Flight Dynamics and Control of Vertical Lift Vehicles

Politecnico di Torino

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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
- Coupled Flight Dynamics, Aeromechanics, and Acoustics
- Time-Periodic Systems

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Course Overview

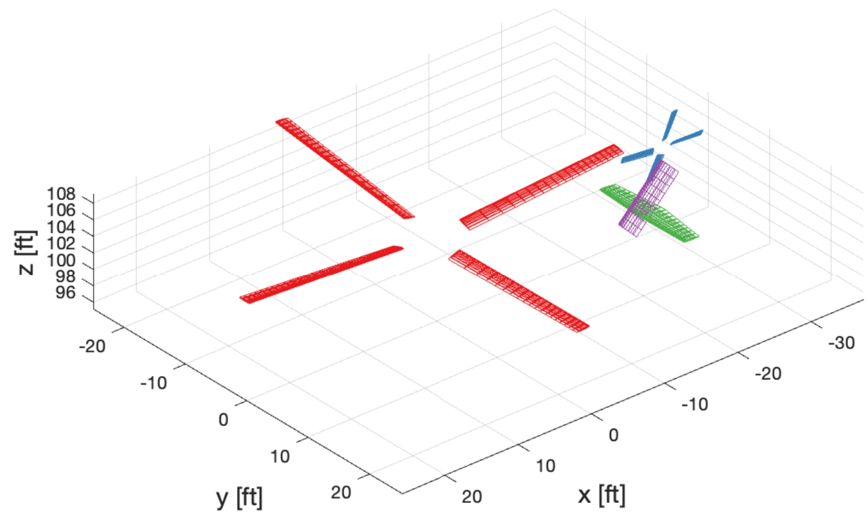
Course Overview

- **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

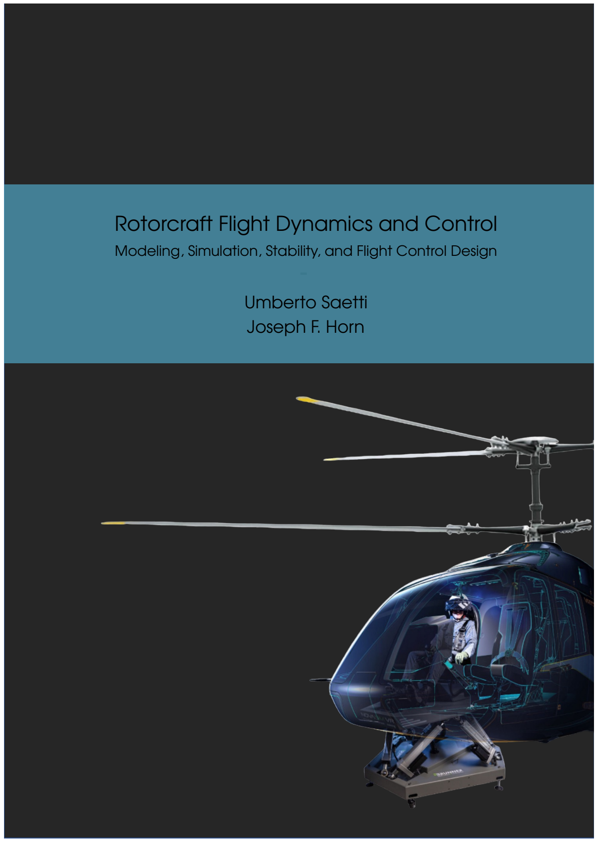
- Basic helicopter aerodynamics + system dynamics

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

A^3 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)
  - ❑AugustraWestland 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 Back 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

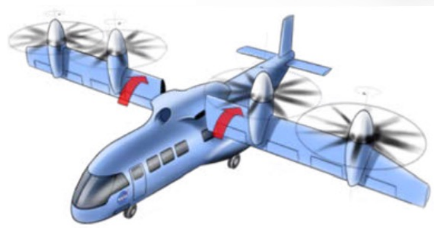
Exciting Times for Rotorcraft

Urban Air Mobility

Quadrotor
"Air Taxi"

Side-by-side
"Vanpool"

Lift + Cruise
Air Taxi



Tilt Wing
"Airliner"

EHang AAV

Uber Elevate's
eVTOL Concept

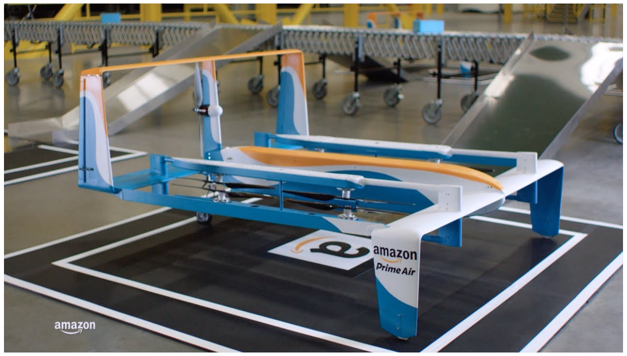
Wisk Cora

Rolls Royce eVTOL

Exciting Times for Rotorcraft

Drone Delivery

Elroy Air



Amazon Prime Air

Google Wing

Rotorcraft Research

Universities

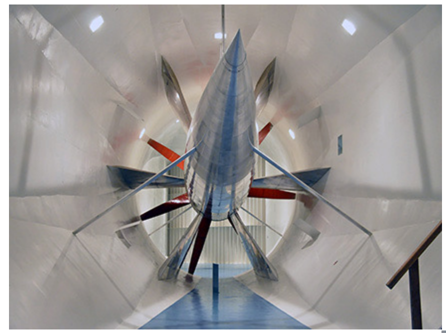
- USA
  - ❑ **Vertical Lift Research Center of Excellence (VLRCOE)**: **U Maryland**, **Georgia Tech**, **Penn State**
  - ❑ Auburn, Texas A&M, Rensslear Polytechnic, UT Arlington, Embry-Riddle
- Europe
  - ❑ **Network for Innovative Rotorcraft Research (Nitros):** Milan Polytechnic (Italy), TU Munich (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

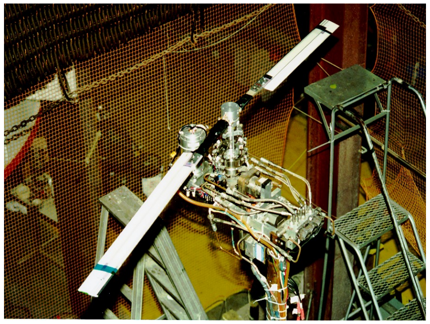
- **Dr. I. Chopra**– Rotorcraft Aerodynamics, Design, Smart Structures
- **Dr. A. Datta** – Structural Dynamics, Rotor Dynamics
- **Dr. J. Baeder** – CFD, Aeroacoustics
- **Dr. U Saetti** – Flight Dynamics & Control

UMD Vertical Flight Society Chapter

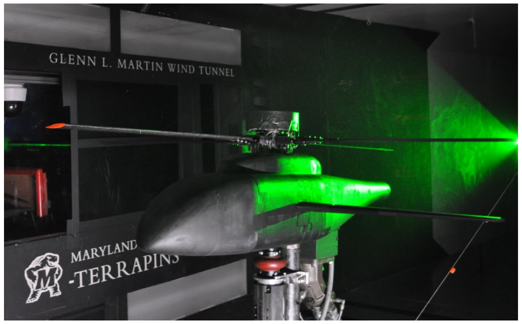
- President: Nathan O'Brien (nobrien2@umd.edu)

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

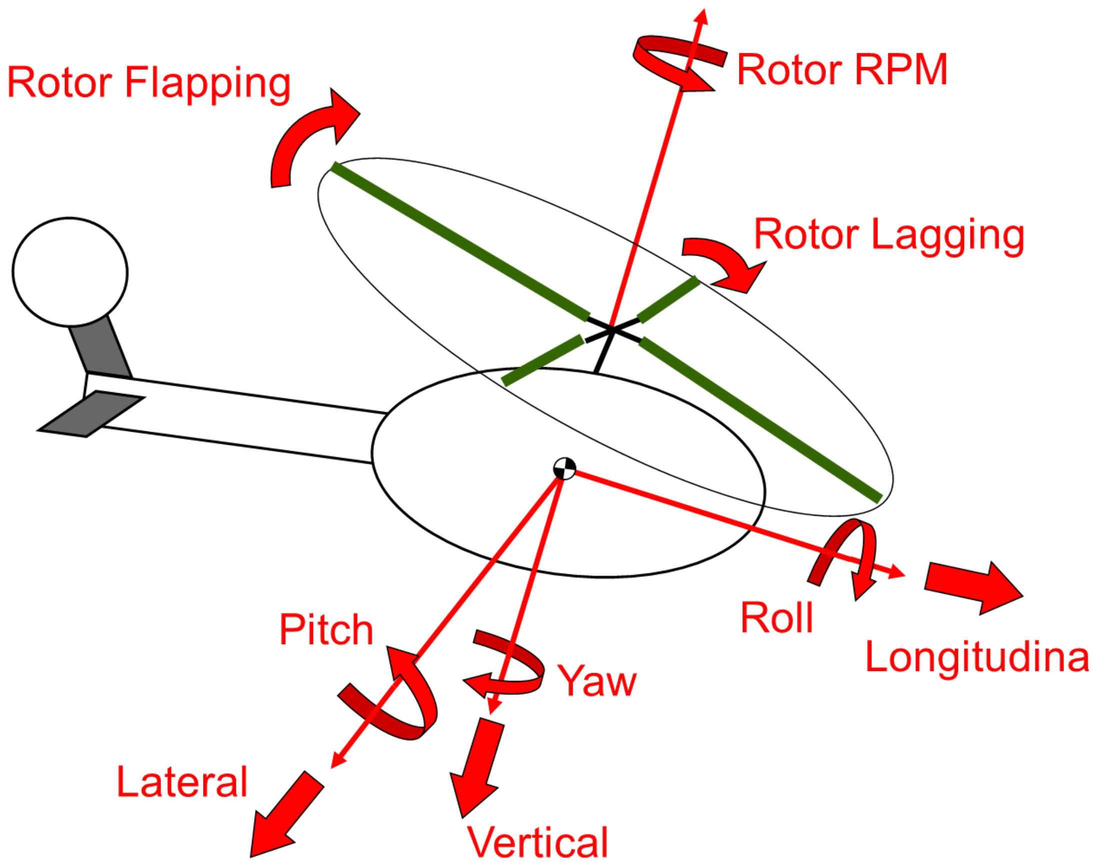
Rotocraft Flight Dynamics

- 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

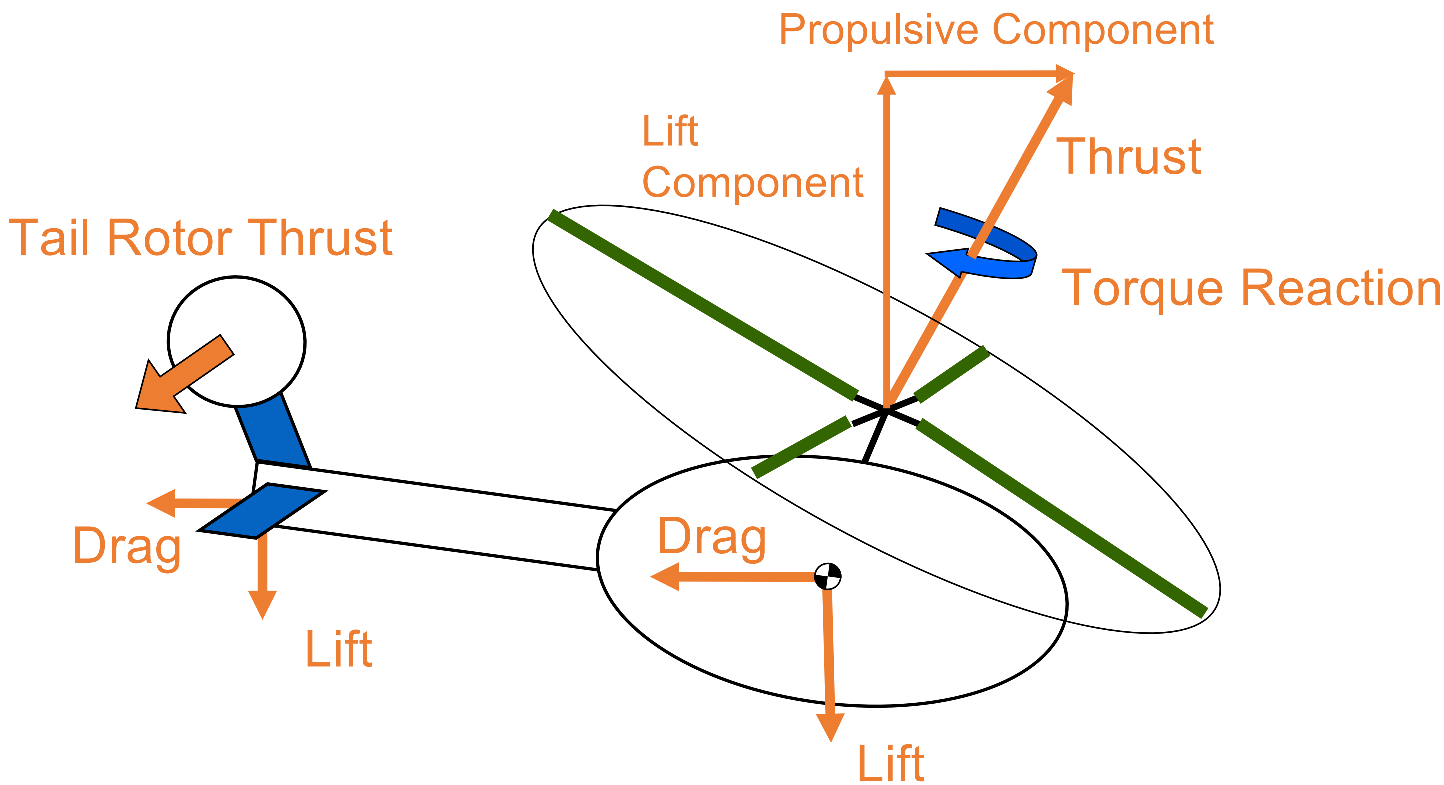
Rotorcraft Dynamics

- 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

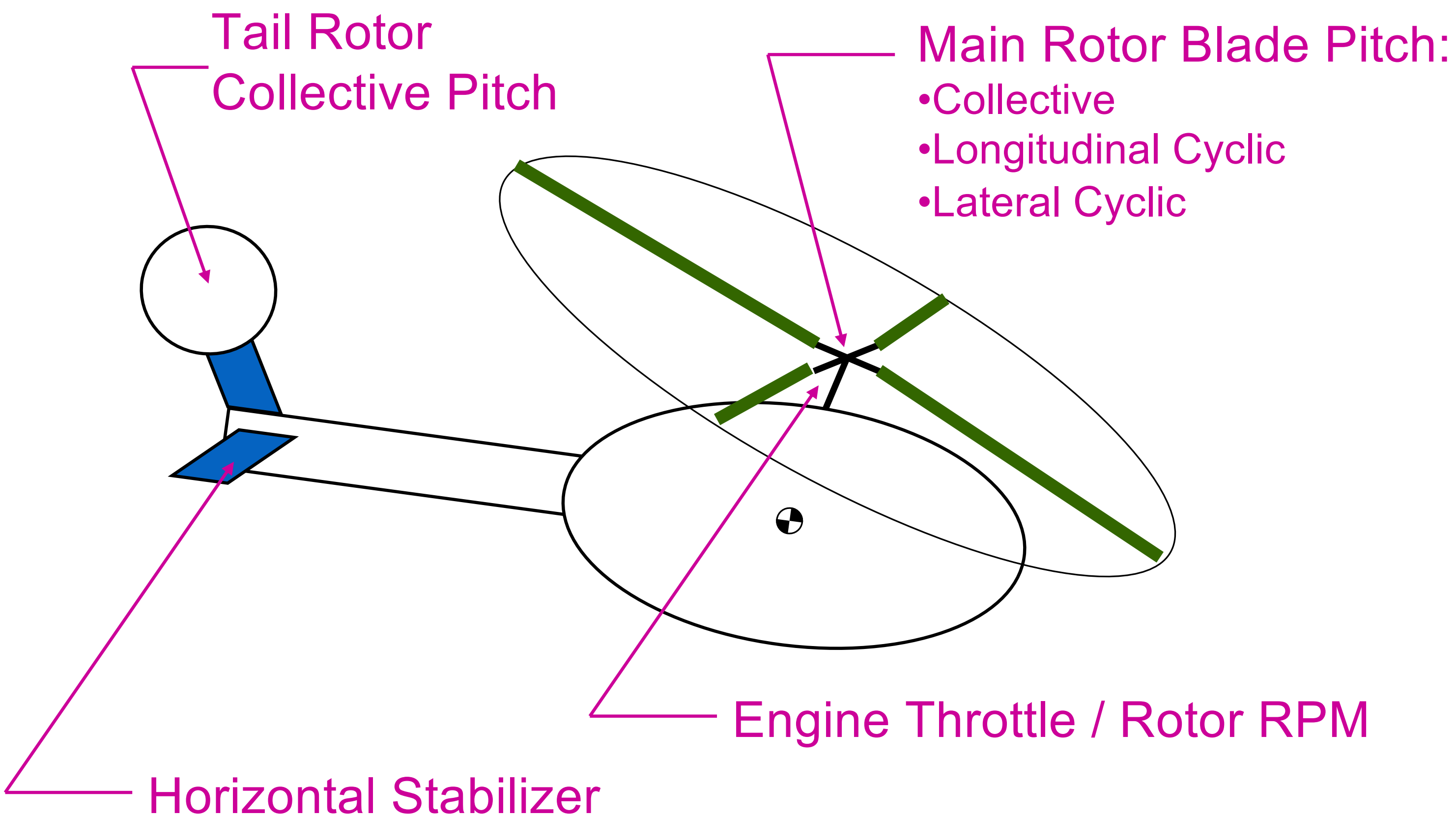
Rigid Helicopter Degrees of Freedom



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

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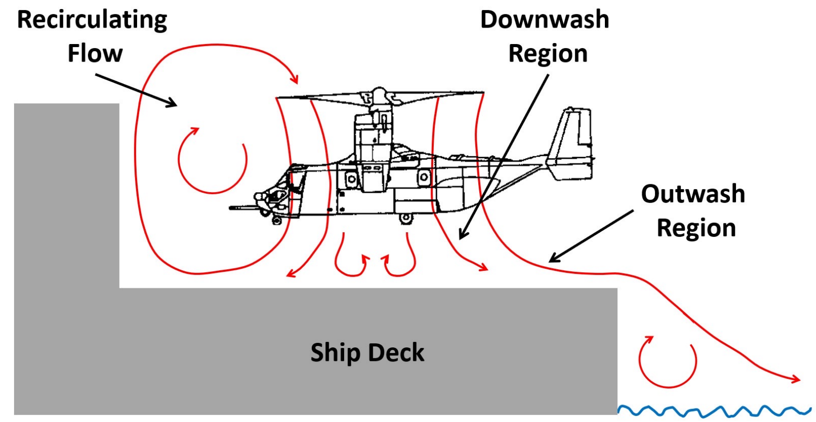
Joby S4

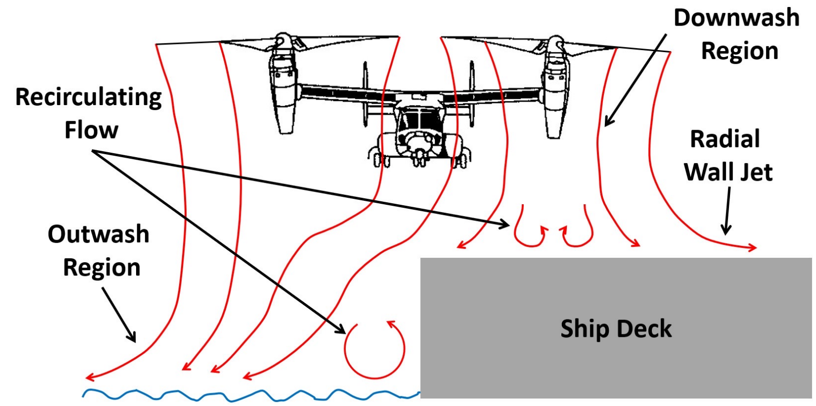
Leonardo AW609

Modeling and Simulation Challenges

Obstacle Interactions

- Shipboard interactions
  - ❑ Ship deck
  - ❑ Ship supestructures
  - ❑ 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

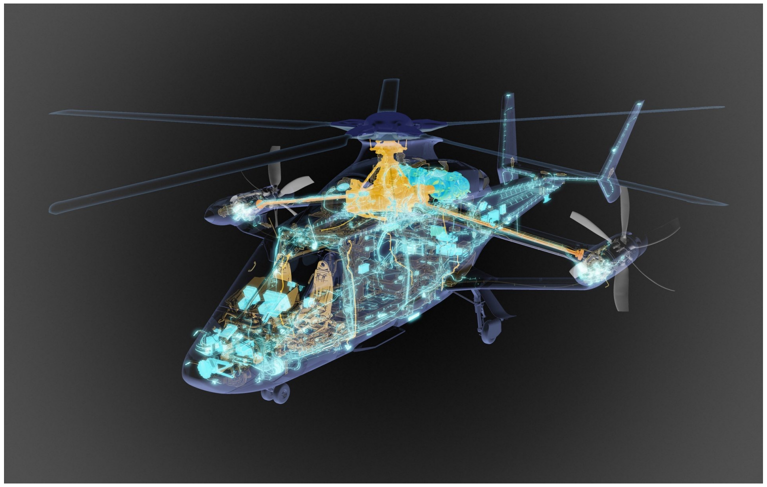
V-22 Osprey in a shipboard approach and landing

V-22 Osprey crash on USS Green Bay

Control Challenges

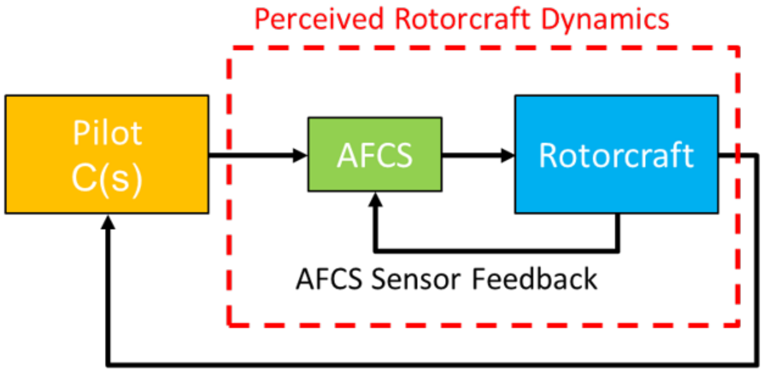
Rotorcraft are difficult to fly

- ❑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

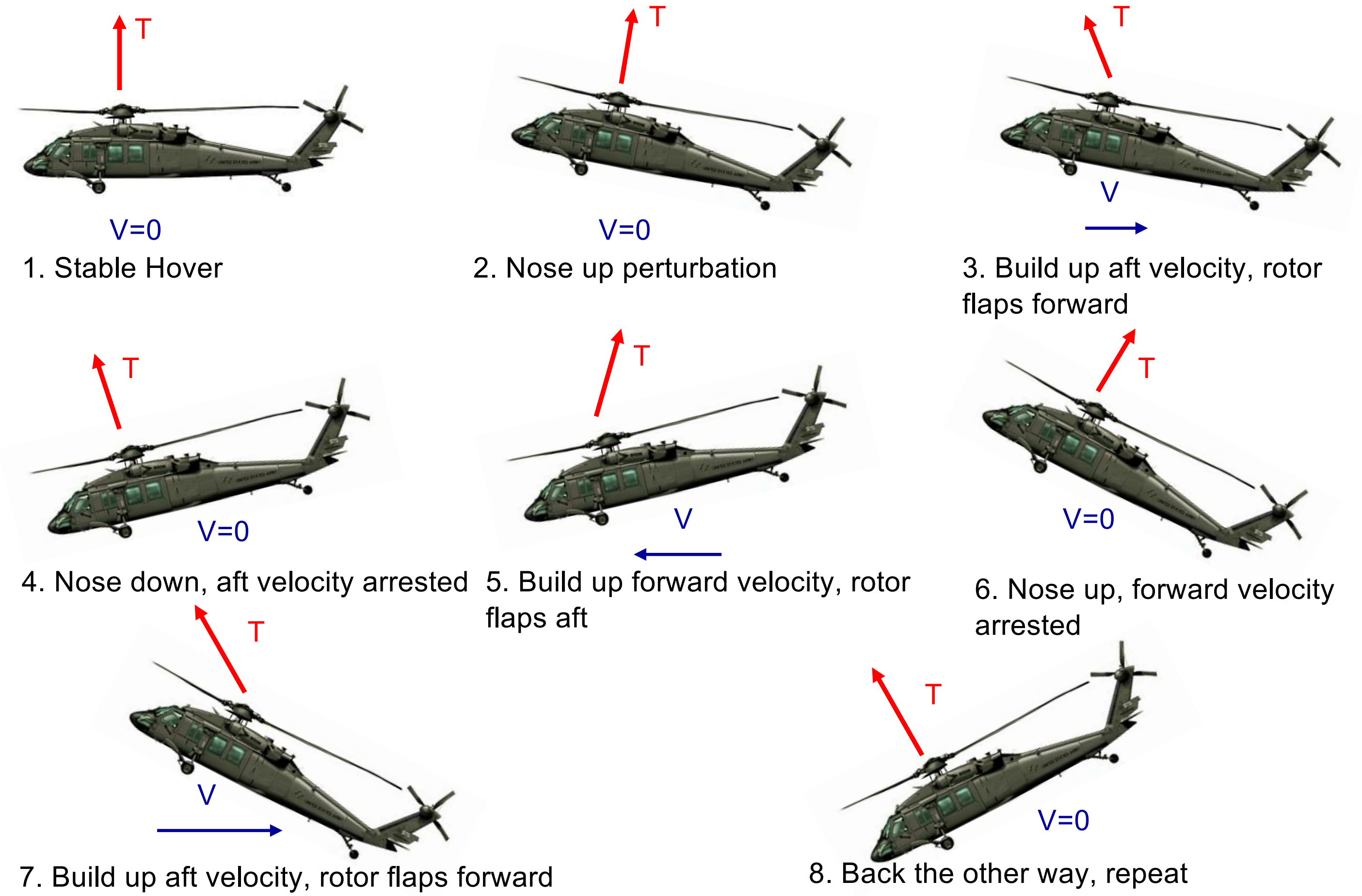


Need for Automatic Flight Control Systems (AFCS)

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



Control Challenges

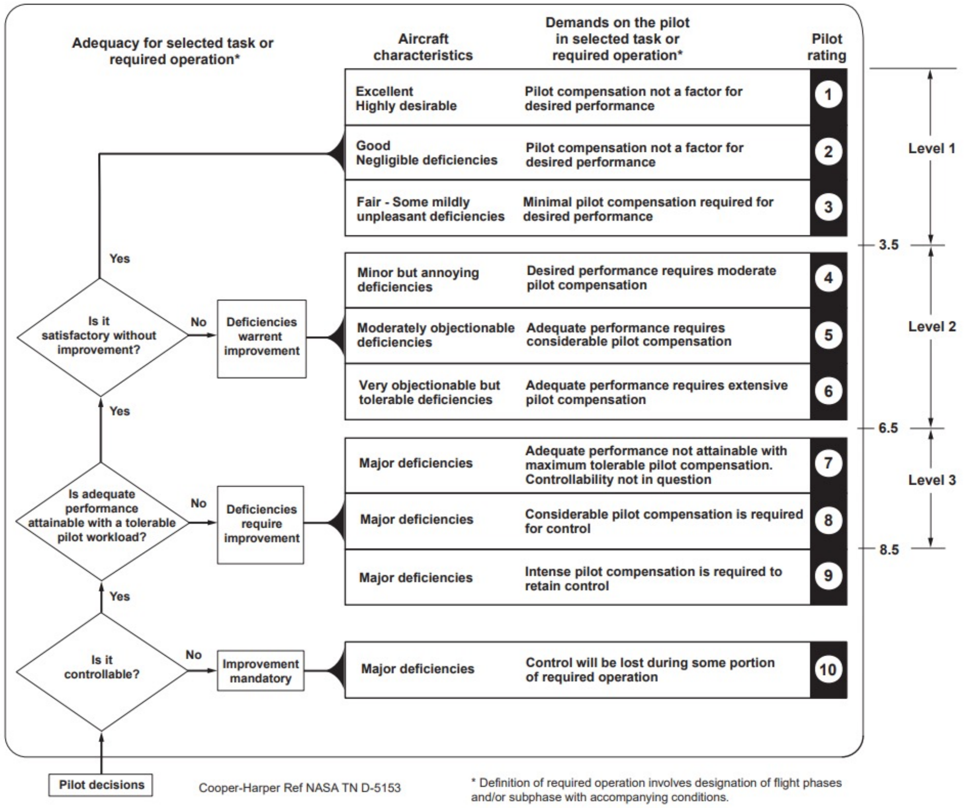


Control Challenges

Rotorcraft Handling Qualities (HQ)

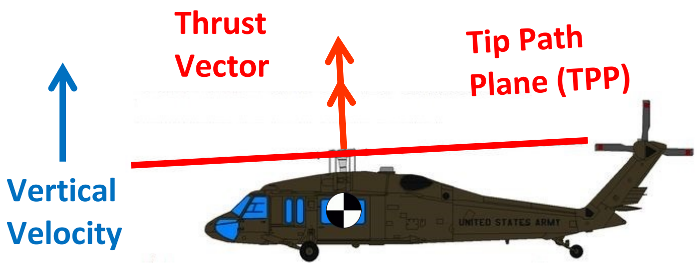
- ❑ Ease and precision with which a pilot can perform aircraft mission
- ❑ Quantitative measures of aircraft response characteristics "Level"

  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

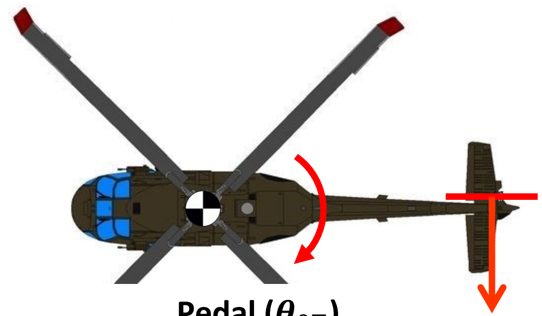


Cooper-Harper HQ Rating Scale

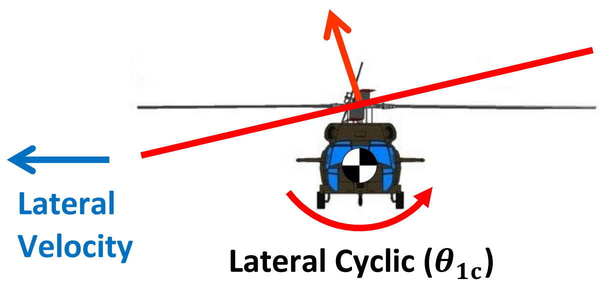
Control Challenges



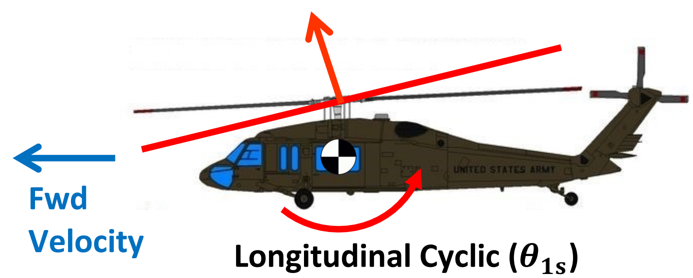
Collective (θ_0)
Increase magnitude
of thrust vector



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

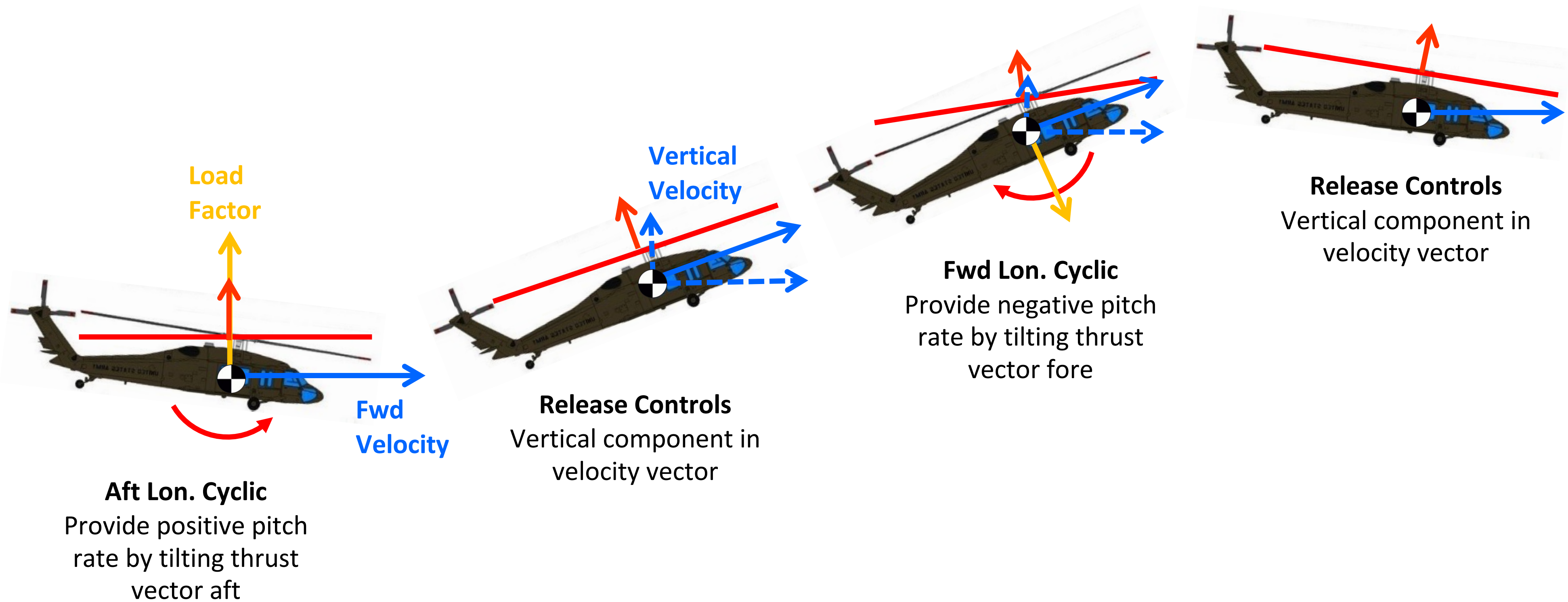


Lateral Cyclic (θ_{1c})
Direct thrust vector
left/right

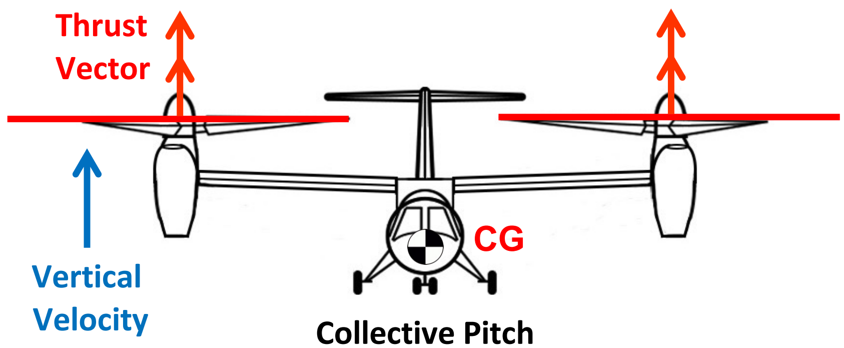


Longitudinal Cyclic (θ_{1s})
Direct thrust vector
fore/aft

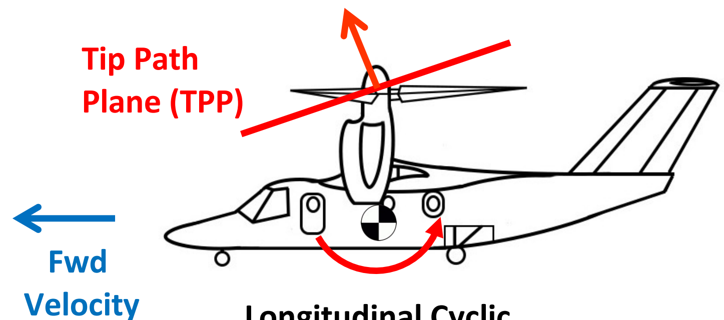
Control Challenges



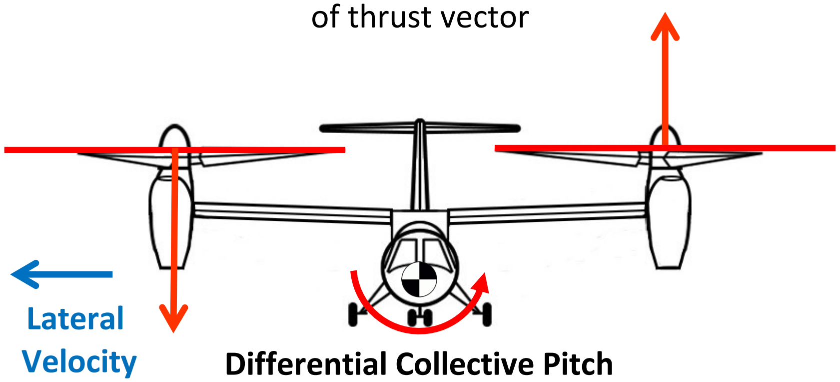
Control Challenges



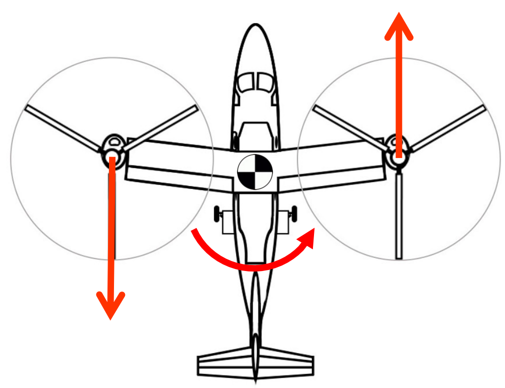
Collective Pitch
Increase magnitude of thrust vector



Longitudinal Cyclic
Direct thrust vector fore/aft

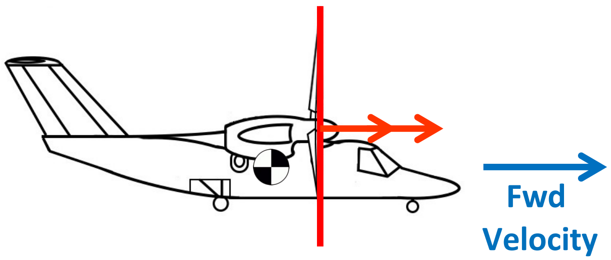


Differential Collective Pitch
Increases thrust vector magnitude on left/right side

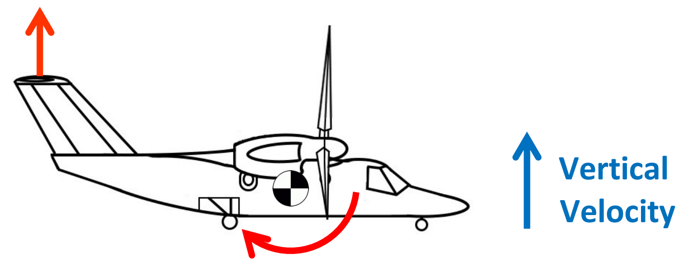


Differential Longitudinal Cyclic
Direct thrust vector fore/aft asymmetrically

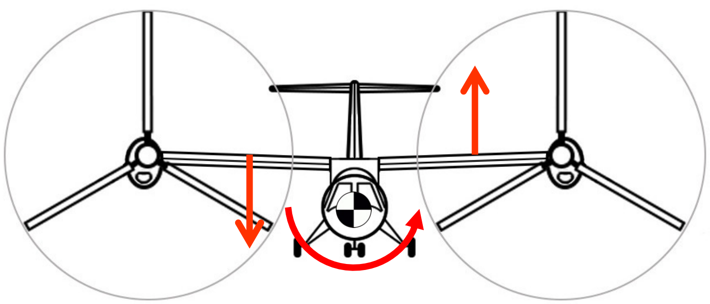
Control Challenges



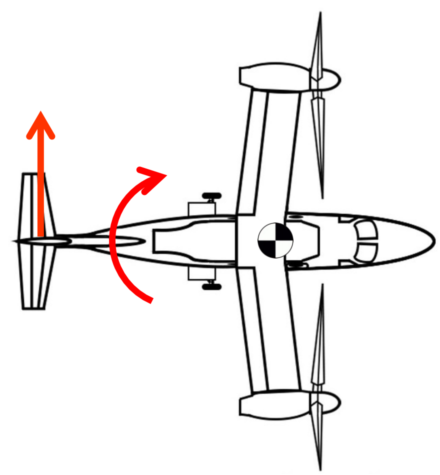
Collective Pitch
Increase magnitude
of thrust vector



Elevator
Provides pitching moment



Flaperons
Provide rolling moment

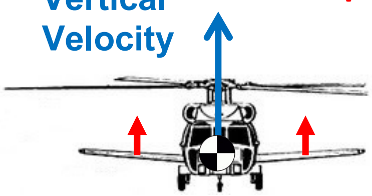


Rudder
Provides rolling moment

Control Challenges

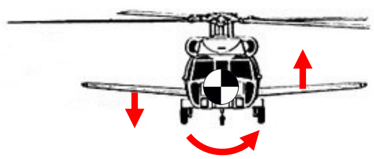
Piasecki X-49A

UH-60 Black Hawk



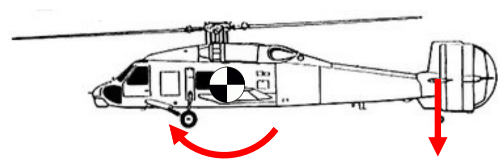
Symmetric Flaps (δ_{sym})

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



Differential Flaps (δ_{dif})

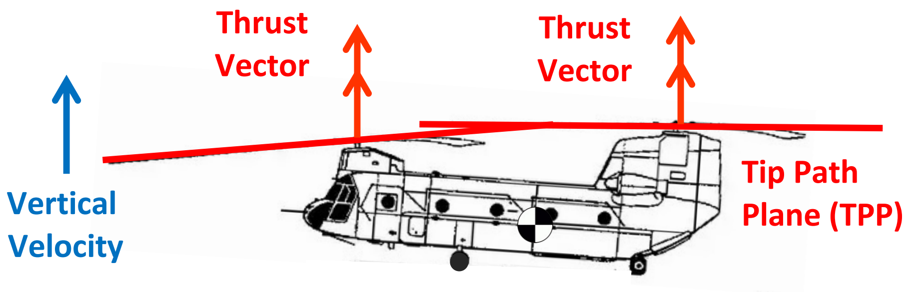
- Provide additional roll moment
- Off-load lat. cyclic



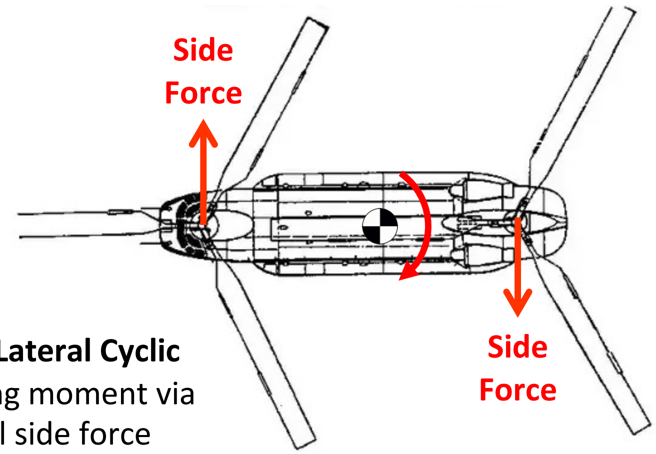
Stabilator (δ_{stb})

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

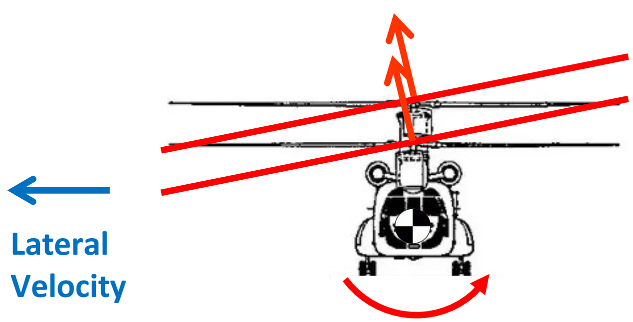
Control Challenges



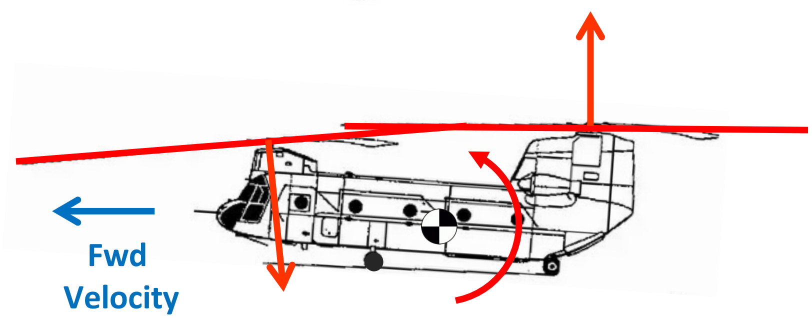
Symmetric Collective Pitch
Increase magnitude
of thrust vector



Differential Lateral Cyclic
Creates yawing moment via
differential side force

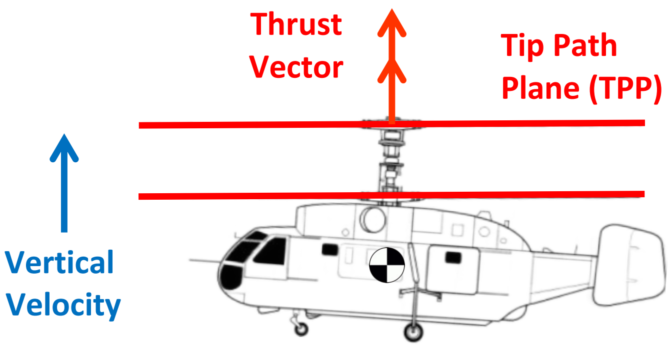


Lateral Cyclic
Direct thrust vector
left/right



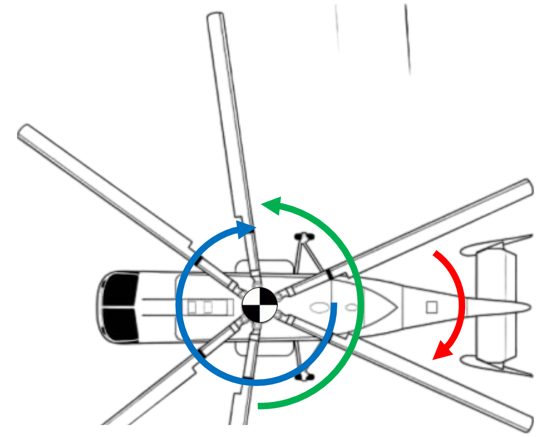
Differential Collective Pitch
Increases thrust vector
magnitude on front/aft side

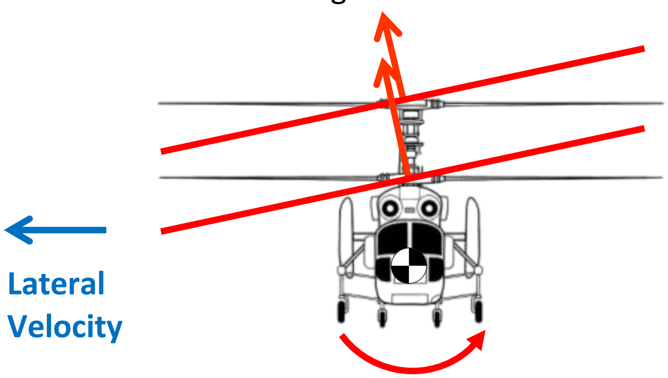
Control Challenges



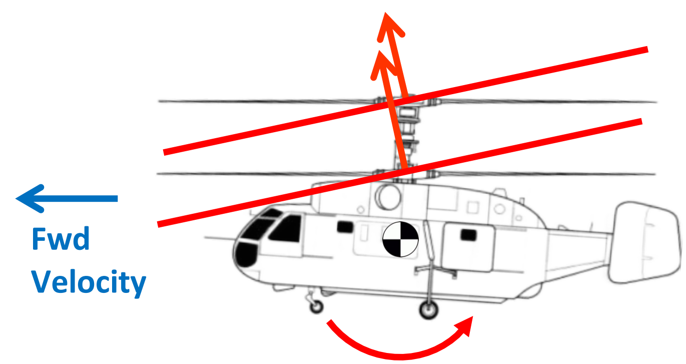
Symmetric Collective Pitch
Increase magnitude of thrust vector

Differential Collective Pitch
Provide torque imbalance



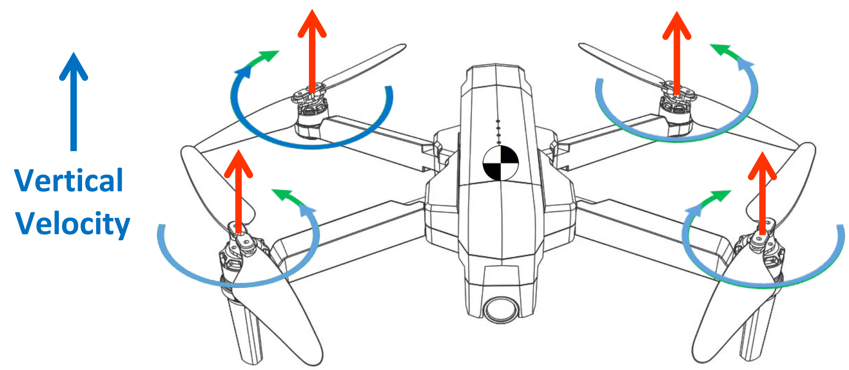


Symmetric Lateral Cyclic
Direct thrust vector left/right

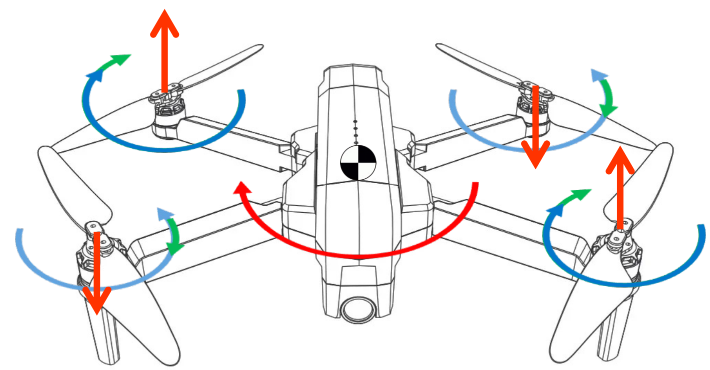


Symmetric Longitudinal Cyclic
Direct thrust vector fore/aft

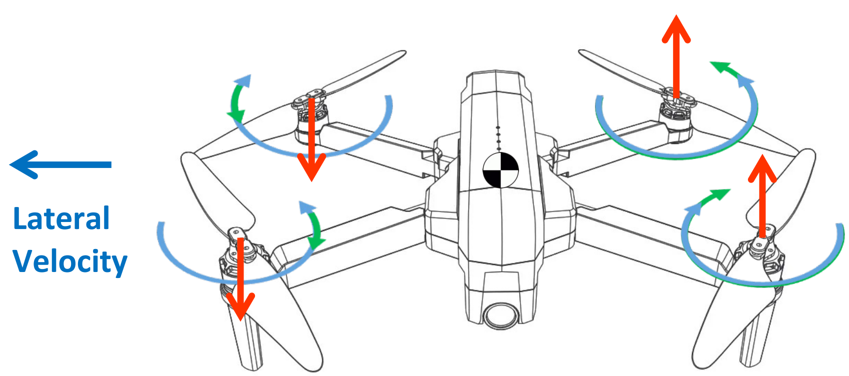
Control Challenges



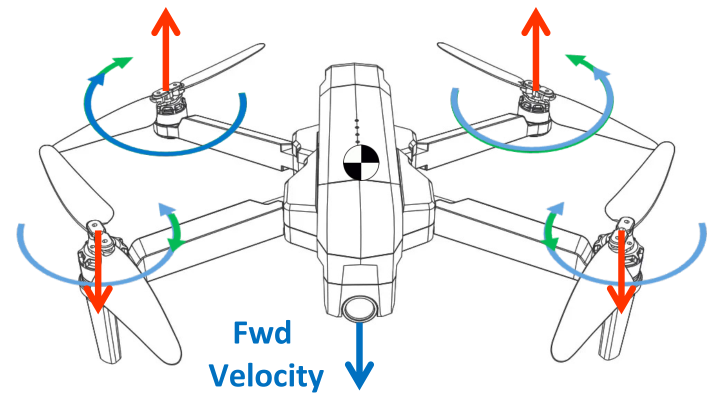
Increase/Decrease Rotor Velocity
Increase magnitude of thrust vector



Increase/Decrease Opposite Rotors Velocity
Creates yaw moment imbalance



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



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

Agusta A109 (Jurassic Park, 1993)