FLIGHT HERITAGE AND STATUS OF THE ENPULSION PROPULSION SYSTEMS: NANO, NANO R3/AR3 AND MICRO R3

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KEYWORDS: FEEP, Flight heritage, Field Emission Electric Propulsion, Micropropulsion

ABSTRACT:

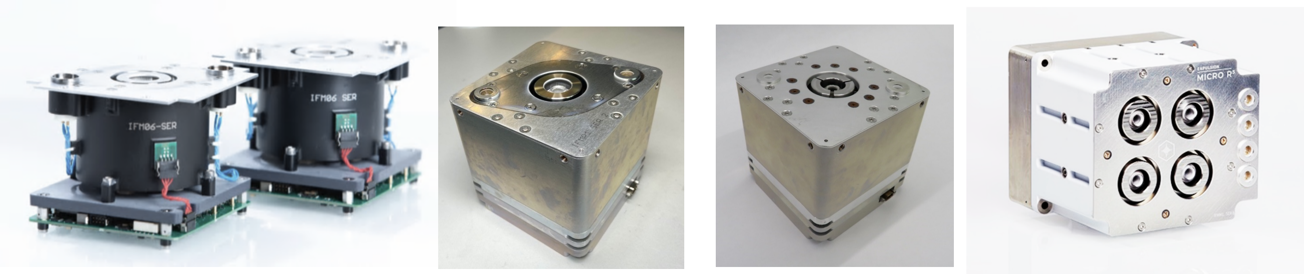
Since the first flight of a Field emission electric propulsion (FEEP) thruster in 2018, 190 heritage ENPULSION NANO systems, 18 higher power MICRO systems and 9 novel NANO R^3/AR^3 systems have been launched. All propulsion systems reported in this work are based on passively fed, Indium based liquid metal FEEP technology that was developed at AIT and later FOTEC, and in which thrust is generated through electrostatic acceleration of ions extracted from a liquid propellant. To achieve this, the liquified metal propellant is suspended in porous, sharp emitter features and biased to high voltage with respect to a counter electrode to induce a Taylor cone on top of the emitter feature. To increase thrust, multiple of these emission sites have been 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 thruster, allowing thrust levels at nominal 1mN. Depending on emitter and extractor voltage settings, propulsion systems can be operated in a specific impulse range from approx. 1000s to beyond 4000s.

1. INTRODUCTION

Field emission electric propulsion (FEEP) thrusters have been able to accumulate a significant amount of flight heritage since the first in orbit validation in 2018 [1,2]. This paper describes the update of the available flight data including notable on orbit applications, discusses data availability and presents an update of the status of the FEEP based propulsion systems NANO R^3 and MICRO R^3.

2. FEEP PRINCIPLES

FEEP propulsion generate thrust by electrostatic acceleration of metal ions. Ionization is achieved from a liquid propellant applying high electrostatic fields between the metal propellant and an extractor electrode. In the ENPULSION FEEP systems, Indium, which is solid at room temperature during integration, AIT and launch, is liquified once in space and used as metal propellant. To achieve the field strength necessary for ionization, the Indium propellant is supported by sharp emitter structures to locally incrase the field strength by means of geometric field enhancing at the sharpened tips. When applying the high voltage potential difference between the liquid and the extractor electrode, a so-



a) b) c) d)

Figure 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

called Taylor cone forms at the tip of the emitter needle, balancing the electrostatic pull and the surface tension of the liquid. The shapr nature of the Taylor cone further enhances the local field strength towards the apex, resulting in ion emission when surpassing the necessary threshold. In ENPULSION FEEP systems, porous emitter structures are used, enabling passive propellant flow from the attached reservoir. To increase the total ion current, multiple emitter needles are arranged in parallel, forming the so called "Emitter crown".
The extractor counter electrode is arranged in a circular fashion surrounding the ion emitter crown to allow for high transparency of the ejected ions while supporting the electrostatic field used for ion extraction and acceleration. This crown shaped ion emitter geometry has a long development heritage [3] and cumulated in the design of the NANO thruster [4]. In a recent development, leveraging the spatial distribution of the emission sites around the emitter crown, the ENPULSION NANO AR3 propulsion system was developed, the uses three different counter extractor elements surrounding the emitter crown. The electric potential of these segments can be individually controlled by the onboard electronics, allowing to throttle the ion emission from the emitter crown spatially, changing the overall thrust vector which is a sum of all individual ion emission beamlets.

3. THRUSTERS

Based on the significant heritage in testing, production and on orbit gained on the heritage NANO thruster that was used in the first in orbit verification in 2018, several successor propulsion systems have been developed: The NANO R^3 as improved version of the NANO featuring among other improvements higher tolerant electronics and improved mechanical design to simplify integration [5], the NANO AR3 that introduces thrust vector control without movable parts [6], and the increased power MICRO R3 which expands thrust range beyond 1 mN. All of these new propulsion systems have been successfully operated on orbit and are shown in Fig. 1. Ground based thrust measurements have been performed for each unit at different facilities, as reported in Refs 7 to 9.

4. FLIGHT HERITAGE

4.1. NANO AR³ in GEO

The NANO AR³ is a configuration of the NANO R3 propulsion system that allows to actively steer the thrust vector by differentially throttling different sections of the ion emitter crown. This technique allows to account for center of gravity mismatch to prevent torque build-up, or to desaturate momentum wheels. This makes this thruster particularly interesting in applications for which other means of attitude control can be less effective such as orbits outside of LEO.

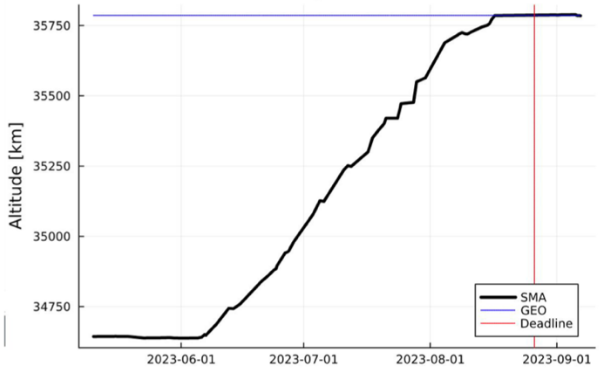


Figure 2. Semi-major axis of a Cubesat acquiring geostationary orbit after launch using multiple AR3 (taken from Ref. 10)

Several NANO AR3 have been successfully in a smallsat mission operating in geostationary orbit, providing thrust for orbit acquisition, transfer to drift orbits to change orbital slots and to reduce wheel momentum [10,11].

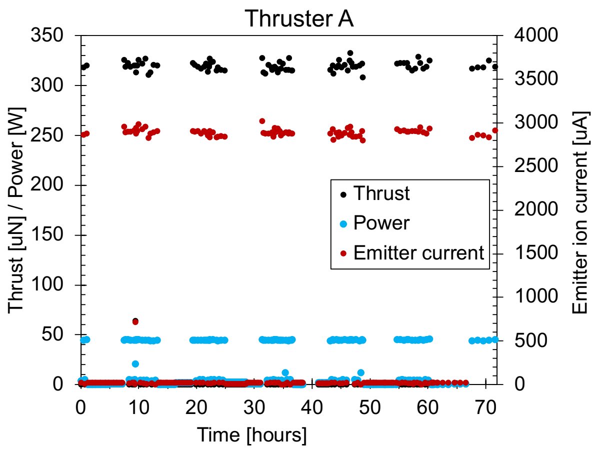


Figure 3. NANO AR³ thrust, total system power including neutralization and propellant heating and ion emission current [11]

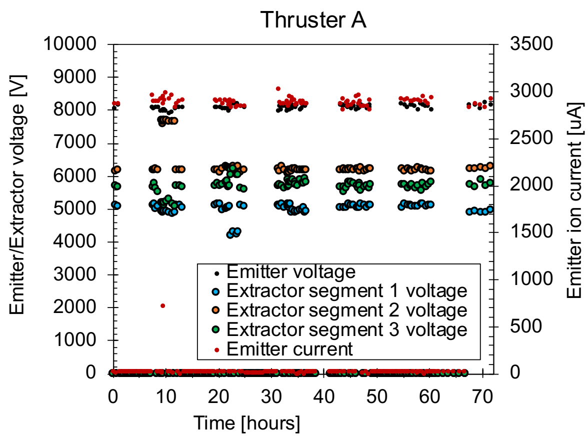


Figure 4. NANO AR³ emission voltage and current, as well as extractor segment voltages used to control thrust vector [11]

Fig. 3 shows telemetry of multiple thrust samples of one of the thrusters, displaying thrust, total system power and ion emission current.
Fig. 4 shows the corresponding emitter current and emitter voltage telemetry, together with the three extractor voltages. Note that the difference in extractor segment voltages applied in this telemetry sample result in the commanded thrust vector by amplifying the emission current towards the geometrical side of higher biasing voltage.

4.2. Extractor Cleaning

During Taylor cone-based emission of charged particles as used in FEEP, the ion emission is accompanied by emission of quasi neutral droplets. These low energy droplets can condense on surfaces that are in direct line of sight, including the extractor electrode, leading to a shrinkage of the spacing between emitter and extractor when accumulating over long firing periods. An example of such extractor shrinking observed during the 50.000 hour test conducted on a FEEP emitter at FOTEC is shown in Ref. [12,13] where extractor shrinkage over thousands of hours was investigated.
Removal of the attached Indium from the extractor electrode has been confirmed to restore firing conditions after extended accumulated firing durations beyond 1000 hours. Based on these results, extractor cleaning experiments, during which the thruster was able to remove the accumulated propellant by ways of changing the operational parameters, have been conducted. While suffering from limitations introduced by the gravitational environment, these experiments have been used to develop cleaning procedures for on orbit operations.

Using these procedures, an extractor cleaning was successfully conducted in LEO after more than 1000 hour of accumulated thrusting time using a heritage NANO propulsion system, and will be presented in a later publication [14].

5. FLIGHT STATISTICS

5.1. Launch Statistics

At time of manuscript submission, over 200 FEEP propulsion systems have been launched, not considering propulsion systems lost in launch accidents. Tab. 1 provides an overview of the launch statistics per propulsion system type. While the majority of FEEP systems on orbit continues to comprise of heritage NANO propulsion systems that remain at high launch cadence, the updated flight statistics also reflects the successful introduction of the successor products NANO R^3/AR^3 and MICRO R^3 reflected in increased numbers being deployed.

Table 1. Launch statistics of the ENPULSION FEEP propulsion systems per type

Propulsion System	Number of s/c	Number of Thrusters	Different launches
NANO	85*	190*	24*
NANO R^3 / AR^3	6	9	6
MICRO R^3	12*	18*	8*

*Annotation: *Propulsion systems lost due to launch vehicle failures not included*

Fig. 5 shows an updated the launch history of the heritage NANO propulsion system, with 190 propulsion systems launched to date and continuing high launch cadence.

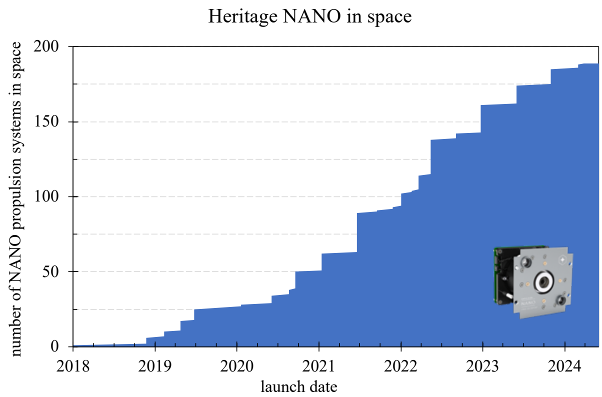


Figure 5. Updated launch history of the ENPULSION NANO propulsion system

5.2. Flight telemetry availability

The limited visibility on flight data, as well as biases introduced by the fact that access to telemetry is often coinciding with specific mission stages such as commissioning, while less visibility is generally possible during regular operations, has been discussed previously [15,16]. In an effort in 2022/2023 to gain visibility on historical telemetry, a significant increase in the available historical data could be achieved for the timeframe up to 2022, increasing the flight telemetry available for this period by almost a factor of approximately 3 compared to previously presented data availability, and confirming previous assumptions on data visibility. Fig 5 shows the currently available telemetry, including a significant increase for the time period previously reported [16]. Data reported includes a 20% margin to account for telemetry overlap.

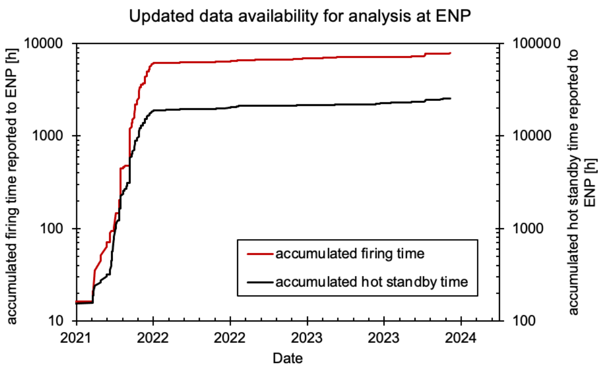


Figure 6. Updated flight telemetry data availability of ENPULSION NANO propulsion system at ENPULSION showing the increase in data made available compared to previous reportings

To date, multiple individual propulsion systems, including R^3 systems, have surpassed accumulated firing times beyond 1000 hours of operations.

6. PROPULSION SYSTEM STATUS

6.1. Extractor design update

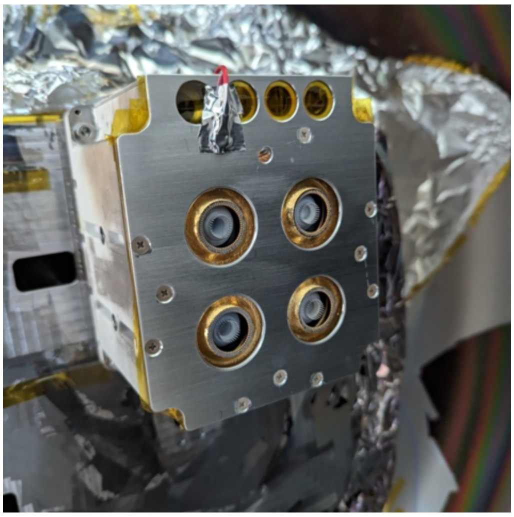


Figure 7. Micro R^3 engineering model equipped with novel extractor design to enhance cleaning capability during subcomponent validation testing

Based on lessons learnt in previous ground test campaigns, FOTEC has developed a novel extractor geometry that improves the cleaning capability and allows in gravity validation [17], validated during successful testing beyond 5000 hours. This novel extractor design will be integrated in the ENPULSION NANO R^3 and MICRO R^3 propulsion systems. Fig. 7 shows an engineering unit of a MICRO R^3 thruster during subsystem validation testing. Fig. 8 shows a closeup of one of the emitter-extractor pairs of a Micro R^3 featuring an early version of the novel extractor design during testing.

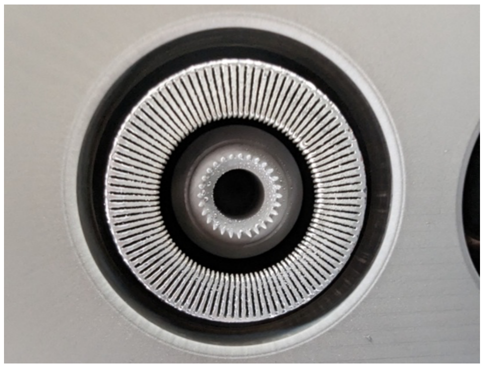


Figure 8. Detailed view of one of the four emitter-extractor elements of a Micro R^3 engineering model equipped with a novel extractor design

6.2. NANO R3 Qualification Testing

Fig. 9 shows a NANO R^3 propulsion unit mounted in the protective test enclosure, equipped with thermocouple to monitor thruster top plate temperature.

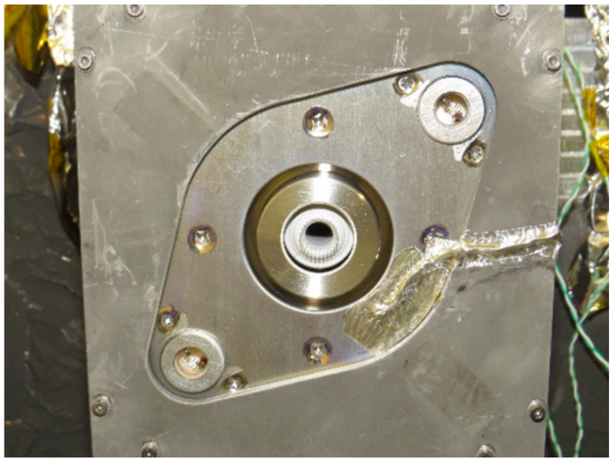


Figure 9. NANO R3 propulsion system mounted in protective test enclosure

Direct thrust measurements were performed on FOTEC's micro thrust balance. Fig. 10 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.

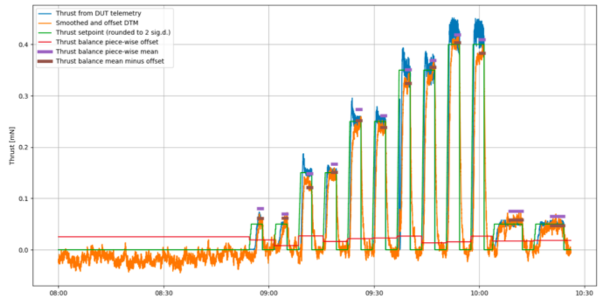


Figure 10. Thrust measurement of the NANO R^3 using the FOTEC micro thrust balance comparing the directly measured thrust to thrust telemetry based on the internal NANO R^3 thrust model

6.3. MICRO R^3 Qualification Testing

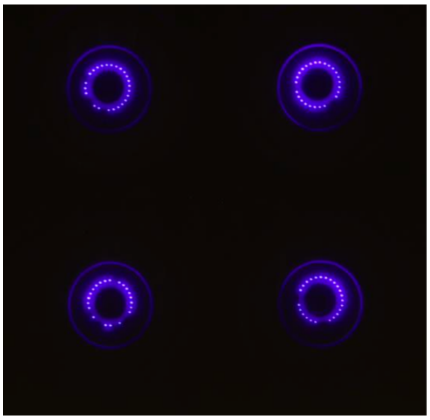


Figure 11. Close up of the MICRO R^3 ion emission sites during direct thrust measurement

Direct thrust measurements of the MICRO R^3 were performed at FOTEC facilities [18,19]. An image of the emissions sites during direct thrust measurement is shown in Fig. 11.

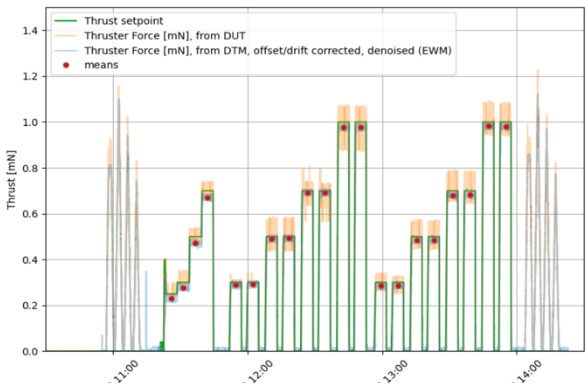


Figure 12. Thrust measurement acquired by FOTEC thrust balance compared to thrust calculated by the internal thrust model used by the MICRO R^3

Fig. 12 shows the thrust measurements recorded by the FOTEC thrust balance, compared to the MICRO R^3 onboard thrust model which is based on measured ion emission parameters. The data presented includes thrust balance calibration performed before and after the thrust measurements to allow drift corrections.

Beam diagnostic measurements of the MICRO R^3 were conducted in FOTEC's large vacuum facility [20]. Fig. 13 shows a scan over the hemisphere using Faraday probes for a high thrust point above 1mN.

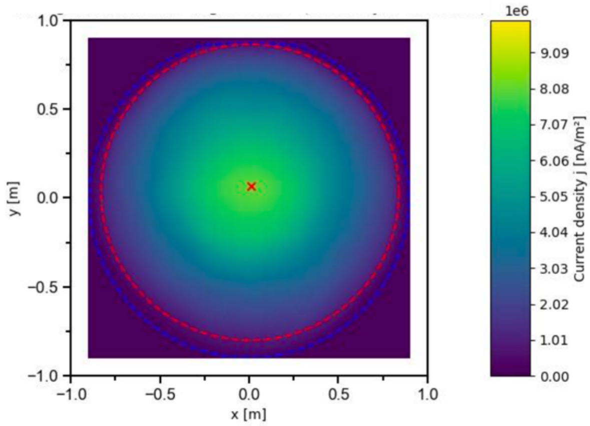


Figure 13. Full beam Faraday probe of a facility MICRO R^3 acquired using the FOTEC beam measurement facility

7. CONCLUSION

With over 200 FEEP propulsion systems deployed in space within the recent yeas, a significant amount of flight heritage becomes available to inform new FEEP propulsion system design. In this work we present an updated flight heritage statistics and discuss increased data availability. To date, all 4 different propulsion systems based on the heritage ion emitter have achieved flight heritage, including the increased power MICRO R^3, and the updated NANO R^3 propulsion systems. We present telemetry and applications of selected on orbit use cases. We then present and discuss design updates currently conducted to enhance the insitu cleaning capabilities of FEEP thrusters, and present selected tests from the ongoing NANO R^3 and MICRO R^3 qualification test campaign, including full beam scan of the MICRO R^3 at high thrust.

ACKNOWLEDGEMENT

ENPULSION wants to acknowledge sincerely the support from ESA within the context of the ARTES (ESA-CSC), InCubed (ESA-EOP), and TDE (ESA-TEC) programs.

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