NanoFEEP on UWE platform - Formation Flying of CubeSats using Miniaturized Field Emission Electric Propulsion Thrusters

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Abstract: **The capability of formation flying of CubeSats would enable novel scientific and technological mission objectives on pico-satellites. Therefore Wuerzburg University, Zentrum fuer Telematik and TU Dresden are planning a mission to demonstrate formation flying of 1U-CubeSats with an envisaged electric propulsion system to achieve two axis attitude control and orbit control developed by TU Dresden. To realize a CubeSat formation flight, a highly power efficient, light-weight and space-saving propulsion system is needed. In order to satisfy these requirements, TU Dresden is currently developing a highly miniaturized field emission electric propulsion system, called NanoFEEP. These miniaturized field emission thrusters (volume less than 3cm^3, weight <6g) are capable of generating continuous thrusts from sub-µN up to 8µN with peaks up to 22µN each. Using Gallium as propellant with its low melting point of 30°C together with power efficient electronics a very low power consumption of the whole propulsion system is achieved, rendering the application on board of a 1U CubeSat possible. To realize two axis attitude control and orbit control four thrusters will be placed on one side of the UWE (University Wuerzburg Experimental) CubeSat platform. Our paper will review and summarize the latest developments and analyze the performance and capabilities of the attitude and orbit control system using miniaturized FEEP thrusters as well as its integration into the UWE CubeSat platform.**

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I. Introduction

PICOSATELLITES like CubeSats are very attractive for universities or research institutes as they enable launching their own satellites for education purposes or testing and qualifying new technologies. Though, science-driven missions on CubeSats are still strongly limited as there is a lack of a proper attitude and orbit control (AOC) systems with high accuracy and the capability of orbit maneuvering[1]. These features would for example be necessary for formation flying of CubeSats which would enable completely new mission scenarios. Due to the strongly limited mass, size and available power on CubeSats as well as due to the restraint of the use of pressurized vessels in the CubeSat standards[2], only highly efficient and lightweight propulsion systems like electric propulsion (EP) systems are reasonable to achieve precise AOC on CubeSats.

Facing these challenges, Wuerzburg University and TU Dresden will combine their expert knowledge in a future joint mission to demonstrate this enabling technology for formation flying of CubeSats based on the UWE (University Wuerzburg Experimental) platform design. Wuerzburg University, the first German university which launched a CubeSat, with its vast experience through the CubeSat missions UWE-1 to UWE-3, will contribute their expertise in CubeSat platform designing and informatics while TU Dresden will provide their highly miniaturized Field Emission Electric Propulsion (FEEP) system, called NanoFEEP[3], to enable orbit maneuvering as well as attitude control capabilities on a 1U-CubeSat.

II. Highly Miniaturized FEEP Thruster - NanoFEEP

To enable attitude and orbit control on a CubeSat with its typical limitation in power and weight, TU Dresden is developing a highly miniaturized field emission thruster, called NanoFEEP. The general working principle of a field emission thruster is illustrated in Fig. 1.

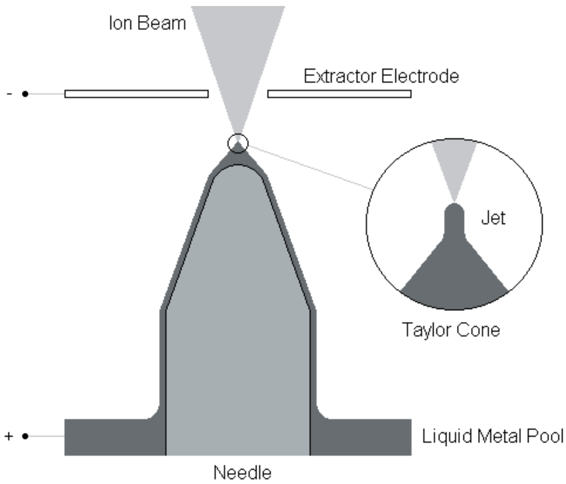

Figure 1. Basic principle of Field Emission Electric Propulsion (FEEP), needle type. [4]

By applying a high voltage potential between a sharp needle tip which is wetted with the liquid metal propellant and an extractor electrode a so called Taylor cone generates. This Taylor cone is caused by the interplay of the liquid metal's surface tension and the applied electric field. If the electric potential is high enough, the evaporation field strength of about 10^{10} V/m is reached at the tip of the jet which sits on top of the Taylor cone and the liquid metal is evaporated and ionized. The generated metal ions are accelerated by the same electric field and exit the extractor electrode. Velocities of more than 100 km/s are possible, depending on the used propellant. With this concept a very high specific impulse of several thousand seconds and thrusts in the µN range can be achieved.

A. Thruster Design of NanoFEEP

With respect to the limitations of available power and weight on a CubeSat, our main goals in the thruster design were miniaturization and power efficiency. A cut away view of our NanoFEEP module is shown in Fig. 2. To achieve a highly efficient and stable ionization we use our novel porous Liquid Metal Ion Source (LMIS) which consists of a very sharp, electrochemically etched porous tungsten needle and a tantalum reservoir filled with the metal propellant[2]. The open porosity of the tungsten needle provides capillary forces, which hold the liquid metal propellant at the needle tip, and enables self-feeding propellant flow during operation. Thus, no valves or propellant feeding devices are required. The porous LMIS is heated up by the heater assembly and is supported by thermal and electrical insulations which shape is optimized by thermal simulations to minimize thermal losses. With this thermal optimization of the thruster geometry, only 50 to 90mW of heating power (depending on satellite structure temperature) are necessary to keep the propellant liquid at a temperature of 50°C. Furthermore Gallium with its low melting temperature of approximately 30°C is used as propellant to keep down the power demand for melting the propellant compared to commonly used propellants, like Indium with a melting temperature of 157°C.

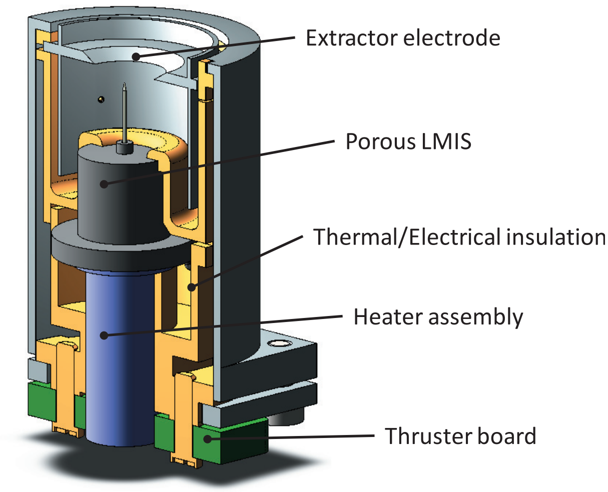

Figure 2. Cut away view of the NanoFEEP CAD model.

To avoid short circuits between the LMIS on high voltage potential and the extractor electrode during long term operation the NanoFEEP module features labyrinth shielding. Thus, possible surface contamination of the inner insulation structure with the electrically conductive propellant caused by micro-droplets will not affect long term operation. The major reason for the given limit of operating time of approximately 1,800h is due to the used amount of propellant (0.25g Gallium per thruster). This maximum operation time is thought to be sufficient for the first precursor mission, but it can be enhanced easily in future missions by using larger reservoirs of the LMIS. Though, the dimensions of the thruster would need to be adjusted in that case.

With the presented NanoFEEP design a field emission thruster could be miniaturized down to Ø13x21mm with a total weight of less than 6g and a volume of less than 3cm^3 per thruster. Figure 3 shows one manufactured NanoFEEP thruster compared to a one Euro coin to visualize the thruster size. A further miniaturization of the thruster is currently under investigation as saving only a few Millimeters in size would strongly simplify the thruster integration in a 1U-CubeSat.

Figure 3. Manufactured, highly miniaturized NanoFEEP thruster; Thruster size compared to a 1 € coin.

B. Thruster Performance

First tests were performed to determine the functionality of the miniaturized thruster design and to roughly characterize the thruster performance. As it can be seen in Fig. 4, stable operation of the thruster with the novel porous LMIS running with Gallium propellant could be demonstrated indicated by the characteristic violet light emission at the needle tip.

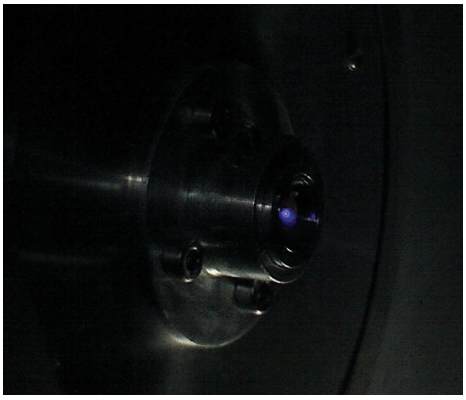

Figure 4. Operating NanoFEEP thruster, tested at the TU Dresden laboratory.

A typical current-voltage characteristic (begin of life) of a NanoFEEP thruster is shown in Fig. 5. NanoFEEP typically starts operating at a voltage between 3.3 and 4kV. The starting voltage increases with operation time to approximately 6 to 7kV while the slope of the current-voltage characteristic, in other words the impedance, decreases. Considering this typical behavior of FEEP thrusters with needle emitters and adding a safety margin to the required voltage range, a high voltage demand of 12kV is defined as maximum for the required power processing unit. NanoFEEP was tested up to an emission current of 250µA which corresponds to a thrust of approximately 22µN without any problems. This emission current limit of 250µA is due to the specified maximum available output current of the high voltage converter which shall be used on the CubeSat platform. However, a maximum emission current of 100µA corresponding to a thrust of approximately 8µN is recommended for long term operation (more than a hundred hours) to prevent needle erosion.

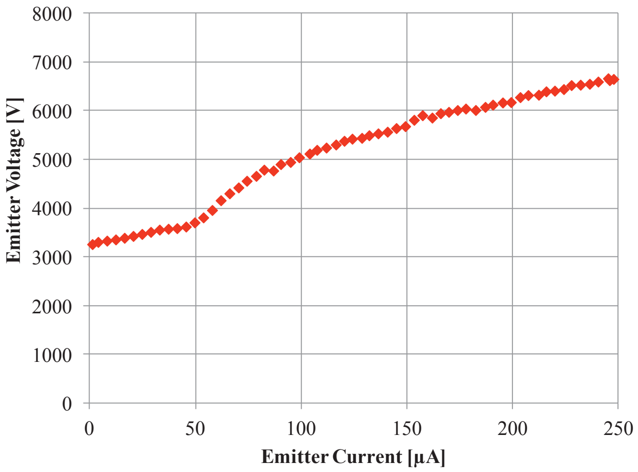

Figure 5. Current-Voltage Characteristic of NanoFEEP.

Additionally, tests were performed to determine the mass efficiency of the novel porous needle LMIS with Gallium propellant used in the NanoFEEP thrusters.[3] During these mass efficiency tests, the LMIS was operating at different constant emission currents and was weighed before and after each test run. Mass efficiency was then calculated by comparing the exhausted charge to the mass difference. The calculated mass efficiency showed the typical exponential decline with increasing emission currents. This decline is due to the increasing amount of unionized droplets at higher emission currents. For calculating the specific impulse of NanoFEEP as a function of thrust, shown in Fig. 6, the described mass efficiency as a function of emission current was used. This is the reason for the decline in specific impulse for higher emission currents which can be seen in Fig. 6.

The generated thrust was calculated analytically using the measured emission current and assuming a constant beam divergence factor of 0.8. To verify the used analytic formulas for thrust and specific impulse it is planned to test the NanoFEEP thruster on our newly developed thrust balance[5] in the near future. Besides measuring the generated thrust directly on a thrust balance, it is also planned to measure the spatial beam divergence of the NanoFEEP module as a function of thrust with a plume diagnostic facility, which is currently under development at TU Dresden.

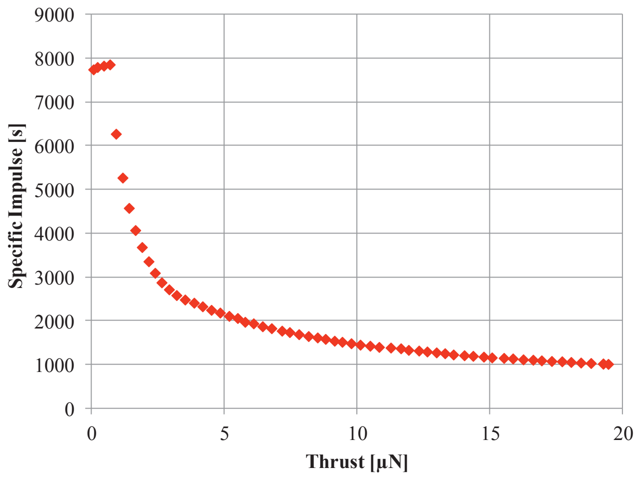

Figure 6. Specific Impulse over thrust range of NanoFEEP, considering decreasing mass efficiency at higher emission currents, respectively higher thrusts.

Besides the mentioned performance tests a first engineering model of the power processing unit (PPU) for NanoFEEP was also tested.[3] This PPU was designed regarding the CubeSat specifications using off-the-shelve DC-to-HV-DC converter from EMCO (two AH60 models in series) to apply the required maximum high voltage of 12kV and the maximum current of 250µA. Though, analyses of the total power demand of this PPU showed a quite poor overall power conversion efficiency of 14-28% depending on the applied thrust level. This low efficiency is due to the low power conversion efficiency of the EMCO DC-to-HV-DC converter especially at low power output. Therefore TU Dresden is currently developing a completely new PPU in cooperation with a local electronics company (GBS Elektronik) with the goal to significantly increase the power conversion efficiency of the PPU. This will significantly improve the possible thrust capabilities of NanoFEEP on a CubeSat with its strong power limitations.

III. CubeSat platform UWE

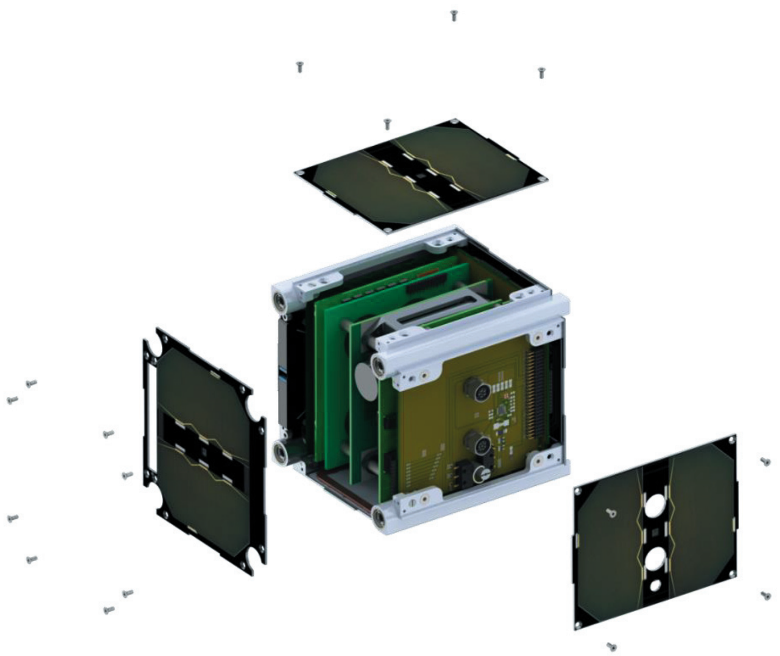

Figure 7. The UWE CubeSat platform with integrated NanoFEEPs in the bars.

The UWE satellites are built from a modular and flexible platform first introduced with UWE-3[6] which was launched in 2013.[7] The satellite bus is shown in Fig. 7 and consists of several subsystems and the multifunctional panels which are interconnected via a backplane using a standardized interface. The platform was developed with focus on low power consumption, high modularization and high reliability by employing redundancies on all essential systems. Therefore, the satellite's on-board data handling system (OBDH) carries two redundant ultra-low-power microcontrollers capable of supervising and repairing each other.[8] The power subsystem is built from two redundant batteries with each power bus having its own set of power regulators. Power switching is distributed to each subsystem that are all fed from the same regulated 3.3V, 5.0V and unregulated 4.2V power busses. The switches are included in the standardized interface and also feature latch-up protection, over- and under-voltage protection as well as power monitoring capabilities.

The UHF communication system carries two antenna/transceiver pairs in redundancy, which are connected to the OBDH via separate communication interfaces. The attitude determination and control system (ADCS), which was in the case of UWE-3 the technical payload of the satellite, computes the satellite's attitude based on magnetometer, sun-sensor and gyroscope data in real-time with update times as high as 30ms and a determination accuracy of about 2°-5°. Attitude control primarily is achieved using magnetic torquers, while UWE-3 also carried a single reaction wheel for fast slew maneuvers.[9] The ADCS is also built as a very low power system and consumes during nominal operation only between 15mW and 60mW which makes it possible to be activated under all operating conditions of the satellite.[10] By incorporating electric propulsion into the platform this system will be extended towards AOCS capabilities. The multi-functional side panels accommodate the solar panels, maximum-power-tracking, sun-sensors, secondary magnetometers, and magnetic torquers and are therefore an integral part of the satellite. A Front-Access board (FAB) ensures access to the satellite's systems even after final integration.

The UWE platform is easily extendible due to its high modularization. New subsystems, such as the electric propulsion system's power processing unit (PPU), are equipped with the standard interface and are therefore directly compatible with the satellite bus. Furthermore, the philosophy promotes testing at subsystem and satellite system level in a flat-sat configuration as well as in full integration.

Future developments of the platform aim for all necessary technologies in order to demonstrate formation flying at the pico-satellite form factor. Developments are in parallel carried out at the Zentrum fuer Telematik (ZfT) in the scope of the European Research Grant NetSat.

IV. Potential integration of NanoFEEP thruster on UWE platform

The integration of NanoFEEP into the UWE platform will be carried out in cooperation of the TU Dresden with the University Wuerzburg and the Zentrum fuer Telematik. The two systems to integrate are the thruster heads and the power processing unit. Due to the standardized setup of the UWE platform, the placement of the PPU in the satellite can be chosen in order to optimize the mechanical behavior of the satellite. This includes the satellite's frequency response and center of mass as well as thermal balancing. The PPU will be supplied from the 3.3V and the unregulated 4.2V power bus in order to supply the micro-controller and the high voltage conversion, respectively. The unregulated bus ensures that no additional voltage conversion losses are present in the highly demanding HV track. The system will be protected and interfaced with the standard UWE interface with its inherent power switching, latch-up and over-/under-voltage protection.

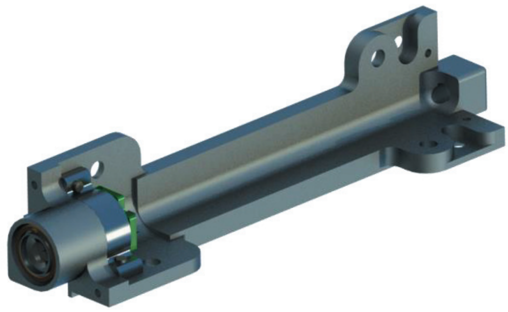

Figure 8. An UWE bar with integrated NanoFEEP.

The placement of the thruster heads is still an on-going development. As shown in Fig. 8 it is being investigated if a placement in the satellite's bars is feasible and advantageous. Currently, the integration can be achieved but might imply certain constraints also related to the launch adapter. With the integration in the bars, the thruster could not only be used for orbit control but will also contribute to attitude control. However, for efficient orbit control it is required to operate two diagonally located thrusters at the same time. Mechanical and thermal simulations show that this solution would withstand the expected orbital and launch loads.

In a different approach, the thruster heads are placed close to the PPU and exit the satellite through the Y-panels where there are exit ports foreseen on the panels. While the integration itself poses much less challenges in this design, the benefit for the satellite platform is decreased due to the limited capabilities to use the thrusters for attitude control. Furthermore, the placement of the PPU is then restricted which complicates the correct placements of other components in order to ensure an advantageous center of mass of the satellite. The exact number of thrusters that would fit into the satellite having this integration method is currently anticipated with at most two (one in each Y-direction). Therefore, the integration of the thruster heads into the satellite's bars is the primary option. Mechanical and electrical issues will be addressed throughout the next months.

V. Performance and capabilities of attitude and orbit control system

For the purpose of a preliminary estimation of the capabilities of a NanoFEEP propulsion system an altitude lowering with multiple thrust maneuvers is simulated using Orekit[11]. For orbit control on the UWE platform, four NanoFEEP thrusters are integrated pointing in the same direction. According to Ref. 3 a thrust generation of 2µN requires a total power of 700mW for one thruster. For efficient orbit control two thrusters with 2µN thrust each are activated in anti-in-track direction for only 10% of an orbit. This maneuvering is done symmetrically around the apogee, thus reducing the apogee velocity and the perigee altitude. Lowering the perigee altitude will have a secondary influence on the specific orbital energy due to the increased atmospheric drag at lower altitudes. The simulation is initialized using a Two-Line-Element of the UWE-3 satellite from 1st January 2014.

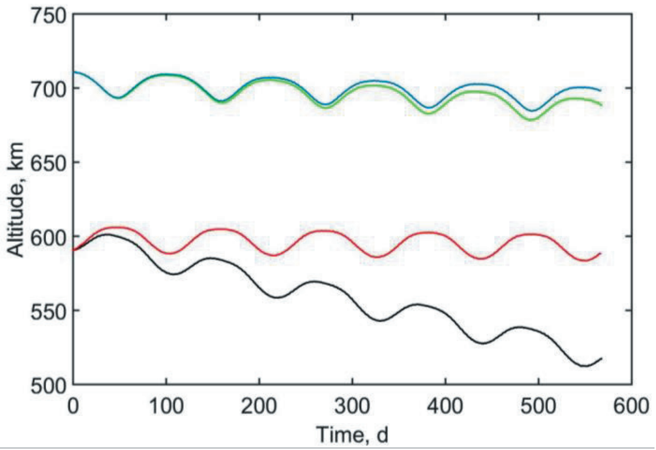

Figure 9. This figure shows the natural progression of apogee (blue) and perigee (red) in comparison to the apogee (green) and perigee (black) progression using NanoFEEP thrusters for orbit control.

The results of this simulation are shown in Fig. 9. After 550 days the perigee would be at an altitude of 512km in contrast to 583km when following natural progression of the orbit without any orbit control. This strategy would contribute strongly to de-orbiting small spacecraft using solely electric propulsion. The necessary propellant mass is less than 0.4g of Gallium.

In terms of attitude control, only the integration option in the satellite's bars is valuable. The attitude control system primarily works with the magnetic torquers as actuators, which typically produce torques in the order of a few µNm. A single thruster head located at the tip of one bar can produce torques up to 1.4µNm, two thrusters in parallel torques of up to 2µNm. Therefore, the inclusion of the thrusters into the attitude control system will be limited to a supporting role during thrust maneuvers. However, the attitude determination system can very well be employed to verify the performance of the electric propulsion system during in-orbit operations.

VI. Conclusion and Outlook

First prototypes of the novel highly miniaturized FEEP thruster, named NanoFEEP, were manufactured, characterized and first performance tests have been executed. These first tests showed that an application of NanoFEEP thrusters on a CubeSat platform is feasible considering typical space, weight and power limitations of CubeSats. It was also shown that the integration of the NanoFEEP propulsion system on a 1U-CubeSat like the UWE platform is possible. Moreover, first results of the capability of an attitude and orbit control system using four NanoFEEP thrusters accommodated in the CubeSat bars were presented. The results of these simulations showed how the use of two parallel working NanoFEEP thrusters operating for only 10% of an orbit with 2µN thrust each are able to decrease the perigee more than 60km compared to natural progression consuming only 0.4g of the Gallium propellant. Regarding these results de-orbiting maneuvers or necessary maneuvers for the altitude regulation for e.g. formation flying of CubeSats seem possible.

Next steps in development will be:

- Performing of long-term operation tests to detect possible lifetime related issues of NanoFEEP
- Direct measurement of generated thrust by using a thrust balance
- Measuring of beam divergence with the plume diagnostic facility
- Investigating further miniaturization of the NanoFEEP thruster heads
- Finishing the development of the new power processing unit with increased power conversion efficiency
- Finalizing the electrical and mechanical integration of NanoFEEP thrusters into the UWE CubeSat platform

Acknowledgments

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