Feed-Forward Parameter Identification for Precise Periodic Quadrocopter Motions

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LET‘S DANCE
... DANCE IN THE AIR

VISION Dance performance of multiple aerial robots

Angela Schoellig - ETH Zurich
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

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TESTBED

• cameras provide position and attitude
• off-board computer run controller
• communication via radio module
VIDEO: https://youtu.be/DrHlgxf0oQw?list=PLD6AAACCBFFE64AC5

Dancing Quadrocopters
IDSC, ETH Zurich

Rise Up
**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**

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**Periodic motions = Basic elements of a rhythmic performance**

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

**Desired periodic motion:**

\[
\begin{bmatrix}
    x_d(t) \\
    y_d(t) \\
    z_d(t)
\end{bmatrix} =
\begin{bmatrix}
    \delta_x^d \\
    \delta_y^d \\
    \delta_z^d
\end{bmatrix} +
\begin{bmatrix}
    A_{d}^x \cos(\omega_d^x t + \theta_d^x) \\
    A_{d}^y \cos(\omega_d^y t + \theta_d^y) \\
    A_{d}^z \cos(\omega_d^z t + \theta_d^z)
\end{bmatrix}
\]

**Reference Signal**

Desired position, velocity, acceleration

**Trajectory Following Controller**

**Adaptation**

**Measured position and attitude**
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

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

Design linear controller
EXPERIMENT > 1D example

Reference Signal

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

Controller

Result  *Constant phase shift and amplitude amplification*

Desired trajectory
Actual motion
1) **Online correction:**

\[
A_c(t) = A_d + A_b(t), \quad A_b(t) = k_A \int_0^t A_{err}(\tau)d\tau, \\
\theta_c(t) = \theta_d + \theta_b(t), \quad \theta_b(t) = k_\theta \int_0^t \theta_{err}(\tau)d\tau
\]

2) **Offline and online correction:**

\[
A_c(t) = \alpha_{b,\infty}A_d + A_b(t), \quad \alpha_{b,\infty} = (A_d + A_{b,\infty})/A_d \\
\theta_c(t) = \theta_d + \theta_{b,\infty}(t) + \theta_b(t)
\]
RESULTS > 1D example

ONLINE CORRECTION

OFFLINE AND ONLINE CORRECTION

IMPROVED TRANSIENT BEHAVIOR

Desired trajectory
Actual motion
**Result**  Linear behavior.

Steady-state correction terms for *various amplitudes*.

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

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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
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 $\omega_d^i$.

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

![Graph showing error in x over time with and without corrections for Circle 3D, Swing 3D, and Horizontal Circle motions.](image-url)
**REDUCED IDENTIFICATION**

**Strategy**  Perform one 3D motion over the relevant frequency range

**Result**  Using parameters from reduced identification
GOAL  Precise tracking of periodic trajectories without transients.

APPROACH  *Practicing prior to demonstration.*

- Adaptation of feed-forward parameters
- *A priori* parameter identification through a small set of motions: one motion per frequency is enough!
LET’S DANCE

video: https://youtu.be/7r281vgfotg?list=PLD6AAACCBFFE64AC5

Dance of the Quadrocopters
Armageddon

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More:

www.FlyingMachineArena.org
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