YEAR OF 2004 - SMALL SATELLITE PROPULSION CHALLENGES

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Introduction

Small satellite (<100kg) propulsion is a primary subject of the following discussion.

Propulsion significantly enhances spacecraft's maneuverability transforming it into space vehicle.

Propulsion is on demand for advanced small satellites for the following reasons:

- Small satellites are usually launched as a secondary payload. The limited number of such opportunities restricts variety of satellite orbits. Small satellite onboard propulsion can be used for final orbit insertion, and thus, extends variety of available small satellite orbits.
- Atmospheric drag compensation extends the spacecraft's lifetime.
- Recent interest in satellite constellations deployment (formation flying) for Earth observation, communications, astronomy, and science purposes requires propulsion capability for spacecraft to be inserted into desired orbit, maintain or change orbit throughout mission.
- Recent demand for big spacecraft inspection and service (space station, space shuttle, *Hubble*, etc.) in orbit requires propulsion for spacecrafts' proximity operations including small satellite docking.
- Prospective asteroid sample return missions would require landing and take-off propulsion capabilities.

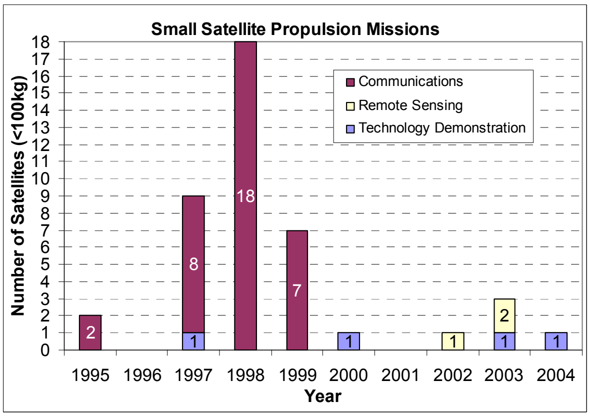

Fig. 1

Deployment of *Orbcomm* small satellite constellation employing nitrogen cold-gas propulsion for station-keeping in late 1990s (see Fig. 1) raised a hope for rapid growth of small satellite propulsion market. Despite the anticipation, following the peak of *Orbcomm* communication satellite constellation deployment in 1997–1999, the number of small satellites equipped with propulsion dropped down to few technology demonstration and remote sensing missions since year of 2000.

Reasoning

Recent sharp drop in small satellite propulsion mission number is due to several commercial and technical reasons.

Severe commercial competition for future space communications market in the late 1990s resulted in simultaneous deployment of three satellite constellations, *Iridium* (1997–1998), *Globalstar* (1998-2000), and *Orbcomm* (1995–1998) causing abundance of services at present. In such a situation there is no need in another small satellite communication constellation that would require propulsion.

Failure of *Mir* space station inspection by small remotely-controlled *Inspector* satellite in 1997 cast a shadow on future propulsion missions of this kind. Besides, *International Space Station* (*ISS*) inspection and services by long-arm manipulators or walking robots are, perhaps, more convenient and safe alternatives.

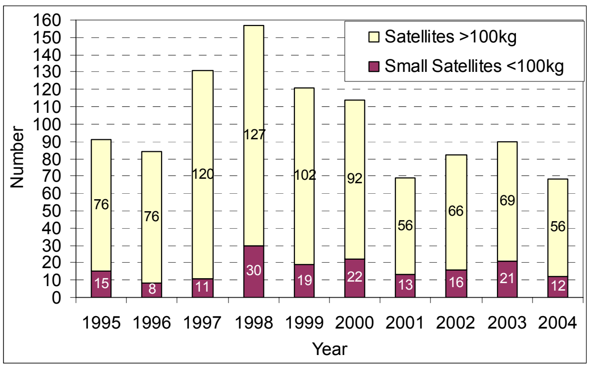

Fig. 2

Current low demand in small satellite propulsion is caused by low need in small satellites in general (see Fig. 2), due to poor performance of their <100kg payloads comparative to technologically-advanced (>500kg) satellites carrying bigger payloads.

Finally, the shortage of small satellite propulsion missions at present is caused by poor performance of existing small satellite propulsion systems. For the most of the propulsion missions, space vehicle velocity changes (ΔV) on the order of >50m/s are desirable while the existing small satellite propulsion systems can provide only 3–24 m/s. [[1]-[3]]

Propulsion Challenges

One of the most important reasons for poor performance of existing small satellite propulsion is that the unique challenges imposed on propulsion system by the spacecraft's small size have yet been resolved.

Launched as a secondary payload, small spacecraft is a subject to unique constraints. As soon as it fits within a margin between total payload lifting capacity of the launcher and primary payload, its mass is of secondary importance. Typically for heavy launchers (such as, for example, the *Ariane* family of launchers) with lifting capacity of several tones, a few extra kilos of auxiliary payload mass margin is only a fraction of percent of primary payload mass. This value is of the same magnitude as uncertainty of primary payload mass. At the same time this mass can comprise a whole spacecraft propulsion system or a small satellite. Unfortunately the similar logic cannot be applied for small satellite volume. This is because the space under the fairing is usually so tight that even the primary payload needs to be optimized to fit in. Hence, volume is often the most severe constraint for small spacecrafts due to the shortage of space available under the fairing. Therefore, small satellites are usually designed to be compact. Tight envelope, in turn, imposes constraints on small spacecraft subsystems such as propulsion and power. Since propulsion system relies on power generated onboard the spacecraft the last one also becomes a major constraint. Space-limited, the existing power systems (typically using Si or Ga/As solar arrays and Ni-Cd batteries) are capable of supplying small satellites with limited power. Deployable solar panels would increase the small satellite power budget as well as its complexity (Sun-pointing, deployment mechanisms, etc.) and cost. Typical values of constraints for small satellites are given in Table 1.

Table 1

Constraints	**Pico-**	**Nano-**	**Micro-**
Mass, kg	<1	1-10	10-100
Propulsion Volume, L	<0.5	<15	<100
Power, W	2.4	6-14	14-160
Cost, €	40K	1M	2-4M

Constrained by available space and power, small satellite propulsion systems are often limited by cost. This is a major constraint for small satellite propulsion, since it prevents using the latest high-performance technological achievements in the area. With application of modern, high-performance space propulsion technologies, the cost of a small spacecraft can be easily doubled, tripled, etc. For most of the small satellite missions this cost rise is unacceptable since it defeats the purpose of "affordable access to space". Low cost involves many different aspects such as: inexpensive propulsion system components, hardware and propellants; minimum labor; "safety overheads" and service, and limited testing. Expensive "safety overheads" are usually associated with application and handling of toxic, flammable, and explosive propellants. Flight qualification testing is a long and expensive process. Its cost can be easy comparable with the cost of whole small spacecraft or even a number of them. In this case, limited qualification testing is a compromise between spacecraft and its propulsion qualification costs.

Along with the constraints, a small satellite propulsion system is a subject of common and unique requirements. A propulsion system must provide spacecraft with necessary propulsion functions to fulfill its mission. Propulsion systems are expected to deliver high performance, and remain reliable throughout their mission. It should be easy to integrate into a spacecraft, service, and maintain. Often a small satellite has already been built and lingers for suitable launch opportunities, or during its production it is reassigned to another launch. Therefore, it is desirable that small satellite propulsion system be flexible to cope with changes in the mission scenario.

Solutions

Enhancement of propulsion system ΔV capabilities would stimulate further increase in number of small satellite propulsion missions. Often in propulsion community such an enhancement is associated with improvement of specific impulse performance. Analysis [[4]&[5]] of ideal rocket equation ((**1**), however, reveals that ΔV enhancement by specific impulse improvement is only efficient if:

$$\Delta V = -I_{sp} g \ln\left(\frac{M_f}{M_i}\right) \qquad \mathbf{(1)}$$

$$\frac{M_f}{M_i} < \frac{1}{e} \approx 0.37$$

where ΔV – vehicle velocity change, m/s; g – acceleration of gravity, 9.81m/s^2; I_{sp} – specific impulse, s; M_f – final vehicle mass, kg; M_i – initial vehicle mass, kg.

Table 2

Satellite Name	***M_i, kg***	***M_f/M_i***
SNAP-1	6.5	0.995
NS-1	25	0.991
AlSat-1	98	0.976

Meanwhile, data for existing small satellite equipped with propulsion demonstrate (see Table 2) the opposite:

$$\frac{M_f}{M_i} > \frac{1}{e} \approx 0.37$$

In this situation specific impulse improvement is much less efficient than reduction of vehicle mass ratio (M_f/M_i). Reduction of vehicle mass ratio can be achieved by increase in propellant loading (M_p) or reduction of vehicle's dry mass.

Increase in propellant loading ($M_p = \rho_p V_t$) can be achieved by increase in tank's volume (V_t) or application of higher density (ρ_p) propellants. The both ways have their limits: propellant tank's size cannot exceed propulsion system envelop while density cannot exceed theoretical value for given substance.

In small satellite propulsion denser liquefied gases (butane, ammonia, nitrous oxide) have already replaced non-liquefied ones (nitrogen, hydrogen, helium) for higher propellant loading. [[1]-[3]]

Reduction of vehicle's dry mass can be done by mass-optimization of propulsion system hardware or the rest of the vehicle. For the simplification of the further analysis the author recommends to represent these shares in the form of mass ratios [[6]]:

$$f_{pd} = \frac{M_{pd}}{M_{PS}}$$ – propulsion dry mass fraction

and

$$m_r = \frac{M_{rp}}{M_{PS}}$$ – mass ratio

where $M_{PS} = M_{pd} + M_p$ – propulsion system mass, kg; M_{pd} – propulsion dry mass, kg; M_p – propellant mass, kg; $M_{rp} = M_i - M_{PS}$ – mass of the rest of the spacecraft (payload, structure, etc.) excluding propulsion, kg.

Whence, vehicle mass ratio can be written as:

$$\frac{M_f}{M_i} = \frac{m_r + f_{pd}}{m_r + 1} \quad (2)$$

Equations (and (together demonstrate that reduction in propulsion dry mass

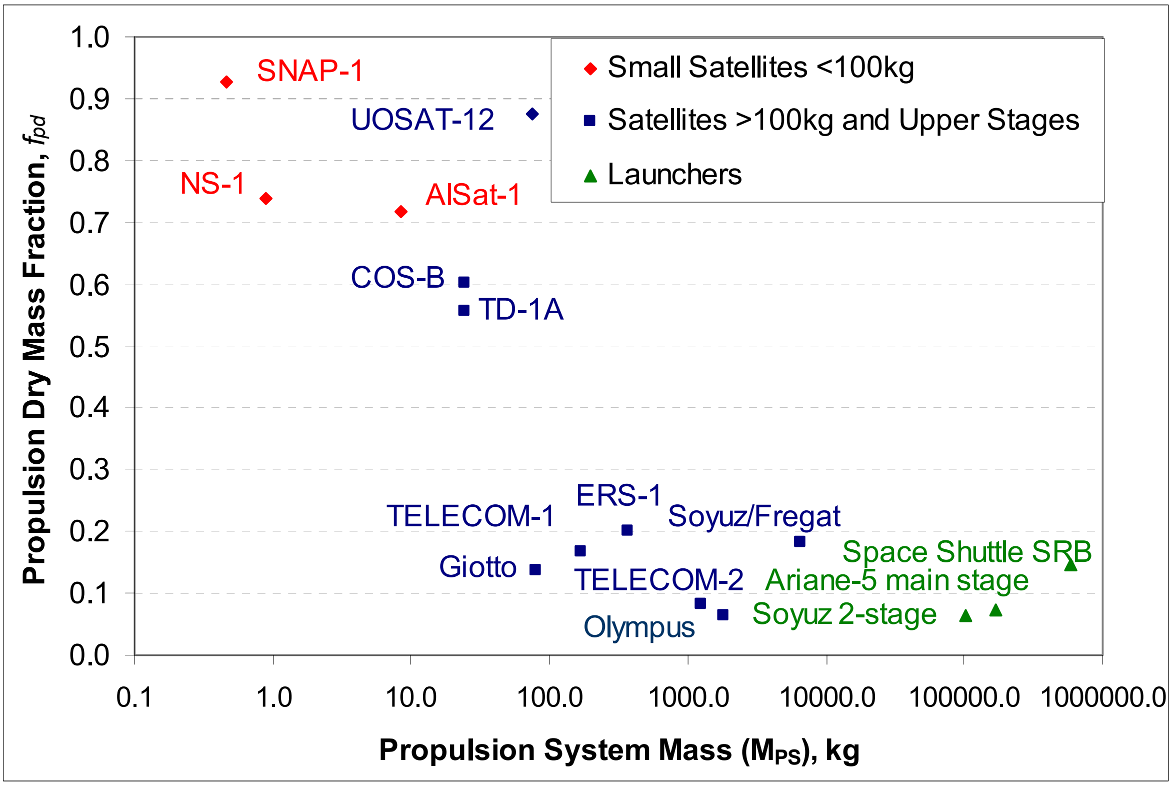

Fig. 3

fraction (f_{pd}) is beneficial for ΔV performance enhancement. At present dry mass fractions of small satellite propulsion are much higher (≥72%) than those ones for big spacecrafts (<20%) (see Fig. 3 and Table 3). Such exceedingly high propulsion dry mass fractions bring ΔV performance for small satellite propulsion down to <28% of its maximum theoretical value (see eqs. (& (, and Fig. 4), and are mainly responsible for poor performance of existing small satellite propulsion systems.

Table 3

Satellite Name	f_{pd}	m_r
SNAP-1	0.93	13.3
NS-1	0.74	27.4
AlSat-1	0.72	10.7

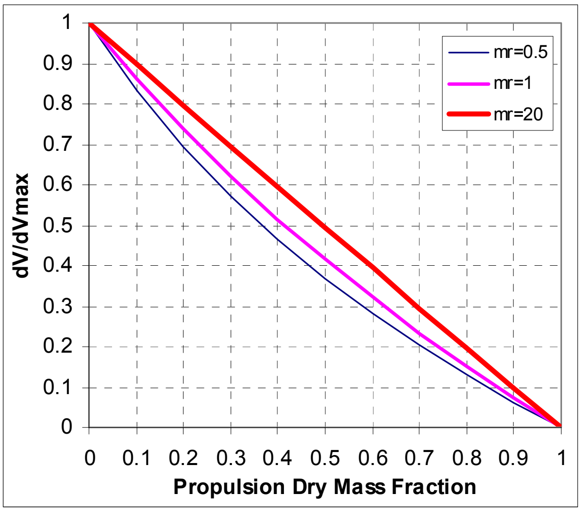

Fig. 4

Lack of miniature propulsion system components such as thrusters, valves, pressure regulators, etc. on market is a main reason for high small satellite propulsion dry mass fractions at present. In this situation small satellite propulsion system manufacturer has to either make them by himself or adopt heavier components existing on market.

The problems that have to be tackled for propulsion components miniaturization are not only of technical but often fundamental kind. Small size (<0.3mm throat diameter) nozzles for low thrusts (<0.1N) generation are challenging to manufacture. They tend to be easily blocked by small particles upstream the feed-line. The further reduction in size may cause flow continuity brake-up resulting in failure of nozzle application for thrust generation. [[7]&[8]] Heat transfer intensification during scaling-down may result in exceedingly high heat losses overtaking heat generation inside thruster's reaction chamber, thus causing failure of conventional chemical propulsion application. [[7]&[8]] Long-term in-orbit storage of small amount of propellant onboard space vehicle imposes severe leak-tight requirements on valves. Typically the requirement for external leakage in existing cold-gas thruster is set to <1scc/min (for gaseous nitrogen), then the propellant loss is <0.6kg a year. Although for 10kg propellant loading this is only <6% of total mass, for 1kg – this corresponds to <60%. Hence, since the same leakage acceptable for bigger propulsion system can be catastrophic for small one, the leak-tight requirement for small propulsion systems must be higher (i.e. <0.1scc/min for the example) or mission duration should be decreased correspondingly. In such a case even tiny obstacle (intruder-particle, micro-crack, or geometry mismatch) residing on valve's seat can cause catastrophic loss of propellant.

Manufacture of miniature propulsion system components, therefore, requires significant research and development (R&D) efforts. Big aerospace companies are careful investing in such R&D work till they see big business coming. Since small satellites are cheap (see Table 1) it would require building them in bigger numbers (perhaps, dozens or hundreds) than now (see fig. 2) to get those companies interested. While the big companies wait for big contracts coming, the majority of small satellites is built by universities and small business companies whose R&D budgets are limited. With the aid of limited governmental R&D grants these universities and small businesses have chosen the strategy of adopting existing too big and heavy propulsion components for small satellite propulsion, thus sacrificing performance to cost.

Without miniature components it will be not possible to achieve reduction of small satellite propulsion dry mass fraction to the same value as for big systems (see Fig. 1). Meanwhile, an improvement can still be suggested.

Propellant selection is critical for propulsion. Denser propellants not only increase propellant loading but also reduce propulsion dry mass fraction. Self-pressurized propellants eliminate a need in expulsion system, thus reducing propulsion hardware mass. Application of single fluid propellant for all propulsion modes required for mission accomplishment will not only save propulsion hardware mass in comparison to different propellants stored in different tanks but also make propulsion flexible to mission scenario change. Liquefied gases (nitrous oxide in particular) were identified by the author to fit the above description the most. [[8]-[11]]

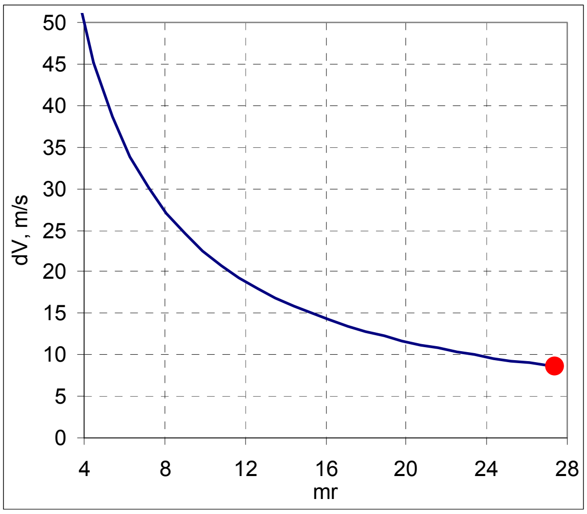

Fig. 5

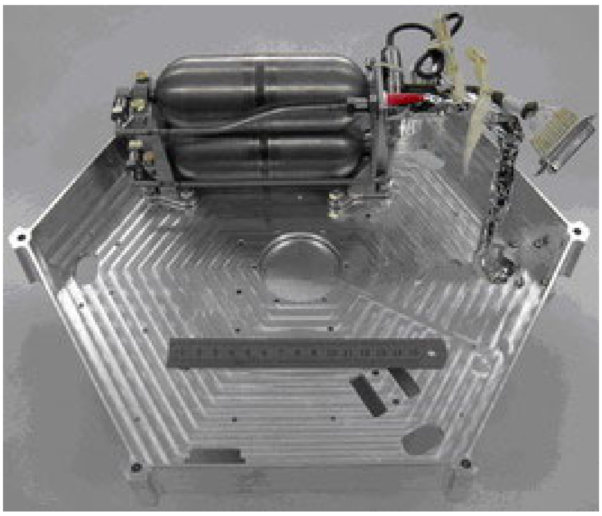

Fig. 6

Small satellite mass-optimization is another way for significant improvement of its propulsion ΔV performance. Because the majority of small satellite missions flown up-to-date lack propulsion, and mass constraint for such a secondary payload (as it was explained earlier in this paper) is typically very relaxed, most of the small satellites have never been mass-optimized. Moreover, the majority of small satellite builders have yet understood the importance of mass-optimization for propulsion ΔV performance. This majority considers propulsion as a satellite subsystem of secondary importance, and it tends to bolt propulsion system to the spacecraft to the place where some spare space has been left from the other subsystems. This approach results in high m_r ratios (see eq. 2 and Table 3). Such high m_r ratios bring ΔV propulsion performance down (see eqs. (().

Mass-optimization will help to reduce m_r ratio for small satellite propulsion missions, and therefore, results in higher ΔV performance. The particular example of potential ΔV performance benefits for *NS-1* small satellite due to mass-optimization is given in Fig. 5. This figure demonstrates that depending on the progress in m_r ratio reduction ΔV performance of *NS-1* propulsion will progressively increase from current ΔV=8.6m/s value. Reduction of m_r ratio for *NS-1* can be achieved by replacing its current, heavy modular box (see Fig. 6) stack structure with more advanced, lighter design. In such a design propellant tank function should be extended from only storing propellant onboard to become a supporting structure for the spacecraft.

Solution for Interplanetary Missions

Mass requirement along with the other design margins limits propellant mass stored onboard small satellite to <100kg severely restricting small space vehicle velocity change while propellant leakage limits propulsion lifetime as well. This makes small satellite interplanetary missions involving rocket propulsion challenging. In this situation application of propellantless propulsion such as, for example, solar sail is a way to enhance ΔV performance and extend propulsion lifetime since the both are no longer functions of propellant stored onboard.

Summary

Poor ΔV performance of existing systems is among the main technical reasons responsible for sharp drop in small satellite propulsion mission numbers since 1999. The performance enhancement requires significant R&D efforts to create advanced technologies capable to cope with unique constraints and requirements associated with small satellite propulsion. For the time being mass-optimization of small satellites and their propulsion systems are more efficient for ΔV performance enhancement than specific impulse improvement. Application of propellantless propulsion (solar sail in particular) is the way to extend small satellite propulsion missions to interplanetary scale.

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