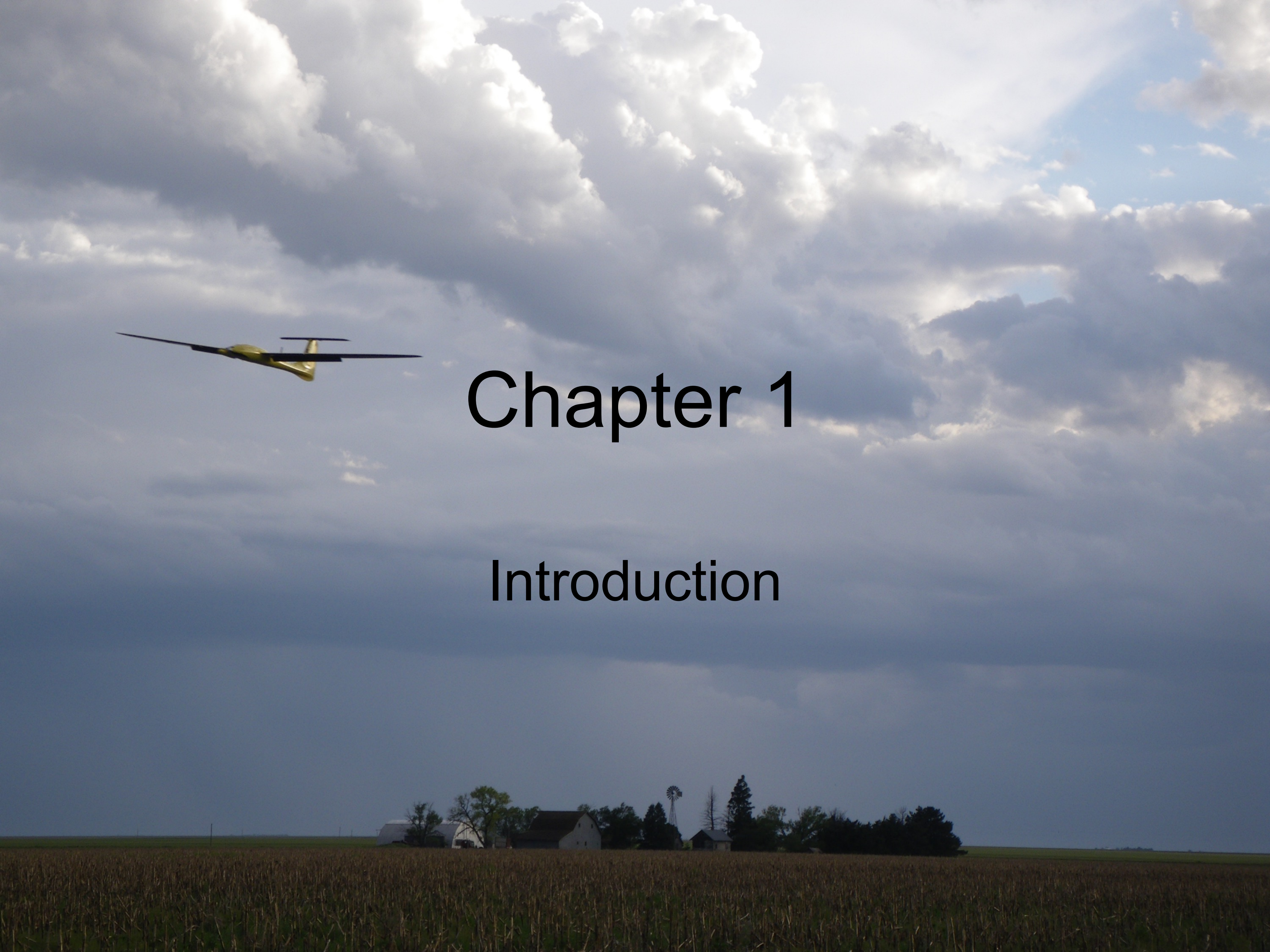
Chapter 1

Introduction



Potential Applications for Small UAVs

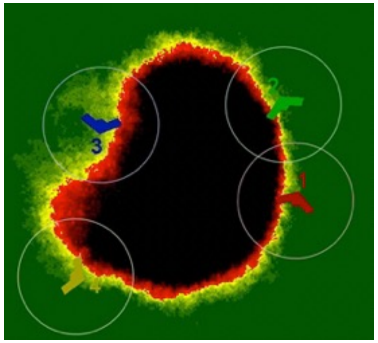
Civil and Commercial:
- Monitoring environment − meteorology, pollution, mapping, mineral exploration
- Monitoring disaster areas − forest fires, avalanches, nuclear contamination
- Communications relays − news broadcasts, disaster relief, sports events
- Law enforcement − road traffic, border patrol, drug control
- Precision agriculture − crop monitoring

Military:
- Special Operations: Situational awareness
- Intelligence, surveillance, and reconnaissance
- Communication node
- Battle damage assessment

Homeland Security:
- Border patrol
- Surveillance
- Rural/urban search and rescue

New related area:
- Air mobility of humans, goods, services

UAS Research at BYU



Cooperative Control

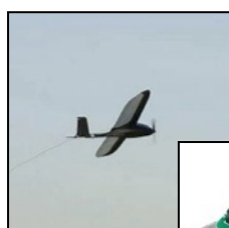
- Cooperative timing problems
- Cooperative persistent imaging
- Cooperative fire monitoring
- Consensus seeking

Path Planning
Trajectory Generation

- 3D Waypoint path planning
- Wind compensation
- Collision avoidance
    - Optic flow sensor
    - Laser ranger
    - EO cameras

Vision-based Control

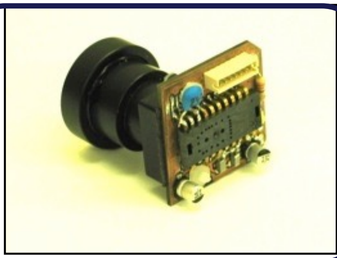
- Image stabilization
- Geo-location
- Vision-aided tracking & engagement

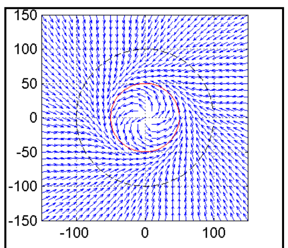


Autonomous Vehicles

- Autopilot design for small UAVs
- Attitude estimation
- Adaptive control
- Tailsitter guidance & control

Autonomous Flight for sUAS with SWaP Constraints





Sensor-based Flight

- Optic flow
- Laser range finder
- EO/IR

Applications

- Canyon following
- Collision avoidance
- GPS-denied navigation

Path Following

- Robust to wind
- Computationally efficient

Applications

- Precision navigation
- Target tracking
- Target geo-location

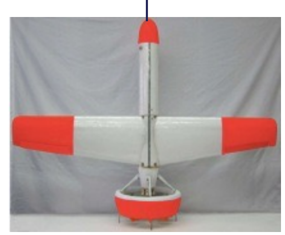
Kestrel Autopilot

- Auto take-off, land
- Waypoint NAV
- GPS guided

Technology Transition

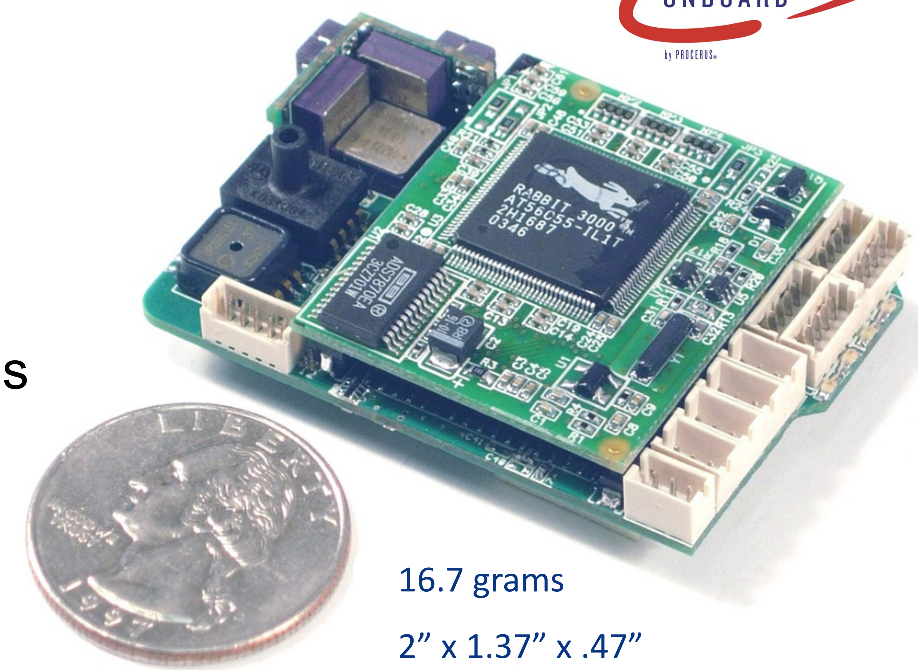
BYU MAGICC LAB ⇨ PROCERUS TECHNOLOGIES ⇨ LOCKHEED MARTIN Procerus Technologies, L.C.

2004 2012



Kestrel Autopilot v2.2

- 3-Axis Angular Rate & Acceleration Measurement
- 20 Point Sensor Temperature Compensation
- Kalman Filter Attitude Estimation
- Optional "piggy-back" Modem
- Configurable Failsafes
- 2-Axis Magnetometer
- 2-Axis Gimbal Support
- Dead reckoning filter gracefully handles GPS outages
- Multiple-UAVs
- Smart Loiters
- Auto-Trim



16.7 grams

2" x 1.37" x .47"

Over 20 years of
UAS research at BYU

The National Science Foundation

Center for Autonomous Air Mobility and Sensing

CAAMS

BYU

VIRGINIA TECH

UNIVERSITY OF MICHIGAN

PennState

Industry Members

Raytheon

UTOPIACOMPRESSION

aerovironment

INSITU

BOEING

bp

AFRL
THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

NASA

NAWC
Aircraft Division
NAVAL AIR WARFARE CENTER

TEXTRON Systems
CIVIL & COMMERCIAL

ARL

Aurora
FLIGHT SCIENCES

National UAS
Training and Certification Center

DEVCOM
C5ISR CENTER

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

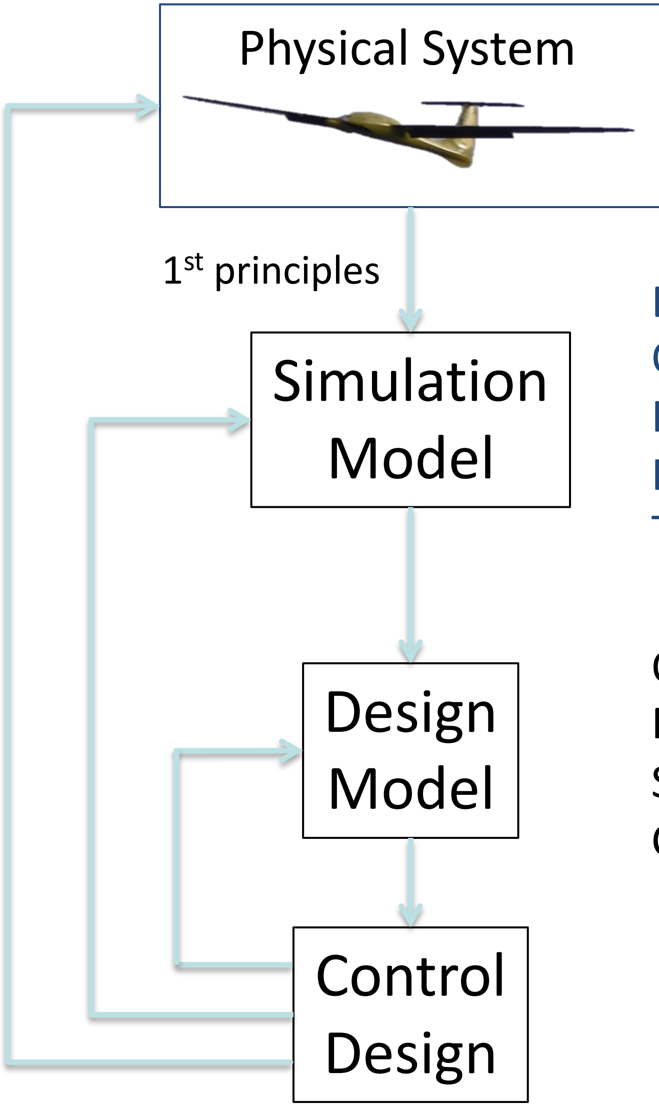
L3

U.S. DEPARTMENT OF
ENERGY

Always a Step Ahead
ARDEC
ARMAMENTS

Honeywell
Aerospace

Control Design Process



The real thing

Detailed model
ODE’s, nonlinear, high order
Includes everything that is feasible to model
Hi-fi representation of real physical system behavior
Too complex for control design

ODE’s, linear, low order
May only consider a portion of dynamic behavior
Simpler to understand
Captures dominant behavior

Simulation Model

$$\dot{p}_n = (\cos\theta\cos\psi)u + (\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi)v + (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)w$$

$$\dot{p}_e = (\cos\theta\sin\psi)u + (\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi)v + (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)w$$

$$\dot{h} = u\sin\theta - v\sin\phi\cos\theta - w\cos\phi\cos\theta$$

$$\dot{u} = rv - qw - g\sin\theta + \frac{\rho V_a^2 S}{2\mathrm{m}}\left[C_X(\alpha) + C_{X_q}(\alpha)\frac{cq}{2V_a} + C_{X_{\delta_e}}(\alpha)\delta_e\right] + \frac{\rho S_{\mathrm{prop}} C_{\mathrm{prop}}}{2\mathrm{m}}\left[(k_{\mathrm{motor}}\delta_t)^2 - V_a^2\right]$$

$$\dot{v} = pw - ru + g\cos\theta\sin\phi + \frac{\rho V_a^2 S}{2\mathrm{m}}\left[C_{Y_0} + C_{Y_\beta}\beta + C_{Y_p}\frac{bp}{2V_a} + C_{Y_r}\frac{br}{2V_a} + C_{Y_{\delta_a}}\delta_a + C_{Y_{\delta_r}}\delta_r\right]$$

$$\dot{w} = qu - pv + g\cos\theta\cos\phi + \frac{\rho V_a^2 S}{2\mathrm{m}}\left[C_Z(\alpha) + C_{Z_q}(\alpha)\frac{cq}{2V_a} + C_{Z_{\delta_e}}(\alpha)\delta_e\right]$$

$$\dot{\phi} = p + q\sin\phi\tan\theta + r\cos\phi\tan\theta$$

$$\dot{\theta} = q\cos\phi - r\sin\phi$$

$$\dot{\psi} = q\sin\phi\sec\theta + r\cos\phi\sec\theta$$

$$\dot{p} = \Gamma_1 pq - \Gamma_2 qr + \frac{1}{2}\rho V_a^2 Sb\left[C_{p_0} + C_{p_\beta}\beta + C_{p_p}\frac{bp}{2V_a} + C_{p_r}\frac{br}{2V_a} + C_{p_{\delta_a}}\delta_a + C_{p_{\delta_r}}\delta_r\right]$$

$$\dot{q} = \Gamma_5 pr - \Gamma_6(p^2 - r^2) + \frac{\rho V_a^2 Sc}{2J_y}\left[C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}\frac{cq}{2V_a} + C_{m_{\delta_e}}\delta_e\right]$$

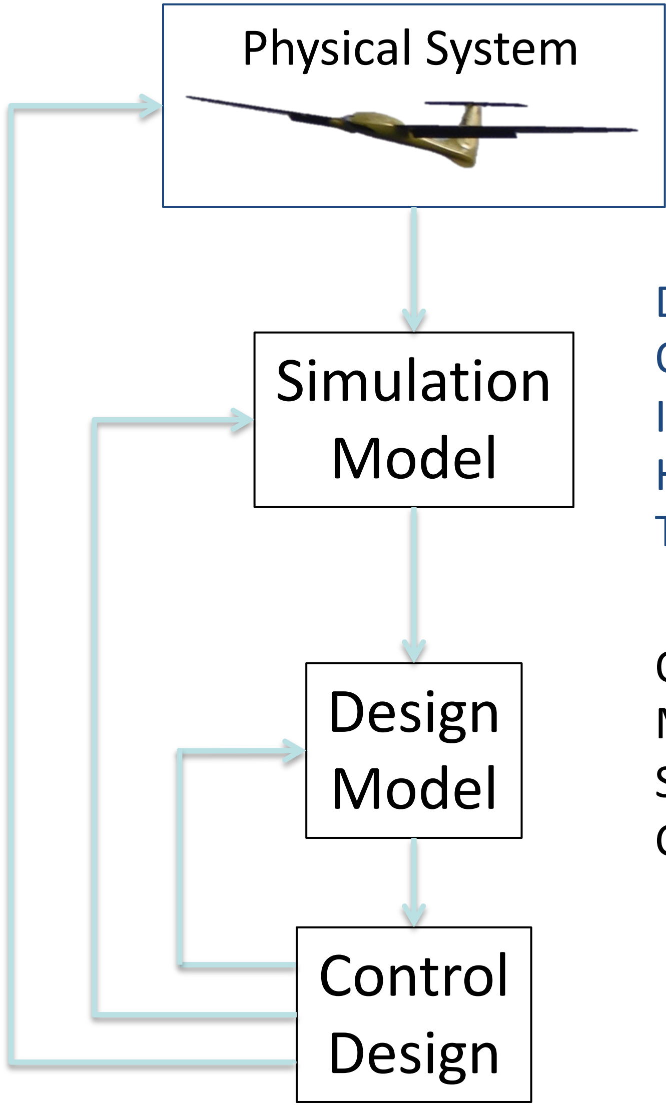
$$\dot{r} = \Gamma_7 pq - \Gamma_1 qr + \frac{1}{2}\rho V_a^2 Sb\left[C_{r_0} + C_{r_\beta}\beta + C_{r_p}\frac{bp}{2V_a} + C_{r_r}\frac{br}{2V_a} + C_{r_{\delta_a}}\delta_a + C_{r_{\delta_r}}\delta_r\right]$$

Simulation Model

$$
\begin{aligned}
C_{p_0} &= \Gamma_3 C_{l_0} + \Gamma_4 C_{n_0} \\
C_{p_\beta} &= \Gamma_3 C_{l_\beta} + \Gamma_4 C_{n_\beta} \\
C_{p_p} &= \Gamma_3 C_{l_p} + \Gamma_4 C_{n_p} \\
C_{p_r} &= \Gamma_3 C_{l_r} + \Gamma_4 C_{n_r} \\
C_{p_{\delta_a}} &= \Gamma_3 C_{l_{\delta_a}} + \Gamma_4 C_{n_{\delta_a}} \\
C_{p_{\delta_r}} &= \Gamma_3 C_{l_{\delta_r}} + \Gamma_4 C_{n_{\delta_r}} \\
C_{r_0} &= \Gamma_4 C_{l_0} + \Gamma_8 C_{n_0} \\
C_{r_\beta} &= \Gamma_4 C_{l_\beta} + \Gamma_8 C_{n_\beta} \\
C_{r_p} &= \Gamma_4 C_{l_p} + \Gamma_8 C_{n_p} \\
C_{r_r} &= \Gamma_4 C_{l_r} + \Gamma_8 C_{n_r} \\
C_{r_{\delta_a}} &= \Gamma_4 C_{l_{\delta_a}} + \Gamma_8 C_{n_{\delta_a}} \\
C_{r_{\delta_r}} &= \Gamma_4 C_{l_{\delta_r}} + \Gamma_8 C_{n_{\delta_r}}
\end{aligned}
$$

$$
\begin{aligned}
C_X(\alpha) &\stackrel{\triangle}{=} -C_D(\alpha)\cos\alpha + C_L(\alpha)\sin\alpha \\
C_{X_q}(\alpha) &\stackrel{\triangle}{=} -C_{D_q}\cos\alpha + C_{L_q}\sin\alpha \\
C_{X_{\delta_e}}(\alpha) &\stackrel{\triangle}{=} -C_{D_{\delta_e}}\cos\alpha + C_{L_{\delta_e}}\sin\alpha \\
C_Z(\alpha) &\stackrel{\triangle}{=} -C_D(\alpha)\sin\alpha - C_L(\alpha)\cos\alpha \\
C_{Z_q}(\alpha) &\stackrel{\triangle}{=} -C_{D_q}\sin\alpha - C_{L_q}\cos\alpha \\
C_{Z_{\delta_e}}(\alpha) &\stackrel{\triangle}{=} -C_{D_{\delta_e}}\sin\alpha - C_{L_{\delta_e}}\cos\alpha
\end{aligned}
$$

Control Design Process



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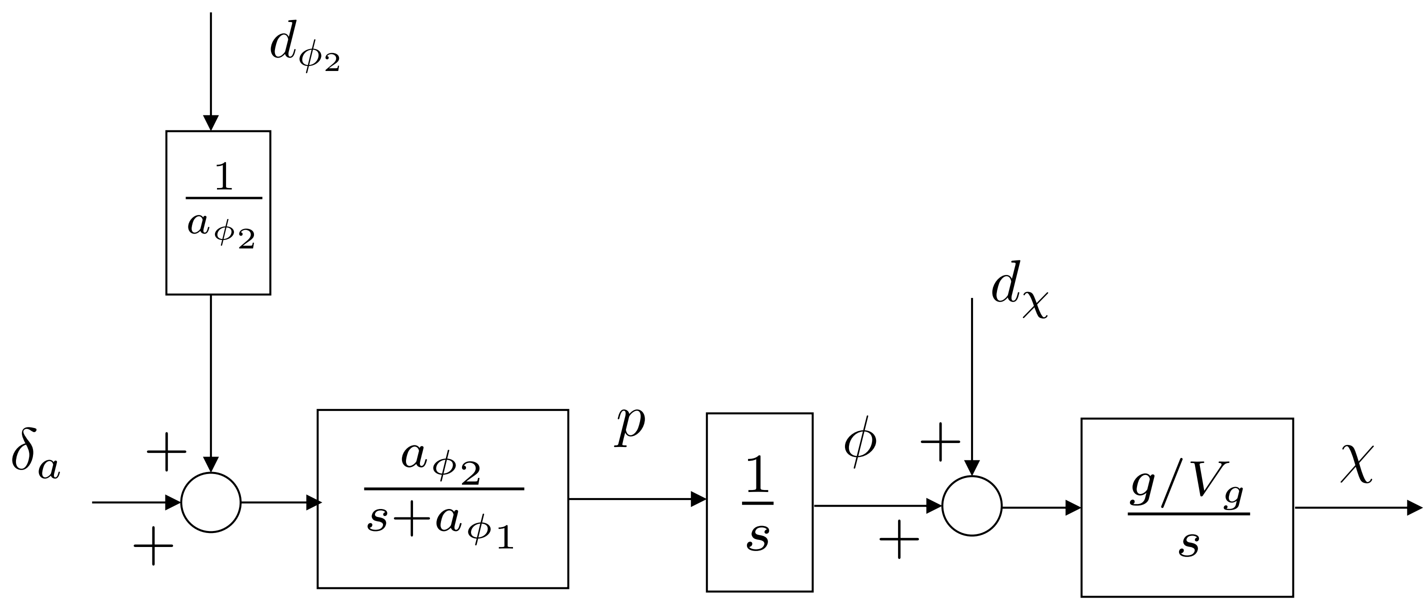
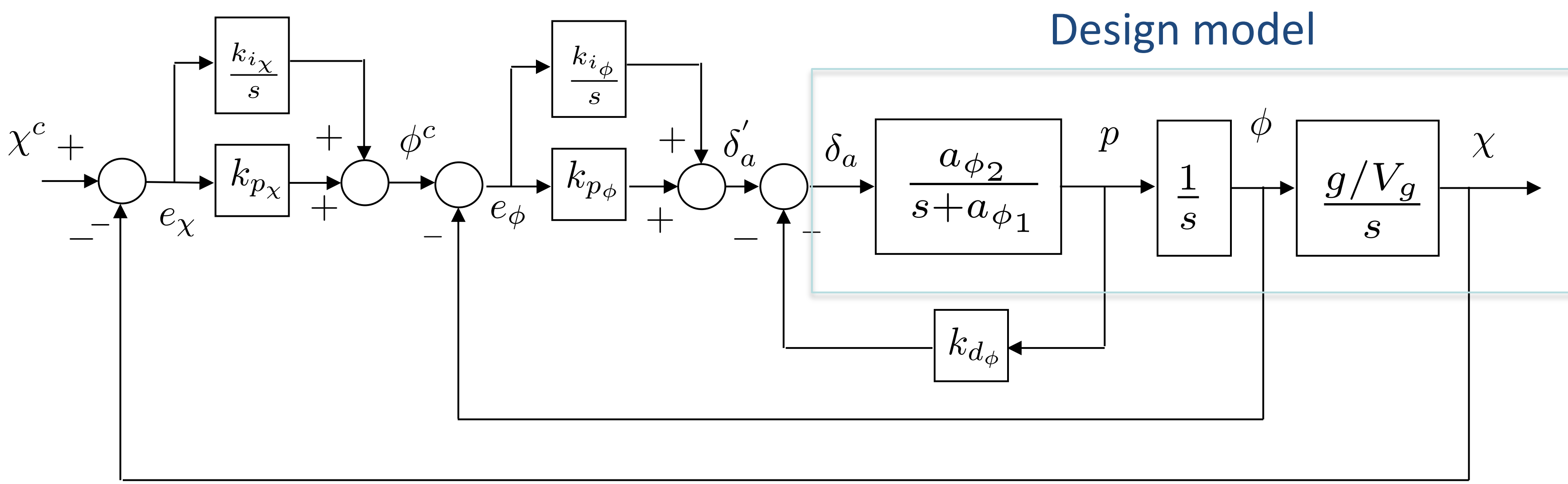
Design Model

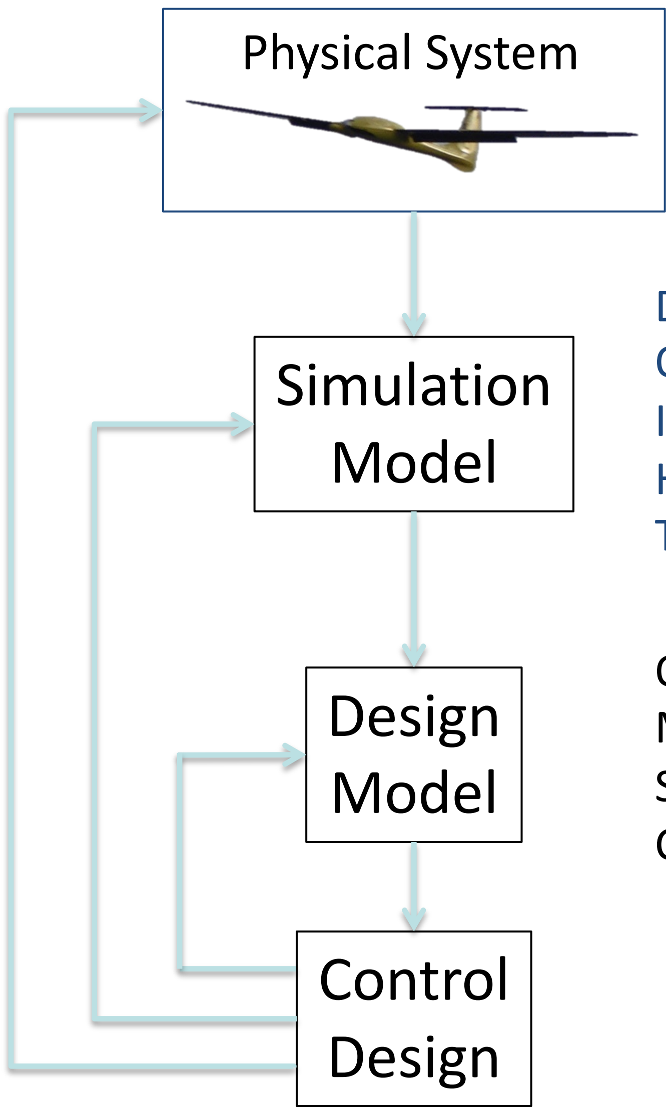
Course from aileron transfer function:



Control Design



Control Design Process



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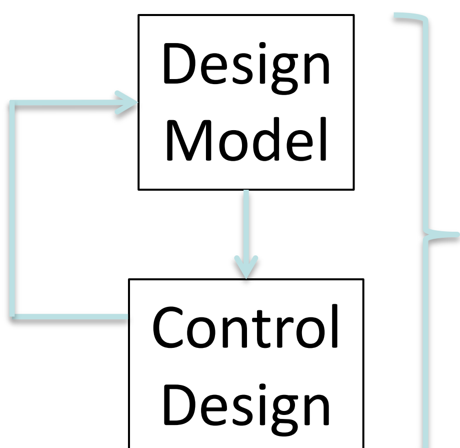
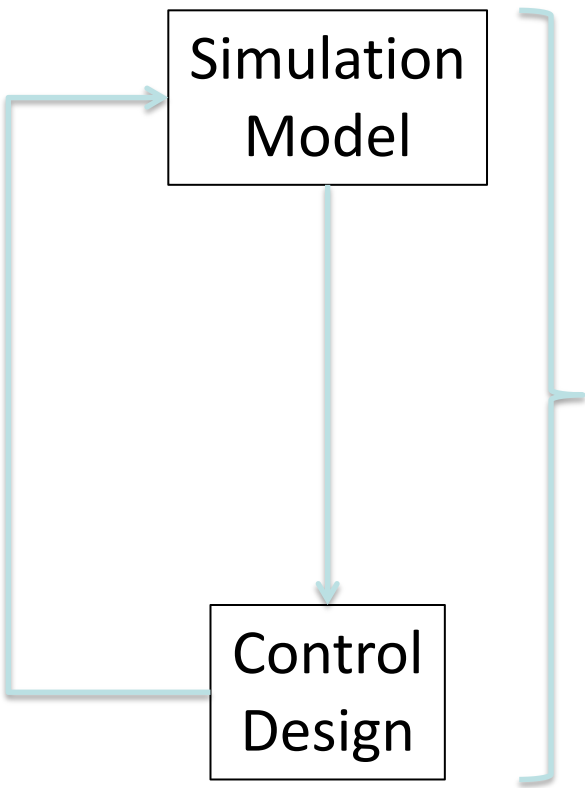


Step 1:
Linear, low-order model
Control design and system model implemented in software

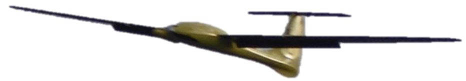
Control Design Process



Step 2:
Detailed system model
Control design and system model implemented in software

Control Design Process

Physical System



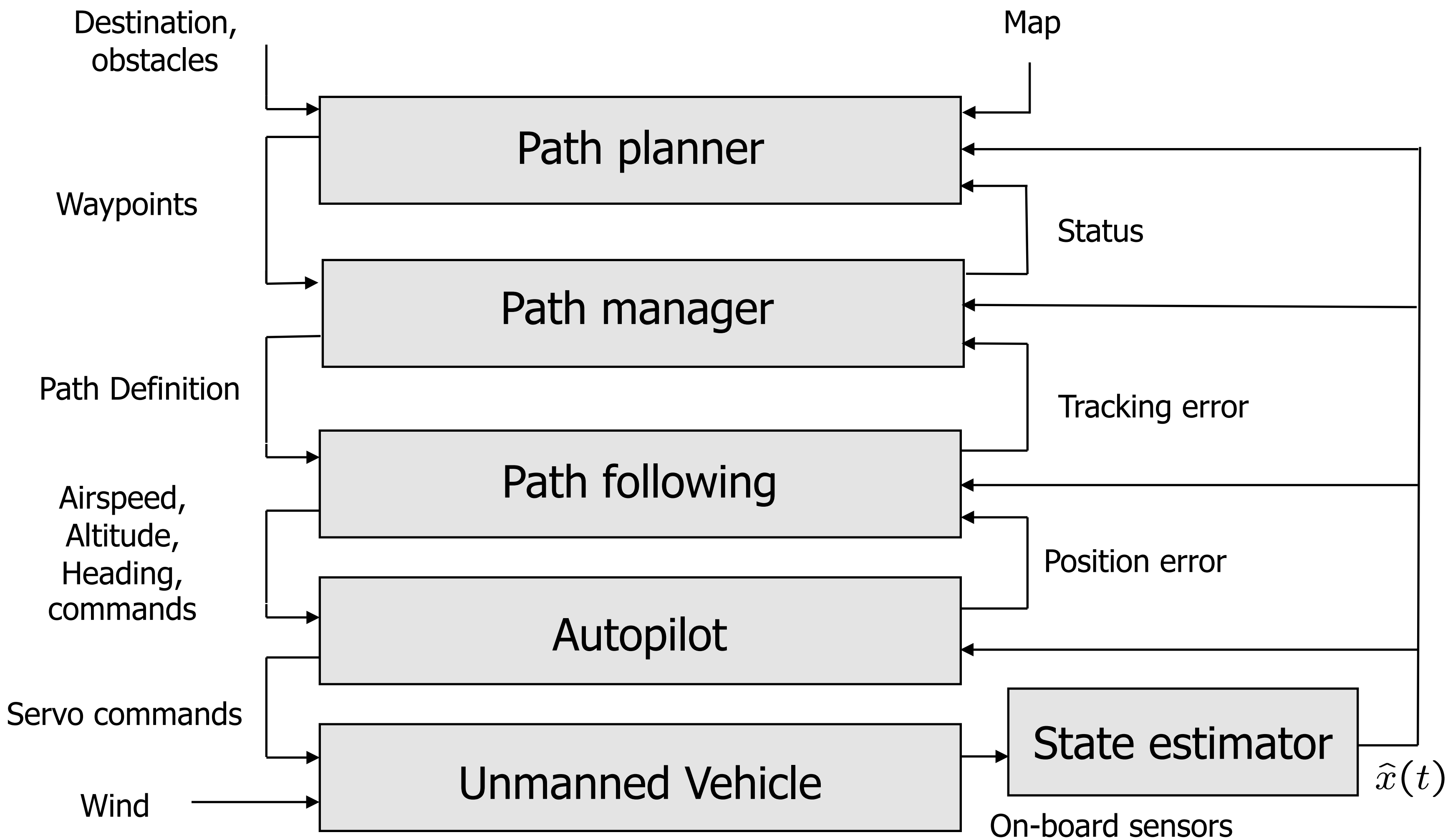
hardware

Step 3:
Real system hardware
Control design implemented
in software

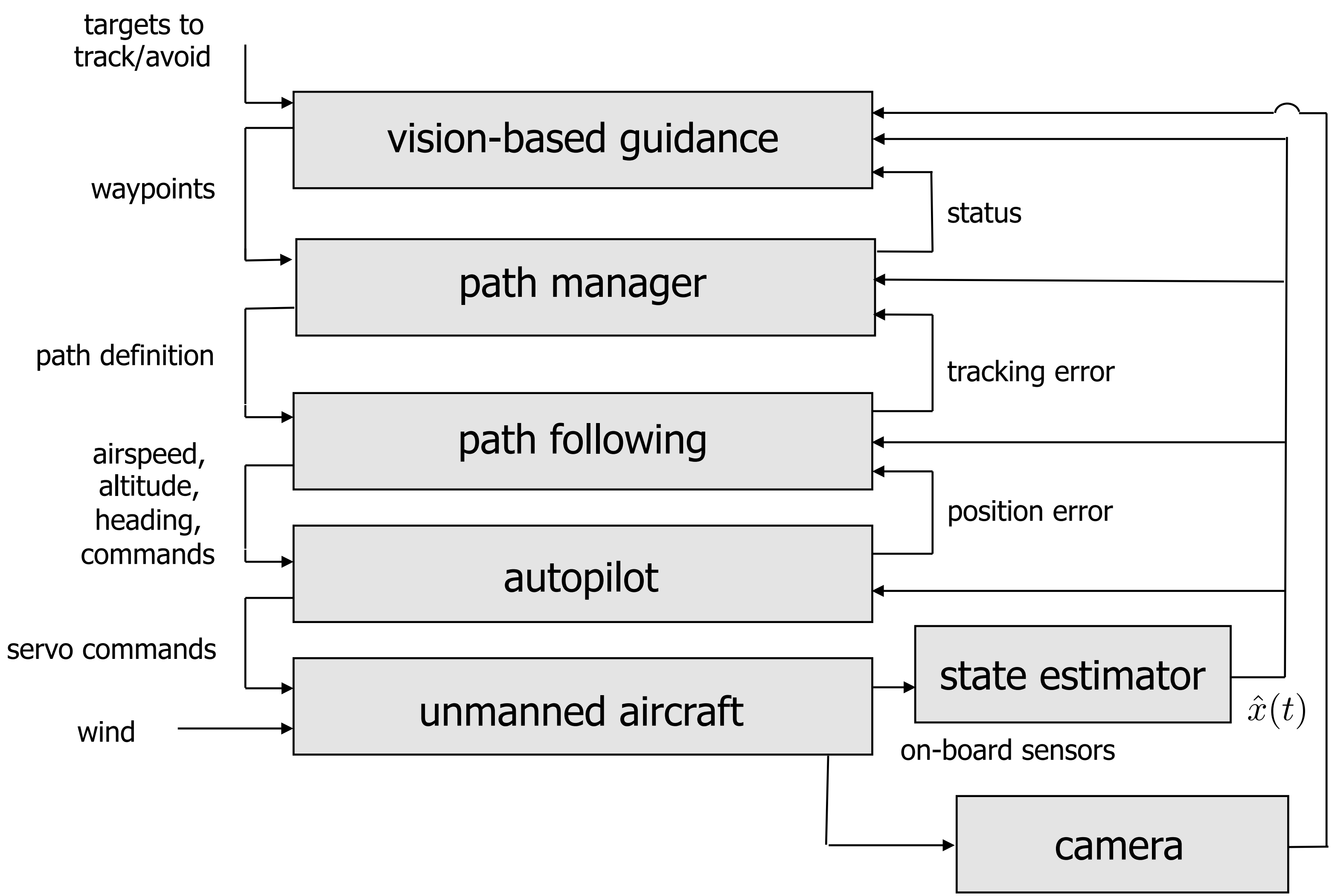
Control
Design

software

Architecture



Architecture w/ Camera



Course Project Ideas

- Small-team (2 or 3 students), students choose project concept
- Implement course simulator in RT Linux/ROS2 framework
- Integrate our course simulator into the AirSim simulator (https://github.com/microsoft/AirSim) or Nvidia Omniverse environment
- Develop learning modules for the African Drone and Data Academy in Malawi (e.g., Jupyter notebooks)
- Extend existing autopilot components to do something in a different way (e.g., perform path following using MPC, state estimation using error-state EKF, path planning with B-splines)
- Extend existing autopilot to do something new (e.g., use machine vision to land on a target, eVTOL aircraft modeling/control)
- Something of your own creation that builds on the concepts of this course