Flight heritage and design updates of the ENPULSION propulsion systems

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***Abstract*— The first ever flight of a Field emission electric propulsion (FEEP) thruster occurred in 2018 using an ENPULSION NANO thruster. Since then, more than 200 heritage ENPULSION NANO systems, 20 higher power MICRO R^3 systems and 40 novel NANO R^3/AR^3 systems have been launched. FEEP propulsion systems are based on passively fed, Indium based liquid metal FEEP technology based on liquid metal ion source heritage developed at FOTEC. In these systems, thrust is generated through electrostatic acceleration of ions extracted from a liquid propellant by suspending the liquified metal propellant in porous, sharp emitter features. This emitter, including propellant, is then biased to high voltage with respect to a counter electrode called extractor to induce a Taylor cone, leading to ion emission at the apex of the Taylor cone. To increase thrust, 28 emission sites are arranged in a characteristic crown shaped emitter geometry for the NANO thrusters, achieving thrust levels in the order of 350 µN. To increase thrust levels, 4 of these emitter crowns are operated in parallel in the MICRO R^3 thruster, allowing thrust levels at nominal 1 mN. Depending on emitter and extractor voltage settings, propulsion systems can be operated in a specific impulse range from approx. 1000 to beyond 4000 s. This work provides a statistical overview of available onorbit data by expanding the flight heritage description to the new propulsion system generations and presenting lessons learnt from onorbit operations. Based on these learnings we will provide a status update of the different products of NANO, NANO R^3/AR^3 and MICRO R^3 thrusters.**

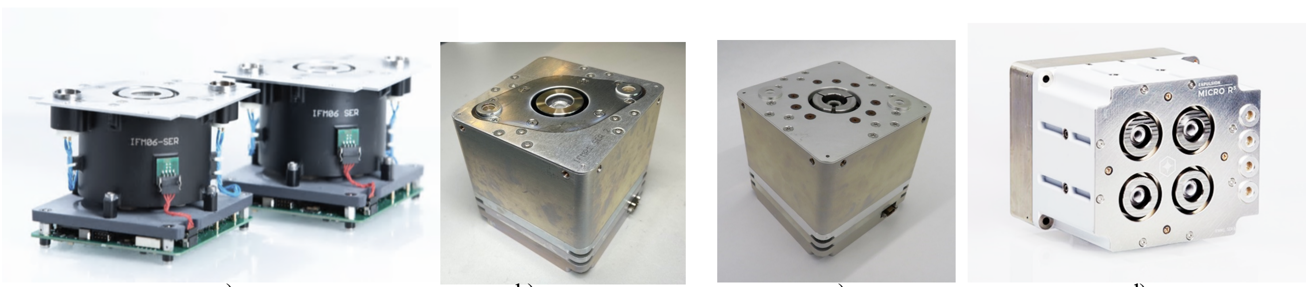
Keywords—FEEP, field emission electric propulsion, electric propulsion, small satellite propulsion, flight heritage

I. Introduction

Field Emission Electric Propulsion (FEEP) have a long heritage building on liquid metal ion sources [1]-[4]. They utilize electrostatic forces to extract, ionize and accelerate propellant from a bulk liquid metal. In the ENPULSION FEEP, liquefied Indium is fed by capillary forces from an integrated propellant reservoir to a porous multi emitter, which arranges 28 sharp needle emitters in a circular pattern. This emitter is biased to high voltage in positive polarity with respect to a negatively biased extractor electrode surrounding the circular ion emitter. The electrical pull on the propellant becomes large enough for the establishment of so-called Taylor cones on the tips of the needle ion emitters, and the electrical field at the apex of these Taylor cones is able to surpass the threshold for ion emission. Ions generated at these locations are then accelerated within the potential drop towards the high transparency extractor electrode, thereby generating thrust. To prevent spacecraft charging due to the emission of positive ions, a neutralizer is used to ensure emission of a negative electron current whenever ion emission is active.

Utilizing an inert propellant that is solid during ambient conditions and is only liquefied after launch allows to ship and integrate the propulsion systems fueled and obviates any active means of propellant containment during launch.

The NANO, NANO R^3 and MICRO R^3 propulsion systems are fully integrated electric propulsion systems including ion emitter, neutralizer, propellant reservoir and power electronics (power processing unit). By actively controlling both emitter and extractor voltages, the propulsion systems can be operated over a wide range of thrust and specific impulse, including independent control of both parameters by decoupling ion emission current from the absolute ion acceleration voltage. The different types of propulsion systems are shown in Fig. 1. The NANO propulsion system (Fig. 1 a) was the first FEEP system to be verified in space. and can provide 350 µN for a total system power input of 40 W including propellant heating and neutralization. A variety of onorbit telemetry is available



a) b) c) d)

Fig. 1: ENPULSION FEEP propulsions systems that have achieved space heritage: a) NANO b) NANO R^3, c) NANO AR^3 and d) MICRO R^3

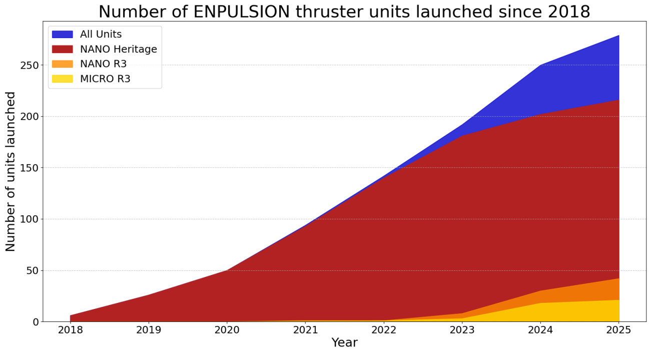


Fig. 2 Launch evolution of the FEEP propulsion systems

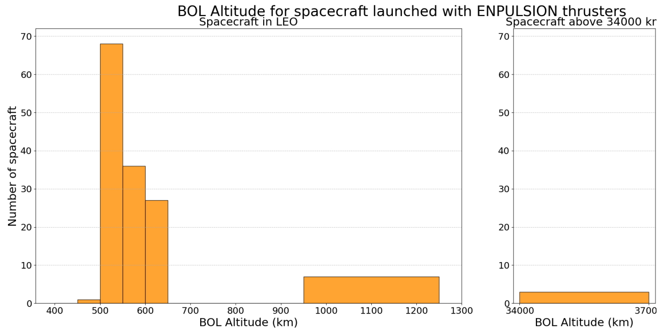


Fig. 3 BOL altitude distribution of spacecraft using FEEP propulsion systems

[5], [10] showing the operational characteristics of the system including propellant liquification.

Building on the extensive flight heritage gained by the NANO propulsion system and lessons learnt [6], two successor products were developed: The NANO R^3 [7] as direct successor of the NANO thruster and the NANO AR^3 which additionally includes thrust vectoring capability by spatially throttling regions of the ion emitter, therefore allowing to control the thrust vector [8]. While both products share similar performance parameters to the heritage NANO thruster, they feature improved electronics design and parts quality, more robust integration concept and automatic thruster control features.

The MICRO R^3 is a higher power and thrust unit that is based on the same heritage ion emitter, parallelizing 4 ion emitters increase maximum available thrust, increasing the total system input power to above 100 W [9] .

These FEEP propulsion systems have been tested in multiple external facilities including direct thrust and beam diagnostics measurements [8], [13],[14].

II. Flight Heritage

A. *Onorbit telemetry and longest firing*

All of the FEEP propulsion systems in Fig. 1 have achieved flight heritage on multiple systems and on multiple spacecraft, with the longest accumulated thrusting times above 2000 hours of thrust generation, and significantly longer times of accumulated propellant liquification (>10 000 hours).

B. *Launch statistics*

In 2018, the NANO thruster (former: IFM Nano thruster) became the first FEEP propulsion system to achieve space heritage. The in orbit demonstration was conducted onboard of a Nanosatellite [10][11] together with FOTEC, which allowed for the first time ever to compare the existing thrust model developed during ground testing to the in-space performance. Comparison of orbital altitude change expected by thrust model based on measured ion emission current and emitter and extractor voltages to independent GPS measurements confirmed validity of the thrust estimated by the propulsion system onboard electronics within the measurement accuracies achieved by the GPS determination [10].

Since then, 216 NANO thruster have been launched on more than 100 different spacecrafts.

The successor products NANO R^3 and the NANO AR^3 were first launched in in the first half of 2022, with steadily increasing launch cadence as they start replacing the heritage NANO thruster. To date, 42 propulsion systems have been launched, on 39 different spacecraft.

Note that the numbers quoted for NANO and NANO R^3 do not include propulsion systems lost in launch failures.

The higher power MICRO R^3 was first launched in the first half of 2022, with currently 21 propulsion systems launched.

Fig. *2* shows the launch evolution of FEEP propulsion systems since first ion orbit demonstration in 2018.

C. *Orbit altitude distribution and applications*

Fig. 3 shows the distribution of beginning-of-life (BOL) altitudes of the spacecraft carrying ENPULSION FEEP propulsion systems. This shows the bulk of systems deployed in low earth orbit, with peak in the BOL range of 500-550 km altitude, and decreasing number for 550-600km and 600-650km. This is in line the commercial nature of the majority of customers addressing different earth observation applications.

In addition to the majority of propulsion systems in LEO below 700km, there are a number of spacecraft with ENPULSION FEEP systems deployed in the range of 950–1250km.

It is also notable that several spacecraft equipped with ENPULSION FEEP propulsion systems are deployed in or

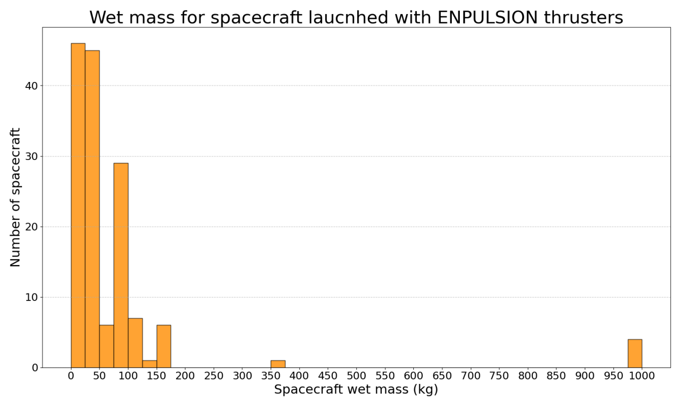


Fig. 4 Mass distribution of spacecraft using FEEP propulsion systems

near GEO altitudes, with applications including orbit insertion, transfer between slots and momentum wheel desaturation [12].

D. *Spacecraft sizes and applications*

Fig. 4 shows a distribution of spacecraft masses carrying ENPULSION FEEP propulsion systems. This plot is generated from publicly available mass data of spacecraft. The majority of spacecraft carrying FEEP systems to date is in the range up to 50kg and 75 to 100kg spacecraft initial mass. Several larger spacecraft have been deployed with FEEP systems, including spacecraft of 150-175kg and approximately 1 000 kg (employing multiple FEEP systems), showing the versatility with regards to the platforms the standardized FEEP propulsion systems have been integrated in.

The standardized propulsion systems are not only used in a wide variety of platforms, but also cater to different applications. To date, the standardized FEEP propulsion systems have been used in the following applications:

- Orbit acquisition
- Constellation Rollout
- Formation control
- Precise ground track
- Conjunction avoidance
- Momentum desaturation

In addition, multiple propulsion systems are planned to be used for deorbiting purpose once the spacecraft end of life is achieved.

III. NANO R^3 STATUS AND INTERFACE UPDATE

Direct thrust measurements of the NANO R^3 have been conducted on FOTEC's micro thrust balance and reported in [15]. Fig. 6 shows a measurement plot with stepwise increasing thrust levels up to 0.4mN. The plot compares measurement output from the micro thrust balance to the thrust computed by the NANO R^3 using the internal thrust model based on measured electrical parameters including the emitted ion current.

The standardized propulsion system approach used in all ENPULSION FEEP systems allows to rapidly gain flight experience over a wide range of spacecraft bus types, applications and orbits, allowing to infuse lessons learnt

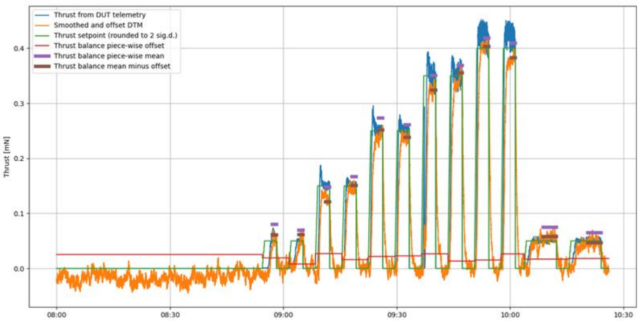


Fig. 6 Thrust measurements of the NANO R3 performed at FOTEC thrust balance comparing directly measured thrust to thrust calculated by the onboard electronics based on telemetry measurements [15].

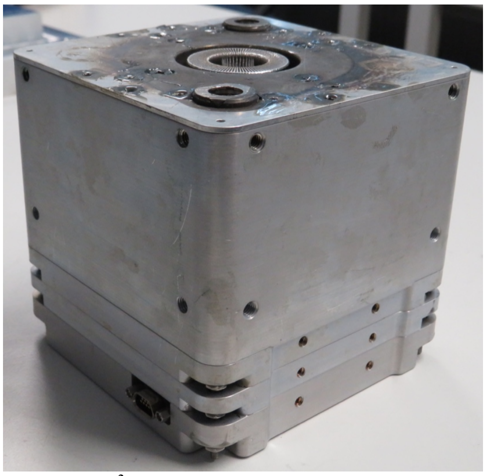


Fig. 5 NANO R^3 EM with additional mechanical interface

across different missions as discussed in [6] and lead to design updates. Based on key customer feedback, an additional option for mechanical interface was added to the NANO R^3 design. An Engineering model (EM) of the updated thruster design is shown in Fig. 5, exhibiting significant vacuum chamber backflow after testing.

Recently, thermal correlation tests were performed to correlate the thermal model to experimental data. Fig. 7 shows the propulsion system mounted inside a protective housing equipped with thermocouples that is attached to the thermal interface structure before closing the vacuum chamber for testing.

IV. CONCLUSION

This work presents the launch statistics of the ENPULSION FEEP propulsion systems. We present statistics of the spacecraft equipped with FEEP propulsion systems based on BOL altitude, as well as distribution of spacecraft mass, showing the large variety of platforms, orbits and applications the standardized propulsion systems are being used. We then present an update to the interface NANO R^3 integration interface and present selected testing performed on the NANO R^3.

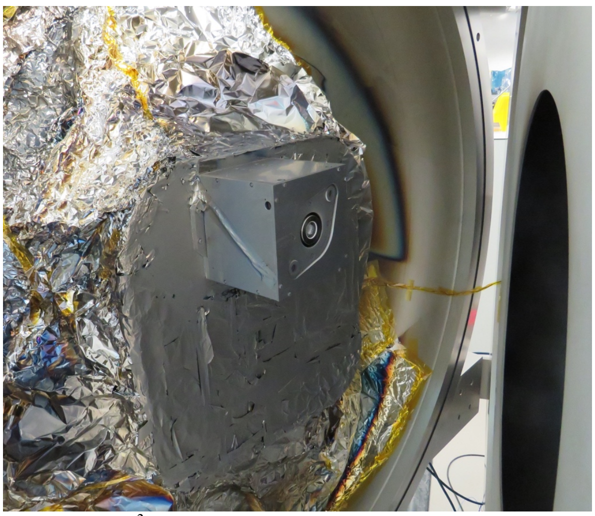


Fig. 7 NANO R^3 during thermal correlation testing housed within test enclosure which is mounted on the thermal interface system.

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