Outline

$\Rightarrow$ Benefits - Why tight formation flight?

$\Rightarrow$ Challenges

$\Rightarrow$ Sliding Mode Guidance laws

$\Rightarrow$ Overview

Small UAS

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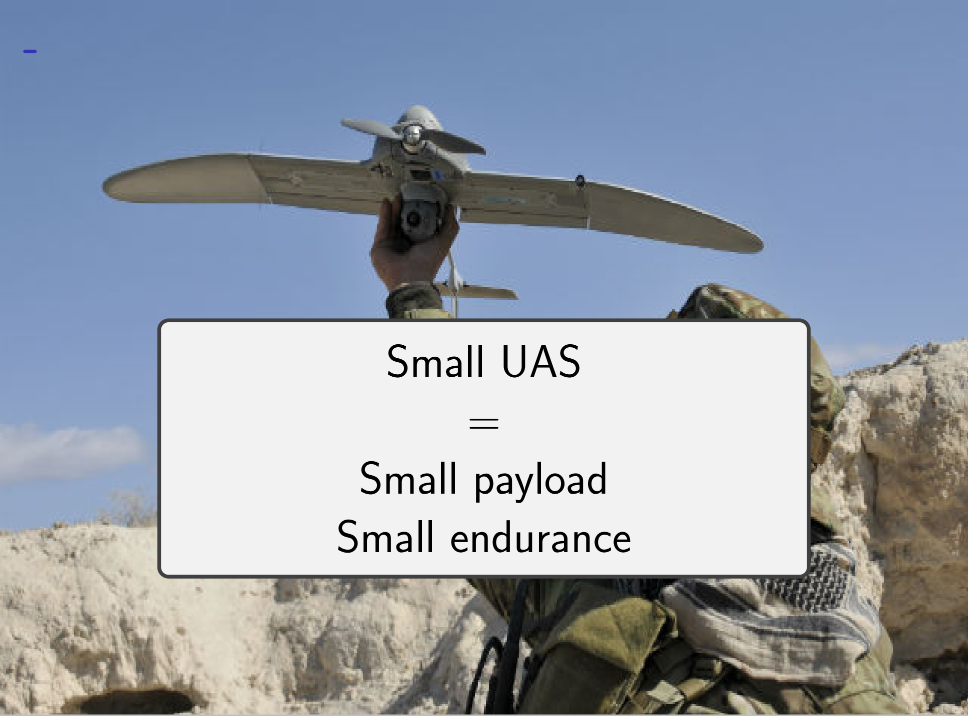
Inexpensive

Easy to operate



Small UAS

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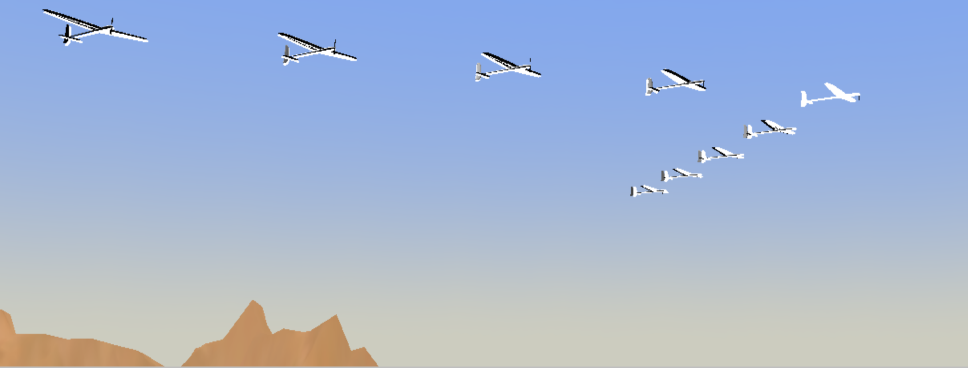
Small payload

Small endurance

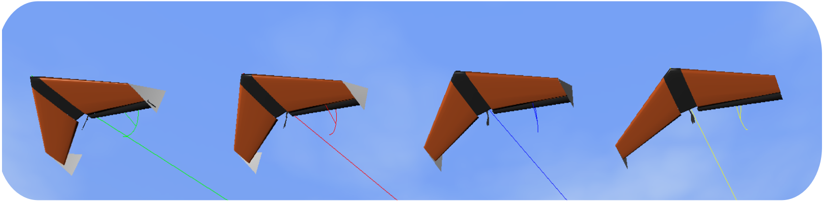
Fleets of UAS

- Distributed payload
- Enhanced endurance (order of Magnitude: 10-20 %)
- Limited hardware modifications

$\Rightarrow$ **(hopefully) less expensive**

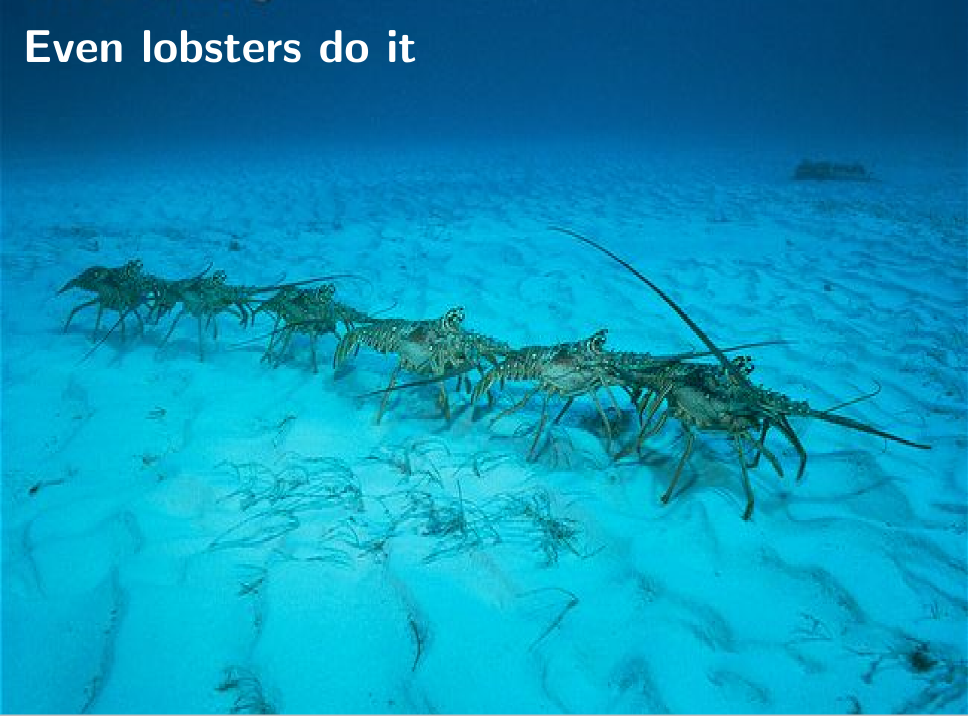


Inspired by migratory birds

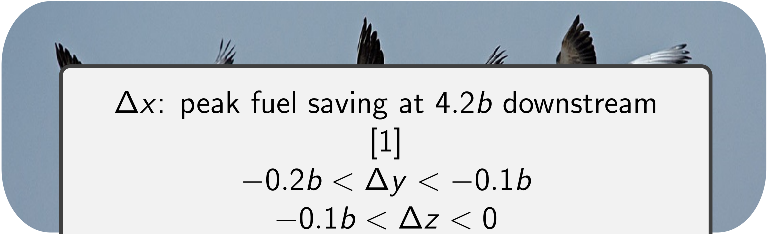


NASA **A**utonomus **F**ormation **F**light
Program:
2x F-18 $\Rightarrow$ -18 % fuel flow

Even lobsters do it



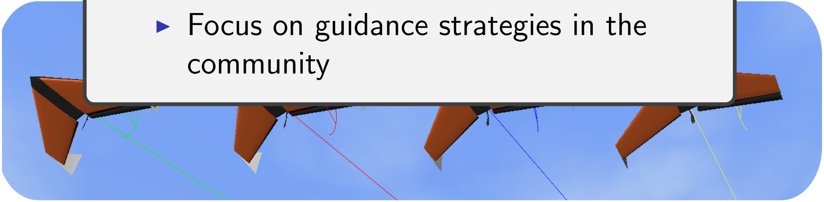
Why is it hard for small UAS?



Δx: peak fuel saving at $4.2b$ downstream [1]

$-0.2b < \Delta y < -0.1b$

$-0.1b < \Delta z < 0$



- Heavy perturbations by vortices
- Focus on guidance strategies in the community

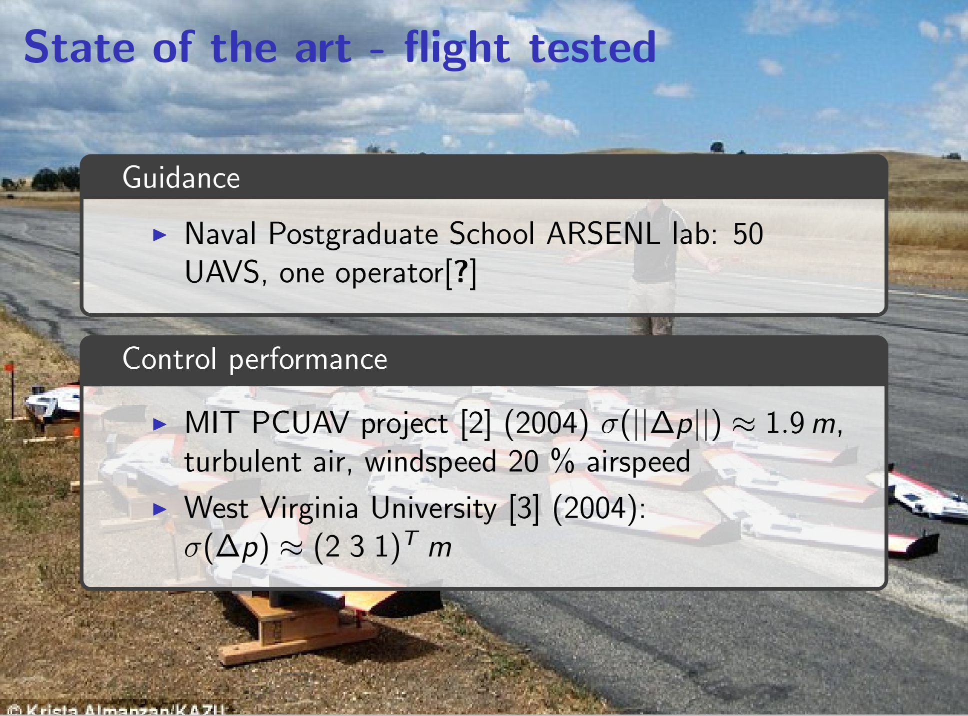
State of the art - flight tested

Guidance

- Naval Postgraduate School ARSENL lab: 50 UAVS, one operator[**?**]

Control performance

- MIT PCUAV project [2] (2004) $\sigma(||\Delta p||) \approx 1.9\, m$, turbulent air, windspeed 20 % airspeed
- West Virginia University [3] (2004): $\sigma(\Delta p) \approx (2\ 3\ 1)^T\ m$



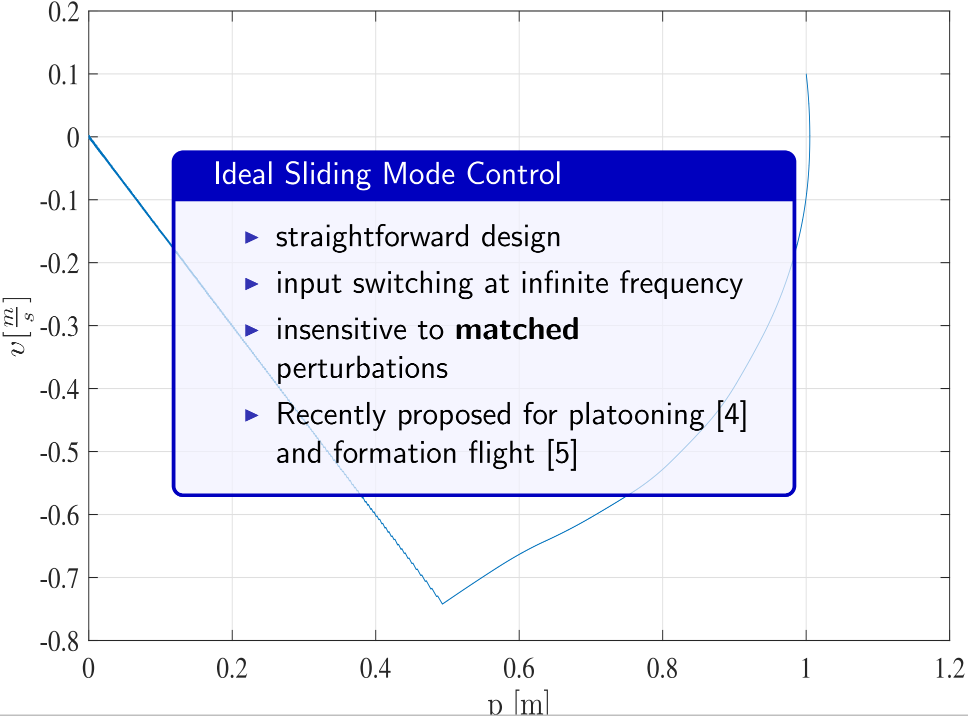
Missing parts

- Lack of implementable control approaches for
  - dm-level relative position control in the wake
  - with relative state information
    - Mature linear control approaches, **require leader information** for mesh stability

Sliding Mode Guidance laws

Ideal Sliding Mode Control

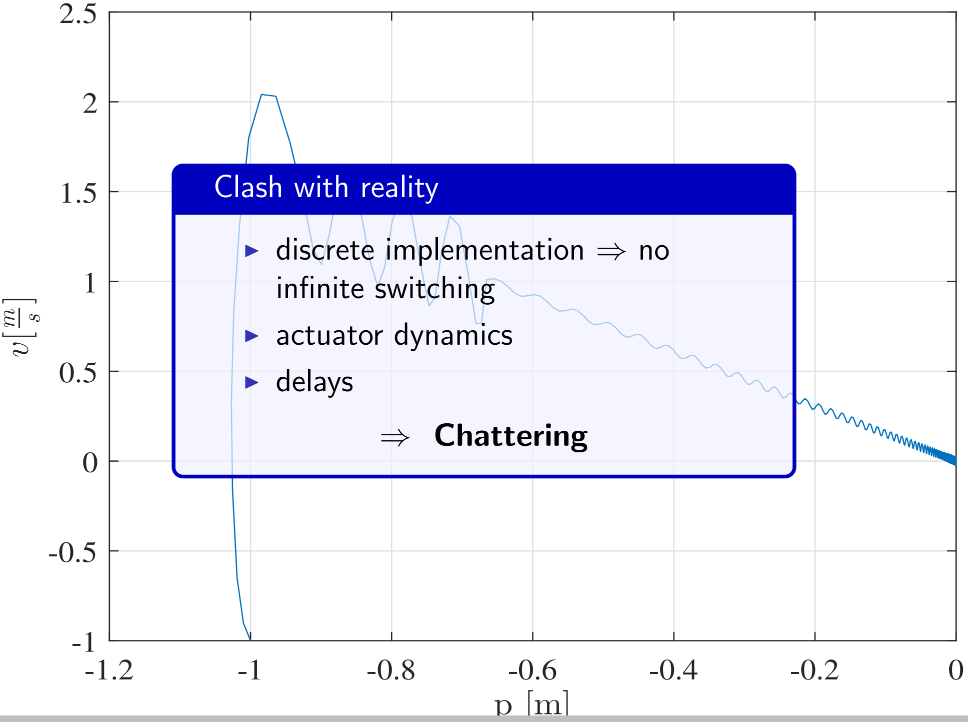
- straightforward design
- input switching at infinite frequency
- insensitive to **matched** perturbations
- Recently proposed for platooning [4] and formation flight [5]



Sliding Mode Control

Potential Benefits

- Decentralized and scalable: mesh stability with local state information
- Robustness towards exogenous perturbations



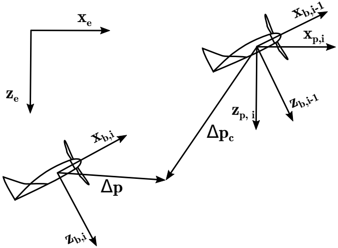
Clash with reality

- discrete implementation ⇒ no infinite switching
- actuator dynamics
- delays

⇒ **Chattering**

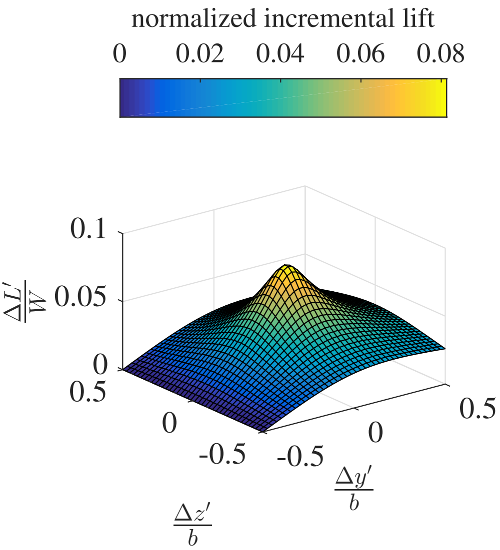
Continuous Time Sliding Mode Control applied to the UAS guidance loop

Guidance level: system dynamics



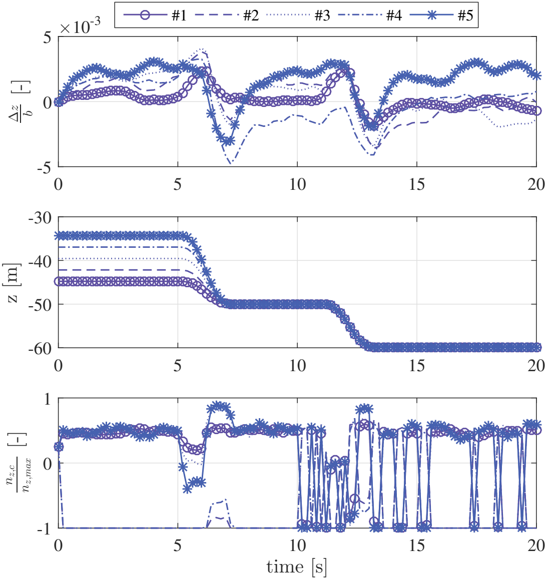
$$
\begin{aligned}
\Delta\mathbf{p}(t) &= \mathbf{p}_i(t) - \mathbf{p}_{i-1}(t) - \Delta\mathbf{p}_c(t) \\
\Delta\dot{\mathbf{p}}(t) &= \mathbf{v}_i(t) - \mathbf{v}_{i-1}(t) - \Delta\dot{\mathbf{p}}_c(t) \\
\Delta\dot{\mathbf{v}}(t) &= \mathbf{a}_i(t) - \mathbf{a}_{i-1}(t) - \Delta\ddot{\mathbf{p}}_c(t) \\
&= \mathbf{a}_{c,i}(t) + \mathbf{a}_{w,i}(t) - \mathbf{a}_{i-1}(t) - \Delta\ddot{\mathbf{p}}_c(t) \\
&= \mathbf{u}(t) + \mathbf{a}_{w,i}(t) - \mathbf{a}_{i-1}(t) - \Delta\ddot{\mathbf{p}}_c(t)
\end{aligned}
$$

Vortex perturbations: MHVM [6]

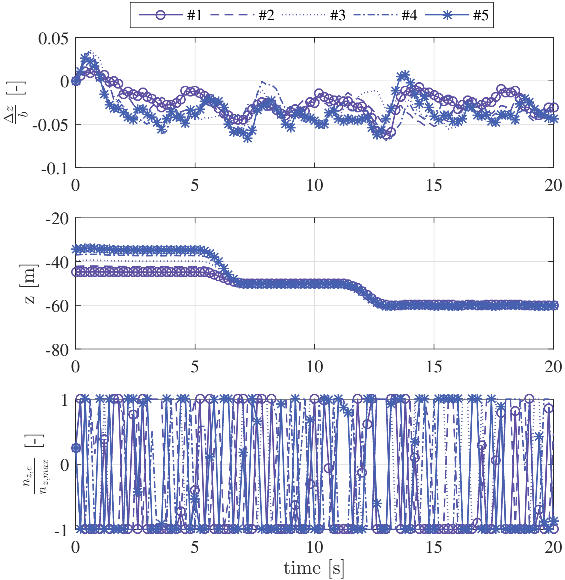


Reference: **T**ime **S**ampled **C**ontinuous Higher Order **S**liding **M**ode **C**ontroller [5]

Simulation: TSCSMC [5] at 1000Hz



Simulation: TSCSMC at 100Hz



Predictive Discrete Sliding Mode Control

PDSMC

- Recent approach [7]
- Design directly in discrete time
- Preserve spirit of Sliding Mode Control: moving on the sliding surface
- Can accommodate hard input constraints
- Minimizes boundary layer without tuning

Predictive Discrete Sliding Mode Control

What it looks like

$$\sigma(k) = \mathbf{G} \begin{pmatrix} \Delta \mathbf{p}(k) \\ \Delta \mathbf{v}(k) \end{pmatrix}$$

$$\sigma(k+1) = \sigma(k) + T(\mathbf{\Phi}'_k(k) + \mathbf{\Phi}'_u(k) + \mathbf{u}(k))$$

$$\underset{\mathbf{u}(k)}{\text{minimize}} \qquad |\sigma(k+1)|$$

Predictive Discrete Sliding Mode Control

Adding hard magnitude and rate constraints [?]

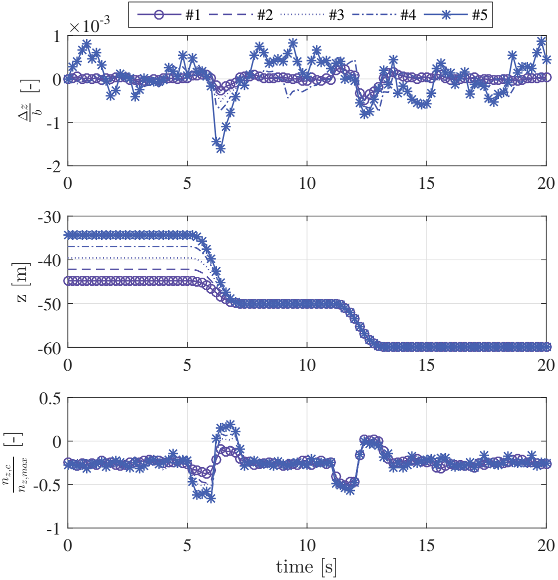
$$\begin{aligned} \underset{\mathbf{u}(k)}{\text{minimize}} \quad & |\sigma(k+1)| \\ \text{subject to} \quad & \mathbf{U}_{min}(k) \leq \mathbf{u}(k) \leq \mathbf{U}_{max}(k) \end{aligned}$$

$$|\mathbf{u}(k) - \mathbf{u}(k-1)| \leq \mathbf{\Delta U}$$

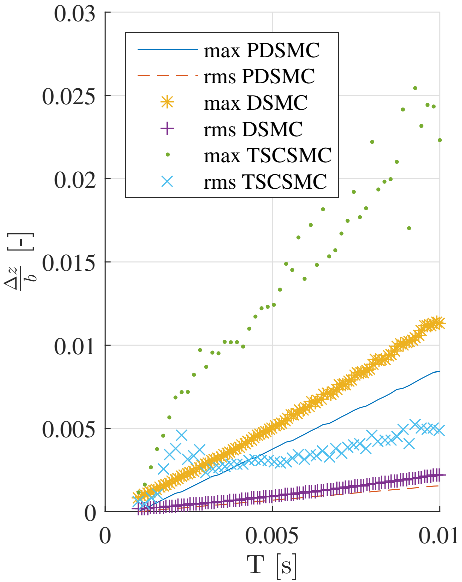
$$\mathbf{U}_{max}(k) = sat(\mathbf{u}(k-1) + \mathbf{\Delta U}, -\mathbf{U}, \mathbf{U})$$
$$\mathbf{U}_{min}(k) = sat(\mathbf{u}(k-1) - \mathbf{\Delta U}, -\mathbf{U}, \mathbf{U})$$

How does it compare
to
discretized Continuous-time Sliding Mode
Control (TSCSMC)?

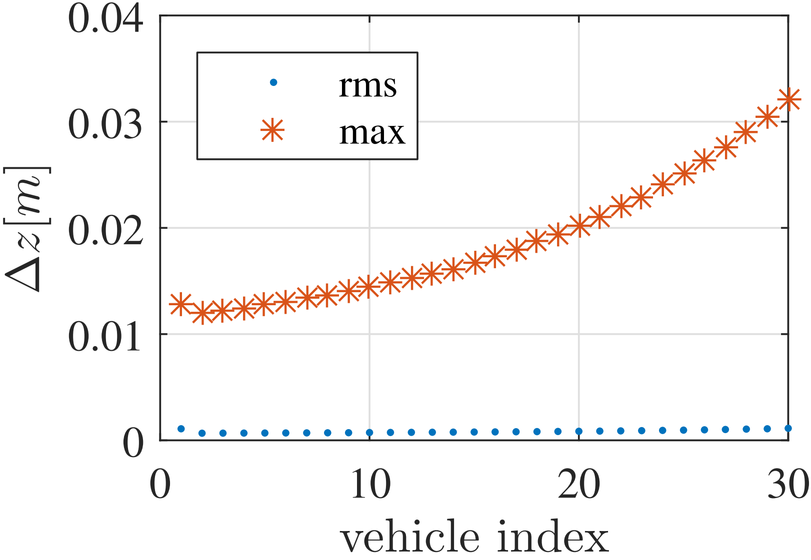
Simulation: PDSMC at 100Hz



Figures of Merit vs. sampling time



What about scalability?



Conclusion

- PDSMC viable for tight FF
- Overcomes chattering issue of existing TSCSMC, preserves attractive properties of CSMC
- Extended existing PDSMC approaches to respect inner loop constraints [**?**]
- Very good performance on perturbed guidance system

- Extend PDSMC further: inner loop dynamics, lower sampling rates
- Quantify mesh instability

- V. Jake, R. Ray, K. Ennix, and K. Walsh, "F/A-18 Performance Benefits Measured During the Autonomous Formation Flight Project," tech. rep., NASA/TM-2002-210732, Sept, 2003.
- S. Park, *Avionics and Control System Development for Mid-Air Rendezvous of Two Unmanned Aerial Vehicles*. PhD thesis, MIT, 2004.
- Y. Gu, B. Seanor, G. Campa, M. R. Napolitano, L. Rowe, S. Gururajan, and S. Wan, "Design and flight testing evaluation of formation control laws," *Control Systems Technology, IEEE Transactions on*, vol. 14, no. 6, pp. 1105–1112, 2006.
- F. Fahimi, "Sliding-mode formation control for underactuated surface vessels," *Robotics, IEEE Transactions on*, vol. 23, no. 3, pp. 617–622, 2007.

- D. Galzi and Y. Shtessel, “UAV formations control using high order sliding modes,” in *American Control Conference, 2006*, pp. 6–pp, IEEE, 2006.
- A. Dogan, S. Venkataramanan, and W. Blake, “Modeling of aerodynamic coupling between aircraft in close proximity,” *Journal of Aircraft*, vol. 42, no. 4, pp. 941–955, 2005.
- B. M. Houda, D. Khadija, and N. A. Said, “New discrete predictive sliding mode control for non minimum phase systems,” *International Journal of Computer Applications*, vol. 70, no. 11, 2013.