CubeSat Solid Rocket Motor Propulsion Systems providing ∆Vs greater than 500 m/s

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Typical Functions and Requirements for Space Propulsion*

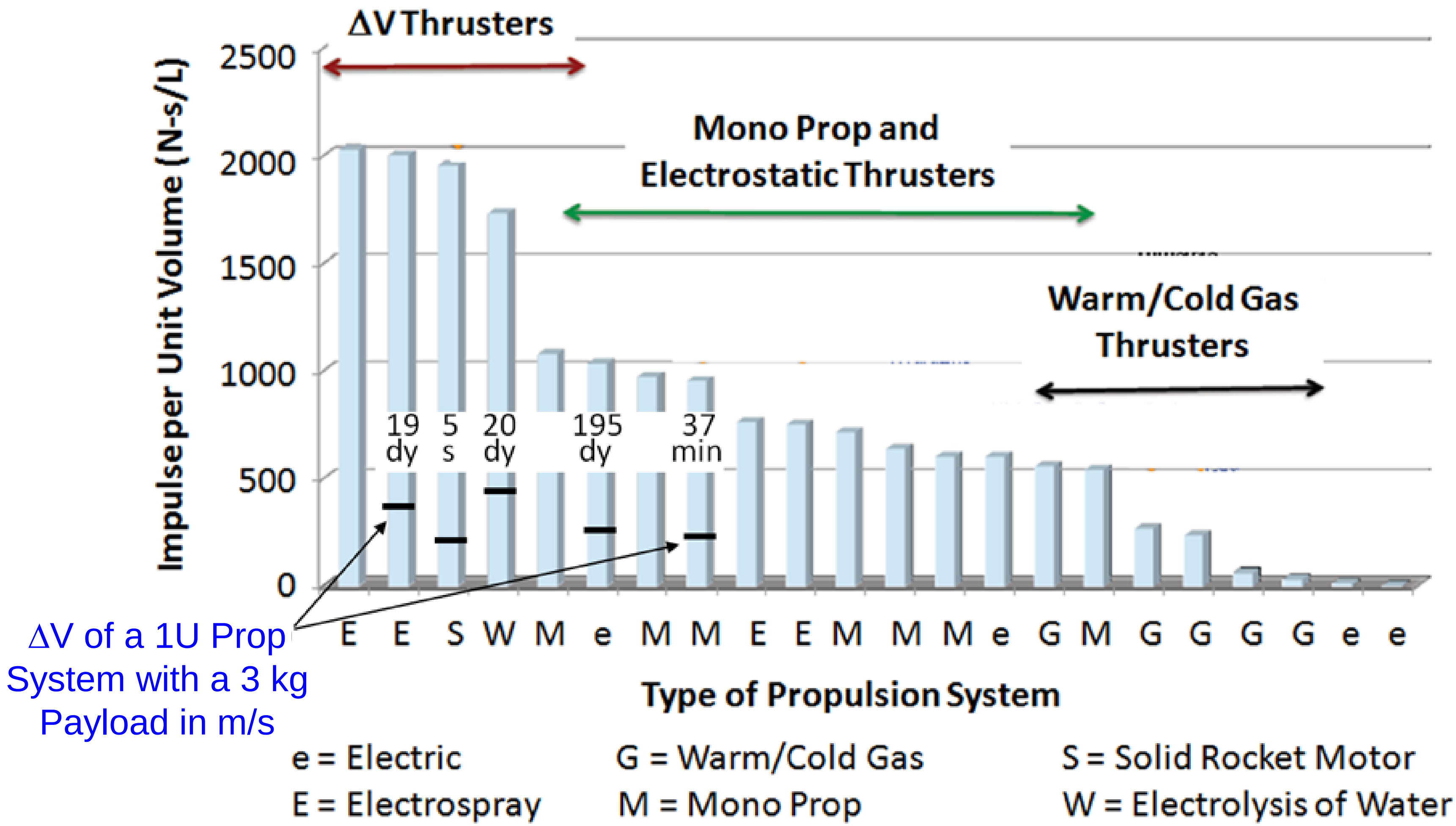
- **Orbit raising and transfers**
  - **LEO Altitude Change of 500 km:** **270 m/s**
  - **LEO Altitude Change of 1000 km:** **510 m/s**
  - **LEO 10 deg Plane Change:** **1280 m/s**
  - **LEO-to-GEO Transfer:** **4290 m/s**

- **Orbit maintenance and attitude control**

  < 75 m/s per year

*Wertz, J.R. and Larson, W.J., Space Mission Analysis and Design, 3rd Edition, Kluwer Academic Publishers, Netherlands, 1991.

Impulse per Unit Volume of CubeSat Propulsion Systems*



*Hargus, W.A. and Singleton, J.T., "Annual Assessment of CubeSat Propulsion Technology and Maturity," Proceedings of the 6th Government CubeSat Technical Interchange Meeting, Pasadena, CA, April 2014.

Proof-of-Concept Solid Rocket Motor System Requirements

- >500 m/s for a 3 kg Payload, in a 1U package
- As Simple as Possible
- No Changes to the Rocket Motor or its Nozzle
- Minimal Modifications to the CubeSat Payload
  - Guidance software added to ACS software
  - Appropriate sensors on CubeSat for closed-loop guidance
  - Data and Electrical Power interfaces only
  - Electrical Power < 5W

Solid Rocket Motor Options for CubeSat Applications

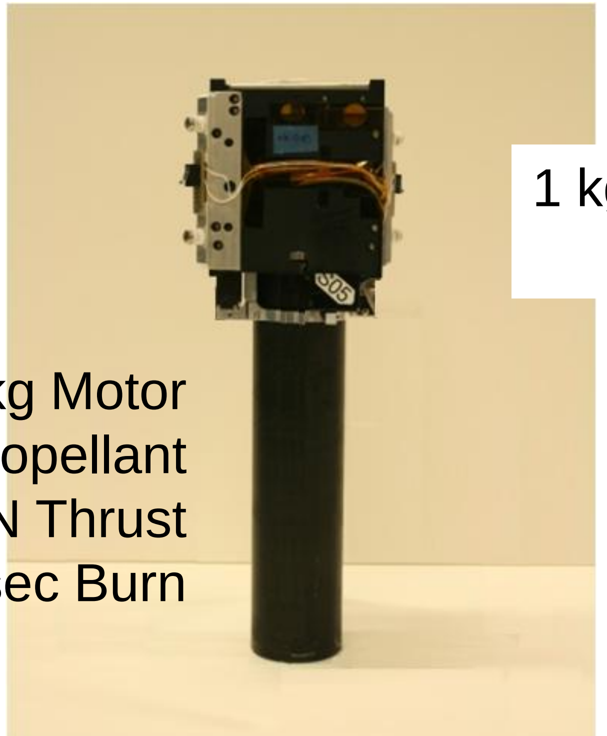
	ISP 30 sec Motor	ATK STAR 4G	ATK STAR 12GV
Diameter, cm:	6	11	31
Length, cm:	25	14	57
Total Impulse, N-s:	997	2,657	91,200
Average Thrust, N:	37	258	6561
Burn Time, s:	27	10.3	13.9
Specific Impulse, s:	187	277	282
Initial Mass, kg:	0.95	1.50	42.0
Propellant Mass, kg:	0.54	0.98	32.9
Propellant Mass Frac:	0.57	0.65	0.78
TVC included?	NO	NO	YES

NOTE: High performance tactical-class rocket motors typically have thrust misalignment errors of between 0.15° and 0.25° *

*Knauber, R.N., "Thrust Misalignments of Fixed-Nozzle Solid Rocket Motors," Paper 95-2874, AIAA/ASME/SAE/ASEE 31st Joint Propulsion Conference, San Diego, CA, 10-12 July 1995.

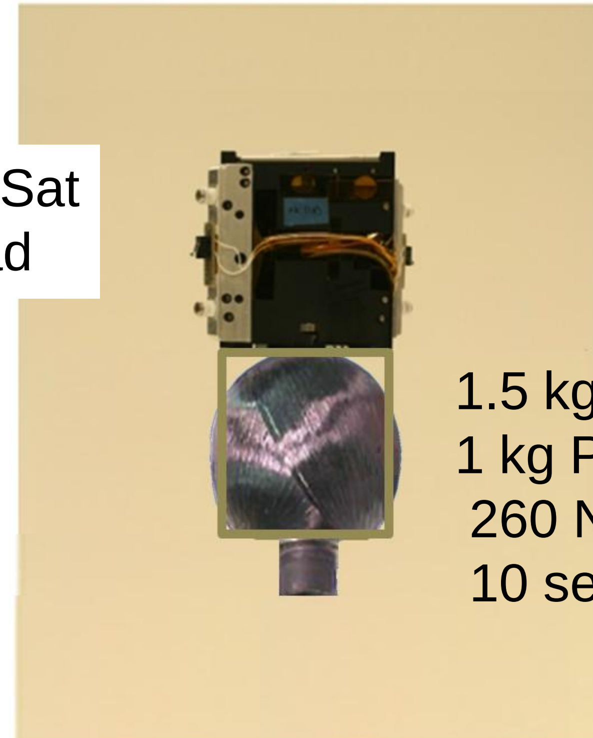
1U CubeSat with Solid Rocket Motor (SRM)

ISP Motor



1 kg Motor
0.5 kg Propellant
40 N Thrust
30 sec Burn

ATK Motor



1.5 kg Motor
1 kg Propellant
260 N Thrust
10 sec Burn

1 kg CubeSat Payload

ΔV = 600 m/s

ΔV = 1200 m/s

But No Steering!

Conventional & Unconventional TVC Methods, 1 of 2

Photo courtesy of Wikipedia

Jet Vanes of a V-2

Photo courtesy of Wikipedia

Jet Vanes of a Scud

Photo courtesy of Raytheon © 2003

Jet Vanes of an AIM-9X Sidewinder

Photo courtesy of ATK

Gimbaled Nozzle of ATK's STAR 12GV

Photo courtesy of NASA

Gimbaled & Variable Thrust Engines of SpaceX's Falcon 9

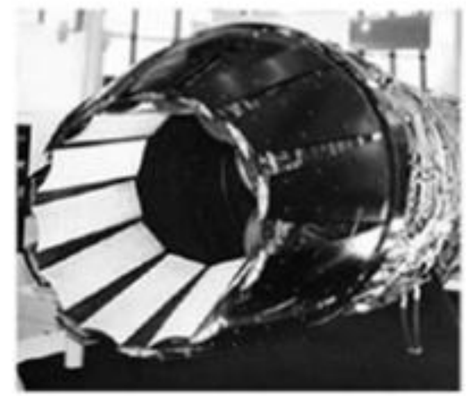
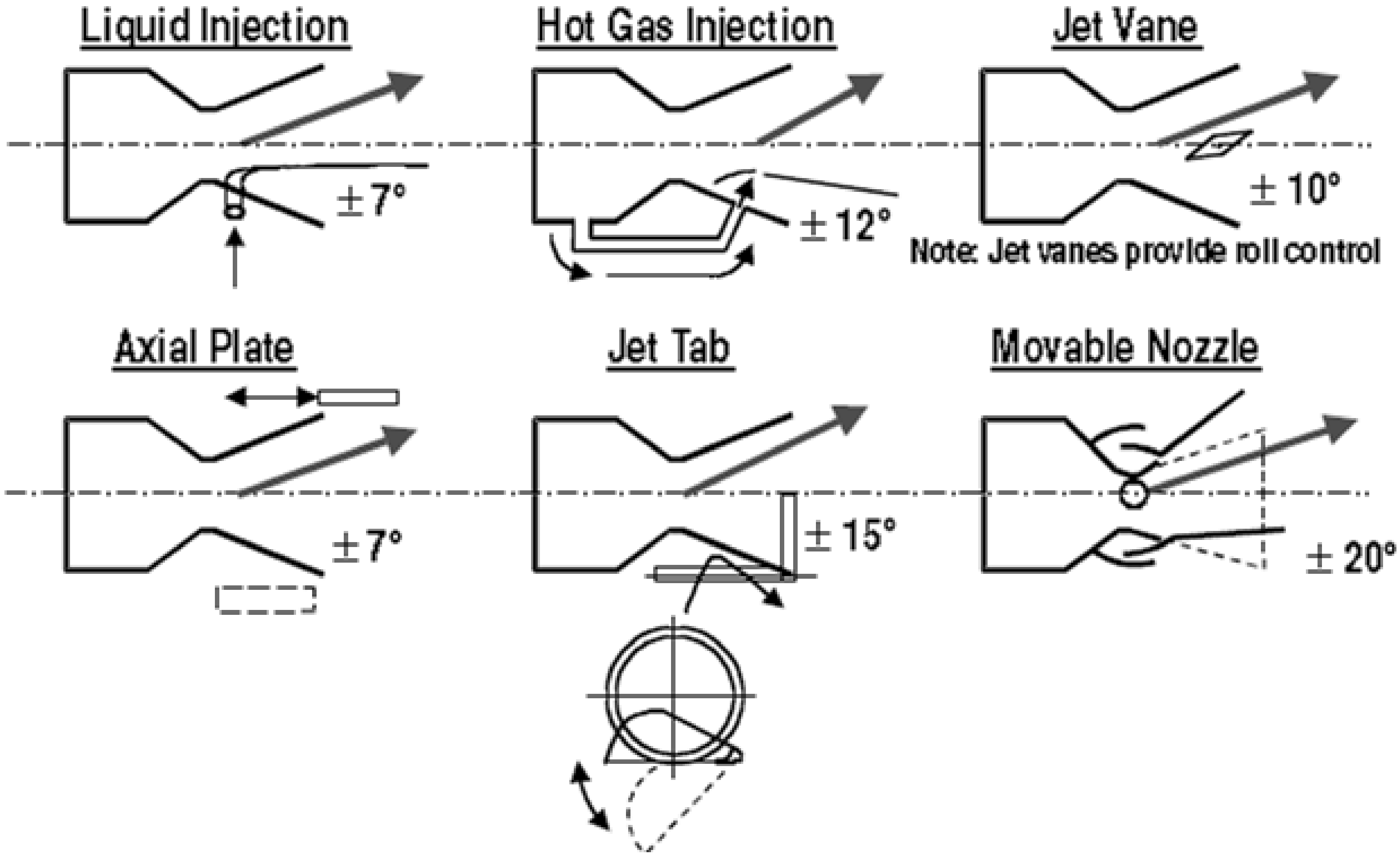


Photo courtesy of Wikipedia

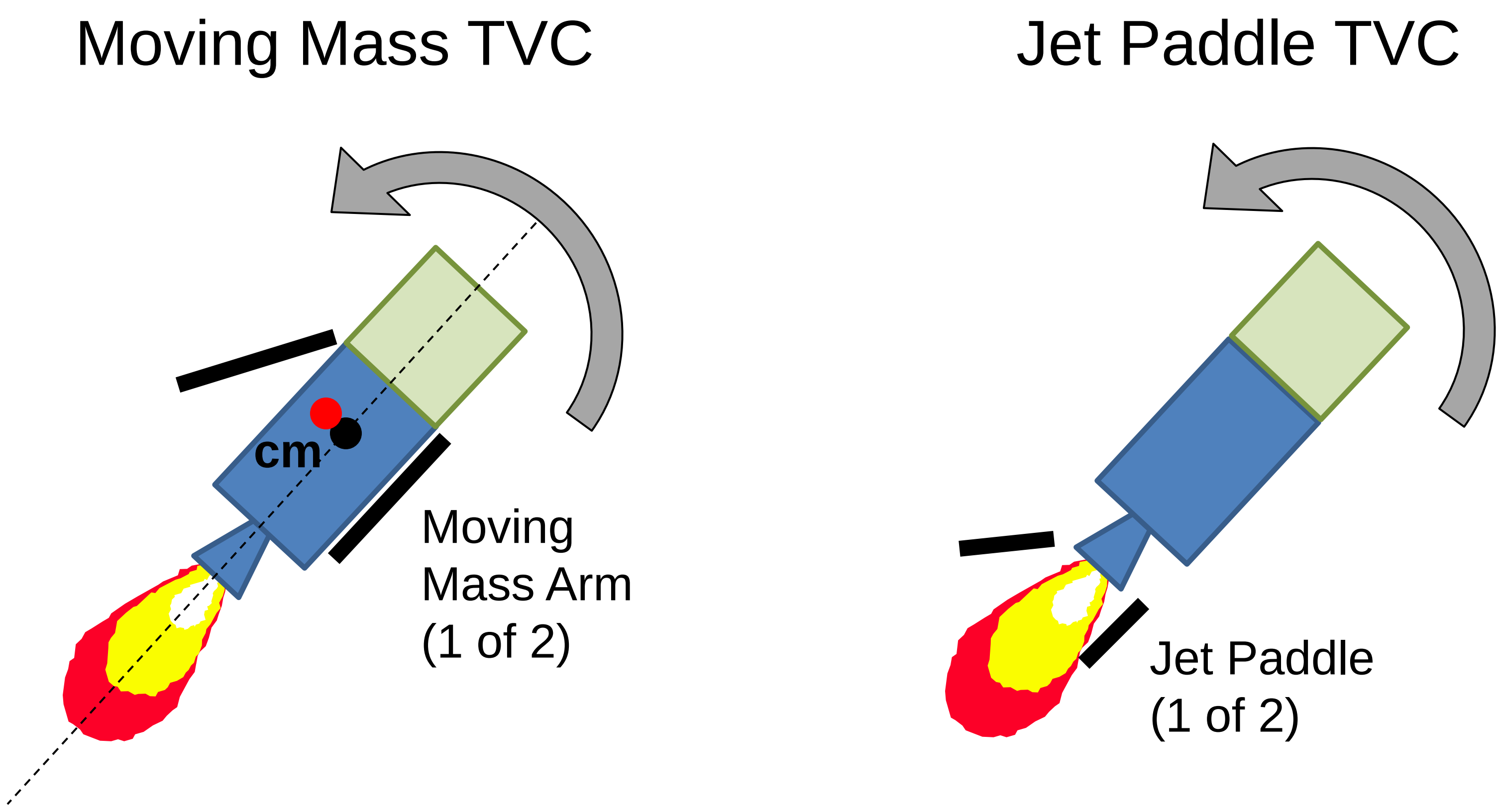
GE Axisymmetric Vectoring Exhaust Nozzle

Conventional & Unconventional TVC Methods*, 2 of 2



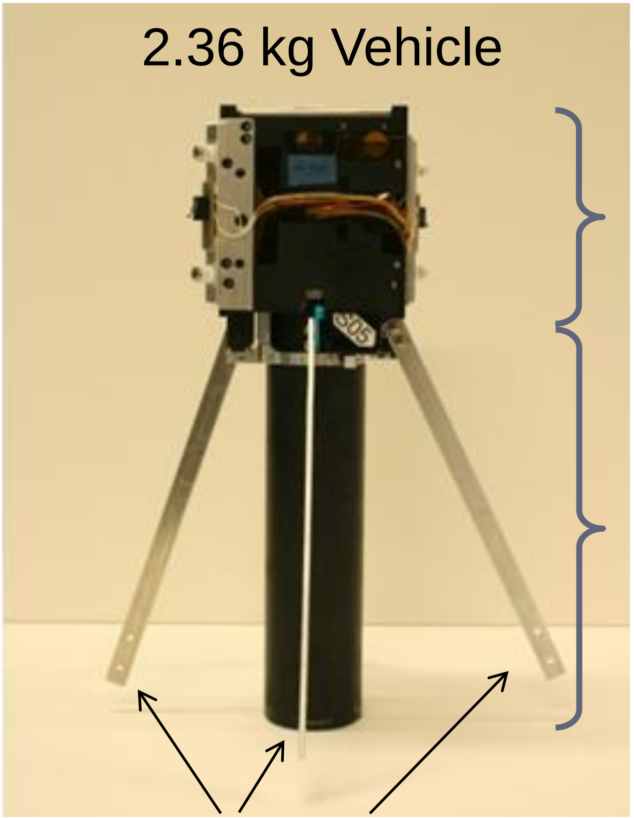
*Fleeman, E.L., Tactical Missile Design, 2nd Edition, AIAA, 2006.

Small SRM Thrust Vector Control (TVC) Concepts



Both Methods are Patent Pending

Moving Mass TVC Proof-of-Concept CubeSat Vehicle



1 kg CubeSat Payload

1 kg Rocket Motor

Option for up to a 50 gram end mass for each arm

Moving Mass Assembly is 360 grams (with 50 gram end masses) and achieves up to a 2º thrust angle and up to 1000 deg/s² of pitch/yaw acceleration with the 40 N ISP motor

Each Servo draws ~5W under load

Each arm has a maximum speed of 225 deg/s

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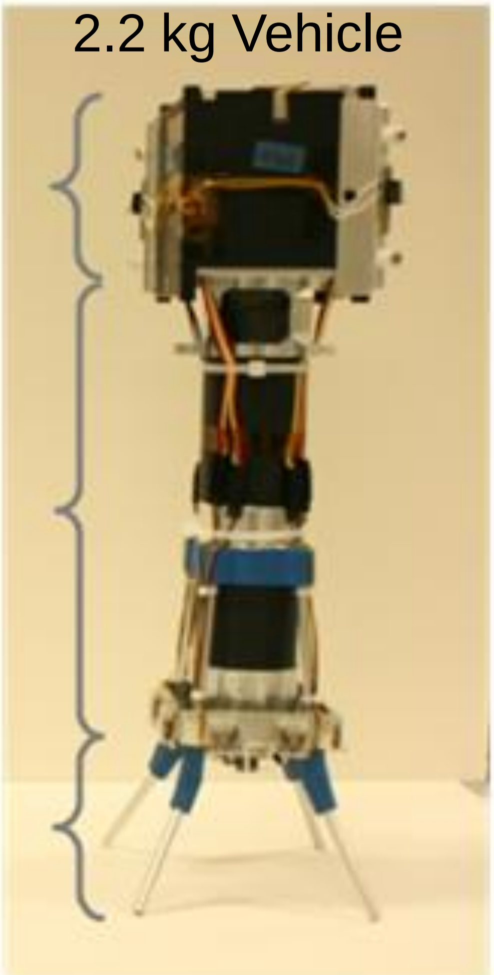
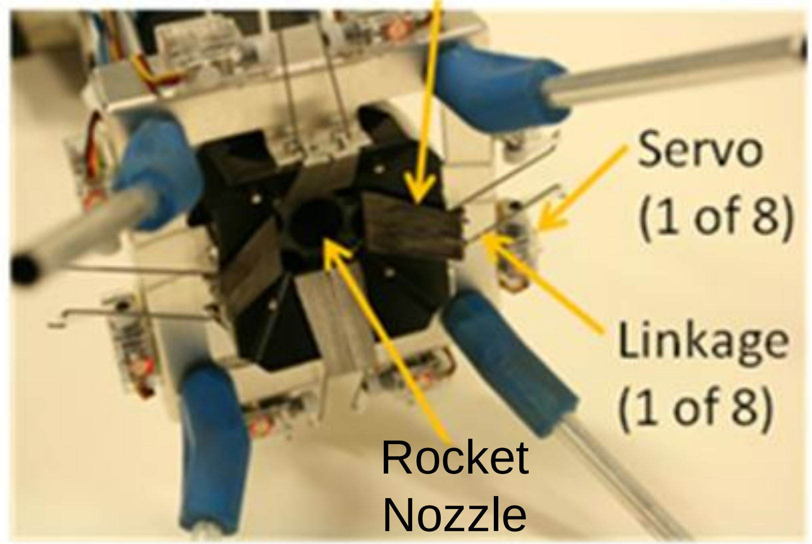
Jet Paddle TVC Proof-of-Concept CubeSat Vehicle

1 kg
CubeSat
Payload

1 kg
Rocket
Motor

0.2 kg
Jet Paddle
Assembly
& Legs





Jet Paddle Assembly is 150 grams and achieves a 6º thrust angle; each Servo draws ~2W under load; each Paddle has a maximum speed of 1350 deg/s

Flights of CubeSats with SRM Propulsion and TVC, 1 of 2

Moving Mass TVC

Jet Paddle TVC

Both 2 kg Vehicles have Flown Successfully! Each is Capable of Achieving 600 m/s (Mach 2, or 1/12 orbital speed)

Flights of CubeSats with SRM Propulsion and TVC, 2 of 2

No TVC

Moving Mass TVC

Summary & Future Plans

- Two TVC systems for Kilogram-Class Solid Rocket Motors (SRMs) have been developed and flown successfully
- These 1U (1000 cm^3) SRM+TVC systems can provide 1 kg CubeSat payloads with steerable ΔVs up to 1200 m/s, and 3 kg CubeSat payloads with up to 600 m/s
- Orbit Changes using Hohmann Transfers require 2 Burns
- Investigating Two Options to Achieve Multiple Burns
  - Propulsion Systems with Multiple Solid Rocket Motors
  - Re-startable Hybrid Motors

BACKUP

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Typical Functions and Requirements for Space Propulsion*

Propulsion Function	Typical Requirement
Orbit transfer to GEO (orbit insertion)	
• Perigee burn	2,400 m/s
• Apogee burn	1,500 (low inclination) to 1,800 m/s (high inclination)
Initial spinup	1 to 60 rpm
LEO to higher orbit raising ΔV	60 to 1,500 m/s
• Drag-makeup ΔV	60 to 500 m/s
• Controlled-reentry ΔV	120 to 150 m/s
Acceleration to escape velocity from LEO parking orbit	3,600 to 4,000 m/s into planetary trajectory
On-orbit operations (orbit maintenance)	
• Despin	60 to 0 rpm
• Spin control	±1 to ±5 rpm
• Orbit correction ΔV	15 to 75 m/s per year
• East-West stationkeeping ΔV	3 to 6 m/s per year
• North-South stationkeeping ΔV	45 to 55 m/s per year
• Survivability or evasive maneuvers (highly variable) ΔV	150 to 4,600 m/s
Attitude control	3 to 10% of total propellant mass
• Acquisition of Sun, Earth, Star	Low total impulse, typically <5,000 N-s, 1K to 10K pulses, 0.01 to 5.0 sec pulsewidth
• On-orbit normal mode control with 3-axis stabilization, limit cycle	100K to 200K pulses, minimum impulse bit of 0.01 N-s, 0.01 to 0.25 sec pulsewidth
• Precession control (spinners only)	Low total impulse, typically <7,000 N-s, 1K to 10K pulses, 0.02 to 0.20 sec pulsewidth
• Momentum management (wheel unloading)	5 to 10 pulse trains every few days, 0.02 to 0.10 sec pulsewidth
• 3-axis control during ΔV	On/off pulsing, 10K to 100K pulses, 0.05 to 0.20 sec pulsewidth

*Wertz, J.R. and Larson, W.J., Space Mission Analysis and Design, 3rd Edition, Kluwer Academic Publishers, Netherlands, 1991.

Typical CubeSat Total Impulse and Vehicle Mass to Perform an Orbit Maneuver

2nd Stage Isp, sec =	277
2nd Stage Propellant Mass Fraction =	0.60
1st Stage Isp, sec =	282
1st Stage Propellant Mass Fraction =	0.78
Fraction of ΔV provided by 1st Stage =	0.70

Propulsion Function	ΔV m/s	Rocket Stage Used	Total Impulse & Vehicle Mass		
			1 kg Payload	3 kg Payload	10 kg Payload
LEO Orbit Raising of 500 km	270	2nd	304 N-s 1.2 kg	913 N-s 3.6 kg	3,040 N-s 11.8 kg
LEO Orbit Raising of 1000 km	510	2nd	647 N-s 1.4 kg	1,940 N-s 4.2 kg	6,470 N-s 13.9 kg
10° Plane Change 1000 km Alt	1,281	2nd	2,680 N-s 2.6 kg	8,050 N-s 7.9 kg	26,800 N-s 26.2 kg
LEO (28.5° inc) to GEO (0° inc)	4,290	1st & 2nd	34,700 N-s 17.5 kg	104,000 N-s 52.4 kg	347,000 N-s 175 kg