Self-Sustainability in Nano Unmanned Aerial Vehicles: A Blimp Case Study

*D. Palossi*\(^a\), A. Gomez\(^a\), S. Draskovic\(^a\), K. Keller\(^a\), L. Benini\(^{ab}\), L. Thiele\(^a\)

\(^a\)ETH Zürich, \(^b\)University of Bologna
Introduction

- Current **nano-size** (i.e., Ø ~10cm, ~50g) UAVs require few Watts (~10W) to fly
- Current battery technology has limited capacity → few minutes of flight (~15 min)

**Can we have nano-UAVs with extended lifetimes?**

- There are many potential applications for self sustainable nano-UAVs
  - Surveillance
  - Smart Buildings
  - Agriculture
  - Assisted Living

We focus on indoor scenarios
Nano-UAV Power Requirements

High energy requirements $\rightarrow$ short lifetime

Reduced energy requirements

[3] Experimental testing
Nano-UAV Power Requirements

[3] Experimental testing

High energy requirements → short lifetime

Reduced energy requirements

Blimp is the best candidate
Can we increase runtime, possibly reach self-sustainability?

**Nano UAV System**
- Battery powered

**Proposed Nano UAV System**
- Harvest power + battery
Target capability: Hovering

- Hovering: keep the desired altitude over time
- Hovering is a basic building block for complex autonomous navigation
- The required thrust can be dynamically adjusted (inertial, visual, ultra-sound, etc.). Not in this work
- Design choice: heavier-than-air
Maximize Lifetime: Duty-Cycling Rotors

In this work we will evaluate both continuous and duty-cycled hovering.

Quadcopter
High energy due to small $\Delta Y$

Blimp
Low energy due to large $\Delta Y$

Nano-Blimp + Harvesting + Duty-Cycling

$\Delta Y$
Outline

- System Model
  - Power requirements and lifetime
  - Weight distribution
- Blimp Prototype
  - Prototype
  - Hardware/Firmware Design
- Experimental Evaluation
  - Initial Characterization
  - Experimental Results
- Conclusion
Lifetime Evaluation: Power Model

- Power modeled as Markov process
- States represent discrete energy levels
- Model time step: 1 duty cycle
- **Consumption**: it consumes 2 quantum of energy
- **Harvesting**: it produces [0-3] quantum of energy

\[
\begin{align*}
\text{States} &\quad & \text{Consumption} &\quad & \text{Harvesting} \\
0 &\quad & 0 &\quad & 0.1 \\
1 &\quad & 0 &\quad & 0.15 \\
2 &\quad & 1 &\quad & 0.5 \\
3 &\quad & 0 &\quad & 0.25 \\
n-2 &\quad & 0.1 &\quad & 0.1 \\
n-1 &\quad & 0.15 &\quad & 0.15 \\
n &\quad & 0.5 &\quad & 0.5 \\
n+1 &\quad & 0.25 &\quad & 0.25 \\
\end{align*}
\]
Charging/Discharging Probabilities

- **Discharging** rate is deterministic
  - Continuous: 0.576 W
  - Duty Cycle: 0.198 W

- **Charging** rate is probabilistic
  - Not only mean value → better environment characterization
  - It includes low insulation that may lead to error state
  - $P_{\text{in}} > 0$ (i.e., no night)

Log-normal distribution, mean 0.1 W and $\sigma = 0.5$. 
Power Model: Outcomes

- Predict lifetime for a given configuration
- Determine input power / battery capacity requirements for a desired lifetime
Battery/Panel Trade-Off: Weight Distribution

Limited payload → maximize lifetime solving the weight distribution problem

Parameters:
- Lifetime ($\tau$)
- Illuminance (intensity, variance and duration)
- $W_{\text{MAX}}$ 55 g, Payload 40 g

$$\tau \cdot P_{\text{load}} \leq E_{\text{in}} (W_{\text{panel}}, \text{Light}) + E_{\text{batt}} (W_{\text{batt}})$$

$$W_{\text{tot}} \leq W_{\text{max}}$$
Limited payload → maximize lifetime solving the weight distribution problem

Parameters:
- Lifetime ($\tau$)
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$W_{\text{tot}} \leq W_{\text{max}}$

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>6 g</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>31 g</td>
</tr>
<tr>
<td>Connections</td>
<td>4 g</td>
</tr>
<tr>
<td>Rotorcraft</td>
<td>11 g</td>
</tr>
</tbody>
</table>
Outline

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Prototype

Configuration: only one rotor (hovering), solar panel 25x9 cm, balloon Ø 91 cm
# Electronics Architecture

### Device Power Consumption Table

<table>
<thead>
<tr>
<th>Device</th>
<th>Task</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRF51</td>
<td>Power distribution</td>
<td>20 mW</td>
</tr>
<tr>
<td>STM32</td>
<td>Motor speed control</td>
<td>180 mW</td>
</tr>
</tbody>
</table>

### Device Interactions

- **Thin film solar panel** (Always ON power domain)
- **Power supplies and TI bq2920**
- **NRF51822**
  - 16Mhz Cortex-M0
  - 16kB RAM, 256kB Flash
  - BLE and NRF radio
  - UART
  - Charge/VBAT/VCC
- **STM32F405**
  - 168Mhz Cortex-M4
  - 196kB RAM, 1MB Flash
  - UART
  - Wkup/OWN/GPIO
  - PWM motor driver
  - Expansion port
Introducing Duty-Cycling to Nano-Blimps

Dynamic Power Management

**Duty-Cycle:** $T_{ON}, T_{OFF}$

**Power Consumption**
- **ON:** $\sim 4 \, W$
- **OFF:** $\sim 5 \, \mu W$

**Continuous Mode:**
Disabled the timer interrupt in the NRF51
Outline

- System Model
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Rotor Activation Overhead

Single burst of 2 sec, 100% rotor intensity

Power [W]

Time [s]

Peak at 5.75W, after 220ms steady 4.1W (Avg.)
**Rotor Activation Overhead**

Single burst of 2 sec, 100% rotor intensity

- Peak at 5.75 W, after 220 ms steady 4.1 W (Avg.)

- Activation Overhead: 0.18 J
  - Negligible for continuous mode
  - Extra cost for each duty-cycle period
Duty-Cycle Characterization ($T_{\text{ON}}$, $T_{\text{OFF}}$)

Max height deviation ($\Delta Y$): ±25 cm

With $T_{\text{ON}}$ of 250 ms it rises to ~ 50 cm

Duty-Cycle Selection

<table>
<thead>
<tr>
<th>$Y$ Displacement</th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Regression</td>
<td></td>
</tr>
</tbody>
</table>

Height

$\Delta Y = 0$

Continuous Rotor

$\Delta Y > 0$

Duty-Cycle Rotor

Time

$0.1$ $0.2$ $0.3$ $0.4$ $0.5$ $0.6$

$0$ $0.5$ $1$ $1.5$ $2$ $2.5$ $3$

$25$ $50$ $75$ $100$ $125$ $150$

D. Palossi et al. | 16.05.2017 | 21
Duty-Cycle Characterization ($T_{ON}$, $T_{OFF}$)

Max height deviation ($\Delta Y$): $\pm 25 \text{ cm}$

With $T_{ON}$ of 250 ms it rises to $\sim 50 \text{ cm}$

$T_{OFF}$ long enough to reach the max height (+25) and returning to the initial position (-25) → 5 seconds

<table>
<thead>
<tr>
<th>Mode</th>
<th>Rotor Intensity</th>
<th>$T_{ON}$</th>
<th>$T_{OFF}$</th>
<th>Power Consumption</th>
<th>Energy per Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>9%</td>
<td>Always</td>
<td>Never</td>
<td>0.576 W</td>
<td>3.024 J</td>
</tr>
<tr>
<td>Duty-Cycle</td>
<td>100%</td>
<td>250 ms</td>
<td>5 s</td>
<td>0.198 W</td>
<td>1.04 J</td>
</tr>
</tbody>
</table>
Experimental Results

- **Setup**: constant energy harvesting vs. probabilistic energy harvesting
- **Battery**: ideal storage

- Probabilistic Model
Experimental Results

- **Setup:** constant energy harvesting vs. probabilistic energy harvesting
- **Battery:** ideal storage

- Probabilistic Model
- Constant Model

Self-sustainable at:
- Continuous Mode ~600mW
- Duty-Cycle Mode ~200mW
Experimental Results

- **Setup**: constant energy harvesting vs. probabilistic energy harvesting
- **Battery**: ideal storage

- Probabilistic Model
- Constant Model
- Constant Measurements

Self-sustainable at:
- Continuous Mode  
  ~600\(mW\)
- Duty-Cycle Mode  
  ~200\(mW\)
Model Comparison

$P_{\text{IN}}$ constant 193 $mW$ (~39$kLux$), $P_{\text{IN}}$ probabilistic mean 193 $mW$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$P_{\text{IN}} = 0$ (i.e., only battery)</th>
<th>$P_{\text{IN}}$ constant</th>
<th>$P_{\text{IN}}$ probabilistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>1.5 $h$</td>
<td>2.3 $h$</td>
<td>2.2 $h$</td>
</tr>
<tr>
<td>Duty-Cycle</td>
<td>3.9 $h$</td>
<td>151 $h$</td>
<td>127 $h$</td>
</tr>
</tbody>
</table>

- **Duty-Cycle** extends the lifetime of 2.6x
- **Energy Harvesting** extends the lifetime of 1.5x and 38.7x, respectively for Continuous and Duty-Cycle ($P_{\text{IN}}$ constant)
Conclusion

Nano-Blimp + Solar Harvesting + Duty-Cycling

- We have introduced duty-cycling in nano-UAVs to save energy
- Extended lifetime, up to 39x with harvesting and duty-cycling
- Self sustainability $P_{\text{IN}}$:
  - $\sim 200\, mW$ for Duty-Cycle mode
  - $\sim 600\, mW$ for Continuous mode

Extended Lifetime - Self Sustainability not yet indoor

Future Work:
- Dynamic Duty-Cycle based on on-board sensors
- 3D movements and on-board computation
Thank you for your attention.

Questions?
Backup: Helium Leakage & Rotor Configuration

- Constant helium leakage (~10g/month)
- Increased lifetime → we will need a backwards configuration (A)
- We avoid weight overhead with backwards configuration and **Heavier-than-air** configuration
Backup: Brushless DC Electric Motor (Efficiency vs. Input Current)

Intensity: 9%  Intensity: 100%

Motor efficiency example [4]

Backup: Weight Distribution

Optimistic: ☀️☀️☀️☀️

Average: ☀️☀️❑❑❑

Duty-Cycle Constant Input Power @ 39 kLux

Duty-Cycle Constant Input Power @ 19.5 kLux