Mars Science Helicopter Mid-Year Review

NASA Ames Research Center Activities

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Mars Science Helicopter — NASA Ames Activities

- NASA Ames Aeromechanics Branch Tasks for MSH
  - Explore aircraft sizing and packaging for MSH
  - Define baseline rotor designs for future helicopters on Mars
- Team
  - NASA Ames Research Center
    - Wayne Johnson, Shannah Withrow-Maser, Larry Young, Carlos Malpica, Witold Koning
    - Winnie Kuang, Mireille Fehler, Allysa Tuano, Athena Chan, Malorie Travis, Siobhan Whittle, Noah Del Coro, Kaitlin O'Dell, Hima Patel, Cuyler Dull, Asa Palmer
  - Alfred Gessow Rotorcraft Center, University of Maryland
    - Prof. Anubhav Datta
    - Lex Chi, Ravi Lumba, Daniel Escobar
- Documentation of work
  - NASA TP 2020-220485, “Mars Science Helicopter Conceptual Design” to be published March 2020

NASA Ames Aeromechanics Branch Tasks for MSH

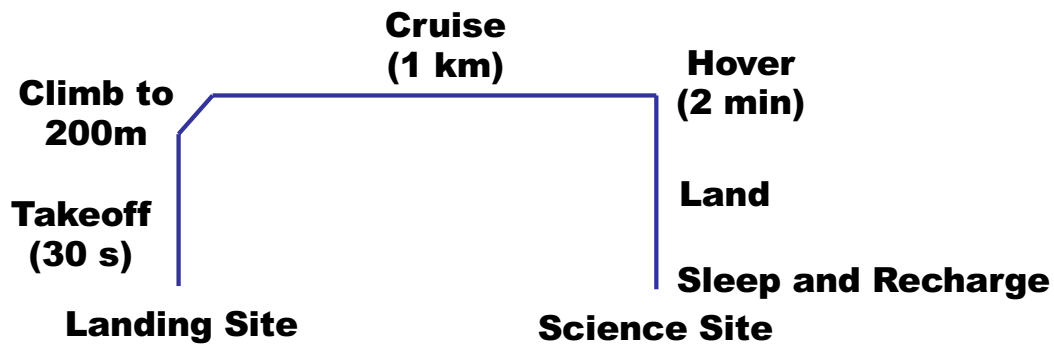
- Initial Designs (March 2019)
  - Useful (but not too hard) mission, packaging constraint => Coaxial and Hexacopter
  - Sizing with low Re airfoils, weights calibrated to MH, JPL battery technology forecast
  - Structural design and flight dynamics => feasible aircraft configurations
- Design Refinements
  - Packaging
    - MSH in Viking aeroshell; small MSH hexacopter in Pathfinder lander

  - Rotor blade aerodynamic optimization
    - Improved rotor performance, higher Mach numbers feasible
    - Structural analysis: Inboard thickness requirement, rotor weight estimate
  - Coaxial and hexacopter design update
    - Based on improved performance with optimized airfoils
    - Double range and hover time for same gross weight

  - Designs for representative Mars sites
    - Demonstrate robustness of Mars Science Helicopter concept
  - Exploration of limits of design assumptions
  - Potential capability of Mars Science Helicopter
    - Including application of improved design features to MH-size helicopter

Initial Sizing of MSH

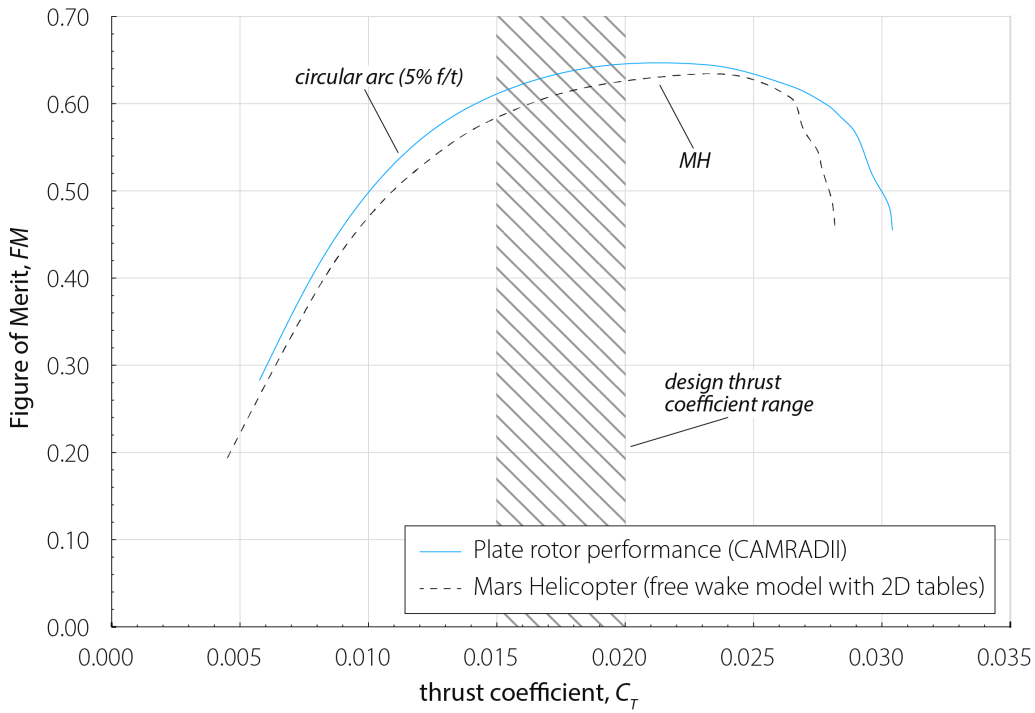
- Initial design mission: useful science but not too hard
  - Payload = 2.02 kg
  - Jezero Crater in the spring: 0.015 kg/m^3, –50°C

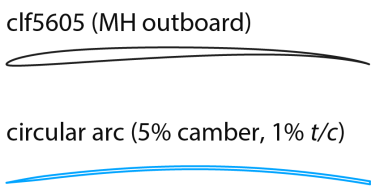


- Mars helicopter sizing spreadsheet (calibrated to MH)
  - Packaging: constrained to 2.5m diameter
- Two configurations: weight about 20 kg
  - Coaxial helicopter (radius = 1.25 m)
    - Legacy (MH) configuration
    - Concern: flight dynamics
  - Hexacopter (radius = 0.64 m)
    - Good performance (more disk area), operate with failed motor, flight dynamics
    - Concern: weight of airframe

NDARC Sizing of MSH

- NDARC (NASA Design and Analysis of Rotorcraft)
  - Detailed performance models (rotor, battery, motor), detailed mission analysis
  - Rotor: Circular arc airfoils for low Reynolds number of Mars
    - Better airfoil L/D => higher efficiency, lower power
    - Better stall => higher maximum thrust
  - Weight: calibrated to MH
  - Battery: JPL technology forecast

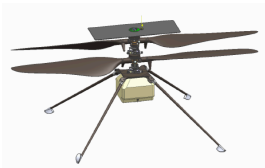




Design Variables

- Design $C_T/\sigma = 0.11$ (MH + 10% for airfoil)
- Hover tip Mach = 0.7 (MH experience, airfoil calculations)
- Flight speed = 30 m/s (min power, assume enabled by nav system)

- Designs:
  - Coaxial helicopter: rotor radius 1.25 m, weight 18.0 kg, power 3.2 kW, battery 128 Ah, rotor solidity = 0.310
  - Hexacopter: rotor radius 0.64 m, weight 17.7 kg, power 3.3 kW, battery 113 Ah, rotor solidity = 0.193



Structural Design and Flight Dynamics

- Preliminary blade structural analysis (University of Maryland)
  - Design to target flap frequency and blade weight
- Flight dynamics and control (Grip and Malpica)
  - Control bandwidth limited by low damped flap mode of blade
    - Regressive flap mode for coaxial (cyclic control)
    - Coning flap mode for hexacopter (collective or rpm control)
- Feasible aircraft configuration for Mars Science Helicopter: Hexacopter, with rotational fold
  - High-gain control possible with either collective or rpm control
- Difficult to design larger coaxial helicopter for Mars that will meet control requirements
  - Coaxial configuration would be feasible if have sufficient mechanical or structural damping of flap mode
  - Or if can design lightweight blades with very high flap stiffness

Packaging for Mars

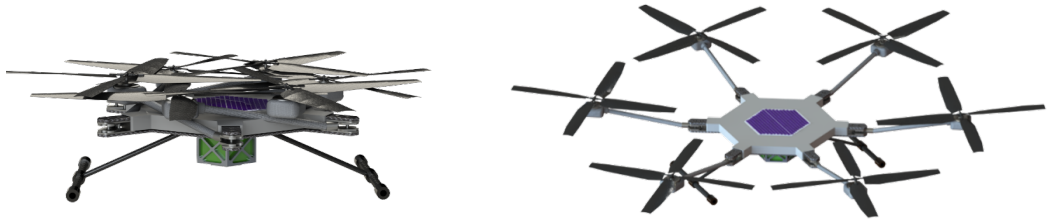
- Entry, descent, and landing (EDL) system needed to get to surface of Mars
  - Initial sizing based on 2.5 m diameter constraint
  - New aeroshell and lander could be developed for MSH
  - Likely project efficiencies if existing design can be used

Pathfinder
1997, Diameter 2.65 m

Viking
1976, Diameter 3.505m

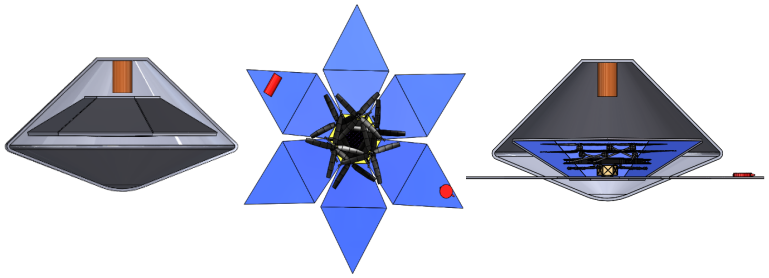
Mars Science Lab
2012, Diameter 4.5 m

- Hexacopter (R=0.64 m) with rotating fold fits in Pathfinder aeroshell, but not in Pathfinder petal lander

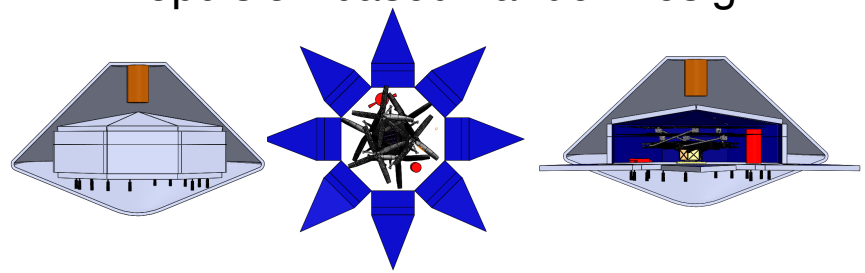


- Developed new airbag-based and propulsion-based designs for Viking aeroshell

Airbag-based Lander Design



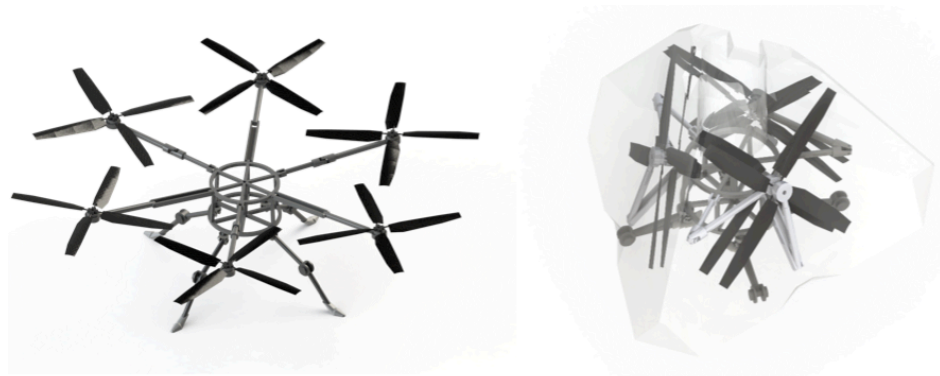
Propulsion-based Lander Design



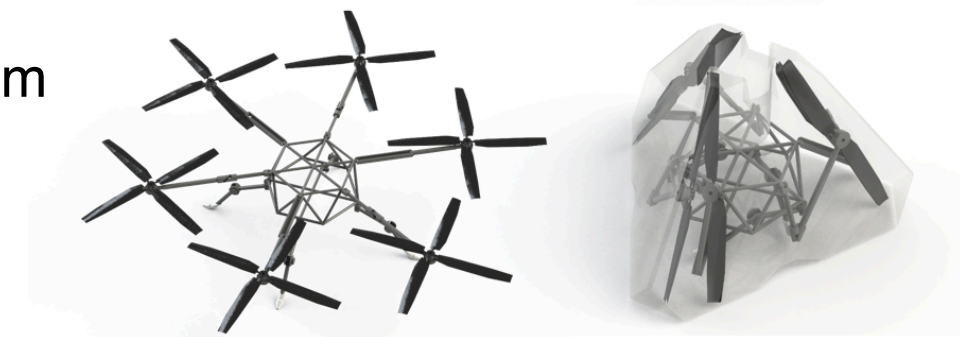
Packaging for Mars

- Designed two hexacopters with smaller rotors, to fit in Pathfinder tetrahedral petal lander
  - Higher weight, power, and energy; less growth capability

- Fold arms: Radius=0.50 m
  - 19.1 kg, 3.5 kW
  - rotor solidity=0.25



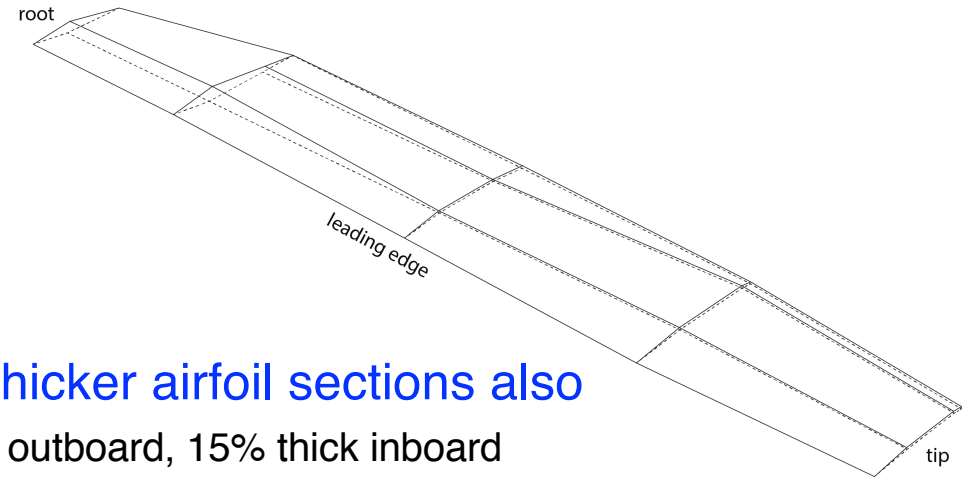
- Also scissor blades: Radius=0.58 m
  - 18.0 kg, 2.9 kW
  - rotor solidity=0.176

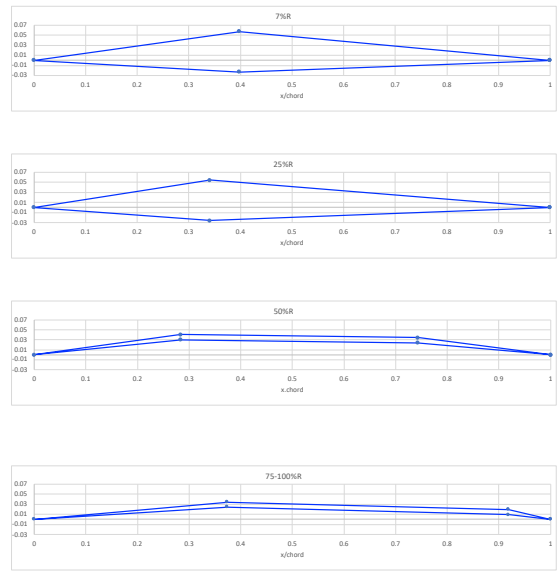


- Still volume in lander for other payload or science applications
- **Larger aeroshells allow larger rotorcraft**

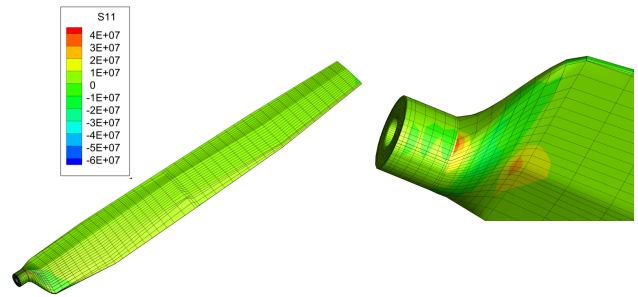
Rotor Blade Aerodynamic Optimization

- Optimized airfoil shapes for unique environment of a second-generation Mars rotorcraft
  - Double edged plate best outboard
  - Thickness-constrained diamond inboard
- Optimized planform and twist





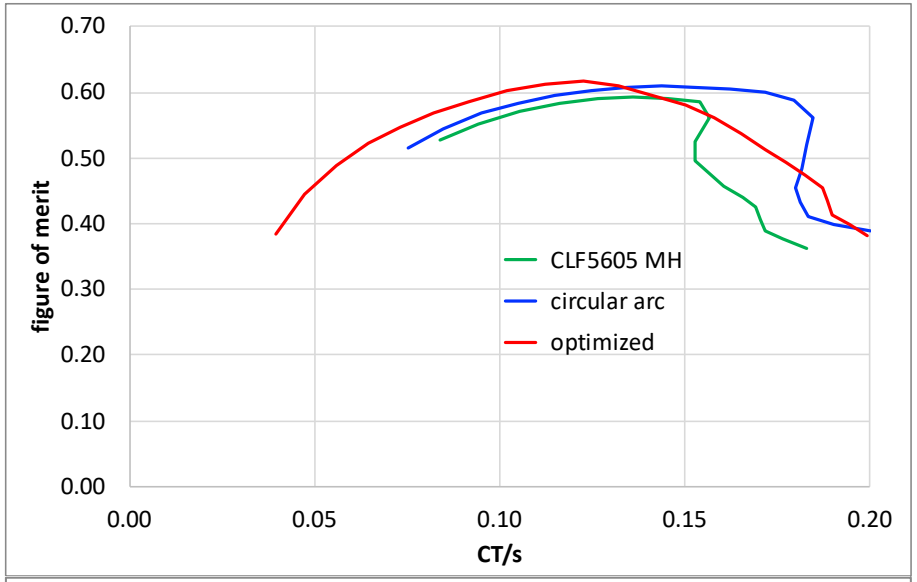
- Designing thicker airfoil sections also
  - 5% thick outboard, 15% thick inboard
  - For more structural design options
- Initial structural analysis and free vibration mode calculation (University of Maryland)
  - For optimized blade aerodynamic shapes
  - Confirmed can meet frequency and weight targets for hexacopter blade, with acceptable stress/strain levels

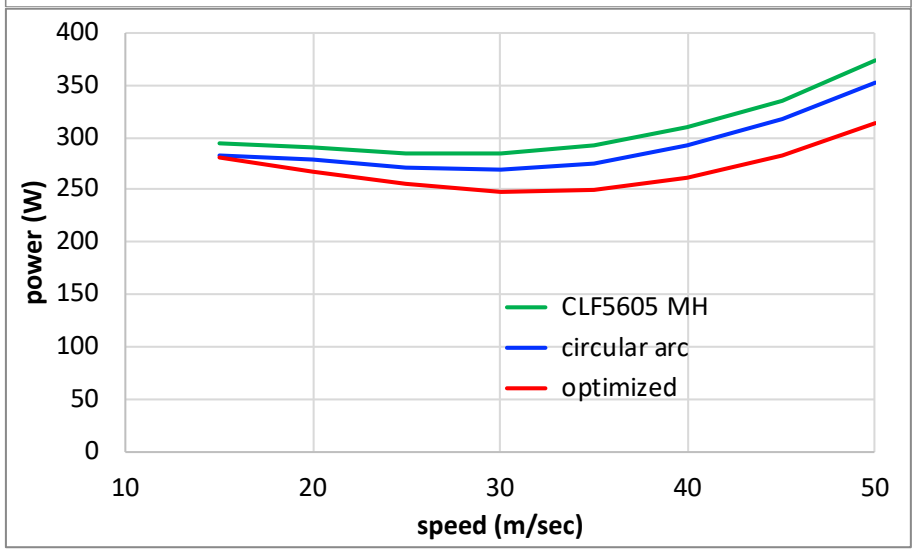


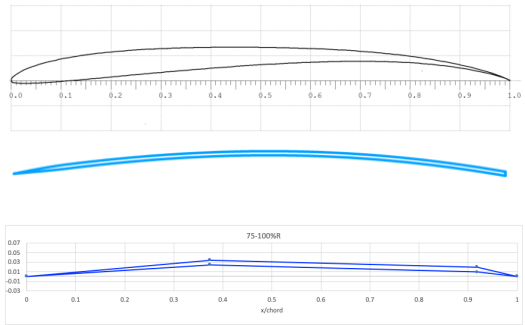
Single Rotor Performance

- Optimized airfoils
  - Hover: increased peak figure of merit, lower power, better stall behavior
  - Forward flight: lower power at fixed flight speed
- No evidence of drag divergence (to $M_{at} = 0.95$)

- Conclude can increase design C_T/σ, increase tip speed







Mars Science Helicopter Design Update

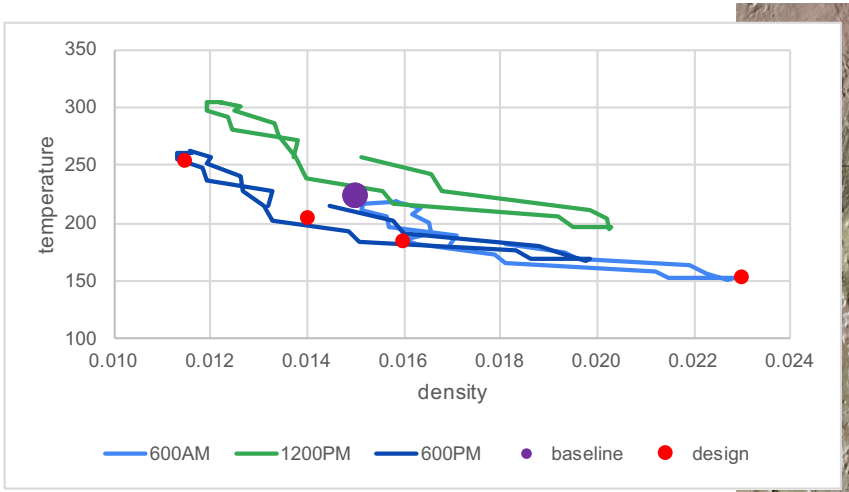
- Model and parameter changes
  - Rotor performance model based on optimized aerodynamics
    - Lower power in hover and forward flight
  - Increased design blade loading to $C_T/\sigma = 0.115$
  - Increased tip Mach number to $M_{tip} = 0.80$
    - Reduces blade area => reduced structural weight => can increase battery weight => more mission capability
- Updated designs
  - Coaxial helicopter: 19.3 kg, 3.6 kW, 225 Ah, rotor solidity=0.244
  - Hexacopter: 17.7 kg, 2.8 kW, 172 Ah, rotor solidity=0.142
  - With greater operational capability: 2 km, 4.5 min hover

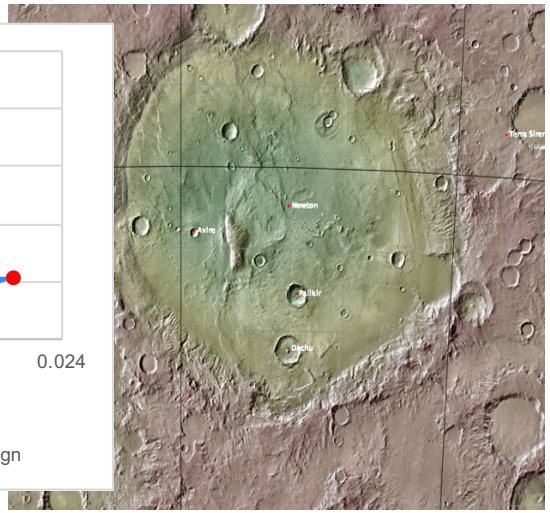
- **These updated designs established MSH feasibility**
- Next explored possible capabilities of MSH
  - Beyond the initial atmosphere, payload, and mission requirements

Designs for Representative Mars Sites

- JPL identified three representative Mars landing sites (examples, not site recommendations)
  - Atmospheric conditions depend on location (latitude, longitude, elevation) and time of day & year
  - Weight and performance depend on atmospheric density and payload

- Example: Palikir Crater
  - Payload 2.1 kg
  - Aircraft 21.0 kg, 3.8 kW, 236 Ah, rotor solidity=0.198





- Results demonstrated robustness of hexacopter concept
  - Substantial capability even with updated design (2 kg payload, density = 0.015 kg/m^3)

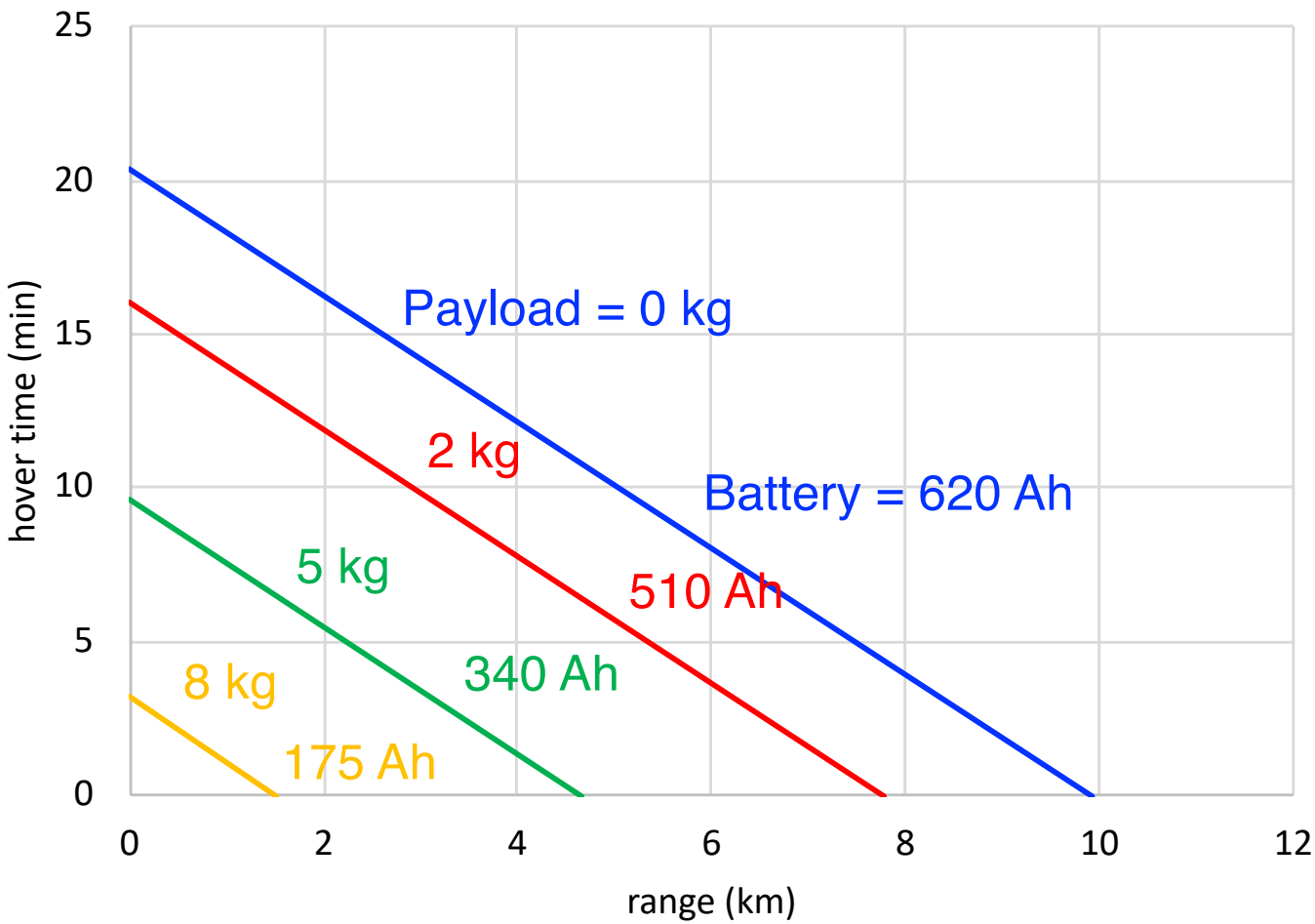
Exploration of Limits of Design Assumptions

- Need enough confidence in design assumptions to fix aircraft size and rotor radius, and chose aeroshell/lander
  - Anticipating growth of weight and power that are encountered in all aircraft development programs
  - Anticipating growth in requirements, especially payload weight
- Project manager and designer must recognize when a helicopter designed for constrained size is near limits of technical feasibility
  - Limit indicated by accelerating growth of aircraft size as function of mission parameters or design uncertainty
  - Examined impact of mission: payload, range, hover time
  - Examined impact of uncertainty: contingency weight; fuselage, motor, or control weight

- **Conclusion:** feasible designs exist that are more capable (range and hover time), and also more conservative (larger contingency weight)
  - Gross weight ~30 kg, rotor solidity = 0.25
- **Or larger aeroshell and lander, enabling larger rotors and aircraft**

Potential Capability of Mars Science Helicopter

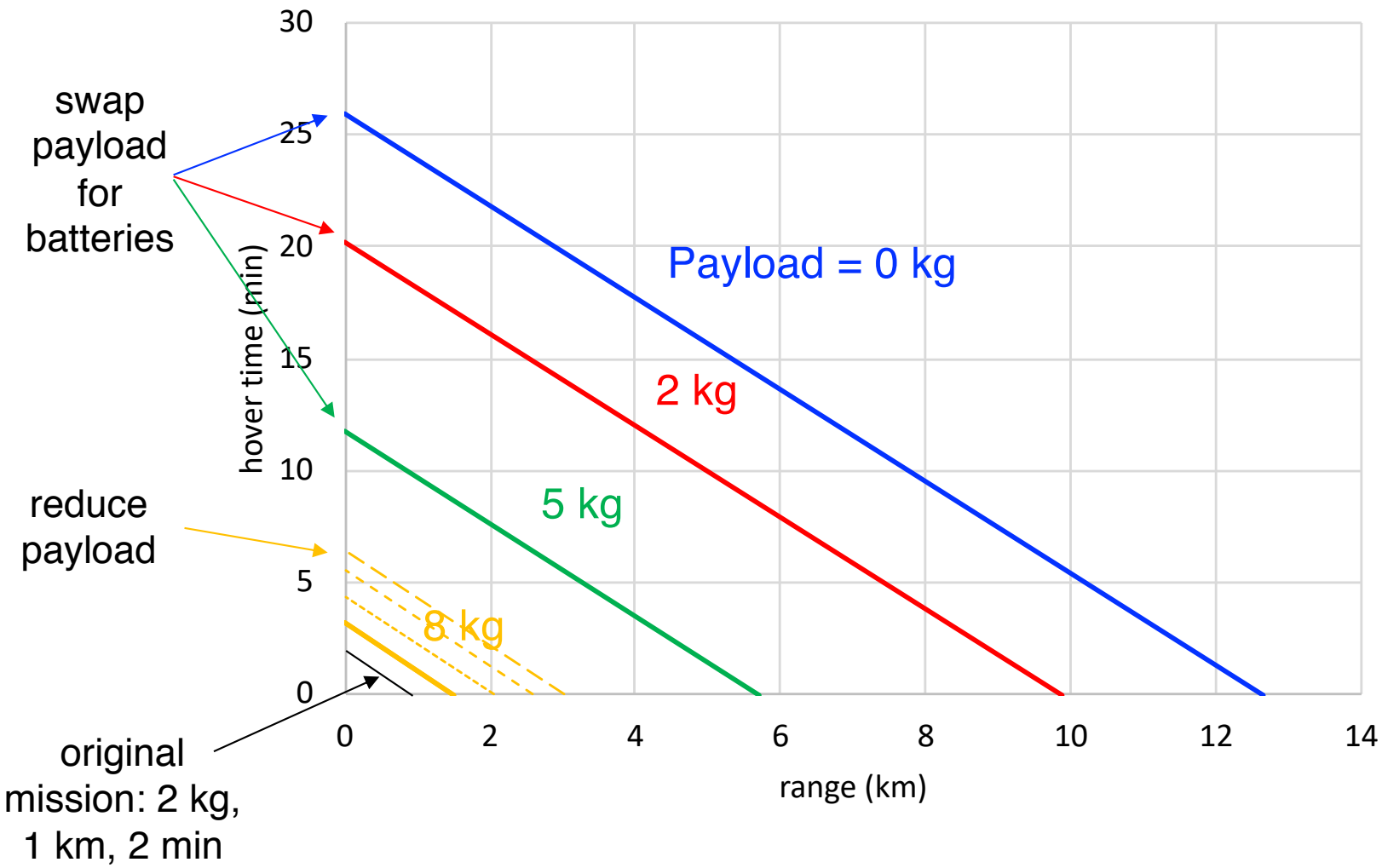
Trade design payload for battery weight (total energy)



Hexacopter, rotor radius = 0.64 m
atmosphere: 0.015 kg/m^3, –50°C
gross weight = 31.2 kg, power = 6.2 kW

Potential Capability of Mars Science Helicopter

Design for payload = 8 kg, then reduce payload or swap for batteries



Hexacopter, rotor radius = 0.64 m
atmosphere: 0.015 kg/m^3, –50°C
gross weight = 31.2 kg, power = 6.2 kW

Advanced Mars Helicopter Scout

Apply improved design features to helicopter same size and configuration as Mars Helicopter demonstrator

coaxial helicopter, radius = 0.605 m

		MH demo	Advanced MHS
design C_T/σ		**0.10**	**0.115**
design M_{tip}		**0.7**	**0.8**
cruise speed	m/sec	**2**	**30**
payload	kg	0	**1.3**
range	km	0.18 km OR	**2 km AND**
hover time	min	1.5 min	**2 min**
rotor radius	m	**0.605**	**0.605**
gross weight	kg	1.8	4.6
solidity		**0.148**	**0.248**
total power	kW	0.36	0.88
battery	Ah	12	46