A Survey of Micro-Thrust Propulsion Options for Microspacecraft and Formation Flying Missions

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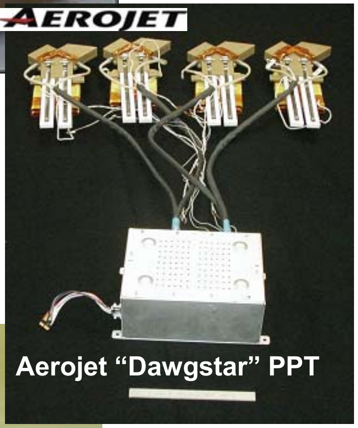
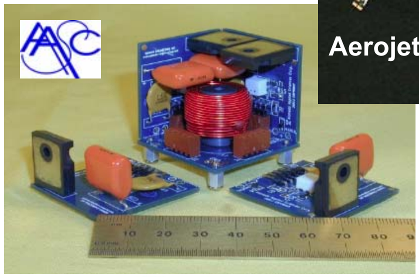
Overview

- CubeSat Propulsion Challenges Overview
- Survey of Chemical Propulsion Options for Microspacecraft
- Survey of Electric Propulsion Options for Microspacecraft
- Evaluation of Propulsion Options Suitable for CubeSats
- Conclusions

Propulsion Challenges for Cubesats

- Cube Sats are standardized spacecraft buses 10 x 10 x 10 cm in size and 1 kg in mass.
- Multiple cube buses (up to 3) have been built.
- Power is user supplied, but typically no more than a few Watts per cube using no deployable arrays so far.
- Substantial challenges exist in placing propulsion systems on cubesats within the mass, size, and power design cosntraints.
- Some propulsion options have been developped for cubesats and other microsats, but none have flown on cubesats to date.
- An existing micro-thrust propulsion data set has been filtered for propulsion systems that are or may be (with some additional development) suitable to Cube Sats.





Representative Microspacecraft Attitude Control Requirements:

S/C Mass (kg)	S/C Typ. Dimension* (m)	Moment of Inertia (kg m²)	Required Impulse Bit (Ns) 17 mrad (1°) 20 s	17 mrad (1°) 100 s	0.3 mrad (1 arcmin) 20 s	0.3 mrad (1 arcmin) 100 s	0.02 mrad (5 arcsec) 20 s	0.02 mrad (5 arcsec) 100 s	Minimum Thrust for Slew (mN)
1	0.1	0.017	1.4×10^{-4}	2.9×10^{-5}	2.5×10^{-6}	5.1×10^{-7}	1.7×10^{-7}	3.4×10^{-8}	0.06
10	0.3	0.150	4.3×10^{-4}	8.5×10^{-5}	7.5×10^{-6}	3.0×10^{-6}	1.0×10^{-6}	1.0×10^{-7}	1.75
20	0.4	0.533	1.1×10^{3}	2.3×10^{-4}	2.0×10^{-5}	4.0×10^{-6}	1.3×10^{-6}	2.7×10^{-7}	4.65

* Assume cubical spacecraft shape

Survey of Chemical Propulsion Candidates for Microspacecraft

JPL Hydrazine Milli-Newton Thruster (HmNT)

Description:

- **Miniature hydrazine thruster development by JPL.**
- **Drops minimum I-bit over conventional MR-103 by factor of >100 to 50 µN-s by mating very small thruster with small flow passages to a fast acting valve.**
- **Significant mass (5x) and size (10x) reduction over SoA hydrazine thruster technology.**
- **Performance data (compared to Aerojet MR-103):**

Comparison Parameter	Aerojet MR103H Current SOA	HmNT
Thrust	0.9 N	0.020 N
Envelope Volume	94 cc	8 cc
Valve Power	5/1 W	8/2 W
Cat Bed Heater	1.9	0.25 W (est.)
Mass	195 g	40 g
Min. Impulse	5,000 µN¡sec	**50 µN¡Sec**

Application:

>20-30 kg S/C attitude control

- **Application for attitude control on conventional spacecraft requiring ultra-fine attitude control (reaction wheel replacement), or microsats (approx. > 20-30 kg) depending on mission deadband requirements.**
- **Well suited for > 20-30 kg spacecraft ACS where I-bit requirements may be low (depending on deadband requirement) and a liquid system is needed (low leakage concerns, low tank mass).**
- **Thruster may not be usable on very small microspacecraft (< 20-30 kg) where power is limited.**

Status:

TRL 3-4. Laboratory development.

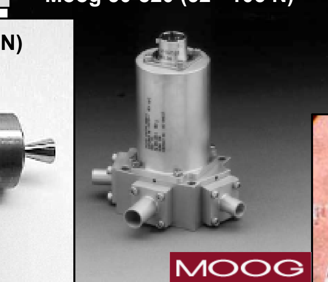
- **Pulsed mode operation demonstrated in 2007 in relevant environment (vacuum) on JPL micro-Newton thrust stand. Continuous firing testing planned for 2008.**

HmNT Feedsystem installed on JPL Milli-Newton Thrust Stand

Cold Gas Thrusters

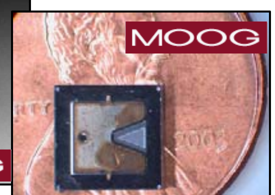
Moog 58X125A (4.4 mN)

Moog 50-820 (52 - 105 N)



Moog 58E142 (0.12 N)

Marotta Cold Gas Thruster (0.05 - 2.36 N)



Moog Torque Motor on-a-Chip

Description:

- Pressurized gaseous propellant is vented through a valve and nozzle to produce thrust.
- Relatively simple, low cost technology.
- Typically using N_2 as propellant, but any gas can be used.
- Benign propellants - no contamination risks.
- No power requirements except for valve.
- Very low Isp - < 100 sec.
- Heavy tankage due to pressurized gas.
- Typical performances range from 4.5 mN - 105 N thrust, 10 g to 0.4 kg mass, 1 - 50 W power. Isp propellant dependent, typically 65 sec for N_2 (see Table next sheet).

Application:

Attitude control and very limited delta-v.

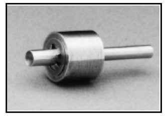
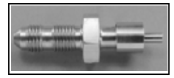
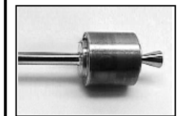
- Application primarily to ACS and very limited delta-v only due to low Isp.
- Very small, light-weight components, but potentially high system weight due to heavy, high pressurant tanks may pose integration difficulties to CubeSats.
- Several benign propellant options make these thrusters a choice for contamination sensitive environments (sensitive optics, IR cooled S/C).
- Long mission durations may pose risks due to long term leakage concerns.

Status:

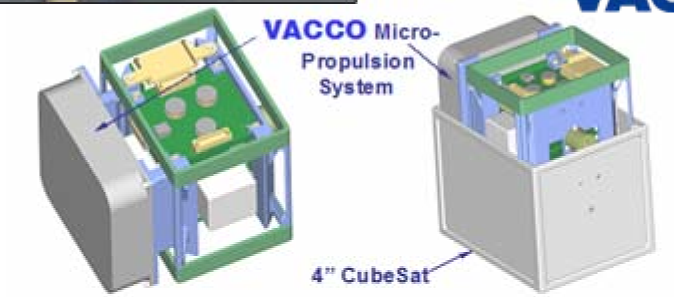
TRL 9. Flight proven technology.

- Cold gas technology has been used in space since the 1960s.
- Proven technology -some remaining leakage concerns by some customers.
- Several commercially available thruster options from two remaining US vendors (Moog, Marrotta). VACCO providing novel butane thruster technology (separate sheet).
- Newer developments on chip based thrusters (TRL 3) and stepper motor valves covering range of thrusts from 1 μN to 1.2 mN (Moog), and ultra-low power thrusters (1 W, Marotta, 0.1W VACCO)

Cold Gas Thrusters - Cont'd

							
Manufacturer	Moog	Moog	Moog	Moog	Marotta	Moog	Moog
Model	58X125A	58E143 58E144 58E145 58E146	58E142	58E151	Cold Gas Micro-Thruster	58-118	50-820
Propellant	N2	N2	N2	N2	N2	N2	N2
Thrust (N)	0.0044	0.016 - 0.040	0.12	0.12	0.05 - 2.36	3.6	52-105
Mass (g)	9	40	16	70	<70	23	430
Size (mm)	11.9x34.7	13.97x57.2	14x20.3	19.05x 40.87		6.6x25.4	98.2x104.1
Valve Power (Open) (W)	10	10	<35	10.5	<1	30	47
Valve Power (Hold) (W)		1					
Isp (sec)	65	>60	>57	65	65	65	65
Operat. Pressure (psia)	0-50	0-36	50-300	0-400	100-2240	230	215-2515
Proof Pressure (psia)	300	290	600	1015	3360	1115	3765
Burst Pressure (psia)		508	1200	1615	5600		6265
Response (Open) (ms)	2.5	2.5	3.5	5	5	<4	<10
Response (Close) (ms)	2.5	2.5	3.5	3	5		<10
Minimum Ibit (mNs)					<44		
Life (No. of Cycles)	>15,000	500,000 - 2,000,000	20,000	1,000,000		>10,000	>6,000
Status	Flight Qual	Flight Qual	Flight Qual	Flight Qual	Flight Qual	Flight Qual	Flight Qual
Comments	Brlliant Pebbles, SAFER, Pluto Fast Flyby	CHAMP, GRACE	SIRTF	SIRTF	Developped for GSFC Nanosats, ST-5	SCIT, SAFER, Pluto Fast Fly-by	COMET, Pegasus Cluster of 3 thrusters: 2 @ 52N, 1 @ 105N

VACCO/JPL Butane Micro-Thruster



Description:

- Solenoid-based microthruster development by VACCO in collaboration with Aerospace Corp. for MEPSI for AFRL/DARPA.
- Piezoelectric valve based microthruster development by VACCO in collaboration with JPL for Micro-Inspector developed under NASA ESMD.
- Piezoelectric valve version is ultra-low power (100 mW avg., 4 W peak) for low-power microsat applications.
- Using butane propellant, stored in its liquid phase, expanded as gas. Combines cold gas thruster simplicity with liquid propellant storage.
- Piezovalve Thruster Performance Characteristics:

Supplier	Designation	Thrust (mN)	Mass (g)	Isp (sec)	Power (W)
Vacco	Butane Micro Thruster	10-25	30	70	1 (open, depend. on ramp rate) , 10 uW (Hold)

Application:

>5 kg S/C attitude control

- Application for attitude control on microspacecraft, such as Cube Sats.
- Piezovalve version is ideally suited for microspacecraft attitude control due to very low power consumption in addition to appropriate other performance parameters (thrust).
- The MEPSI module is a self-contained, Cube Sat based propulsion module including fuel for easy bolt-on integration.

Status:

TRL5. Breadboard models exist.

- The solenoid based MEPSI module for AFRL/DARPA has been assembled and is still awaiting Get-Away Special flight on shuttle after Columbia accident.
- The piezovalve based thruster has undergone testing in relevant environment (vacuum) on JPL micro-Newton thrust stand and performances verified under the JPL Micro-Inspector project for NASA ESMD .
- Use of two VACCO piezovalve-actuated butane thrusters was studied by "Kathy Sat". Thrusters are available for this or other Cube Sat missions.

Solid Rocket Motors

Description:

- Typically HTPB (Hydroxyl-terminated Polybutadiene) matrix with Al fuel and Ammoniumperchlorate oxidizer.
- Many different fuel mixture to obtain desired burn rate, outgassing characteristics, space-storability, etc.
- Many different geometry fuel grains (cylindrical, star-shaped, end grain) to achieve different thrust profiles and burn-times.
- Most motors feature burn rates that are too short and thrust/acceleration levels that are too high for microsats. Possible exception: ATK STAR 4G

Supplier	Designation	Thrust (lbf)	Size (in)	Mass (lbm)	Prop Mass (lbm)	Isp (sec)	Burn Time (sec)	Total Impulse(lbf-s)
ATK	STAR 4G	58 (avg)	4.5 x 5.4	3.3	2.16	269.4	10.3	595

Application:

Kick stage for cube sats - externally mounted/staged

- Tight packaging of solid motors compared to liquid propulsion systems suited to small spacecraft.
- Good Isp performances > 290 sec for large kick stages.
- Generally, single burn - cannot be halted or restarted.
- Generally requires a separate (liquid) system for orbit trimming, ACS during burn, or spin-up/spin-down.
- Generally, high thrust, short burns impart high vehicle accelerations (several g's). ATK nanosat motor may meet cube sat design envelope.
- Solid motor can be added to a CubeSat as an external stage, as is done conventionally.

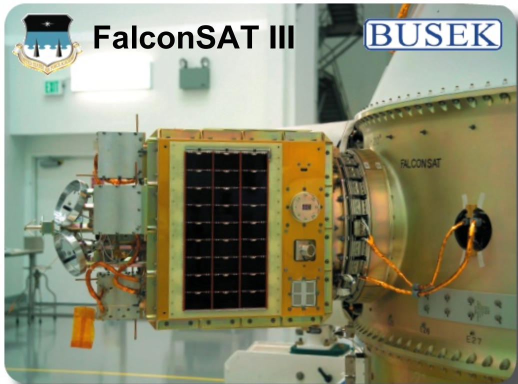
Status:

TRL 9. Flight proven technology.

- Solid motors have been used since the dawn of the space age. STAR 4G is a newer development of lower TRL.
- Proven technology with many catalogued existing motor options.
- May require dedicated developments for smaller spacecraft matching required masses, thrusts, burn times, g-loads.

Survey of Electric Propulsion Candidates for Microspacecraft

Pulsed Plasma Thrusters (PPTs)



Busek 3-axis MicroPPT (MPACS)

Aerojet “Dawgstar” PPT

Description:

- Thrust generated through ablation of a solid Teflon fuel bar in an arc discharge across its face.
- Plasma generated in arc discharge is accelerated between two electrodes by electrodynamic forces through interaction of self-generated magnetic field and current.
- Teflon fuel bar is spring-loaded and brought into position for next firing.
- Thruster is inherently pulsed, and modular - carrying its own fuel.

Supplier	Designation	Mass (kg)	Fuel (kg)	Isp (sec)	Ibit (microNs)	Impulse (Ns)	Rep Rate (Hz)	Power (W)	Efficiency
Aerojet	EO-1	4.95	0.7	650-1400	90-860	460	single - 1	70 (1 Hz)	8%
Aerojet	Dawgstar	4.1	0.6	625	66	3000			3%
Busek	MPACS			830	80				16%

Application:

> 1 kg S/C attitude control

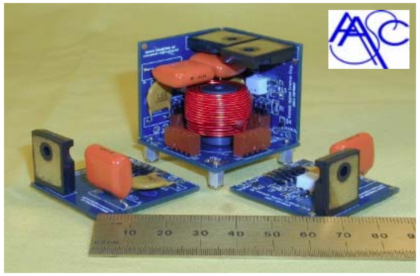
- Application mostly for attitude control of conventional to microsats (Dawgstar thruster).
- Use as main engine is possible in a continuously pulsed fashion, but may pose life issues for electrodes.
- Inherently pulsed operation may induced jitter on flexible structures.
- Contamination concerns related to Teflon propellant largely refuted on EO-1 mission, but need to be re-evaluated for each mission for extensive firings near sensitive surfaces (optics).

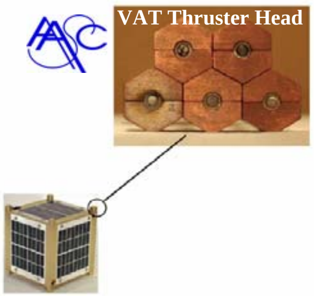
Status:

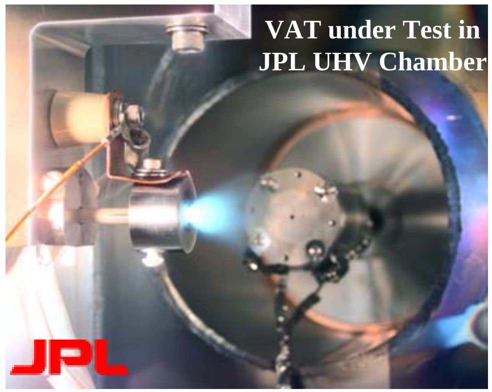
TRL 9. Flight proven on EO-1 and FalconSAT III

- The EO-1 thruster has flown on NM EO-1.
- The Busek MPACS MicroPPT has flown on Air Force Academy’s FalconSAT III (2007)
- Smaller “Dawgstar” version was under development for a university nanosat.

Alameda/JPL Vacuum Arc Thruster (VAT)







Description:

- Vacuum discharge between two metal electrodes.
- Surface roughness spikes form attachment points for arcs, high power density in attachment points lead to localized phase transition from solid to plasma.
- Plasma expands rapidly into vacuum due to high localized pressure (1000 atm) at attachment points to produce thrust.
- High precision thrust and impulse bits. Inherently pulsed thrust characteristics, modular design.
- Typical performance parameters:

Supplier	Designation	Thrust (mN)	Mass (g)	PPU Mass (g)	Isp (sec)	Power (W)
AASC	VAT	0.125	40	600	1,500	10

Application:

> 1 kg S/C Attitude control

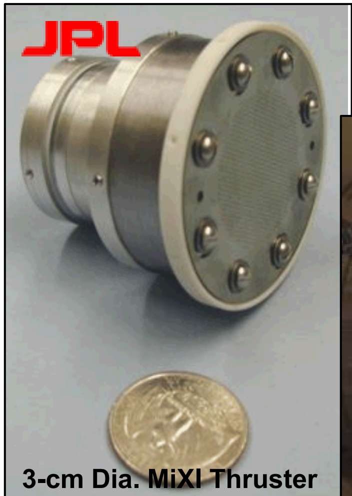
- For attitude control on very small microspacecraft (> 1kg) or ultra-precision attitude control on larger spacecraft for constellation/formation flying applications.
- Delta-v capability very limited due to inherently pulsed design, and small total impulses.
- Compact, modular design with thruster-integrated propellant supply.

Status:

TRL 3-4. Laboratory development.

- Laboratory development by Alameda Applied Sciences Corp. (AASC) in collaboration with Aerojet.
- Resulted from SBIR funded activities.
- 2004 Vacuum test series, incl. thrust stand tests at JPL
- A VAT thruster system has been designed and built by AASC Inc. and tested by AASC and JPL but not yet flown.

JPL Miniature Xenon Ion (MiXI) Thruster



3-cm Dia. MiXI Thruster

MiXI in Operation in JPL Test Lab

Description:

- Electrostatic thruster. Ions are generated in a plasma discharge by electron bombardment and accelerated through extraction grids by DC electric field.
- High specific impulse (3000 s), propellant eff (>70%), and power eff (>40%), and non-contaminating propellant.
- Much smaller (3 cm) and lower power than conventional ion thrusters.
- Typical MiXI performances:

Supplier	Designation	Thrust (mN)	Thruster Mass (kg)	Dia (cm)	Isp (s)	Power (W)
JPL	MiXI	0.01-1.5	0.2	3	2500-3200	13-50

Application:

~30-100 kg S/C main propulsion, formation flying

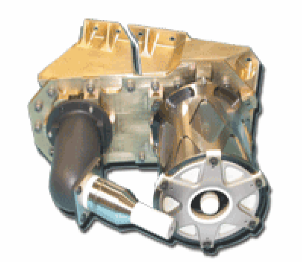
- For main delta-v propulsion of 30-100 kg spacecraft if power > 20 W is used.
- Well-suited for near-Earth/lunar/interplanetary missions where high delta-v is needed due to relatively high specific impulse (3000 s).
- Low thrust requires long mission trip times - spiral trajectories.
- Special applications include formation flying of a constellation of spacecraft, or drag make-up in low Earth orbits.

Status:

TRL 4. Laboratory development/component verification

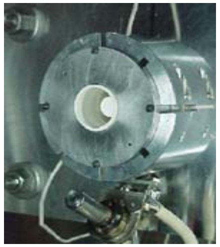
- Based on proven (TRL 9) Ion engine technology (i.e., Boeing's 13 and 25 cm thrusters (116 thrusters on 29 GEOSATS) and NASA's 30 cm NSTAR (DS-1, DAWN).
- Extensive flight history of larger-scale thrusters (SERT I - 1964, SERT II - 1970, Boeing XIPS 1997-present, NSTAR 1999-present)
- Power processing unit (PPU) to be developed. PPU challenges minimized by low power levels.
- Miniature feed system to be developed. Mass/complexity will be reduced with simple proportional flow control.

Hall Thrusters



Busek BHT-200 Hall Thruster
Power: 200 W
Thrust: 13 mN

First US Hall thruster to be operated in space (TacSat-2, Dec. 2006)



Cylindrical Hall Thruster (CHT)
Princeton Plasma Physics Laboratory (PPPL)

Power: 50-170 W
Thrust: 3-6 mN

Description:

- **Electromagnetic thruster concept where ions are accelerated in crossed electric and magnetic fields to produce thrust.**
- **Quasineutral plasma increases thrust density compared to gridded ion thrusters**
- **Uses non-contaminating xenon propellant.**
- **Many Russian models - this technology was preferred EP choice in the former Soviet Union. Now being adopted by nearly every GEO satellite provider worldwide.**

Supplier	Designation	Power (W)	Thrust (mN)	Isp (s)	Efficiency	Mass (kg)	Dia (cm)	TRL
Busek	BHT-200	200	13	1390	44%	> 1	2.9	9
KIAE (Russia)	SPT-25	100-200	5-10	900-1300	25-32%	~ 1	2.5	3
MIT	MHT-9	30-200	1-10	300-1500	5-25%	< 1	0.9	3
PPPL	CHT	50-170	3-6	1200-2000	30-40%	< 1	2.6	3

Application:

>100 kg S/C for drag makeup, attitude control, & orbit insertion

- **Presently limited to >100 kg spacecraft due to mass, volume, and power demands for complete subsystem.**
- **Moderately-high specific impulse (1000-2000 s) trades well for applications near large bodies where thrust offsets gravity losses**

Status:

TRL 9 at >200 W power. TRL 3 at ~10-100 W.

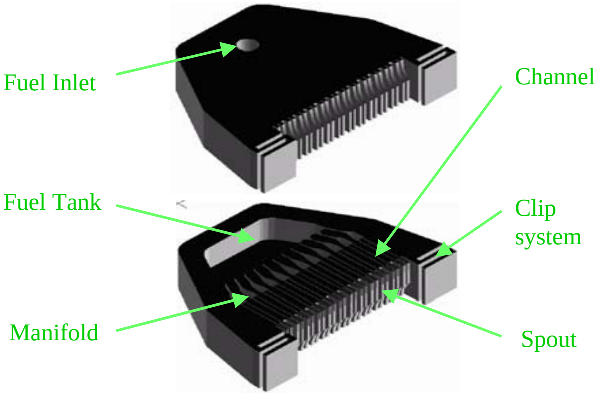
- **Hall thruster technology has reached TRL 9 for >200 W models. Over 200 thrusters have flown on Russian, European, and US space missions since 1971.**
- **Low-power laboratory thrusters (TRL 3) have been tested. Significant miniaturization of thruster, power system, and feed system would be needed for CubeSat applications**

Micro-fabricated Colloid and FEEP

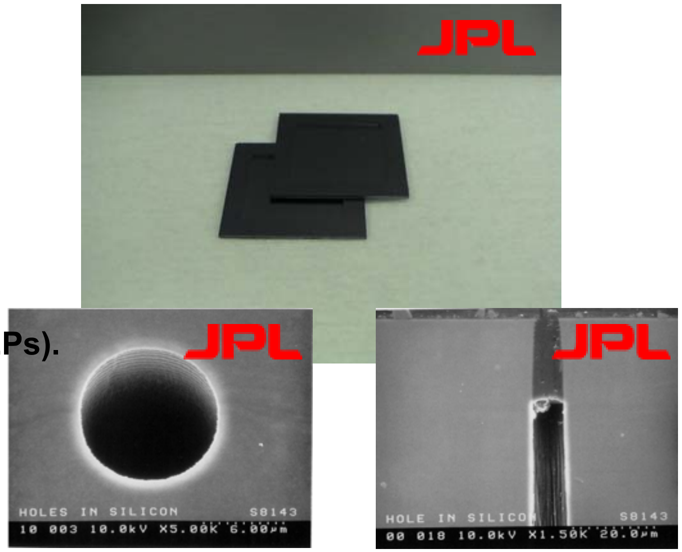
Description:
- Micromachined versions of colloid thruster technology.
- Micromachining allows for the precise fabrication of a much greater number of emitters than in conventional approaches.
- Since emitter tips are on micron-scale for conventional architectures, increased number of emitter tips may result in increased thrust levels at smaller device mass and volume for micromachined devices.

Status:
- Laboratory development - feasibility studies.
- Micro-colloid/FEEP work past and ongoing at MIT (in collaboration Yale U, Busek Corp.), Almeda Applied Sciences (AASC), JPL, SRI International, Sandia, U. Southampton/UK, Kings College/UK.
- TRL ~2-3.

Key Technology Characteristics:
- Application: Constellation control, even of large constellation craft, attitude control, small delta-v of micro/nanosats (constellations).
- Very high precision thrust and impulse bits.
- Widely scalable thrust levels by adjusting number of emission sites per chip.
- Relatively high thrust-to-power for electrostatic devices (colloids, not FEEPs).
- Compact propellant storage.
- Low TRL - requires substantial development.
- Neutralizer development, contamination studies, etc. required as for larger scale devices.



MIT Micro-Colloid Concept



JPL Micro-Colloid Test Fabrication Articles

JPL Micro-Thrust Propulsion Facilities

JPL Micro-Thrust Propulsion Laboratory

MiXI Thruster installed in JPL vacuum facility

HmNT Feedsystem installed on JPL Milli-Newton Thrust Stand

- JPL Micro-Thrust Propulsion Laboratory includes:
  - 2m diameter x 2m long Ultra-High Vacuum (UHV) environment for testing precision microthrusters
  - Class-10 clean room environment
  - Nano-Newton Thrust Stand for performance measurement
  - Exhaust beam profiling and contamination diagnostics
  - Load-lock system for rapid turn around and in-situ thruster inspection
  - Long-duration unattended operation for microthruster lifetesting
- Hydrazine Test Facility includes milli-Newton Thrust Stand
- Multiple smaller vacuum facilities for prototype development and thruster testing with fast turn around

Summary of Propulsion Candidates for CubeSats

- **A limited number of thruster technologies are emerging that may satisfy propulsive needs and fit the Cube Sat design envelope.**

- **Chemical Thrusters: Higher thrust, lower Isp for slew and limited delta-v**
  - **Cold Gas Thrusters:**
    - Small size and mass of components, however, limited Isp performance suitable to only ACS or very limited delta-v
    - System integration issues of high-pressurant tanks: system mass and total impulse issues.
  - **Butane Thrusters:**
    - Recently developed by VACCO Industries for a JPL micro-inspector spacecraft. Previoulsy explored on Surrey SNAP-1A.
    - Butane thruster combines simplicity and low mass of a cold gas system with compact, low mass liquid propellant storage, and piezovalve technology for low-power operation
  - **Hydrazine thrusters:**
    - Hydrazine thrusters are the workhorse for attitude control and small delta-v on conventional S/C.
    - A hydrazine milli-Newton thruster (HmNT) is under development at JPL, primarily for precision attitude control of larger spacecraft - it may potentially serve as main propulsion on CubeSats.
    - Issues are system integration (valves, filters, tanks) and safety issues due to hydrazine use (may not be compatible with low cost Cube Sat missions).
  - **Solid Motor Kick Stages:**
    - Small solid motors with sufficient burn duration (e.g. ATK STAR 4G) may be used as kick stages for Cube Sats similar as for larger spacecraft.
    - Need for separate (liquid) propulsion system for orbit trimming, ACS or spin-up/spin-down.

Summary of Propulsion Candidates for CubeSats - cont'd

- **Electric Propulsion: Precision attitude control or high-Isp delta-V**
  - **Miniature Ion Propulsion (MiXI):**
    - JPL developed miniature ion engine technology may satisfy Cube sat design envelope for multi-cube (3-cube "brick", 6 cube "six pack") architectures with deployable arrays.
    - Power limitations may require MiXI to be operated in throttle mode at limited thrust, however, at T/W ratios not unlike on larger EP propelled spacecraft.
  - **Vacuum Arc Thruster:**
    - Developed by Almeda Applied Sciences for micro- and formation flying control
    - Cube sat architectures have already been explored (single cube).
    - Primarily suited for attitude control due to inherently pulsed operation and low total impulse.
  - **Pulse Plasma Thrusters:**
    - Smaller PPT versions have been developed for micro-sat application (Dawgstar).
    - Primarily suited for attitude control due to inherently pulsed operation and low total impulse.

Conclusions

- **Some existing, and some newer thruster developments may be "borderline" applicable to Cube Sat design envelopes.**

- **Besides thruster performances and component size and mass, integration issues have to be considered:**
  - Need for improved subsystems, high pressure tanks
  - Power issues

- **Some newer developments offer exciting applications:**
  - VACCO developed Butane thrusters combine low power piezovalve technology and low-pressure compact propellant storage for efficient attitude control and low delta-v in a simple system.
  - JPL developed Miniature xenon ion engine technology (MiXI) offers potential of exciting new CubeSat missions requiring high-delta-V for large (multiple cube) Cube Sat busses using deployable arrays.