Feed-Forward Parameter Identification for Precise Periodic Quadrocopter Motions

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ETH
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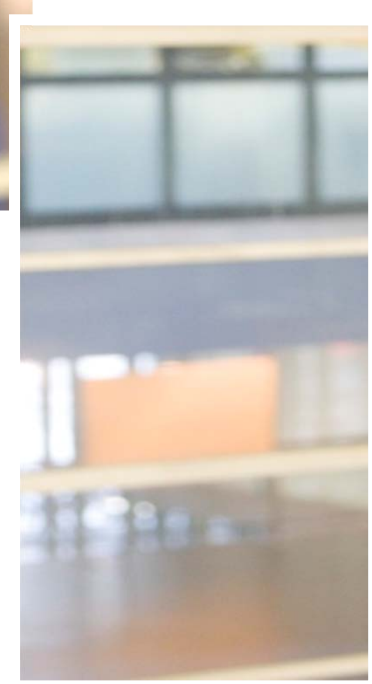
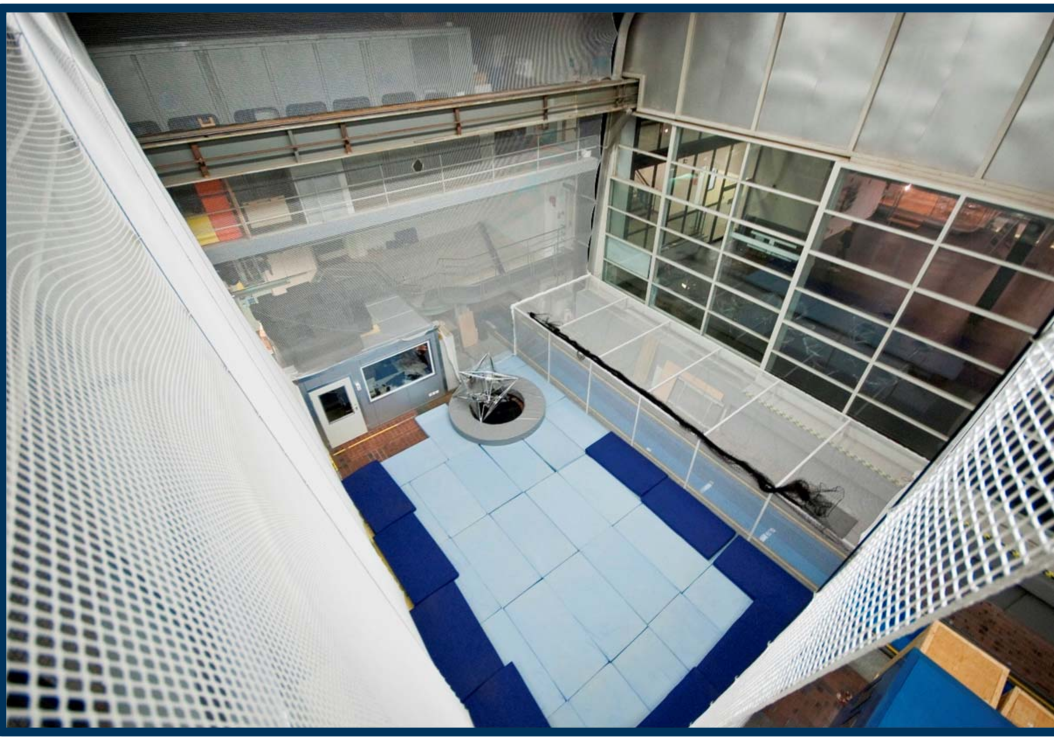
LET'S DANCE

... DANCE IN THE AIR

VISION Dance performance of multiple aerial robots





ACTORS

Type: **Quadrocopter**

Size: **Ø 3 feet**

Weight: **1 pound**

Flight time: **15 minutes**

STAGE

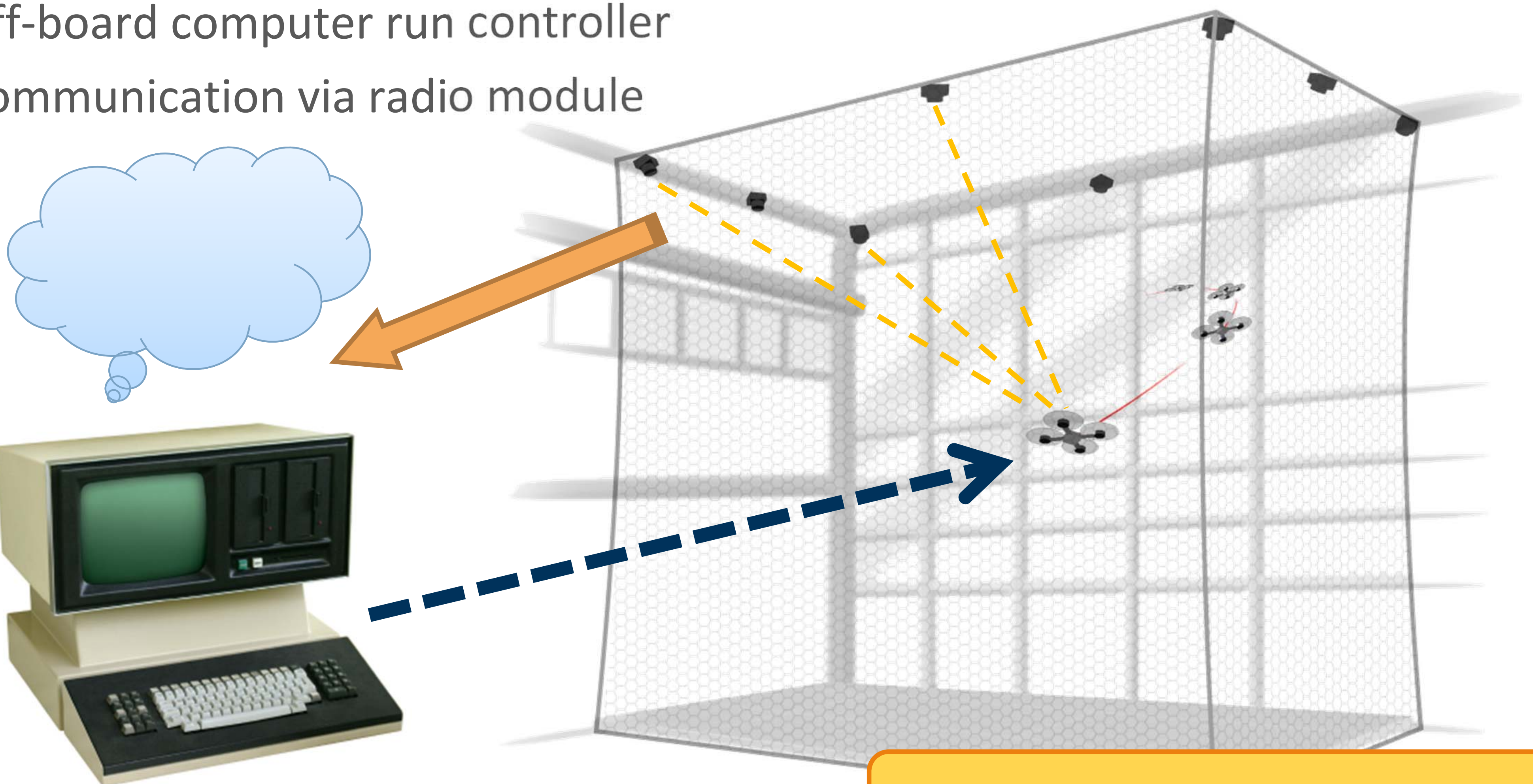
Name: **Flying Machine Arena**

Size: **33 x 33 x 33 feet**

Protection: **Nets, Padded floor**

TESTBED

- cameras provide position and attitude
- off-board computer run controller
- communication via radio module



Autonomous flight.

VIDEO: https://youtu.be/DrHlgxf0oQw?list=PLD6AAACCBFFE64AC5

FOCUS

Music is pre-processed. **Motion** is pre-programmed.

USER INTERFACE

Music Analysis
Extract temporal structure of the music piece

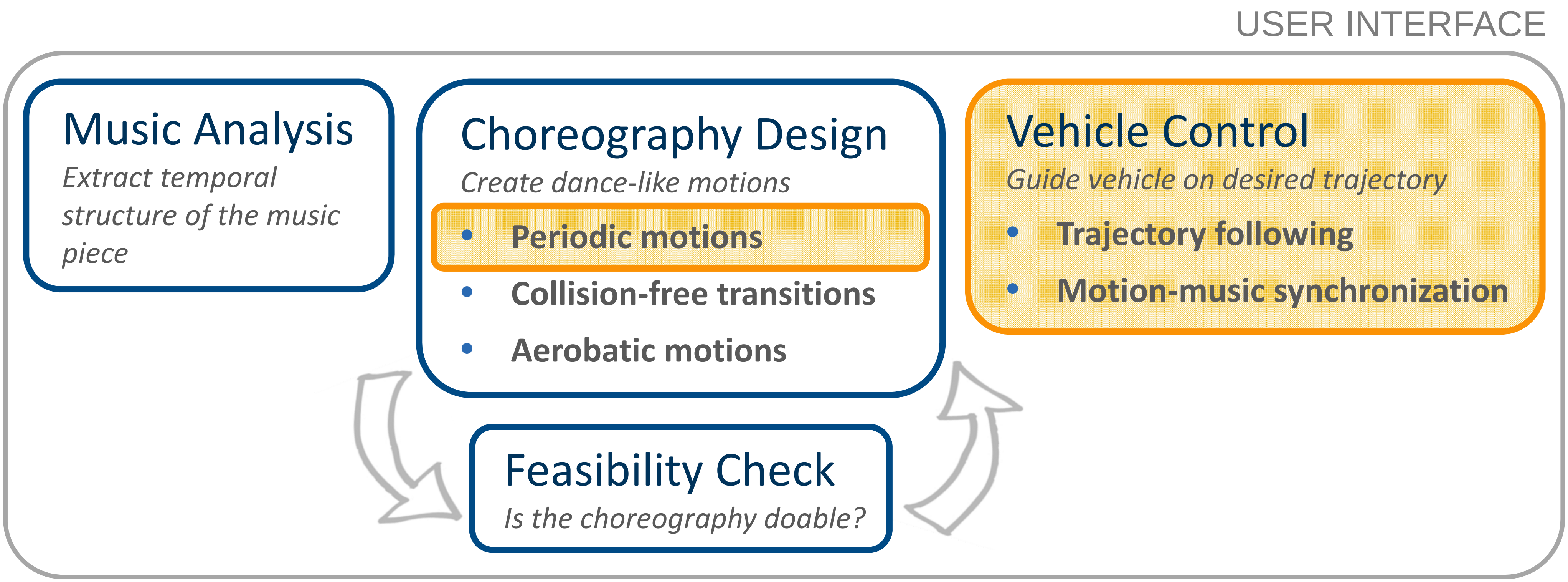
Choreography Design
Create dance-like motions
- **Periodic motions**
- **Collision-free transitions**
- **Aerobatic motions**

Vehicle Control
Guide vehicle on desired trajectory
- **Trajectory following**
- **Motion-music synchronization**

Feasibility Check
Is the choreography doable?

FOCUS

Music is pre-processed. **Motion** is pre-programmed.



Periodic motions = Basic elements of a rhythmic performance

OBJECTIVE

GOAL Precise tracking of periodic trajectories.

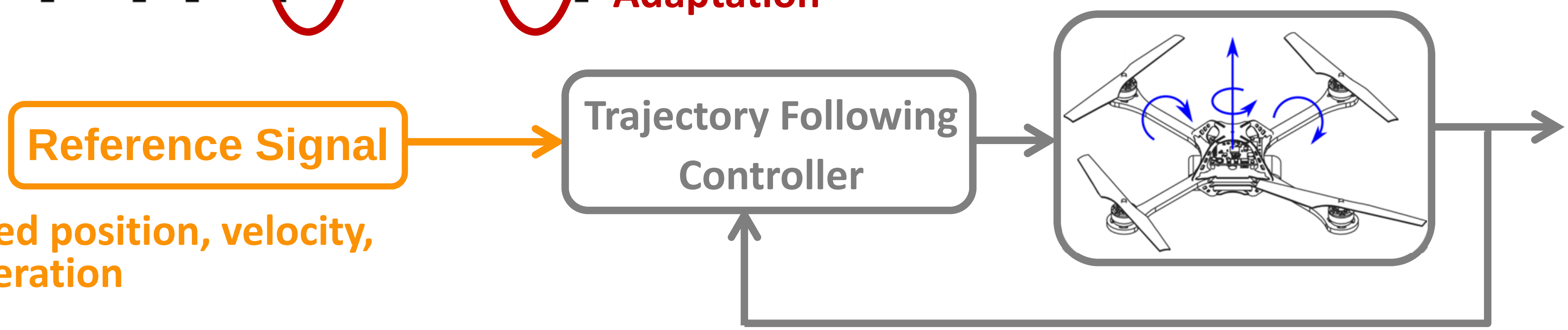
Why? Rhythmic behavior, predictable and reliable performance.

How? Rely on same trajectory following controller, adapt the parameter of the feed-forward input.

Desired periodic motion:

$$\begin{bmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{bmatrix} = \begin{bmatrix} \delta_d^x \\ \delta_d^y \\ \delta_d^z \end{bmatrix} + \begin{bmatrix} A_d^x \cos(\omega_d^x t + \theta_d^x) \\ A_d^y \cos(\omega_d^y t + \theta_d^y) \\ A_d^z \cos(\omega_d^z t + \theta_d^z) \end{bmatrix}$$

Adaptation

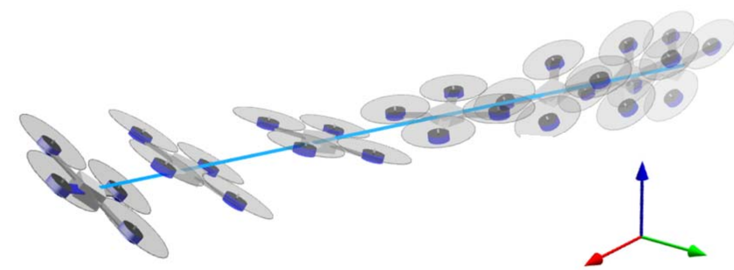


Desired position, velocity, acceleration

Measured position and attitude

APPROACH > 1D example

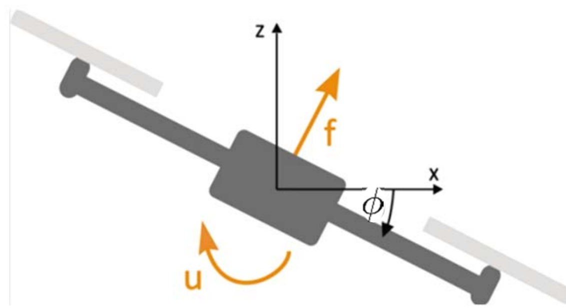
Side-to-side motion.



$$\begin{bmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{bmatrix} = \begin{bmatrix} A_d \cos(\omega_d t + \theta_d) \\ 0 \\ 0 \end{bmatrix}$$

Nominal model.

$$\ddot{x}(t) = f(t)\sin\phi(t)$$
$$\ddot{z}(t) = f(t)\cos\phi(t) - g$$
$$\dot{\phi}(t) = u(t)$$



Control. **Feedback linearization**

- Constant height

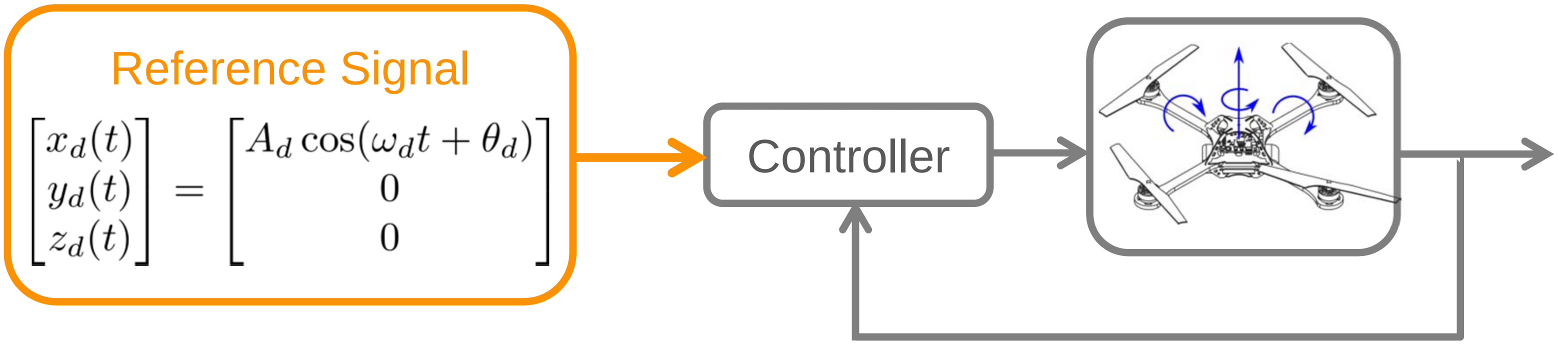
$$f(t) \approx \frac{g}{\cos\phi(t)}$$

- Translational dynamics

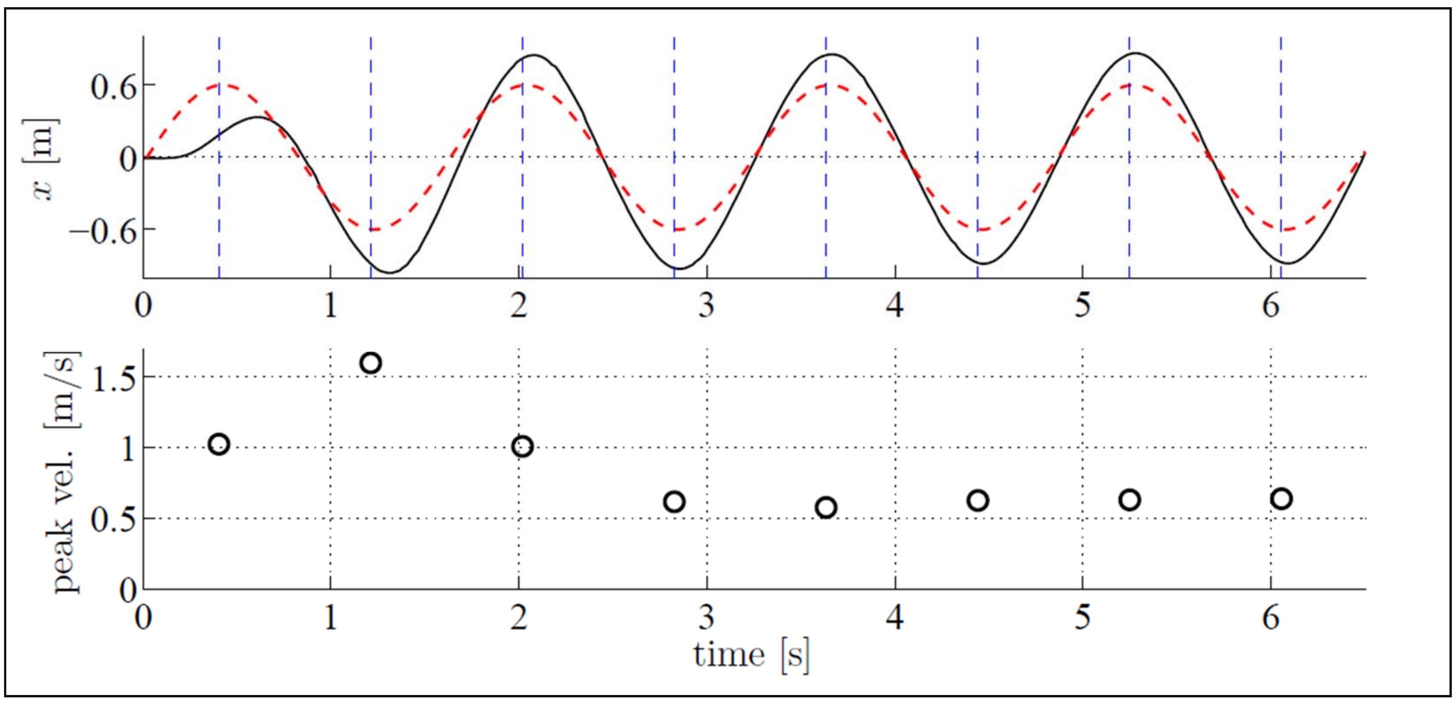
$$\ddot{x}(t) = g\tan\phi(t) \quad \rightarrow \quad \ddot{x}(t) = \bar{u}(t), \quad \bar{u}(t) = \frac{g}{\cos^2\phi(t)}u(t)$$

Design linear controller

EXPERIMENT > 1D example

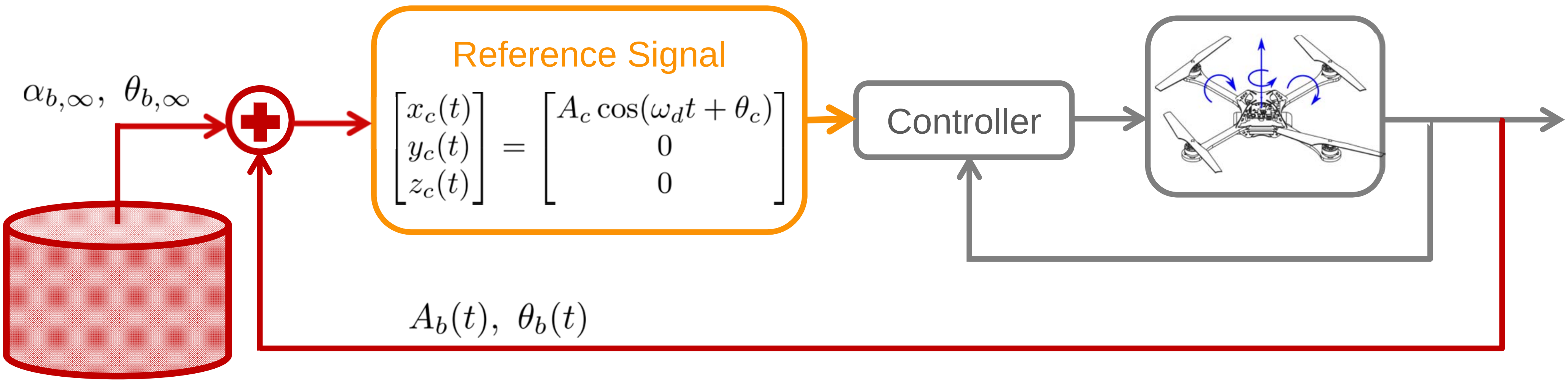


Result ***Constant phase shift and amplitude amplification***



Desired trajectory
Actual motion

FEED-FORWARD ADAPTATION > 1D example



1) Online correction:

$$A_c(t) = A_d + A_b(t), \qquad A_b(t) = k_A \int_0^t A_{err}(\tau) d\tau,$$

$$\theta_c(t) = \theta_d + \theta_b(t), \qquad \theta_b(t) = k_\theta \int_0^t \theta_{err}(\tau) d\tau$$

Factors converge

$$A_{b,\infty},\ \theta_{b,\infty}$$

2) Offline and online correction:

$$A_c(t) = \alpha_{b,\infty} A_d + A_b(t),$$

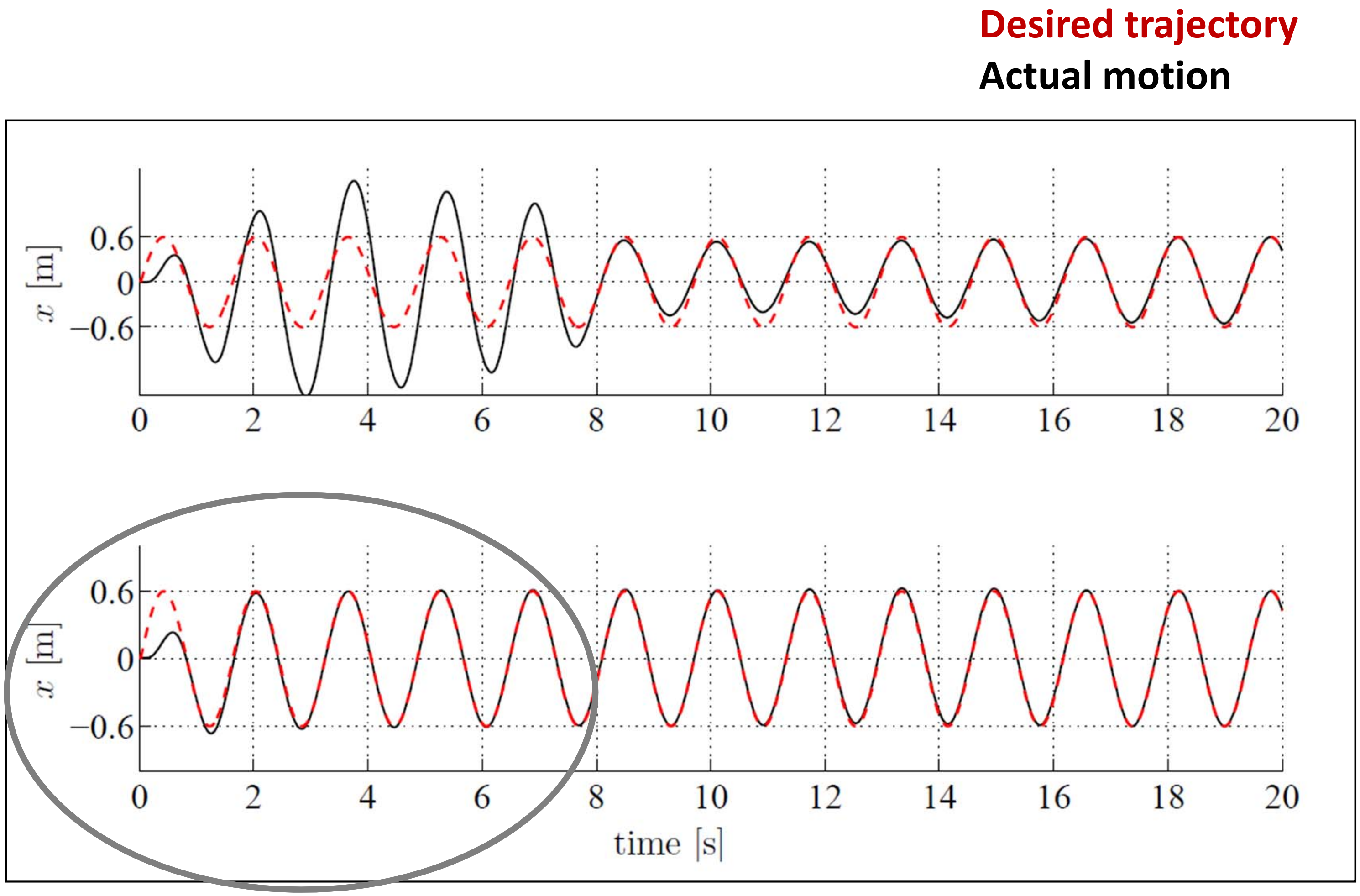
$$\theta_c(t) = \theta_d + \theta_{b,\infty}(t) + \theta_b(t),$$

$$\alpha_{b,\infty} = \left(A_d + A_{b,\infty}\right) / A_d$$

RESULTS > 1D example

ONLINE CORRECTION

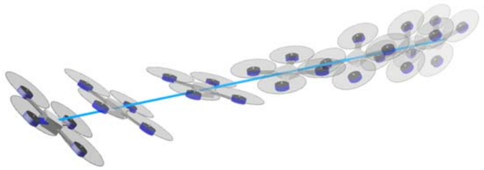
OFFLINE AND ONLINE CORRECTION



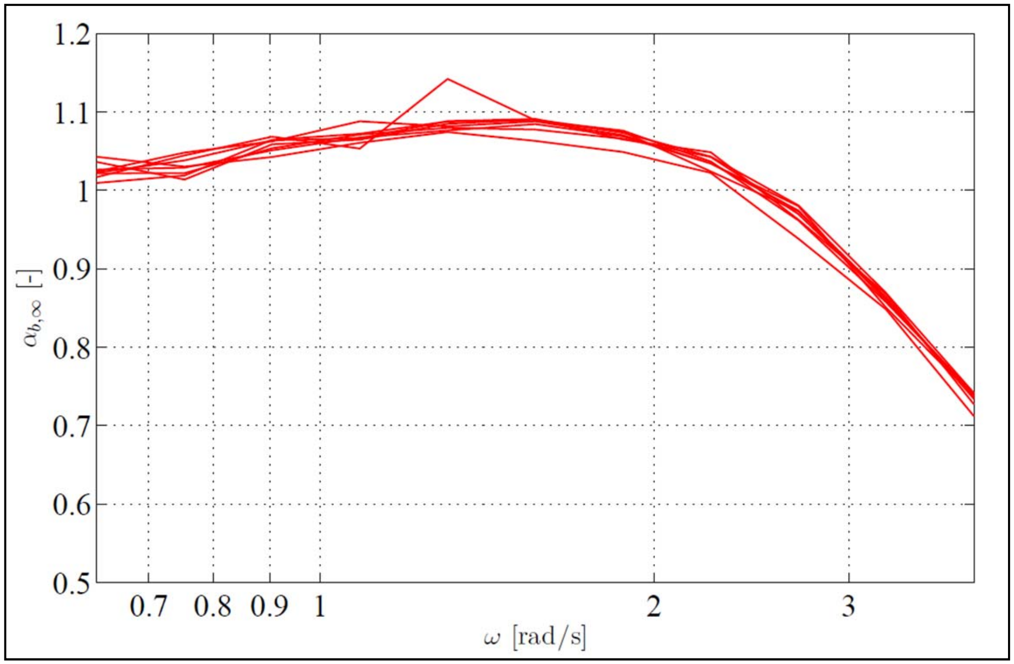
IMPROVED TRANSIENT BEHAVIOR

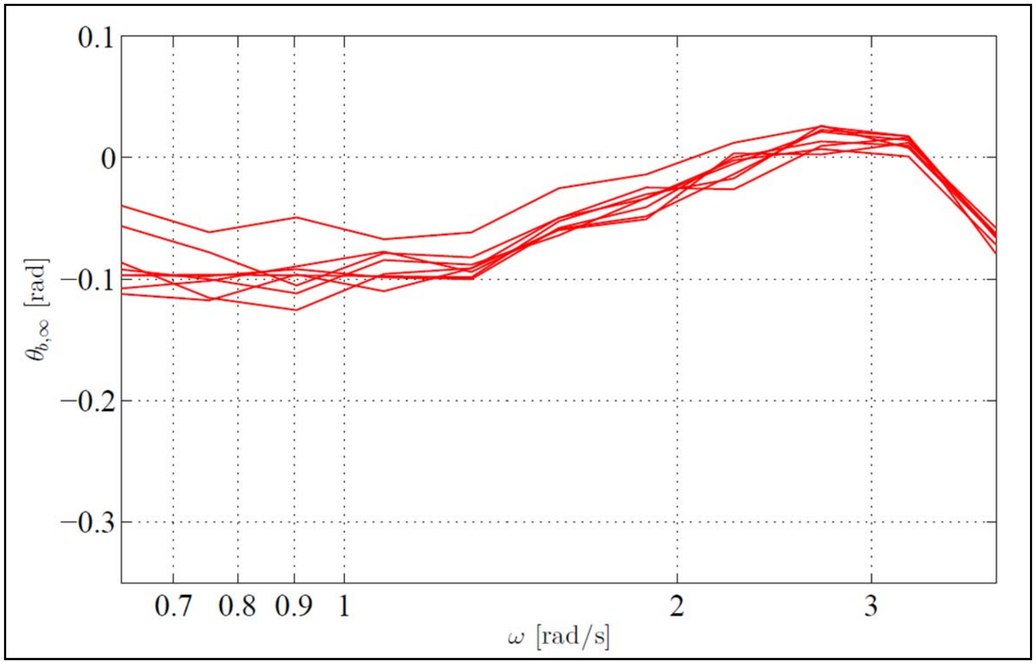
EXPERIMENTAL EVALUATION > 1D example

Result Linear behavior.



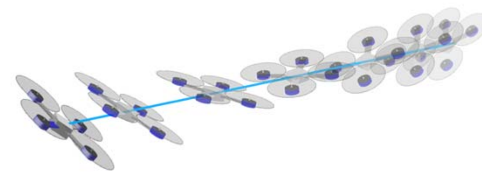
Steady-state correction terms for *various amplitudes*.





Steady-state correction terms do not depend on motion amplitude.

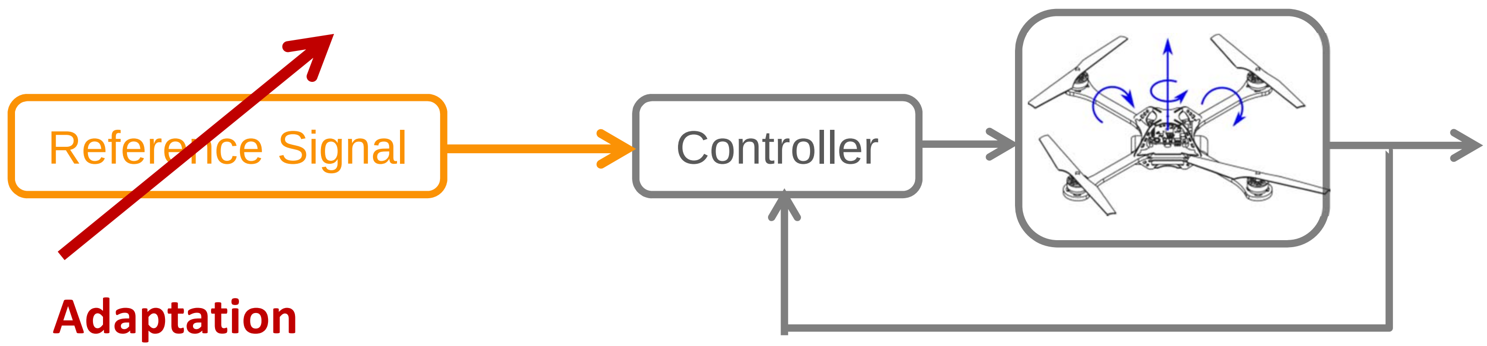
SUMMARY > 1D example



Achieved high-performance tracking without incurring transients by

1. **Offline identification of steady-state correction terms**
   - linear behavior: correction terms only depend on motion frequency
   - prior to flight
   - reduces transient behavior

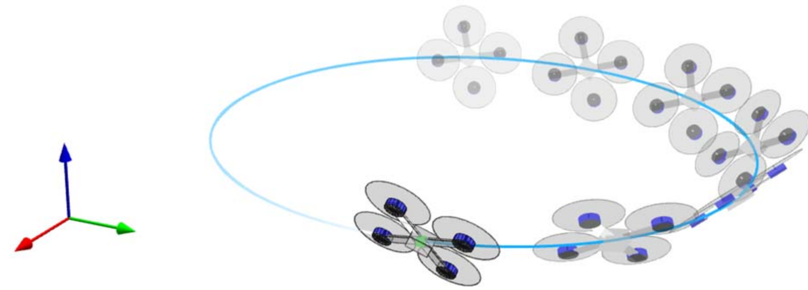
2. **Online correction for small non-repetitive errors**



3D MOTIONS > main result

Periodic motion primitives

$$\begin{bmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{bmatrix} = \begin{bmatrix} \delta_d^x \\ \delta_d^y \\ \delta_d^z \end{bmatrix} + \begin{bmatrix} A_d^x \cos(\omega_d^x t + \theta_d^x) \\ A_d^y \cos(\omega_d^y t + \theta_d^y) \\ A_d^z \cos(\omega_d^z t + \theta_d^z) \end{bmatrix}$$



Decoupled directions.

The correction values $\alpha_{b,\infty}^i$, $\theta_{b,\infty}^i$ in each direction i are independent of the other directions.

Linear system behavior.

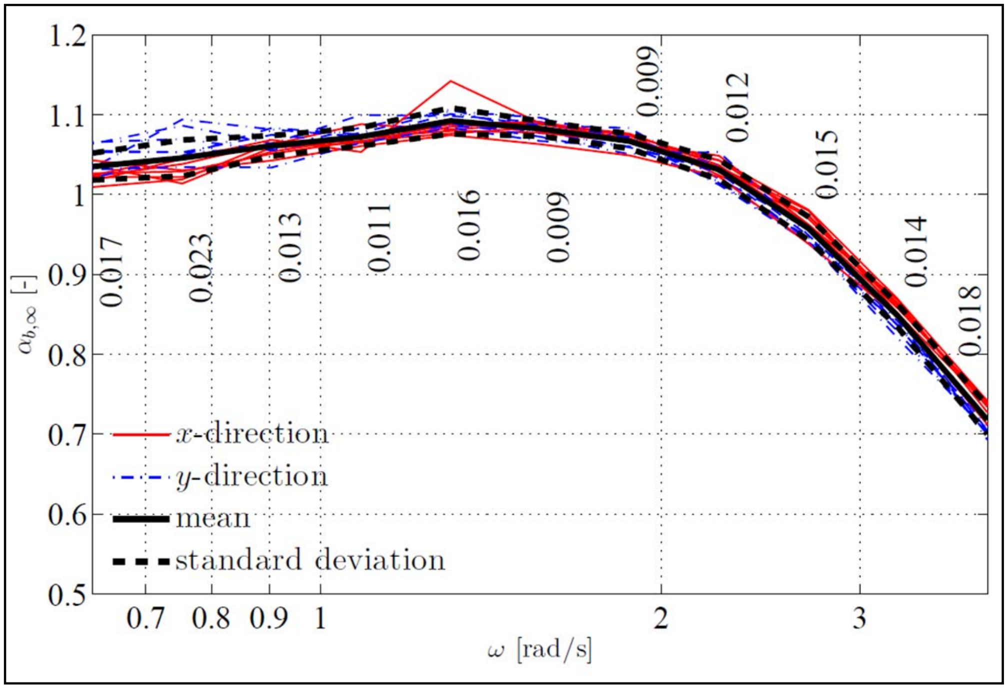
The correction values of one direction i depend only on the frequency of the motion component in this direction ω_d^i .

Symmetry.

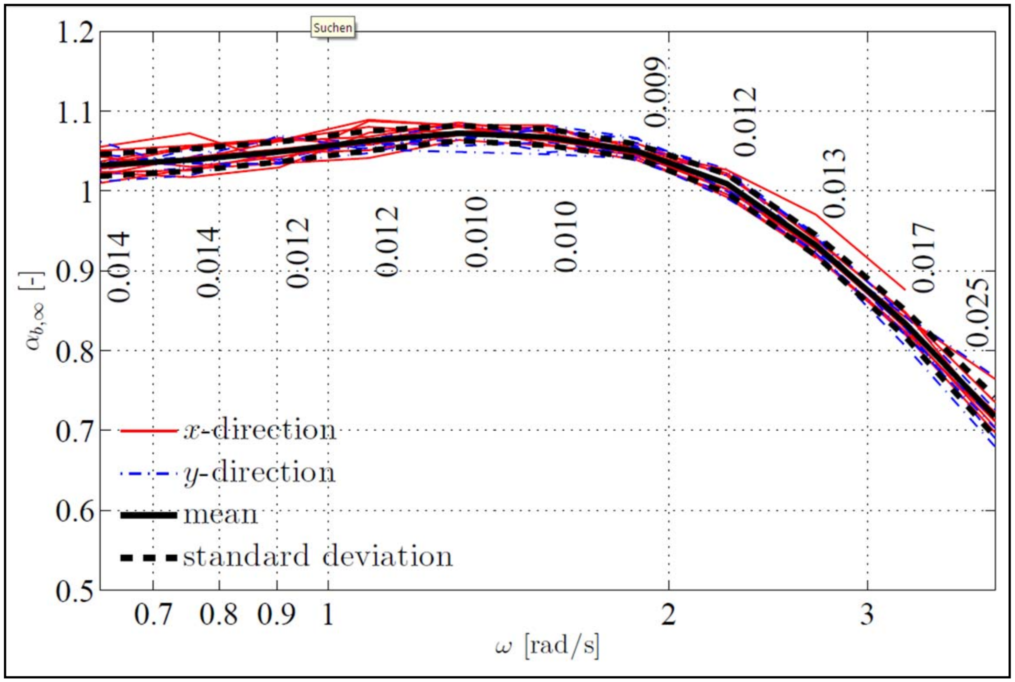
The corrections in x- and y-direction are identical.

3D MOTIONS > verification

Circle in 3D
executed multiple times,
same amplitude



Various 3D periodic motions
circles, swing motions, spirals, ...

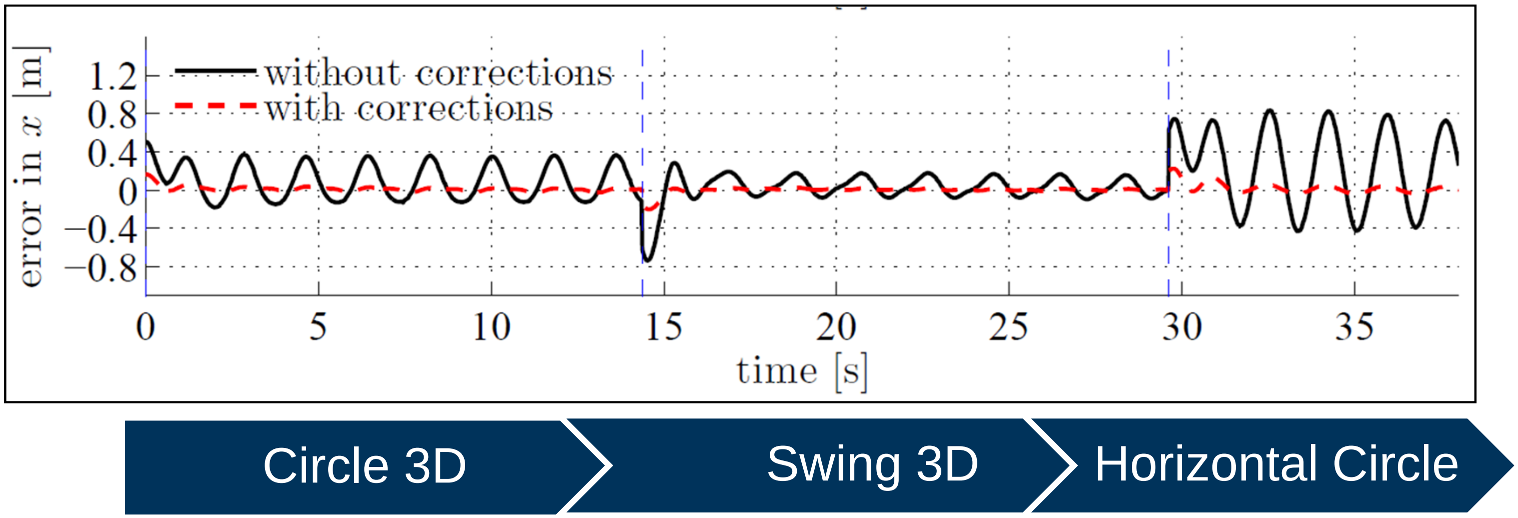


→ COMPARABLE VARIANCES

REDUCED IDENTIFICATION SCHEME

Strategy Perform one 3D motion over the relevant frequency range

Result Using parameters from reduced identification



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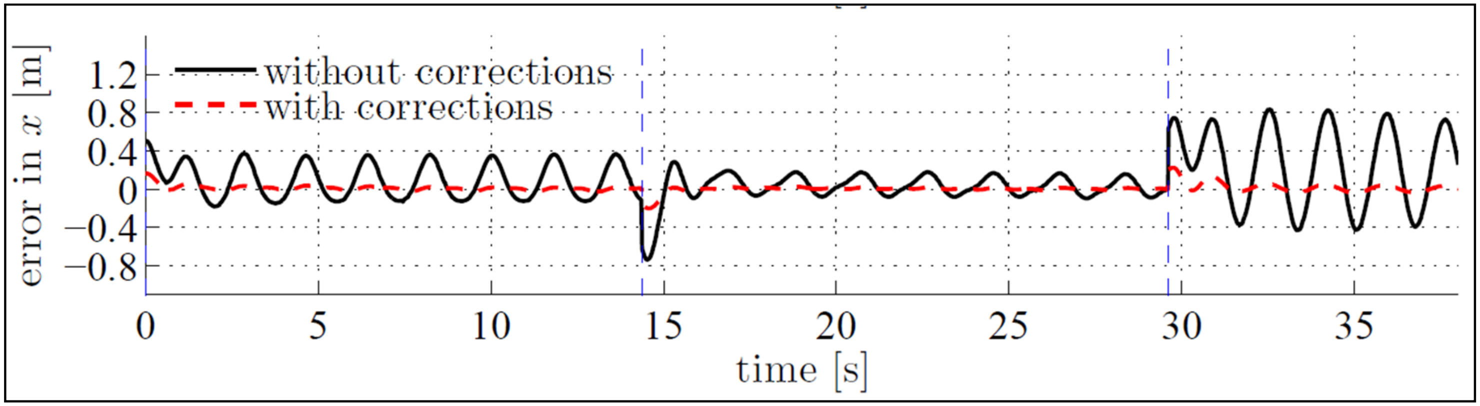
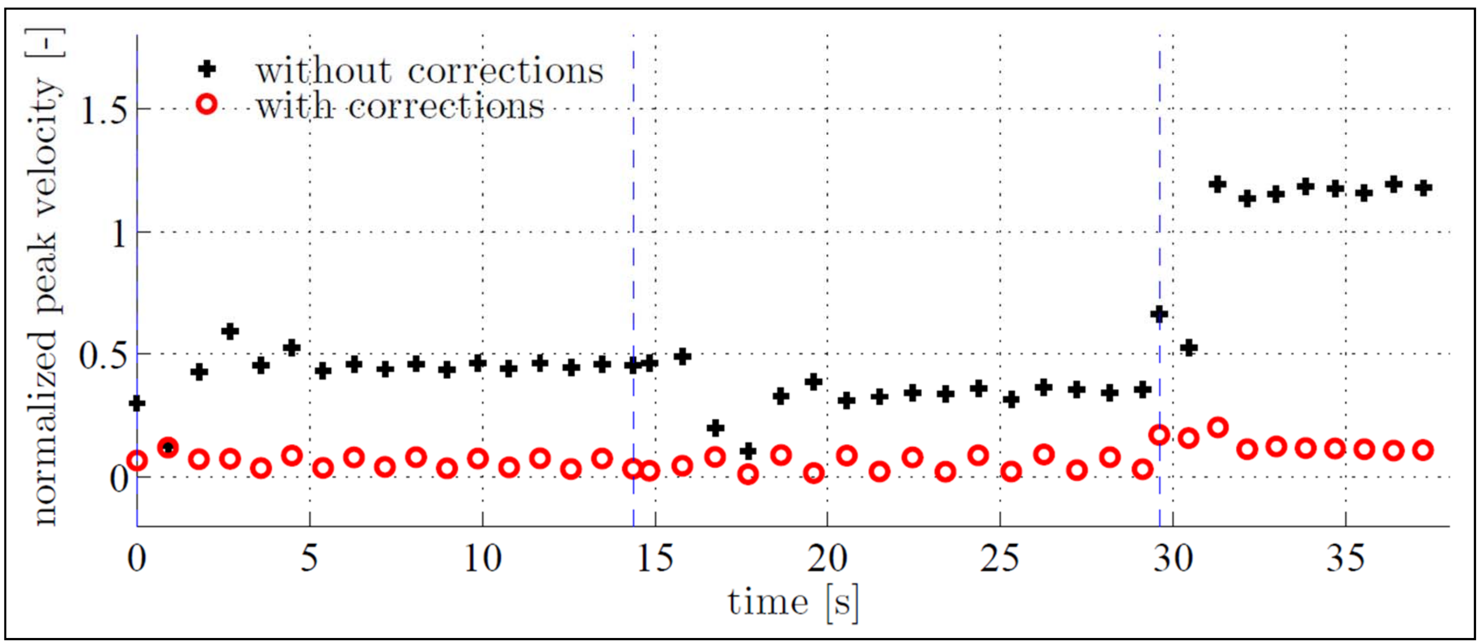


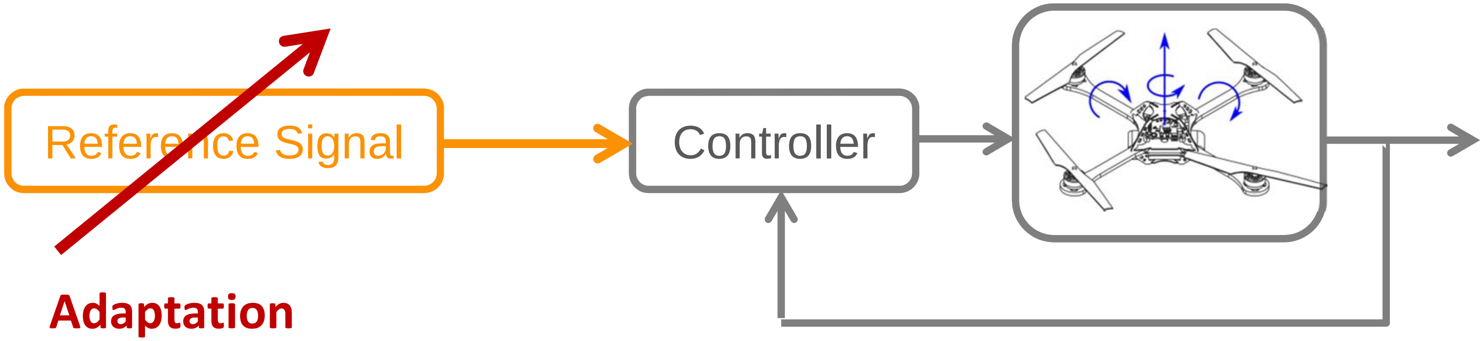


SUMMARY

GOAL Precise tracking of periodic trajectories without transients.

APPROACH *Practicing prior to demonstration.*

- Adaptation of feed-forward parameters
- *A priori* paramter identification through a small set of motions: one motion per frequency is enough!



LET‘S DANCE video: https://youtu.be/7r281vgfotg?list=PLD6AAACCBFFE64AC5

More:

www.FlyingMachineArena.org

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