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

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Horizon 2020 Programme

Introduction

- Current ***nano-size*** (i.e., Ø ~10*cm*, ~50*g*) UAVs require few Watts (~10*W*) 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

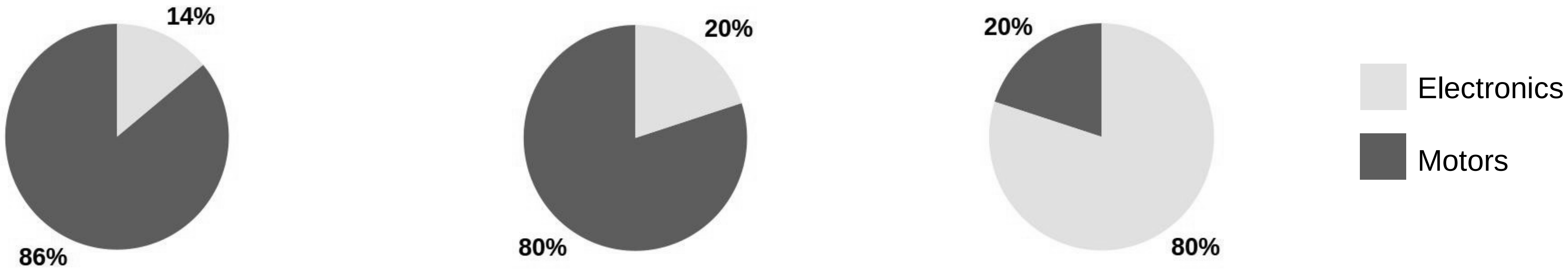
We focus on indoor scenarios

Nano-UAV Power Requirements

Rotorcraft [1]

Fixed Wing [2]

Blimp [3]



High energy requirements → short lifetime

Reduced energy requirements

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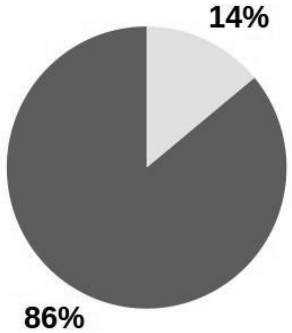
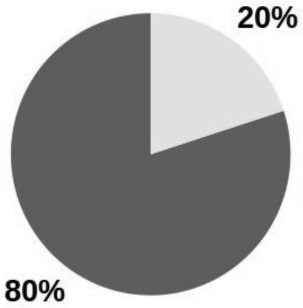
[1] Wood et al., “Progress on 'pico' air vehicles”, International Symposium on Robotics Research (invited paper), Aug. 2011.
[2] P. Oettershagen et al.t, “Long-Endurance Sensing and Mapping Using a Hand-Launchable Solar-Powered UAV,” Springer Tracts in Advanced Robotics Field and Service Robotics, 2016.
[3] Experimental testing

Nano-UAV Power Requirements

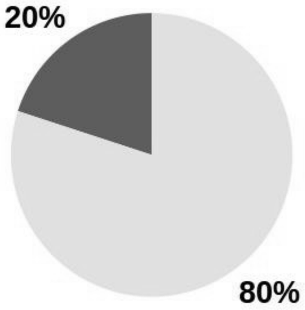
Rotorcraft [1]



Fixed Wing [2]



Blimp [3]



⬜ Electronics

⬛ Motors

Blimp is the best candidate

High energy requirements → short lifetime

Reduced energy requirements

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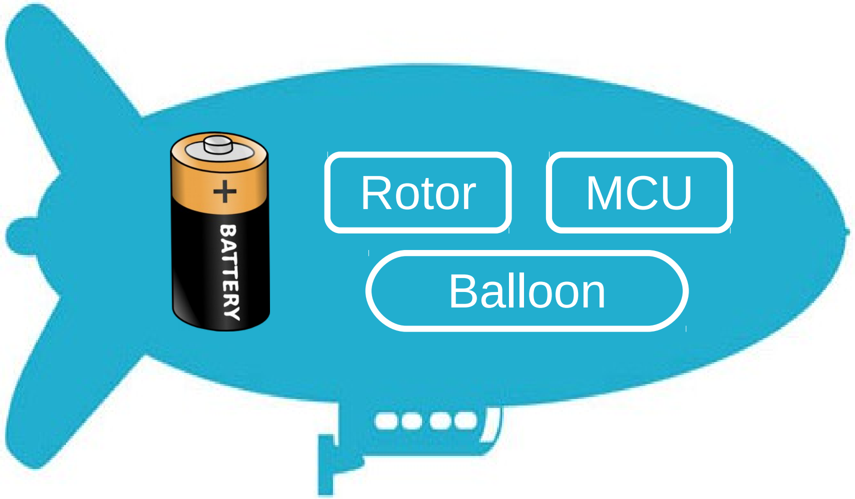
Self-sustainable UAV blimp

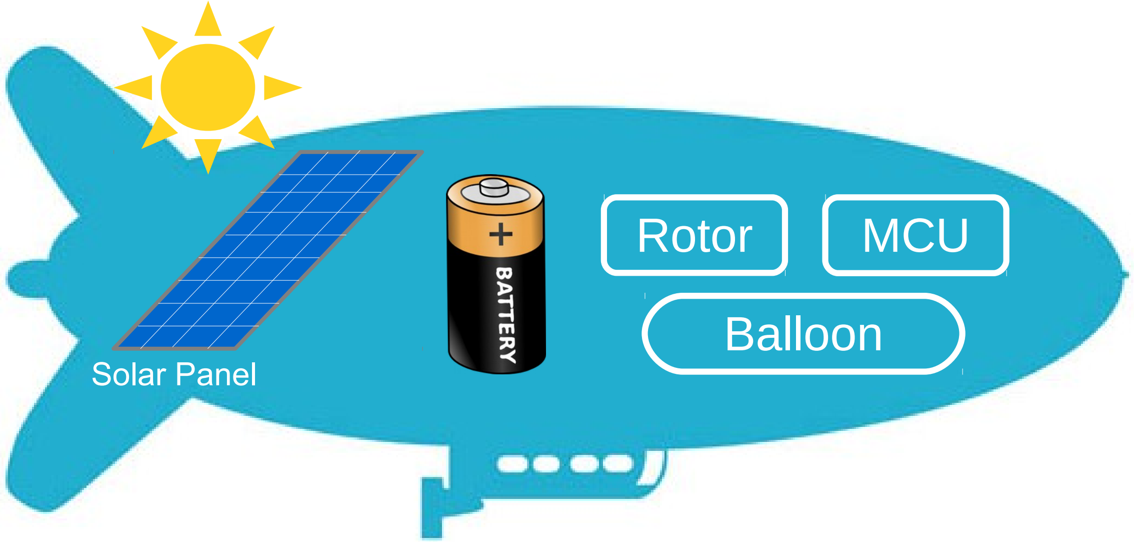
Can we increase runtime, possibly reach self-sustainability?

Nano UAV System



- Battery powered

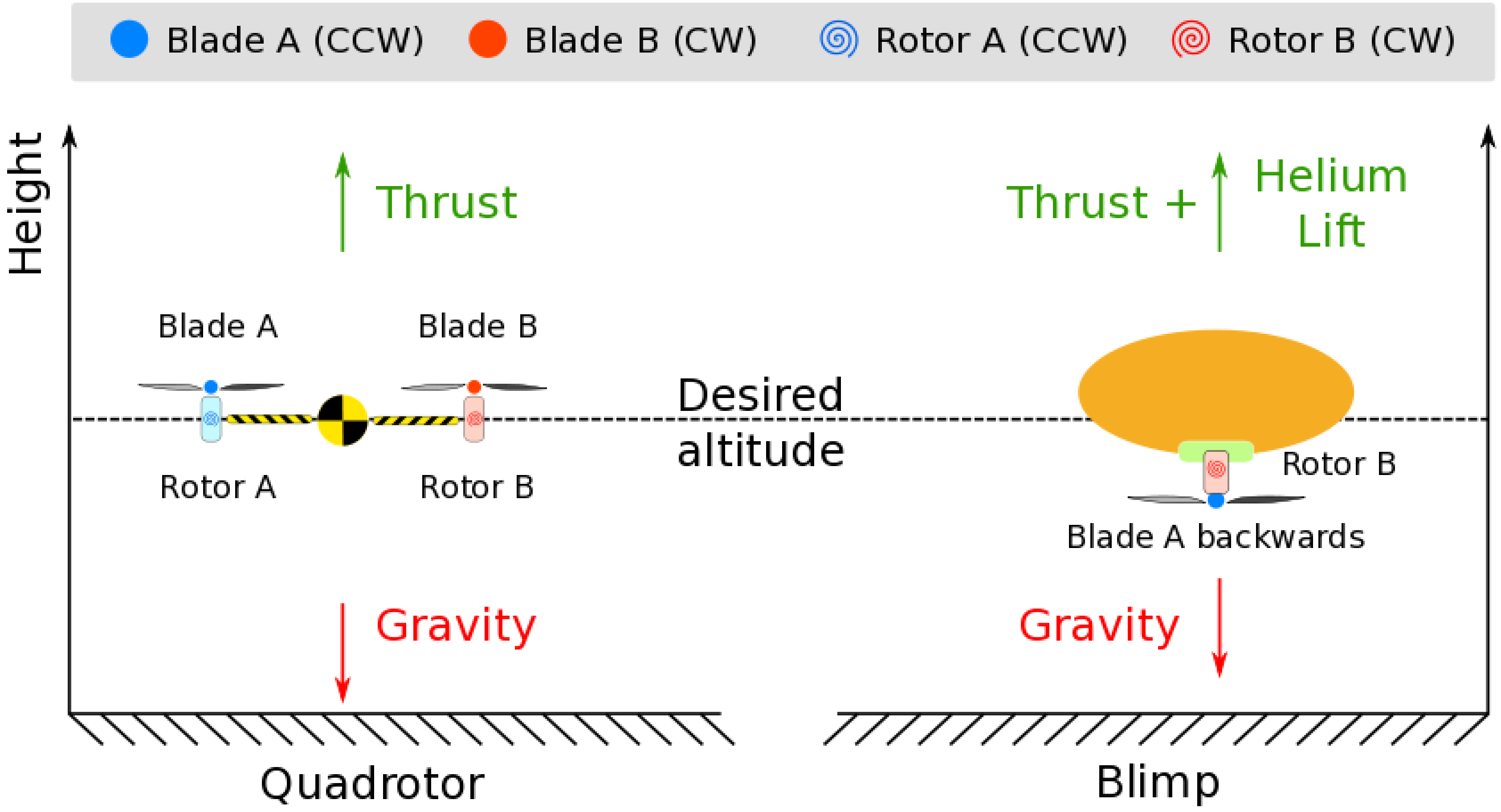
Proposed Nano UAV System



- Harvest power + battery

Target capability: Hovering

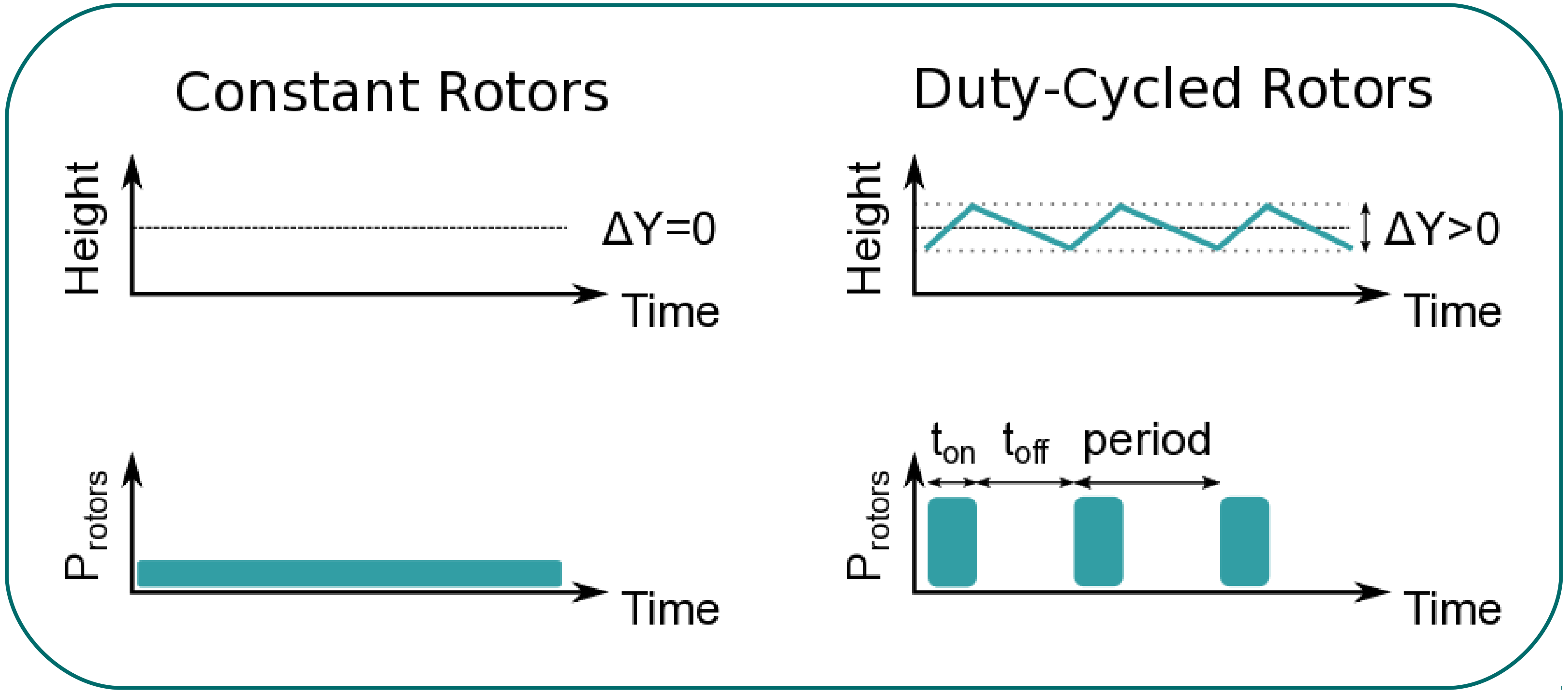
- Hovering: keep the desired altitude over time
- Hovering is a basic building block for complex autonomous navigation
- The required thrust can be dynamically adjusted (inertial, visual, ultra-sound, etc.). Not in this work
- Design choice: heavier-than-air



Maximize Lifetime: Duty-Cycling Rotors

Quadcopter

High energy due to small **ΔY**



Blimp

Low energy due to large **ΔY**

Nano-Blimp + Harvesting + Duty-Cycling

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

Outline

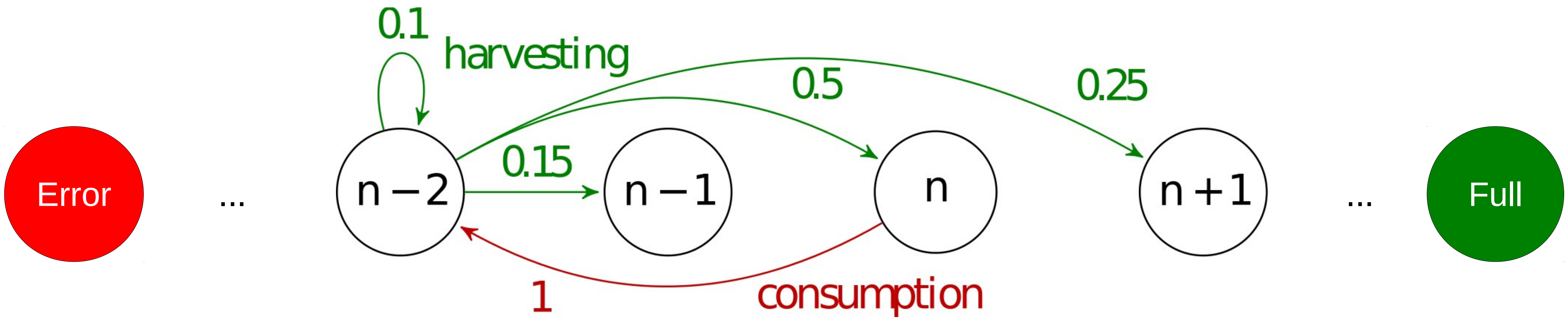
- **System Model**
  - Power requirements and lifetime
  - Weight distribution
- Blimp Prototype
  - Prototype
  - Hardware/Firmware Design
- Experimental Evaluation
  - Initial Characterization
  - Experimental Results
- Conclusion

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

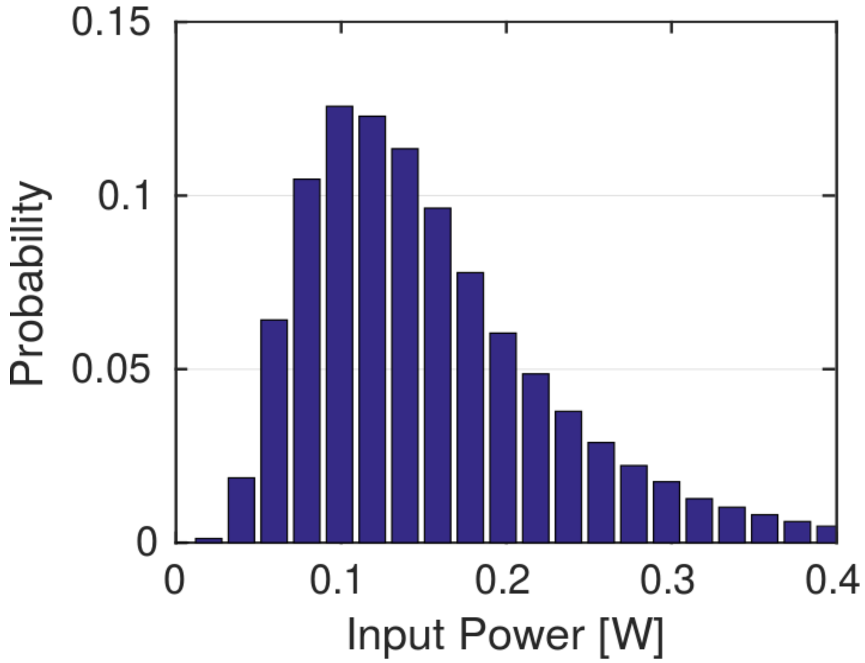
$$\left\{\begin{array}{cccc}0 & 1 & 2 & 3\\ 0.1 & 0.15 & 0.5 & 0.25\end{array}\right\}$$

$$\left\{\begin{array}{cccc}n-2 & n-1 & n & n+1\\ 0.1 & 0.15 & 0.5 & 0.25\end{array}\right\}$$



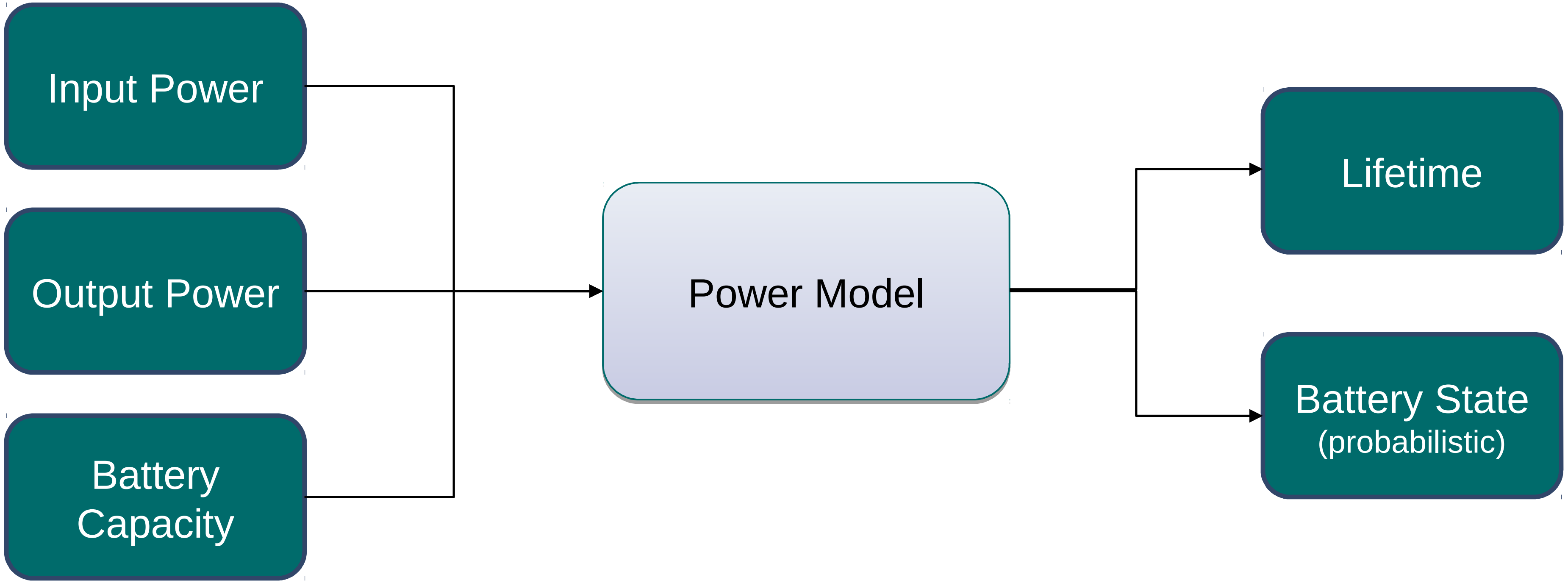
Charging/Discharging Probabilities

- *Discharging* rate is determistic
  - 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 leads to error state
  - $P_{IN} > 0$ (i.e., no night)



Log-normal distribution, mean 0.1*W* and σ = 0.5.

Power Model: Outcomes



Input Power

Output Power

Battery Capacity

Power Model

Lifetime

Battery State
(probabilistic)

- Predict lifetime for a given configuration
- Determine input power / battery capacity requirements for a desired lifetime

Battery/Panel Trade-Off: Weight Distribution

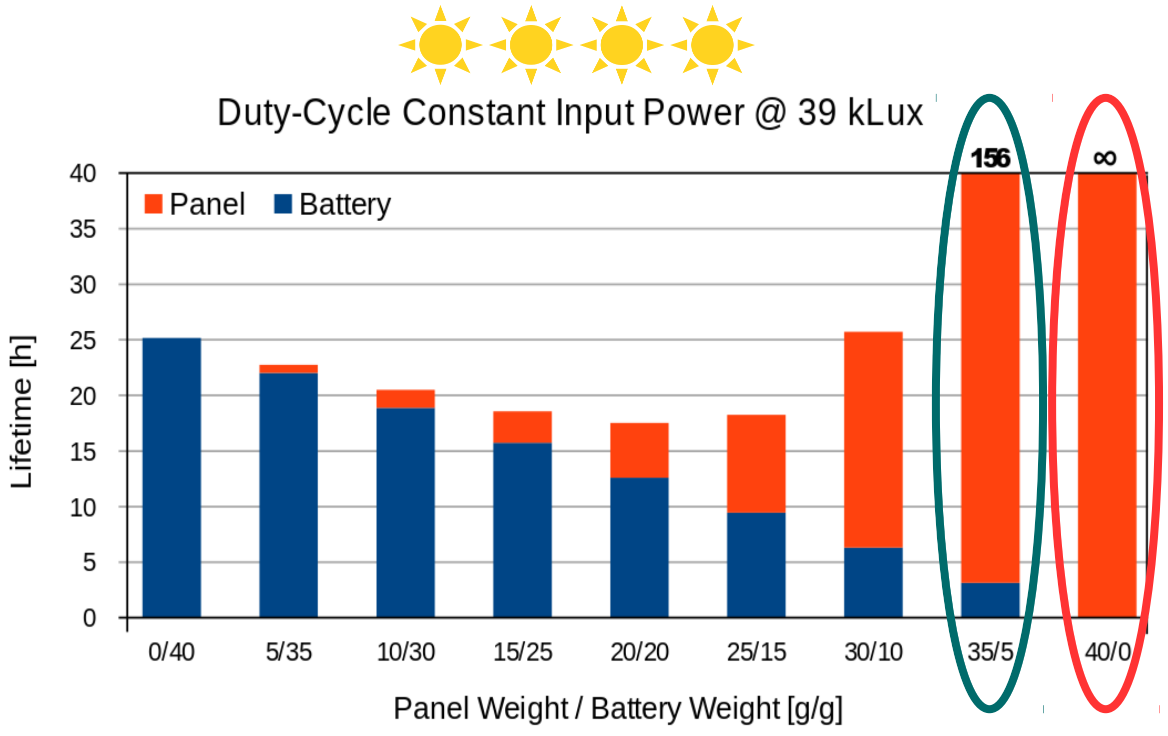
Limited payload → maximize lifetime solving the weight distribution problem

Parameters:

- Lifetime (τ)
- Illuminance (intensity, variance and duration)
- W_{MAX} 55 *g*, Payload 40 *g*

$$\tau \cdot P_{load} \le E_{in}\left(W_{panel}, Light\right) + E_{batt}\left(W_{batt}\right)$$

$$W_{tot} \le W_{max}$$



Not feasible

Our configuration

Battery/Panel Trade-Off: Weight Distribution

Limited payload → maximize lifetime solving the weight distribution problem

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- W_{MAX} 55 *g*, Payload 40 *g*

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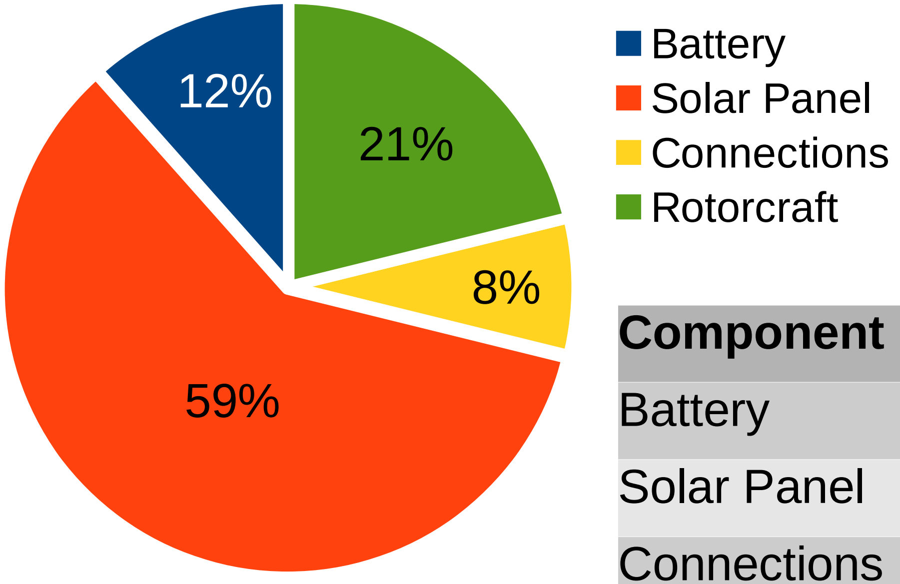

Component	Weight
Battery	6 *g*
Solar Panel	31 *g*
Connections	4 *g*
Rotorcraft	11 *g*

Outline

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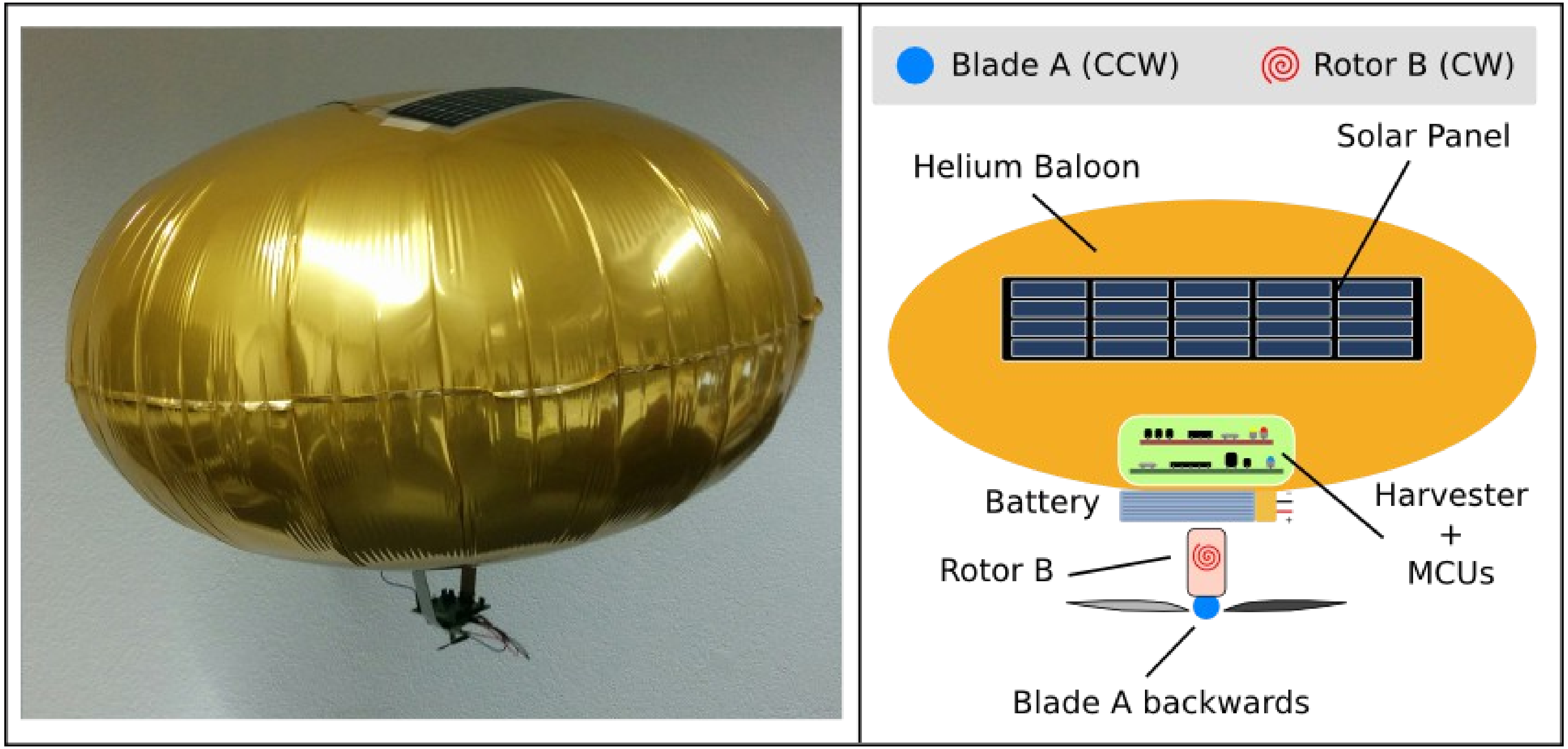
Prototype

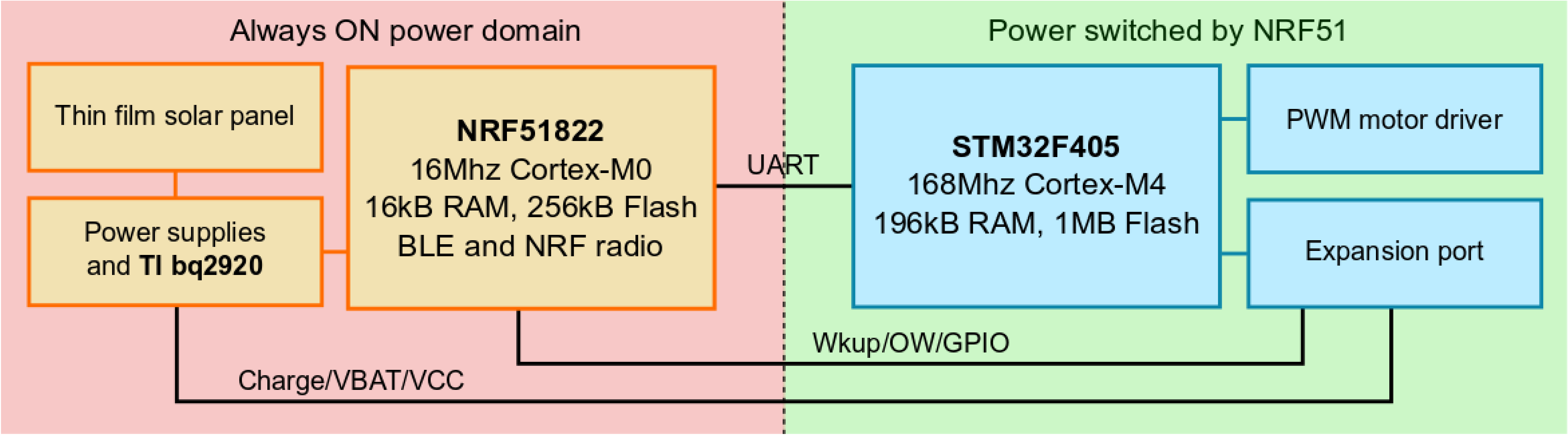


Configuration: only one rotor (hovering), solar panel 25x9 *cm*, balloon Ø 91 *cm*

Original CrazyFlie 2.0

Blimp's core frame

Electronics Architecture



Device	**Task**	**Power Consumption**
NRF51	Power distribution	20 *mW*
STM32	Motor speed control	180 *mW*

Introducing Duty-Cycling to Nano-Blimps

Dynamic Power Management

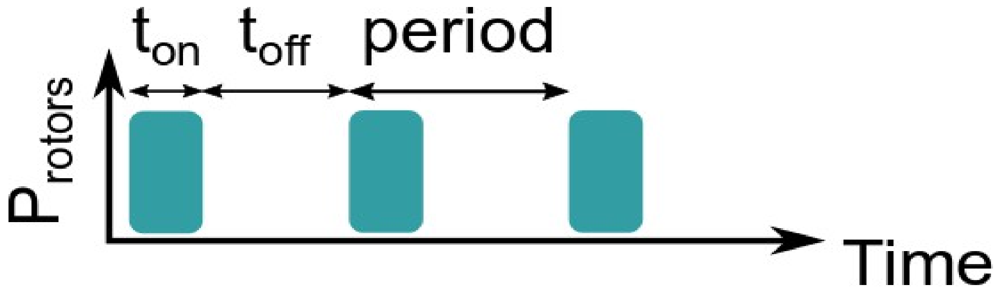
Duty-Cycle: T_{ON} , T_{OFF}

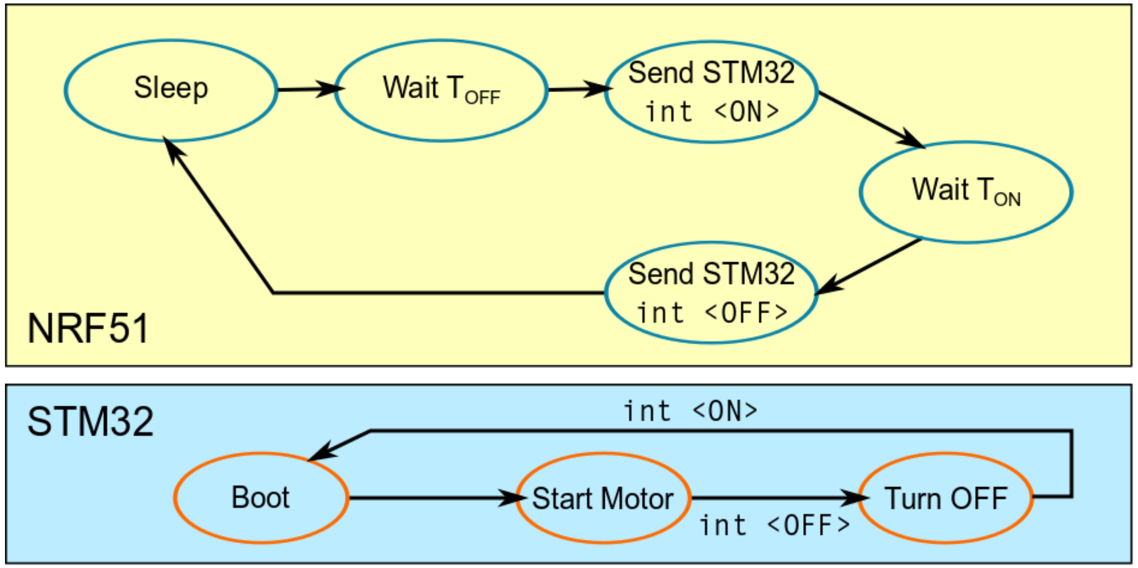
Power Consumption

- ON: ~ 4 *W*
- OFF: ~ 5 *μW*

Continuous Mode:

Disabled the timer interrupt in the NRF51




NRF51
Sleep
Wait T_{OFF}
Send STM32 `int <ON>`
Wait T_{ON}
Send STM32 `int <OFF>`

STM32
Boot
Start Motor
Turn OFF
`int <ON>`
`int <OFF>`

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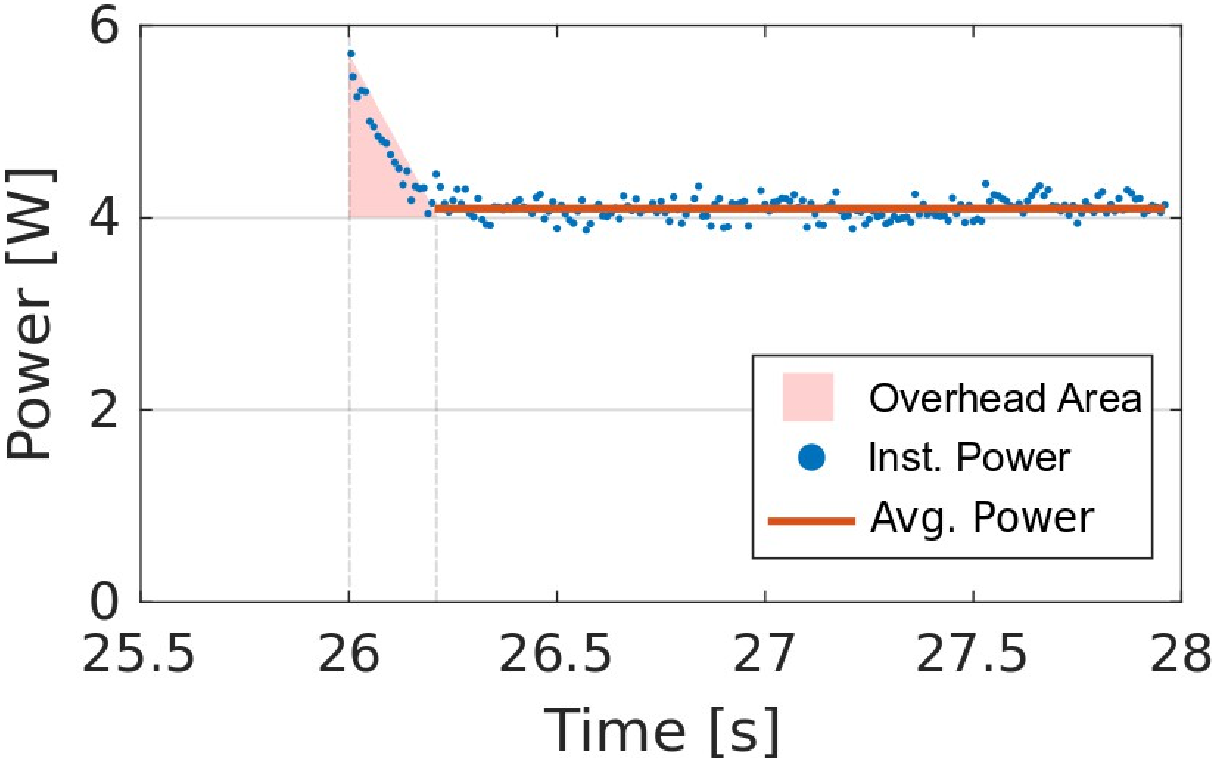
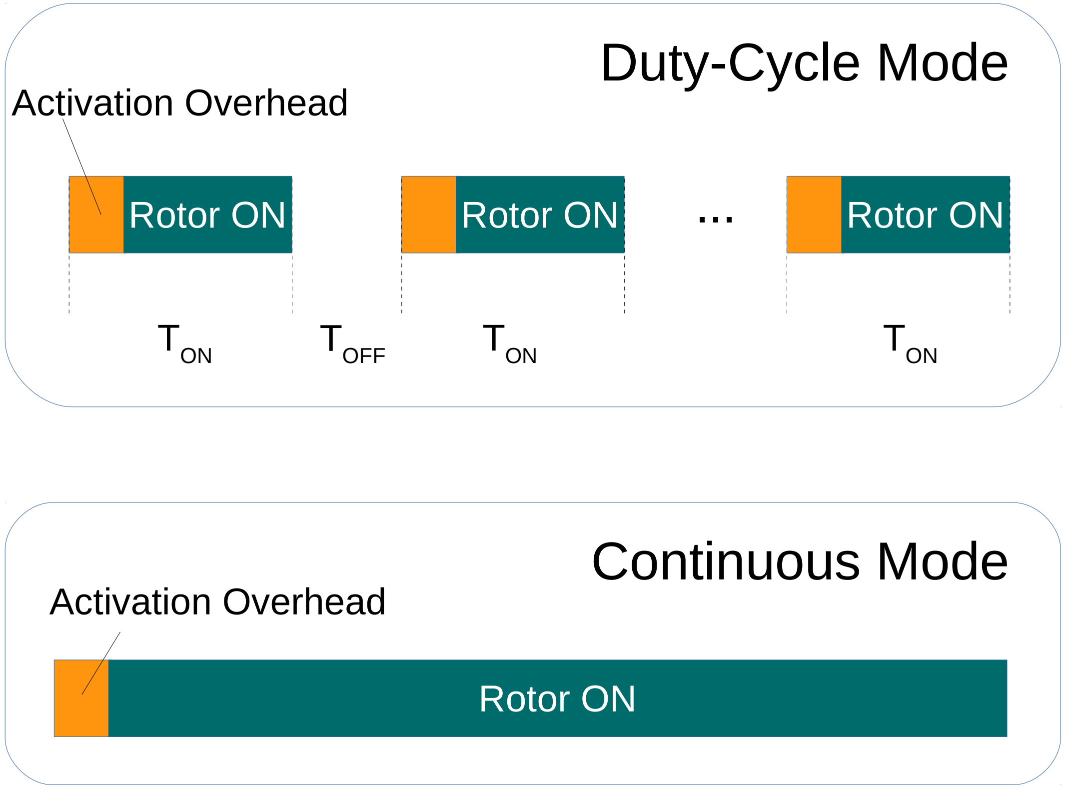
Rotor Activation Overhead

Single burst of 2 sec, 100% rotor intensity

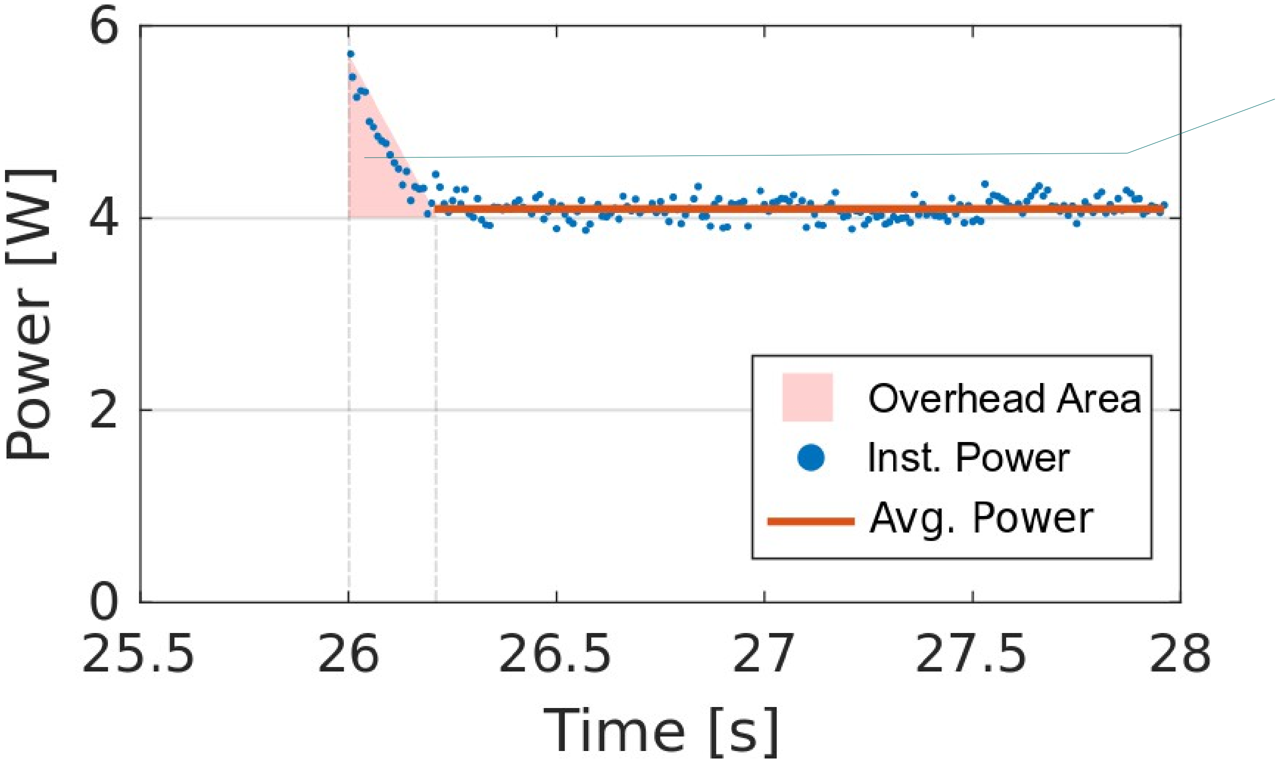


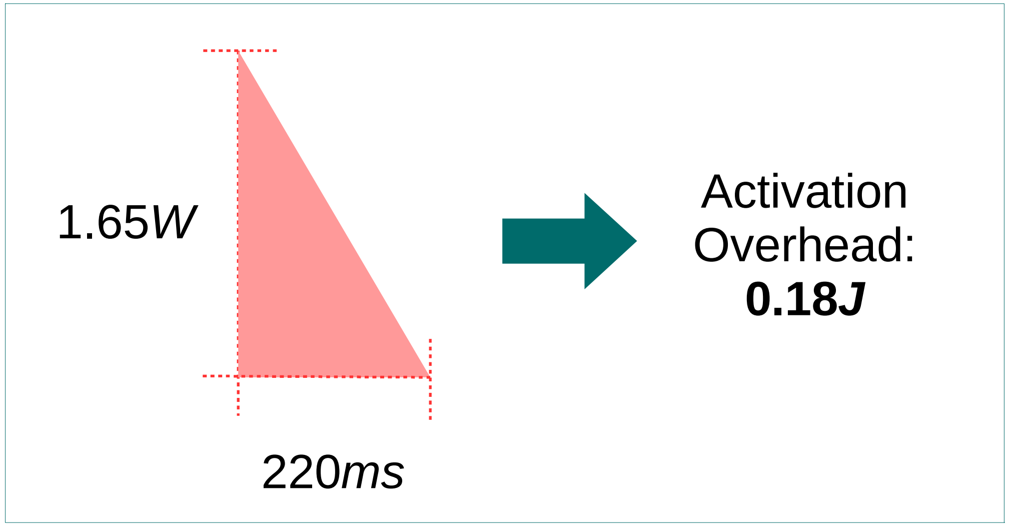


Peak at 5.75*W*, after 220*ms* steady 4.1*W* (Avg.)

Rotor Activation Overhead

Single burst of 2 sec, 100% rotor intensity





Activation Overhead:
0.18J

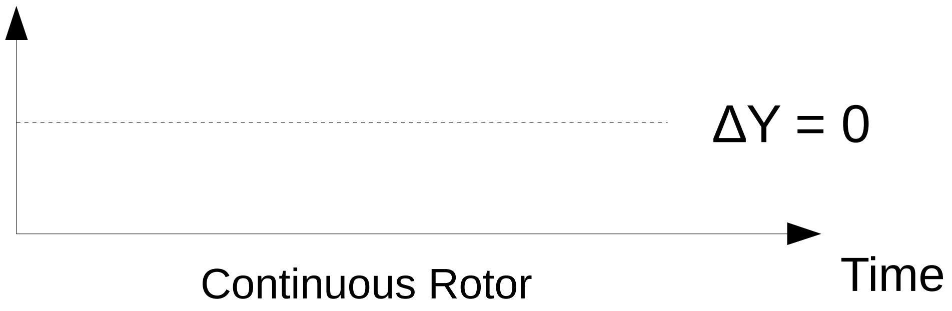
- Negligible for continuous mode
- Extra cost for each duty-cycle period

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

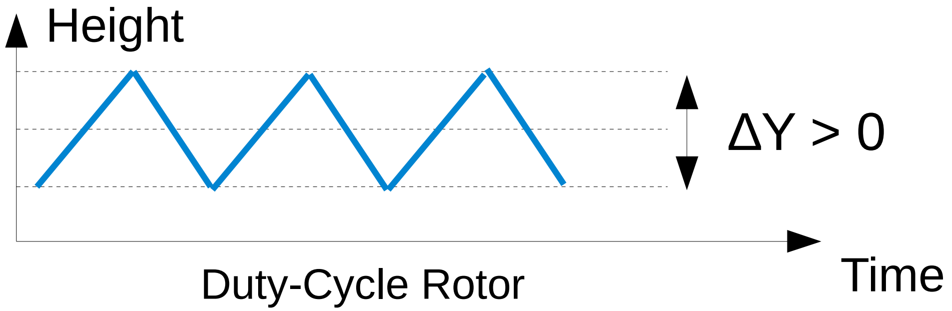
Duty-Cycle Characterization (T_{ON}, T_{OFF})

Max height deviation (ΔY): ±25 *cm*

With T_{ON} of 250 ms it rises to ~ 50 *cm*

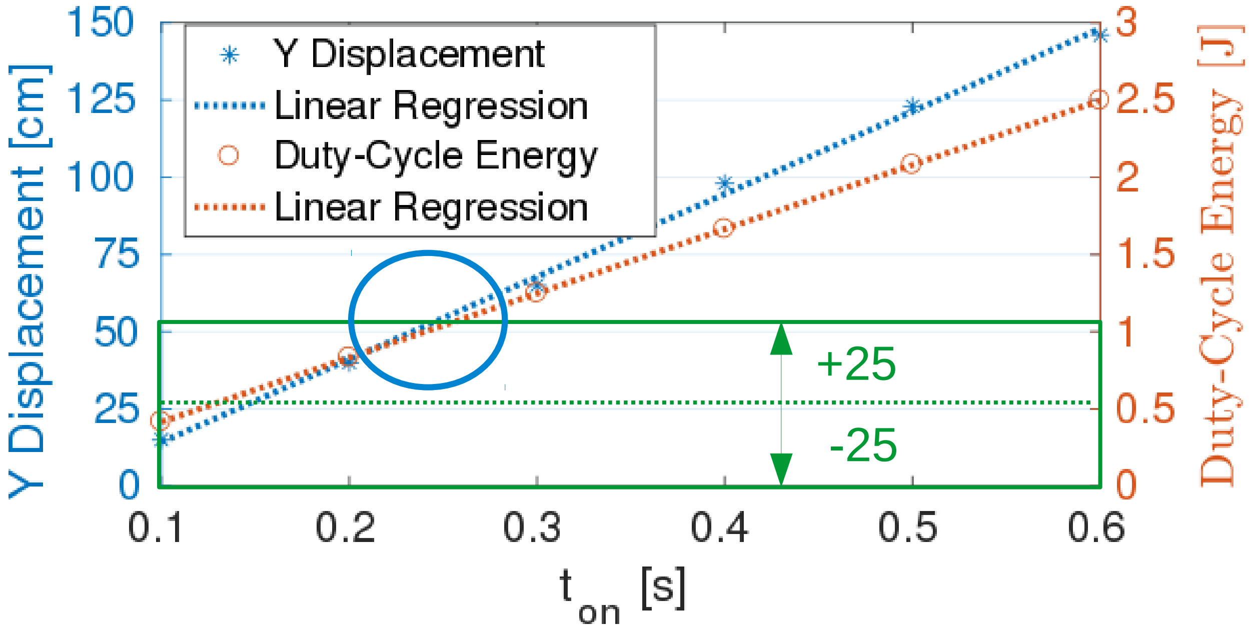


Continuous Rotor



Duty-Cycle Rotor

Duty-Cycle Selection



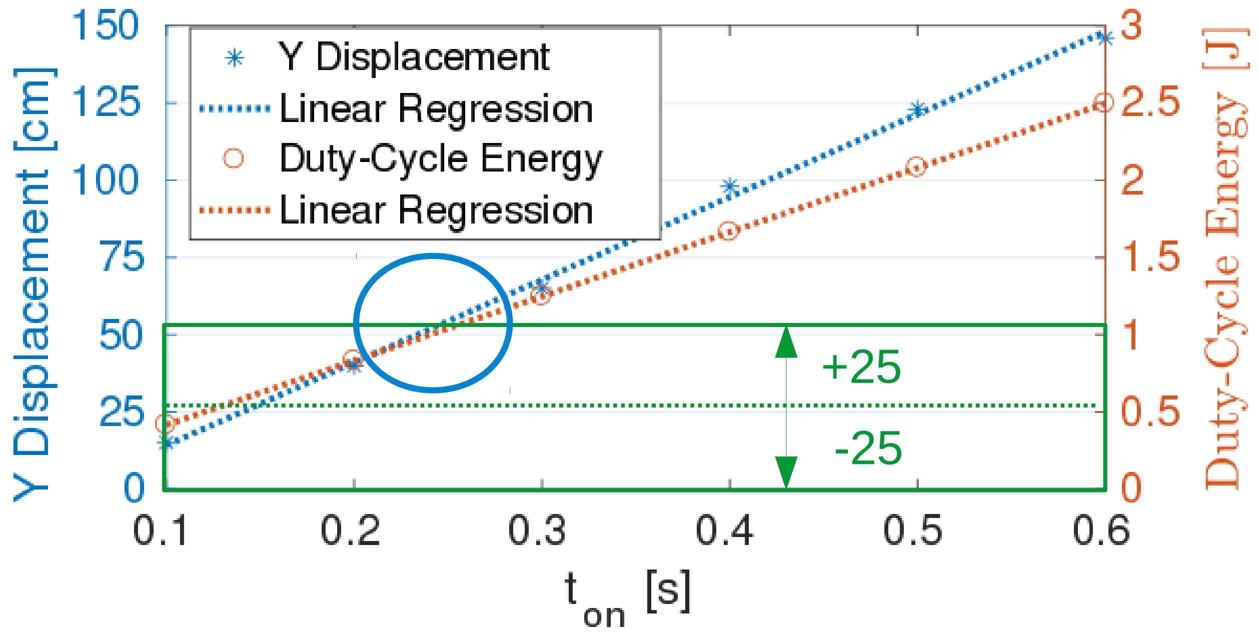
Duty-Cycle Characterization (T_{ON}, T_{OFF})

Max height deviation (ΔY): ±25 *cm*

With T_{ON} of 250 *ms* it rises to ~ 50 *cm*

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

Duty-Cycle Selection

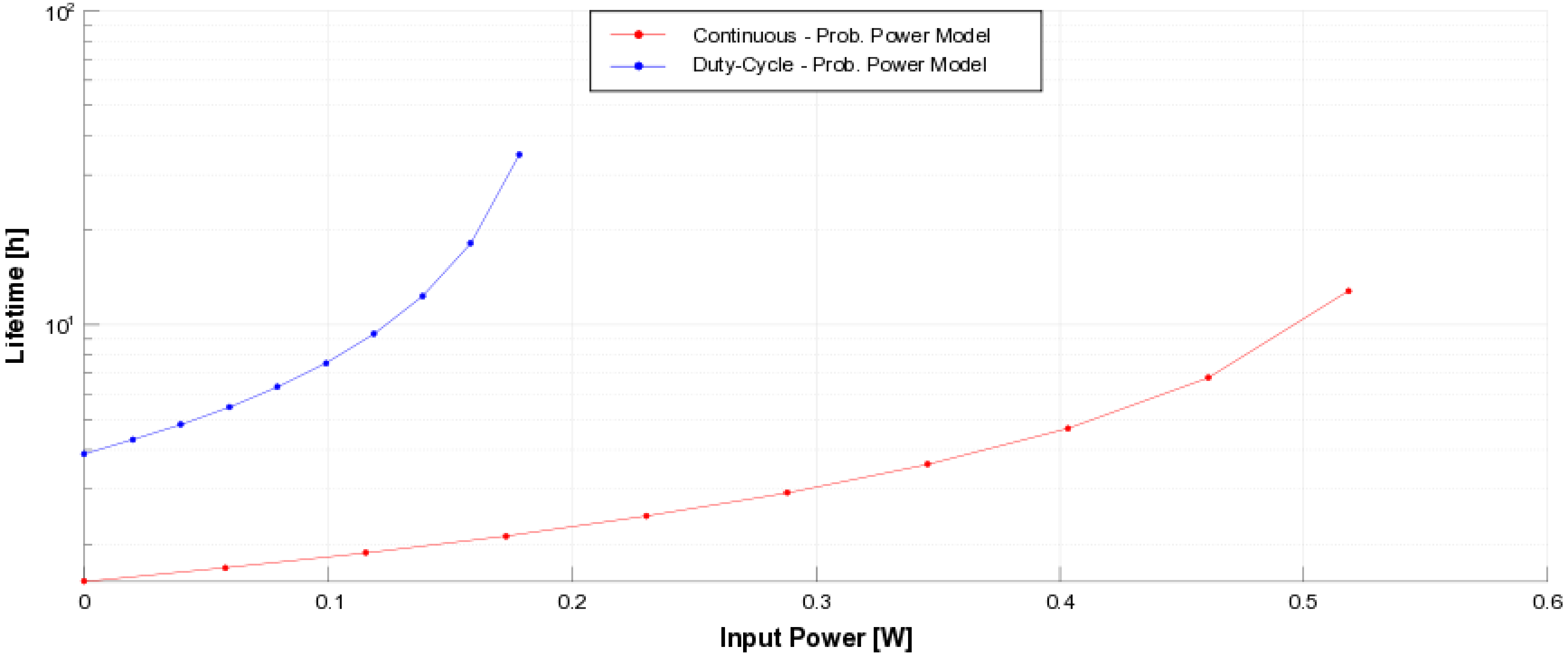


Mode	Rotor Intensity	T_{ON}	T_{OFF}	Power Consumption	Energy per Period
Continuous	9%	Always	Never	*0.576 W*	3.024 *J*
Duty-Cycle	100%	250 *ms*	5 *s*	0.198 *W*	1.04 *J*

Experimental Results

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

- Probabilistic Model

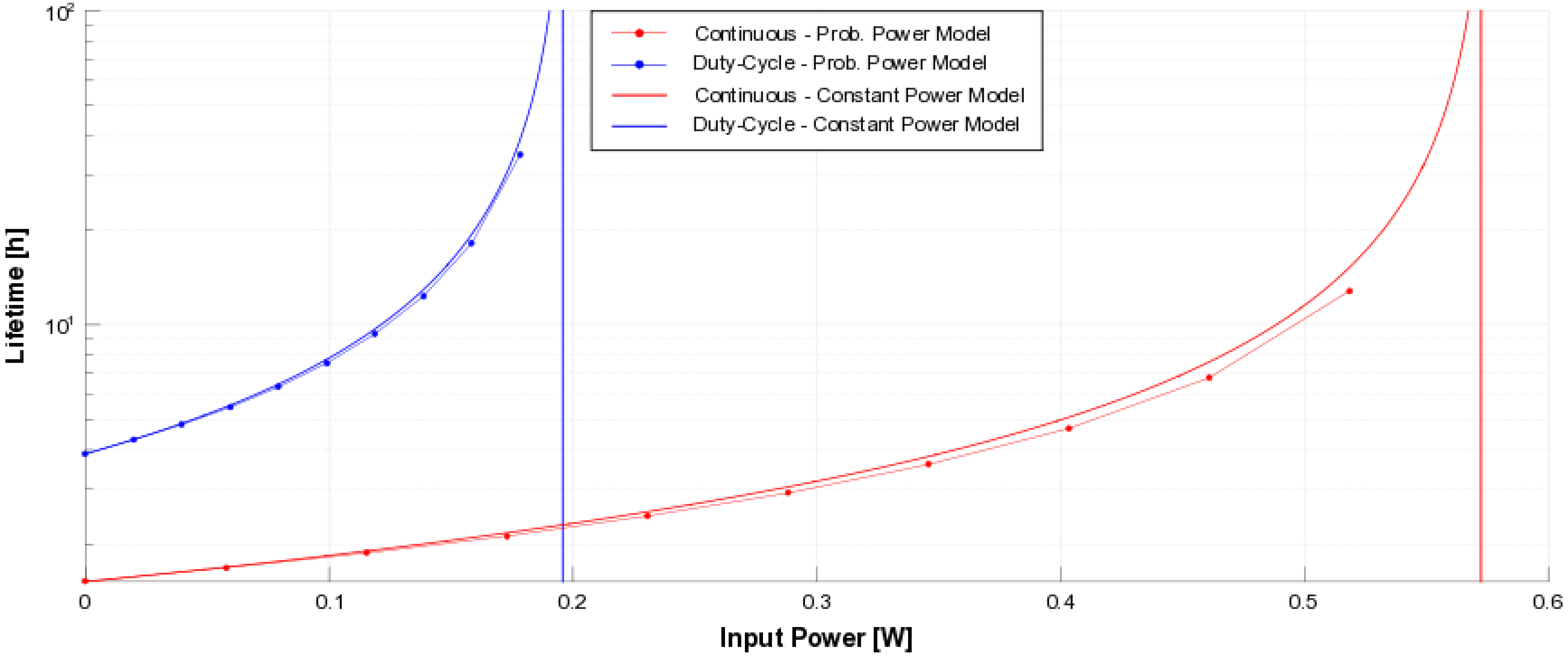


Experimental Results

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

- Probabilistic Model
- Constant Model

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



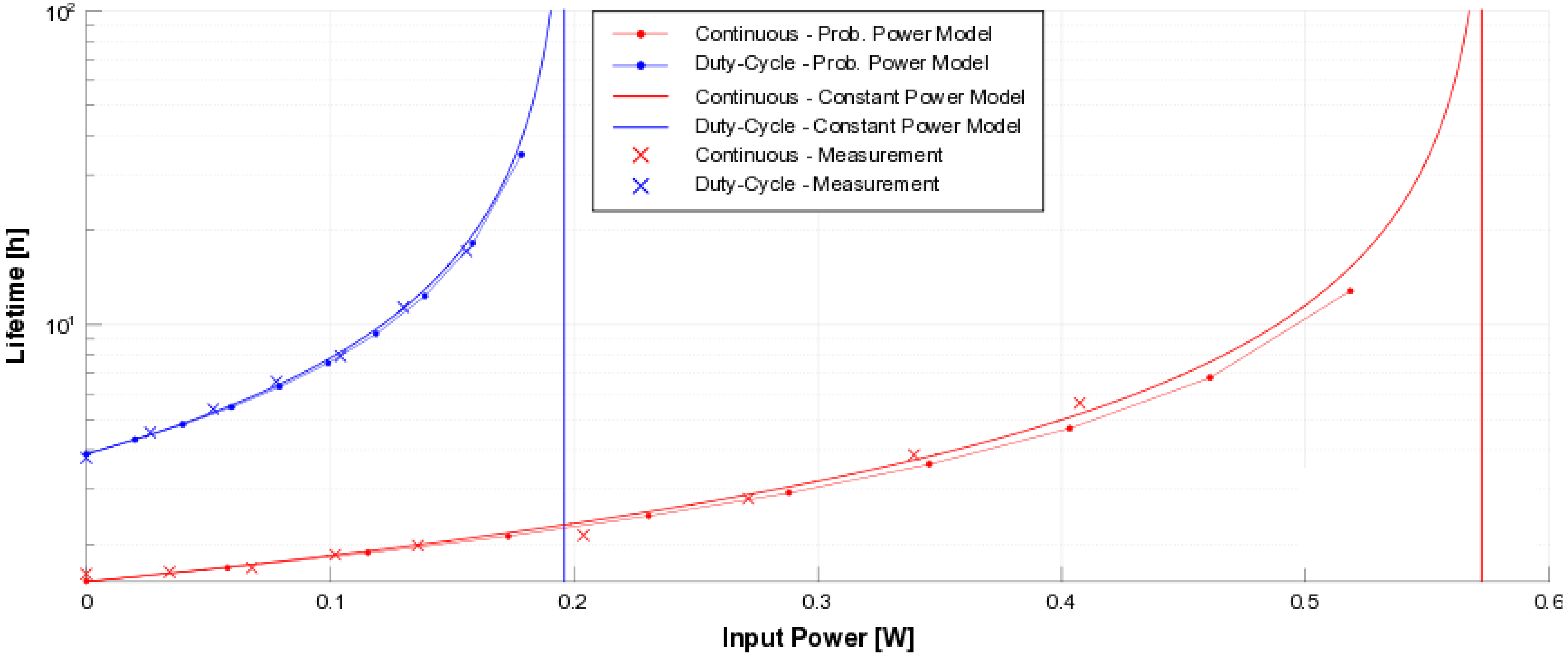
Experimental Results

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

- Probabilistic Model
- Constant Model
- Constant Measurements

Self-sustainable at:

- Continuous Mode
  ~600mW
- Duty-Cycle Mode
  ~200mW



Model Comparison

P_{IN} constant 193 *mW* (~39*kLux* ☀☀☀☀), P_{IN} probabilistic mean 193 *mW*

Mode	**P_{IN} = 0 (i.e., only battery)**	**P_{IN} constant**	**P_{IN} probabilistic**
Continuous	1.5 *h*	2.3 *h*	2.2 *h*
Duty-Cycle	3.9 *h*	151 *h*	127 *h*

Lifetime

- 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_{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_{IN} :
  - ~200*mW* for Duty-Cycle mode
  - ~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

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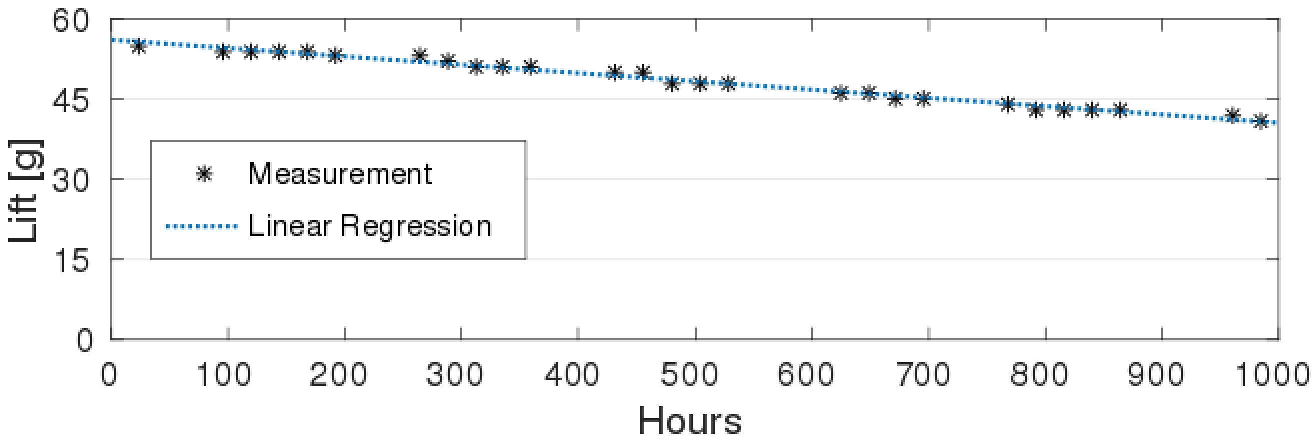
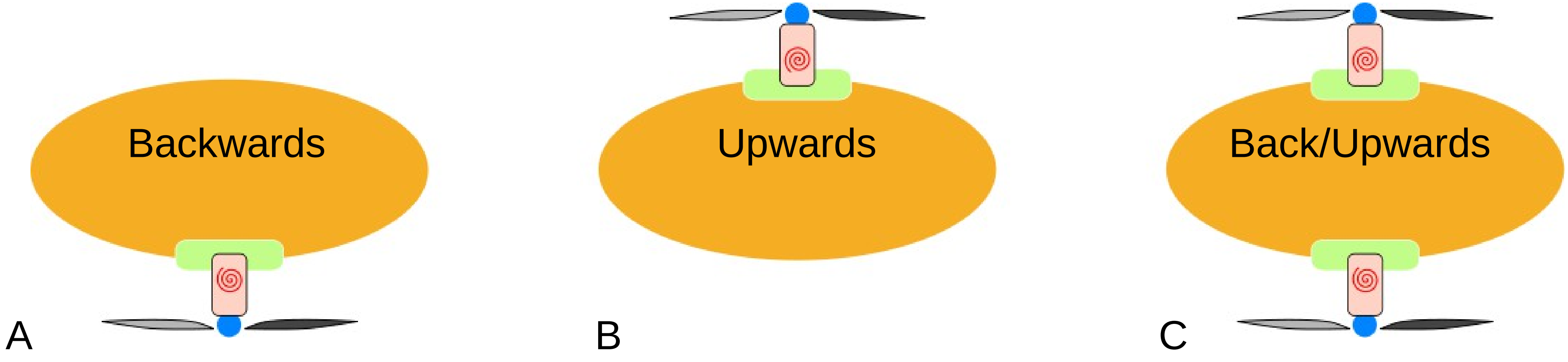
Thank you for your attention.

Questions?

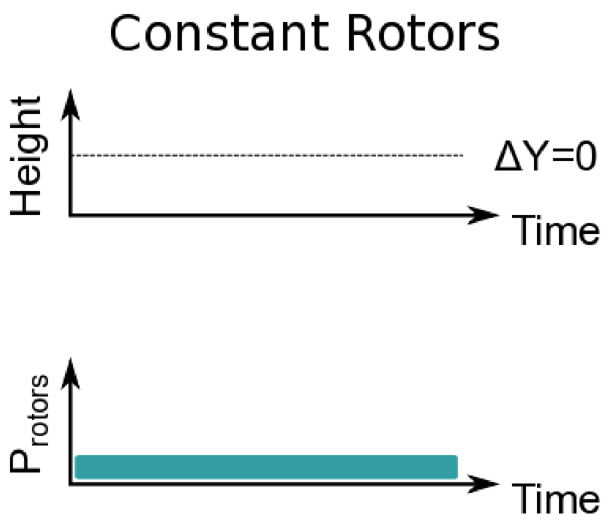
Backup: Helium Leakage & Rotor Configuration

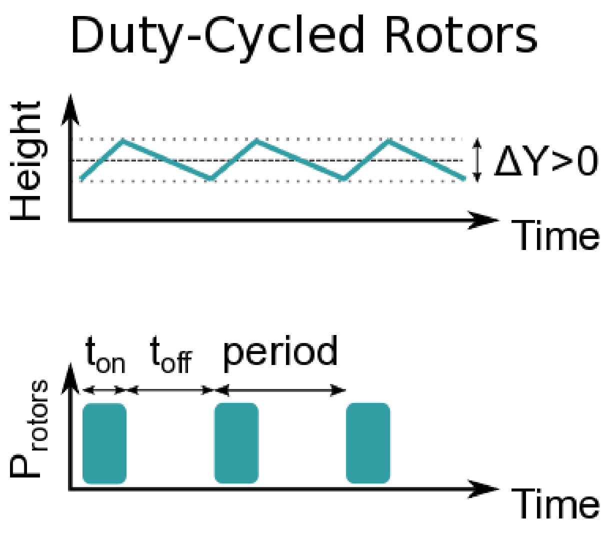


- Constant helium leakage (~10g/month)
- Increased lifetime → we will need a backwards configuration (A)
- We avoid weight overhead with backwards configuration and **Heavier-than-air** configuration



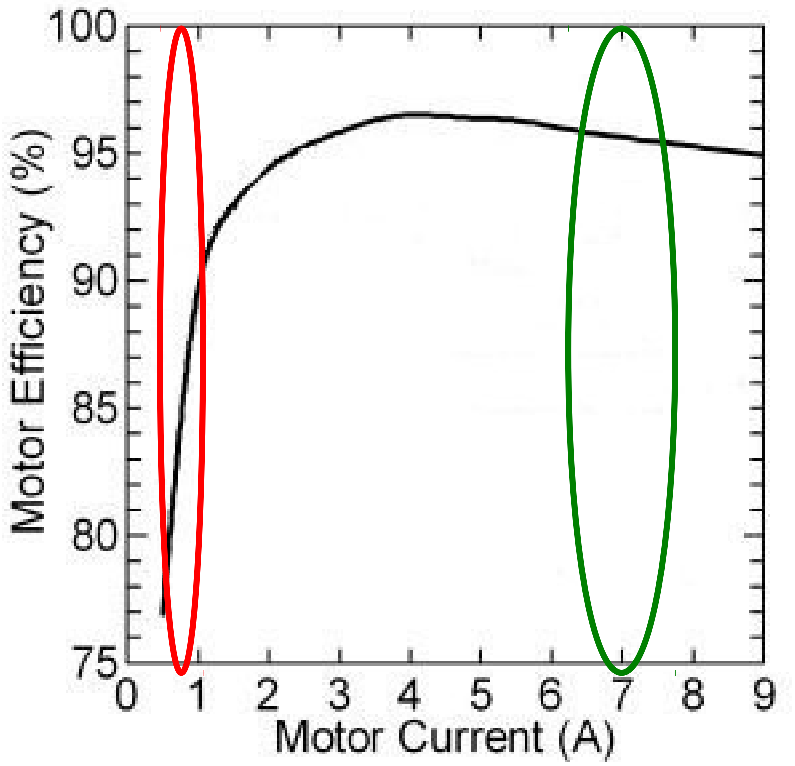
Backup: Brushless DC Electric Motor (Efficiency vs. Input Current)





Intensity: 9%

Intensity: 100%



Motor efficiency example [4]

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[4] „Breakthrough 96% Electric Motor Efficiency“, H. Kimura et al., Department of Electrical and Electronic Engineering, School of Engineering at Tokai University. 2009

Backup: Weight Distribution

Optimistic: ☀ ☀ ☀ ☀

Average: ☀ ☀ ☼ ☼