An Optimal Energy Absorption and Utilization Design for Deformable/Reconfigurable Modular Solar-Powered UAVs in Near Space

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Outline

INTRODUCTION

- Global issues like climate change and energy shortage demand sustainable aviation solutions.
- Solar-powered UAVs (SP-UAVs) can achieve long-endurance, low-cost, and flexible flight operations.
- Conventional fossil-fuel and battery-powered aircraft are limited in endurance.
- Challenges exist in solar energy absorption and energy storage efficiency.
- Deformable and reconfigurable modular UAVs enhance solar utilization and mission performance.

MOTIVATION

- Growing demand for clean and sustainable aviation solutions.
- Need for long-endurance platforms for surveillance, communication, and disaster management.
- Limitations of conventional fossil-fuel and battery-powered aircraft.
- Potential of solar-powered UAVs to provide near-permanent flight.
- Opportunity to enhance performance using deformable and reconfigurable modular designs.

OBJECTIVES

- Design an efficient solar-powered UAV platform.
- Maximize solar energy absorption and utilization.
- Reduce structural weight while maintaining payload.
- Improve endurance and mission adaptability.
- Develop an optimization framework for sustainable flight.

LITERATURE SURVEY

Reference	Focus Area	Key Findings / Contributions
Youngblood et al. (1984)	Early solar aircraft design	Proposed design methodology integrating solar and fuel cell propulsion for long endurance.
Noth (2008)	Analytical design frameworks	Developed subsystem models and analytical tools for continuous solar-powered flight.
Aurora Flight Sciences (2007)	Morphing (Odysseus concept)	Introduced Z-shaped wing configuration to maximize solar absorption.
Wu et al. (2017–2019)	Sun-tracking / morphing UAVs	Investigated Z-shaped, N-shaped, and 3-shaped wings for improved energy capture and endurance.
Montalvo & Castello (2015), Magill (2002)	Reconfigurable / meta-aircraft	Explored wingtip connection and docking concepts, showing 20–40% aerodynamic performance improvement.
Wang et al. (2020, 2022)	Mission-oriented path planning	Proposed 3D path optimization with ant colony and cooperative energy optimization for modular UAVs.
Gao et al. (2014), Li et al. (2020)	Battery and propulsion optimization	Highlighted importance of gravity energy storage, propulsion-focused design, and battery mass minimization.

RELATED WORK

Solar-Powered UAV Development

- **Youngblood et al. (1984)**: Pioneered solar aircraft design methodology integrating solar and fuel cell propulsion
- **Noth (2008)**: Developed analytical frameworks and subsystem models for continuous solar-powered flight
- **Aurora Flight Sciences (2007)**: Introduced Odysseus concept with Z-shaped wing for maximum solar absorption
- **Wu et al. (2017-2019)**: Investigated Z-shaped, N-shaped, and Λ-shaped wings for improved energy capture
- **Montalvo & Costello (2015)**: Proposed meta-aircraft concept with wingtip connection
- **Magill (2002)**: Showed 20-40% aerodynamic improvement through wingtip docking
- **Wang et al. (2020, 2022)**: Developed mission-oriented 3D path planning with energy optimization

Mass Prediction Model

$$m_{total} = m_{struc} + m_{batt} + m_{sc} + m_{mppt} + m_{prop} + m_{fixed}$$

Aerodynamic Model

$$C_D = C_{D0} + C_{Dp} + \frac{C_L^2}{\pi eAR}$$

Energy Balance

$$\int_{24h} P_{absorb}\, dt \geq \int_{24h} P_{consume}\, dt$$

Solar Radiation Model

$$P_{sc} = \sum_{i}^{n} (\eta_{sc} S I_h \cos(\mathrm{n_s}, \mathrm{n_{sc}}) S)_i$$

DEFORMABLE/RECONFIGURABLE CONCEPT

Innovative Platform Design

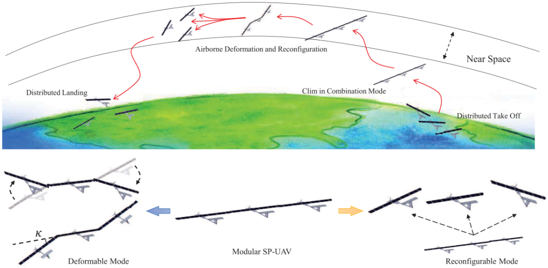

Figure 1: Concept for a deformable/reconfigurable SP-UAV

- **Deformable SP-UAV:** Wings adjust dihedral angle for optimal solar absorption
- **Reconfigurable SP-UAV:** Multiple aircraft connect/disconnect for mission flexibility

Key Features:

- Outer wings deform upward/downward
- Dihedral angle range: $\kappa \in [-30^\circ, 30^\circ]$
- Adaptive control: $\kappa = \min(\kappa_{max}, 90^\circ - \alpha)$
- Real-time optimization based on solar position

Operational Strategy:

- **Day:** Adjust wings to maximize solar absorption
- **Night:** Maintain flat configuration for aerodynamics

DEFORMABLE SP-UAV

Performance Benefits

Advantages:

- Increased solar energy capture during daylight
- Improved aerodynamic efficiency at night
- Extended mission endurance
- Adaptive to varying solar conditions
- Optimal energy management

Key Improvement

17.2% mass reduction compared to conventional design

Configuration Modes:

- **Combined Mode:**
  - Single entity operation
  - Energy conservation during night
  - Reduced power consumption
- **Separated Mode:**
  - Independent operation
  - Multiple simultaneous missions
  - Increased coverage area

Separation Constraints:

- Real-time: $P_{consume}(t) \leq P_{absorb}(t)$
- Daily: $\int_{24h} P_{consume} dt \leq \int_{24h} P_{absorb} dt$
- Mission requirements and conditions

System Benefits:

- 97% increase in feasible mission days
- Enhanced mission adaptability
- Improved operational flexibility
- Better resource utilization

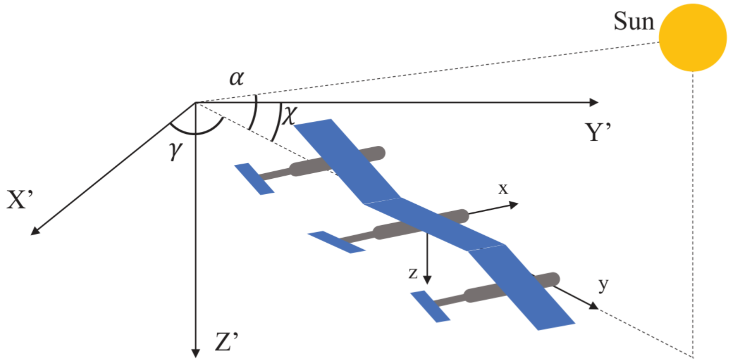

Figure 2: Flight profile of reconfigurable SP-UAV showing separation and combination points

FLIGHT STRATEGY

Energy Balance Constraints

Key Constraints:

$$\begin{cases} P_{consume}(t_1) \leq P_{absorb}(t_1) \\ \int_{24h} P_{consume}\, dt \leq \int_{24h} P_{absorb}\, dt \end{cases}$$

Constraint Explanation:

- **Real-time constraint:** Instantaneous power consumption must not exceed absorption
- **Daily constraint:** Total daily energy consumption must not exceed total absorption
- Ensures continuous operation without energy depletion
- Guides separation/combination timing decisions

Application:

- Determines when to separate into individual units
- Controls when to combine for energy conservation

OPTIMIZATION FRAMEWORK

Overall Optimization Process

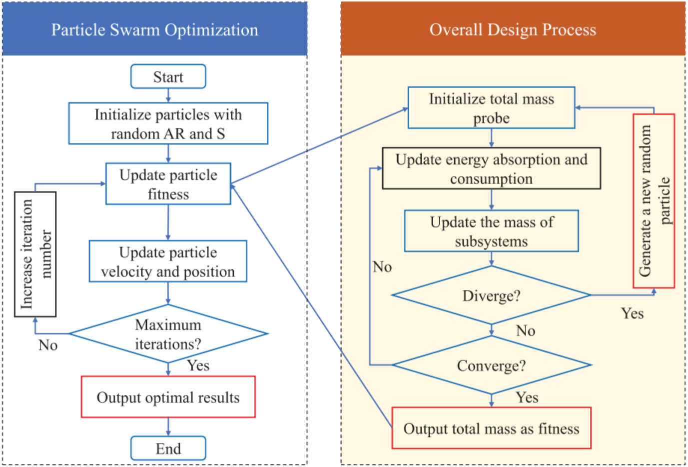

Figure 3: Particle Swarm Optimization Framework

Objective Function:

$$\min : m_{total} \quad \text{subject to:} \quad b_{min} < b < b_{max}, \quad S_{min} < S < S_{max}$$

PSO Update Equations:

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 (P_i^k - X_i^k) + c_2 r_2 (P_g^k - X_i^k)$$
$$X_i^{k+1} = X_i^k + V_i^{k+1}$$

Algorithm Parameters:

- ω: Inertia weight (controls momentum)
- c_1, c_2: Cognitive and social acceleration coefficients
- r_1, r_2: Random numbers uniformly distributed in [0,1]
- P_i^k: Personal best position of particle i
- P_g^k: Global best position in the swarm

OPTIMIZATION FRAMEWORK

Design Variables and Optimization Process

Design Variables:

- Reference area (S_{ref}) - Wing surface area
- Aspect ratio (AR) - Ratio of wingspan to chord length
- Optimized for minimum total weight while maintaining performance

Optimization Process Features:

- Population-based stochastic optimization
- Particles represent potential design solutions
- Fitness evaluation based on mass minimization
- Constraint handling for energy balance
- Convergence to global optimum through swarm intelligence

Key Advantages:

- Handles non-linear design spaces effectively
- Robust convergence characteristics
- Suitable for multi-variable optimization problems

OVERALL DESIGN PROCESS

Iterative Mass and Energy Balance

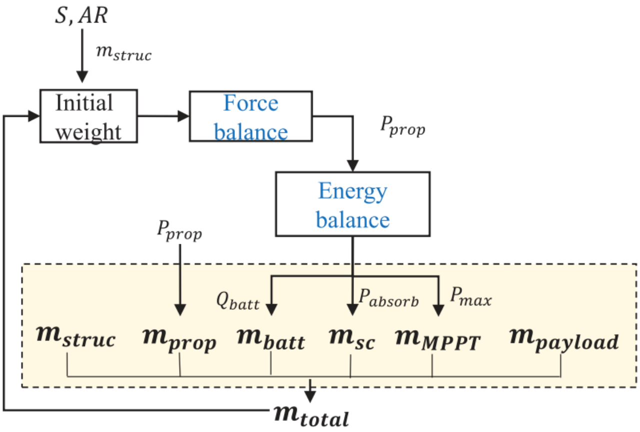

Figure 4: Overall parameter selection and optimization flow

Parameter	Planar	Deformable	Change
Total mass (kg)	1224.2	1013.8	-17.2%
Reference area (m^2)	285.2	219.1	-23.2%
Aspect ratio	29.6	29.6	-

Table 1: Optimal design results comparison

Key Improvements:

- 17.2% reduction in total mass
- 23.2% reduction in reference area
- Same aspect ratio maintained
- Payload remains constant at 50 kg

ENERGY PERFORMANCE

Solar Absorption and Battery Management

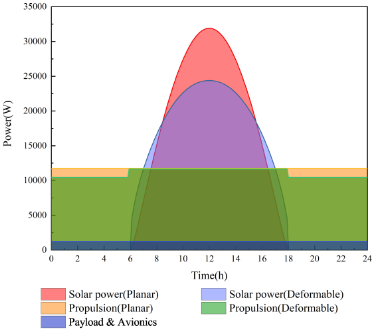

Figure 5: Power absorption and consumption

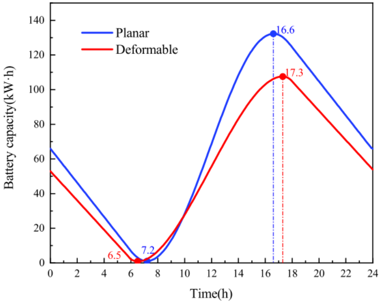

Figure 6: Battery state of charge

Key Improvements:

- Extended equivalent daytime period
- Reduced battery discharge duration (14.6h $\rightarrow$ 13.2h)
- Faster battery recharge during daylight
- Improved energy utilization efficiency
- Enhanced power management system

Impact on Mission Performance:

- Longer operational endurance
- Increased mission reliability
- Better adaptation to varying solar conditions
- Optimized energy storage utilization

MISSION PERFORMANCE

Feasible Operation Analysis

Configuration	Left Boundary	Right Boundary	Days
Deformable	April 11th	September 1st	142
Planar	May 15th	July 25th	72

Table 2: Feasible mission duration comparison

Performance Gains:

- 97% increase in feasible mission days (72 $\rightarrow$ 142 days)
- Wider operational latitude and date range
- Enhanced mission adaptability

Case Study: Urumqi to Haikou (3408 km) mission feasibility

PARAMETER SENSITIVITY

System Parameter Effects

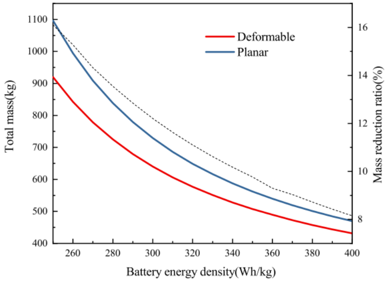

Figure 7: Effect of battery energy density

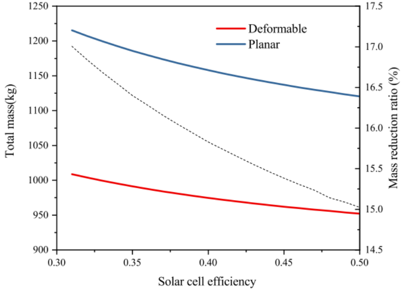

Figure 8: Effect of solar cell efficiency

Key Findings:

- Battery density: 240-400 Wh/kg reduces mass by ~50%
- Solar efficiency: 0.3-0.5 provides moderate mass reduction
- Optimal aspect ratio around 30 for both configurations
- Battery technology has highest impact on system mass
- Solar cell efficiency shows diminishing returns above 0.4

Design Implications:

- Focus on battery technology advancement for maximum benefit
- Target solar efficiency in the 0.35-0.45 range for cost-effectiveness
- Maintain aspect ratio near 30 for optimal performance
- Balance trade-offs between different subsystem improvements

CONCLUSION

Key Contributions and Findings

Main Achievements:

- Developed innovative deformable/reconfigurable SP-UAV platform
- Proposed integrated design methodology with PSO optimization
- Achieved 17.2% mass reduction compared to conventional design
- Extended feasible mission duration from 72 to 142 days (97% increase)
- Enhanced energy utilization through adaptive wing morphing

Technical Innovations:

- Joint optimization of energy absorption and mission utility
- Comprehensive modeling of mass, aerodynamics, and energy systems
- Adaptive flight strategies for different solar conditions
- Modular architecture enabling multiple mission profiles

FUTURE WORK

Potential Extensions and Improvements

- Investigate asymmetrical wing parts or subunits
- Explore multiple flight profiles and mission scenarios
- Develop advanced control strategies for morphing aircraft
- Integrate weather prediction for adaptive mission planning
- Study thermal effects on solar cell efficiency at high altitudes
- Investigate hybrid energy storage systems
- Develop real-time optimization algorithms for dynamic environments

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Thank You

Questions?