Coordination and Synchronization for a Rhythmic Flight Performance

Angela Schoellig
Institute for Dynamic Systems and Control
ETH Zurich, Switzerland
LET’S DANCE
... DANCE IN THE AIR

VISION Dance performance of multiple quadrocopters.

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
VIDEO http://youtu.be/DrHlgxf0oQw?list=PLD6AAACCBFFE64AC5
OBJECTIVE & FOCUS

How do we create an *intuitive interface* for the design of choreographies?  

How do we achieve a *rhythmic flight* performance?

... use controls and system dynamics.

MOTION DESIGN  FEASIBILITY  
[Schoellig, Hehn, Lupashin and D'Andrea, ACC 2011]

CONTROL  SYNCHRONIZATION  
[Schoellig, Augugliaro and D'Andrea, ICRA 2010 & IROS 2010]

PREPROGRAMMED. DONE AHEAD OF TIME.
MOTION CONTROL

CONTROLLER

position, attitude

full state information

ESTIMATOR

desired trajectory (+ desired velocities, accelerations)

CONTROLLER

desired collective thrust, desired rotational rates

ESTIMATOR

RATE GYROS

rotational rates

motor commands

CAMERAS
RHYTHMIC MOTION

First... Synchronize the SIDE-TO-SIDE MOTION of a quadrocopter to music.

Music.

Side-to-side motion.

\[
s_d(t) = \begin{bmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{bmatrix} = \begin{bmatrix} A \cos(\Omega t) \\ 0 \\ 0 \end{bmatrix}.
\]

Reference signal

Angela Schoellig - ETH Zurich
Quadrocopter response shows **constant phase error** after a transient phase.
Quadrocopter response shows **constant phase error** after a transient phase.

Linear system behavior. Repeatable.
SYNCHRONIZATION

**OPTION 1:** Online phase detection and correction
→ transient behavior

**OPTION 2:** Learn phase offset ahead of time, feedforward compensation
→ less robust

COMBINE!
OBJECTIVE & FOCUS

How can we create an **intuitive interface** for the design of choreographies?

How can we achieve a **rhythmic flight** performance?

... use controls and system dynamics.

**MOTION DESIGN**
Parameterized motion primitives.

**FEASIBILITY**
Based on model.

**CONTROL**

**SYNCHRONIZATION**
PREPROGRAMMED. DONE AHEAD OF TIME.

Angela Schoellig - ETH Zurich
Specify motion through **position** and **yaw** (4DOF):

\[
\begin{align*}
    s(t) &= (x(t), y(t), z(t)) \\
    \alpha(t)
\end{align*}
\]

Introduce parametrized motion primitives:

\[
\begin{align*}
    s_d(t) &= s_d(p, t), & t \in [t_0, t_f] \\
    \alpha_d(t) &= \alpha_d(p, t)
\end{align*}
\]
MOTION DESIGN – example

Periodic motion primitive.

\[ s_d(t) = a_0 + \sum_{k=1}^{N} a_k \cos (k \Omega t) + b_k \sin (k \Omega t), \quad \Omega = \frac{2\pi}{T}. \]

includes
- side-to-side motions
- circles
- spirals
- ....

DESIGN PARADIGM. space – time – energy – structure
Periodic motion primitive.

\[ s_d(t) = a_0 + \sum_{k=1}^{N} a_k \cos (k \Omega t) + b_k \sin (k \Omega t), \quad \Omega = \frac{2\pi}{T}. \]

includes

- side-to-side motions
- circles
- spirals
- ....
MOTION FEASIBILITY – model/constraints

First principles model.

Constraints.

(1) Collective thrust (*input*) \( f_{min} \leq f \leq f_{max} \)

(2) Single motor thrust \( f_{i,min} \leq f_i \leq f_{i,max} \)

CHECK 1: Collective thrust limits.

\[
f_d = \sqrt{(\ddot{x}_d)^2 + (\ddot{y}_d)^2 + (\ddot{z}_d + g)^2}
\]
MOTION FEASIBILITY – model/constraints

First principles model.

Constraints.

(1) Collective thrust (input) \( f_{min} \leq f \leq f_{max} \)

(2) Single motor thrust \( f_{i, min} \leq f_i \leq f_{i, max} \)

CHECK 1: Collective thrust limits. 
\[
f_d = \sqrt{(\ddot{x}_d)^2 + (\ddot{y}_d)^2 + (\ddot{z}_d + g)^2}
\]

CHECK 2: Single motor thrust limits.
MOTION FEASIBILITY – example

Side-to-side motion.

\[ s_d(t) = \begin{bmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{bmatrix} = \begin{bmatrix} A \cos(\Omega t) \\ 0 \\ 0 \end{bmatrix}. \]

Feasibility.

- Violates collective thrust limit (CHECK 1)
- Violates single motor thrust limit (CHECK 2)
Side-to-side motion.

\[ s_d(t) = \begin{bmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{bmatrix} = \begin{bmatrix} A \cos(\Omega t) \\ 0 \\ 0 \end{bmatrix}. \]

**EXPERIMENTAL RESULTS:**

motor commands saturated 1% of the time.
CURRENT STATUS

Motion design.

Work with Federico Augugliaro
CURRENT STATUS

Feasibility.

Work with Federico Augugliaro

Angela Schoellig - ETH Zurich
SUMMARY

• choreographies based on motion primitives that are adjustable in their parameters
• feasibility check prior to flight based on first principles models
• synchronization to the music while flying

... One step towards creating choreography in a simple and intuitive way.

Angela Schoellig - ETH Zurich
LET’S DANCE [link]

Armageddon
@ the Flying Machine Arena

April 2011

Angela Schoellig - ETH Zurich
Videos:
www.tinyurl.com/dance2gether
www.tinyurl.com/tripleDance

More:
www.FlyingMachineArena.org