Virtual Research Presentation Conference

Earth-Analog Testing of a Mars Helicopter Mid-Air Deployment

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Program: Spontaneous Concept

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Jet Propulsion Laboratory
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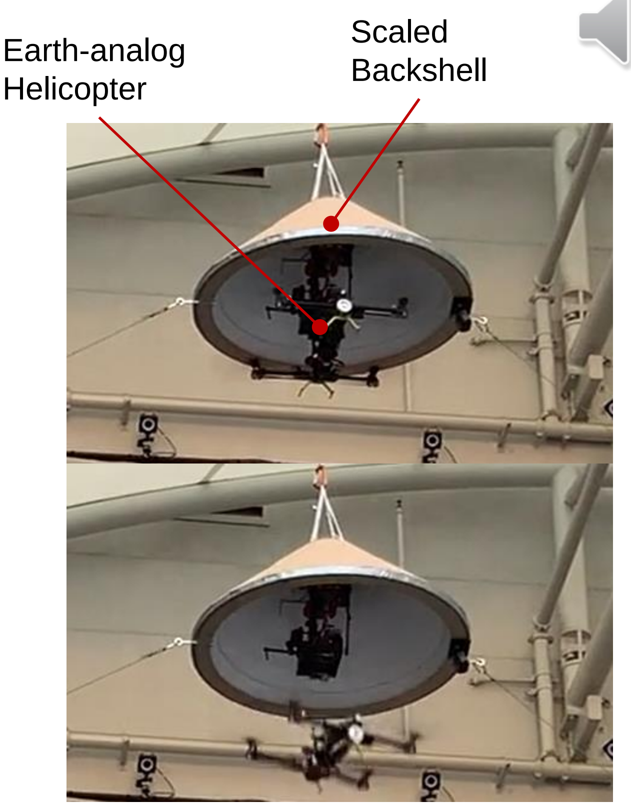
Tutorial Introduction

Abstract

Mid Air Deployment (MAD) of a Mars Helicopter has numerous advantages over a helicopter that lands via traditional means (skycrane, airbags, etc.) prior to it's first flight. The lack of landing system reduces mass and cost, while the low-mass entry vehicle also decelerates at higher altitudes which could enable missions to the Mars Highlands.

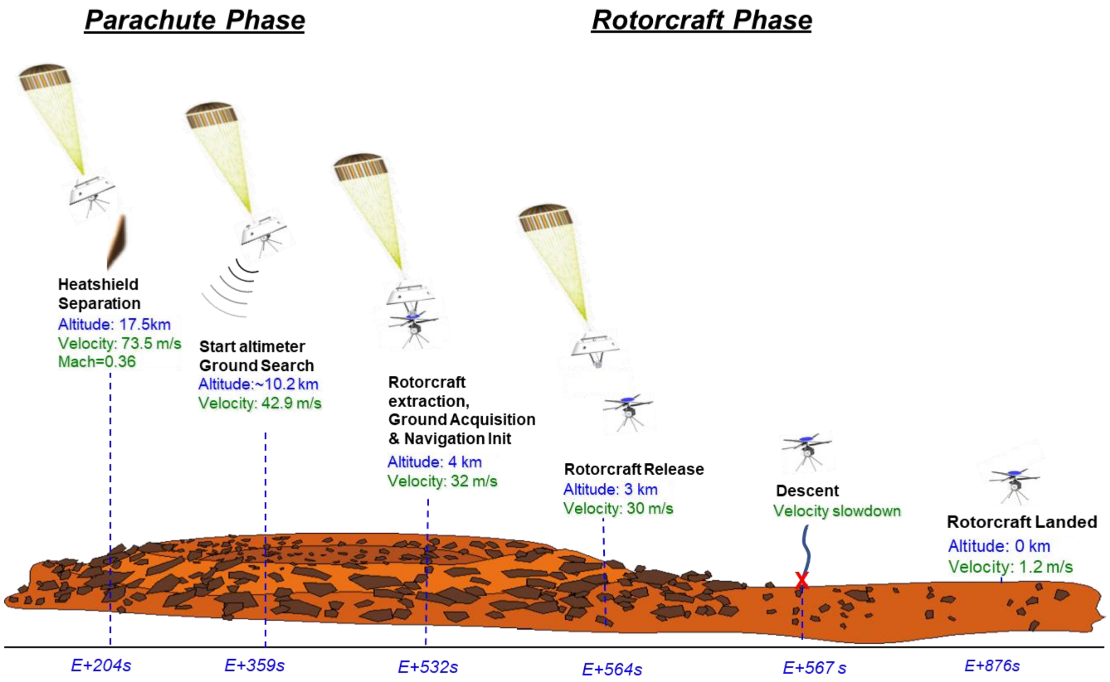
In this study, we performed a proof-of-concept experiment of Mid Air Deployment, using an Earth-analog helicopter. We deployed the helicopter from a 1:3 scale Pathfinder backshell, and also flew it over the Caltech fanwall to provide a vertical airstream that simulates descent.

We logged control effort and acceleration, noted low-level implementation details, and matched certain similarity parameters to the Mars case. We further determined that Vortex Ring State, a thrust-loss effect, should be expected if this architecture is used on Mars and must be accounted for by the flight control.



Problem Description

- Mid-Air Deployment (MAD) has two primary advantages
  - Lower mass (and cost)
  - Access to the Mars Highlands
- Fundamental complexity is the instant of release of the helicopter
  - In fast descents, helicopters can exhibit Vortex Ring State (VRS) which can cause unexpected changes in dynamics
  - A mechanism must be designed that allows for rotor spinup prior to deployment and avoids recontact



Parachute Phase

Rotorcraft Phase

Heatshield Separation
Altitude: 17.5km
Velocity: 73.5 m/s
Mach=0.36

Start altimeter Ground Search
Altitude:~10.2 km
Velocity: 42.9 m/s

Rotorcraft extraction, Ground Acquisition & Navigation Init
Altitude: 4 km
Velocity: 32 m/s

Rotorcraft Release
Altitude: 3 km
Velocity: 30 m/s

Descent
Velocity slowdown

Rotorcraft Landed
Altitude: 0 km
Velocity: 1.2 m/s

Objective: Perform an Earth-analog test of Mid-Air Deployment to validate our understanding of the dynamics change, and gain operational experience with the details of this deployment method.

Choosing an Earth-Analog

- Mars highlands helicopter (MHH) point design provided by NASA Ames.
- Variable-pitch rotor blades is required to avoid stall, but number of rotors is not as important
    - Not a standard quadrotor!
- Descending helicopter airflows are dominated by the descent-rate-ratio
    - This ratio can be matched exactly in our analog experiment

Primary Scaling Quantity

Mars Highland Helicopter Design, at ~3km MOLA

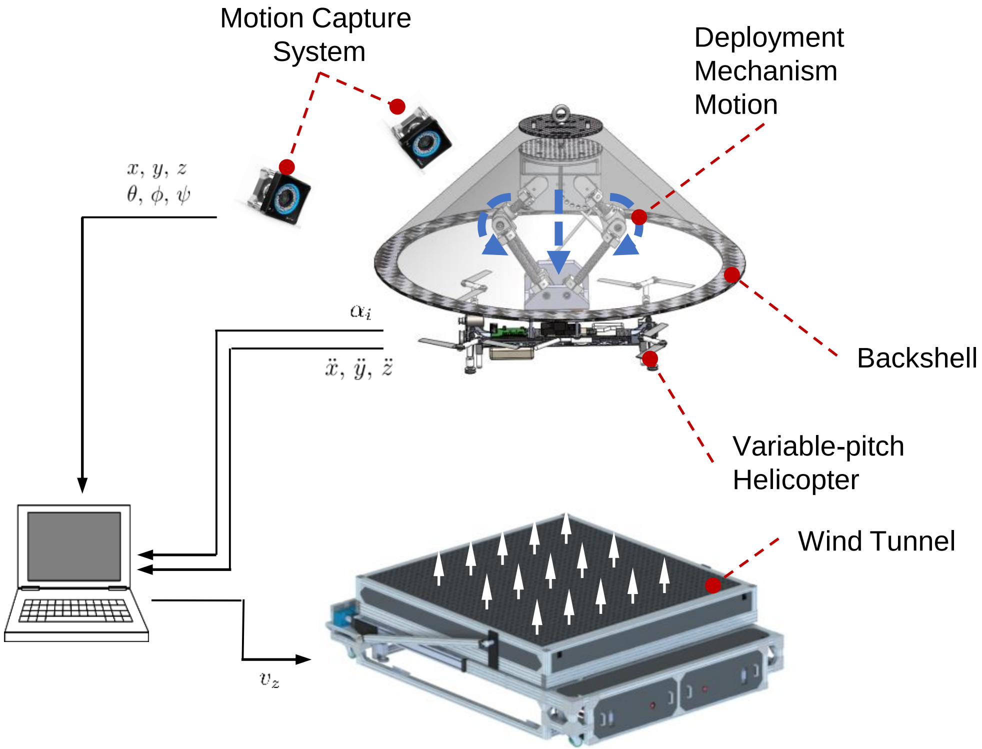
Symbol	Property	Value
Helicopter		
m	Mass	4.141kg
R	Rotor Radius	0.605m
n	Num. Rotors	2
σ	Rotor solidity	0.404
v_{tip}	Tip Speed	194m/s
N_b	Num. Blades per rotor	4
Ω	Rotor Speed	3063 RPM
c	Rotor Mean chord	0.096m
v_h	Hover Downwash	29.08m/s
Backshell		
v_z	Descent speed	30 m/s
D	Diameter	2.65m
Atmosphere/Environment		
g	Gravity	3.711 m/s^2
ρ	Density	0.0079 kg/m^3
a	Speed of Sound	228 m/s
μ	Dynamic Viscosity	1.04 x 10-5 kg/m-s
Non-Dimensional Scaling Quantities		
v_z/v_h	Descent Rate Ratio	1.03
Ma_{tip}	Rotor Tip Mach	0.85
Ma_z	Descent Mach	0.13
Re_{tip}	Rotor Tip Reynolds	14,152
Fr_{tip}	Rotor Tip Froude $v_{tip}/\sqrt{gR}$	129.5

Stingray 500, Earth-Analog Platform

Symbol	Property	Value
Helicopter		
m	Mass (Experiment Dependent)	1.684kg
R	Rotor Radius	0.14m
n	Num. Rotors	4
σ	Rotor solidity	0.0857
v_{tip}	Tip Speed	92m/s
N_b	Num. Blades per rotor	2
Ω	Rotor Speed	6300 RPM
c	Rotor Mean chord	0.024m
v_h	Hover Downwash	5.23m/s
Backshell		
v_z	Descent speed	5.38m/s (0-14m/s)
D	Diameter	0.883m
Atmosphere/Environment		
g	Gravity	9.81 m/s^2
ρ	Density	1.225 kg/m^3
a	Speed of Sound	342 m/s
μ	Dynamic Viscosity	1.825 x 10-5 kg/m-s
Non-Dimensional Scaling Quantities		
v_z/v_h	Descent Rate Ratio	1.03 (0-2.7)
Ma_{tip}	Rotor Tip Mach	0.27
Ma_z	Descent Mach	.016 (0 – 0.0408)
Re_{tip}	Rotor Tip Reynolds	148,208
Fr_{tip}	Rotor Tip Froude $v_{tip}/\sqrt{gR}$	78.5

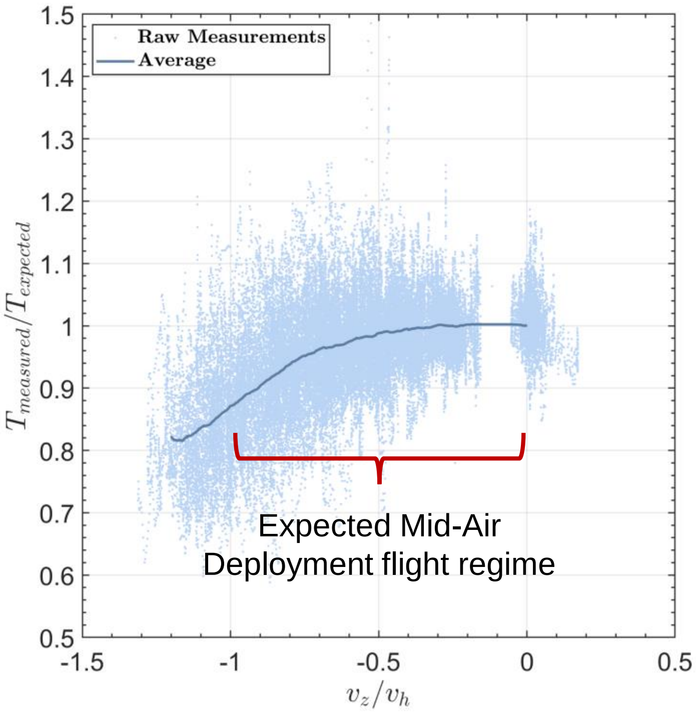
Methodology

- Built a 1:3 scale Pathfinder backshell out of foam
- Designed and built a parallel-bar linkage deployment mechanism to extract the helicopter below the backshell
    - Followed by a radio-controlled pin-puller release
- Suspended assembly and flew helicopter (piloted) above wind tunnel
- Measured:
    - Acceleration from IMU (to derive thrust)
    - Pitch of each rotor blade
    - Pose (6DOF) via motion-capture cameras, which can be double-differentiated to validate the thrust
    - Wind tunnel vertical speed



Results (2): Thrust Loss

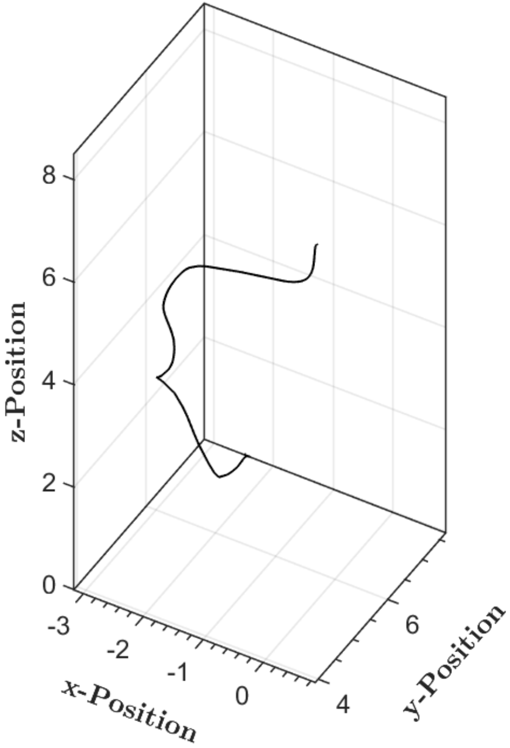
- **We observed Vortex Ring State** when flying in the vertical tunnel, in the form of thrust loss on the vehicle
- This thrust loss in is expected Mid-Air Deployment flight regime, and is roughly 15%.
- Thrust loss is unstable, as increasing descent rate will further decrease the thrust



Expected Mid-Air Deployment flight regime

Results (3): Descent from Backshell

- Successfully descended three times in quiescent air, tracked trajectories with offboard cameras
- Experienced unpredictable pitch & roll disturbances at release
- Possible causes:
    - Flow blockage effects of the backshell on the rotors
    - Unbalanced push-off forces or timing in release mechanism
    - Control windup on the flight computer, not expecting the changed system dynamics



Significance

- Our experiments provided operational experience and scaled Earth-analog dynamics for Mid-Air Deployment, a lower mass & higher altitude entry alternative for Mars

<u>Lessons:</u>

1. Thrust loss should be expected for a mid-air deployed helicopter. This was confirmed with scale-analog experiments, and is consistent with the regime expected from Vortex Ring State models
    - However, the helicopter remained controllable via pilot, so presumably an autonomous controller could be developed to accommodate it in future work
2. The transition between touchoff and free flight is complex, even with a stationary backshell (no vertical wind)
    - Control switching, rotor inflow blockage, and active pushoff should be investigated to reduce uncertainly in release dynamics

- Neither of these details is fundamentally unsolvable, but require some technology investment
    - Multibody simulation of the instant of release
    - Vortex ring state models implemented in helicopter simulator (HELICAT)
    - Deploy mechanism design iteration to mitigate more of the touchoff dynamics

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