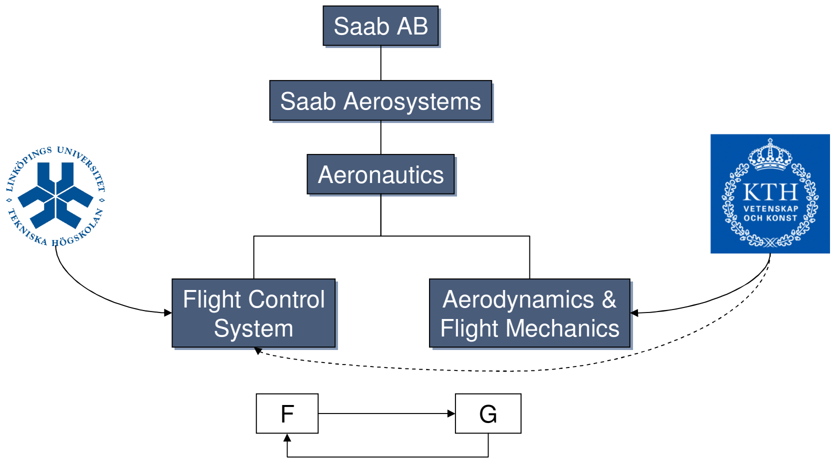
The Skeldar V-150 flight control system

Modeling, identification and control of an unmanned helicopter

Ola Härkegård
LiTH, November 8, 2007

Organization



Aircraft

JAS 39 Gripen

Sharc

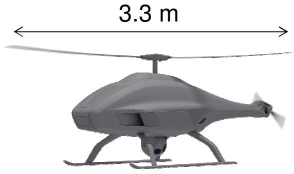
Filur

Skeldar V-150

Skeldar V-150

- Unmanned helicopter for surveillance
- Under development
- Based on APID-55 by CybAero

3.3 m



150 kg

Levels of control

UAV pilot

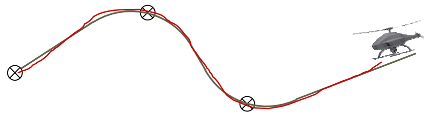
1. Break point list
2. High level commands
   - Heading, speed, altitude
   - Adjust position

Guidance

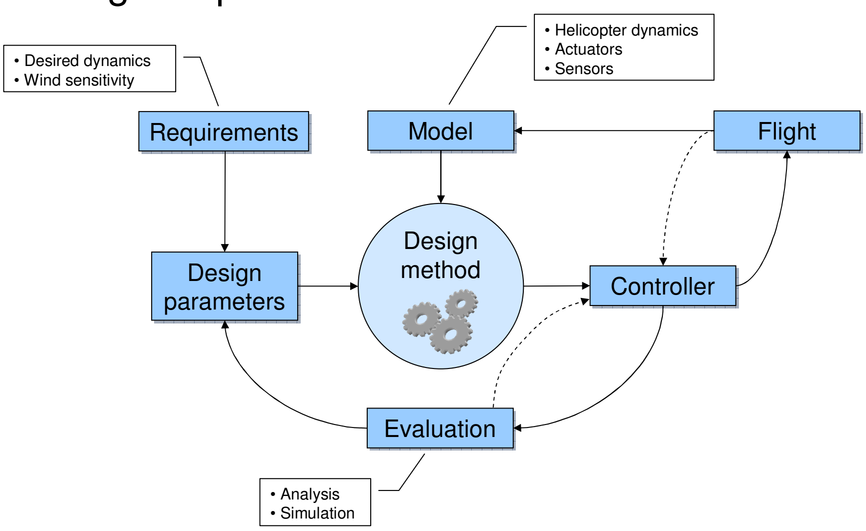
Path generation

Flight Control System

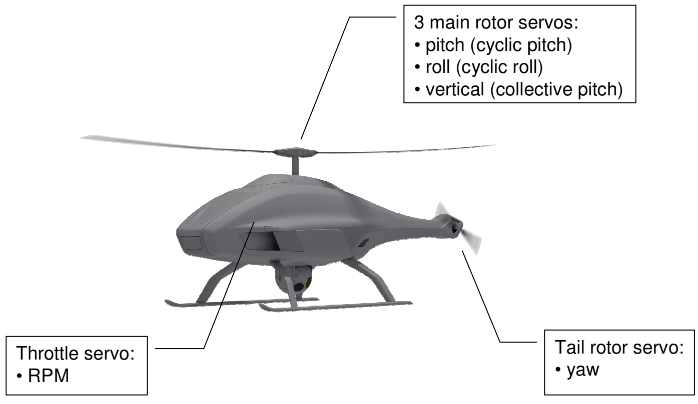
Control



Design loop



Actuators



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Sensors

- AHRS-GPS
  - Rate gyros
  - Accelerometers
  - Magnetometers
  - GPS

Sensor fusion →

- Angular velocity
- Orientation
- Velocity (relative ground)
- Position

- Radar altimeter
- Air-data system

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Dynamics

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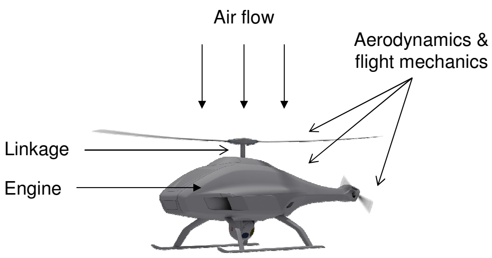
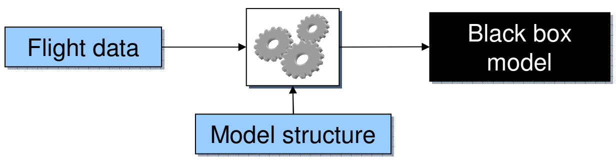
Modeling

1. Physical modeling

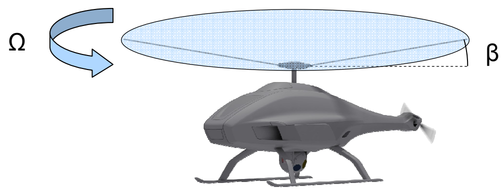


Σ: 26th order nonlinear cross-coupled system

2. System identification



Rotor dynamics



- Flapping equation

$$\beta'' + \;\beta' + (1+d)\beta = \;(\psi)$$

• blade pitch angle
• body rotation
• 2π-periodic

- Parametrization

$$\beta = \beta \;+ \beta_s \sin\psi + \beta \;\cos\psi$$

- Tip-path-plane (TPP) dynamics:

$$\begin{aligned} \beta'' + c\beta_0' + (1+d)\beta_0 &= u_0 \\ \beta'' + c\beta_s' + d\beta_s - 2\beta_c' - c\beta_c &= u_s \\ \beta'' + c\beta_c' + d\beta_c + 2\beta_s' + c\beta_s &= u_c \end{aligned}$$

Reduced TPP-dynamics

$$\begin{aligned} \beta'' + c\beta_0' + (1+d)\beta_0 &= u_0 \\ \beta'' + c\beta_s' + d\beta_s - 2\beta_c' - c\beta_c &= u_s \\ \beta'' + c\beta_c' + d\beta_c + 2\beta_s' + c\beta_s &= u_c \end{aligned} \quad \approx \quad \begin{aligned} \beta_0 &= u_0 \\ \beta_s' &= -\frac{1}{\tau}\beta_s + \frac{1}{2}u_c \\ \beta_c' &= -\frac{1}{\tau}\beta_c - \frac{1}{2}u_s \end{aligned}$$

First order dynamics from inputs to rotor disc orientation

Body dynamics

- Pitch moment

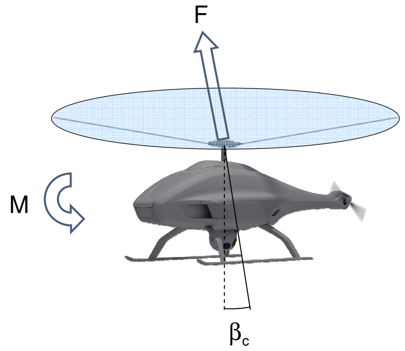
$$M \approx (k + hF)\beta_c$$

Distance to c.g.

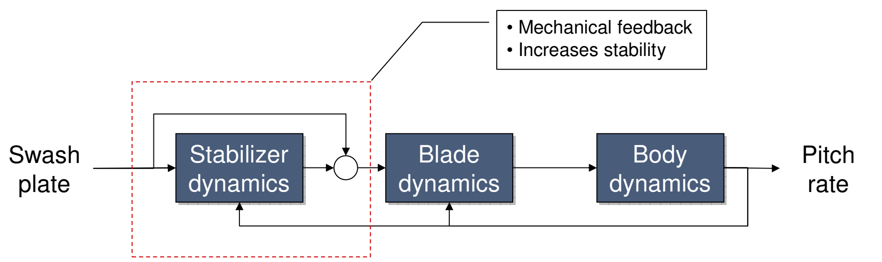
Spring constant

- Pitch dynamics

$$\dot{q} = -\frac{M}{J}$$



Coupled rotor – body dynamics

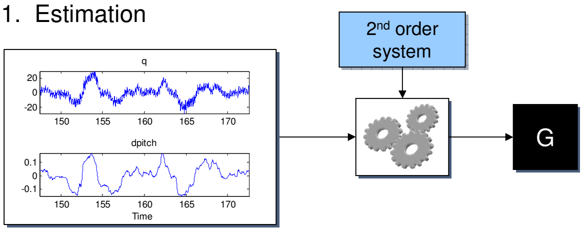


Use sensor feedback instead?

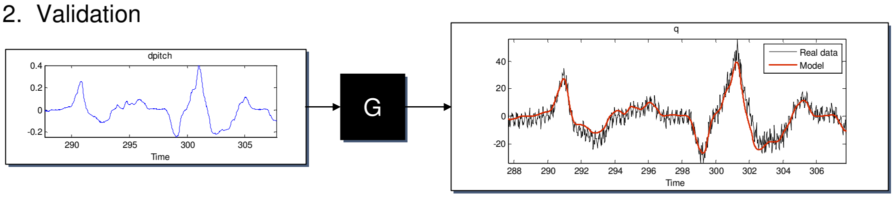
Mikado virtual flybar

System id – pitch dynamics

1. Estimation



2. Validation



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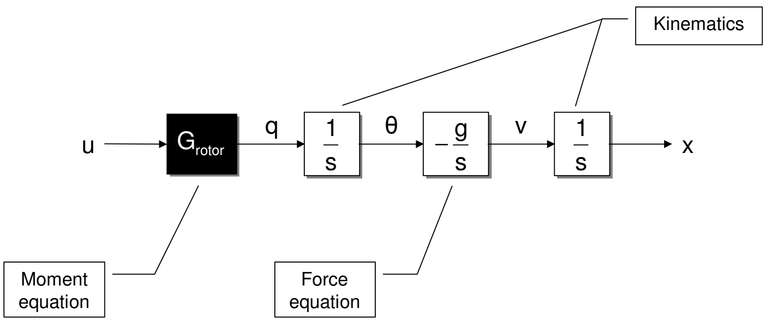
Open loop pitch dynamics



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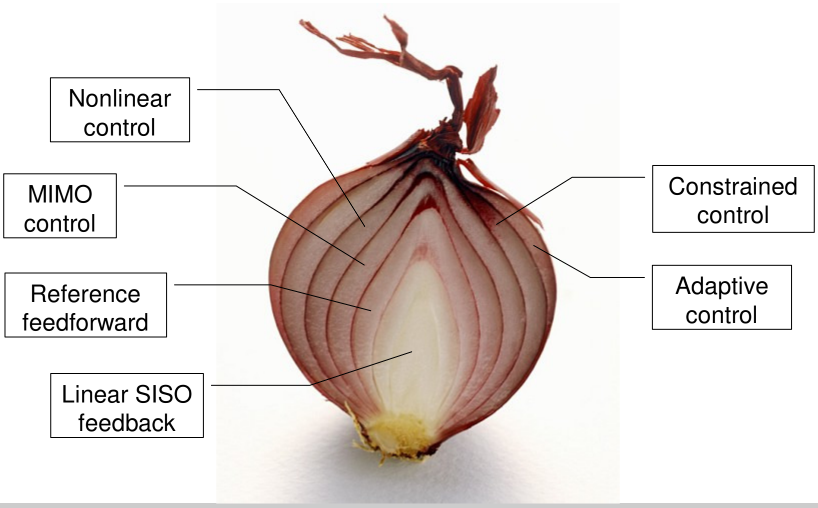
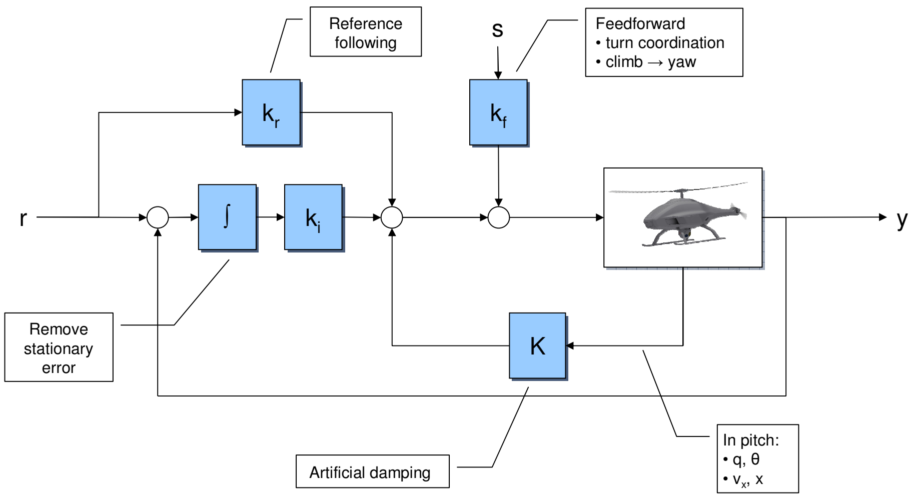
Control design

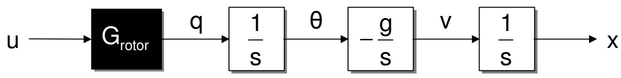


Control laws



Feedback

- Open loop dynamics



- LQ design

1. Hover $u = -k_q q - k_\theta \theta - k_v v - k_x x - k_i \int x$
2. Flight: $u = -k_q q - k_\theta \theta - k_v v - k_x \int v$

Are LQ robustness properties retained?

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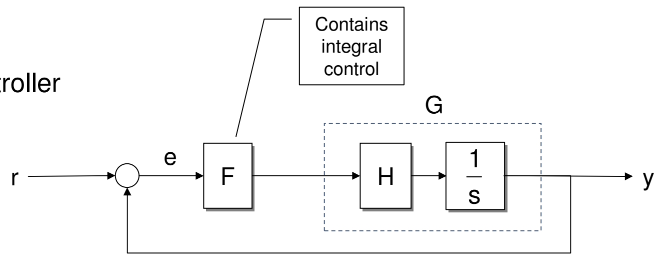
Feedforward

- 1 DOF controller



- Nice structure BUT...

$$\lim_{t\to\infty} \int e = \lim_{s\to 0} s \frac{1}{s} E = \lim_{s\to 0} \frac{1}{1+FG} \frac{1}{s} = \lim_{s\to 0} \frac{1}{sFG} = 0$$

Overshoot – No good!

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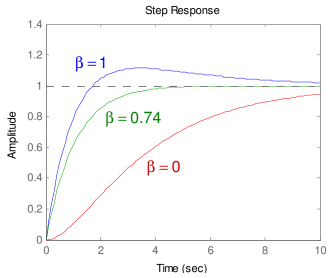
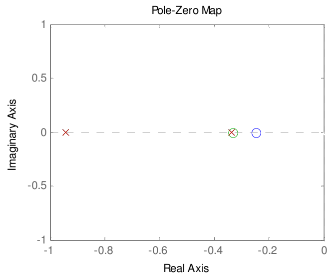
Solution: Set-point weighting

- Modified PI-controller $u = k_p(\beta r - y) + k_i \int (r - y)$

Set-point weight $0 \le \beta \le 1$

- Example: $G = \frac{1}{s}, \quad k_p = 1.3, \quad k_i = 0.3 \quad \Rightarrow$ closed loop poles: -0.94, -0.34





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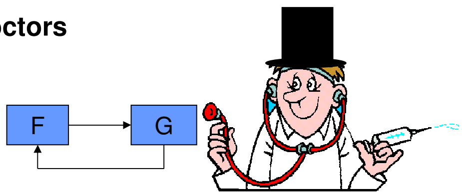
Conclusions

- Many control tools useful **if you know them**
  - identification, LQ, phase diagrams, Nyquist theorem, model reduction, feedforward, anti-windup, bumpless transfer, ...
- **Dynamic intuition** valuable
- Saab needs more **control doctors**



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