Discrete Sliding Mode control of small UAS in tight formation flight under information constraints

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Outline

⇒ Why tight formation flight with small UAS?

⇒ Problem Statement

⇒ Predictive Discrete Sliding Mode Guidance laws

⇒ Overview & where to go from here

Small UAS

=

Inexpensive

Easy to operate

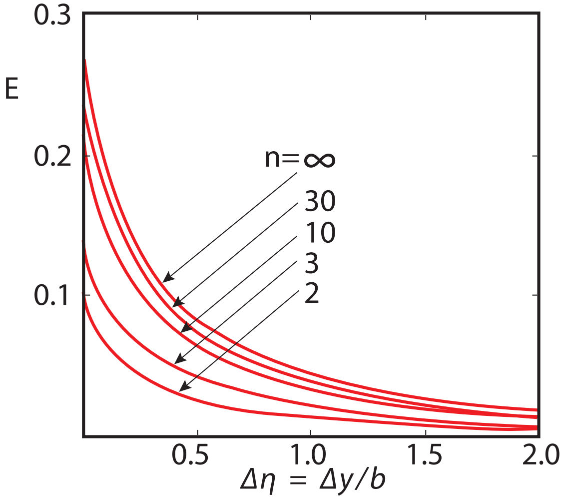
Small UAS

=

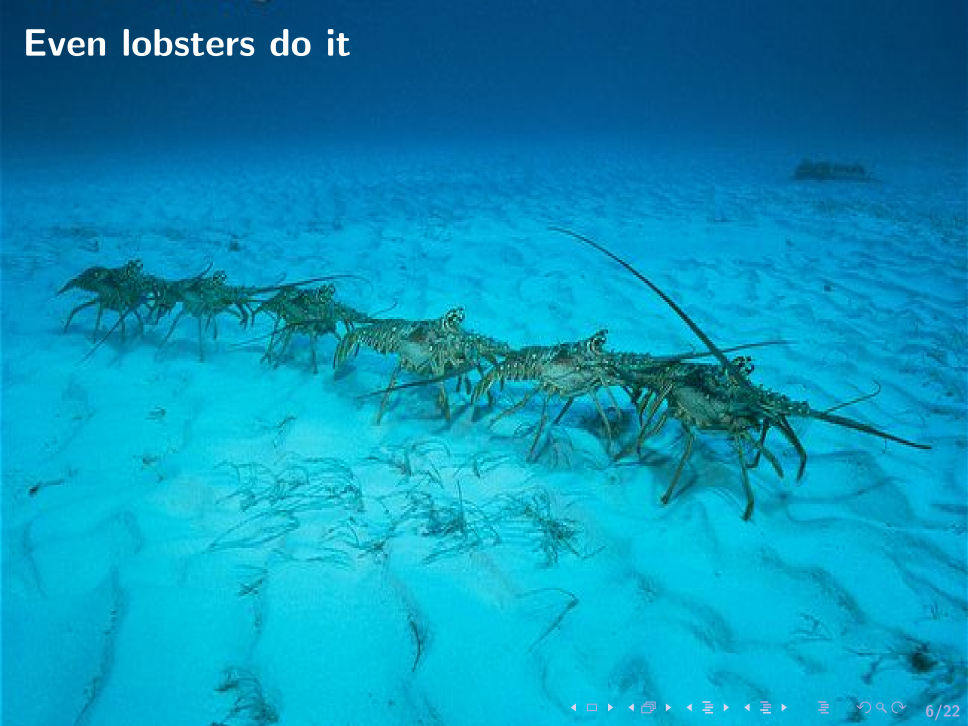
Small payload

Small endurance

Tight, large formations enhance range[1]

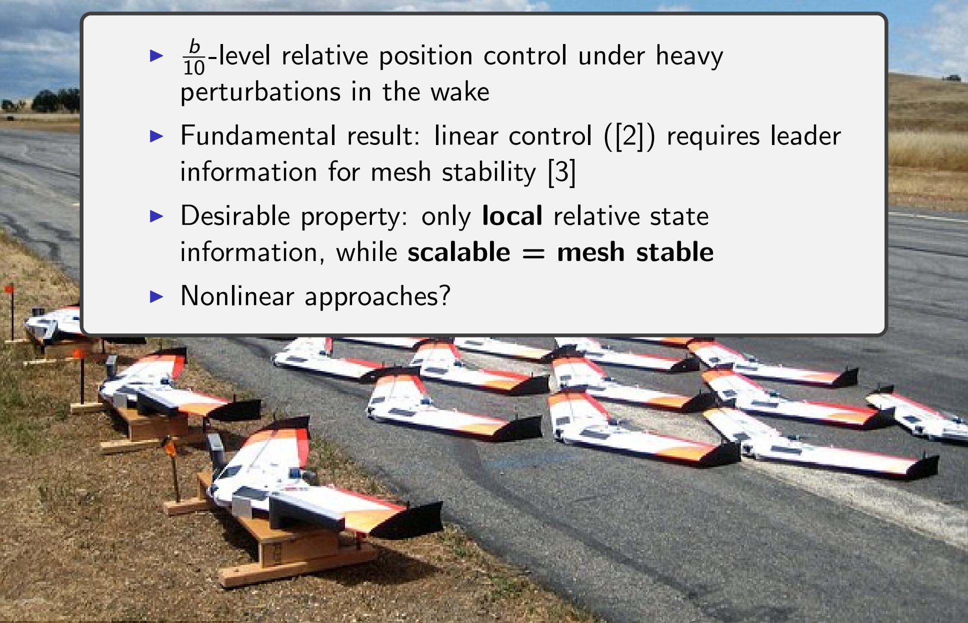


Even lobsters do it

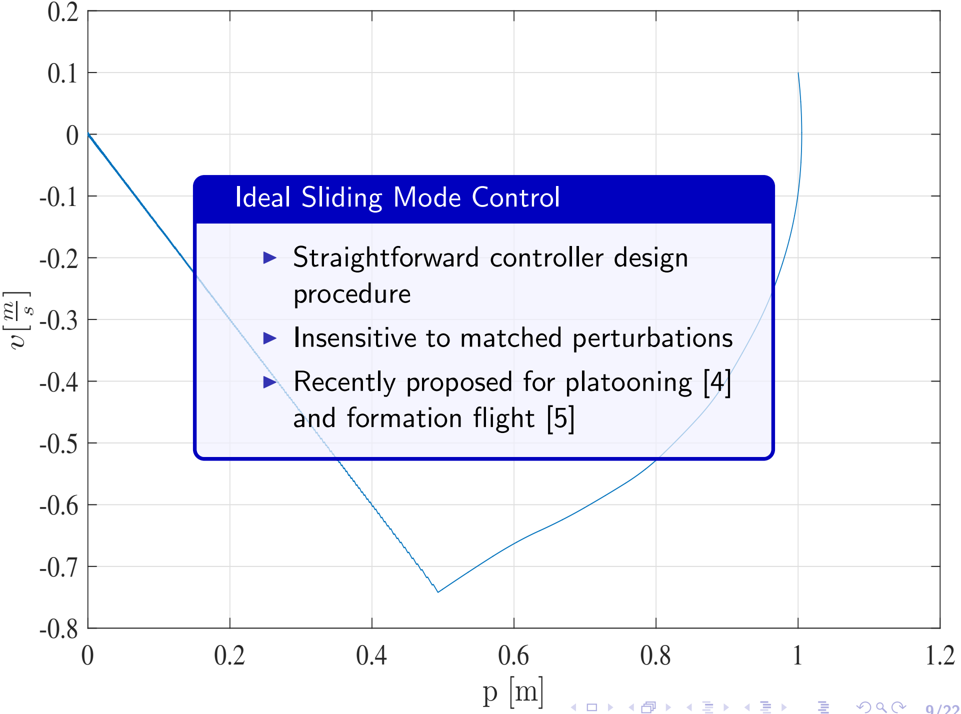


Why is it hard for small UAS?

- $\frac{b}{10}$-level relative position control under heavy perturbations in the wake
- Fundamental result: linear control ([2]) requires leader information for mesh stability [3]
- Desirable property: only **local** relative state information, while **scalable = mesh stable**
- Nonlinear approaches?

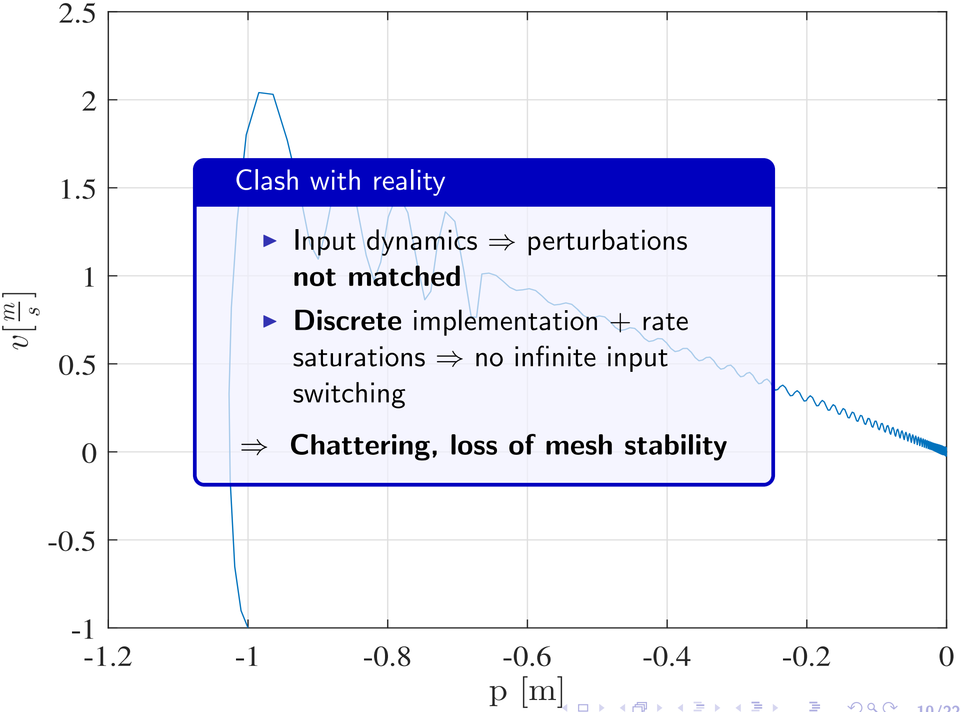


One candidate:
Sliding Mode Control:
performance & mesh stability



Ideal Sliding Mode Control

- Straightforward controller design procedure
- Insensitive to matched perturbations
- Recently proposed for platooning [4] and formation flight [5]

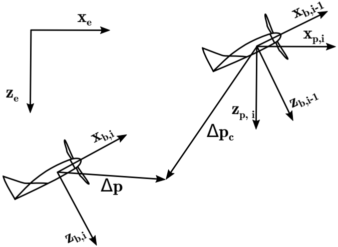


Clash with reality

- Input dynamics $\Rightarrow$ perturbations **not matched**
- **Discrete** implementation + rate saturations $\Rightarrow$ no infinite input switching

$\Rightarrow$ **Chattering, loss of mesh stability**

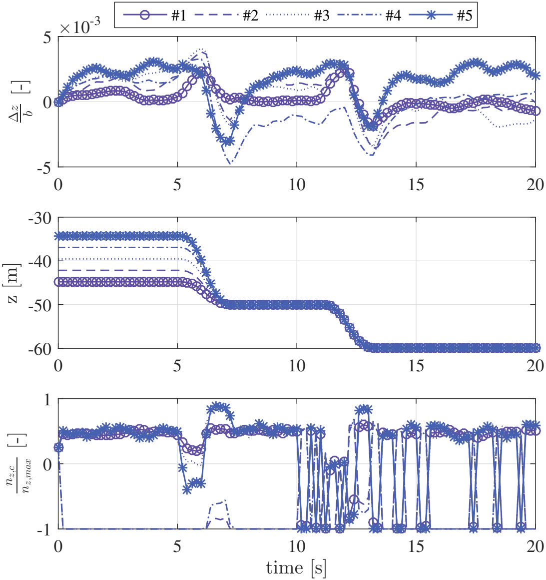
Guidance level: system dynamics



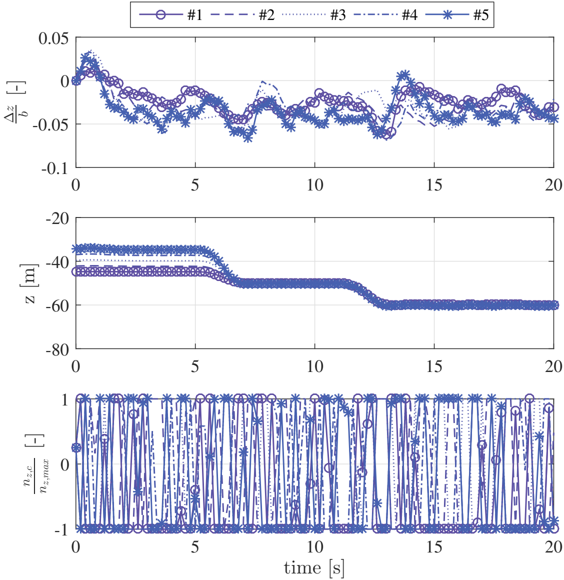
$$
\begin{aligned}
\Delta\mathbf{p}(t) &= \mathbf{p}_i(t) - \mathbf{p}_{i-1}(t) - \Delta\mathbf{p}_c(t) \\
\Delta\dot{\mathbf{p}}(t) &= \mathbf{v}_i(t) - \mathbf{v}_{i-1}(t) - \Delta\dot{\mathbf{p}}_c(t) \\
\Delta\dot{\mathbf{v}}(t) &= \mathbf{a}_i(t) - \mathbf{a}_{i-1}(t) - \Delta\ddot{\mathbf{p}}_c(t)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

Continuous Time Sliding Mode Control applied to the UAS guidance loop:
Longitudinal maneuver

Longitudinal: TSCSMC [5] at 1000Hz



Longitudinal: TSCSMC at 100Hz



Predictive Discrete Sliding Mode Control

PDSMC

- Extends recent approach [6]: input magnitude and rate **constraints**
- Design directly in discrete time
- Preserve spirit of Sliding Mode Control: stay in **boundary layer** of sliding surface
- Minimizes boundary layer without tuning parameters

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

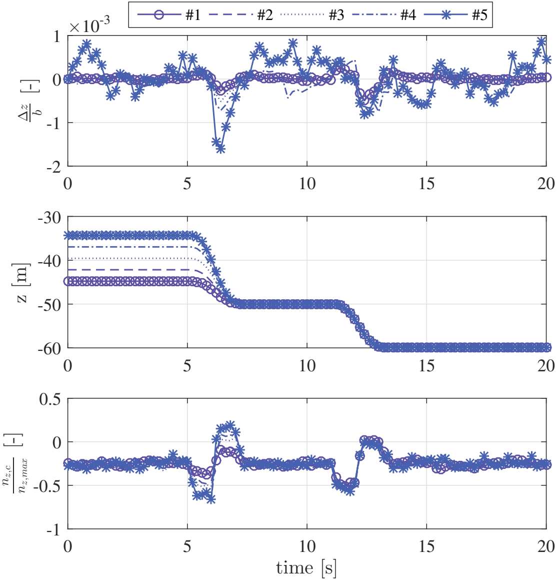
Adding hard magnitude and rate constraints

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

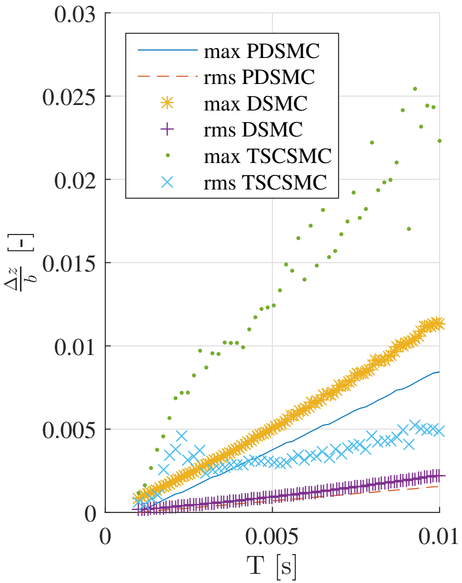
$$|\mathbf{u}(k) - \mathbf{u}(k-1)| \leq \mathbf{\Delta U}$$

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

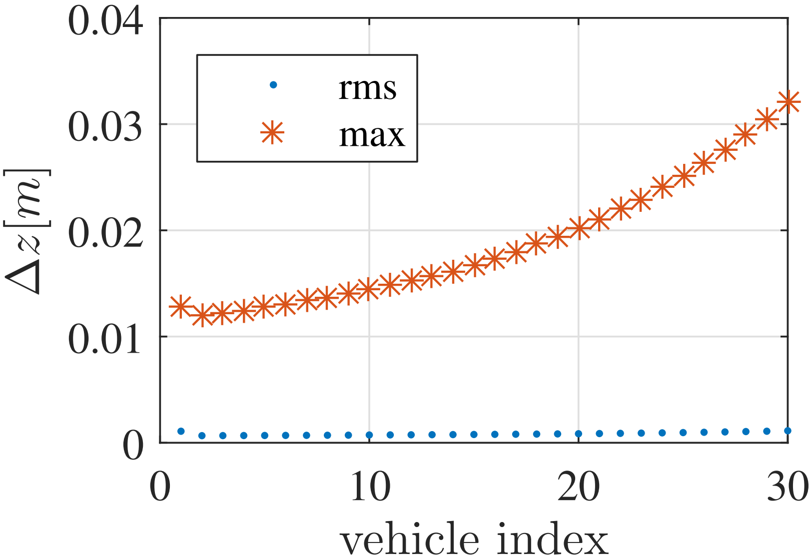
Simulation: PDSMC at 100Hz



Figures of Merit vs. sampling time



What about scalability?



Conclusion & Outlook

- PDSMC alleviates discretization issue of TSCSMC controller for TFF
- Extends existing PDSMC approaches to respect inner loop constraints

- Extend PDSMC further: inner loop dynamics, lower sampling rates, observation noise
- Better understand and quantify mesh instability
- Quantify maximum boundary layer thickness

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