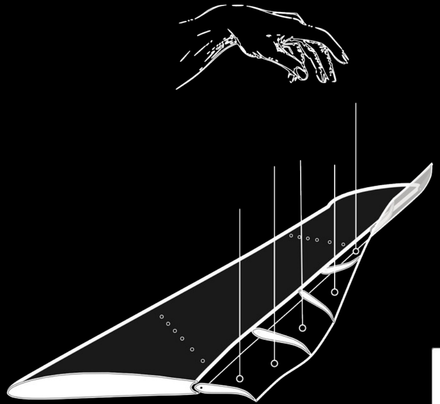
Virtual, ASME 2020 SMASIS, 15 September 2020



Virtual, ASME 2020 SMASIS, 15 September 2020

# Design and Real-Time Implementation of a Vision-Based Adaptive Model-Free Morphing Wing Motion Control Method

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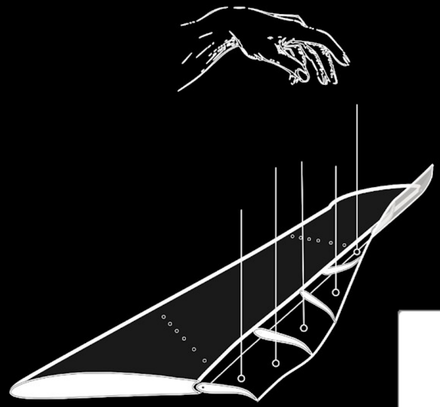

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SMARTX-AL

# Flexible Structures

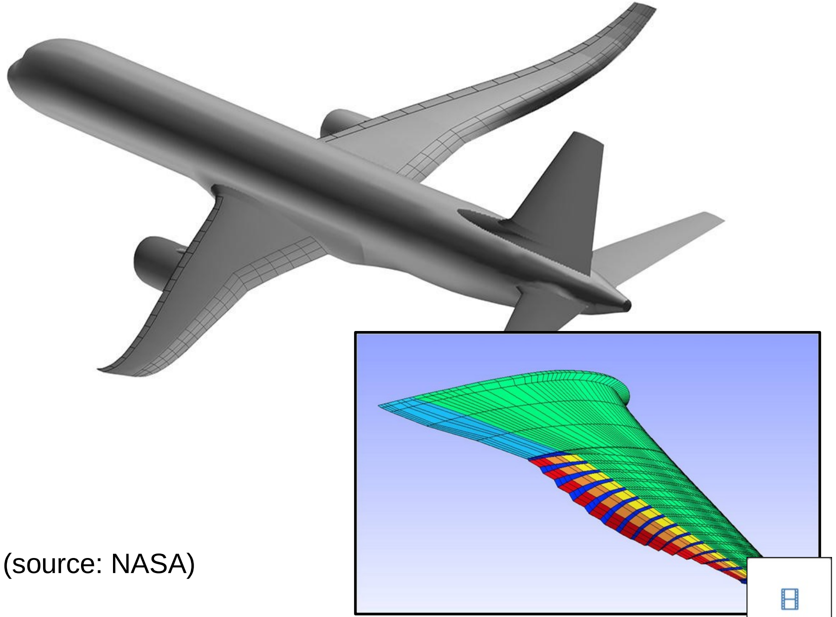
# Introduction

## Trend towards flexible configurations:

**Adaptive Compliant Trailing Edge**


(source: NASA)

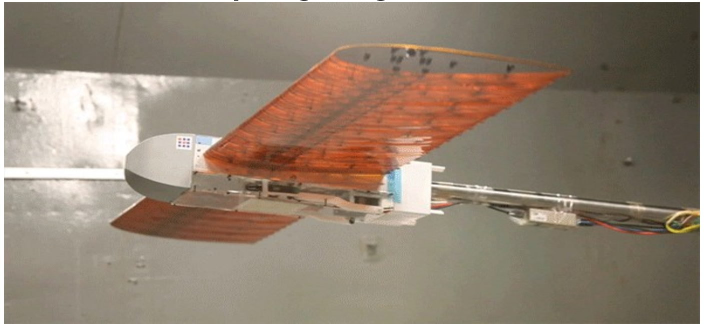
**Variable camber continuous trailing edge flap flap**



(source: NASA)

# Applications: slender flexible (morphing) aircraft

**Cellular morphing wing**



(source: NASA AMES/MIT)

**HALE solar power aircraft**

(source: NASA)

**Facebook drone aquila**

(source: Facebook)

# Smart-X

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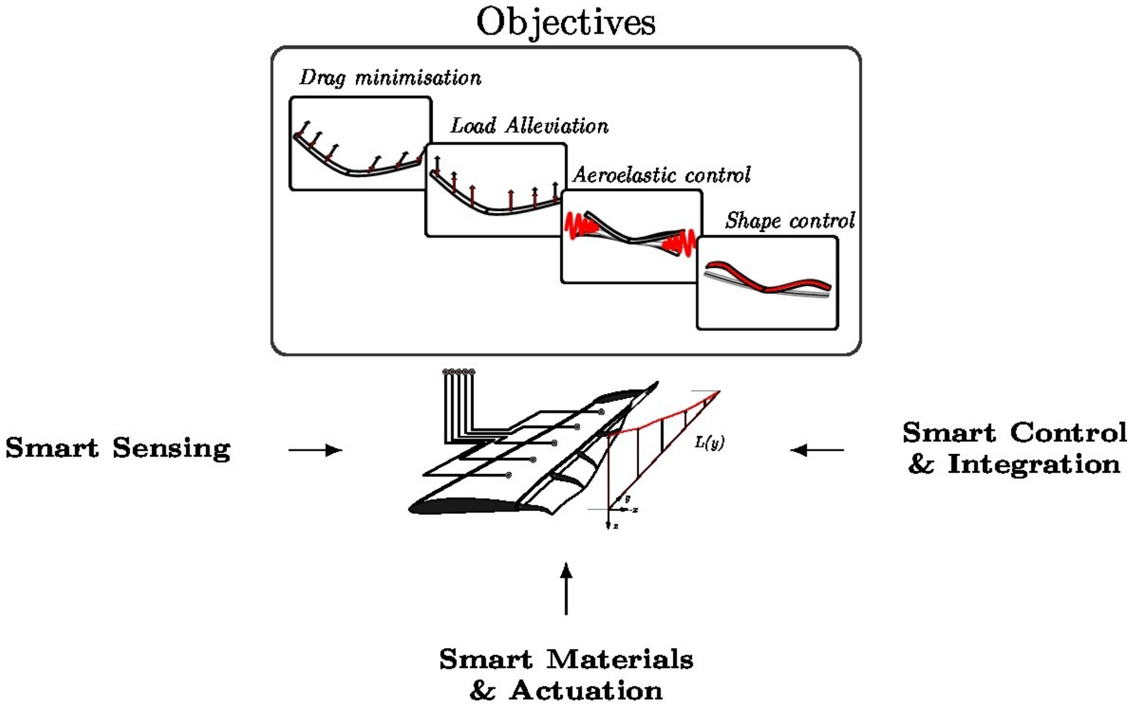
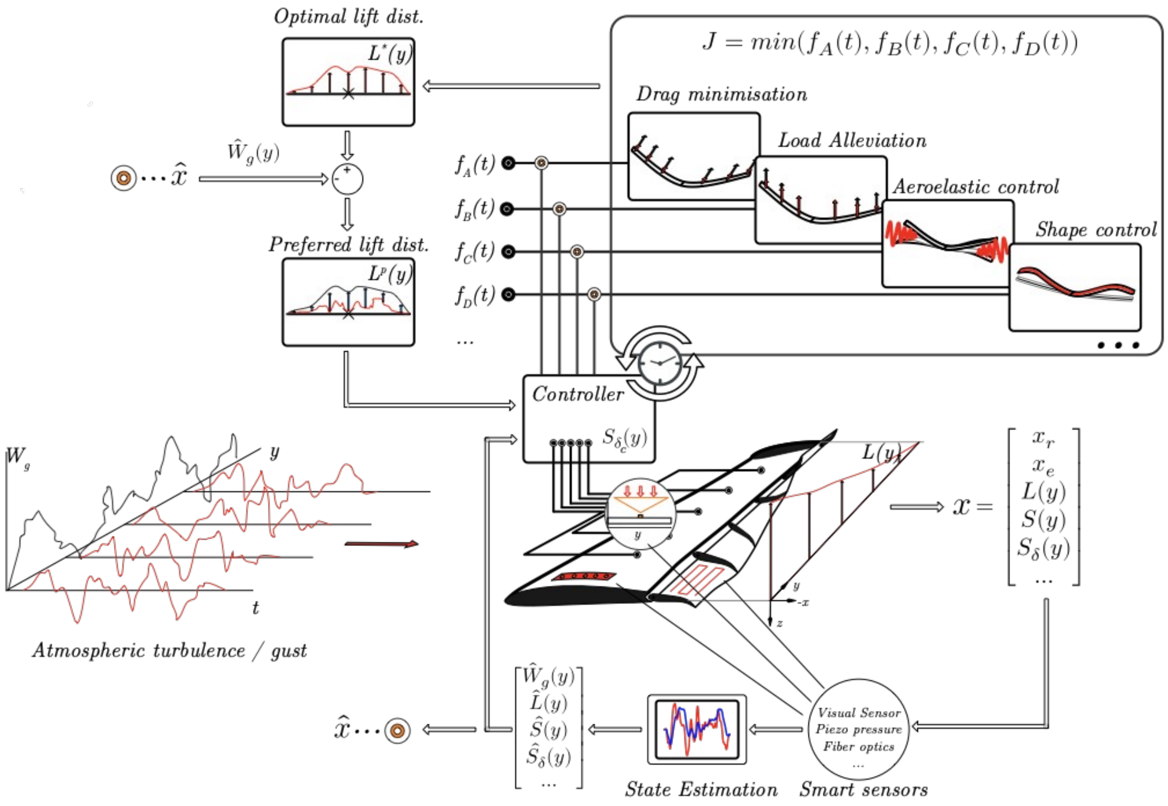
# Goal: the Smart Morphing Wing

*How can we use multidisciplinary integration of <u>novel control laws, sensing methods, and actuation mechanism</u> for real-time, in-flight, multi-objective optimisation of actively morphing wing?*



# Real-time multi-objective performance optimisation



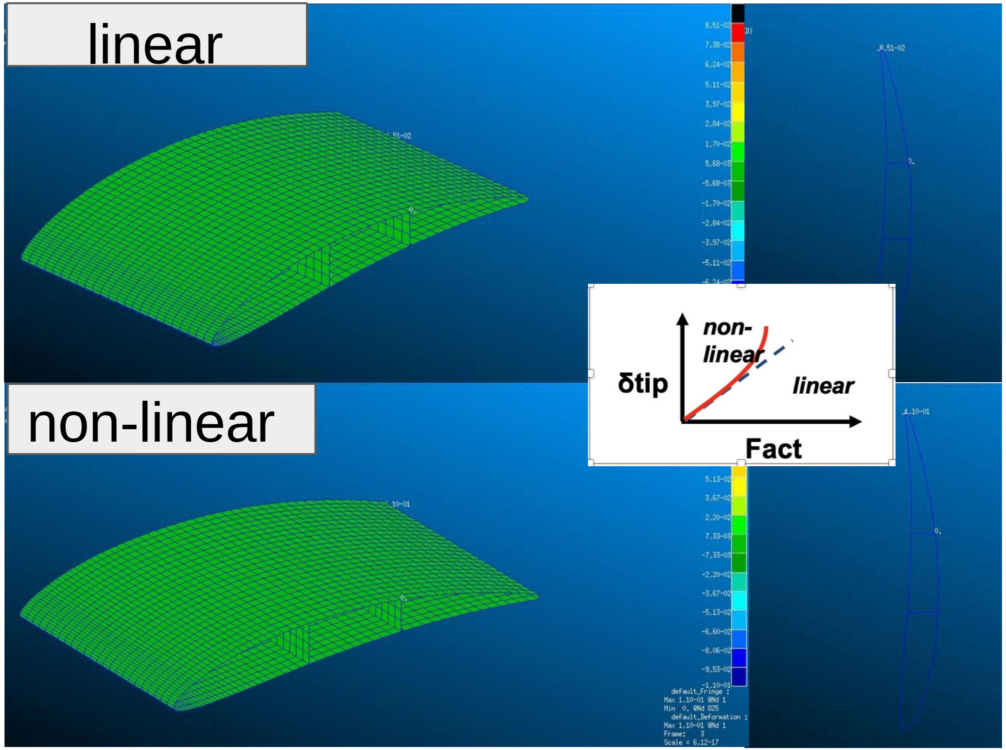
# Challenges Morphing Structures

# Challenges control design morphing: non-linearity

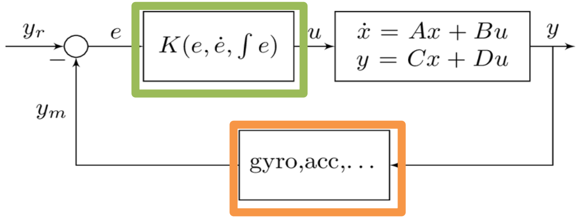
actuator force non-linear control effectiveness mapping:

sensor

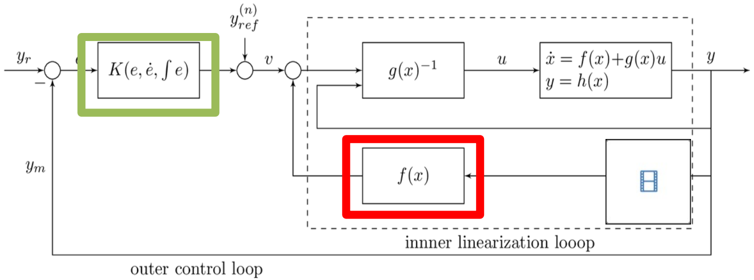
PID controller



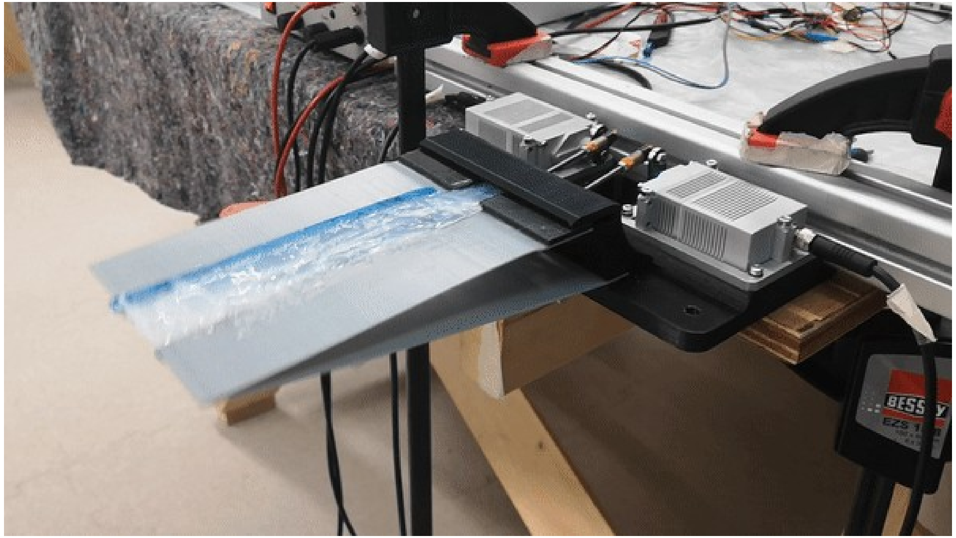

**Typical: Linear + PID**




**non-linear dynamics (act + model)**



# Smart-X morphing in action



# Gaps in Literature: Control & Sensors

**Current** → **Needed** ← **Current**

| | | | |
|---|---|---|---|
| Largely linear and slow | Fast, accurate non-linear models | Non-linear CA method for IBS → IBSCA | Non-Linear CA methods active research area |
| Large $N_{states}$ → Empiric ROM | *Justified* ROM for control | Justified model reduction (control) | Large $N_{states}$ slow for RT control models |
| Design methodology passive (tayloring) | Design methodology active (control) | Lyapunov stability distributed coupled systems | Stability of distributed coupled systems unsolved |
| Quasi steady aerodynamics (2D models) | Unsteady aerodynamics (2D and 3D models) | Model free adaptive sensing techniques | Novel control methods sensors dependent |

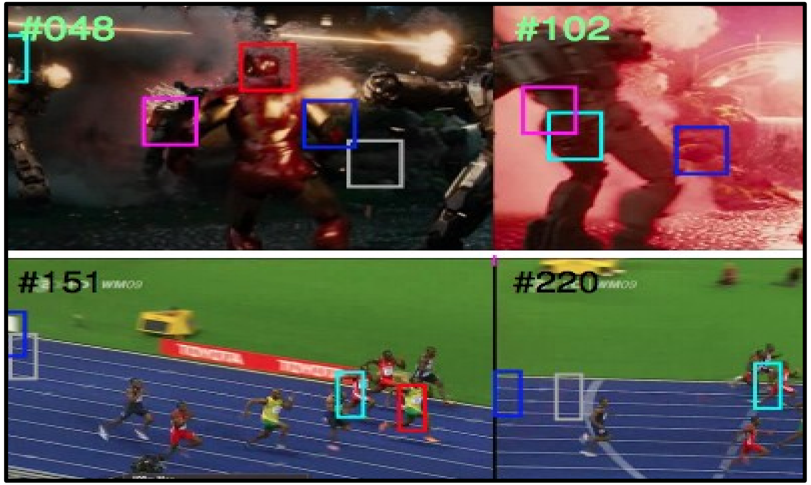
Aeroelastic Modelling

Control & Sensors

# VISUAL TRACKING

# Proposed Concepts: Control & Sensors

Visual tracking

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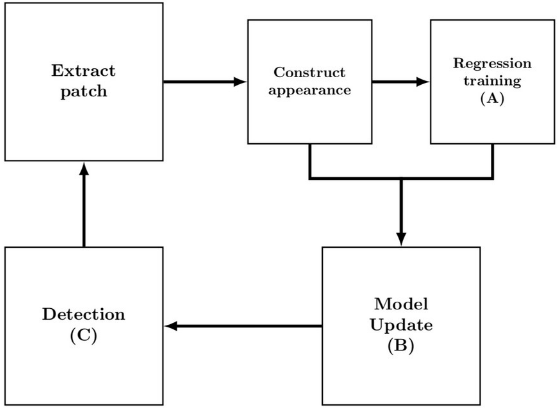
Kalman Filter

# Visual tracking KCF-Kalman couple

- Novel method for monitoring wing displacements and loads real-time with simple camera feed (e.g. mounted in the fuselage)
- Combines speed of KCF (Kernelized Correlation filter) with robustness and prediction of the KF (Kalman Filter)

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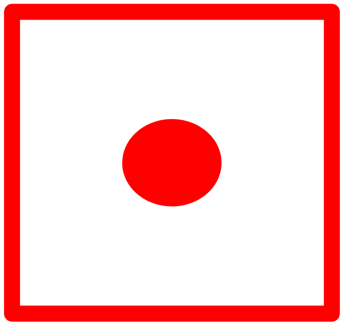
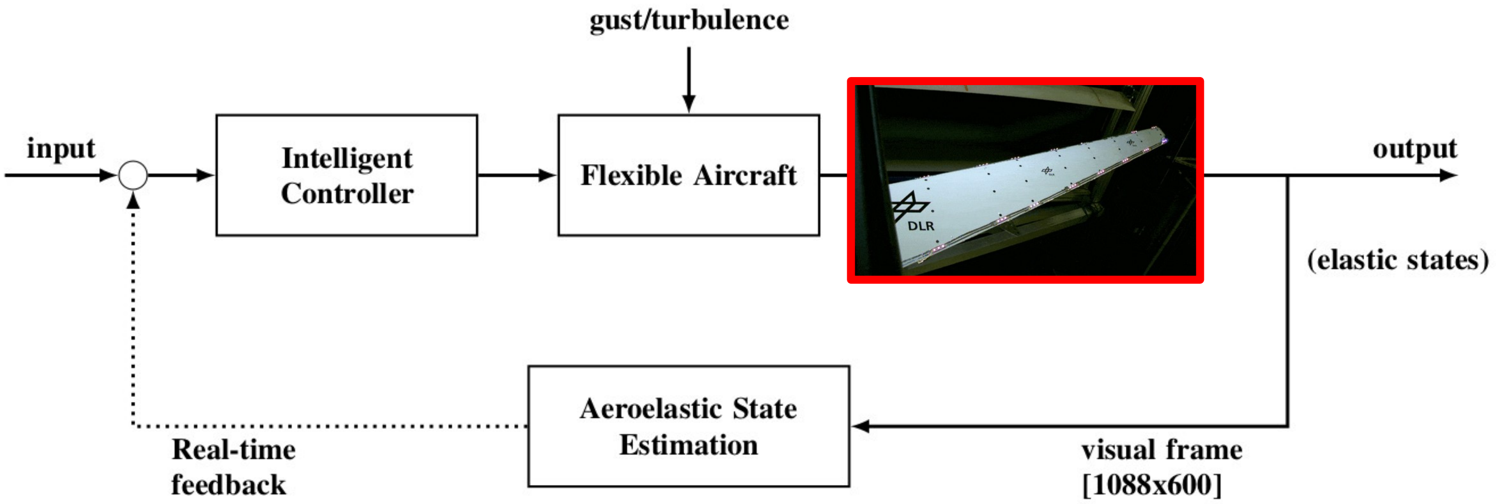
KF *(prediction)*



# A Simplified Control diagram Visual Tracking

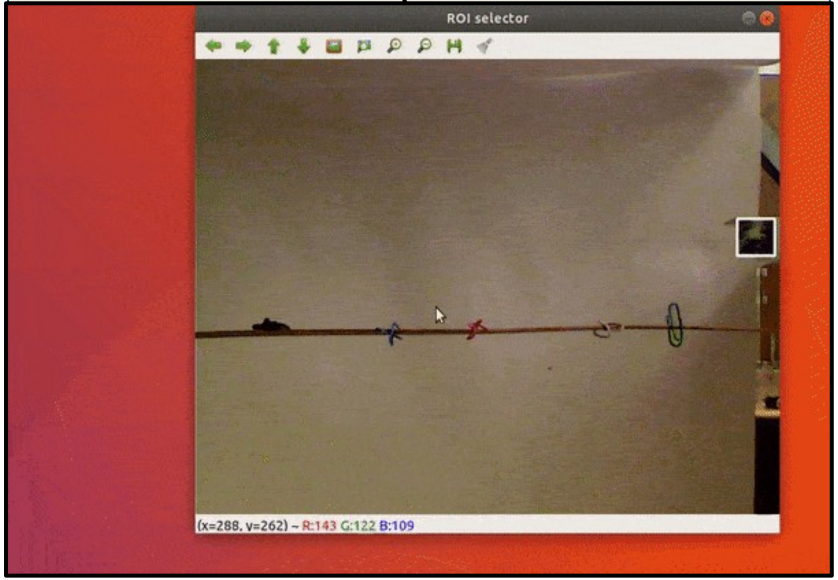



**Question**: *Can we provide aeroelastic feedback with alternative sensors for Real-time control?*

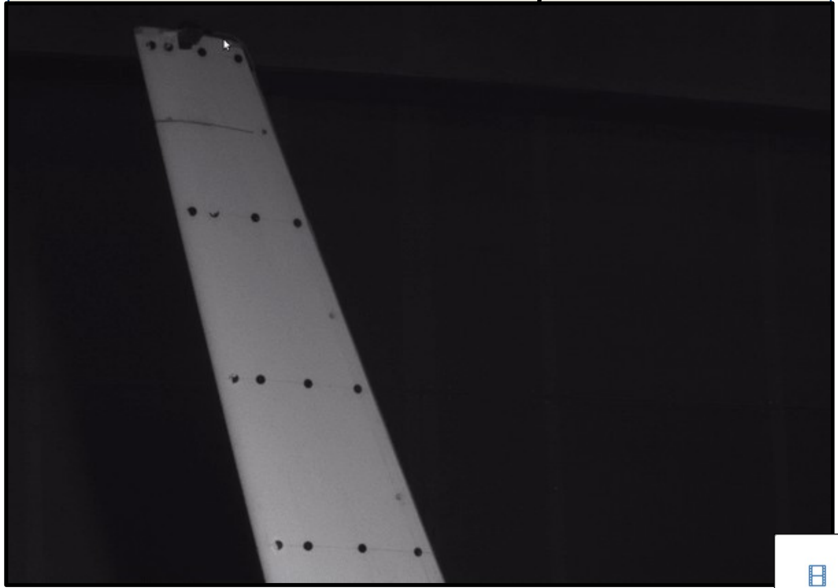
**Purpose**: *Investigate how to eliminate dependency on both model (f(x)) control effectiveness (g(x))*

# Visual tracking KCF-Kalman couple

clamped beam



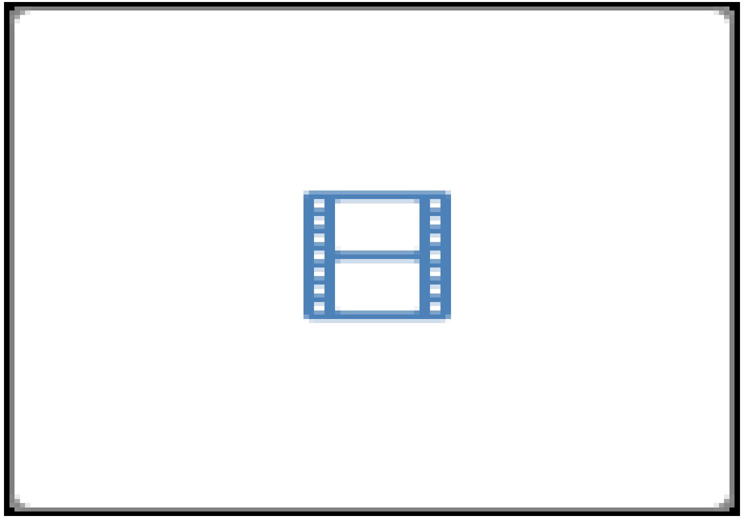

actual wing wt



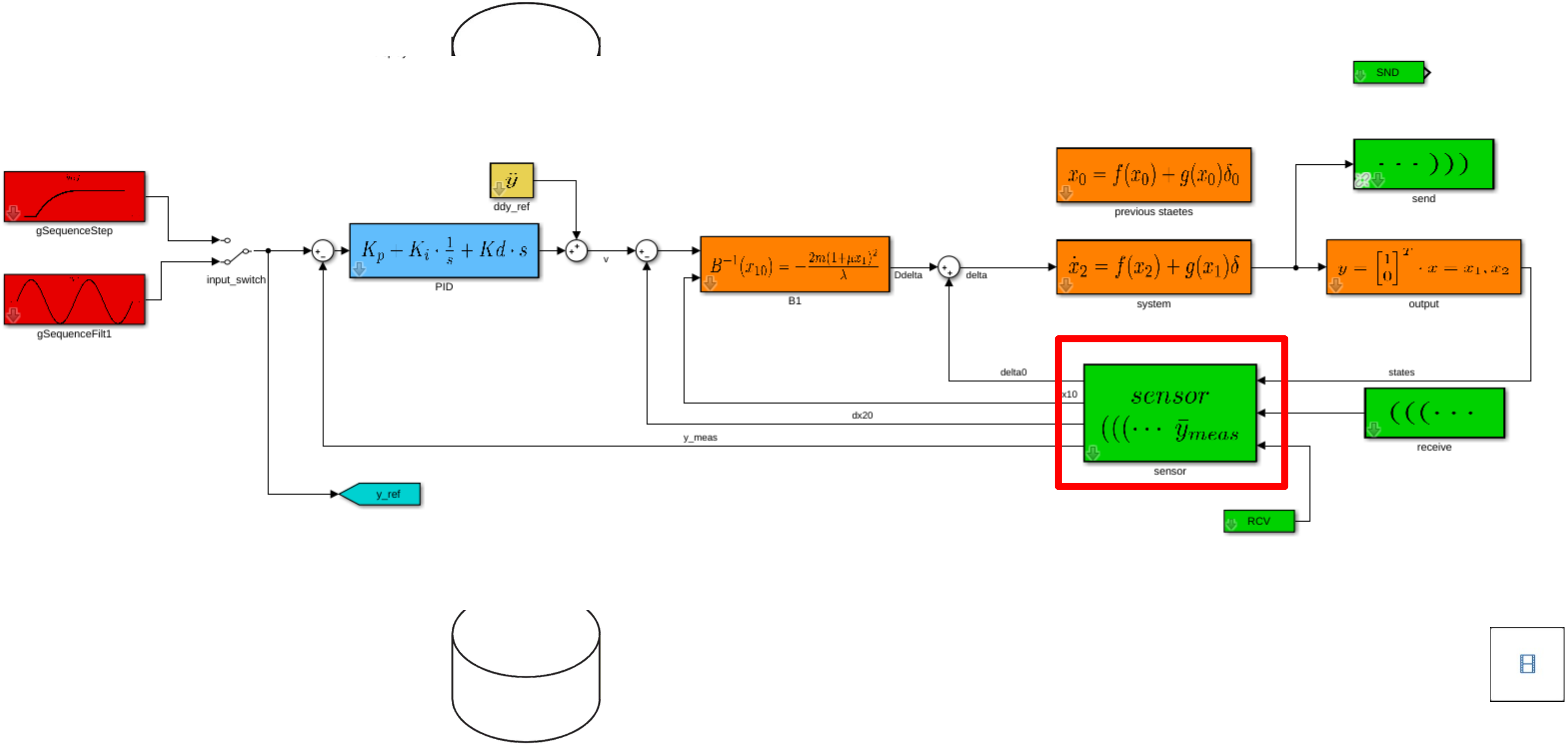
# Visual tracking KCF-Kalman couple

clamped beam

actual wing wt

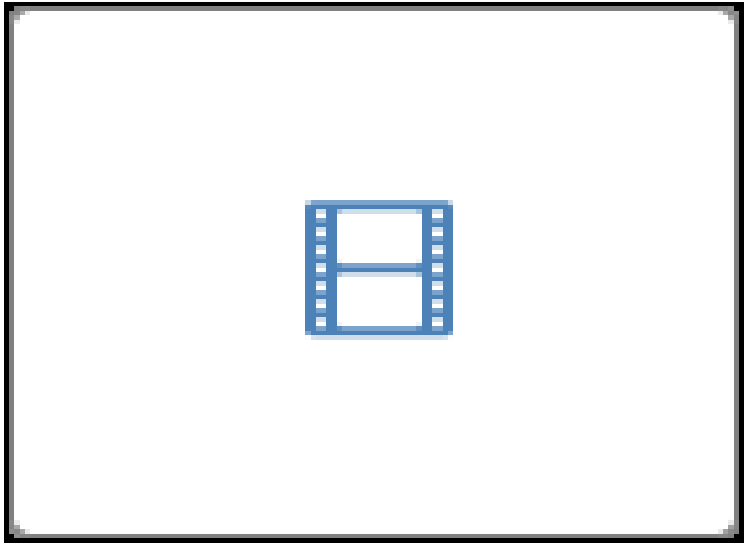


# Control problem: suspended magnet

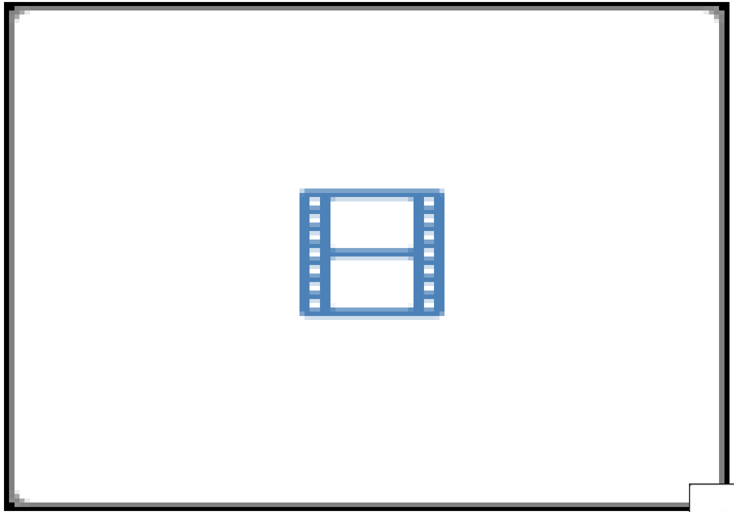


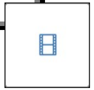
# Visual tracking control feedback

Closed loop: Motion feedback



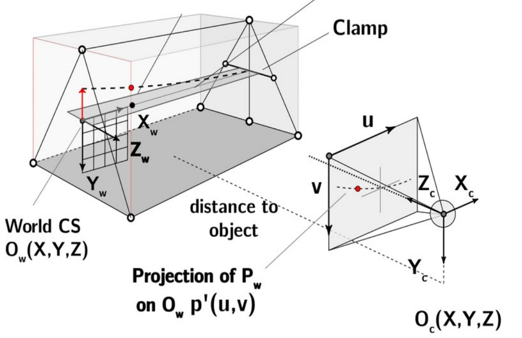
Freehand: Tracking actuator motion

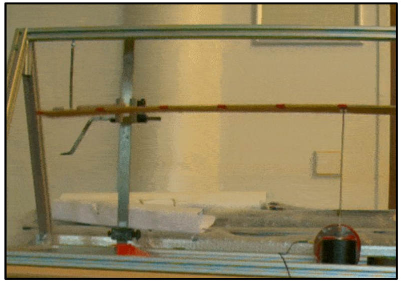




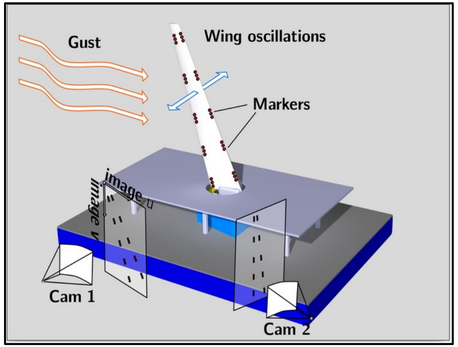
# Experiments in wind tunnel and flight test

Single camera clamped beam:



WT test stereo setup:

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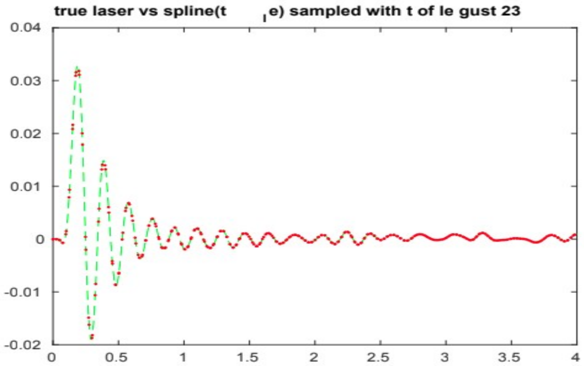
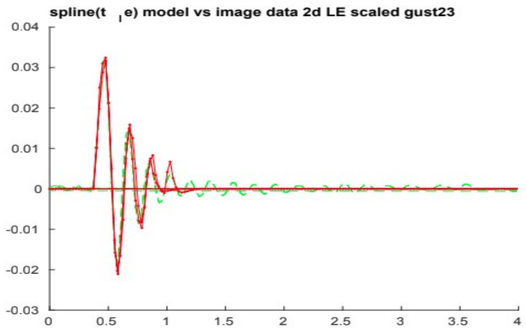
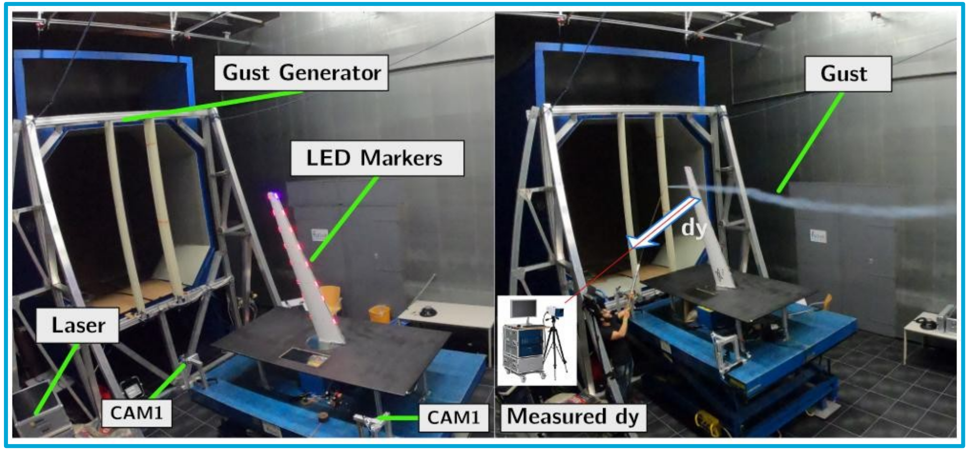
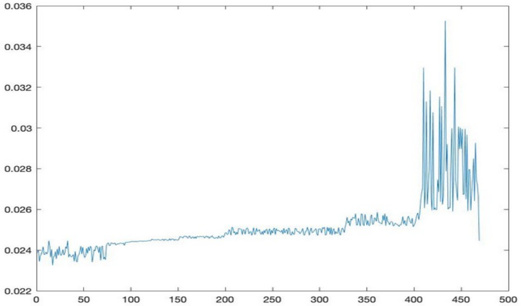
# Adaptive Visual Tracking experimental data

Laser data sampled at non-uniform time step of camera:



# Kalman Filter: Adding Dynamics to visual motion:

$$x(t+h) = x(t) + f'(x(t))h$$

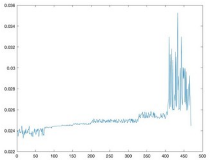
**Kalman Filter (KF):** Predicting linear motion

$$x_k = x_{k-1} + \dot{x}_{k-1}h$$

$$y_k = y_{k-1} + \dot{x}_{k-1}h$$

$$\dot{y}_k = \dot{y}_{k-1} + \ddot{y}_{k-1}h$$

**Extended KF (EKF):** Non-linear motion,
non-uniform timestep



The general differential equation is given as:

$$\ddot{y}(t) = -\frac{c}{m}\dot{y}(t) - \frac{k}{m}y(t)$$

In state space form we have:

$$\frac{d}{dt}\begin{bmatrix} y_k \\ \dot{y}_k \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k/m & -c/m \end{bmatrix}\begin{bmatrix} y_k \\ \dot{y}_k \end{bmatrix}$$

**Augmented (AEKF):** Non-linear motion, time-varying, learn unknown dynamics

$$\ddot{y}(t) = -\frac{c(t)}{m(t)}\dot{y}(t) - \frac{k(t)}{m(t)}y(t)$$

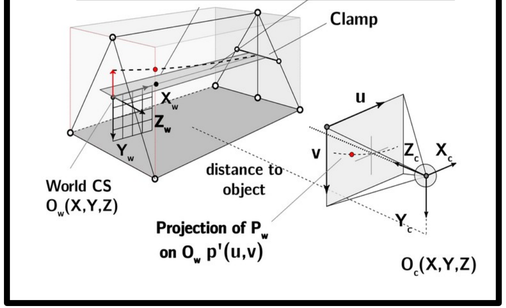
$$\bar{x}_k = \begin{bmatrix} y_k \\ \dot{y}_k \\ K_k \\ c_k \\ m_k \end{bmatrix} = \begin{bmatrix} y_{k-1} + \dot{x}_{k-1}h \\ -K_{k-1}/m_{k-1} \cdot y_{k-1} - (1 - c_{k-1}/m_{k-1}h) \cdot \dot{y}_{k-1} \\ K_{k-1} + 0 \cdot h \\ c_{k-1} + 0 \cdot h \\ m_{k-1} + 0 \cdot h \end{bmatrix} \quad (13)$$

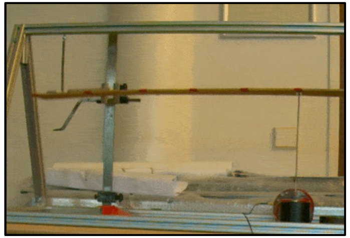
$$J(\bar{x}_k) = \begin{matrix} 1 & h & 0 & 0 & 0 \\ -K_{k-1} \cdot m_{k-1}^{-1} \cdot h & 1 - c_{k-1} \cdot m_{k-1}^{-1} \cdot h & m_{k-1}^{-1} \cdot y_{k-1} \cdot h & -m_{k-1}^{-1} \cdot \dot{y}_{k-1} \cdot h & m_{k-1}^{-2} \cdot c_{k-1} \cdot \dot{y}_{k-1} \cdot h - m_{k-1}^{-2} \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{matrix}$$

# Tracking and identification cantilever beam

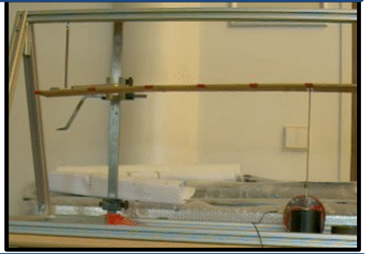
$$m_s\ddot{q} + c_s(q)\dot{q} + k_s(q)q = d_s + F_u$$

Single camera clamped beam:

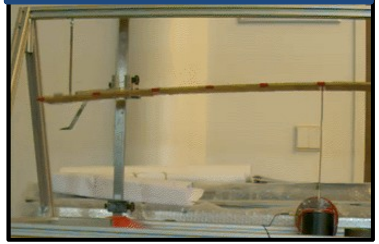


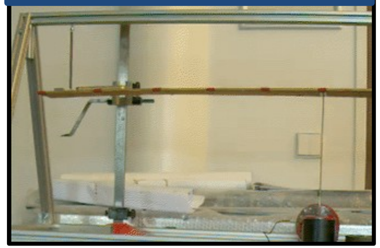
5 Hz



5.3 Hz



8 Hz



# CONTROL DESIGN

# Control Design

- System dynamics

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{G}(\boldsymbol{x})\boldsymbol{u} + \boldsymbol{d}_x \qquad \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x})$$

- Input-output dynamics

$$\boldsymbol{y}^{(\boldsymbol{r})} = \boldsymbol{\alpha}(\boldsymbol{x}) + \mathcal{B}(\boldsymbol{x})\boldsymbol{u} + \boldsymbol{d}$$

Assume the vector relative degree is constant and known, and the corresponding internal dynamics are stable.

- Sliding variable

$$\boldsymbol{\sigma} = \boldsymbol{y} - \boldsymbol{y}_c$$

- R-th order sliding set

$$\mathcal{S}^r = \{\boldsymbol{x} | \sigma_i(\boldsymbol{x}) = \dot{\sigma}_i(\boldsymbol{x}) ... = {\sigma_i}^{(r_i - 1)}(\boldsymbol{x}) = 0, \ i = 1, ...m\}$$

Motions on  is called the r-th order sliding mode with respect to σ

# Incremental Sliding Mode Control

- Incremental dynamic equation [1]

First-order Taylor series expansion around the condition at , denoted by subscript 0

$$\boldsymbol{y}^{(r)} = \boldsymbol{y}_0^{(r)} + \mathscr{B}(\boldsymbol{x}_0)\Delta\boldsymbol{u} + \Delta\boldsymbol{d} + \left.\frac{\partial[\boldsymbol{\alpha}(\boldsymbol{x}) + \mathscr{B}(\boldsymbol{x})\boldsymbol{u}]}{\partial\boldsymbol{x}}\right|_0 \Delta\boldsymbol{x} + \boldsymbol{R}_1$$

- Sensor-based control input structure

$$\Delta\boldsymbol{u}_{\text{indi-}s} = \bar{\mathcal{B}}^{-1}(\boldsymbol{x}_0)(\boldsymbol{\nu}_n + \boldsymbol{\nu}_s + \boldsymbol{y}_c^{(r)} - \boldsymbol{y}_0^{(r)})$$

Designs the control increments in

$$\boldsymbol{u}_{\text{indi-}s} = \boldsymbol{u}_{\text{indi-}s,0} + \Delta\boldsymbol{u}_{\text{indi-}s}.$$

Uses the latest sampled information

- Closed-loop sliding variable dynamics

$$\begin{aligned}\boldsymbol{\sigma}^{(r)} &= \boldsymbol{y}^{(r)} - \boldsymbol{y}_c^{(r)} = \boldsymbol{y}_0^{(r)} + \bar{\mathcal{B}}(\boldsymbol{x}_0)\Delta\boldsymbol{u}_{\text{indi-}s} + \boldsymbol{\varepsilon}_{\text{indi-}s} - \boldsymbol{y}_c^{(r)} \\ &= \boldsymbol{\nu}_n + \boldsymbol{\nu}_s + \boldsymbol{\varepsilon}_{\text{indi-}s} \qquad (9)\end{aligned}$$

Achieves r-th order sliding motion

- Perturbation term

$$\boldsymbol{\varepsilon}_{\text{indi-}s} = \left.\frac{\partial[\boldsymbol{\alpha}(\boldsymbol{x}) + \mathscr{B}(\boldsymbol{x})\boldsymbol{u}_{\text{indi-}s}]}{\partial\boldsymbol{x}}\right|_0 \Delta\boldsymbol{x} + \boldsymbol{R}_1|_{\boldsymbol{u}=\boldsymbol{u}_{\text{indi-}s}} + (\mathscr{B} - \bar{\mathscr{B}})|_0\Delta\boldsymbol{u}_{\text{indi-}s} + \Delta\boldsymbol{d}$$

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[1] X. Wang, E. van Kampen, Q. Chu, and P. Lu, “Incremental Sliding- Mode Fault-Tolerant Flight Control,” Journal of G
Control, and Dynamics, vol. 42, no. 2, pp. 244–259, feb 2019.

# Incremental Sliding Mode Control

- Super twisting sliding mode disturbance observer

auxiliary sliding variable

$$s = \sigma^{(r-1)} - \int \nu_n$$

Closed-loop dynamics

$$\dot{s} = \nu_s + \varepsilon_{\text{indi-}s}$$

Observer design

$$\nu_s = -\lambda |s|^{1/2} \text{sign}(s) - \beta \int \text{sign}(s)$$

Observer gains can be adaptive [2]

→ The auxiliary sliding variable is stabilized in finite-time

→ The nominal dynamics are recovered in spite of disturbances and model uncertainties $\sigma^{(r)} = \nu_n$

[2] C. Edwards and Y. Shtessel, “Adaptive dual-layer super-twisting control and observation,” International Journal of Cor
no. 9, pp. 1759–1766, 2016.

# Incremental Sliding Mode Control

- Stabilization of the nominal dynamics

$$\boldsymbol{\sigma}^{(\boldsymbol{r})} = \boldsymbol{\nu}_n$$

- Asymptotic stabilization

$$\boldsymbol{\nu}_n = -\boldsymbol{K}_{r-1}\boldsymbol{\sigma}^{(\boldsymbol{r-1})} - \boldsymbol{K}_{r-2}\boldsymbol{\sigma}^{(\boldsymbol{r-2})} \ldots - \boldsymbol{K}_0\boldsymbol{\sigma}$$

- Finite-time stabilization

$$\begin{aligned}
\boldsymbol{\nu}_n &= [\nu_{n,1}, \nu_{n,2}, \ldots, \nu_{n,m}]^T \\
\nu_{n,i} &= -K_{r-1,i}|\sigma_i^{(r_i-1)}|^{\alpha_{r_i,i}}\operatorname{sign}(\sigma_i^{(r_i-1)}) - \ldots \\
&\quad -K_{0,i}|\sigma_i|^{\alpha_{1,i}}\operatorname{sign}(\sigma_i), \quad i = 1, \ldots, m
\end{aligned}$$

# SIMULATION

# Dynamic Model

- Dynamic equation

$$m_s\ddot{q} + c_s(q)\dot{q} + k_s(q)q = d_s + F_u$$

Generalized coordinate

$$m_s = 0.5, \quad c_s(q) = 0.05 \cdot f(q), \quad k_s(q) = 554.4744 \cdot f(q)$$

$$f(q) = 0.5 \cdot (q/0.05)^2 + 1$$

Nonlinear stiffness and damping

Actuator with first-order dynamics and time constant of 0.04

- External disturbances

$$d_s = 7.5\sin(5t)$$

Transport delay of 3 seconds

- Initial conditions

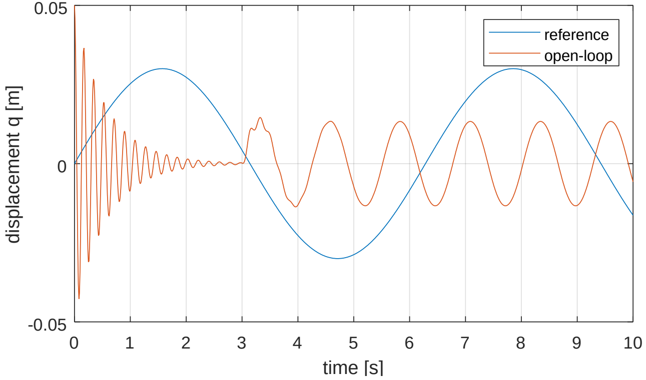
$$\dot{q}(t=0) = 0, \quad q(t=0) = 0.05$$

- Tracking reference

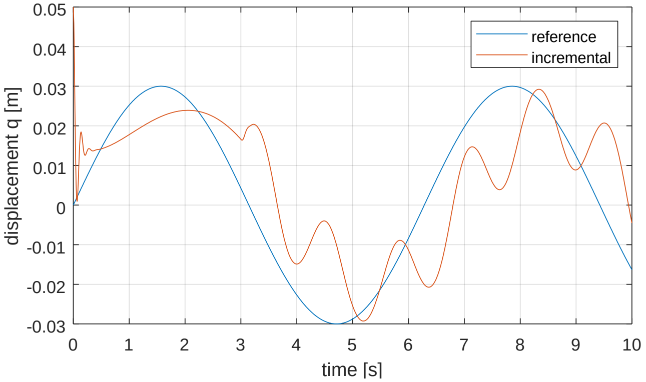
$$q_{\text{ref}} = 0.03\sin(t)$$

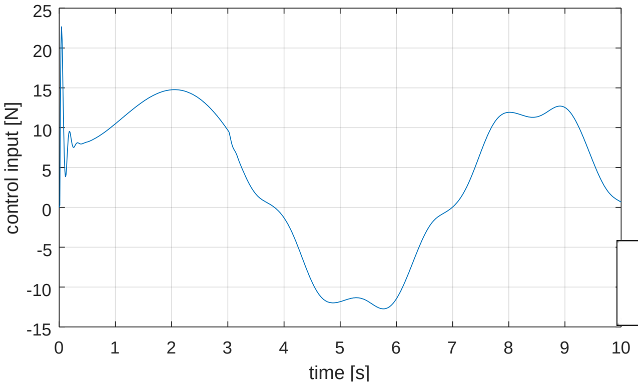
# Simulation Results

- Open-loop responses




- Incremental control

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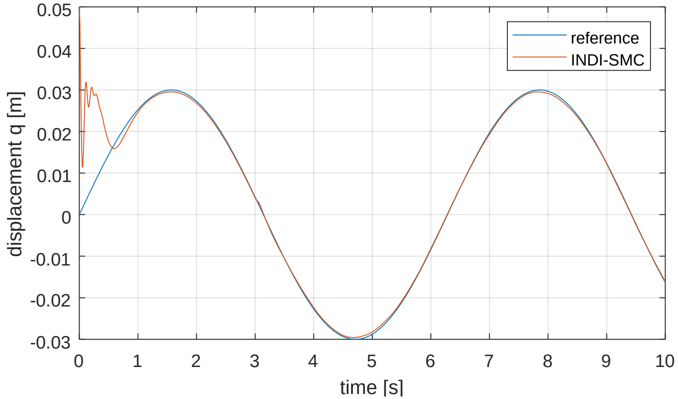
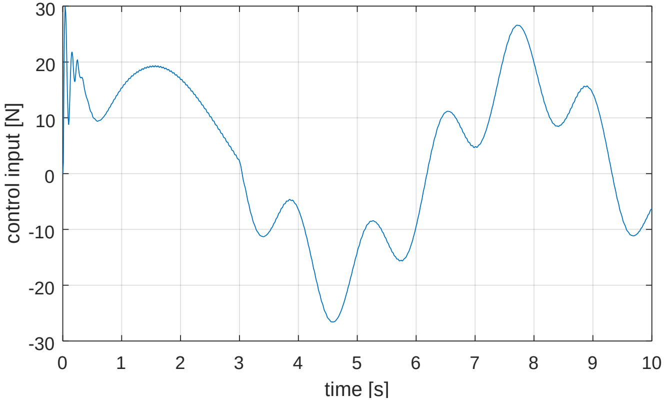
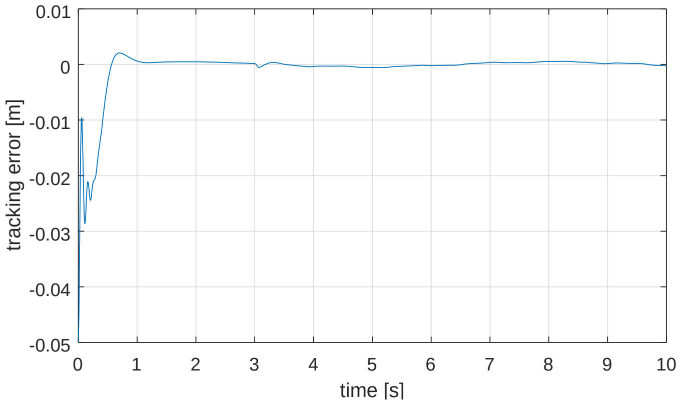
# Simulation Results

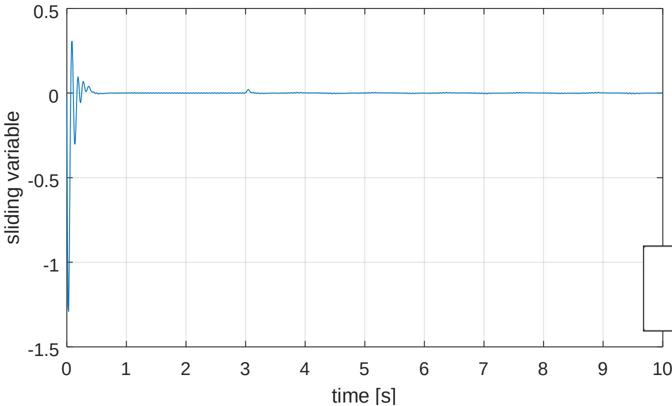
- Incremental control + sliding mode disturbance observer




first-order actuator dynamics with time constant of 0.04



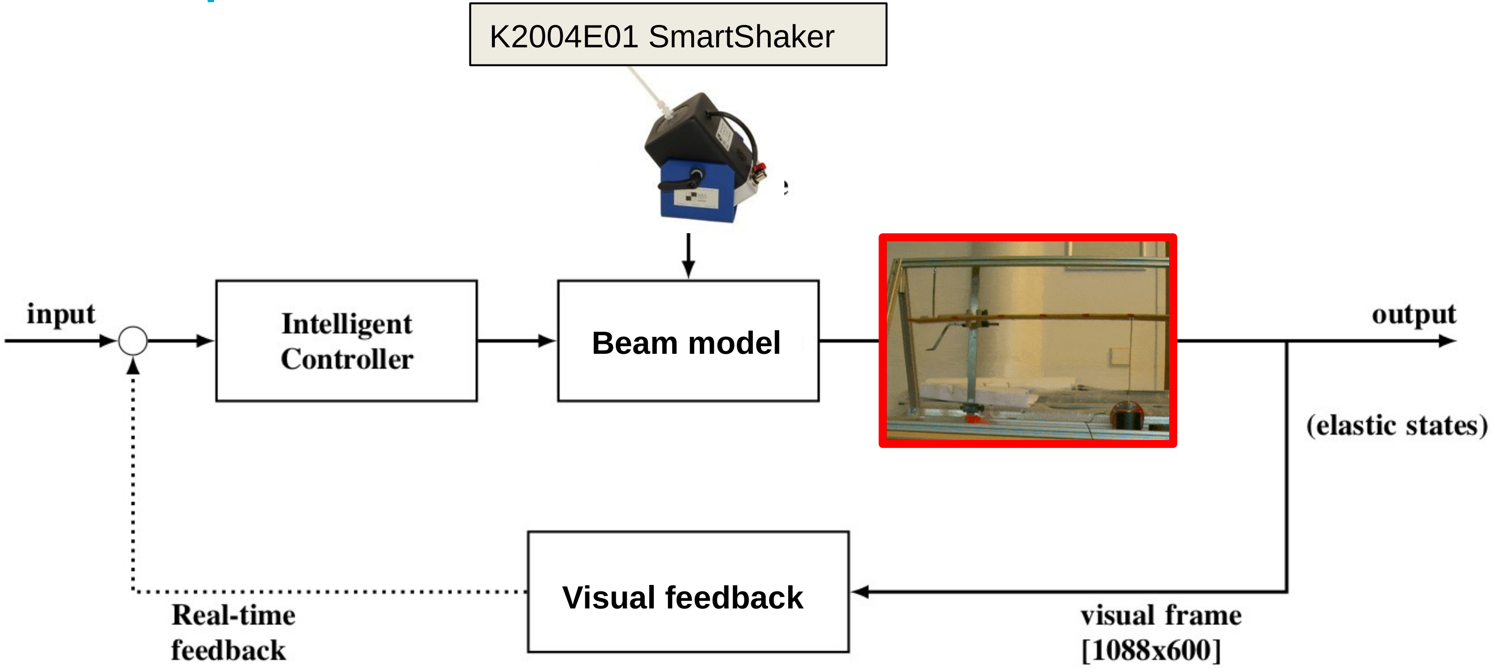
# CONCLUSIONS

# Conclusions

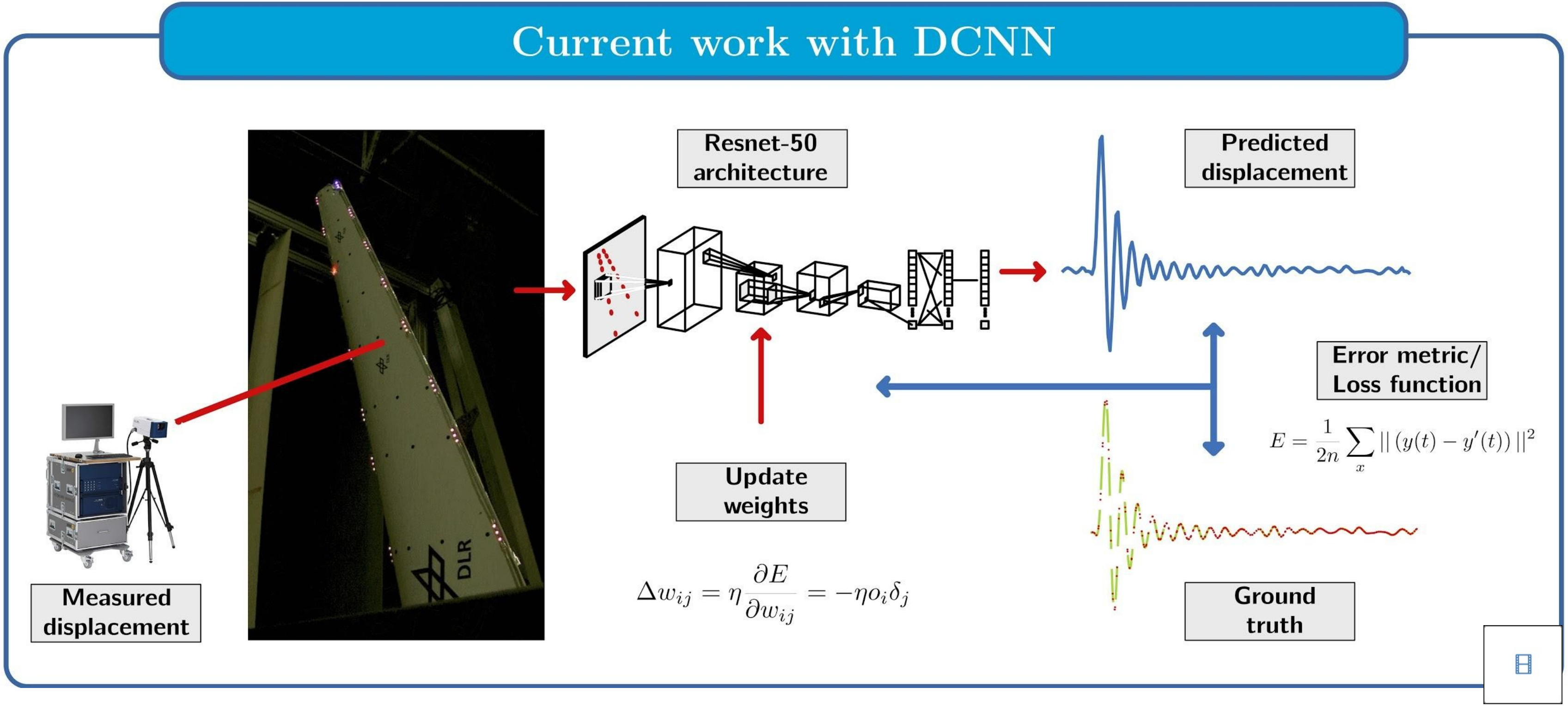
- Visual tracking is suitable as adaptive model free sensor
- Incremental sliding mode tracks well but performance can be improved
- Sliding mode disturbance observer significantly improved performance
- Morning control and non-linear dynamics can benefit from robust model-free sensing and control methods

# FUTURE WORK

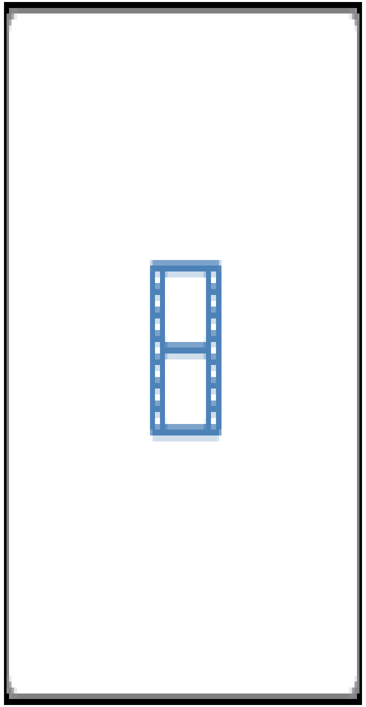
# Closed loop visual feedback control

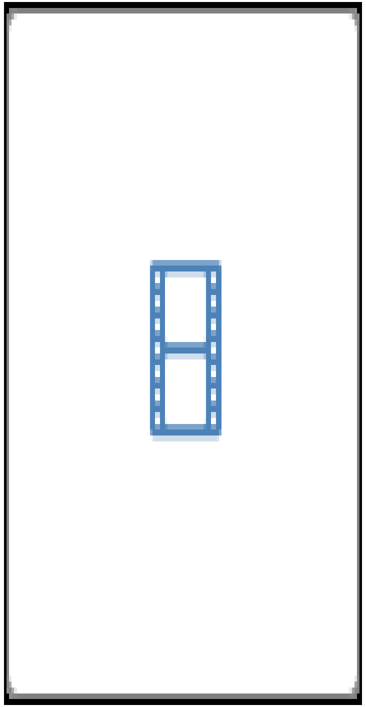


# Deep learning methods



# Smart-X adaptive morphing control





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# THANK YOU