft configurations more complex
 - ❑ FVL and UAM
 - ❑ Multiple rotors
 - ❑ High-level of aero interaction
 - ❑ High rotor RPM (UAV)
- Difficult to achieve real time
 - ❑ Small dt
 - ❑ Multiple rotors
 - ❑ Rotor-on-rotor/wing interactions





Modeling and Simulation Challenges



Background

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Joby S4



Leonardo AW609

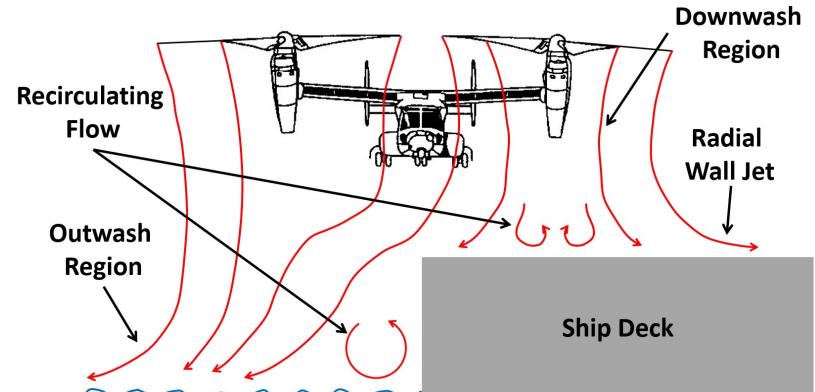
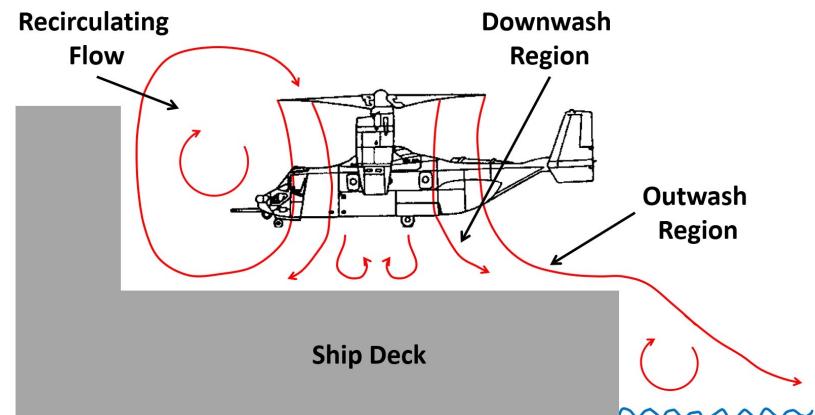


Modeling and Simulation Challenges



Obstacle Interactions

- Shipboard interactions
 - Ship deck
 - Ship superstructures
 - Sea surface
- Interactional aerodynamics affects
 - Performance
 - Handling qualities
- Fatal MV-22 Osprey crashes
 - USS Green Bay (2017)
 - New Orleans (2015)
- Investigation outcomes
 - Rotor downwash recirculated in rotor
 - Increased power and adverse HQ





Modeling and Simulation Challenges



V-22 Osprey in a shipboard approach and landing



V-22 Osprey crash on USS Green Bay

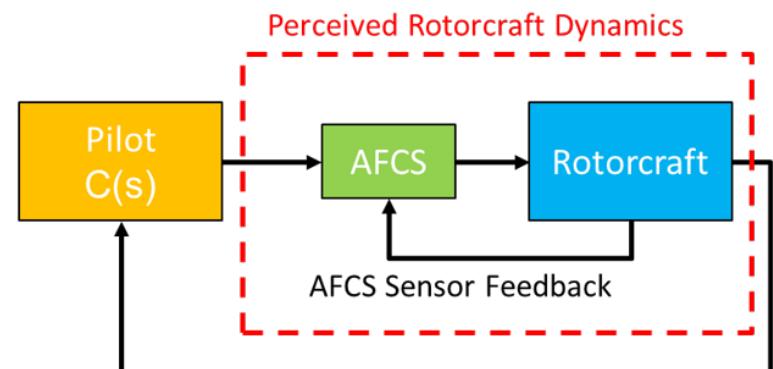
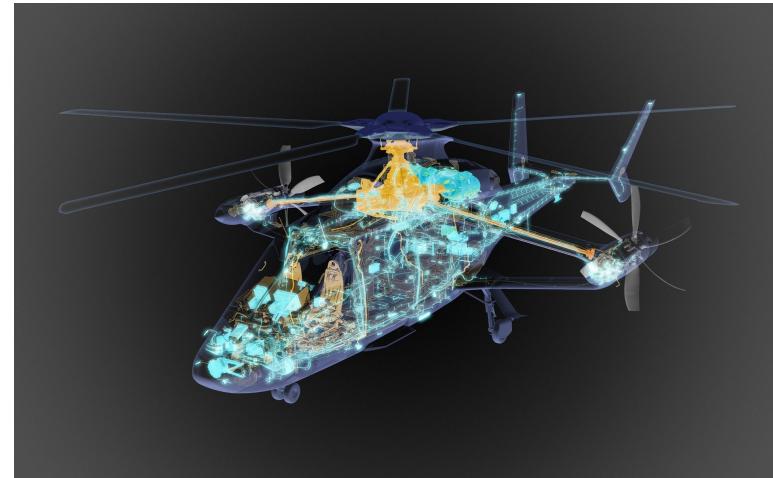
Control Challenges

Rotorcraft are difficult to fly

- ❑ Inter-axis coupling
- ❑ Unstable + high-order flight dynamics
- ❑ Pilot must actively regulate all four control axes
- ❑ Restrictive flight envelope due to complex power and structural limits
- ❑ Flight dynamics changes across flight envelope

Need for Automatic Flight Control Systems (AFCS)

- ❑ Improve handling qualities
- ❑ Alleviate pilot workload
- ❑ Closed-loop dynamics yield simple, predictable response to commanded output, $Y/R(s)$



Control Challenges



1. Stable Hover



2. Nose up perturbation



3. Build up aft velocity, rotor flaps forward



4. Nose down, aft velocity arrested



5. Build up forward velocity, rotor flaps aft



6. Nose up, forward velocity arrested



7. Build up aft velocity, rotor flaps forward



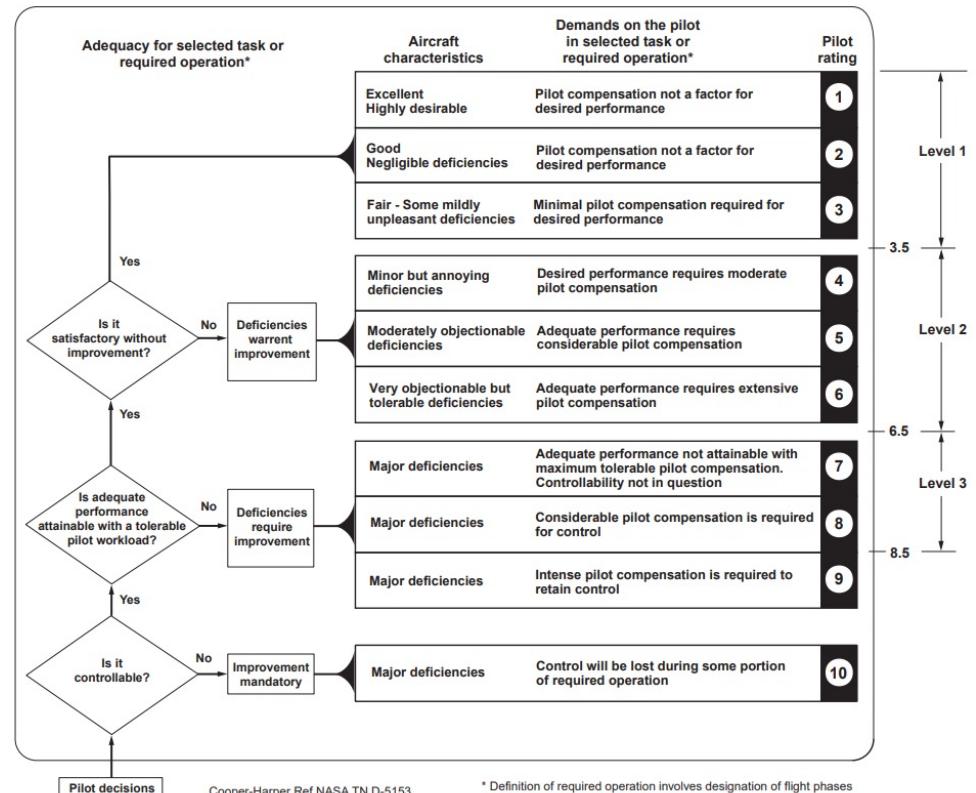
8. Back the other way, repeat



Control Challenges

Rotorcraft Handling Qualities (HQ)

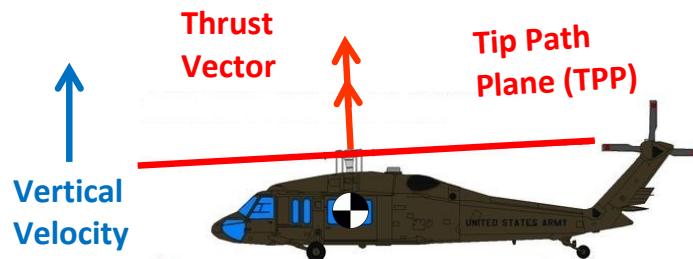
- ❑ Ease and precision with which a pilot can perform aircraft mission
- ❑ Quantitative measures of aircraft response characteristics “Level”
Level 1 = Good, Level 3 = Bad
- ❑ Aeronautical Design Standard 33 (ADS-33) is HQ Standard for military rotorcraft
- ❑ HQ standards still in development for UAM + other categories (tiltrotors)
- ❑ “Response Type”: which state exhibits proportional response to pilot input
- ❑ Natural helicopter response type of is angular rate command



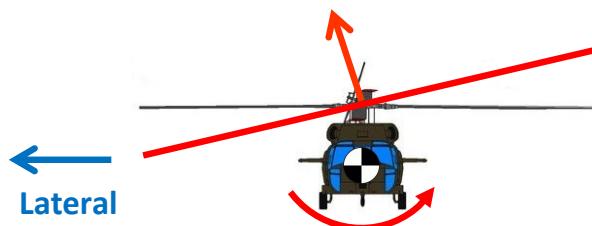
Cooper-Harper HQ Rating Scale



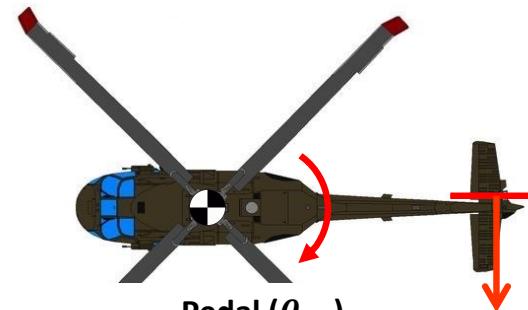
Control Challenges



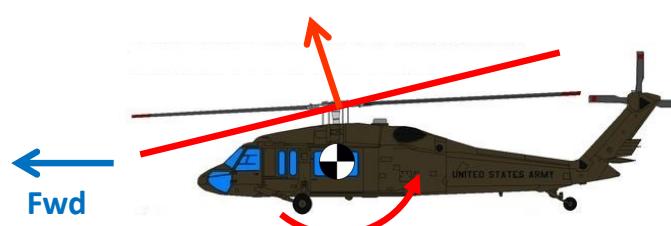
Collective (θ_0)
Increase magnitude
of thrust vector



Lateral Cyclic (θ_{1c})
Direct thrust vector
left/right

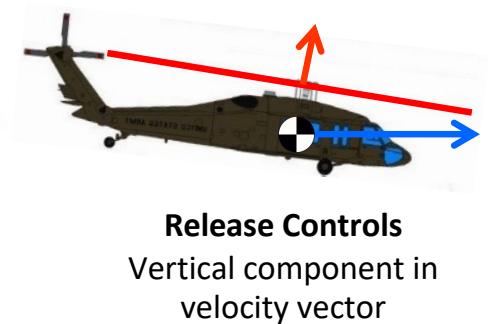
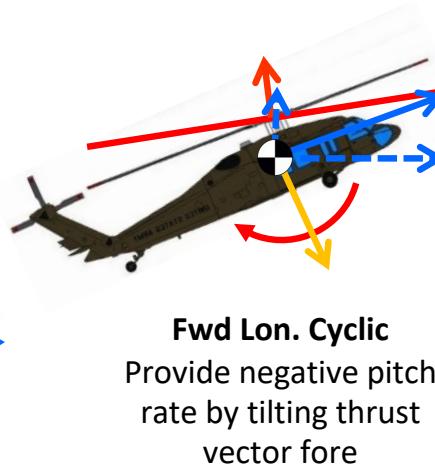
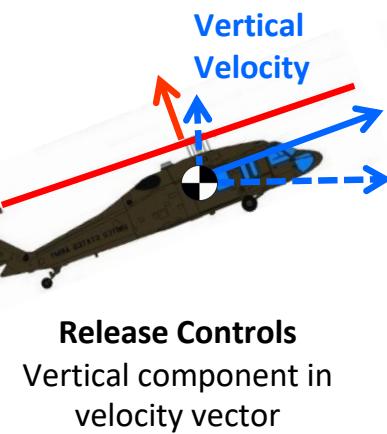
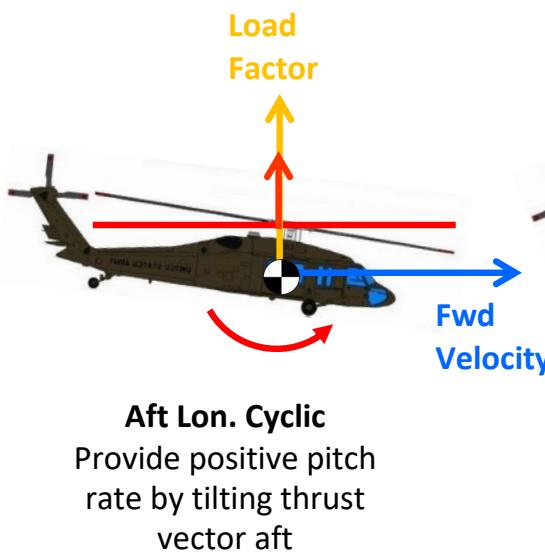


Pedal (θ_{0T})
Increase magnitude
of tail rotor thrust vector



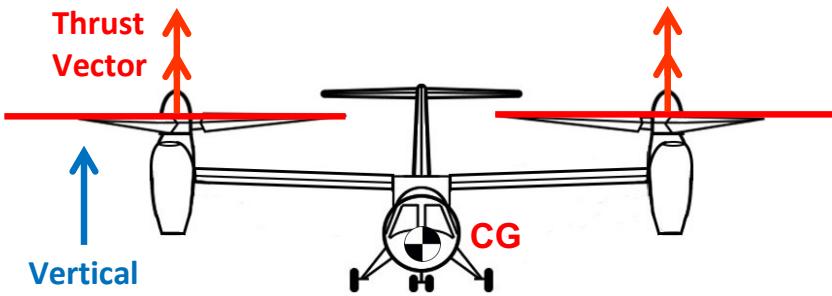
Longitudinal Cyclic (θ_{1s})
Direct thrust vector
fore/aft

Control Challenges

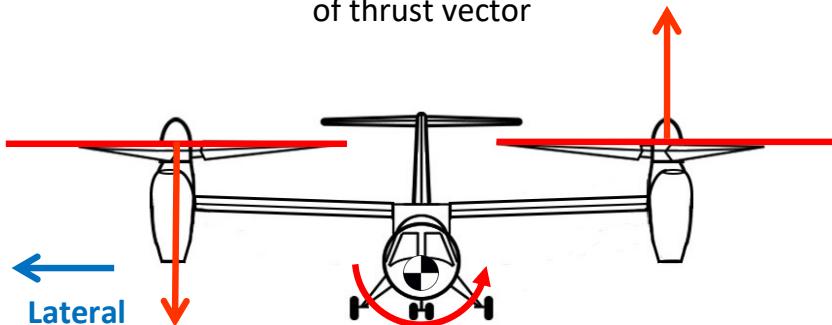




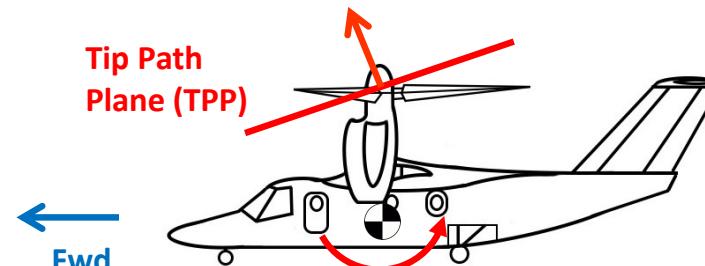
Control Challenges



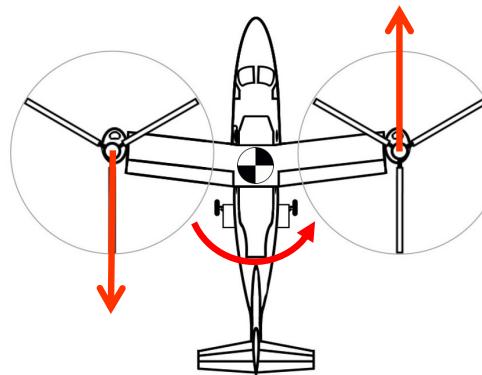
Collective Pitch
Increase magnitude
of thrust vector



Differential Collective Pitch
Increases thrust vector
magnitude on left/right side



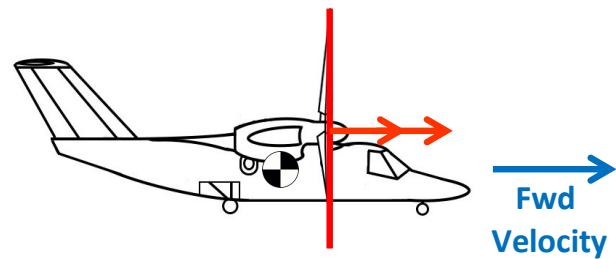
Longitudinal Cyclic
Direct thrust vector
fore/aft



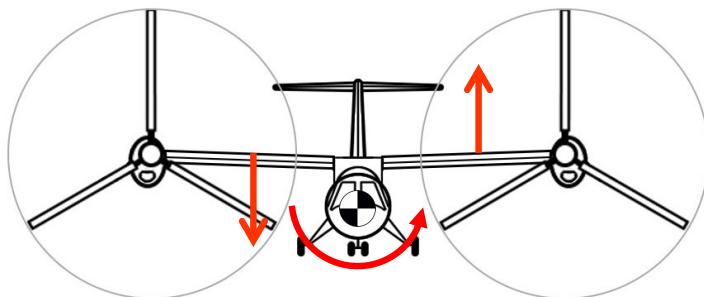
**Differential Longitudinal
Cyclic**
Direct thrust vector
fore/aft asymmetrically



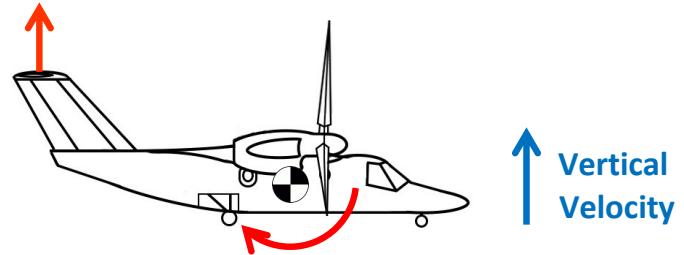
Control Challenges



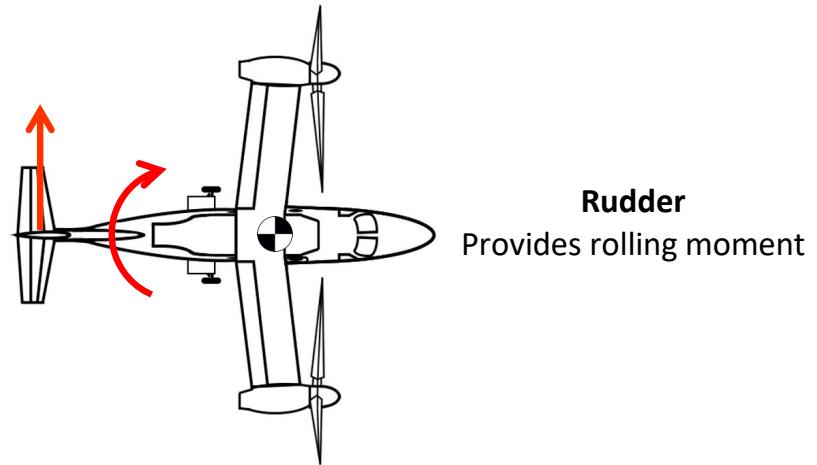
Collective Pitch
Increase magnitude
of thrust vector



Flaperons
Provide rolling moment



Elevator
Provides pitching moment



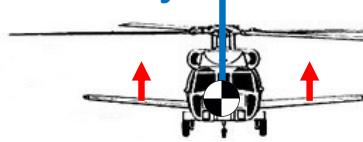
Rudder
Provides rolling moment

Control Challenges

Piasecki X-49A



Vertical Velocity
Flaperons



Symmetric Flaps (δ_{sym})

- Provide vertical speed/load factor
- Off-load long. cyclic

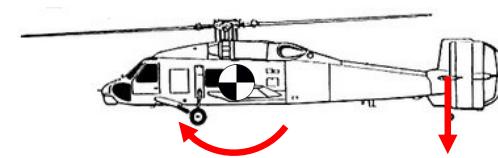
Differential Flaps (δ_{dif})

- Provide additional roll moment
- Off-load lat. cyclic

UH-60 Black Hawk



Stabilator

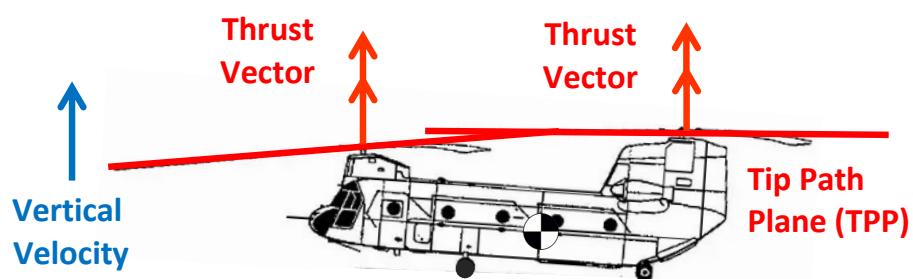


Stabilator (δ_{stb})

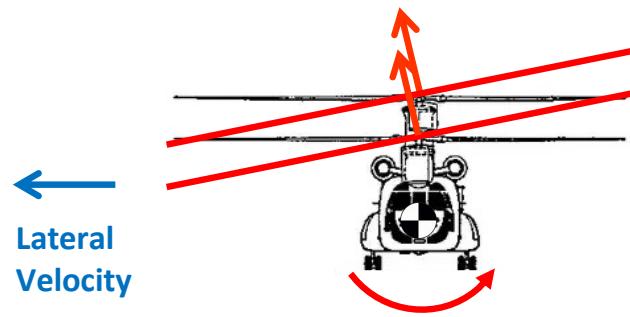
- Provide additional pitch moment
- Off-load long. cyclic



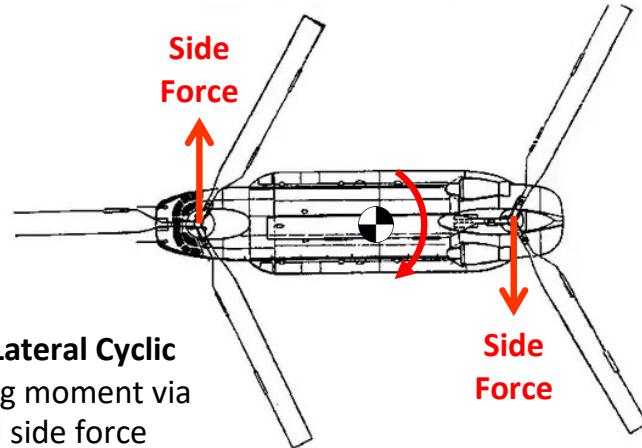
Control Challenges



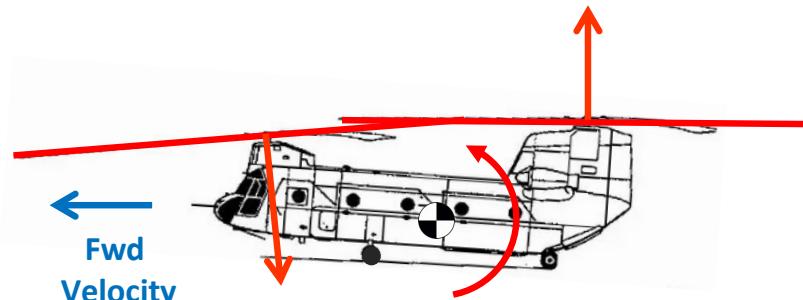
Symmetric Collective Pitch
Increase magnitude
of thrust vector



Lateral Cyclic
Direct thrust vector
left/right

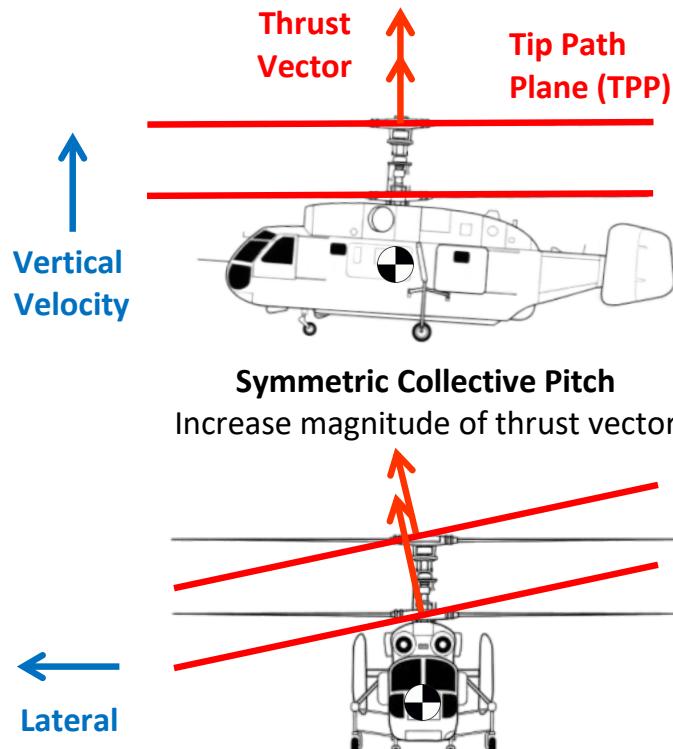


Differential Lateral Cyclic
Creates yawing moment via
differential side force

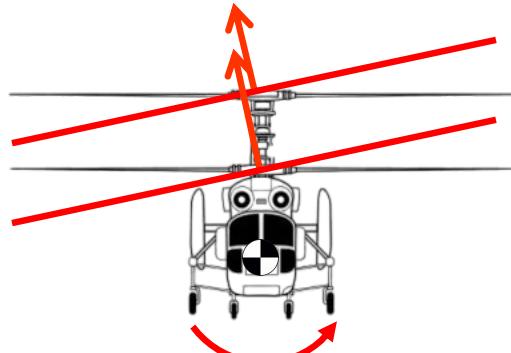


Differential Collective Pitch
Increases thrust vector
magnitude on front/aft side

Control Challenges

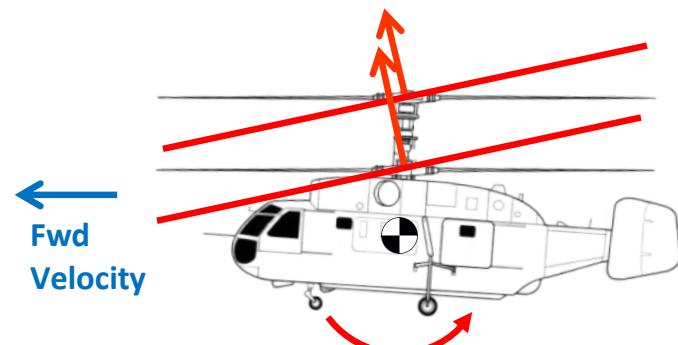
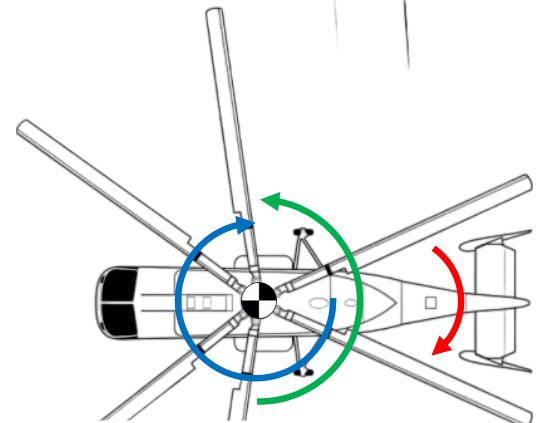


Symmetric Collective Pitch
Increase magnitude of thrust vector



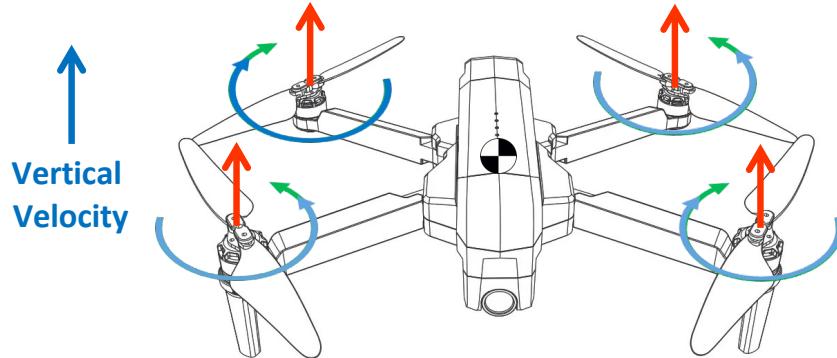
Symmetric Lateral Cyclic
Direct thrust vector left/right

Differential Collective Pitch
Provide torque imbalance

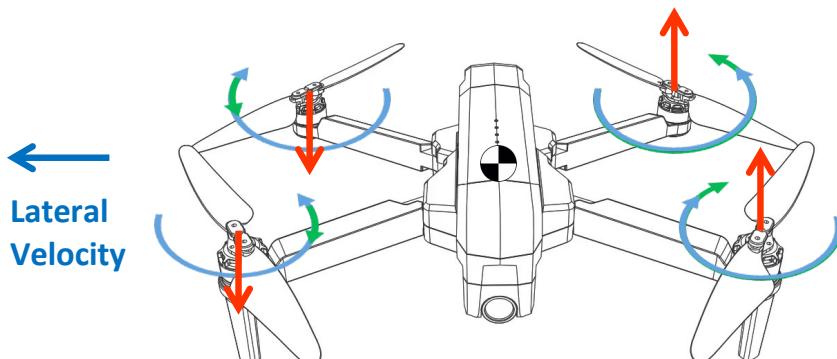


Symmetric Longitudinal Cyclic
Direct thrust vector fore/aft

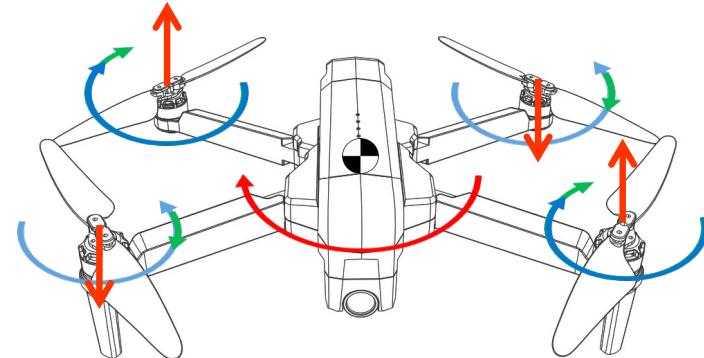
Control Challenges



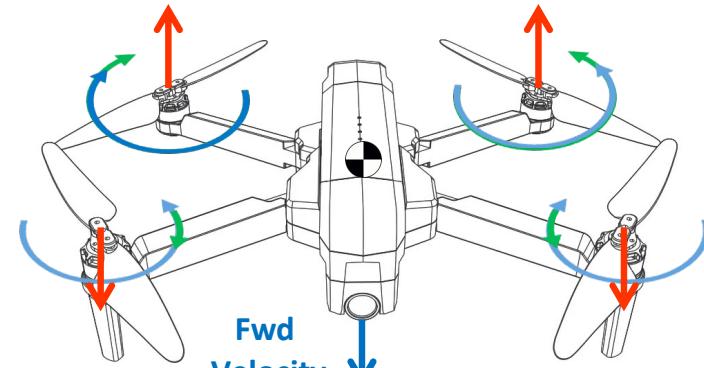
Increase/Decrease Rotor Velocity
Increase magnitude of thrust vector



Increase/Decrease Velocity of Left/Right Rotors
Creates rolling moment



Increase/Decrease Opposite Rotors Velocity
Creates yaw moment imbalance



Increase/Decrease Velocity of Front/Aft Rotors
Creates rolling moment



Helicopters in Pop Culture



Agusta A109 (Jurassic Park, 1993)



AgustaWestland AW 101 (Skyfall, 2012)



Mil Mi-17 (Everest, 2015)



Helicopters in Pop Culture



 KAPWING

Agusta A109 (Jurassic Park, 1993)