Designing aerial robots (and aerial taxis?)

Mark W. Mueller

June 9, 2021

Berkeley
UNIVERSITY OF CALIFORNIA

HiPeR Lab
HIGH PERFORMANCE ROBOTICS

3D Urban transportation

Want systems that are:

- small^{+}
- quiet^{+}
- safe^{+*}
- comfortable*
- clean (electric)$^{+}$
- capable of useful range^{+}

How to design for this?

$+$ focus on efficiency

$*$ modify physics

Creating autonomous aerial systems for 3D urban mobility requires the tight integration of mechanical and control design

(my somewhat wild vision of UAM)

Multicopter power consumption – multicopter

Medium - large scale: Mechanical power to drive motors

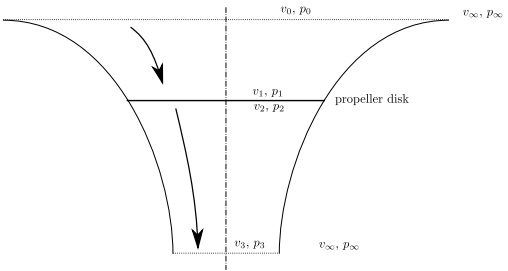
Multicopter power consumption – multicopter

Medium - large scale: Mechanical power to drive motors

Simple propeller model

- Actuator disk
- Incompressible, inviscid flow

$$\text{power} \sim \frac{(\text{force})^{\frac{3}{2}}}{\text{radius}}$$



Long duration flights:

- Low force per propeller
- Large propellers

Rough scaling (battery electric flight time):

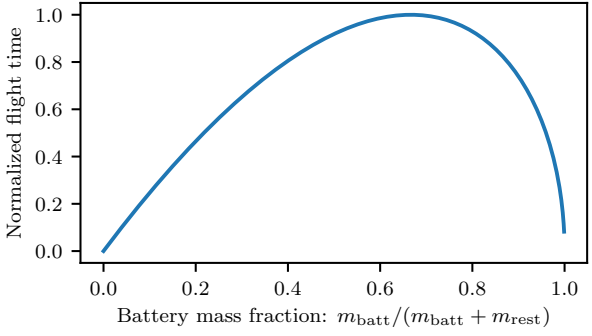
$$\text{power} \sim \frac{(\text{force})^{\frac{3}{2}}}{\text{radius}}$$

- force $\propto$ vehicle mass $= m_{\text{batt}} + m_{\text{rest}}$:
  - m_{batt} energy storage
  - m_{rest} payload, structure, powertrain
- flight time $\propto \frac{E_{\text{batt}}}{P_{\text{elec}}}$
  - $E_{\text{batt}} \propto m_{\text{batt}}$ battery mass
  - $P_{\text{elec}} \propto (m_{\text{batt}} + m_{\text{rest}})^{\frac{3}{2}}/r$

$$T_{\text{flight}} = \frac{E_{\text{batt}}}{P_{\text{elec}}} \sim r\frac{m_{\text{batt}}}{(m_{\text{batt}} + m_{\text{rest}})^{\frac{3}{2}}}$$

Rough scaling (battery electric flight time):

$$T_{\text{flight}} = \frac{E_{\text{batt}}}{P_{\text{elec}}} \sim r \frac{m_{\text{batt}}}{(m_{\text{batt}} + m_{\text{rest}})^{\frac{3}{2}}}$$



Thus: optimal at battery $\frac{2}{3}$ of total mass (insane design point!)

Battery electric:

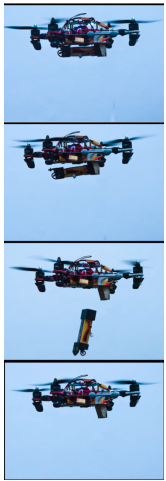
Fundamental challenge

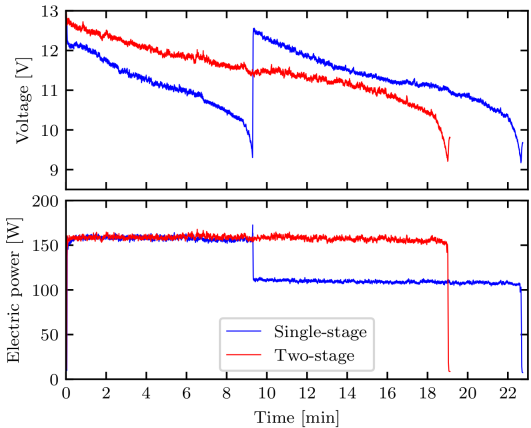
- Low specific energy of batteries
- Constant mass (unlike combustion)

Two ideas to “cheat” the physics:

- In-air refuelling
- Staged energy

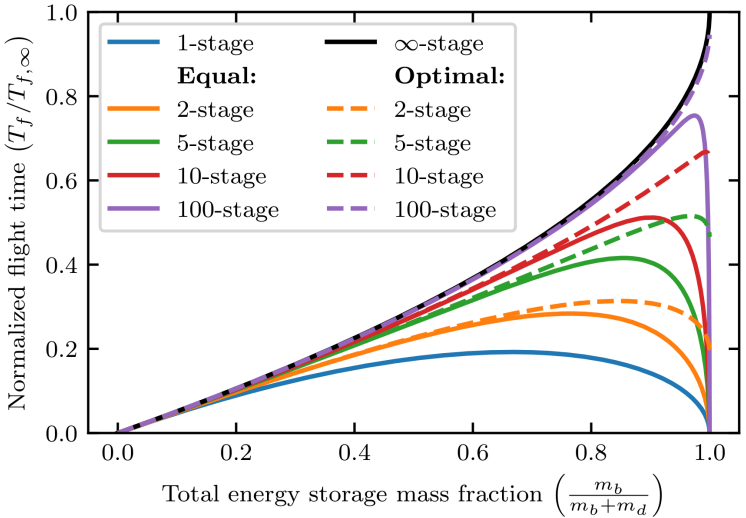
Staged batteries: Discard battery as depleted[1]





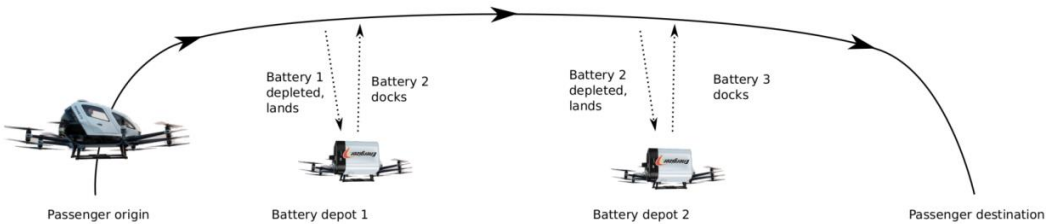
[1] Jain et al., IROS2020 (Has obvious environmental concerns!)

Staged batteries: Discard battery as depleted

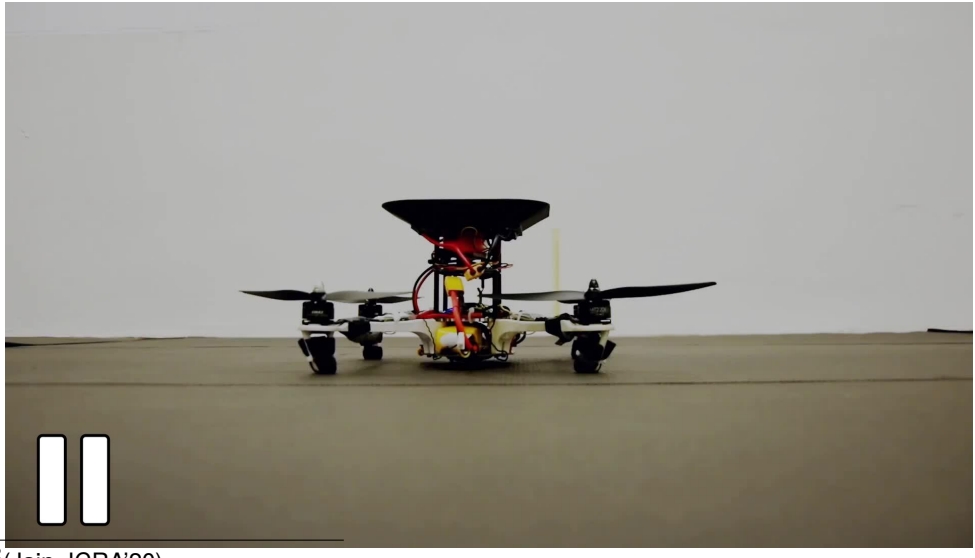


Flying batteries – in-air battery replacement

- Allow for light takeoff mass, but useful range
- Equip city with “flying battery hubs”
- Keep vehicle mass low

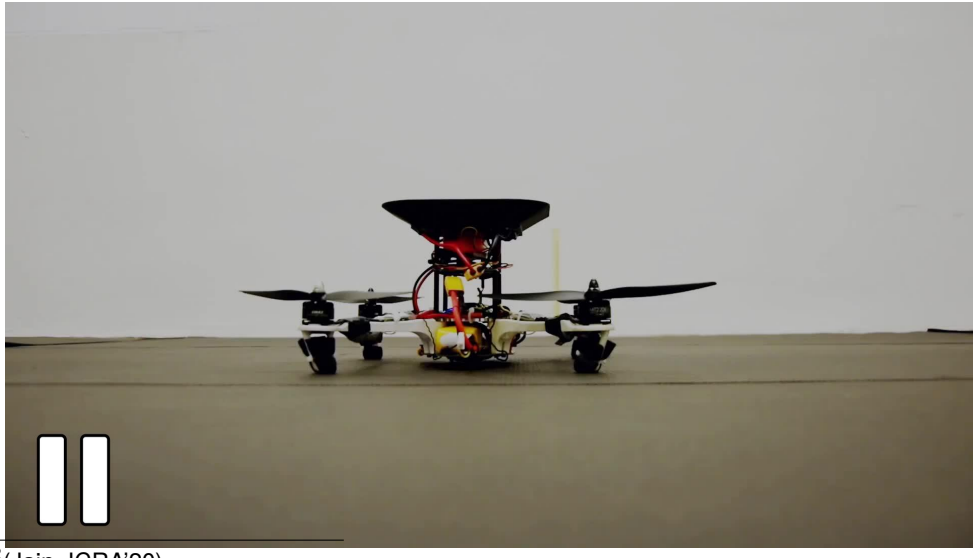


One solution: flying batteries[2]



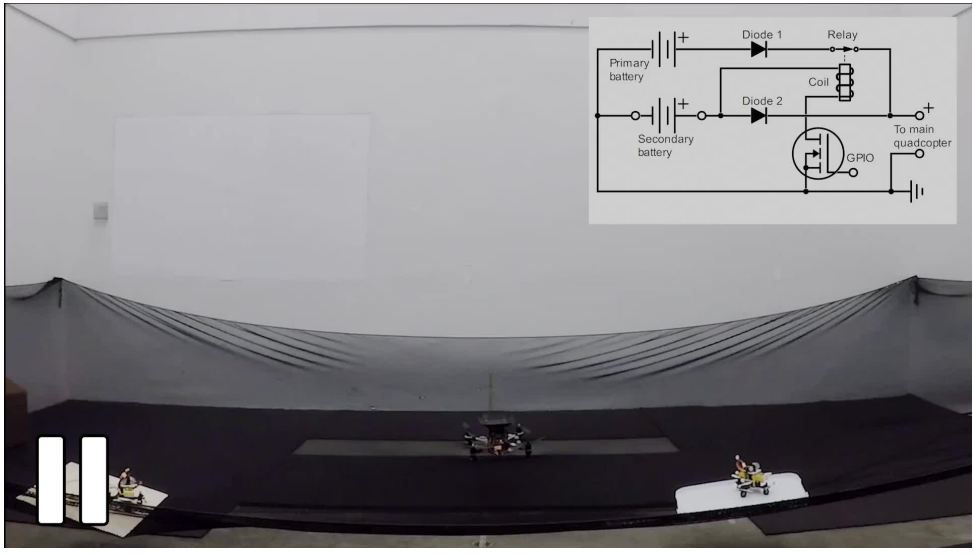
[2] (Jain, ICRA'20)

One solution: flying batteries[2]

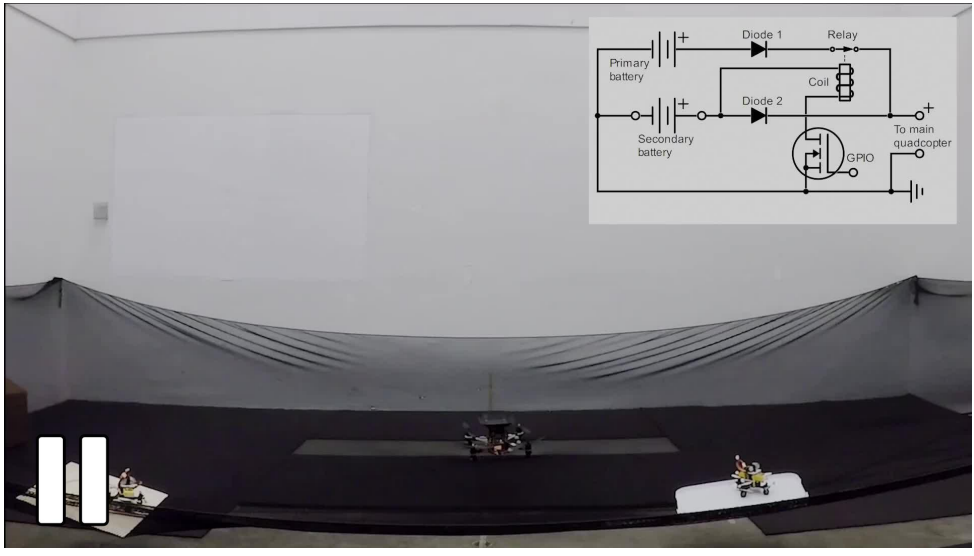


[2] (Jain, ICRA'20)

Flying batteries

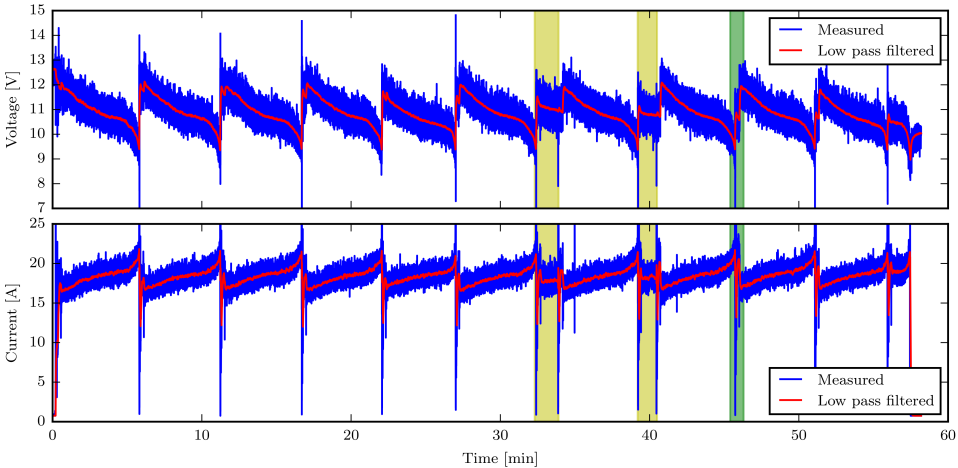


Flying batteries



Flying batteries – results

Total flight time: 57min (more than 2x theoretical maximum)
Low mass – safe vehicle



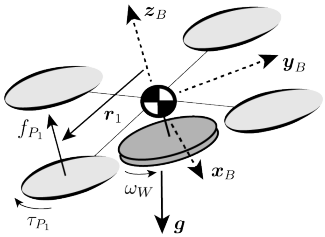
Disturbance rejection: cheating with physics

The Canadian Arcade. “CRAZY GOLF BALL SIZED HAIL STORM.” *YouTube*, 30 Jul. 2016, https://youtu.be/vTFCMUg20JU

Disturbance rejection: cheating with physics

The Canadian Arcade. “CRAZY GOLF BALL SIZED HAIL STORM.” *YouTube*, 30 Jul. 2016, https://youtu.be/vTFCMUg20JU

Quadcopter with added angular momentum[3]



Only affects angular velocity dynamics:

$$\boldsymbol{J}^{\Sigma}\dot{\boldsymbol{\omega}}^{B} = -\boldsymbol{J}^{W}\dot{\boldsymbol{\omega}}^{WB} - [\![\boldsymbol{\omega}^{B}]\!]\boldsymbol{J}^{\Sigma}\boldsymbol{\omega}^{B} - [\![\boldsymbol{\omega}^{B}]\!]\boldsymbol{J}^{W}\boldsymbol{\omega}^{WB} + \sum_{i=1}^{4}[\![\boldsymbol{r}_{P_i}]\!]\boldsymbol{z}f_{P_i} + \boldsymbol{z}\tau_{P_i} + \boldsymbol{\tau}_{\text{dist}}$$

with $\boldsymbol{\omega}^{WB} = \left(0, 0, \pm\left\|\boldsymbol{\omega}^{WB}\right\|\right)$

First-order coupling through $[\![\boldsymbol{\omega}^{B}]\!]\boldsymbol{J}^{W}\boldsymbol{\omega}^{WB}$

Inputs:

- 4 motor forces – 3D torque & scalar force
- Angular acceleration of wheel

[3] (Bucki IJIRA19; IROS18)

Experimental validation: large vehicle

$m^{\Sigma} = 922\text{g}, \bar{\omega}^{W} = 0\text{rad/s}$

Experimental validation: large vehicle

$m^{\Sigma} = 922\text{g}, \bar{\omega}^{W} = 0\text{rad/s}$

Conclusion

- Interest in highly dynamic, agile aerial systems
- Autonomy and safety
  - Complex environments
  - Large disturbances
- Tight integration of intelligence & physical design
- mwm@berkeley.edu

Funding: Code42.ai, Navelabs, NSF, Powley Fund