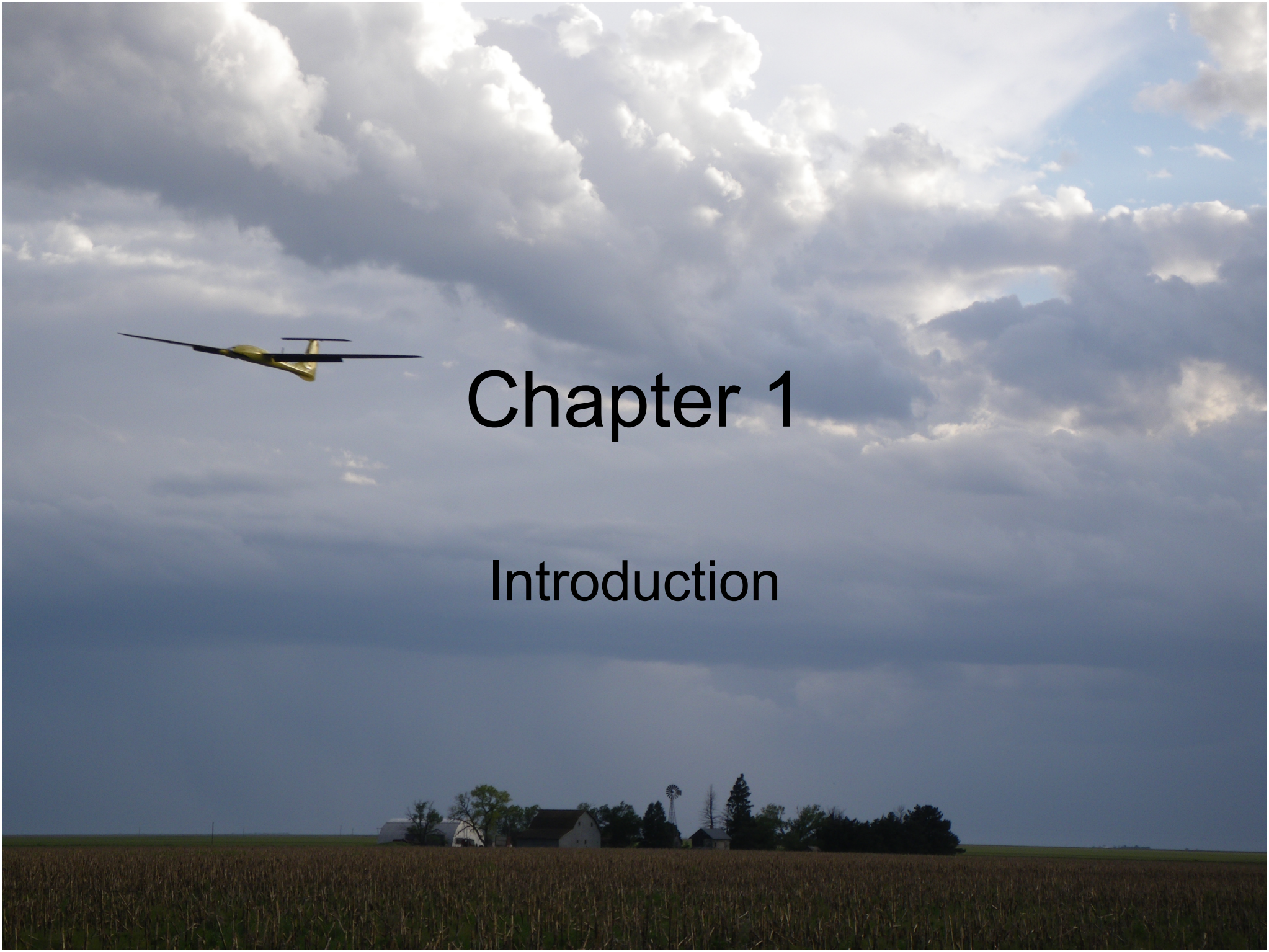


Chapter 1

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

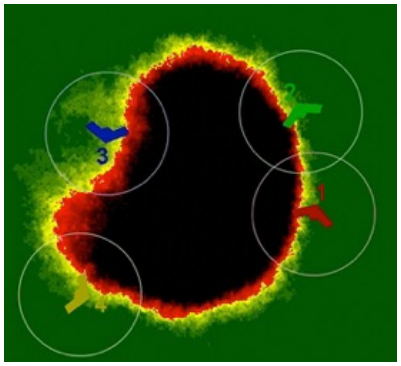
Homeland Security:

- Border patrol
- Surveillance
- Rural/urban search and rescue

New related area:

- Air mobility of humans, goods, services

UAS Research at BYU

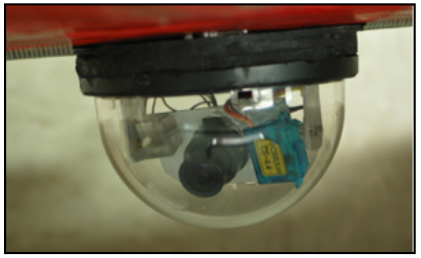


Cooperative Control

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

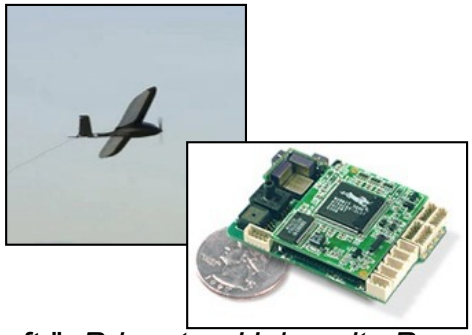
Path Planning
Trajectory Generation

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



Vision-based Control

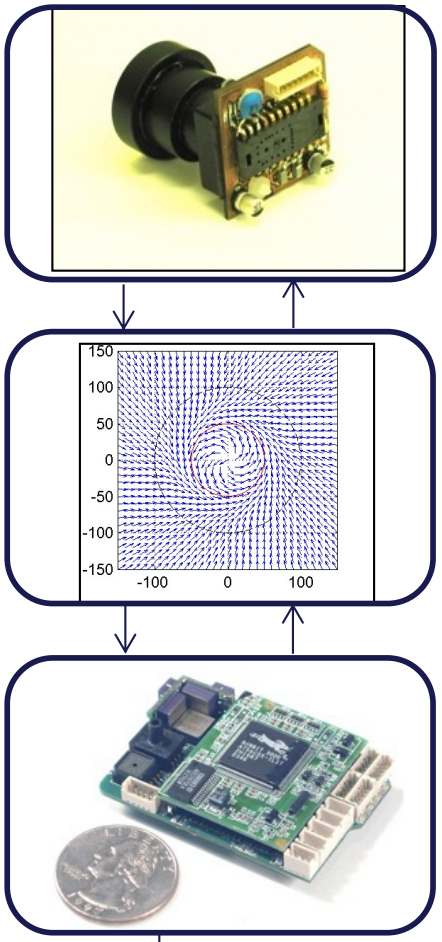
- Image stabilization
- Geo-location
- Vision-aided tracking & engagement



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

Path Following

- Robust to wind
- Computationally efficient

Kestrel Autopilot

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

Applications

- Canyon following
- Collision avoidance
- GPS-denied navigation

Applications

- Precision navigation
- Target tracking
- Target geo-location

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”

PROCERUS TECHNOLOGIES

Over 20 years of UAS research at BYU

The National Science Foundation

Center for Unmanned Aircraft Systems

C-UAS

BYU

VIRGINIA TECH

UNIVERSITY OF MICHIGAN

PennState

Industry Members

Raytheon

UTOPIACOMPRESSION

AV 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

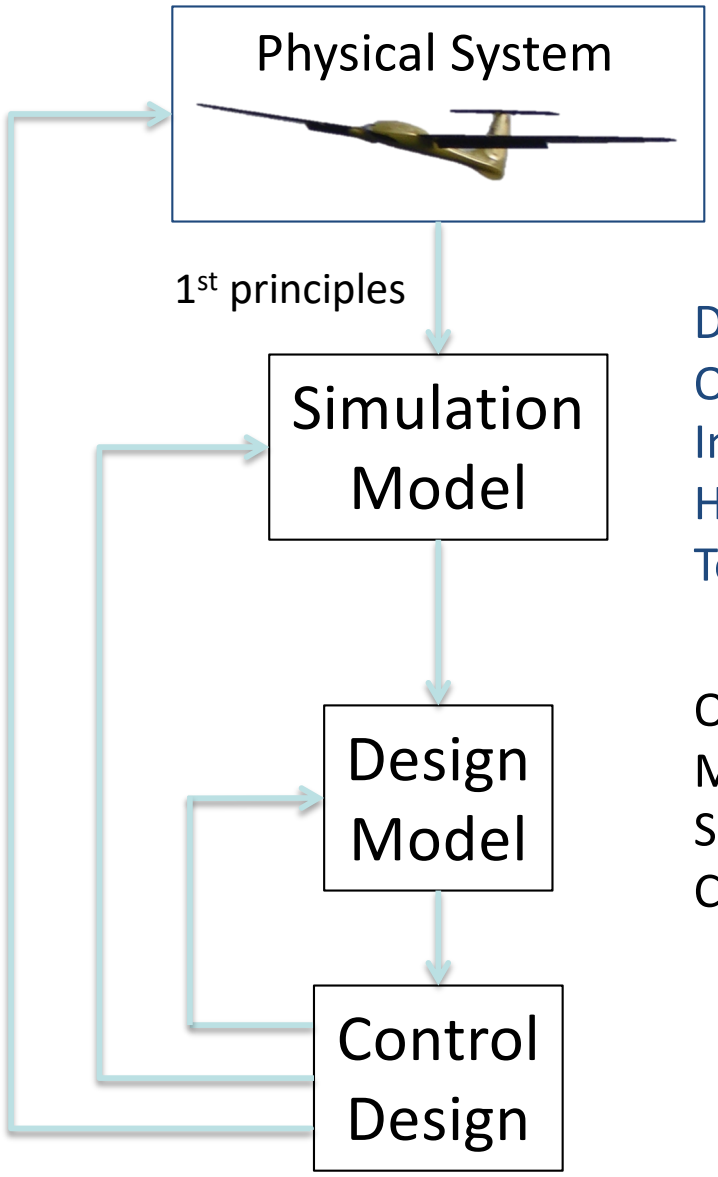
U.S. DEPARTMENT OF ENERGY

Always a Step Ahead ARDEC ARMAMENTS

GE

Honeywell Aerospace

Control Design Process



The real thing

Detailed physics 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

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

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

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

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

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

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

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

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

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

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

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

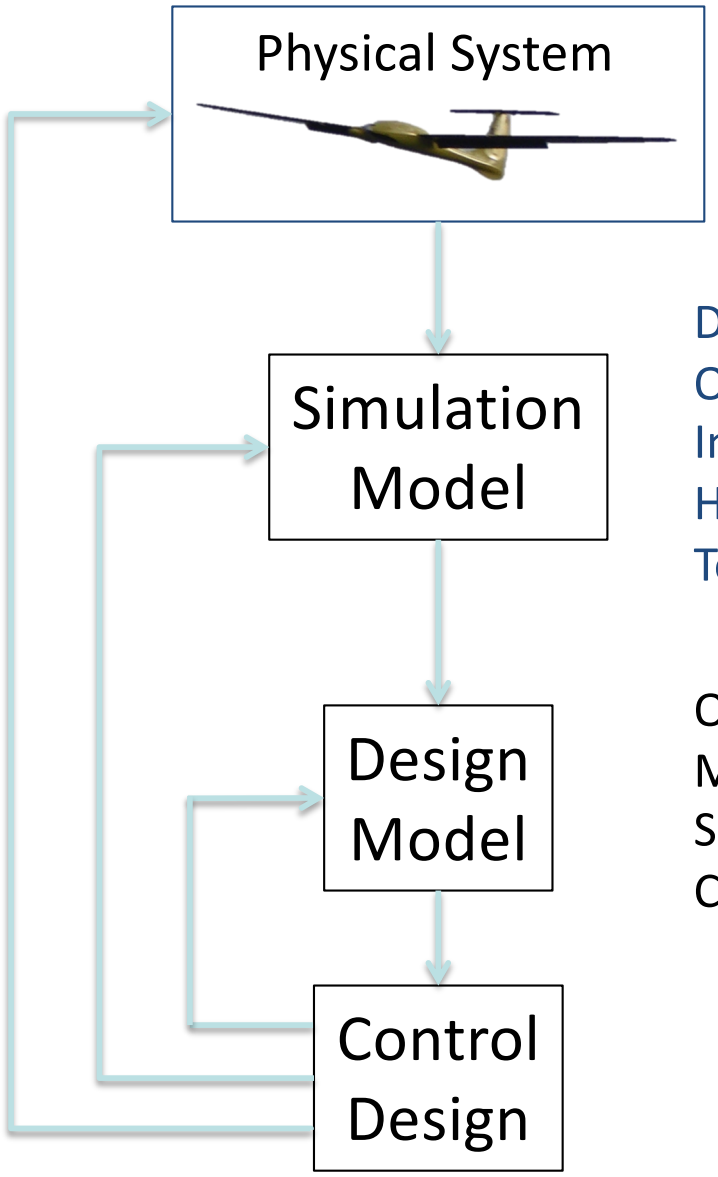
$$\dot{r} = \Gamma_7 pq - \Gamma_1 qr + \frac{1}{2}\rho V_a^2 Sb\left[C_{r_0} + C_{r_\beta}\beta + C_{r_p}\frac{bp}{2V_a} + C_{r_r}\frac{br}{2V_a} + C_{r_{\delta_a}}\delta_a + C_{r_{\delta_r}}\delta_r\right]$$

Simulation Model

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

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

Control Design Process



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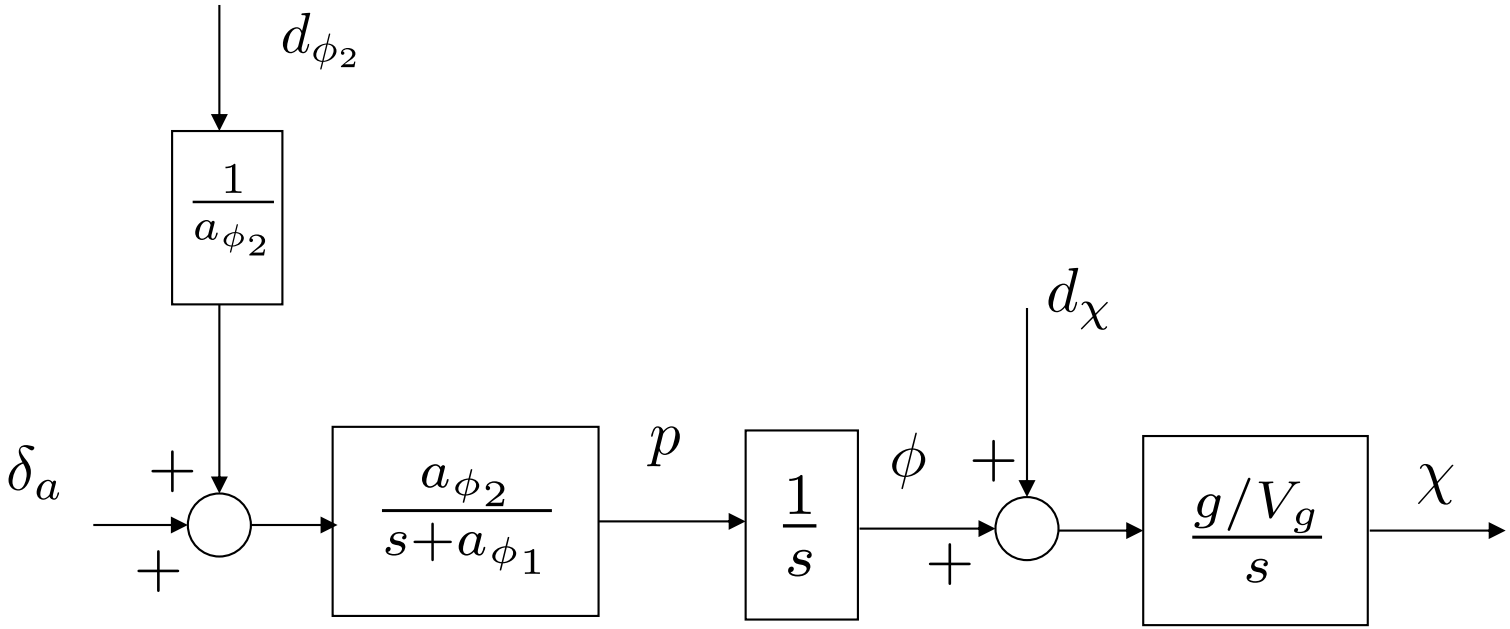
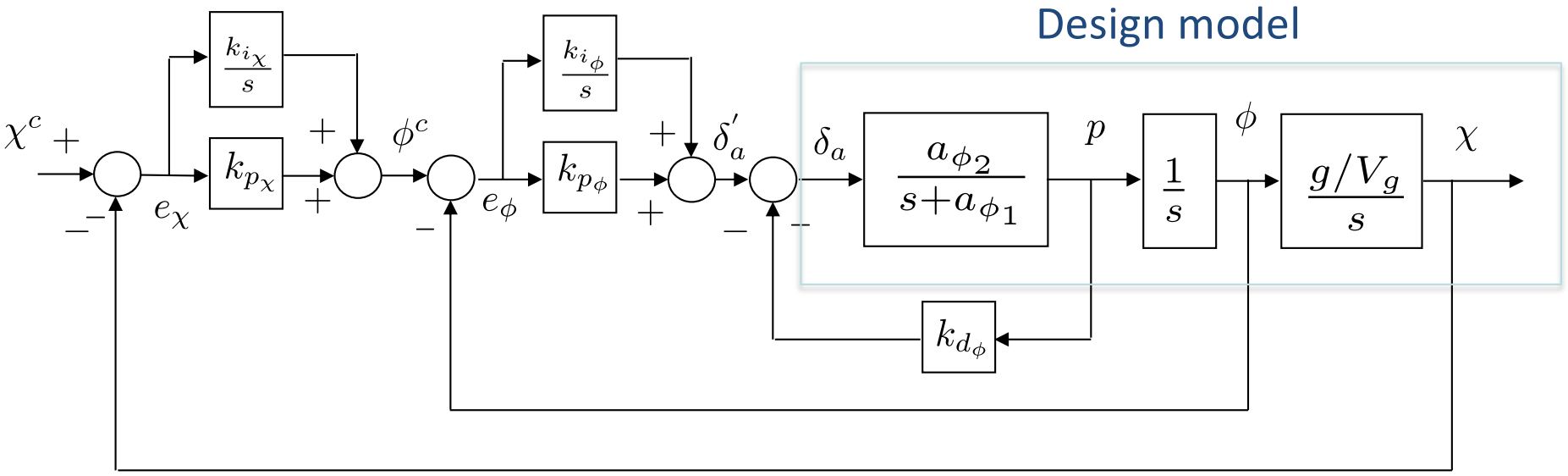
Design Model

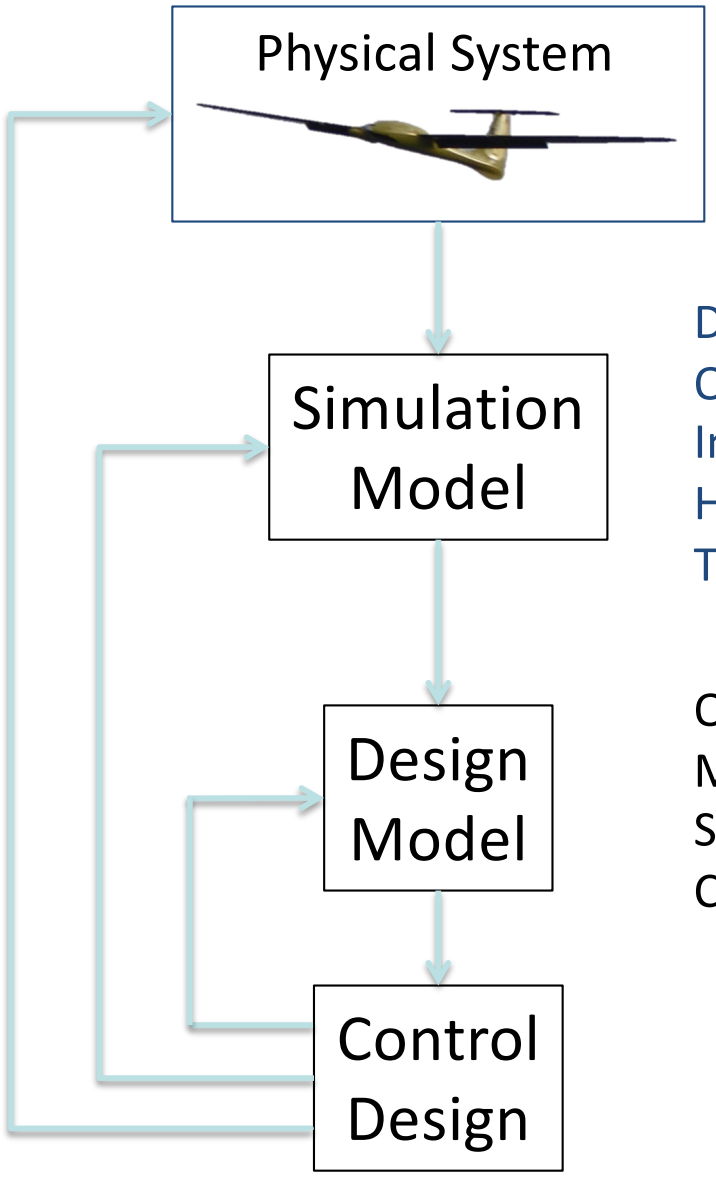
Course from aileron transfer function:



Control Design



Control Design Process



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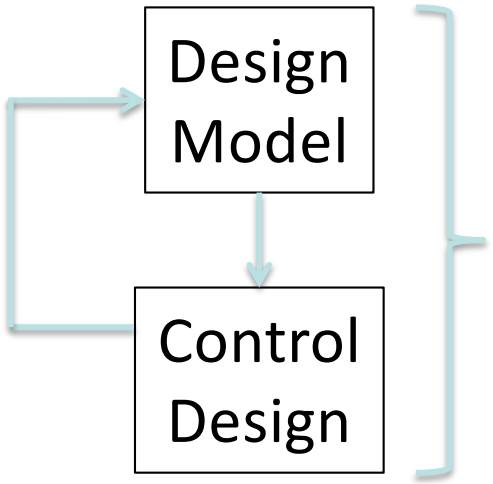
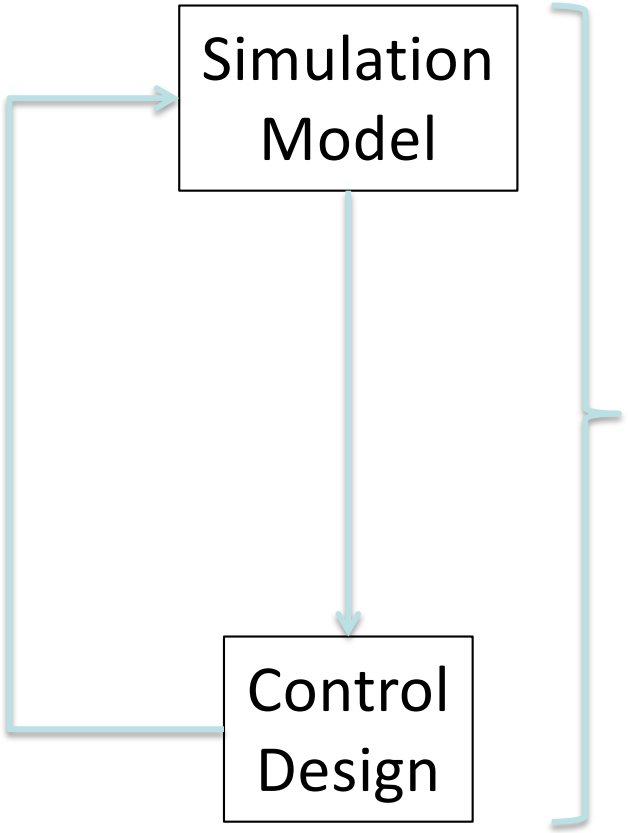


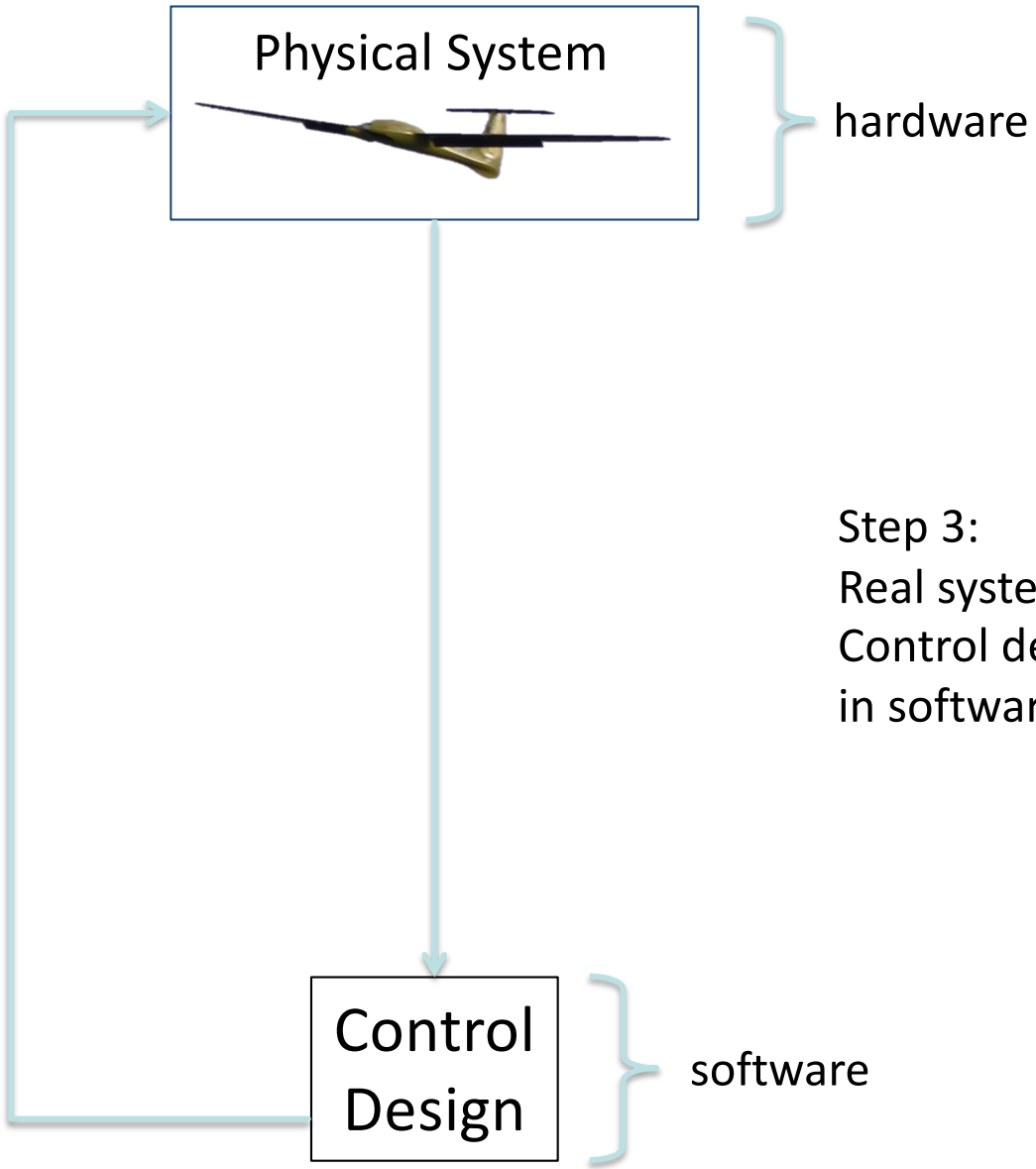
Step 1:
Linear, low-order model
Control design and system model implemented in software

Control Design Process



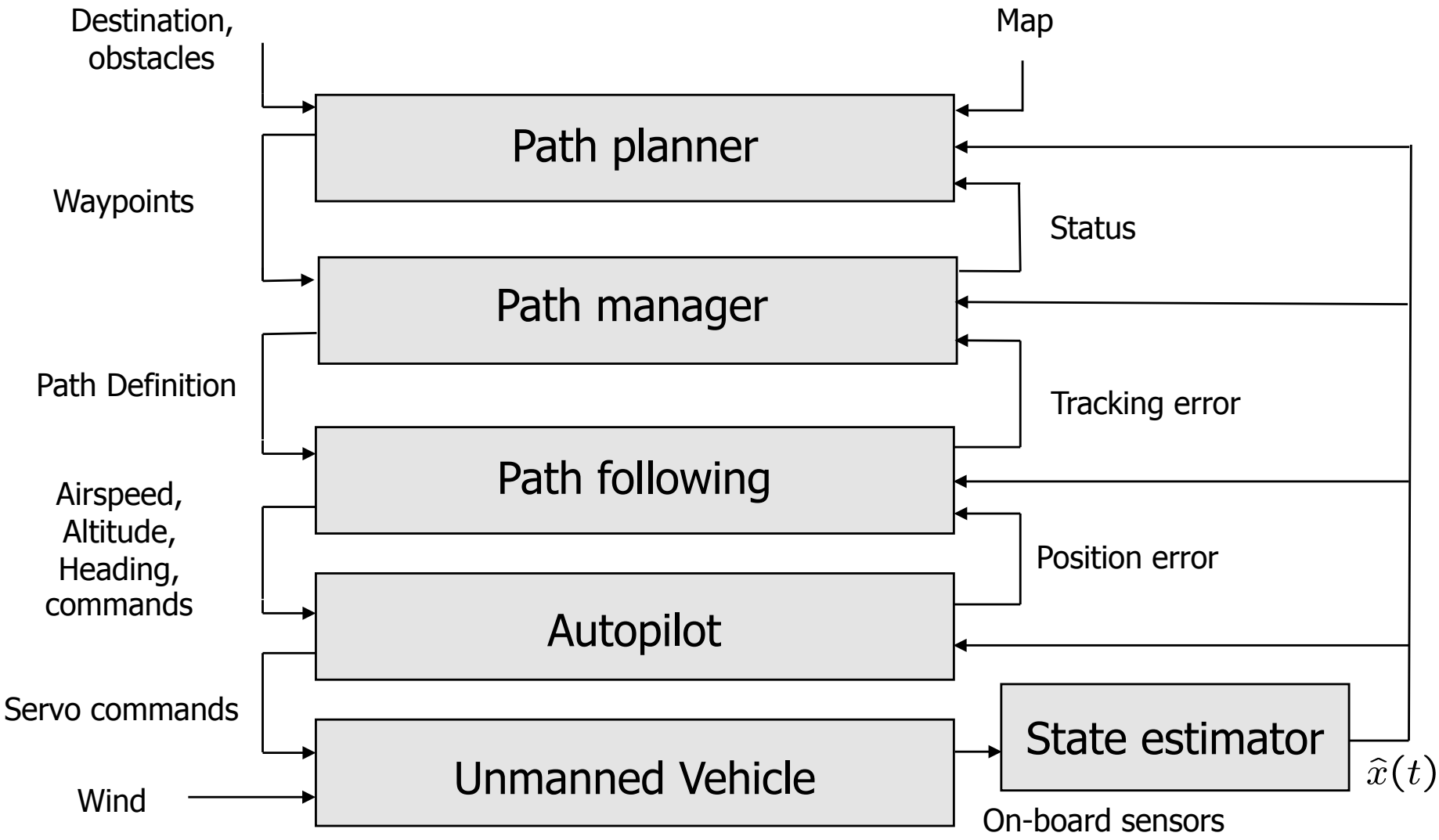
Step 2:
Detailed system model
Control design and system model implemented in software

Control Design Process

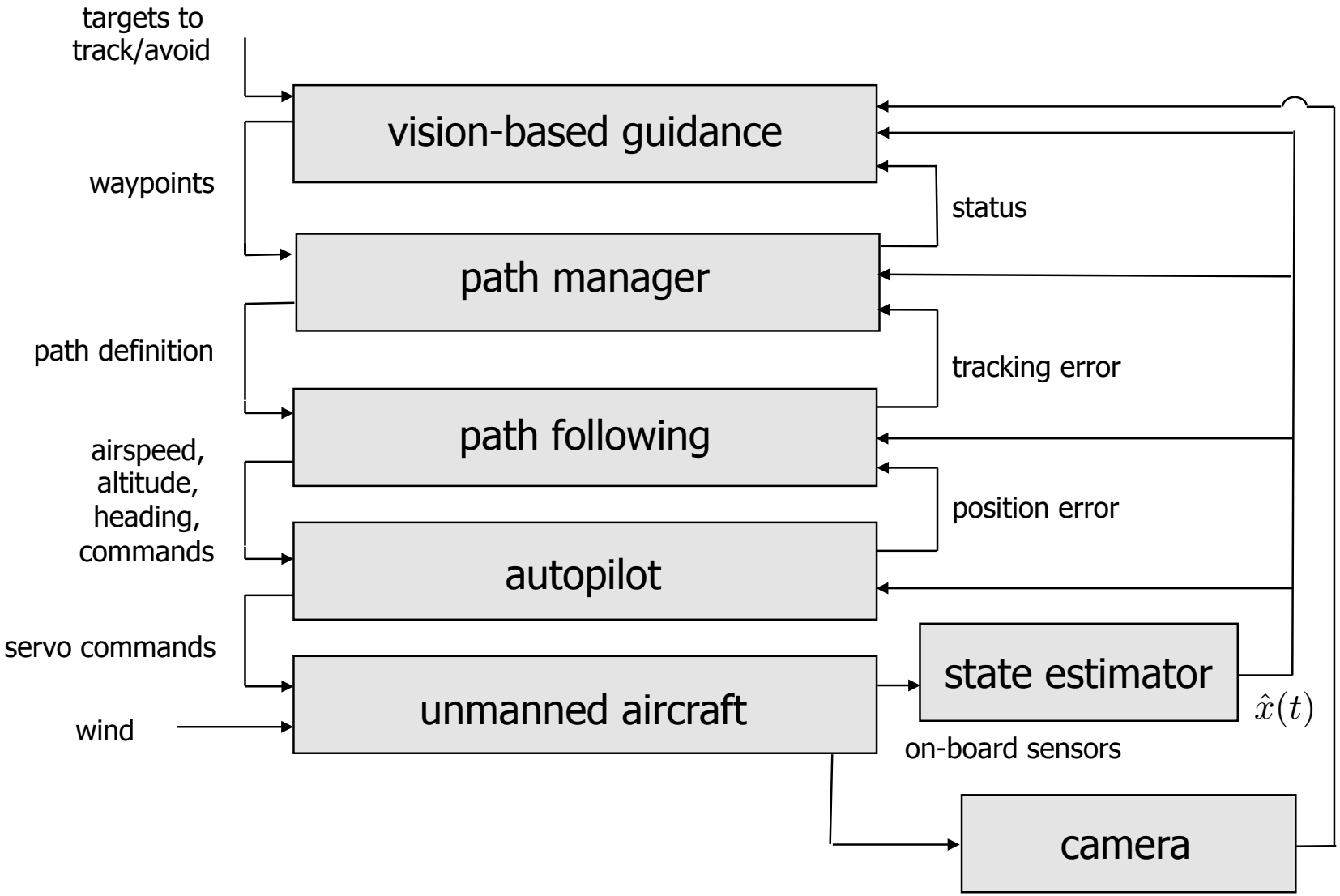


Step 3:
Real system hardware
Control design implemented in software

Architecture



Architecture w/ Camera



Course Project Ideas

- Implement autopilot components on hardware using ROSflight, PixHawk, or another autopilot
- Develop learning modules for the African Drone and Data Academy in Malawi (e.g., Jupyter notebooks)
- Integrate our course simulator into the AirSim simulator (https://github.com/microsoft/AirSim)
- Extend existing autopilot components to do something in a different way (e.g., perform path following using MPC)
- Extend existing autopilot to do something new (e.g., use machine vision to land on a target)
- Something of your own creation that builds on the concepts of this course