Survey of the State-of-the-Art in Micro-Thrust Propulsion

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New classes of space missions are emerging within the European Space Agency (ESA), the National Aeronautics and Space Administration (NASA), and the defense communities. These missions consist of constellations or formations of multiple spacecraft. Per definition, in formations multiple spacecraft form a single large instrument distributed amongst the formation, such as an interferometer, for example, and typically require a much tighter attitude control than in a constellation. In a constellation, on the other hand, each spacecraft is equipped to perform measurements individually, to be assembled into large data arrays. These spacecraft may be very small, such as in the NASA Magnetospheric Constellation, which aims to use dozens of 10-kg spacecraft to map the magnetic field around Earth, or large, as in future formation flying missions aiming to detect Earth-like planets around distant starts, such as NASA's Terrestrial Planet Finder (TPF), or ESA's Darwin missions.

As a result of severe attitude control requirements, or small spacecraft size, a unique requirement for micro-thrust propulsion devices emerges. In the case of formation flying missions, this translates into high-precision thrust requirements of micro-Newtons to a few milli-Newtons, ideally at high specific impulses (> 500 sec) in order to be operated quasi-continuously, with the additional requirement of contamination-free propellants to protect sensitive optics of interferometer experiments. Size and power are typically not severely constrained on large formation flying spacecraft, hence thrust devices may be physically large, as represented by state-of-the-art thruster hardware. For constellation missions, attitude control requirements may be reduced, and the small size of these spacecraft may make very small thrust values necessary, perhaps in the micro- to milli-Newton range as well. In addition, low power requirements of perhaps 1 W or less, and small size and weight (grams) are required to fit multiple thrusters on very small spacecraft to provide 3-axis stabilization.

Multiple research activities are ongoing around the world to address these propulsion needs. The present paper seeks to provide a state-of-the-art survey of new developments and significant advances made in this area. According to the applications discussed above, technologies will be separated in high-specific impulse, precision micro-thrust devices for formation flying missions, and new micropropulsion developments for microspacecraft.

Among high-specific impulse, precision thrust devices, field emission electric propulsion (FEEP), colloid thrusters, pulsed plasma thrusters (PPT), vacuum arc thrusters (VAT), and miniature ion thrusters will be surveyed. Although many of these devices have been studied for some time, new developments have taken place in both Europe and the US in response to new missions, such as those discussed above.

Among micropropulsion devices, cold gas thrusters, vaporizing liquid thrusters, so called digital solid micro-motor arrays, and new electric propulsion options, such as micromachined colloid thrusters will be surveyed. Each section will provide a description of concept, performance data obtained to date, and list remaining technical issues and additional work required.

As will be shown, precision thruster technologies have reached relatively high levels of technical maturity due to many years of previous research and development work, flight experience, or recently planned flight activities, such as the formation flying pre-cursor missions Smart-II of ESA and NASA's New Millennium ST-7. Micropropulsion devices, in particular those involving MEMS, on the other hand, are still relatively early in their development stages, as are their intended applications, i.e. microspacecraft missions. However, crucial initial performance measurements have been obtained, and system integration issues are now being addressed.